Hazus Tsunami Model Technical Manual

Hazus 6.1

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Acronyms and Abbreviations

Acronym/ Abbreviation	Definition
AEBM	Advanced Earthquake Building Model
AGL	Above Ground Level
ASCE	American Society of Civil Engineers
C	Complete Damage State
CON	Contents
DART	Deep Ocean Assessment of Tsunami
DDFs	Depth-Damage Functions
DEM	Digital Elevation Model
DOGAMI	Department of Geology and Mineral Industries
E	Extensive Damage State
EERI	Earthquake Engineering Research Institute
EGLA	Energy Grade Line Analysis
EOC	Emergency Operations Center
EQ	Earthquake
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
fps	Feet per second
ft	Foot/feet
ft^2	Square Feet
GBS	General Building Stock
GEBCO	General Bathymetric Chart of the Ocean
GIS	Geographic Information System
km	Kilometer
LEHD	Longitudinal Employer-Household Dynamics
LNG	Liquified Natural Gas
M	Earthquake Magnitude
M	Moderate Damage State
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
MOST	Method of Splitting Tsunami
MSL	Mean Sea Level
NCTR	NOAA Center for Tsunami Research
NGDC	National Geophysical Data Center
NIBS	National Institute of Building Sciences
NOAA	National Oceanic and Atmospheric Administration
NSA	Nonstructural Acceleration-Sensitive Systems
NSD	Nonstructural Drift-Sensitive Systems
NSI	National Structure Inventory
NSS	Nonstructural Systems
NTHMP	National Tsunami Hazard Mitigation Program
ORNL	Oak Ridge National Labs
PEER	Pacific Earthquake Engineering Research Institute
PMEL	Pacific Marine Environmental Laboratory
PTH	Potential Tsunami Hazards
S	Slight Damage State

Acronym/ Abbreviation	Definition
SBT	Specific Building Type
SCHEMA	Scenarios for Hazard-induced Emergencies Management
SDCs	Seismic Design Categories
SLTT	State, Local, Tribal, and Territorial
STD	Standard Deviation
sec	Second
Sec^2	Square Second
SIFT	Short-Term Inundation Forecasting for Tsunamis
SRSS	Square-root-sum-of-the-squares
STR	Structure
TIGER	Topologically Integrated Geographic Encoding and Referencing
TS	Tsunami
UDF	User-Defined Facility
USACE	U.S. Army Corps of Engineers
USGS	United States Geological Survey
WDS	World Data Service

Section 1. Introduction to the FEMA Tsunami Loss Estimation Methodology

1.1 Background

The Hazus Tsunami Loss Estimation Methodology provides state, local, tribal, and territorial (SLTT) officials with a decision support software for estimating potential losses from tsunami events. This loss estimation capability enables users to anticipate the consequences of tsunamis and develop plans and strategies for reducing risk. The Geographic Information Systems (GIS) based software can be applied to study geographic areas of varying scale with diverse population characteristics and can be implemented by users with a wide range of technical and subject matter expertise.

This Methodology has been developed, enhanced, and maintained by the Federal Emergency Management Agency (FEMA) to provide a tool for developing tsunami loss estimates for use in:

- Anticipating the possible nature and scope of the emergency response needed to cope with a tsunami-related disaster.
- Developing plans for recovery and reconstruction following a disaster.
- Mitigating the possible consequences of tsunamis.

The Hazus Tsunami Model provides the capability to quantify potential building impacts and losses, as well as casualties. The model analyzes the potentially catastrophic tsunami scenarios associated with near-source tsunamis by combining tsunami and earthquake losses, as well as distant-source tsunamis.

The current capability addresses High to Very High Tsunami Risk States and U.S. territories, as defined by the National Tsunami Hazard Mitigation Program (NTHMP). The Tsunami Model itself was developed and implemented from the Tsunami Methodology developed by FEMA in 2013, but is not completely congruous with that methodology, having been modified based on newer developments, or for software development. Estimates can also help guide the allocation of federal resources to stimulate risk mitigation efforts and to plan for a federal tsunami response.

The Hazus Tsunami Model is currently available for the five Very High Risk U.S. states and the five High Risk U.S. territories.

- Alaska
- Washington
- Oregon
- California
- Hawaii

- Northern Mariana Islands (Tsunami only)
- American Samoa (Tsunami only)
- Guam (Tsunami only)
- Puerto Rico
- U.S. Virgin Islands

This *Hazus Tsunami Model Technical Manual* documents the methods used in calculating losses. A companion document, the *Hazus Inventory Technical Manual* (FEMA, 2024), provides more detailed methodology and data descriptions for the inventory shared by each hazard model. Together, these documents provide a comprehensive overview of this nationally applicable loss estimation methodology.

The *Hazus Tsunami Model User Guidance* (FEMA, 2024) outlines the background and instructions for developing a Study Region and defining a scenario to complete a tsunami loss estimation analysis using Hazus. It also provides information on how to modify inventory, improve hazard data and analysis parameters for advanced applications, and guidance on calculating and interpreting loss results.

1.2 Hazus Uses and Applications

Hazus can be used by various types of users with a wide range of informational needs. A state, local, tribal, or territorial government official may be interested in the costs and benefits of specific mitigation strategies, and thus may want to know the expected losses if mitigation strategies have (or have not) been applied. Health officials may want information regarding the demands on medical care facilities and may be interested in the number and severity of casualties for different tsunami scenarios. Emergency response teams may use the results of a loss study in planning and performing emergency response exercises. In particular, they might be interested in the operating capacity of emergency facilities such as fire stations, emergency operations centers, and police stations. Emergency planners may want estimates of temporary shelter requirements for different tsunami scenario events. Federal and state government agencies may conduct a loss analysis to obtain quick estimates of impacts in the hours immediately following a tsunami to best direct resources to the disaster area. Insurance companies may be interested in the estimated monetary losses so they can determine asset vulnerability.

Tsunami loss estimation analyses have a variety of uses for various departments, agencies, and community officials. As users become familiar with the loss estimation methodology, they are able to determine how to use it to best suit their needs and how to appropriately interpret the study results.

The products of Hazus analyses have several pre- and post-tsunami applications in addition to estimating the scale and extent of damage and disruption. Examples of pre-tsunami applications of the outputs include:

- Development of tsunami hazard mitigation strategies that outline policies and programs for reducing tsunami losses and disruptions indicated in the initial loss estimation study. Strategies can involve rehabilitation of hazardous existing buildings (e.g., unreinforced masonry structures), building code enforcement, development of appropriate zoning ordinances for land use planning in tsunami inundation zones, and the adoption of advanced building codes.

- Development of preparedness (contingency) planning measures that identify alternate transportation routes, planning tsunami preparedness, and education seminars.
- Anticipation of the nature and extent of response and recovery efforts including the identification of alternative housing, the location, availability, and scope of required medical services, and the establishment of a priority ranking for restoration of water and power resources.

Post-tsunami applications of the outputs include:

- Projection of immediate economic impact assessments for state and federal resource allocation, and support for state and/or federal disaster declarations by calculating direct economic impact on public and private resources, local governments, and the functionality of facilities in the area.
- Activation of immediate emergency recovery efforts including search and rescue operations, rapid identification and treatment of casualties, provision of emergency housing shelters, and rapid repair and availability of essential utility systems.
- Application of long-term reconstruction plans that include the identification of long-term reconstruction goals, implementation of appropriate wide-range economic development plans for the impacted area, allocation of permanent housing needs, and the assessment of land use planning principles and practices.

1.3 Assumed User Expertise

Users can be divided into two groups: those who perform the analysis and those who use the analysis results. For some analyses, these two groups occasionally consist of the same people, but generally this will not be the case. However, the more interaction that occurs between these two groups, the better the analysis will be. End users of the loss estimation analysis need to be involved from the beginning to make results more usable.

Any risk modeling effort can be complex and would benefit from input from an interdisciplinary group of experts. A tsunami loss analysis could be performed by a representative team consisting of the following:

- Geologists
- Geotechnical engineers
- Structural engineers
- Coastal engineers
- Architects

- GIS specialists
- Economists
- Social scientists
- Emergency planners
- Policy makers

The individuals needed to perform the study can provide valuable insight into the risk assessment process and depend on the desired level of analysis, explained in greater detail in Section 2.3. In addition to subject matter expert involvement, at least one GIS specialist should participate on the team.

If a state, local, tribal, or territorial agency is performing the analysis, some of the expertise may be found in-house. Experts are generally found in several departments: building permits, public works, planning, public health, engineering, information technologies, finance, historical preservation, natural resources, and land records. Although internal expertise may be most readily available, the importance of the external participation of individuals from academic institutions, citizen organizations, and private industry cannot be underestimated.

1.4 When to Seek Help

The results of a loss estimation analysis should be interpreted with caution because baseline values have a great deal of uncertainty. Baseline inventory datasets are the datasets that are provided with Hazus. Further information on these can be found in the *Hazus Inventory Technical Manual* (FEMA, 2024). If the loss estimation team does not include individuals with expertise in the areas described above, it is advisable to retain objective reviewers with subject matter expertise to evaluate and comment on map and tabular data outputs.

If an expert is not available to assist in the selection of tsunami flood depth, velocity, and momentum flux, the user should defer to readily available data provided by the United States Geological Survey (USGS). This will allow users to take advantage of USGS subject matter expertise when defining their deterministic tsunami scenario.

If the user intends to modify the baseline inventory data or parameters, assistance from an individual with expertise in the subject will be required. For example, if the user wishes to change percentages of specific building types for the region, collaborating with a structural engineer with knowledge of regional design and construction practices will be helpful. Similarly, if damage-motion relationships (fragility curves) need editing, input from a structural engineer will be required.

1.5 Technical Support

Technical Support contact information is provided in the Hazus application at **Help|Obtaining Technical Support**; technical assistance is available via the Hazus Help Desk by email at FEMA-Hazus-support@fema.dhs.gov (preferred) or by phone at 1-877-FEMA-MAP (1-877-336-2627). The FEMA Hazus website also provides answers to Frequently Asked Questions, and information on software updates, training opportunities, and user group activities.

FEMA-provided resources also include the Hazus Virtual Training Library, a series of short videos arranged into playlists that cover various Hazus topics, from an introduction to Hazus methodologies, to targeted tutorials on running Hazus analyses, to best practices when sharing results with decision makers. This easily accessible learning material provides quick topic-refreshers, free troubleshooting resources, and engaging guides to further Hazus exploration.

The application's **Help** menu references the help files for ArcGIS. Since Hazus was built as an extension to ArcGIS functionality, knowing how to use ArcGIS and ArcGIS Help Desk will help Hazus users.

Technical support on any of the four hazards is available at the contacts shown via **Help|Obtaining Technical Support.**

1.6 Uncertainties in Loss Estimates

Although the Hazus software offers users the opportunity to prepare comprehensive loss estimates, it should be recognized that uncertainties are inherent in any estimation methodology, even with state-of-the-art techniques. Any region or city studied will have an enormous variety of buildings and facilities of different sizes, shapes, and structural systems that have been built over a range of years, under diverse design codes.

Due to this complexity, there is inherent uncertainty in modeling the structural resistance of most buildings and other facilities. Further, there are not sufficient data from past tsunamis to determine precise estimates of damage based on known momentum flux and tsunami depths, even for specific buildings and other structures. To deal with this complexity and lack of data, buildings and components of infrastructure systems are grouped into categories based upon key characteristics. The relationships between key tsunami features and average degree of damage with associated losses for each building category are based on current data and available theories.

The results of a tsunami loss analysis should not be looked upon as a prediction. Instead, they are only an estimate, as uncertainty inherent to the model will be influenced by quality of inventory data and the hazard parameters. This is particularly true in areas where tsunami events are infrequent or where recorded data is scarce.

Section 2. Introduction to Tsunami Loss Estimation Methodology

This brief overview of the Tsunami Methodology is intended for SLTT officials contemplating a tsunami analysis.

The Hazus Methodologies will generate an estimate of the consequences of a scenario tsunami event to a coastal city, county, or region. The resulting "loss estimate" will generally describe the scale and extent of damage and disruption that may result from the modeled tsunami event. The following information can be obtained:

- *Quantitative estimates of losses* in terms of direct costs for repair and replacement of damaged buildings, direct costs associated with loss of function (e.g., loss of business revenue, relocation costs), and casualties.
- *Functionality losses* in terms of loss of function and restoration times for user-defined facilities provided by the user.

To generate this information, the Hazus Methodology contains baseline inventory data, including:

- Classification systems used in assembling inventory and compiling information on the General Building Stock (GBS), demographic, and economic data.
- Standard calculations for estimating type and extent of damage, and for summarizing losses.
- National and regional databases containing information for use as baseline (built-in) data useable in the calculation of losses if there is an absence of user-supplied data.

These systems, methods, and data have been combined in a user-friendly GIS software for this loss estimation application.

The Hazus software uses GIS technologies for performing analyses with inventory data and displaying losses and consequences on applicable tables and maps. The Methodology permits estimates to be made at several levels of complexity, based on the level of inventory data entered for the analysis (i.e., baseline data versus locally enhanced data). The more concise and complete the inventory information, the more accurate the results.

The following figure provides a graphic representation of the modules that the Hazus Tsunami Model Methodology is comprised of, and their interrelation in deriving estimates.

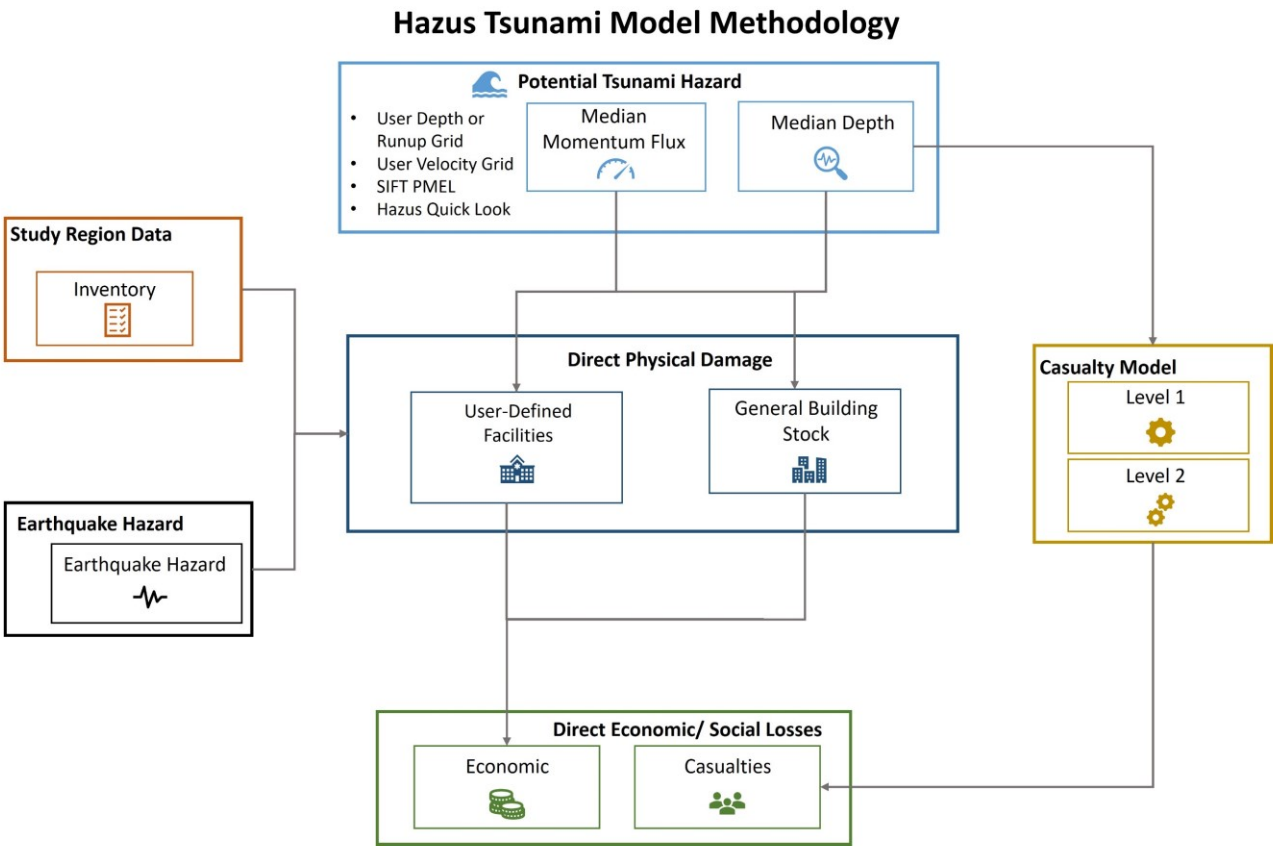

Figure 2-1 Hazus Tsunami Model Methodology Schematic

While Figure 2-1 shows the conceptual relationships, the steps used in the Hazus Tsunami Model are as follows:

- *Select the area to be studied.* The Hazus Study Region (the region of interest) is created based on Census block, tract, or county level aggregation of data. The area generally includes a city, county, or group of municipalities. It is generally desirable to select an area that is under the jurisdiction of an existing regional planning group.
- *Specify the tsunami hazard scenario.* In developing the scenario tsunami, consideration should be given to the availability of data including median momentum flux, median depth, and median velocity grids using National Oceanic and Atmospheric Administration (NOAA) and other datasets, or subject matter experts.
- *Integrate local inventory data.* Include user-defined facilities and updates to GBS characteristics.
- *Use the formulas embedded in Hazus*. Compute probability distributions for damage to different classes of buildings, facilities, and infrastructure system components. Then, estimate the loss of function.
- *Compute estimates of direct economic loss, casualties and shelter needs using the damage and functionality information.*

The user plays a significant role in selecting the scope and nature of the output of a loss estimation analysis. A variety of maps can be generated for visualizing the extent of the losses. Generated reports provide numerical results that may be examined at the level of the Census tract or aggregated by county or region.

2.1 Tsunami Hazards Considered in the Methodology

The Hazus Tsunami Methodology consists of three basic analytical processes: hazard analysis, damage assessment, and impact analysis. In the hazard analysis phase, source characteristics, and bathymetry data are used to model the spatial variation in flood depth, velocity, and momentum flux. During the damage assessment phase, structural, nonstructural, and content damage is calculated based on the results of the hazard analysis using fragility curves. The impact phase translates the severity of tsunami and damage assessment into social and economic losses.

The tsunami-related hazards considered by the Hazus Methodology in evaluating damage, resultant losses, and casualties are collectively referred to as potential tsunami hazards (PTH). Most damage and loss caused by a tsunami is directly or indirectly the result of water velocity and depth. Thus, Hazus evaluates the geographic inundation as a result of a specific tsunami scenario and expresses tsunami characteristics using several quantitative parameters (e.g., median momentum flux, median velocity, and median depth). Most casualties result from drowning and trauma associated from being in the water.

The following two features of tsunamis can cause structural damage and loss of life:

- *Tsunami Momentum Flux*: The transport of momentum acting in the direction of the water flow and is equal to the force per unit area. This tsunami parameter drives the structural damage.
- *Tsunami Depth*: This is the median depth of the tsunami and drives the contents losses and casualty estimates.

2.2 Definitions of Structures

There are differences between terminology used to designate distinctions between types or categories of structures. The term “structure” refers to all constructions, such as a building, bridge, water tank, shed, carport, or other man-made thing that is at least semi-permanent. A building is a structure with a roof and walls that is intended for use by people and/or inventory and contents, such as a house, school, office, or commercial storefront. A facility corresponds to a particular place, generally a building, with an intended purpose such as a school, hospital, electric power station, or water treatment facility. Some facilities are defined as ‘essential facilities’ meaning the facility is critical to maintaining services and functions vital to a community, especially during disaster events. The buildings, essential facilities, and transportation and utility systems considered by the Methodology are as follows:

- *General Building Stock:* The key GBS databases in Hazus include square footage by occupancy and building type, building count by occupancy and building type, building and content valuation by occupancy and building type, and general occupancy mapping. Most of the commercial, industrial, and residential buildings in a region are not considered individually when calculating losses.

Buildings within each Census block are aggregated and categorized. Building information derived from Census and employment data are used to form groups of 36 specific building types and 33 occupancy classes (additional information on the Hazus baseline GBS inventory data is provided in the *Hazus Inventory Technical Manual* (FEMA, 2024). Degree of damage is computed for each grouped combination of model building type and occupancy class.

- *User-Defined Facilities (UDFs)*: Destruction of critical coastal structures could cause significant increase in losses, even if residents were evacuated to safe areas. Critical coastal structures can include schools, hospitals, fire and police stations, shelters and Emergency Operations Centers (EOCs). Since the Hazus Tsunami Model does not yet provide an Essential Facility loss model, these facilities can be modeled as user-defined facilities. Modeling as UDF will provide the user with direct economic losses for both tsunami-only, as well as combined earthquake and tsunami losses.

Specific data can be used to estimate potential damage and hazard effects using UDF module, which is addressed in Section 9 of the *Hazus Tsunami Model User Guidance* (FEMA, 2024).

2.3 Level of Analysis

Hazus is designed to support two general types of analysis (Basic and Advanced), split into three levels of data updates (Levels 1, 2, and 3). Figure 2-2 provides a graphic representation of the various levels of analysis. These are generally defined in Hazus based on the quality of the input hazard data, although improvement of inventory data should always be considered. The hazard data available for tsunami loss modeling frequently does not include velocity data, which is the critical driver of all structural losses in tsunami. Therefore, if the input hazard data lack user supplied velocity, the term Level 1 (Basic) is used. Level 2 (Advanced) is used where both inundation depth and velocity data exist, and Level 3 when the user directly provides momentum flux and depth. In addition, the casualty model (Section 6) provides only two levels of analysis (Level 1 and 2).

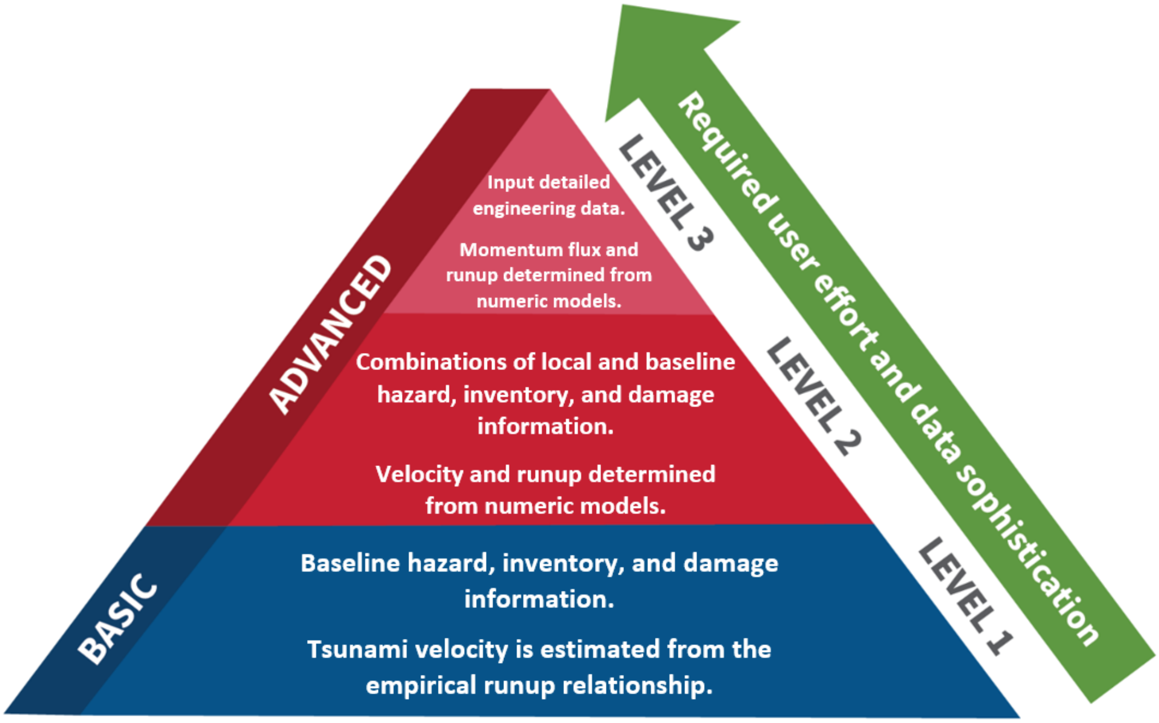

Figure 2-2 Level of Hazus Analysis

2.3.1 Analysis Based on Baseline Information

The basic level of analysis uses only the baseline databases built into the Hazus software and Methodology on building square footage and value, population characteristics, costs of building repair, and certain basic economic data. This level of analysis is commonly referred to as a Level 1 analysis. In a Level 1 (Basic) analysis, tsunami hazard velocity grid data are developed using an empirical relationship and as little as a single observation of runup height may be used. This is an important limitation to note with Level 1 data, since in the Hazus Tsunami Model all building structural losses are driven based on velocity information (non-structural and content losses are based on inundation depth alone). The user is not expected to have extensive technical knowledge. While the methods require some user-supplied input to run, the type of input required could be gathered by referring to published information. At this level, estimates will have much greater uncertainty than Levels 2 or 3 (Advanced) and will likely be appropriate only as initial loss estimates to determine where more detailed analyses are warranted.

2.3.2 Analysis with User-Supplied Inventory

Results from an analysis using only baseline inventory data can be improved greatly with at least a minimum amount of locally developed input. Improved results are highly dependent on the quality and quantity of improved inventory data. The significance of the improved results also relies on the user's analysis priorities. This level of advanced analysis is commonly referred to as a Level 2 or Level 3 (Advanced) analysis. The following inventory improvements impact the accuracy of Level 2 and Level 3 (Advanced) analysis results:

- Use of locally available data or estimates of the square footage of buildings in different occupancy classes.
- Use of local expertise to modify (primarily by professional judgment) the databases that determine the percentages of specific building types associated with different occupancy classes.
- Preparation of a detailed inventory of all essential facilities (integrated as user-defined facilities).
- Use of locally available data concerning construction costs or other economic parameters.

The Level 2 (Advanced) tsunami hazard analysis is defined by having both velocity as well as runup grid information provided from an external hazard model. The purpose of this type of analysis is to provide the user with the best estimates of tsunami damage/loss that can be obtained using the methods included in the Methodology. All components of the Hazus Methodology can be performed at this level. In addition, loss estimates based on user-developed local inventories could further improve this level of analysis. As the user provides more complete data, the quality of the analysis and results improve. Depending on the size of the region and the level of detail desired by the user, as well as user experience, the required input for this type of analysis could take weeks to months to develop.

The Level 3 (Advanced) tsunami hazard analysis is defined by including both momentum flux, as well as runup grid provided from an external numeric tsunami hazard model. At this level, one or more technical experts could further improve the analysis by acquiring data, performing detailed analyses, assessing damage/loss, and assisting the user in gathering more extensive inventory. It is anticipated that at this level there will be extensive participation by local utilities and owners of at-risk facilities that could provide more accurate inventories and attributes.

There are no standardized procedures for conducting an advanced data and models analysis study. The quality and detail of the results depend upon the level of effort. Development of advanced data and analysis of the models could take six months to two years to complete. Each subsequent level builds on and adds to the data and analysis procedures available in previous levels.

2.4 Model Limitations

The current version of the Hazus Tsunami Model does not estimate the following:

- Damage, loss, and functionality estimations for Essential Facilities and Lifeline Infrastructure
- Shelter Requirements
- Debris
- Indirect economic losses

Note that, at this time, the standalone earthquake model analysis is not complete for the U.S. Pacific territories and will not run independent of the tsunami analysis. The functionality to run the standalone earthquake hazard analysis is available for these territories, but the building and infrastructure inventory tables specific to earthquake have not been completed.

For Combined Earthquake and Tsunami Losses Global Report, casualties are calculated and presented separately for earthquake and tsunami, at this time, so there is some potential for double counting. However, it is possible that injuries as a result of the earthquake would slow evacuation times for those persons and anyone who remains to assist them, which could result in an increase in casualties caused by the tsunami.

Section 3. Inventory Data

The technical guidance related to inventory data associated with the Hazus Tsunami Model Methodology and software is detailed in the *Hazus Inventory Technical Manual* (FEMA, 2024). The *Hazus Inventory Technical Manual* (FEMA, 2024) describes the classification of different buildings and utility and transportation infrastructure systems, data and attributes required for performing damage and loss estimation, and the data supplied with the Hazus software. Additionally, the National Structure Inventory (NSI) data used to develop the Tsunami model is covered extensively in the *Hazus Inventory Technical Manual* (FEMA, 2024).

Section 4. Tsunami Hazard Analysis

Tsunami impacts can range from minor to catastrophic, depending on the location and magnitude of the source earthquake. While there is no scientific definition of a “mega-tsunami,” the term is often used to denote the most devastating occurrences. Mega-tsunamis are rare but generate high social and economic impacts. The 2004 Indian Ocean Tsunami took almost 230,000 lives (National Geophysical Data Center (NGDC)/World Data Service (WDS) Tsunami Event Database) in Indonesia, Thailand, Malaysia, Myanmar, Bangladesh, India, Sri Lanka, Maldives, and eastern Africa. This mega-tsunami was created by a Magnitude (M) 9.1 earthquake that ruptured the subduction fault for more than 1,000 kilometers (US Geological Survey Earthquake Hazards Program, M9.5 - 1960 Great Chilean Earthquake). The 2011 Tohoku Tsunami that was triggered by an M 9.0 earthquake ruptured a 500-kilometer length of a subduction fault, killed 15,893 people in Japan, and 2,556 people were still categorized as missing as of December 9, 2016 (Japanese National Police Agency, 2016). This Tohoku Tsunami propagated across the Pacific Ocean, causing over $49 million in damage to nearly two dozen harbors in California (Ewing, 2011). The largest earthquake measured in the 20th century was the 1960 Chile Earthquake with a moment magnitude (M) 9.5. Approximately 15 hours after the earthquake, tsunami waves inundated Hawaii, 10,000 kilometers from Chile, causing $75 million in damage and 61 fatalities (US Geological Survey Earthquake Hazards Program, M9.1 - 2004 Sumatra - Andaman Islands Earthquake). In 1964, the M 9.2 Great Alaskan Earthquake generated tsunamis that killed 122 people and caused approximately $300 to $400 million in damage to Alaska alone (NOAA, 2017).

Smaller but significant tsunamis are more common; even in the relatively short duration between the 2004 Indian Ocean Tsunami and the 2011 Tohoku Tsunami, there were at least seven significant events that affected Northern Sumatra in 2005 (M 8.7, 10 dead), South Java in 2006 (M 7.7, 802 dead), Kuril Islands in 2006 (M 8.3), Solomon Island in 2007 (M 8.1, 52 dead), Samoa in 2009 (M 8.0, 192 dead), Chile in 2010 (M 8.8, 156 dead), and Mentawai in 2010 (M 7.8, 431 dead). All of the death tolls presented in this paragraph are obtained from the NOAA NGDC/WDS Global Historical Tsunami Database.

A locally generated mega-tsunami could potentially strike the Pacific Northwest of North America. Such a tsunami could be generated by a rupture of the 800 kilometers long fault along the Cascadia subduction zone from British Columbia to Northern California (e.g., Atwater et al., 2005; Priest et al., 1997). In Southern California, there is a tsunami threat that could be triggered by a large submarine landslide off Santa Barbara or the Los Angeles Basin (Borerro et al., 2004). A similar tsunami threat is also present in Puerto Rico, where, in 1918, six-meter-high tsunami waves killed 116 people (ten Brink et al., 2006). A more detailed discussion of the tsunami threat in the United States can be found in a report by Dunbar and Weaver (2008).

4.1 Background

Several characteristics are unique to tsunami hazards. First, tsunami-risk areas are limited to narrow strips along the shoreline (typically less than a few kilometers from the shoreline). Within the inundation zones, damage and losses are, in general, not uniform: the nearer the shoreline, the higher the tsunami power. Second, because of the propagation, tsunamis could affect entire oceans. Transoceanic tsunamis can cause serious damage in coastal communities far away from the earthquake. Those characteristics are different from other natural hazards such as earthquakes, river floods, and hurricanes; although rapid, intense flows caused by dam failures could have a similar effect.

Because tsunamis are infrequent and forewarning of tsunami arrival is possible, the primary mitigation tactic for public safety is evacuation. Most mitigation efforts have focused on the development of effective warning systems, inundation mapping, and tsunami awareness (e.g., the National Tsunami Hazard Mitigation Program, 2005). Table 4-1 shows the characteristics of different types of natural hazards. The forewarning times for river floods, hurricanes, and storm waves are much longer than the available times for 'local' tsunamis; hence, evacuation strategies would be different from tsunami cases. Such forewarning for evacuation is impractical for earthquakes.

Tsunami hazards are often classified into two types: "local" or "near source" tsunami and "distant" or "far source" tsunami. Local tsunamis are those generated within 100 kilometers of a locality of interest. In the event of a local tsunami, earthquake ground shaking would precede the tsunami inundation, and the lead-time for tsunami warning would be short, a few minutes to an hour. Note that warning of a local tsunami includes the natural cue (ground shaking). Distant tsunamis are those generated far away (more than 1,000 kilometers) from a locality of interest. Therefore, prior to the tsunami arrival, no ground shaking can be felt. The distant tsunami arrives a few to several hours after the remote-source earthquake. Therefore, systematic and official tsunami warnings are possible for the coastal communities through NOAA's existing tsunami warning systems. There are some data maintenance considerations Hazus users should keep in mind related to Census boundary data, as shown in Table 4-1.

Table 4-1 Census Regions and Divisions

Hazards	Time Scale	Typical Pressure Head	Forewarning Time
River Flood	days	3 meters	a few days
Hurricane/Storm Surge	hours	5 meters	several days
Storm-Generated Waves	seconds	10 meters	several days
Tsunami	minutes	10 meters	minutes to hours
Earthquake	seconds	N/A	none to seconds

The possibility of forewarning for tsunamis is distinctly different from earthquake hazards. The primary focus of earthquake mitigation is to prevent buildings and infrastructure from collapse because a majority of earthquake casualties are due to crushing and/or suffocation by structure collapses. In contrast, tsunamis kill people by drowning. As stated earlier, the 2011 Tohoku Tsunami resulted in 15,893 people dead, 2,556 missing, and 6,151 people injured as of December 9, 2016 (Japanese National Police Agency, 2016), with 94.5% of the total death count attributed to drowning and only 1.2% of fatalities caused by the earthquake (see Vervaeck and Daniell, 2011), and the rest were caused by fires, landslides, and disease. Only 3% of the deaths were attributed to extensive injuries incurred during the tsunami, while 97% of the deaths occurred during the tsunami. Similar statistics are anticipated for a similar extraordinary tsunami event, but it should be cautioned that the outcomes could be different for a smaller tsunami or an event that occurs near a sparsely populated area.

However, in addition to drowning hazards, an understanding of tsunami effects on buildings and infrastructure is also important. The provision of safe areas in the form of tsunami evacuation buildings can significantly reduce the loss of life in tsunami-prone communities where residents might not have sufficient time to evacuate to higher ground prior to a tsunami's arrival. This condition would exist, for example, where people live on a wide coastal plain, a long narrow spit, or areas bounded by rivers or canals. The 2011 Tohoku Tsunami clearly demonstrated the effectiveness of tsunami evacuation buildings in saving lives. It is noted, however, that not all the evacuation buildings provided total protection to the people for this extreme tsunami event due to insufficient building height or elevation.

Destruction of 'critical' coastal structures could cause a significant increase in casualties, even if residents were evacuated to safe areas. Critical coastal structures include nuclear power plants, oil and liquefied natural gas (LNG) storage and refinery facilities, and oil and LNG tankers at terminal berths. This was demonstrated in the 1964 Great Alaskan Earthquake's resulting tsunamis, which caused massive fires at the oil storage tanks in Seward, Alaska. Many significant fires broke out in Japan because of the 2011 Tohoku tsunami. The worst critical structure incident was the meltdown accident at Fukushima Dai-Ichi Nuclear Power Plant. Another important factor is debris; destruction of buildings and infrastructure by tsunamis create substantial amounts of debris that enhance the tsunami forces, resulting in further destruction of structures by impact force. Debris also blocks critical transportation systems (roads, bridges, railroads, and ports and harbors), causing a significant delay of rescue personnel and equipment during recovery and hampering efforts to fight fires.

Tsunami impacts on structures are substantially affected by the surrounding environment. Figure 4-1 shows the town of Onagawa immediately after the 2011 Tohoku Tsunami (approximately 18 hours after). The pattern of damage suggests that the sturdy waterfront buildings (a pair of brown-colored buildings in the photo) must have functioned as a barrier for the smaller buildings behind them. Video footage shows a strong water jet formation in the gap between the two large forward buildings, which destroyed everything in its path. The presence of the sturdy reinforced concrete buildings altered the tsunami flow, which in turn affected their surroundings. It should be noted that the present state of tsunami modeling is not capable of accurately predicting such local effects.

Figure 4-1 Tsunami Destruction Pattern in Onagawa, Japan 2011 Tohoku Tsunami

In summary, tsunami hazard characteristics are unique from other natural hazards, such as floods, hurricanes, and earthquakes.

- Tsunami risk areas are limited to narrow strips along the shoreline, and tsunami strength is not uniform within the inundation zones. Also, tsunami impacts are substantially affected by local surroundings. Because tsunamis propagate, transoceanic tsunamis can cause significant damage, including loss of lives, far away from the earthquake source.
- Because tsunamis are infrequent and forewarning of these events is possible, the primary public safety mitigation tactic is evacuation. Requirements for short-time effective evacuation resemble evacuation from tornados. (Note that such forewarning is impractical for earthquakes.)
- Most deaths from tsunamis are due to drowning and the trauma associated with being in the water. For an extraordinarily mega tsunami event (e.g., the 2004 Indian Ocean Tsunami and the 2011 Tohoku Tsunami), the number of injuries is considerably smaller than the number of fatalities.
- Tsunami-induced fires and landslides are not evaluated in the present methodology.

Throughout this documentation, the following terminologies will be used to identify various tsunami inundation measures (see Figure 4-2):

- *Maximum runup height R*: the vertical elevation of the most landward penetration of the tsunami with respect to the initial sea level. The locations of the most landward penetration are denoted by X (x, y).

- *Maximum inundation height (this is also R)*: the vertical elevation of the flood level at the object within the tsunami inundation, with respect to the initial sea level.
- *Maximum inundation depth H*: the maximum local flow depth with respect to the ground level.

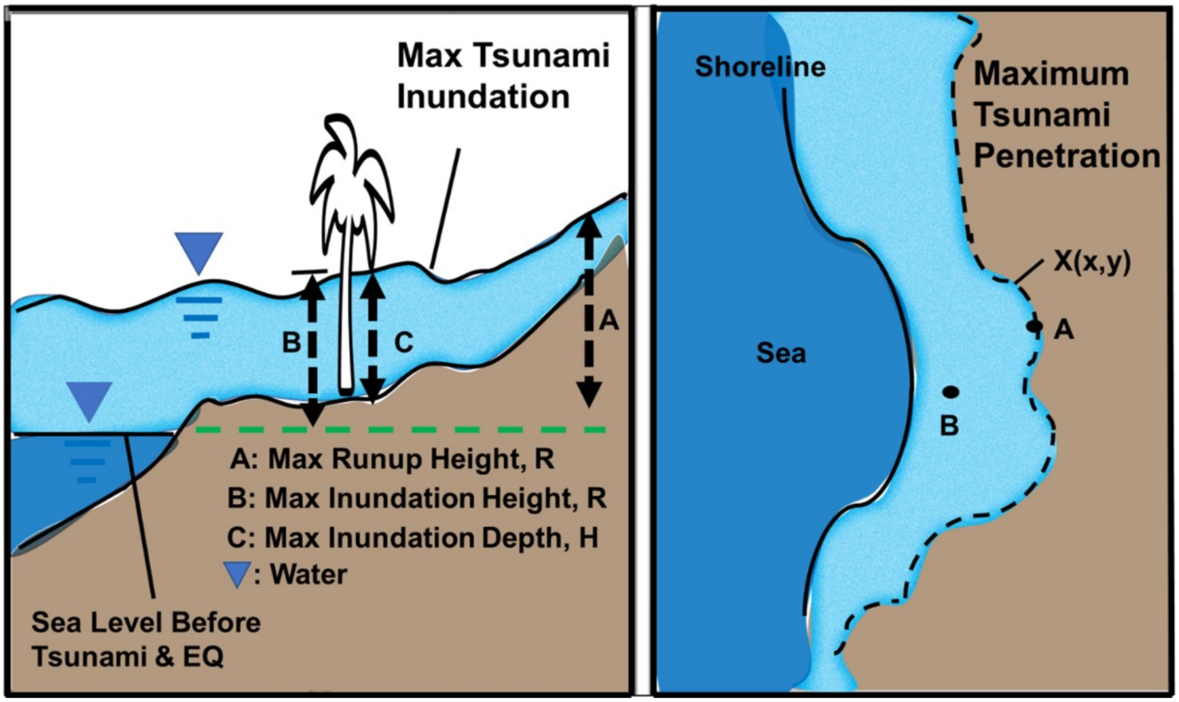

Figure 4-2 Definition Sketch for Tsunami Inundation Terminologies

4.2 Description of Tsunami Hydrodynamic Models

Hydrodynamic simulation of tsunamis involves several stages of modeling:

- Tsunami generation, which defines the initial condition
- Tsunami propagation in the open ocean, continental shelf, and near shore zone
- Runup onto the land

Most tsunamis are created by the seafloor deformation caused by co-seismic fault dislocation. Given information on seismic parameters (i.e., earthquake seismic moment, location of the epicenter and the hypocenter, the seismic parameters such as the slip angles: strike, dip, and rake), the resulting seafloor displacement can be calculated based on linear elastic dislocation theory (see: Mansinha and Smylie 1971; Okada, 1985).

The prediction of seafloor deformation involves great uncertainties in the seismic parameters, as well as inhomogeneity of the seismic fault rupture processes. Typically, the seafloor deformation takes place in a short time and occurs over a large area (approximated 50 ~ 100 kilometers across the fault and 100 ~ 1,000 kilometers along the fault). Because the fault rupture speed is much faster (on the order of 1.25 kilometers per second) than the water-wave speed (~ 0.1 kilometers per second), tsunami generation can be considered an instantaneous deformation of the sea surface that is directly translated from the seafloor deformation.

It should be noted, however, that the recent advances in seismic inversion and numerical modeling revealed that the temporal process of the seafloor displacement makes a notable difference in tsunami amplitude (approximately by 20%) near the source, as in the case of the 2011 Tohoku Tsunami (Takagawa, 2012). Such a large difference may be attributed to the exceptionally deep tsunami source (the over-7,000-meter-deep Japan trench) of the 2011 Tohoku event.

Hydrodynamic simulation for tsunami propagation and runup requires accurate bathymetry and coastal digital elevation module (DEM) data. A typical tsunami wavelength in deep water is on the order of several tens to hundreds of kilometers. Even in a 4,000-meter deep abyssal plain, the flow induced by a tsunami can reach the seafloor; consequently, tsunami propagation and evolution are strongly affected by bottom bathymetry. This is not the case for wind-generated waves, which are typically less than 500 meters long. Waves with a wavelength less than twice their depth are not affected by the presence of the ocean bottom.

Because of the unique characteristics of tsunamis, analysis requires integrating bathymetry data over the entire ocean basin as well as DEM information. The models need data for areas with over-10,000-meter-deep ocean trenches, 4,000-meter-deep abyssal plains, 200-meter-deep continental shelves, and DEM data. If the analysis is for a local tsunami event, then the Ground Deformation DEM for post-earthquake coastal topography is also needed for accurate modeling.

After a series of tsunami bathymetry-data workshops in Tokyo, Seattle, and Birmingham, UK (Yeh, 1998), bathymetry and DEM databases – specifically for tsunami modeling – have been improved significantly by the efforts of NOAA/NGDC and GEBCO (General Bathymetric Chart of the Ocean). The global bathymetry data are now available with a grid size of 1-arc minute: ETOPO-1 (NOAA, n.d.) and GEBCO One Minute Grid. NGDC also developed a 3-arc second coastal relief model for the entire U.S. coast, providing the combined coastal bathymetry and topography data (NOAA, n.d.). Note that seamless bathymetry and DEM data are critical for inundation modeling. Furthermore, NGDC has developed combined near-shore bathymetry and DEM data with higher resolution (1-arc-second and one third-arc second): NGDC Tsunami Inundation Gridding Project (NOAA, n.d.). Those datasets were developed specifically for PMEL's (Pacific Marine Environmental Laboratory) tsunami forecasting modeling effort with the MOST (Method of Splitting Tsunami) numerical code used for the SIFT (Short-term Inundation Forecasting for Tsunamis) operation. The MOST is NOAA's standard numerical simulation code capable of simulating tsunami evolution: earthquake, transoceanic propagation, and inundation of dry land. The SIFT system is the numerical estimate of amplitude, travel time, and additional tsunami properties using an inundation model constrained by real-time tsunami observations.

The required resolution of bathymetry data for tsunami hydrodynamic models depends mainly on the depth. The GEBCO Guiding Committee Report 21 (IOC-IHO/GEBCO, 2005) states that a minimum of 30 grid points per wavelength are needed for adequate propagation modeling. The same resolution requirement should be applied to resolve the relevant bathymetry features. When the tsunami approaches the shore where the depth is shallow, it may break; then, further refinement of the grid size (for example, less than 20 meters) is required. The GEBCO Guiding Committee Report 21 (IOC-IHO/GEBCO, 2005) also recommended that the grid spacing for tsunami modeling should be no more than 1 arc-minute (≈ 2 kilometers) in a 4,000-meter-deep abyssal plain; 10 arc-second (≈ 300 meters) in a 100-meter-deep continental shelf; 3 arc-second (≈ 90 meters) in 10-meter-deep near-shore waters, and even higher resolution is needed to model flooding and associated velocities accurately.

Although tsunamis contain a wide range of spectral components at the source, most of the energy is contained in the long wave components, and shorter-length (higher frequency) waves are dispersed: note that shorter-length waves propagate slower than the longer ones for gravity-driven waves. For this reason, tsunami propagations are often computed based on the shallow-water-wave theory. The theory comprises the conservation of fluid volume and the conservation of depth-averaged linear momentum with the assumptions of hydrostatic pressure field and uniform horizontal velocities over depth.

Typical formulations of the theory can be expressed respectively as:

Equation 4-1

$$\frac{\partial h}{\partial t} + \nabla \cdot (h\vec{u}) = 0$$

Equation 4-2

$$\left(\frac{\partial}{\partial t} + \vec{u} \cdot \nabla\right)\vec{u} + g\nabla h + \gamma \frac{g|\vec{u}|\vec{u}}{h^{4/3}} = g\nabla d$$

Where:

$\vec{u}$	is depth-averaged water velocity
h	is the water depth
d	is the water depth from the referenced datum (e.g., the quiescent water level)
γ	is the friction coefficient

The resulting model is non-dispersive in frequency so that the propagation of wave energy (e.g., the group celerity) is independent of wave number (or wavelength). The use of shallow-water-wave theory can be justified because tsunamis from co-seismic sources are very long (on the order of 100 kilometers or more). The ocean depth is relatively shallow (on the order of 4 kilometers in the abyssal plain). If the earthquake happened in a depth h of 4 kilometers and the generated tsunami wavelength L was 100 kilometers, then the measure of nonlinearity is $\varepsilon = a/h = 0.00025$ which is very small, and tsunami propagation can be reasonably approximated by the shallow-water-wave theory. In addition, the nonlinearity effect is not prominent for tsunamis propagating in deep oceans. Typically, the tsunami amplitude in 'deep' water is less than a meter. For tsunami amplitude, say a = 1 meter in a depth h of 4 kilometers, the frequency dispersion can be measured by $\mu^2 = (h/L)^2 = 0.0016$, which is very small. Therefore, linear shallow-water-wave theory with large spatial discretization (say, the grid size being more than 1 minute = 2 kilometers) should work adequately for the propagation computation in deep oceans (Yeh et al., 1996).

When the tsunami reaches the continental slope, a portion of incident tsunami energy could reflect back to the 'deep' ocean, depending on how abrupt the depth change is. When the tsunami intrudes onto the continental shelf, the amplitude increases due to the shoaling effect; hence nonlinearity effect (i.e., measured by the ratio of wave amplitude to the depth) becomes important. This is because the tsunami's kinetic energy (velocity) that is uniformly distributed throughout the 'deep water' depth is squeezed into the shallower depth on the continental shelf, causing the conversion of some portion of kinetic energy to potential energy (wave height).

As the tsunami reaches the continental shelf, the dispersion effect – measured with $\mu^2 = (h/L)^2$ – could become important depending on the length of the incoming tsunami and the width of the continental shelf. When the continental shelf is sufficiently wide compared with the tsunami wavelength, a single pulse of the incoming tsunami could be transformed into a series of shorter waves by the dispersion effect. However, when the continental shelf is narrow relative to the incident tsunami wavelength, there is not sufficient time for dispersion to occur. Thus, the tsunami reaches the shore with little dispersion. In the former case, when the dispersion effect is important, the model based on the Boussinesq approximation (weakly nonlinear and weakly dispersive model) may be appropriate. In the latter case (the narrow continental shelf), it is appropriate to use fully nonlinear shallow-water-wave theory to model the tsunami propagation towards the shore.

When a tsunami approaches the shore and floods inland, friction effects and turbulence have a greater impact, and the tsunami motion becomes intrinsically nonlinear. Any shore interaction model must also consider natural and artificial configurations, such as buildings, trees, mounds, or roadways. When the detailed effect of tsunami forces on structures is the focus, then more sophisticated numerical models with a structural engineering component may need to be implemented. When the maximum runup is a focus, then such natural and man-made obstacles could be parameterized, for example, by assigning proper friction factor values.

The foregoing descriptions of hydrodynamic modeling of tsunami generation, propagation, and runup evidently demonstrate that the problem is complex and multi-scale. It is complex because it involves multi-phase (water, air, solid) interactions in a three-dimensional real-world domain where some fundamentals, such as turbulence, remain unsolved. It is multi-scale because the length scale of tsunamis in the ocean is on the order of hundreds of kilometers, while the effects of inundation phenomena must be described at scales of a few meters or less. Hence, at present, even the best tsunami modeling yields substantial errors in prediction, and there is much room for improvement in every aspect of the modeling.

4.3 Tsunami Hazard Analysis

Tsunami Hazard Analysis produces the necessary physical tsunami conditions for a coastal community of interest. The role of Tsunami Hazard Analysis is shown in the overall flow chart in Figure 2-1 (note that for distant events, the earthquake hazard components can be bypassed).

Prediction of a tsunami hazard is a formidable task because of the uncertainty involved in the tsunami generation mechanism, ocean bathymetry, and most importantly the occurrence of a tsunamigenic earthquake itself. Given these uncertainties, probabilistic methods rather than deterministic methods are typically used to analyze tsunami hazards. The analysis is an extension of the existing methodology for probabilistic seismic hazard analysis and involves identifying all possible tsunami sources that could affect a coastal community of interest: see Geist and Parsons (2006). Probabilistic tsunami hazard analysis requires combining tsunami hydrodynamic simulations with the analysis in the field of probabilistic seismic hazard assessment. The resulting database of tsunami simulations is subjected to a statistical analysis that provides the recurrence estimates for tsunami amplitudes that exceed given values.

González et al. (2009) made a detailed probabilistic tsunami hazard assessment for the coastal town of Seaside, Oregon. They used 15 seismic tsunami sources in five Pacific subduction zones: 14 of them are the distant source events and one is the local source (Cascadia) event. Each of the seismic events is described with a Poisson distribution model with its recurrence interval. Tsunami inundation in Seaside is then numerically computed for each seismic event. Combining all the events and performing the statistical analysis yields a "hazard curve" (i.e., the cumulative distribution function of the exceedance amplitude vs. the annual exceedance probability: see Figure 4-3 as an example). A similar methodology was introduced by PG&E (2010), which included tsunami events triggered by landslides. Instead of González et al.'s Poissonian model, PG&E assumed that tsunami wave heights are lognormally distributed. Again, the end results are a "hazard curve."

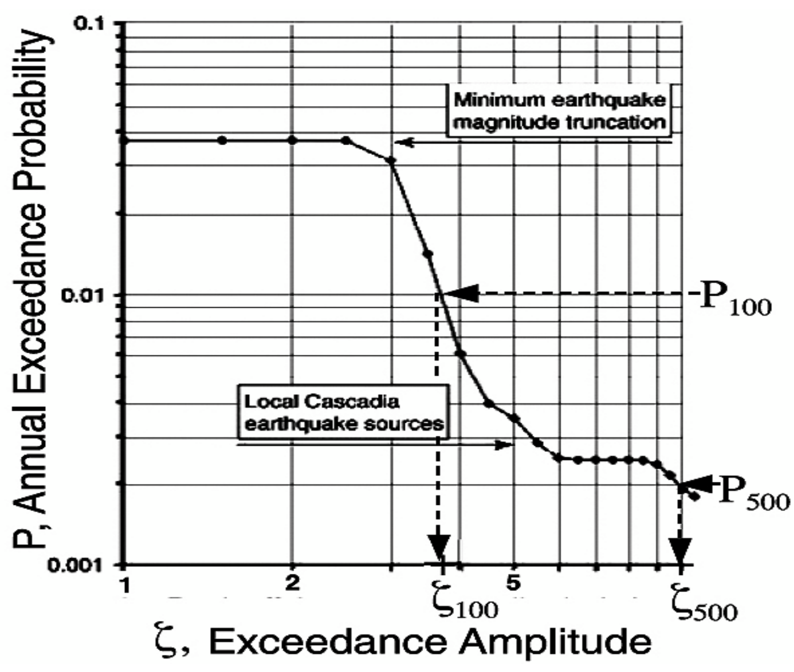

Figure 4-3 Example Hazard Curve

Probabilistic tsunami hazard analysis involves significant computational effort, even for the analysis of one specific coastal community. The analysis itself contains substantial uncertainty because of the lack of sufficient samples (data) to form a proper probability space (see any elementary probability textbook for the concept of a probability space). The most important point to recognize is that the probability is originated from the seismic events that generate tsunamis, while the computation of tsunami propagation and runup itself is deterministic. Considering this, the Hazus Methodology incorporates probabilistic elements in physical tsunami inundation as a given input parameter to the tsunami hazard analysis. In other words, the users can specify the input tsunami conditions with a given probability, and the probability is evaluated independently of the Hazus Methodology. It is anticipated that a systematic probabilistic tsunami database will be developed and become available in the future: for example, PEER (Pacific Earthquake Engineering Research Institute) is currently developing such a database. The present Hazus Methodology is designed to enable linking with such a database.

4.4 Input Requirements and Output Information

4.4.1 Input Requirements

The Input/Output structure for hazard analysis is depicted in Figure 4-4. The input data and information needed for Tsunami Hazard Analysis identifies geographical, geophysical, and seismological conditions for a specified tsunami event. More specifically, a Hazus Tsunami Model analysis requires the following as the input data:

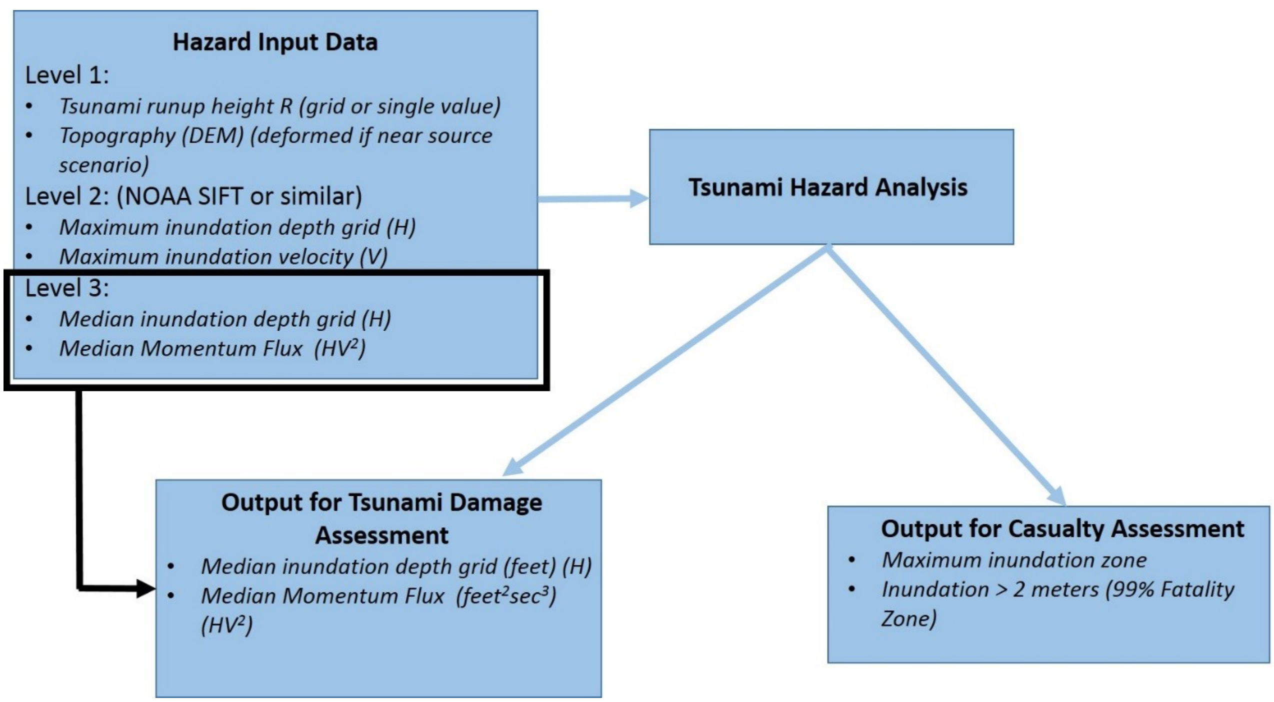

Figure 4-4 Tsunami Hazard Analysis Input Requirements and Output

4.4.2 Level 1 (Basic)

For Level 1 (Basic), input is an expected tsunami runup height, R, for the coastal community, which can be a single measurement for a “quick-look” assessment or can be the runup height as a grid across a region. With a Level 1 analysis, the estimation of velocity is based on an empirical equation that utilizes the maximum runup height and the topography (DEM) as described in Section 4.5. For near-source events, the deformed (post-event) DEM should be used. The location of the tsunami source may be selected from a map of potential tsunami sources provided in the inventory data as shown in Figure 4-5.

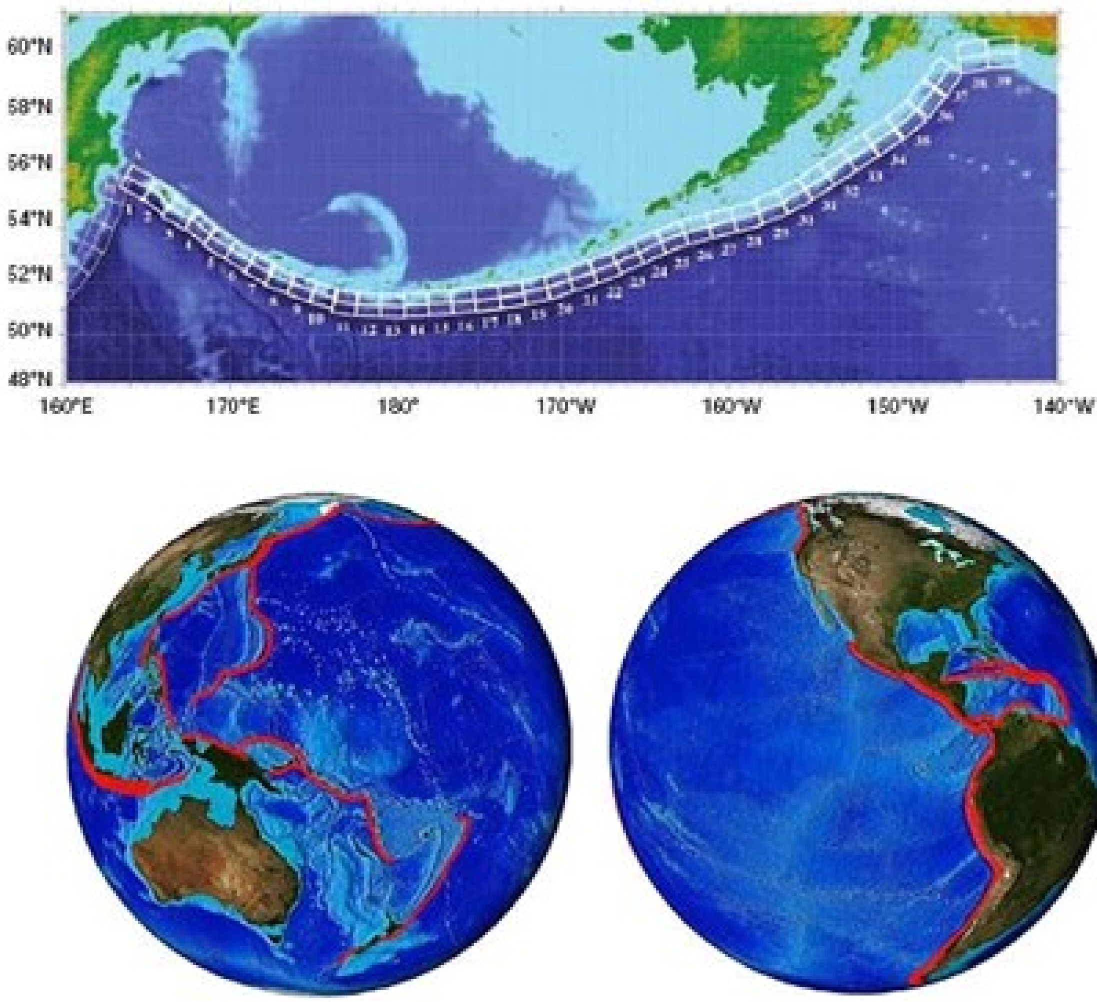

Figure 4-5 Locations of Potential Tsunami Sources

Note that the height, R, can be the outcome from a probabilistic tsunami hazard analysis performed elsewhere. In practice, the tsunami runup height can be the height at the maximum tsunami penetration found in the tsunami inundation/evacuation map for the community (refer to Figure 4-2). For example, Figure 4-6 shows the inundation map of Cannon Beach, Oregon, which provides two different inundation zones: one for local tsunamis and the other for distant tsunamis.

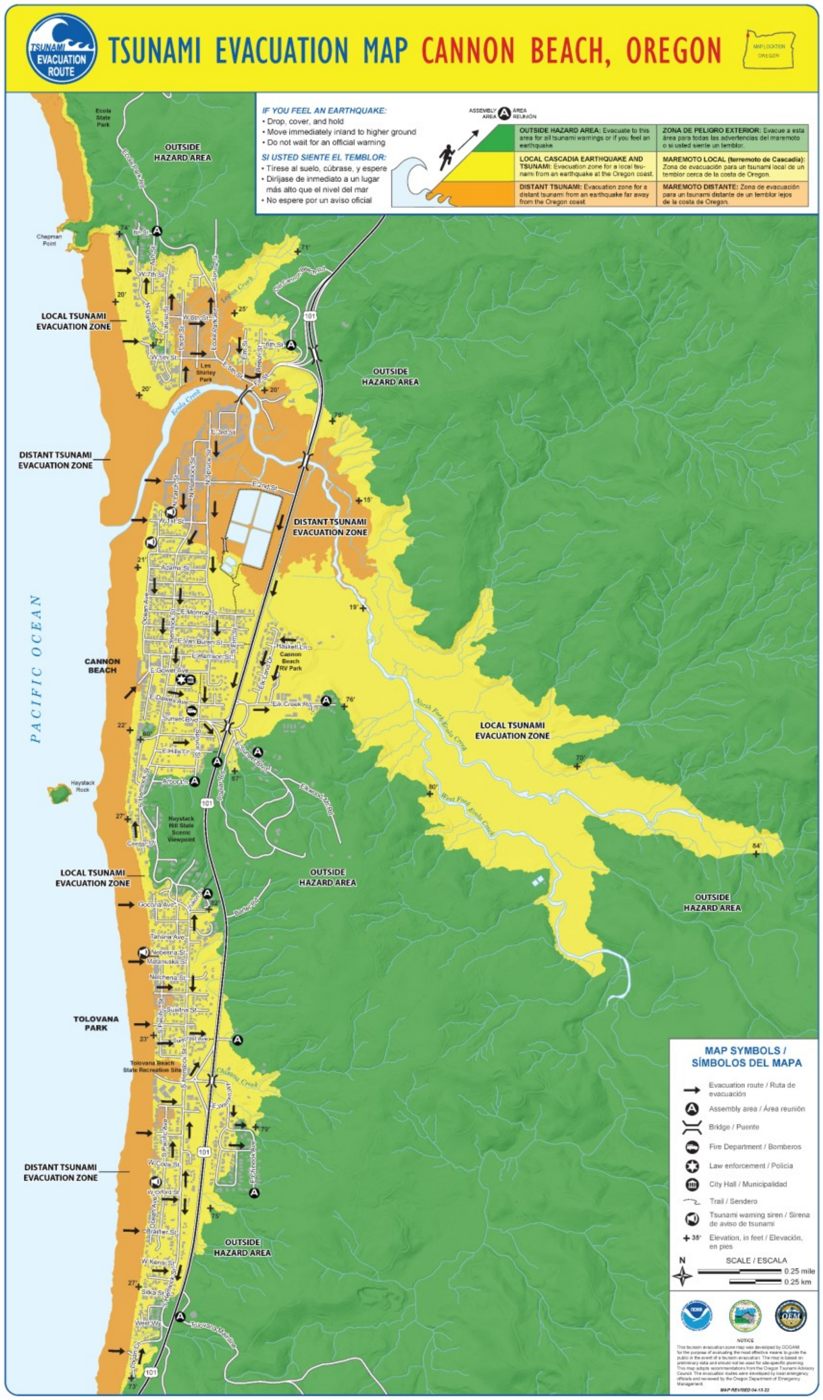

Figure 4-6 Tsunami Evacuation Map, Canon Beach, Oregon

Shown in Figure 4-7 is an inundation map for a variety of possible tsunamis for Canon Beach, Oregon. Although users can select any runup height, R, and are not constrained by those found in the inundation maps, the runup height, R, could be selected at the maximum elevation within the inundation zone shown in the map. However, the user should define their region based on where the runup height could be reasonably applied. Applying the maximum runup throughout a large Study Region would result in erroneously high losses.

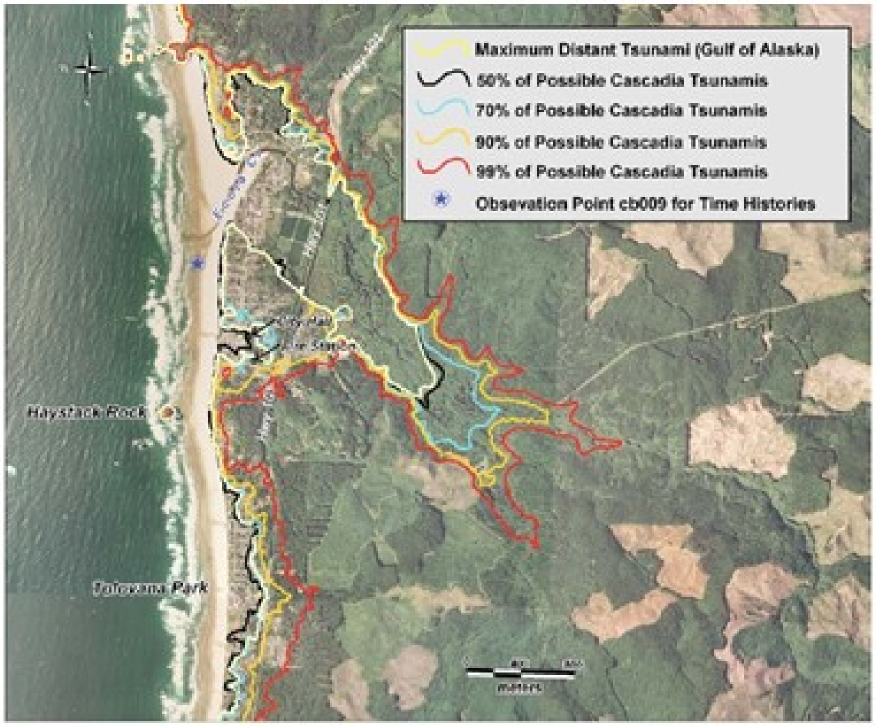

Figure 4-7 Percent Probability of a Tsunami in Cannon Beach, OR

4.4.3 Level 2 (Advanced)

For Level 2 (Advanced), the inputs are raster grids of the maximum flood depth and maximum velocity. This information can also be probabilistic with the return interval. As discussed in Section 4.8, this Hazus Methodology is tied closely to the existing NOAA's SIFT prediction model. Hazus will reduce these inputs to medians as described in Section 4.6 and calculate momentum flux by squaring velocity and multiplying by depth.

4.4.4 Level 3 (Advanced)

For Level 3 (Advanced), the inputs are raster grids of Median Inundation Depth (feet) and Median Momentum Flux (ft^3/sec^2) directly from the user. Because these two inputs are user-defined, Hazus does not generate any tsunami hazard data in Level 3.

Regardless of the level of input, Hazus building damage and loss (Section 5) requires both the Median Inundation Depth (feet) (H) for the estimation of nonstructural and content losses, and Median Momentum Flux (ft^3/sec^2) (HV^2) for the estimation of structural losses as shown in Figure 4-4.

4.4.5 Third Party Input Data

There are two major third party input data sources to consider:

- The DEM (x, y, z) is required for Level 1 (Basic) and should consist of the modeled post-event (deformed) topography in the case of near-source events. These are modeled deformations and can result in several meters of DEM deformation and substantially change the inundation area and potential losses. The *Hazus Tsunami Model User Guidance* (FEMA, 2024) contains further information on how to locate and utilize this data.

- SIFT and other tsunami models have frequently pre-run libraries of scenarios associated with known potential tsunami sources (Figure 4-5).

For assessing combined earthquake and tsunami losses, it is important to ensure the same source parameters are used for the earthquake loss modeling, as is used to design the tsunami scenario. The *Hazus Earthquake Model Technical Manual* and *User Guidance* documents (FEMA, 2024) outline the source parameter inputs required for earthquake loss modeling.

4.4.6 Output Data:

Output from a Tsunami Hazard Analysis must fulfill the needs for the tsunami damage assessment and casualty estimates and debris modules. These outputs consist of:

- Median of maximum inundation depth (H) at the structures of interest.
- Median of maximum specific force or momentum flux HV2 at the structures of interest.

The following outputs are provided by the Tsunami Hazard Analysis or are provided by the user and fed into the Tsunami Impact module, which calculates casualties (see Section 6):

- Maximum inundation locations X (x, y) (depth > 0, along the maximum runup contour line)
- Fatality boundary, where depth is greater than 2 meters and fatality rate is modeled as 99%
- Arrival time of the leading tsunami, T_0
- Time of max runup, T_{max}
- Time of maximum recession, T_1

Note that tsunamis often approach the coast as a series of inundating waves. Therefore, the times of maximum runup and maximum recession may not necessarily occur at the first tsunami inundation. The maximum runup may result from the second, third, or later tsunami inundation, and the maximum recession may not occur in the excursion associated with the maximum runup.

Because the present Hazus Methodologies of the tsunami loss estimation do not adopt an agent-based modeling for evacuation simulation (see Section 6), it is necessary to assume, for simplicity and conservation, that the times of maximum runup and maximum recession happen at the first tsunami inundation excursion.

4.5 Estimates Without the Use of Runup Height or Velocity (Level 1 Methodology)

Tsunami Hazard Analysis for Level 1 (Basic) provides hazard methodology without the use of the simulation model, which requires both runup height and velocity hazard data. Level 1 input data for the tsunami hazard are available from NOAA, as well as state sources:

- Alaska Division of Geological & Geophysical Surveys
- California Geological Survey, California Emergency Management Agency
- University of Hawaii
- Oregon Department of Geology and Mineral Industries
- Washington Department of Natural Resources

NOAA's Forecast Inundation Models have not covered all the U.S. coastal communities: the models are currently available for 75 communities at the NOAA Center for Tsunami Research. For any of the 75 communities included in the NOAA inundation models, a Level 2 (Advanced) analysis is highly preferred, and the Level 1 (Basic) methodology at these locations should be used for educational and comparative purposes only. For a given earthquake location, the tsunami arrival time T_0 to a community of interest from the time of earthquake is estimated by:

Equation 4-3

$$T_0 = \int_d (gh)^{-1/2}\, dl$$

Where:

h	is the water depth along the propagation path l from the tsunami source to the community
g	is the gravitational constant, 32.174 ft/s^2
d	is the distance from source to community along path l

Note that travel time maps based on calculated travel times to communities from any ocean location are provided online by the NOAA Centers for Environmental Information.

For a tsunami height (R) given as input, the maximum inundation depths (H) can be estimated by:

Equation 4-4

$$H(x, y) = R - z(x, y)$$

Where:

z	is the ground elevation at a given location (x, y) in the community, and the maximum inundation location X (x, y) can be determined along the contour where z = R.

The Hazus Tsunami Model utilizes raster math, specifically ArcGIS's Spatial Analyst Extension Raster Calculator Geoprocessing tool, to subtract the ground elevation (z) DEM from the grid that represent the runup heights (R).

4.5.1 Estimating Velocity from Runup (Level 1):

It is common that users will have estimated runup depths or heights from tsunami hazard models, evacuation studies, or actual events and ***not*** velocity. Velocity, and more specifically Momentum Flux (HV^2), is a required input parameter for all structural losses, while contents and nonstructural losses are based on depth only. The FEMA 2013 methodology proposed an empirical relationship between runup and velocity be used to produce and estimate momentum flux that was available in FEMA P-646: Guidelines for Design of Structures for Vertical Evacuation from Tsunamis (FEMA, 2012). This relationship is described in greater detail in Section 4.7.

Equation 4-5

$$u = f_v \sqrt{2gR\left(1 - \frac{z}{R}\right)}$$

Where:

f_v	is a reduction factor
g	is the gravitational constant, 32.174 ft/s^2

The reduction factor is needed because Equation 4-5 yields an over-conservative value. The formula is analytic for the runup of a bore (a broken wave of an infinite wavelength propagating into quiescent water) onto a frictionless uniformly sloping beach. Therefore, the runup process results in perfect conversion of the kinetic energy to potential energy (e.g., Ho and Meyer, 1962).

According to laboratory experiments by Yeh et al. (1989), the reduction factor f_v should be less than 0.7. The factor f_v is further adjusted based on the ground roughness in the inundation zone. Analyzing video footage, Fritz et al. (2012) reported the flow speeds near the shoreline of the town of Kesennuma during the 2011 Tohoku Tsunami. They found max $V \approx 6$ meters per second where the maximum runup $R \approx 9$ meters. Koshimura (2011) also reported similar data for the town of Onagawa: max $V \approx 7.5$ meters per second where the maximum runup $R \approx 18$ meters. Based on these limited data, the factor $f_v \approx 0.5$ is used for this implementation and Figure 4-8 demonstrates that factor f_v =0.5 reproduces approximately the flow conditions recorded in Kesennuma and Onagawa.

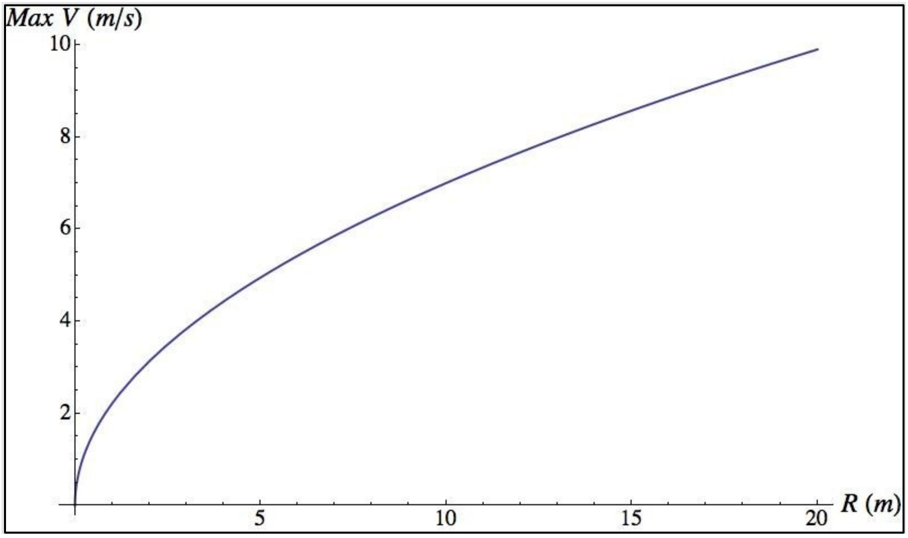

Figure 4-8 The Relation of Maximum Flow Speed (Max V) at the Shoreline with the Maximum Runup Height (R)

It appears the value of f_v depends not only on the roughness of the runup surface (including the effects of macro roughness such as buildings etc.), but also depends on the ground slope as well as the tsunami source. For a distant tsunami, the waveform tends to become very long: hence the tsunami runup motion is likely a gradual increase in water level (meaning a small value of f_v). Alternatively, a local tsunami often (but not always) creates a leading depression wave that leads to formation of a bore near the shore (Yeh, 2009). Therefore, a relatively large value of f_v can be expected.

However, a newer American Society of Civil Engineers (ASCE) 7 equation modified to use the maximum runup (R_a) is used. This is used for the two Level 1 options, either by an imported runup grid or by the user provided maximum runup value associated with the Level 1 Quick Look feature. The Quick Look feature is intended to be used for a localized area where only a single observation of runup is available.

Equation 4-6

$$u = 0.85\sqrt{gH\left(1 - \frac{z}{Ra}\right)}$$

Where:

0.85	is based on analysis by Patrick Lynette for ASCE, recommended by Ian Robertson in personal communication (2016) for loss modeling, over 1.0 for tsunami surge and 1.3 for tsunami bore, since both the latter are biased high to ensure conservative design per ASCE 7-16
g	gravitational constant, 32.174 ft/s^2
H	is the depth, in feet, at site of interest
z	is surface elevation, in feet, from the DEM at site of interest

R_a is using the maximum runup, in feet, above mean sea level (MSL) from each case study grid

4.5.2 Modify H and HV^2 Maximums to Median Values

The Hazus Tsunami Model building damage functions are based on median rather than maximum depth and momentum flux values. Following the approach used for the EGLA described in Section 4.6, which produces h_{max}, the maximum flow depth, and u_{max}, the maximum flow velocity, at any point along the flow transect for the ASCE 7-16 design provisions, medians are estimated as 2/3 $h_{max}(u_{max})^2$, or 2/3 of the momentum flux assuming both h_{max} and u_{max} occur together and are used to estimate the median flux and depth. The selection of 2/3h_{max} to correspond to u_{max} for ASCE was based on numerical modeling and analysis of survivor videos from the Tohoku Tsunami.

Based on the integration of the ASCE methodologies, the sequence of Level 1 (Basic) computations is summarized in Figure 4-9.

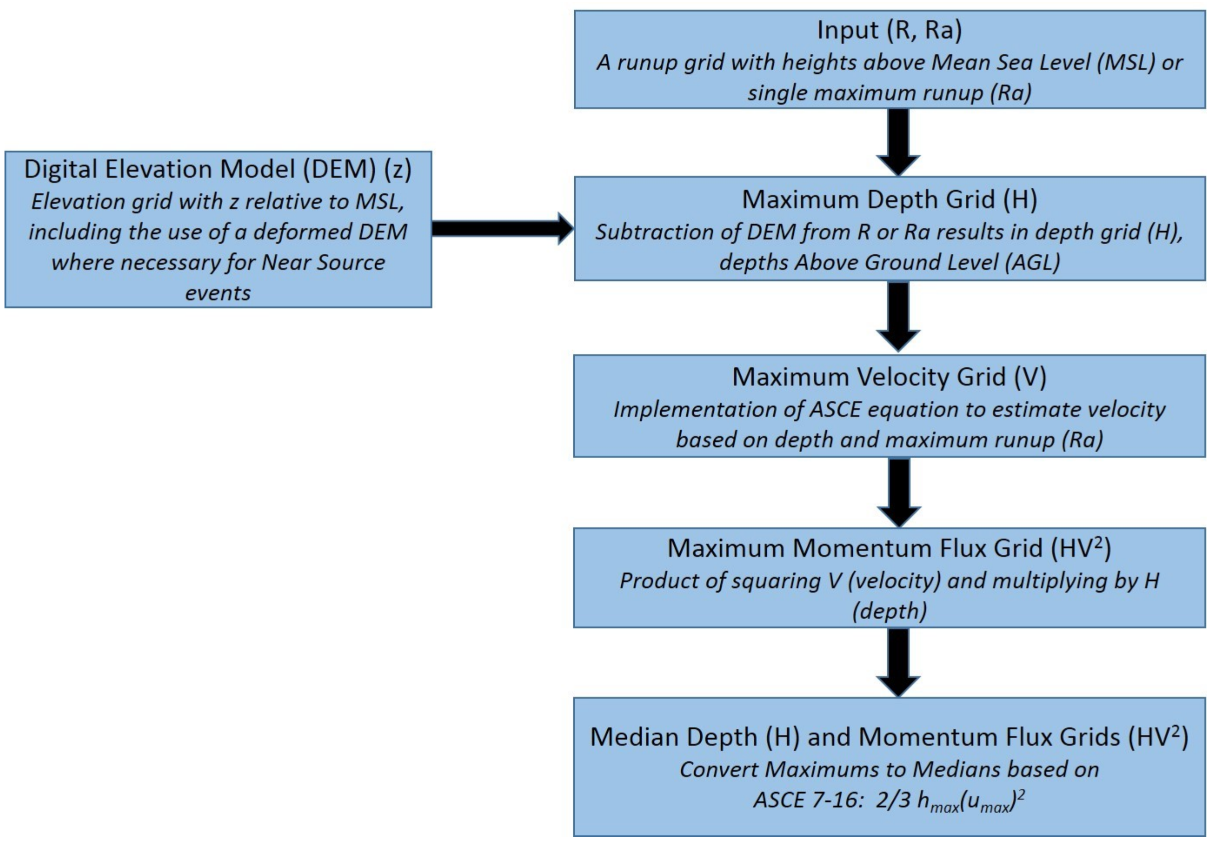

Figure 4-9 Flowchart for Level 1 (Basic) Methodology

4.6 NOAA's Short-term Inundation Forecasting for Tsunamis (SIFT)

At the NOAA Center for Tsunami Research (NCTR), the standard numerical model for tsunami propagation and runup is called MOST. The code is based on nonlinear shallow-water-wave theory (see Equation 4-7 and Equation 4-8). In MOST, the spatial dimensions are split so that the original 2D problem is reduced to a sequence of 1-D problems. The resulting formulations are then rearranged to solve in terms of the Riemann invariants (r and s) and the eigenvalues λ_r and λ_s:

Equation 4-7

$$r = u + 2\sqrt{gh};\ s = u - 2\sqrt{gh}$$

Equation 4-8

$$\lambda_{r,s} = u \pm \sqrt{gh}$$

Where:

u	is the water velocity
g	is the gravitational constant, 32.174 ft/s^2
h	is the water depth, in feet

This procedure is an application of the classic analytic solution algorithm for a nonlinear hyperbolic equation called the method of characteristics. The numerical code MOST also selects the grid sizes, and the time increments so that the physical wave dispersion effects can be modeled utilizing the numerical dispersion that is inherent in the finite difference scheme. MOST can simulate the entire tsunami processes: generation by earthquake, transoceanic propagation, and inundation of dry land.

NOAA has established a comprehensive and efficient system to estimate tsunami inundation, flow velocities, and arrival times for given earthquake information. NOAA called this operation SIFT, which is designed to support a rapid tsunami warning system for the U.S. coasts, and MOST is the foundation for NOAA's SIFT operation. The following is a brief description of SIFT.

With the use of MOST, NOAA had developed what it calls a "propagation database," which is a collection of pre-computed propagation model runs in which tsunamis are generated from selected locations along known and potential earthquake zones (see Figure 4-5 for an example). The database was made for a pre-defined source called a "unit source," which is a tsunami source due to an earthquake with a fault length of 100 kilometers, fault width of 50 kilometers, and a slip value of 1 meter, equivalent to the moment magnitude of (**M**) 7.5. A combination of the pre-computed tsunami model runs in the propagation database can provide a quick forecast of the oceanwide propagation of the tsunami as a linear combination of unit sources selected to represent the initial earthquake parameters (epicenter and magnitude). The forecast is updated by improving the linear combination of the source units with more accurate seismic information that had not been available at the initial computation, and the tsunami data recorded by the Deep Ocean Assessment of Tsunami (DART) system. Note that the DART buoys are real-time tsunami monitoring systems that are positioned at strategic locations throughout the ocean and play a critical role in tsunami forecasting. The current locations of the buoys are shown in Figure 4-11.

For a given coastal area of interest, tsunami wave height, current speeds, and inundation extent are predicted numerically with the use of the Forecast Inundation Model. First, offshore tsunami waves at any specified location are obtained with a linear combination of the propagation database as described above, and the wave data offshore are used for the tsunami inundation numerical model based on the MOST code, which provides high resolution predictions of tsunami inundation. For a given community of interest, the customized Forecast Inundation Model was developed to achieve the optimal accuracy and an adequate speed of computation.

Currently, NOAA has developed the Forecast Inundation Models for a total of 75 U.S. communities. The list of communities where the Forecast Inundation Models are available is shown in Figure 4-10.

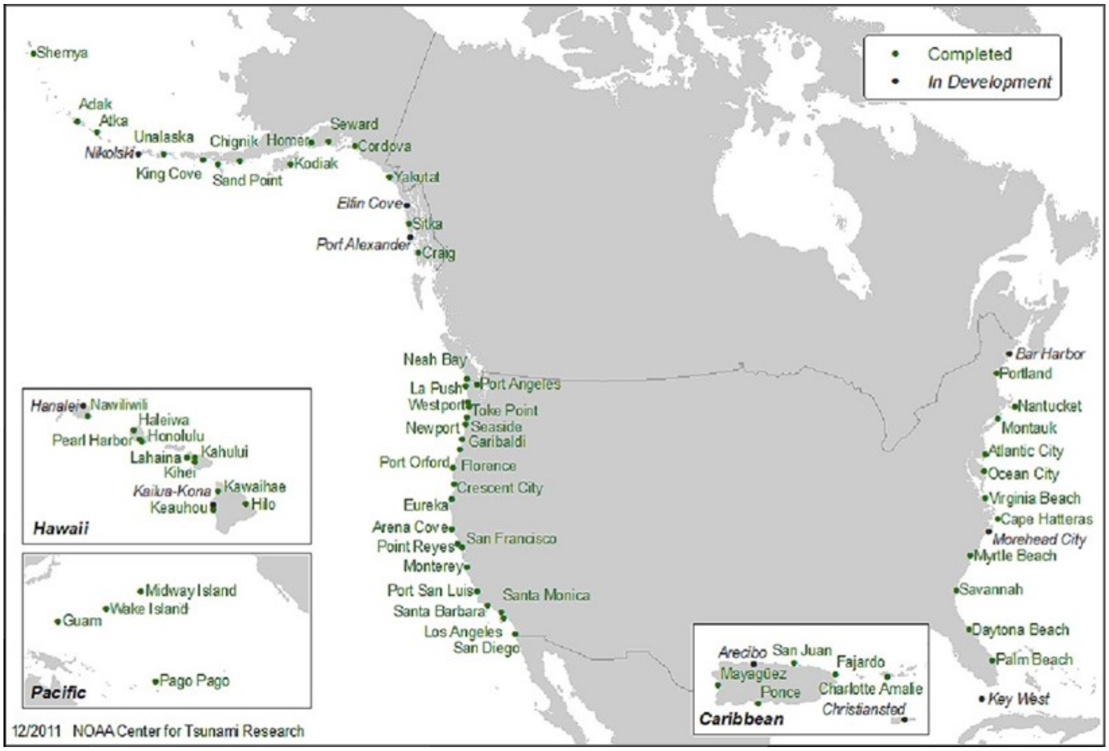

Figure 4-10 Location and Development Status of Forecast Inundation Models

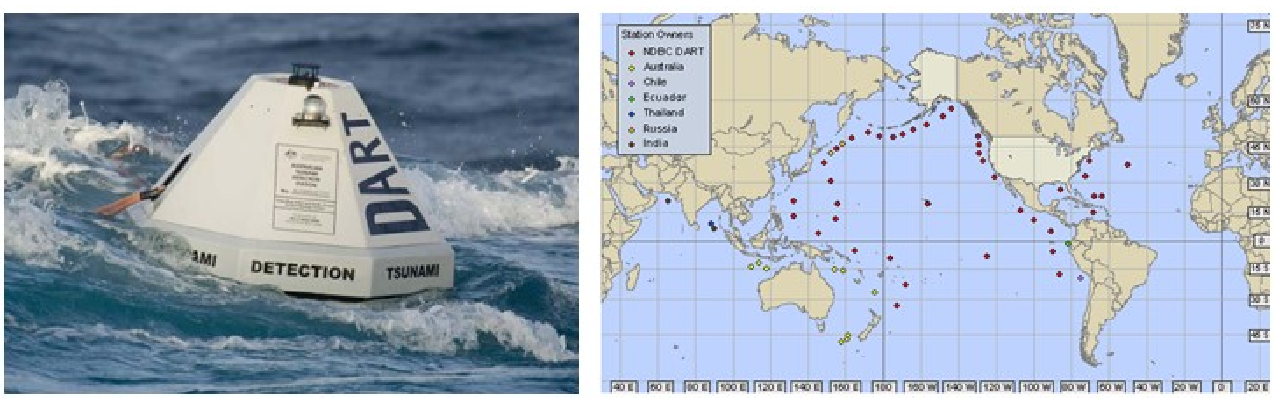

Figure 4-11 Deep Ocean Assessment of Tsunami (DART) and Current DART Deployments

4.7 Evaluation of FEMA P-646 and ASCE Approaches

The FEMA 2013 methodology proposed use of the empirical relationship between runup and velocity that was available in FEMA P-646: Guidelines for Design of Structures for Vertical Evacuation from Tsunamis. To implement the empirical relationship, a reduction factor (f_v) is used in the equation to prevent overestimation of velocity by reducing flow based on surface roughness and other available factors.

The 2013 methodology further suggests a fv value commonly measured in the lab, 0.7, and that two observations during the 2011 Sendai Japan Tsunami suggest a value of 0.5 for fv. The methodology describes the need to develop a lookup table to assist in assigning this value, however, such values are currently not available. Since the velocity once converted from runup with the empirical equation is squared and then multiplied by depth to estimate the Momentum Flux to be applied to estimate building damage states, the difference in damage state and associated losses just by varying between the two values (0.7 and 0.5) suggested in the methodology can almost double the Momentum Flux (Table 4-2).

Table 4-2 Influence of f_v on Momentum Flux

Input Runup (ft) (z=5)	Velocity (fps); Equation 4.4 with [fv=0.5]	Momentum Flux HV2 (ft^3/sec^2)	Velocity (fps) Equation 4.4 with [fv=0.7]	Momentum Flux HV^2 (ft^3/sec^2)
15	12.68	1,608.70	17.76	3,153.05
16	13.31	1,946.53	18.62	3,815.19
17	13.89	2,316.53	19.45	4,540.39
18	14.46	2,718.70	20.25	5,328.66
19	15.01	3,153.05	21.01	6,179.98
20	15.53	3,619.58	21.75	7,094.37

4.7.1 ASCE Energy Grade Line Analysis (EGLA):

ASCE also recognized the need to relate runup to velocity and developed the EGLA as a method to support “Tsunami Loads and Effects Design Standards for the United States” (ASCE 7-16). This method recognizes the decay of energy and velocity with distance from the shoreline, as well as the influence of the ground profile (Figure 4-12).

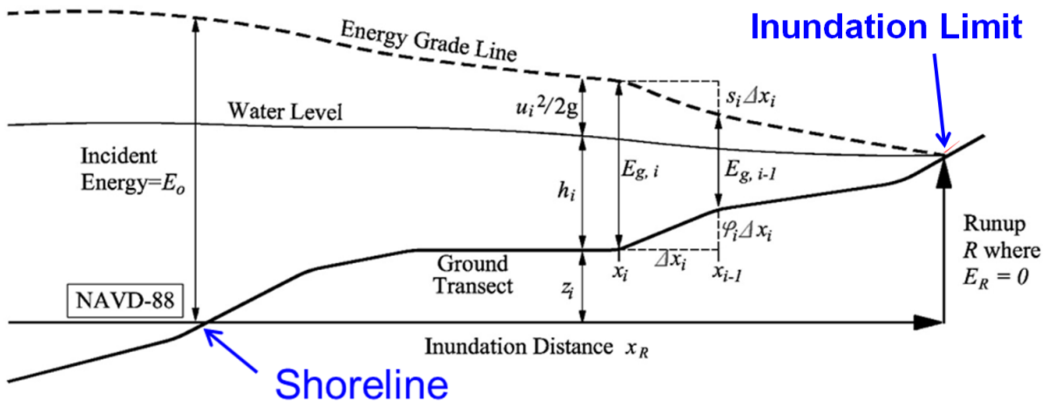

Figure 4-12 ASCE Energy Grade Line Analysis Approach

The EGLA methodology has the potential to provide a grid with a range of all possible depths and velocities at each grid, based only on the Runup Inundation Limit (Figure 4-13).

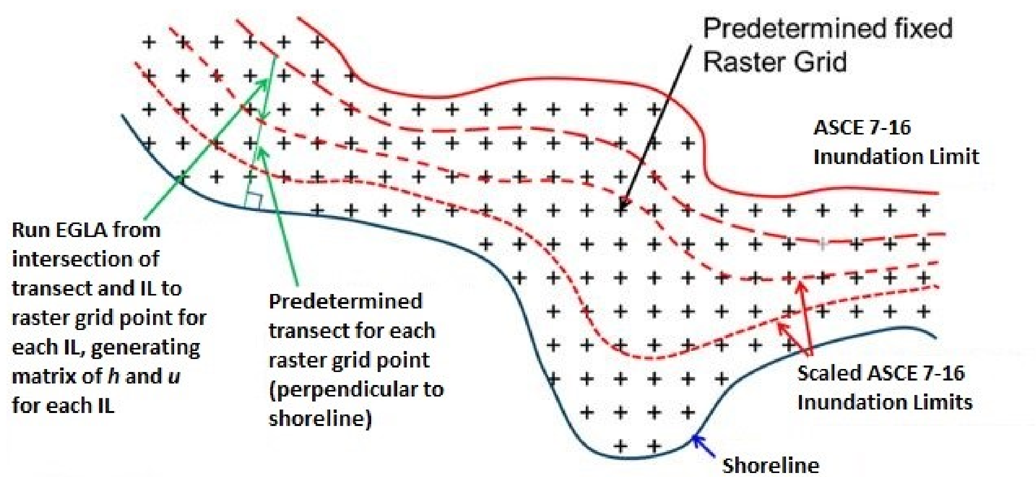

Figure 4-13 The EGLA Methodology Potential Grid Approach

This approach has the benefit of aligning with the Building Code methodology, as well as the ability to reduce the required user input to only the Inundation Limit. However, since the data to support an EGLA grid approach is not yet available, this approach is currently limited to integration in the Level 2 (Advanced) hazard input Methodology.

4.7.2 Evaluation of Level 1 Methods to Estimate Velocity from Inundation Grids

Based on the findings from above concerning the P-646, testing of the ASCE 7 equation and modifying it to use the maximum runup (Ra) provided by an imported runup grid was performed. This evaluation summarizes the results comparing the two estimation methods for tsunami velocity against a numerical simulation of tsunami velocity provided by NOAA's SIFT model for five Case Study communities. These empirical equations provide the capability for Hazus to model potential structural losses when only runup (Level 1- Basic) data are available. Numerical modeling provided by SIFT and other tools provides a far more detailed assessment of tsunami velocity for Hazus Level 2 and 3 (Advanced) assessments. Implementing the two equations in ArcGIS's Raster Calculator Geoprocessing tool based on the SIFT grid for the community of Westport, WA, based on the Cascadia scenario designated as L1 by Witter and others (2011) with a recurrence interval of 800 years:

ASCE Example for Westport:

Equation 4-9

$$0.85 * \sqrt{32.174 * \text{"wes\_maxdg\_ft"} * \left(1 - (\text{wes\_dem\_ft}/71.2847)\right)}$$

P-646 Example for Westport:

Equation 4-10

$$0.5 * \sqrt{2 * 32.174 * \text{"wes\_maxR\_ft"} * \left(1 - (\text{wes\_dem\_ft}/71.2847)\right)}$$

Where:

wes_maxdg_ft	is the maximum flow depth grid Above Ground Level (AGL) provided by the SIFT model
wes_maxR_ft	is the maximum runup grid relative to Mean Sea Level (MSL) provided by the SIFT model
wes_dem_ft	is the deformed post-event topography grid provided by the SIFT model
71.2847	is the maximum runup elevation (R_a) provided by the SIFT model

The SIFT model velocity grid for Westport, WA based on the Cascadia L1 scenario is illustrated in Figure 4-14.

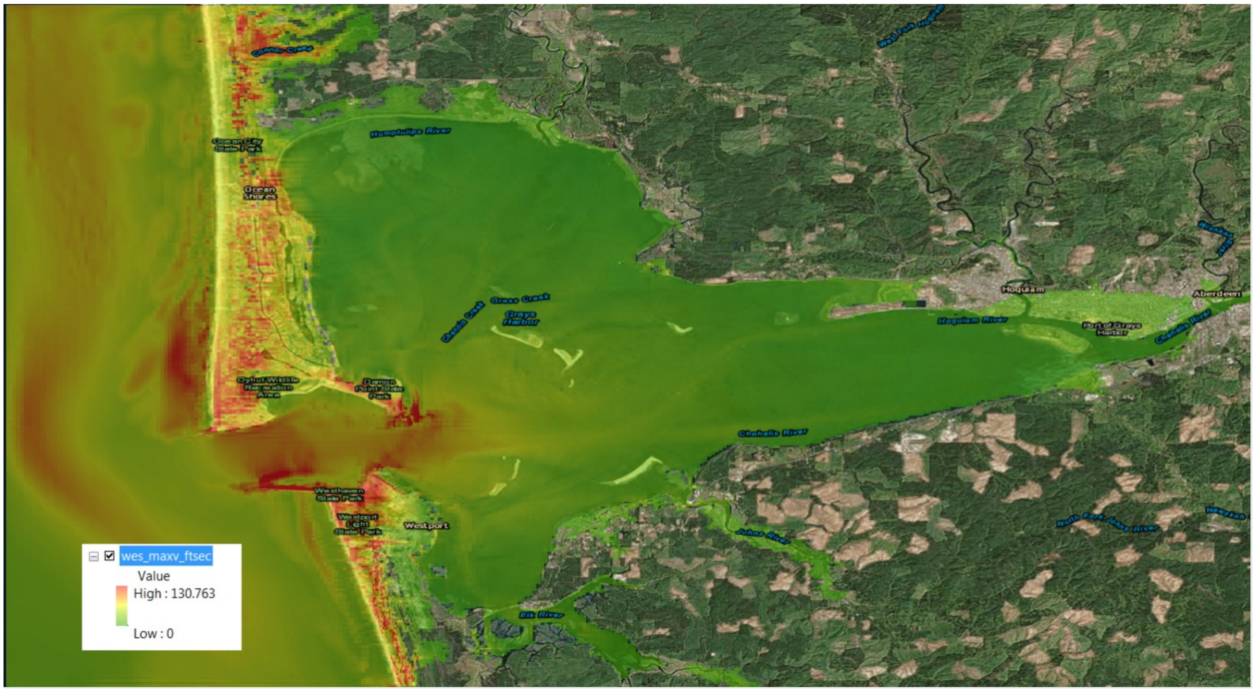

Figure 4-14 SIFT Model Velocity Grid for the Cascadia L1 Scenario, Westport, WA

Neither velocity grid estimation method can reflect the detail provided through velocity modeling, however, the velocity grids estimated using the empirical equations are intended to approximate the values providing a Level 1 (Basic) capability. This will provide loss estimation capability in areas where only the runup data are available. The velocity grid based on the ASCE equation for the Cascadia L1 scenario for Westport, WA is illustrated in Figure 4-15.

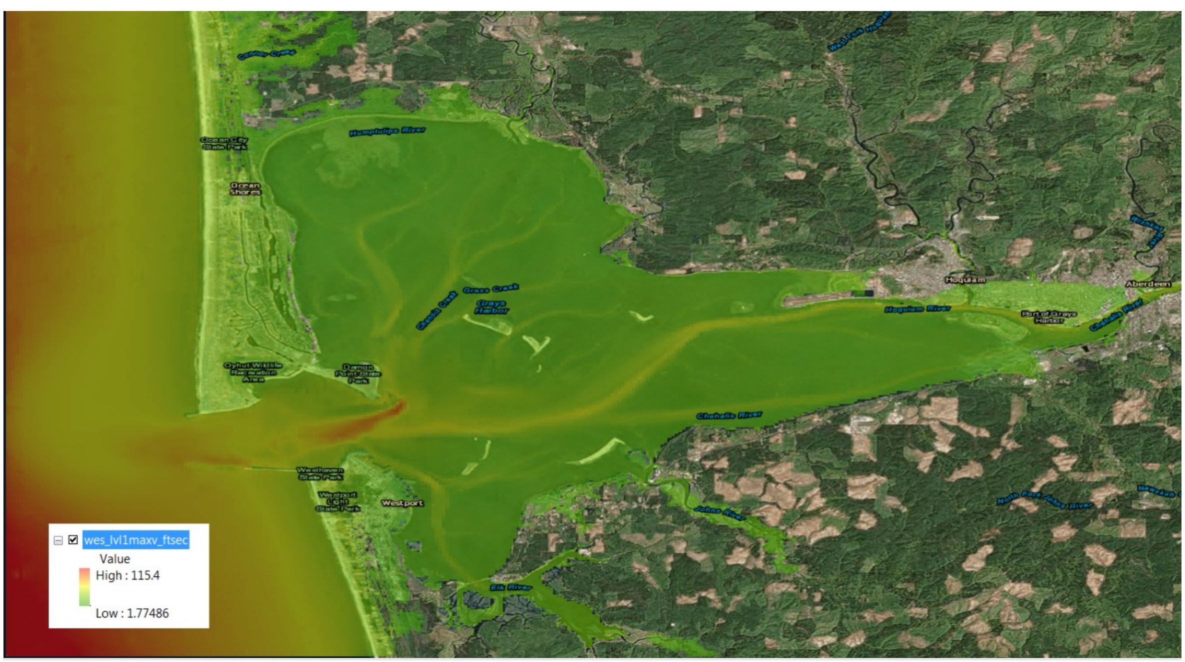

Figure 4-15 ASCE Equation-Based Velocity Grid for the Cascadia L1 Scenario, Westport, WA

Table 4-3 summarizes the results associated with the two Level 1 (Basic) equations when comparing with the SIFT output. Difference grids were produced by subtracting the SIFT model maximum velocities from those produced using the ASCE and P-646 equations. Further, these grids were masked to include only the on-land inundation areas where the Hazus modeled losses will occur. The cells with italics highlight which of the methods showed the best agreement. A mean of 0 represents good overall agreement, while negatives represent an underestimation of the Level 1 (Basic) approach as compared to the SIFT model products.

Table 4-3 Results of the Two Level 1 (Basic) Equations Compared to SIFT Output

Method	Case Study	R_{max} (feet)	SIFT V_{max} (fps)	Lvl1 (of Method) V_{max} (fps)	Mean (fps)[1]	Std Dev (fps)	Max (fps)	Min (fps)
ASCE Method	Kahului, HI	20.6691	22.5277	*20.4363*	*2.53*	3.59	15.11	-16.52
	Crescent City, CA	64.3254	42.0679	*36.0605*	*-0.19*	*5.37*	26.86	-25.96
	Garibaldi, OR	50.4182	41.3166	*31.5*	*3*	8.56	27.87	-25.46
	Homer, AK	10.8768	14.4897	*14.0235*	*7.3*	3.1	12.75	-3.78
	Westport, WA	71.2847	99.1494	*37.5062*	*0.23*	*8.43*	34.32	-74.05
P-646 Equation Method f_v=0.5	Kahului, HI	20.6691	22.5277	17.1825	4.86	*2.8*	12.6	-12.43
	Crescent City, CA	64.3254	42.0679	30.4499	2.75	6.3	26.48	-24.2
	Garibaldi, OR	50.4182	41.3166	26.2744	3.84	*7.65*	22.63	-27.41
	Homer, AK	10.8768	14.4897	12.3227	7.31	*1.82*	10.59	-4.5
	Westport, WA	71.2847	99.1494	31.3574	1.77	8.39	28.58	-75.76

* Shaded cells with italics highlight the methods that show the best agreement.

[1] Difference Grid – Inundation Area (Method Lvl 1 minus SIFT)

Figure 4-16 and Figure 4-17 below provide both the histogram and map illustrating the Difference Grids for the Westport, WA community case study area. Negatives reflect velocity values that are lower in the Level 1 (Basic) approach as compared to SIFT. Agreement appears primarily controlled by depth. Where depths are greater, Level 1 (Basic) techniques overestimate compared to SIFT, and where depths are shallow, the Level 1 (Basic) empirical approaches tend to underestimate velocities.

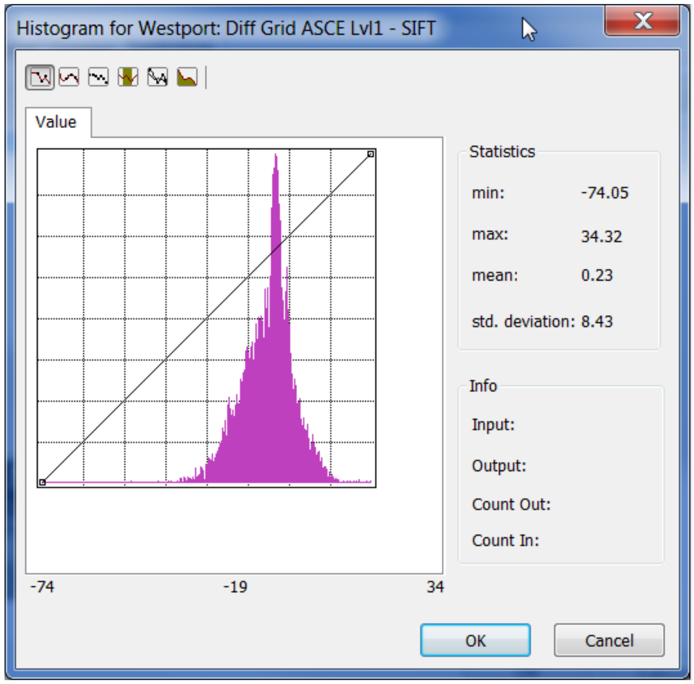

Figure 4-16 Difference Grid Histogram – Westport, WA

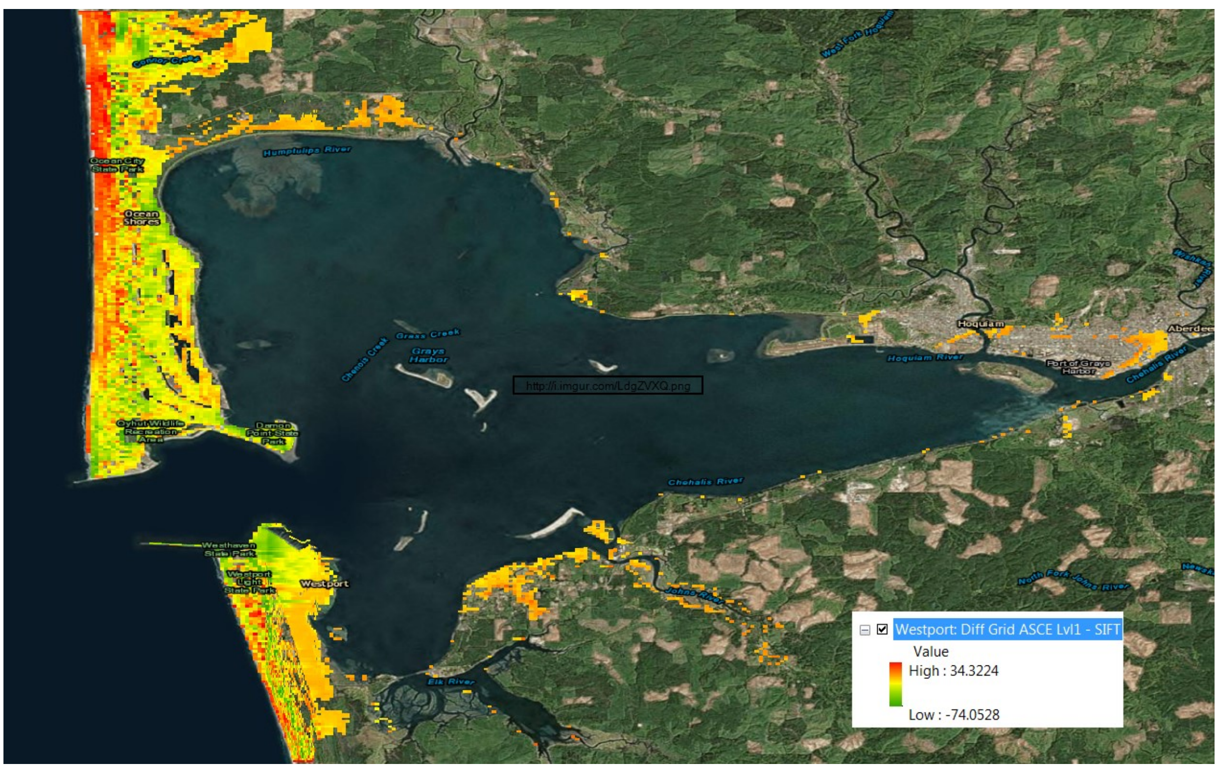

Figure 4-17 Difference Grid Map – Westport, WA

Overall, the ASCE method produced maximum velocity values closer to the numeric modeling grid for all scenarios. ASCE also showed better overall agreement for the scenarios with the largest runups and greatest depths (Westport R_{max} = 71' and Crescent City R_{max} = 64'). This is especially important since creation of the momentum flux grid requires multiplying these values by depth, amplifying any uncertainty in velocity.

4.8 Numerical Simulation Models (Level 2 and 3 Methodology)

A numerical model is used to obtain the best estimates of the output information and data. Numerical simulations involve modeling the tsunami source, propagation, and runup. There are several numerical codes available for tsunami simulations. Some of the codes are capable of simulating tsunamis in the entire process from earthquake source to runup. For example:

- COMCOT is a model based on nonlinear shallow-water-wave theory (Liu et al., 1994).
- NEOWAVE is a non-hydrostatic model (Yamazaki et al., 2010).
- MOST is based on nonlinear shallow-water-wave theory (NOAA/PMEL's code).
- SELFE uses a semi-implicit finite-element Eulerian-Lagrangian algorithm (Zhang and Baptista, 2008).
- GeoCLAW is based on a finite volume method with adaptive grid refinement (LeVeque and George, 2007).

Among the available simulation codes, NOAA's SIFT (Gica et al., 2008) appears the most widely available for Level 2 (Advanced) applications since it provides both depth and velocity grids. More importantly, NOAA has already prepared tsunami inundation models – called Forecast Inundation Models – specifically designed and developed for each of the 75 U.S. coastal communities shown in

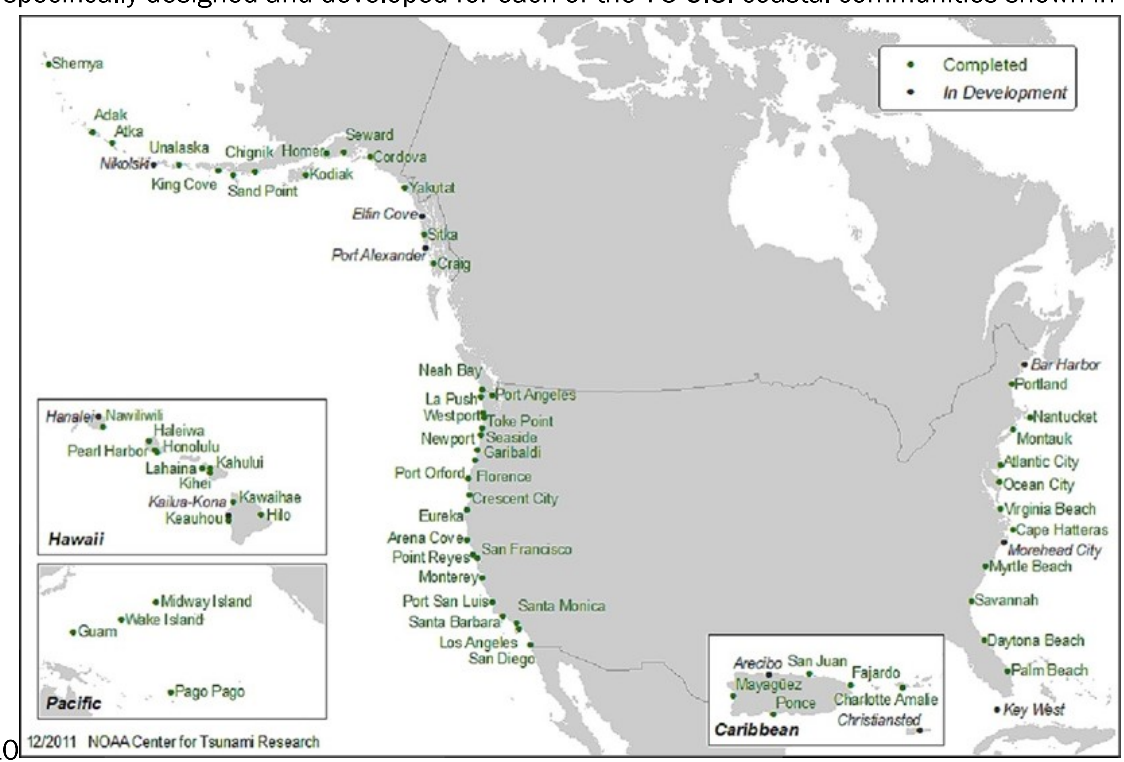

Figure 4-10

Figure 4-10. NOAA's SIFT operation produces very rapid tsunami predictions with optimized local tsunami runup models. With the cooperation of NOAA, Hazus directly utilizes NOAA's SIFT functionality for the Level 2 (Advanced) Methodology, available from the 75 U.S. coastal communities supported under the SIFT program. However, the Level 2 (Advanced) Methodology allows the integration of maximum depth and maximum velocity grids from other numeric models. For Level 3 (Advanced), more sophisticated, numerical models providing both median depth and median momentum flux inputs can be used. To date, only Oregon has these files readily available online from Oregon Department of Geology and Mineral Industries (DOGAMI) Open File Reports.

Section 5. Damage Assessment for Buildings

This section describes methods for determining the probability of Moderate, Extensive, and Complete damage to GBS UDF due to tsunami inundation (flood) and tsunami lateral force (flow). The GBS in the Hazus Tsunami Model is represented by National Structure Inventory (NSI) points attributed with specific building type, occupancy class, and other building inventory characteristics, distributed within the developed portions of Census blocks as described in the *Hazus Inventory Technical Manual* (FEMA, 2024). The GBS data support both economic losses and casualty modeling at a Census block level. UDF consist of site-specific points that represent structures and include the specific building characteristics required for tsunami damage assessment. In the Hazus Tsunami Model, the loss results available for UDF include damage states, functionality, and structural-, non-structural-, and content-economic losses at a site-specific level.

This section also describes methods for combining the probability of building damage due to a tsunami with the probability of building damage due to the earthquake that generated the tsunami (i.e., for evaluation of local tsunami damage and loss).

Building damage state probabilities are used in the evaluation of damage to UDF and economic losses (Section 7). The flow of hazard input from tsunami (Section 4) and earthquake damage (from the Earthquake Model), and the damage state probability output to current damage and loss components of the Hazus Tsunami Model is illustrated in Figure 5-1.

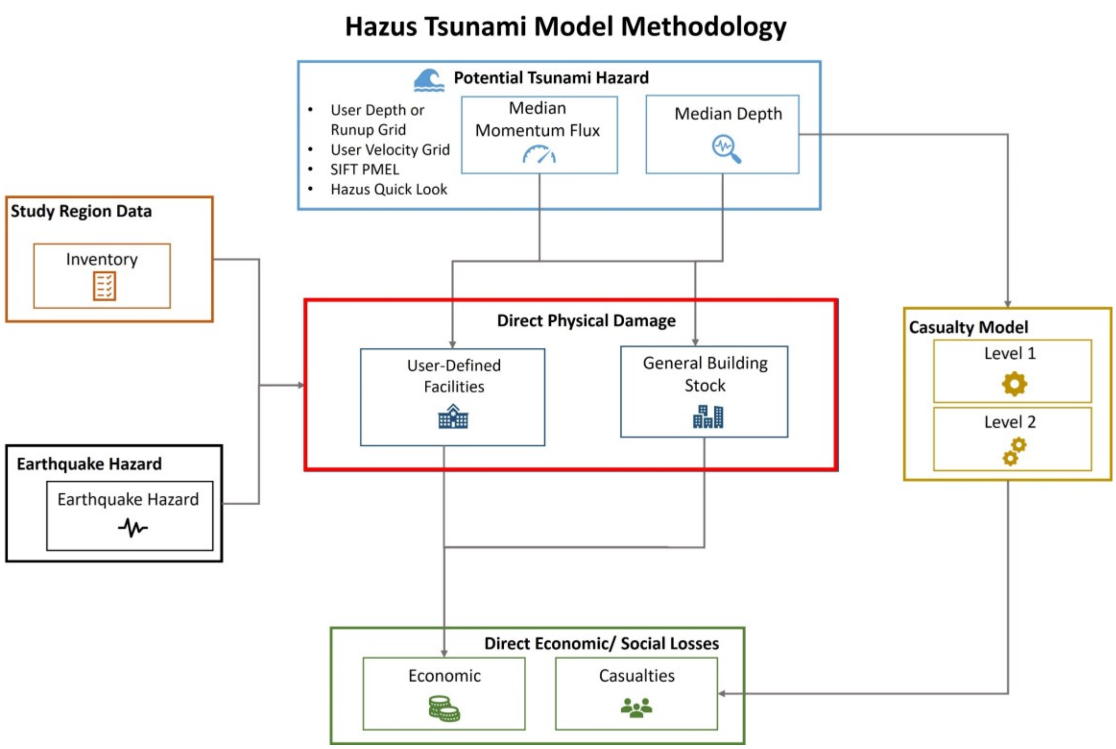

Figure 5-1 Hazus Tsunami Model Methodology Schematic

5.1 Building Damage Functions Approach

This section outlines the development of building damage functions for the 36 specific building types of the Tsunami Model. Separate sets of damage functions are developed for tsunami "flood" hazard and tsunami "flow" hazard.

Building damage functions describe the extent and severity of damage to:

- The structural system (i.e., structural elements supporting gravity loads and resisting lateral loads)
- Nonstructural systems and components (i.e., components of architectural, mechanical, electrical, and plumbing systems)
- Contents (i.e., furnishings and nonpermanent equipment, etc.)

5.1.1 Input Requirements and Output Information

Input information and data required to estimate building damage due to tsunami include the following items related to building inventory data, tsunami hazard parameters, and prior earthquake damage (for a local tsunami scenario):

Building Inventory Data

1. Specific Building Type (SBT) – one of 36 SBTs, including light-frame wood, W1, low- rise reinforced-concrete shear wall, C2L, etc.
2. Height of the first floor above the base of the building (h_F).
3. Height of the base of the building (z) above sea level datum used to define tsunami inundation height (R).
4. Seismic Design Level (e.g., high-code (HC), moderate-code (MC), low-code (LC), pre-code (PC), high-special (HS), moderate-special (MS), or low-special (LS)).

Tsunami Hazard Data

1. Median value of maximum inundation height (R) at building location point of interest.
2. Median value of maximum momentum flux (HV^2) at building point of interest.

Earthquake Damage Data (from the Earthquake Model)

1. Structural damage state probabilities.
2. Nonstructural drift-sensitive damage state probabilities.
3. Nonstructural acceleration-sensitive damage state probabilities.

4. Contents damage state probabilities.

Typically, specific building type and other inventory data are not known for each building of a given Census block and must be inferred on a square footage basis from the inventory of facilities using specific building type and occupancy relationships (see the *Hazus Inventory Technical Manual* (FEMA, 2024) for more information on constructing inventory data). The tsunami hazard data may be developed for grids of varying resolution. Thus, while the concepts are developed on a building-specific basis, they are typically applied on a pro rata basis to an aggregated building stock.

Output data developed by the building damage module are estimates of the cumulative probability of being in, or exceeding, each damage state for hazard parameter (or parameters, if combined) of interest. Discrete damage state probabilities are created from the cumulative damage probabilities, as described in Section 5.1.2. Discrete damage state probabilities for specific building types and occupancy classes are the outputs of the building damage module. These outputs are used directly as inputs to direct economic and societal loss modules, as shown in the flowchart of Figure 5-1.

While the building damage functions are applicable, in theory, to individual buildings, as well as to all buildings of a given type, they are more reliable as predictors of damage for large, rather than small, population groups. They should not be considered reliable for prediction of damage to a specific facility without confirmation by a seismic/structural engineering expert using the specific building properties (e.g., pushover strength, etc.).

5.1.2 Form of Damage Functions

Building damage functions are in the form of lognormal fragility curves that relate the probability of being in, or exceeding, a discrete state of damage given the median estimate of the hazard parameter of interest (i.e., median peak inundation height or median peak momentum flux). Figure 5-2 illustrates fragility curves that describe Moderate, Extensive, and Complete structure damage due to tsunami flow (i.e., median peak momentum flux, F), in this case for an older mid-rise reinforced-concrete shear wall building (specific building type C2M in Table 5-13)

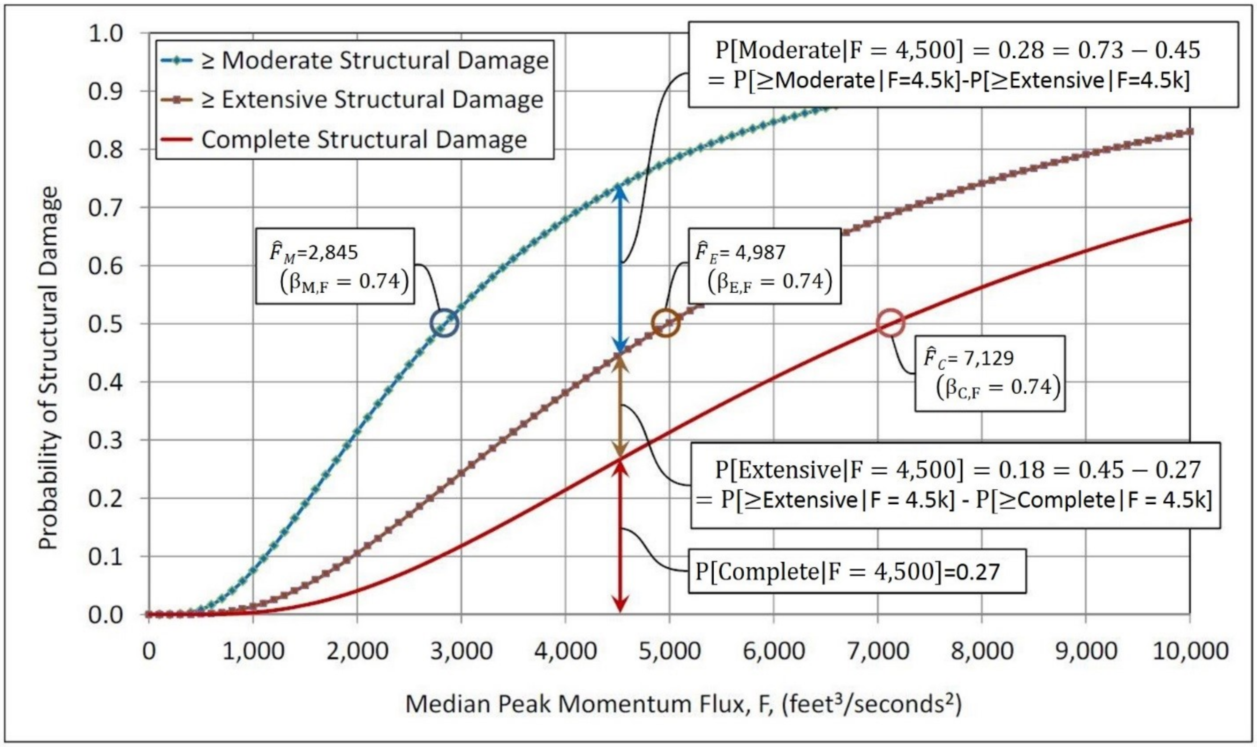

Figure 5-2 Example Fragility Curves for Tsunami Flow

Conceptually, the form of the tsunami building damage functions is the same as the lognormal "fragility" curve format used by the Earthquake Model. Each damage state curve is defined by the median value and associated variability of the fragility parameter of interest. The variability of these fragility curves has two fundamental components: the variability of the median estimate of the hazard parameter (i.e., uncertainty in demand) and the variability of the median value of the damage state (i.e., uncertainty in capacity) for the hazard of interest. The fragility random variable is expressed in terms of these two sources of uncertainty in Equation 5-1 for damage due to tsunami flood, R_{dsi}, and in Equation 5-2 for damage due to tsunami flow, F_{dsi}, as follows:

Equation 5-1

$$R_{dsi} = \hat{R}_{dsi}\, \varepsilon_{dsi\backslash R}\, \varepsilon_{R}$$

Equation 5-2

$$F_{dsi} = \hat{F}_{dsi}\, \varepsilon_{dsi\backslash F}\, \varepsilon_{F}$$

Where:

$\hat{R}_{dsi}$ is the median value of maximum inundation height associated with damage state, ds_i

$\varepsilon_{dsi \backslash R}$ is the lognormal random "capacity" variable with unit median and logarithmic standard deviation associated with the uncertainty in the damage state, ds_i, when damage is due to tsunami flood (maximum inundation height)

ε_R is the lognormal random "demand" variable with unit median and logarithmic standard deviation associated with the uncertainty in the median estimate of tsunami flood (maximum inundation height)

$\hat{F}_{dsi}$ is the median value of maximum momentum flux associated with damage state, ds_i

$\varepsilon_{dsi|F}$ is the lognormal random "capacity" variable with unit median and logarithmic standard deviation associated with the uncertainty in the damage state, ds_i, when damage is due to tsunami flow (maximum momentum flux)

ε_F is the lognormal random "demand" variable with unit median and logarithmic standard deviation associated with the uncertainty in the median estimate of tsunami flow (maximum momentum flux).

Median values of building damage states for damage due to tsunami flood, $\hat{R}_{dsi}$, are developed in Section 5.4 and median values of building damage states for damage due to tsunami flow, $\hat{F}_{dsi}$, are developed in Section 5.5.

In the above formulations, the "capacity" and "demand" random variables are assumed to be statistically independent, and total uncertainty may be calculated using Equation 5-3 and Equation 5-4, as follows:

Equation 5-3

$$\beta_{dsi,R} = \sqrt{\left(\beta_{dsi|R}\right)^2 + (\beta_R)^2}$$

Equation 5-4

$$\beta_{dsi,F} = \sqrt{\left(\beta_{dsi|F}\right)^2 + (\beta_F)^2}$$

Where:

$\beta_{dsi,R}$ is the logarithmic standard deviation describing the total uncertainty of damage state, ds_i, due to tsunami flood (maximum inundation height)

$\beta_{dsi|R}$ is the lognormal standard deviation associated with the uncertainty in the damage state, ds_i, capacity when damage is due to tsunami flood (maximum inundation height)

β_R is the logarithmic standard deviation associated with the uncertainty in the median estimate of tsunami flood (maximum inundation height)

$\beta_{dsi,F}$ is the logarithmic standard deviation describing the total uncertainty of damage state, ds_i, due to tsunami flow (maximum momentum flux)

$\beta_{dsi|F}$ is the logarithmic standard deviation associated with the uncertainty in the damage state, ds_i, capacity when damage is due to tsunami flow (maximum momentum flux)

β_F is the logarithmic standard deviation associated with the uncertainty in the median estimate of tsunami flow (maximum momentum flux).

It is important to distinguish the “demand” and “capacity” components of uncertainty, since the “demand” uncertainty component used for evaluation of losses due to a deterministic (scenario) tsunami is not required for evaluation of probabilistic losses when using tsunami hazard functions that directly incorporate this uncertainty in the hazard. For evaluation of probabilistic losses with a given deterministic tsunami, values of tsunami hazard uncertainty (β_F and β_R) should be assumed to be nil.

Values of the lognormal standard deviation parameter associated with the uncertainty in the damage state are developed in Section 5.4 and values of the lognormal standard deviation parameter associated with the uncertainty in the damage state are developed in Section 5.5.

The conditional probability of being in, or exceeding, the damage state, dsi, of interest, is given by Equation 5-5 and Equation 5-6:

Equation 5-5

$$P[ds_i|R] = \Phi\left[\frac{1}{\beta_{dsi,R}}\ln\left(\frac{R}{\hat{R}_{dsi}}\right)\right]$$

Equation 5-6

$$P[ds_i|F] = \Phi\left[\frac{1}{\beta_{dsi,F}}\ln\left(\frac{F}{\hat{F}_{dsi}}\right)\right]$$

The symbol Φ represents the normal distribution in Equation 5-5 and Equation 5-6.

The probability of being in a specific damage state, ds_i, is calculated as difference of the conditional probability of being in, or exceeding, the damage state of interest, ds_i, and the probability of being in, or exceeding, the next more severe damage state, ds_{i+1}, as illustrated in Figure 5-2, and as given by Equation 5-7 and Equation 5-8:

Equation 5-7

$$P[DS_i|R = r] = P[ds_i|R = r] - P[ds_{i+1}|R = r]$$

Equation 5-8

$$P[DS_i|F = f] = P[ds_i|F = f] - P[ds_{i+1}|F = f]$$

Where:

r and f	represent specific values of the random variables, R and F, respectively
$P[ds_{i+1}\|R = r]$	values are zero when the term ds_i represents the Complete damage state
$P[ds_i+1\|F = f]$	values are zero when the term ds_i represents the Complete damage state.

5.2 Description of Specific Building Types

Table 5-1 lists the 36 specific building types of the Hazus Tsunami Model, height ranges, and typical heights. The list is the same as the one presented in the *Hazus Inventory Technical Manual* (FEMA, 2024).

Table 5-1 Specific Building Types, Height Ranges, and Typical Heights

Label	Description	Height Range: Name	Height Range: Stories	Typical Height: Stories	Typical Height: Feet
W1	Wood, Light Frame (≤ 5,000 ft^2)		All	1	14
W2	Wood, Greater than 5,000 ft^2		All	2	24
S1L	Steel Moment Frame	Low-Rise	1-3	2	24
S1M	Steel Moment Frame	Mid-Rise	4-7	5	60
S1H	Steel Moment Frame	High-Rise	8+	13	156
S2L	Steel Braced Frame	Low-Rise	1-3	2	24
S2M	Steel Braced Frame	Mid-Rise	4-7	5	60
S2H	Steel Braced Frame	High-Rise	8+	13	156
S3	Steel Light Frame		All	1	15
S4L	Steel Frame with Cast-in-Place Concrete Shear Walls	Low-Rise	1-3	2	24
S4M	Steel Frame with Cast-in-Place Concrete Shear Walls	Mid-Rise	4-7	5	60
S4H	Steel Frame with Cast-in-Place Concrete Shear Walls	High-Rise	8+	13	156

Label	Description	Height Range: Name	Height Range: Stories	Typical Height: Stories	Typical Height: Feet
S5L	Steel Frame with Unreinforced Masonry Infill Walls	Low-Rise	1-3	2	24
S5M	Steel Frame with Unreinforced Masonry Infill Walls	Mid-Rise	4-7	5	60
S5H	Steel Frame with Unreinforced Masonry Infill Walls	High-Rise	8+	13	156
C1L	Concrete Moment Frame	Low-Rise	1-3	2	20
C1M	Concrete Moment Frame	Mid-Rise	4-7	5	50
C1H	Concrete Moment Frame	High-Rise	8+	12	120
C2L	Concrete Shear Walls	Low-Rise	1-3	2	20
C2M	Concrete Shear Walls	Mid-Rise	4-7	5	50
C2H	Concrete Shear Walls	High-Rise	8+	12	120
C3L	Concrete Frame with Unreinforced Masonry Infill Walls	Low-Rise	1-3	2	20
C3M	Concrete Frame with Unreinforced Masonry Infill Walls	Mid-Rise	4-7	5	50
C3H	Concrete Frame with Unreinforced Masonry Infill Walls	High-Rise	8+	12	120
PC1	Precast Concrete Tilt-Up Walls		All	1	15
PC2L	Precast Concrete Frames with Concrete Shear Walls	Low-Rise	1-3	2	20
PC2M	Precast Concrete Frames with Concrete Shear Walls	Mid-Rise	4-7	5	50
PC2H	Precast Concrete Frames with Concrete Shear Walls	High-Rise	8+	12	120
RM1L	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Low-Rise	1-3	2	20
RM1M	Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	Mid-Rise	4+	5	50
RM2L	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Low-Rise	1-3	2	20
RM2M	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	Mid-Rise	4-7	5	50
RM2H	Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	High-Rise	8+	12	120
URML	Unreinforced Masonry Bearing Walls	Low-Rise	1-2	1	15
URMM	Unreinforced Masonry Bearing Walls	Mid-Rise	3+	3	35
MH	Mobile Homes		All	1	12

The specific building types of Table 5-1 were originally based on the classification system of FEMA 178, *NEHRP Handbook for the Seismic Evaluation of Existing Buildings* (FEMA, 1992) and may now be found in ASCE 31-03, *Seismic Evaluation of Existing Buildings* (ASCE, 2003). The specific building types of the Earthquake Model (and Tsunami Model) expand FEMA 178 and ASCE 31-03 building types to incorporate building height (e.g., low-rise, mid-rise, and high-rise building types), and to also include manufactured housing (mobile homes). General descriptions of the structural system of specific building types are found in the *Hazus Earthquake Model Technical Manual* (FEMA, 2024) (and ASCE 31-03).

For evaluation of tsunami inundation, Hazus estimates first floor heights as a function of foundation type and building age (pre-FIRM and post-FIRM construction)(Flood Insurance Rate Map), which are based on an assigned distribution of foundation types. Tables 5-23 and 5-24 of the *Hazus Inventory Technical Manual* (FEMA, 2024) provide the data on first floor heights for each foundation type and the distribution of foundation types used in the Tsunami Model.

5.3 Description of Building Damage States

Damage is described by one of three non-nil damage states: Moderate, Extensive, and Complete. These damage states are the same as those (of the same name) used by the Earthquake Model to describe the extent and severity of damage due to ground shaking and ground failure. Building damage due to earthquake ground shaking is also described in terms of Slight damage. Slight damage is not required for tsunami, since it is difficult to distinguish from no damage, it is only used for calculation of earthquake economic losses and is of no significance to tsunami economic losses. Although the specific cause and manifestation of tsunami damage can be quite different from that of an earthquake, tsunami and earthquake damage states are considered to be the same when they represent a common extent and severity of damage.

The damage states define damage to the structure, damage to nonstructural systems, and damage to the contents of the specific building type of interest. These discrete damage states are intentionally based on the same generic damage states as those of the Earthquake Model, to permit combination of damage state probabilities due to tsunami with damage state probabilities due to earthquake (e.g., for evaluation of local tsunami damage and loss).

Table 5-2 (adapted from Table 6-1 of the Hazus *Advanced Engineering Building Module* (AEBM) *Technical* and *User's Manual* (FEMA, 2002)) summarizes the generic guidelines used to establish median values of structure, nonstructural, and contents damage states for tsunami. These guidelines establish, in an approximate sense, the state of physical damage to the structure, nonstructural systems, and contents, in terms of various types of loss parameters. Like earthquake, nonstructural systems and contents damage states are primarily influenced by economic loss considerations, whereas structure damage states are also influenced by other types of losses, such as shelter (probability of building closure) and debris generation (probability of building collapse). However, there are some key differences. For example, an elevated light frame structure in tsunami could have extensive structural losses related to tsunami flow and minimal non-structural and contents losses related to the depth of flooding in structure. In these cases, non-structural and content losses are reset to complete if the structural losses are complete, since it is likely a Complete structural loss would result in Complete non-structural and content economic losses. Further, content losses in earthquake are capped at 50% since salvage is likely even in Complete damage states, however, Complete content losses as a result of tsunami flow or flood likely results in 0% salvage. Table 5-2 shows damage state and likely amount of damage, direct economic loss, or building condition.

Table 5-2 General Guidance Used to Select Building Damage State Parameters for Tsunami Hazard

Damage State	Range of Possible Economic Loss Ratios	Probability of Long-Term Building Closure	Probability of Partial or Full Collapse of the Structure	Immediate Post-Event Inspection[1]
Slight[2]	0% - 5%	P = 0	P = 0	Green Tag
Moderate	5% - 25%	P = 0	P = 0	Green Tag
Extensive[3]	25% - 100%	P ≅ 0.5	P ≅ 0[3]	Yellow Tag
Complete[4]	100%	P ≅ 1.0	P > 0[3]	Red Tag

[1] Post-event safety inspection “tag” nomenclature is based on the ATC-20 report (ATC, 1989), as revised by the ATC-20-2 report (ATC, 1995), which provides guidance for post-earthquake inspection and classification of buildings damage as “Inspected” (Green Tag), “Restricted Use” (Yellow Tag), or “Unsafe” (Red Tag). Similar post-flood safety inspection “tag” nomenclature is provided in the ATC-45 field manual (ATC, 1994).

[2] Slight damage state is not used for tsunami.

[3] Extensive damage may include local collapse of structural elements and nonstructural components (e.g., out-of-plane failure of walls due to tsunami flow).

[4] Complete structural damage includes: 1) structures that are standing, but a total economic loss, 2) structures that have sustained partial or full collapse, but remain largely in place, and 3) structures that have been “washed away” by tsunami flow.

Conceptually, the same building damage states can occur due to either tsunami flood hazard or tsunami flow hazard. This approach is similar to that of the Earthquake Model which uses the same damage states to represent building damage due to either earthquake ground shaking or earthquake ground failure. A common set of damage states permits separately calculated damage state probabilities to be combined using appropriate logic (e.g., assumption of statistical independence of the hazards). The notion of hazard independence is supported by tsunami flood damage functions that are based solely on the effects of inundation (i.e., no damage due to tsunami flow) and tsunami flow damage functions that are based solely on the effects of lateral force. It should be noted that depth-damage functions (DDFs) of the Flood Model for coastal areas (i.e., coastal Zone A and coastal Zone V areas) incorporate damage due to storm waves as well as inundation and are, therefore, not appropriate for comparison with tsunami “inundation only” flood damage. The DDFs of the Flood Model for Zone A (low-water velocity) areas are more appropriate for comparison with tsunami “inundation only” building damage functions.

While tsunami damage states are generally the same as those of the Earthquake Model, fewer damage states are required to adequately address tsunami losses. Slight damage is not required for tsunami, since it is difficult to distinguish from no damage, is only used for calculation of economic losses, and is of no significance to tsunami economic losses. Hazus economic loss rates define Slight damage as only 2% of the building’s replacement value (and only 1% of contents value), so a large number of buildings in the Study Region of interest would need to have a large probability of Slight damage to significantly contribute to economic losses. While this can be true for certain earthquake scenarios, tsunami damage tends to be either nil, in areas not exposed to tsunami runup, or likely to be much greater than Slight damage in inundated areas (since even a relatively small depth of water causes more than 2% loss). Similarly, Moderate and Extensive states of damage are not used for all specific building types and systems. In general, shorter (and lighter) specific building types require fewer damage states to reliably calculate tsunami losses.

Table 5-3 summarizes damage states used to characterize tsunami damage to buildings in terms of building system (i.e., structure, nonstructural, and contents), building height (i.e., specific building type), and tsunami hazard (i.e., tsunami flood or tsunami flow). Damage to the structural system is assumed to be governed solely by tsunami flow hazard and damage to nonstructural systems and contents (in structures that survive) are assumed to be governed solely by tsunami flood hazard.

Nonstructural systems and contents damage states are based solely on tsunami flood hazard (water depth based on maximum inundation height) assuming that if the building survives tsunami flow effects (e.g., is not washed away or otherwise does not sustain Complete damage to the structure), then damage and related losses to these systems are primarily a function of maximum inundation height. Of course, nonstructural systems and contents are also damaged by tsunami flow, but such damage is assumed to be adequately captured by damage due to inundation (e.g., since nonstructural systems and contents of fully inundated floors are assumed to be a complete loss). Additionally, to the extent that tsunami flow causes Complete damage to the structure, then nonstructural systems and contents are also assumed to have Complete damage. Thus, the probability of Complete structural damage (due to tsunami flow) is an important contributor to building damage and loss, particularly for specific building types of shorter, lighter construction (consistent with observations of tsunami damage in past events).

Table 5-3 Possible Building Component Damage States Based on Hazard Type

Specific Building Type	Tsunami Inundation Height			Tsunami Momentum Flux		
(Height/Weight)	Moderate	Extensive	Complete	Moderate	Extensive	Complete
Low-Rise – Light*		NSS, CON	NSS, CON			STR
Low-Rise – Other		NSS, CON	NSS, CON		STR	STR
Mid-Rise	NSS, CON	NSS, CON	NSS, CON	STR	STR	STR
High-Rise	NSS, CON	NSS, CON	NSS, CON	STR	STR	STR

* Table shows Building Systems Modeled by Damage States

** NSS = Nonstructural Systems, CON = Contents, and STR = Structure

Structure damage states are based solely on tsunami flow hazard assuming that the structure of the building is not appreciably damaged unless there is significant tsunami flow velocity. This assumption is consistent with observations of tsunami damage to buildings, and flood modeling assumptions which are documented in the *Hazus Flood Model Technical Manual* (FEMA, 2024):

> "Unless the floodwaters flow at a high velocity and the structure and the foundation become separated, or the structure is impacted by flood-borne debris, it is unlikely that a building will suffer structural failure in a flood. (Structural failure should be distinguished, however, from suffering substantial damage, wherein the damage due to inundation exceeds 50% of the structure's total replacement cost and the building is considered a total loss.) In general, it is expected that the major structural components of a building will survive a flood, but that the structural finishes and contents/inventory may be severely damaged due to inundation."

Table 5-4, Table 5-5, and Table 5-6 provide qualitative descriptions of structure damage states and nonstructural and contents damage states. Subsequent subsections of Section 5 use these descriptions and other data to establish specific values of damage state parameters for different specific building types.

Conceptually, nonstructural systems and components located on fully "inundated" floors are considered to be ruined (i.e., 100% damage), and that only a few feet of water is required to significantly damage contents on a partially inundated floor.

Conceptually, the structure is considered undamaged until lateral forces, due to hydrodynamic loads, including the effects of debris impact, exceed the yield-force capacity of the structural system. Structure damage increases with tsunami force until tsunami flow and debris forces exceed the ultimate-lateral-force capacity of the structural system, and complete failure is assumed to occur. This approach focuses on the global damage to the structure, rather than on failure of individual elements. As described in Table 5-4 through Table 5-6, hydrodynamic loads can also cause localized damage to structural elements, including out-of-plane failure of walls, columns, and braces, which could lead to progressive collapse of the building, and tsunami flow can also erode and scour the structure and compromise the foundation, or cause uplift of the building.

Debris strikes more severely impact load-bearing structural elements than on the overall lateral-force-resisting system. While these are important modes of tsunami damage, quantification of building damage due to failure of individual structural elements, possible progressive collapse, and loss of foundation integrity would require detailed structural information that is not available for generic specific building types. Rather, tsunami damage functions use estimates of global building strength (which can be inferred from building age, etc.) to relate building damage states to tsunami flow and debris forces.

Table 5-4 Qualitative Descriptions of Structure Damage States due to Tsunami Flow

Specific Building Type (Height/Weight)	Moderate Structure Damage	Extensive Structure Damage	Complete Structure Damage
Low-Rise – Light SBTs (W1, W2, S3, MH)			A significant portion of structural elements have exceeded their ultimate capacities and/or many critical elements/connections have failed resulting in dangerous permanent offset, partial

Specific Building Type (Height/Weight)	Moderate Structure Damage	Extensive Structure Damage	Complete Structure Damage
			collapse, full collapse, or building moved off foundation (e.g., "washed away"). Extensive erosion or scour, substantial foundation settlement.
Low-Rise - Other		Localized failure of elements at lower floors. Large diagonal cracks in shear walls, failure of steel braces, large flexural cracks/buckling of rebar, buckled flanges and connection failures– large permanent offsets of lower stories. Localized erosion or scour, limited foundation settlement.	A significant portion of structural elements have exceeded their ultimate capacities and/or many critical elements/connections have failed resulting in dangerous permanent offset, partial collapse, full collapse or building moved off foundation (e.g., "washed away"). Extensive erosion or scour, substantial foundation settlement.
Mid-Rise - All	Limited, localized damage to elements at lower floors. Diagonal cracks in shear walls, limited yielding of steel braces, cracking and hinging of flexural elements – no or only minor permanent offsets (i.e., less than ½ inch per floor).	Localized failure of elements at lower floors. Large diagonal cracks in shear walls, failure of steel braces, large flexural cracks/buckling of rebar, buckled flanges and connection failures– large permanent offsets of lower stories. Localized erosion or scour, limited foundation settlement.	A significant portion of structural elements have exceeded their ultimate capacities and/or many critical elements/connections have failed resulting in dangerous permanent offset, partial collapse, full collapse, or building moved off foundation (e.g., "washed away"). Extensive erosion or scour, substantial foundation settlement.
High-Rise- All	Limited, localized damage to elements at lower floors. Diagonal cracks in shear walls, limited yielding of steel braces, cracking and hinging of flexural elements – no or only minor permanent offsets (i.e., less than ½ inch per floor).	Localized failure of elements at lower floors. Large diagonal cracks in shear walls, failure of steel braces, large flexural cracks/buckling of rebar, buckled flanges and connection failures– large permanent offsets of lower stories. Localized erosion or scour, limited foundation settlement.	A significant portion of structural elements have exceeded their ultimate capacities and/or many critical elements/connections have failed resulting in dangerous permanent offset, partial collapse, full collapse, or building moved off foundation (e.g., "washed away"). Extensive erosion or scour, substantial foundation settlement.

Table 5-5 Qualitative Descriptions of Nonstructural Systems Damage States due to Tsunami Flood

Specific Building Type (Height/Weight)	Moderate Nonstructural Systems Damage	Extensive Nonstructural Systems Damage	Complete Nonstructural Systems Damage
Low-Rise – One-Story		Floor 1 (1/2 height)	Floor 1
Low-Rise – Two-Story		Floor 1	Floors 1 - 2
Mid-Rise – Five-Story	Floor 1	Floors 1 - 3	Floors 1 - 5
High-Rise – 12 Story	Floor 1	Floors 1 - 6	Floors 1 - 12

Table 5-6 Qualitative Descriptions of Contents Damage States due to Tsunami Flood

Specific Building Type (Height/Weight)	Moderate Contents Damage	Extensive Contents Damage	Complete Contents Damage
Low-Rise – One-Story			Floor 1 (3 feet)
Low-Rise – Two-Story		Floor 1 (3 feet)	Floors 1 – Floor 2 (3 feet)
Mid-Rise – Five-Story	Floor 1 (3 feet)	Floors 1 – 2, 3 (3 feet)	Floors 1 – 4, 5 (3 feet)
High-Rise – 12-Story	Floor 1 (3 feet)	Floors 1 – 5, 6 (3 feet)	Floors 1 – 11, 12 (3 feet)

* "(# feet)" designates the depth of water above the specified floor that is needed to cause that level of damage

5.4 Building Damage Due to Tsunami Inundation

This section describes the approach and develops baseline values of building damage functions due to tsunami flood (based on maximum water inundation height). In this case, damage is assumed to be primarily due to maximum water height (essentially nil water velocity), similar to damage caused by riverine flood, and tsunami flood methods have utilized related information contained in the *Hazus Flood Model Technical Manual* (FEMA, 2024). The Flood Model estimates dollar losses directly on water depth using experiential dollar loss data available for certain occupancy classes (depth-damage curves). Tsunami flood methods also use water depth but employ a theoretical approach to estimate inundation damage. When combined with the economic loss functions (Section 7), tsunami flood damage functions yield very similar dollar loss results to those of the Flood Model for the same specific building type (occupancy class) and inundation depth. The theoretical approach of the tsunami flood methods provides a basis to estimate flood-related damage and loss when empirical data are not available for the specific building type of interest. Baseline values of the median and logarithmic standard deviation (STD) describe the probability of damage to nonstructural systems (NSS) and contents (CON) for each specific building type listed in Table 5-1.

5.4.1 Approach

Building damage due to tsunami inundation is assumed to be similar to that caused by other floods that have relatively slow water flow (e.g., riverine flooding). Building damage due to fast moving water flow is treated separately by damage functions that model damage due to hydrodynamic and related loads on the building (Section 5.5).

Damage to nonstructural systems and contents due to tsunami inundation is related directly to the height of the water. Nonstructural systems and contents that are inundated are considered ruined (a total loss) and the damage state (Moderate, Extensive, or Complete) reflects the fraction of the nonstructural systems and contents in the building that is inundated. Consistent with the damage functions of the Flood Model, contents which are primarily floor-supported items are more vulnerable to water depth on a given floor than nonstructural components (which include ceilings, overhead lights, etc., as well as floor supported items. Hence, full-height inundation of a given floor is assumed necessary for 100% damage of nonstructural systems on that floor, whereas 3 feet of water on a given floor is assumed sufficient to cause 100% damage to building contents on that floor.

Since damage is directly related to water depth, it is important to relate the elevation of building floors to the elevation of tsunami inundation, considering both the height, z, of the building's base above the sea level datum used to characterize tsunami inundation height, and the height of the first floor of the building above its base, h_F. Figure 5-3 illustrates these parameters and their relationship to inundation height at building, R, inundation depth at building, H, and inundation depth relative to the first floor of the building, H_F.

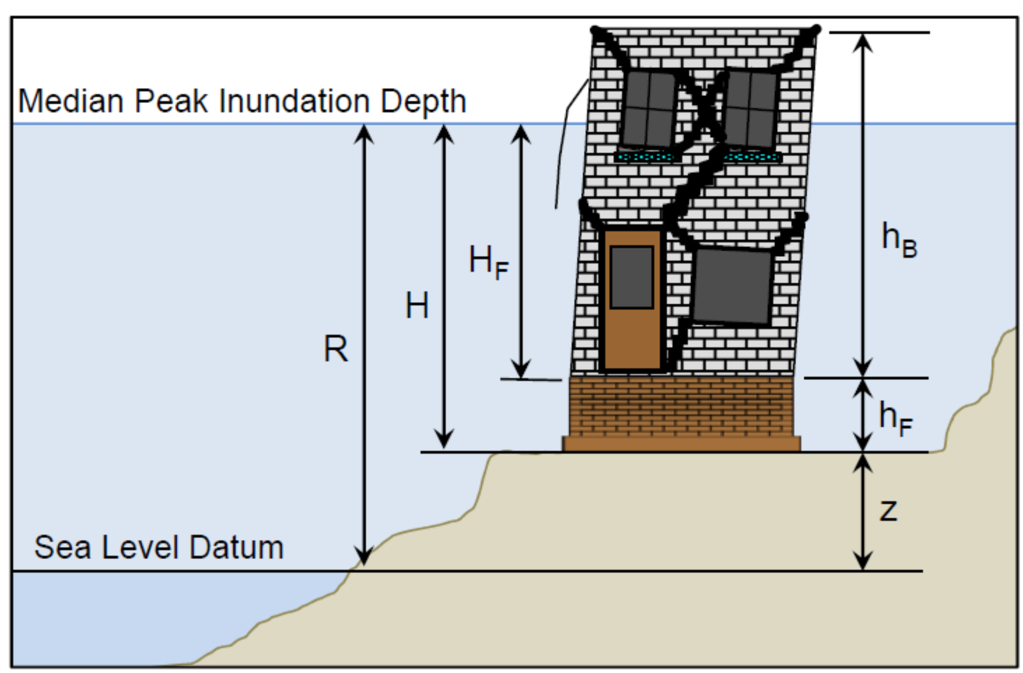

Figure 5-3 Schematic Illustration of Inundation Components

While inundation damage is related to the depth of water in the building (i.e., relative to the elevation of the first floor that defines model building height), the hazard parameter of interest is inundation height relative to the sea level datum. To properly incorporate uncertainty in the damage state with uncertainty in inundation height, it is necessary that fragility parameters, based on water depth above the first floor, be represented in terms of water height relative to the sea level datum used to define inundation height. These parameters are related by Equation 5-9:

Equation 5-9

$$R_{dsi} = H_{Fdsi} + h_F + z$$

Where:

R_{dsi}	is the inundation-height-related random variable with median, $\hat{R}_{dsi}$, and capacity-related logarithmic standard deviation, $\beta_{dsi\|R}$, of damage state, i
H_{Fdsi}	is the building water depth-related random variable with median, $\hat{H}_{Fdsi}$, and capacity-related logarithmic standard deviation, $\beta_{dsi\|H}$, of damage state i
h_F	is the height of first floor above building base (in feet)
z	is the height of building base above sea level datum (in feet)

The height terms, h_F and z, are treated deterministically (i.e., these terms are assumed to be known) and the relationship between the median values of R_{dsi} and HF_{dsi} is given by Equation 5-10 and the relationship between the logarithmic standard values of R_{dsi} and H_{Fdsi} is given by Equation 5-11:

Equation 5-10

$$R_{dsi} = H_{Fdsi} + h_F + z$$

Equation 5-11

$$\beta_{dsi\,|R} = \ln\left(\frac{z + h_F + e^{\beta_{dsi\,|H}}\,\widehat{H}_{Fdsi}}{z + h_F + \widehat{H}_{Fdsi}}\right)$$

Where:

R_{dsi}	is the median value of tsunami inundation height of damage state, i (in feet)
H_{Fdsi}	is the median value of building water depth of damage state, i
h_F	is the height of first floor above building base (in feet)
z	is the height of building base above sea level datum (in feet)
$\beta_{dsi\|R}$	is the lognormal standard deviation associated with the uncertainty in the damage state, ds_i, when damage is due to inundation height
$\beta_{dsi\|H}$	is the logarithmic standard deviation associated with the uncertainty in the damage state, ds_i, when damage is due to maximum depth of water in building.

The sum of terms, z + h_F, used to shift median values in Equation 5-10 and to adjust damage- state uncertainty in Equation 5-11, may be observed to have the following effects:

1. For values of z + hF << $\hat{H}_{Fdsi}$, damage state uncertainty remains essentially the same (i.e., no adjustment to uncertainty for damage states with median values much greater than the median inundation height).

2. For values of z + hF >> $\hat{H}_{Fdsi}$, uncertainty in the median value of the damage state tends to zero and the uncertainty in the hazard (i.e., inundation height) dominates the fragility of buildings whose first-floor elevation is much higher than the median inundation depth of the damage state of interest (e.g., buildings on hills).

5.4.2 Baseline Values of Damage Function Parameters

Baseline values of damage function parameters are described in terms of water depth relative to the first floor by the median value of the damage state of interest, $\hat{H}_{Fdsi}$, and the corresponding measure of damage state uncertainty, $\beta_{dsi|H}$. As described in previous sections, these parameters must be modified before evaluating building damage due to tsunami inundation, as described by the following three steps:

1. The median value of damage state of interest, is $\hat{H}_{Fdsi}$ adjusted using Equation 5-10 to represent the median damage in terms of inundation height, $\hat{R}_{dsi}$

2. The value of the logarithmic standard deviation of the damage state of interest, $\beta_{dsi|H}$, is adjusted using Equation 5-11 to represent the uncertainty of the damage state of interest in terms of inundation height, $\beta_{dsi|R}$, and

3. The uncertainty in the damage state of interest, $\beta_{dsi|R}$, is combined with the uncertainty in the inundation height, β_R, using Equation 5-14 to obtain the total uncertainty of the damage state of interest, $\beta_{dsi,R}$.

The median, $\hat{R}_{dsi}$, and the logarithmic standard deviation, $\beta_{dsi,R}$, define the fragility curve of the damage state of interest for building damage due to tsunami inundation.

Table 5-7 summarizes baseline values of fragility parameters for evaluation of nonstructural system damage states of each specific building type, and Table 5-8 summarizes baseline values of fragility parameters for evaluation of contents damage states of each specific building type. Cells in these tables with italics indicate damage states not required to characterize flood-related damage, as described in Table 5-5 and Table 5-6, for which fragility parameters (median and logarithmic standard deviation values) are set equal to the next, more severe damage state. The basis for the baseline values fragility parameters is summarized below.

5.4.2.1 Basis for Baseline Values of Median Damage

Baseline values of median damage (i.e., water depth above the first-floor level) are based on the descriptions of damage given in Table 5-5 and Table 5-6 (depth of water associated with damage states), and the typical values of the building height (and corresponding number of stories) given in Table 5-1. Note: Height values given in Table 5-1 (and repeated Table 5-5 and Table 5-6) represent buildings whose first floor level is at the base of the building (i.e., h_F = 0).

5.4.2.2 Basis for Baseline Values of Beta (Logarithmic Standard Deviation)

Baseline values of beta (logarithmic standard deviation) are based on the two primary sources of uncertainty in the median values of damage due to tsunami flood, the height of the building and the height at which a particular state of damage is assumed to occur. These two sources of uncertainty are modeled as independent lognormal random variables and estimates of the uncertainty in the height of the building combined with estimates of the uncertainty in the height of the damage state using the square-root-sum-of-the-squares (SRSS) method.

Table 5-7 Baseline Values of Damage State Parameters for Evaluation of Damage to Nonstructural Systems due to Tsunami Flood

Specific Building Type		Moderate Damage		Extensive Damage		Complete Damage	
Name	Height (ft)	Median (ft)	Beta	Median (ft)	Beta	Median (ft)	Beta
W1	14	*7*	*0.77*	7	0.77	14	0.65
W2	24	*12*	*0.78*	12	0.78	24	0.65
S1L	24	*12*	*0.78*	12	0.78	24	0.65
S1M	60	12	0.62	36	0.33	60	0.35
S1H	156	12	0.65	84	0.35	156	0.36
S2L	24	*12*	*0.78*	12	0.78	24	0.65
S2M	60	12	0.62	36	0.33	60	0.35
S2H	156	12	0.65	84	0.35	156	0.36
S3	15	*7.5*	*0.77*	7.5	0.77	15	0.65
S4L	24	*12*	*0.78*	12	0.78	24	0.65
S4M	60	12	0.62	36	0.33	60	0.35
S4H	156	12	0.65	84	0.35	156	0.36
S5L	24	*12*	*0.78*	12	0.78	24	0.65
S5M	60	12	0.62	36	0.33	60	0.35
S5H	156	12	0.65	84	0.35	156	0.36
C1L	20	*10*	*0.78*	10	0.78	20	0.65
C1M	50	10	0.62	30	0.33	50	0.35
C1H	120	10	0.65	60	0.36	120	0.36
C2L	20	*10*	*0.78*	10	0.78	20	0.65
C2M	50	10	0.62	30	0.33	50	0.35
C2H	120	10	0.65	60	0.36	120	0.36
C3L	20	*10*	*0.78*	10	0.78	20	0.65
C3M	50	10	0.62	30	0.33	50	0.35

Specific Building Type		Moderate Damage		Extensive Damage		Complete Damage	
Name	Height (ft)	Median (ft)	Beta	Median (ft)	Beta	Median (ft)	Beta
C3H	120	10	0.65	60	0.36	120	0.36
PC1	15	*7.5*	*0.77*	7.5	0.77	15	0.65
PC2L	20	*10*	*0.78*	10	0.78	20	0.65
PC2M	50	10	0.62	30	0.33	50	0.35
PC2H	120	10	0.65	60	0.36	120	0.36
RM1L	20	*10*	*0.78*	10	0.78	20	0.65
RM1M	50	10	0.62	30	0.33	50	0.35
RM2L	20	*10*	*0.78*	10	0.78	20	0.65
RM2M	50	10	0.62	30	0.33	50	0.35
RM2H	120	10	0.65	60	0.36	120	0.36
URML	15	*7.5*	*0.77*	7.5	0.77	15	0.65
URMM	36	12	0.65	24	0.43	36	0.49
MH	10	*5*	*0.72*	5	0.72	10	0.59

* Shaded cells with italics indicate damage states not required to characterize flood-related damage

Table 5-8 Baseline Values of Damage State Parameters for Evaluation of Damage to Contents due to Tsunami Flood

Specific Building Type		Moderate Damage		Extensive Damage		Complete Damage	
Name	Height (ft)	Median (ft)	Beta	Median (ft)	Beta	Median (ft)	Beta
W1	14	*3*	*0.65*	*3*	*0.65*	3	0.65
W2	24	*3*	*0.78*	3	0.78	15	0.65
S1L	24	*3*	*0.78*	3	0.78	15	0.65
S1M	60	3	0.62	27	0.35	51	0.35
S1H	156	3	0.65	75	0.36	147	0.35
S2L	24	*3*	*0.78*	3	0.78	15	0.65
S2M	60	3	0.62	27	0.35	51	0.35
S2H	156	3	0.65	75	0.36	147	0.35
S3	15	*3*	*0.65*	*3*	*0.65*	3	0.65
S4L	24	*3*	*0.78*	3	0.78	15	0.65
S4M	60	3	0.62	27	0.35	51	0.35

Specific Building Type		Moderate Damage		Extensive Damage		Complete Damage	
Name	Height (ft)	Median (ft)	Beta	Median (ft)	Beta	Median (ft)	Beta
S4H	156	3	0.65	75	0.36	147	0.35
S5L	24	*3*	*0.78*	3	0.78	15	0.65
S5M	60	3	0.62	27	0.35	51	0.35
S5H	156	3	0.65	75	0.36	147	0.35
C1L	20	*3*	*0.78*	3	0.78	13	0.65
C1M	50	3	0.62	23	0.35	43	0.35
C1H	120	3	0.65	53	0.36	113	0.35
C2L	20	*3*	*0.78*	3	0.78	13	0.65
C2M	50	3	0.62	23	0.35	43	0.35
C2H	120	3	0.65	53	0.36	113	0.35
C3L	20	*3*	*0.78*	3	0.78	13	0.65
C3M	50	3	0.62	23	0.35	43	0.35
C3H	120	3	0.65	53	0.36	113	0.35
PC1	15	*3*	*0.65*	*3*	*0.65*	3	0.65
PC2L	20	*3*	*0.78*	3	0.78	13	0.65
PC2M	50	3	0.62	23	0.35	43	0.35
PC2H	120	3	0.65	53	0.36	113	0.35
RM1L	20	*3*	*0.78*	3	0.78	13	0.65
RM1M	50	3	0.62	23	0.35	43	0.35
RM2L	20	*3*	*0.78*	3	0.78	13	0.65
RM2M	50	3	0.62	23	0.35	43	0.35
RM2H	120	3	0.65	53	0.36	113	0.35
URML	15	*3*	*0.65*	*3*	*0.65*	3	0.65
URMM	36	3	0.65	15	0.49	27	0.56
MH	10	*3*	*0.59*	*3*	*0.59*	3	0.59

* Shaded cells with italics indicate damage states not required to characterize flood-related damage

5.4.2.3 Example Estimate of Flood Damage State Uncertainty

The two primary sources of uncertainty in the median values of damage due to tsunami flood are 1) the height of the building, and 2) the height at which a particular state of damage is assumed to occur.

Estimates of the uncertainty in the height of the specific building type are based on the range of heights that the specific building type represents. Since specific building types typically represent a relatively large range of heights (i.e., number of stories) the uncertainty in building height is significant. For example, larger wood structures (W2) are nominally two stories (24 feet) in height but could be only one story (12 feet) or as tall as five stories (60 feet), although heights above three stories are not common. The range of heights of one story to three stories (36 feet) is assumed to roughly represent plus or minus one standard deviation from the median and the corresponding uncertainty in building height is calculated as, ln(36/12)/2, or a beta of about 0.55 due to building height uncertainty.

Estimates of the uncertainty in the height of water associated with the damage state of interest are based on the range of heights that could cause the damage state of interest – typically plus or minus the height of an individual story, or portion thereof for shorter buildings (e.g., one-story and two-story specific building types). For example, the Complete damage state of nonstructural systems of a nominal two-story wood (W2) building has a median water depth of 24 feet (building must be fully inundated to have Complete damage), but the height of water that could cause Complete damage is assumed to vary by as much as plus or minus 8 feet (two thirds of story height) or from 16 feet to 32 feet of water, and the corresponding uncertainty in the median is estimated as, ln(32/16)/2, or a beta of about 0.35, assuming this range roughly represents plus or minus one standard deviation from the median.

The SRSS combination of the uncertainty in actual building height (0.55) and the uncertainty in the level of water that actually causes Complete damage (0.35) yields a combined uncertainty of about 0.65, the value of beta given in Table 5-7 for Complete damage to nonstructural systems of the W2 specific building type. In general, uncertainty is larger for shorter specific building types, since the ratio of the range of heights tend to be larger (i.e., variation of a few feet of water is more important to the variation in damage of one-story or two-story buildings than to the variation damage to mid-rise or high-rise buildings).

5.5 Building Damage Functions Due to Tsunami Flow

While damage due to tsunami flood primarily affects nonstructural systems, components, and contents, lateral forces due to tsunami flow are the primary cause of damage to the building structure, including building collapse (and debris generation). This section develops building damage functions for tsunami flow hazard characterized by median values of maximum momentum flux (HV^2). In this case, damage is assumed to be primarily due to lateral forces caused by drag effects and debris carried along by tsunami flow. Tsunami flow methods take an engineering approach, drawing from the concepts and criteria of FEMA P-646, *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis* (FEMA, 2012), the "pushover" strength of specific building types, as provided in the *Hazus Earthquake Model Technical Manual* (FEMA, 2024), and to lesser degree, Chapter 5 "Flood Loads" of ASCE 7-10 (ASCE, 2010). An engineering approach is utilized to parallel ongoing tsunami research and building code development work, and to provide a framework for future improvement to building damage functions as the technology progresses. Currently, individual structural element failures due to tsunami hydrodynamic pressures are not explicitly included in the systemic fragility relationships for the specific building types. Baseline values of the median and logarithmic standard deviation describe the probability of damage to the structure (STR) for each specific building type listed in Table 5-1.

5.5.1 Approach

Building damage to the structure due to tsunami flow is assumed to be caused by hydrodynamic forces and debris impact forces. Tsunami flow forces also affect nonstructural components and contents (e.g., walls at the building's perimeter), but nonstructural and contents damage due to tsunami flow is assumed to be encompassed by tsunami flood damage functions (e.g., since walls affected by tsunami flow are also damaged by inundation). Further, and of most significance, nonstructural systems and contents of buildings found to have Complete structure damage due to tsunami flow are assumed to have Complete damage. The assumption of Complete building damage, if the structure sustains Complete damage, is consistent with observed damage due to tsunami (i.e., buildings whose structure failed were either collapsed or washed away).

Development of building damage functions for tsunami flow utilizes an engineering approach that is based on the same concepts used for design of structures for tsunami lateral loads, such as those described in the *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis* FEMA P-646 (FEMA, 2012). In general, tsunami flow forces create a variety of different loads on structures, including:

1. Hydrostatic forces (i.e., lateral force on walls, etc., due to the pressure of standing water or very low velocity water flow)

2. Buoyant forces (i.e., vertical hydrostatic forces on the structure due to the volume of water displaced by a submerged building, of portion thereof)

3. Hydrodynamic forces (i.e., lateral force on the structure or individual elements due to water flow moving at moderate- or high-velocities)

4. Impulsive forces (i.e., additional lateral force caused by the leading edge of a surge of water impacting a structure, increasing local hydrodynamic loads by as much a factor of 1.5)

5. Debris impact forces (i.e., lateral force from waterborne debris such as floating trees, automobiles, boats, shipping containers, and debris from other buildings)

6. Debris damming forces (i.e., additional lateral force due to the accumulation of debris across the building components resisting hydrodynamic loads)

Few buildings have been designed for tsunami loads, but the design concepts provide a basis for characterizing the strength of specific building types in terms of tsunami loads and parameters, namely hydrodynamic loads characterized by momentum flux. In addition to hydrodynamic forces, this approach also incorporates, in an approximate manner, additional lateral force due to debris impact forces.

Damage to the structural system due to hydrodynamic forces is highly dependent on the configuration of the building at lower floor levels. For example, buildings that are open at their base or have perimeter elements that fail either by chance or by design (i.e., breakaway walls) and permit water to flow through the building, greatly reduce the hydrodynamic forces on the overall structure. The specific building types represent generic configurations defined solely in terms of the number of floors (height) and the total square footage, so the base of the building could be either fully open, partially open, or closed. The tsunami building damage functions assume that each specific building type is closed at its base (i.e., does not have breakaway walls, or open areas). Although windows and doors are likely to allow some water into the building, tsunami flood waters are assumed to flow around the full footprint of the building. This assumption produces maximum hydrodynamic forces on the structure of the building.

Hydrodynamic forces can cause damage to individual structural elements as well as to the overall structural system. In certain cases, failure of individual elements can lead to the progressive collapse of the building. Specific building types represent generic structural systems defined solely in terms of material, type of construction, and age of construction, which is insufficient information to evaluate damage to individual structural elements and the likelihood of progressive collapse of the structure. The tsunami building damage functions assume that Complete damage to the structural system due to hydrodynamic forces (and debris impact) occurs before progressive collapse (due to failure of individual structural elements). That is, evaluation of the overall capacity of the structural system is considered a reasonable surrogate for other failure mechanisms that are too complex to evaluate for generic specific building types. In addition to hydrodynamic forces, other failure mechanisms include damage to individual structural elements due to hydrostatic forces, impulsive forces, and debris impact forces.

Buoyant forces can cause uplift of smaller buildings when there is a significant difference in the level of water inside and outside of the building that reduces the effective weight of the building required to resist overturning due to lateral (hydrodynamic) forces. The effect of buoyant forces is most significant for shorter, lighter structures which have less effective weight per unit area at their base. For example, manufactured housing (mobile homes) is particularly susceptible to buoyant forces and would only require about one foot of water above the first-floor level to “float away” (assuming the building was unanchored and watertight).

The tsunami building damage functions assume that Complete damage due to hydrodynamic forces will occur before building uplift can occur due to buoyant forces. It may be noted that the specific building types most susceptible to buoyant forces are also the specific building types most susceptible to hydrodynamic forces. In the case of a typical (minimally anchored) manufactured housing unit, the median momentum flux of the Complete damage state is only 16 ft^3/sec^2 (Table 5-14), which corresponds to about one foot of water (moving at four feet/second). That is, the unit would be “washed away” by roughly the same depth of water that could cause it to “float away.”

Debris damming forces can increase the effective hydrodynamic forces on the structure due to accumulation of debris across the structural frame. The effects of debris damming are most critical for buildings with an open configuration at their base for which the accumulated debris restricts water flow through the building, but of little or no consequence to buildings that are closed across their base. The tsunami building damage functions ignore the effects of debris damming since they assume that the building is fully closed at its base such that water must flow around the full footprint of the building.

Debris impact forces can cause damage to the overall structure (as well as to individual structural elements). Debris impact forces are modeled by a factor, K_d, which increases hydrodynamic forces on the structure to account for the additional lateral forces due to debris impact. Values of the K_d factor greater than 1.0 effectively increase the likelihood of Complete damage to the structure when the building is assumed to be impacted by waterborne debris. Note: Values of the K_d factor less than 1.0

are used to effectively decrease the likelihood of Complete damage to the structure when the building is assumed to be shielded from tsunami flow by other buildings or structures.

The tsunami building damage functions do not explicitly include the effects of erosion and scour which can significantly influence stability and settlement of the shallow foundations, particularly for building sites near the shoreline on unconsolidated sediments. While post-FIRM construction in coastal high hazard areas (Zone V) are most likely on piles and piers, pre-FIRM construction and post-FIRM construction in the more inland areas typically use shallow foundations (Table 5-3), unless the building is heavy or tall enough to require a deep foundation.

The tsunami building damage functions assume that hydrodynamic loads (including the effects of debris) cause Complete damage to the structural system prior to foundation failure. It may be noted that the specific building types most susceptible to erosion and scour (i.e., smaller, older buildings) are also the specific building types most susceptible to damage and failure due to hydrodynamic forces. For the most common specific building type, W1, typical of older residences, the median momentum flux of the Complete damage state is 247 ft^3/sec^2 (Table 5-14, Pre-Code), which corresponds to about 6.5 feet of water (moving at 6 feet/second).

The tsunami building functions assume that Complete damage to the structural system occurs when hydrodynamic forces (increased for debris impact or reduced for shielding effects) exceed the lateral force capacity (i.e., pushover) strength of the model building of interest. Estimates of the lateral force capacity of specific building types are available from the Earthquake Model, as described below.

The Earthquake Model is a convenient source of the approximate lateral strength of the structural system of specific building types. Lateral strength is an inherent property of the structural system, whether the building is designed for earthquake loads, wind loads, or not designed for lateral loads (even buildings not designed for lateral loads still have inherent lateral strength). The Earthquake Model includes estimates of lateral strength for buildings not designed for earthquake loads (referred to as Pre-Code buildings) as well as those that are designed for earthquake loads.

Lateral force capacity varies with the seismic design level of the structure, which has been deduced from model building data (e.g., location and age), as described in Section 5.4 of the *Hazus Earthquake Model Technical Manual* (FEMA, 2024). The Earthquake Model defines seven seismic design levels encompassing both “common” buildings (e.g., Risk Category II structures, ASCE 7-10) and “special” buildings, such as hospitals and emergency centers (e.g., Risk Category IV structures, ASCE 7-10).

Table 5-9 describes these seven seismic design levels in terms of the risk categories and seismic design categories (SDCs) of ASCE 7-10 (ASCE 2010). These relationships apply to buildings designed to current code design requirements).

Table 5-9 Relationship of Hazus Seismic Design Levels and ASCE 7 Risk Categories and Seismic Design Categories (SDCs)

Hazus Seismic Design Level	Symbol	ASCE 7 Risk Category	ASCE 7 SDC
High-Code	HC	I - III	D (E)
Moderate-Code	MC	I - III	C
Low-Code	LC	I - III	B
Pre-Code (no seismic design)	PC	I - III	A
Special High-Code	HS	IV	D (F)
Special Moderate-Code	MS	IV	D
Special Low-Code	LS	IV	C

Most buildings were designed and constructed to older vintages of seismic codes (e.g., *Uniform Building Code*) and standards (or not designed for earthquake), and the inventory schemes of the *Hazus Earthquake Model Technical Manual* (FEMA, 2024) associate the most suitable seismic design level with specific building type based on age and other pertinent inventory data. Table 5-10 provides recommendations for selecting the appropriate seismic design level based on the age of the building and the seismic zone location. The Design Vintage age ranges in Table 5-10 are based on the benchmark years of major code adoptions in California. For example, the code enhancements adopted in 1975 were largely driven by lessons from the 1971 San Fernando, CA earthquake, and the 1941 enhancements followed the 1933 Long Beach, CA earthquake. Note that these vintage years along with benchmark code adoption information developed for each tsunami risk state and territory were used to estimate the seismic design level assignments for the General Building Stock inventory described in the *Hazus Inventory Technical Manual* (FEMA, 2024).

Table 5-10 Recommended Seismic Design Levels for Existing Buildings without Retrofit

Uniform Building Code	Design Vintage: Post-1975	Design Vintage: 1941-1975	Design Vintage: Pre-1941
Zone 4	High-Code	Moderate-Code	Pre-Code[1]
Zone 3	Moderate-Code	Moderate-Code	Pre-Code[1]
Zone 2B	Moderate-Code	Low-Code	Pre-Code[2]
Zone 2A	Low-Code	Low-Code	Pre-Code[2]
Zone 1	Low-Code	Pre-Code[2]	Pre-Code[2]
Zone 0	Pre-Code[2]	Pre-Code[2]	Pre-Code[2]

[1] Assume Moderate-Code design for residential wood-frame buildings (W1).

[2] Assume Low-Code design for residential wood-frame buildings (W1).

The Earthquake Model defines the pushover strength (capacity) of specific building types in terms of seismic design parameters (e.g., seismic design coefficient C_S) and other related factors, as shown in Table 5-4. Median values of damage states defined by drift-related criteria are represented by points of peak spectral response located along this curve, as illustrated in Figure 5-4.

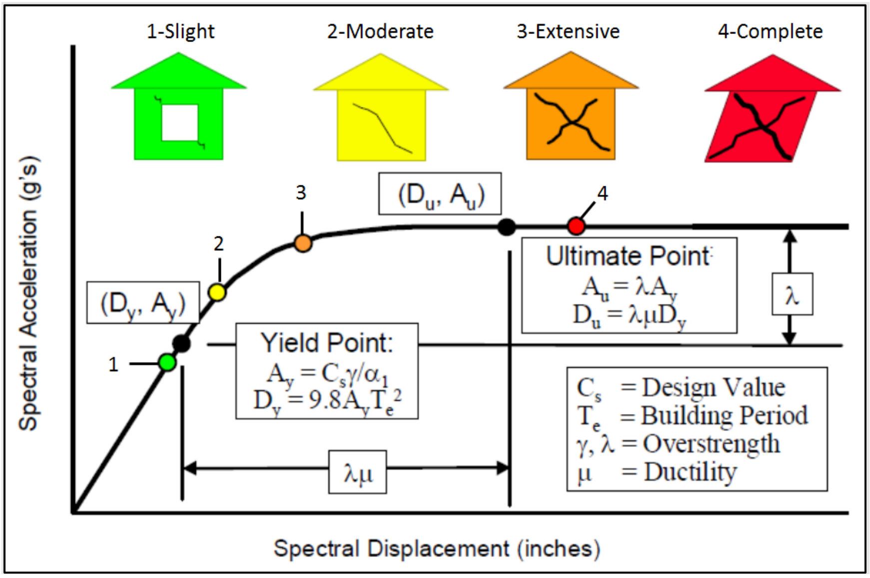

Figure 5-4 Example Building Capacity Curve and Control Points

The simple, underlying notion of building damage functions for damage due to tsunami flow is to equate hydrodynamic forces, incorporating the effects of impulsive and debris loads, with the lateral force (pushover) strength of specific building types as defined by the properties of capacity curves of the Earthquake Model. This approach assumes parity in the building damage states which is reasonable, except for collapse.

Earthquake ground motions are vibratory in nature, often intense, but peak forces are typically of short duration (i.e., a few seconds, at most, in a given direction). Hence, buildings can reach their full strength (i.e., reach the plateau of capacity curve in Figure 5-4), but not necessarily displace far enough to collapse before the earthquake force reverses direction. In contrast, peak tsunami flow force is sustained in a given direction for a relatively long period of time (i.e., several minutes), and buildings that have reached their full strength are much more likely to collapse (and possibly be washed away with the flow). Thus, the likelihood of collapse given Complete damage for tsunami flow forces is much higher than that of earthquake.

The lateral force (pushover) strength of a given specific building type is defined by the yield capacity and the ultimate capacity, as given by Equation 5-12 and Equation 5-13:

Equation 5-12

$$F_Y = \propto_1 A_y W$$

Equation 5-13

$$F_U = \propto_1 A_u W$$

Where:

F_Y is the initial yield force at base of building (kips or 1,000 pounds-force)

F_U is the ultimate (pushover) force at base of building (kips)

α_1 is the modal mass parameter (Table 5-5, *Hazus Earthquake Model Technical Manual* (FEMA, 2024))

A_Y is the spectral acceleration at yield (Table 5-7 *Hazus Earthquake Model Technical Manual* (FEMA, 2024))

A_U is the spectral acceleration at ultimate (Table 5-7 *Hazus Earthquake Model Technical Manual* (FEMA, 2024))

W is the total building seismic design weight (kips).

Lateral shear strength of the structure at the base of the building is assumed to be unaffected by buoyant forces, if any, and W represents the full seismic design weight of the building.

Lateral tsunami flow force, FTS, on a specific building type is given by Equation 5-14:

Equation 5-14

$$F_{TS} = K_d\left(0.5\rho_s C_d B(hv^2)\right) = 0.00219\ K_d B(hv^2)$$

Where:

F_{TS} is the tsunami force on building (kips)

K_d is the coefficient used to modify basic hydrodynamic force for lower values of force due to the effects of shielding, etc., and for higher values of force due to the effects of debris impact, etc. (nominal value, $K_d = 1.0$)

ρ_s is the fluid density assumed to be 1.1 *0.064 kips/ft^3 / 32.2 fps^2)

C_d is the drag coefficient ($C_d = 2.0$, based on *FEMA P-646* (FEMA, 2012))

B is the plan dimension normal to flow direction (feet)

hv^2 is the median value of maximum momentum flux (ft^3/sec^2).

5.5.2 Baseline Values of Damage Function Parameters

Baseline values of damage function parameters are described in terms of maximum momentum flux for the damage state of interest, $\hat{F}_{dsi}$, and the corresponding measure of damage state uncertainty, $\beta_{dsi|F}$.

Table 5-11 through Table 5-17 summarize baseline values of fragility parameters of each specific building type for each of the seven seismic design levels of the Earthquake Model. In these tables, shaded cells indicate damage states not required to characterize flow-related damage, as described in Table 5-6, for which fragility parameters (median and logarithmic standard deviation values) are set equal to the next more severe damage state. The basis for the baseline values of fragility parameters is summarized below.

5.5.2.1 Basis for Baseline Values of Median Damage

Baseline values of median damage (i.e., maximum momentum flux) are based on the descriptions of damage given in Table 5-6 (for damage to the structure) and the following assumptions:

1. *Complete structure damage*: Complete damage to the structure occurs when tsunami force is equal to earthquake ultimate force (F_U) capacity of the specific building type of interest.

2. *Moderate damage:* Moderate damage to the structure occurs when tsunami force is equal to earthquake yield force (F_Y) capacity of the specific building type of interest.

3. Exception: Significant tsunami damage can occur to the foundation and individual structural elements at lower floors of mid-rise and high-rise buildings before the structural system reaches yield. To account for this localized damage, in an approximate manner, Moderate damage (at lower floors) of mid-rise and high-rise buildings is assumed to occur for the same level of tsunami force that causes Extensive damage to low-rise buildings of the same specific building type.

4. *Extensive structure damage:* Extensive damage to the structure occurs when tsunami force is equal to earthquake force corresponding to the average of the yield force and ultimate force, $(F_Y + F_U)/2$, capacities of the specific building type of interest.

The above assumptions are used with Equation 5-12, Equation 5-13, and Equation 5-14, to define damage state medians, as follows:

Equation 5-15

$$\hat{F}_{dsM} = 457(\propto_1 A_Y W)/(K_d B)$$

Equation 5-16

$$\hat{F}_{dsE} = 457\left(\propto_1 \left(\frac{A_y + A_U}{2}\right) W\right)/(K_d B)$$

Equation 5-17

$$\hat{F}_{dsC} = 457(\propto_1 A_U W)/(K_d B)$$

Where:

$\hat{F}_{dsM}$	is the median value of Moderate structure damage due to tsunami flow (fps)
$\hat{F}_{dsE}$	is the median value of Extensive structure damage due to tsunami flow (fps)

$\hat{F}_{dsC}$	is the median value of Complete structure damage due to tsunami flow (fps)
α_1	is the model mass parameter (Table 5-5, *Hazus Earthquake Model Technical Manual* (FEMA, 2024))
A_Y	is the spectral acceleration at yield (g) (Table 5-7 *Hazus Earthquake Model Technical Manual* (FEMA, 2024))
A_U	is the spectral acceleration at ultimate (g) (Table 5-7 *Hazus Earthquake Model Technical Manual* (FEMA, 2024))
W	is the total building seismic design weight (kips), as defined in Table 5-18
K_d	is the coefficient modifying basic hydrodynamic force (nominal value, K_d = 1.0)
B	is the plan dimension normal to flow direction (feet), as defined in Table 5-18

Table 5-18 summarizes the assumed values of specific building type total seismic design weight (W), total building area, average unit floor weight per square foot (w), and plan dimension (B) used to develop baseline parameters of tsunami flow building damage functions. Damage state medians are based on hydrodynamic loads that assume no debris impact and no shielding from other buildings and structures (i.e., Kd = 1.0).

5.5.2.2 Basis for Baseline Values of Beta (Logarithmic Standard Deviation)

Baseline values of beta (logarithmic standard deviation) are based on the three primary sources of uncertainty in the median values of tsunami flow damage, the uncertainty in building capacity associated with median damage (i.e., $\alpha_1 A_u W$ term), the uncertainty in hydrodynamic loads associated with possible debris impact or conversely, possible shielding from other structures (i.e., the K_d factor), and the uncertainty associated with the plan dimension of the side of the building facing tsunami flow (i.e., the B dimension of the building). These three sources of uncertainty are modeled as independent lognormal random variables, and individual estimates of the uncertainties are combined using the SRSS method.

Table 5-11 Baseline Values of Damage State Parameters for Evaluation of Damage to the Structure of High-Code Seismic Design Specific Building Types due to Tsunami Flow

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta
W1	*494*	*0.74*	*494*	*0.74*	494	0.74
W2	*1,371*	*0.73*	*1,371*	*0.73*	1,371	0.73
S1L	*3,913*	*0.74*	3,913	0.74	5,868	0.74
S1M	3,913	0.79	9,656	0.79	15,399	0.79
S1H	3,913	0.79	13,706	0.79	23,500	0.79
S2L	*4,407*	*0.60*	4,407	0.60	5,876	0.60

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta
S2M	4,407	0.67	12,491	0.67	20,575	0.67
S2H	4,407	0.67	19,859	0.67	35,311	0.67
S3	*823*	*0.60*	*823*	*0.60*	823	0.60
S4L	4,583	0.64	4,583	0.64	6,346	0.64
S4M	4,583	0.70	12,574	0.70	20,565	0.70
S4H	4,583	0.70	19,939	0.70	35,295	0.70
S5L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
S5M	1,170	0.79	2,724	0.79	4,278	0.79
S5H	1,170	0.80	3,838	0.80	6,505	0.80
C1L	*4,696*	*0.74*	4,696	0.74	7,041	0.74
C1M	4,696	0.79	13,755	0.79	22,813	0.79
C1H	4,696	0.79	14,399	0.79	24,102	0.79
C2L	*6,170*	*0.67*	6,170	0.67	8,814	0.67
C2M	6,170	0.73	17,360	0.73	28,551	0.73
C2H	6,170	0.73	25,720	0.73	45,270	0.73
C3L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
C3M	1,170	0.79	3,259	0.79	5,347	0.79
C3H	1,170	0.80	3,588	0.80	6,005	0.80
PC1	*2,350*	*0.60*	2,350	0.60	2,350	0.60
PC2L	5,288	0.60	5,288	0.60	7,051	0.60
PC2M	5,288	0.67	14,075	0.67	22,861	0.67
PC2H	5,288	0.67	20,752	0.67	36,216	0.67
RM1L	*5,872*	*0.60*	5,872	0.60	7,829	0.60
RM1M	5,872	0.67	16,648	0.67	27,423	0.67
RM2L	*7,046*	*0.60*	7,046	0.60	9,395	0.60
RM2M	7,046	0.67	18,758	0.67	30,470	0.67
RM2H	7,046	0.67	27,656	0.67	48,265	0.67
URML	506	0.66	506	0.66	506	0.66
URMM	506	0.67	1,884	0.67	3,261	0.67
MH	*33*	*0.60*	*33*	*0.60*	33	0.60

* Shaded italicized cells indicate damage states not required to characterize flow-related damage

Table 5-12 Baseline Values of Damage State Parameters for Evaluation of Damage to the Structure of Moderate-Code Seismic Design Specific Building Types due to Tsunami Flow

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta
W1	*370*	*0.74*	*370*	*0.74*	370	0.74
W2	*686*	*0.73*	*686*	*0.73*	686	0.73
S1L	*1,959*	*0.74*	1,959	0.74	2,938	0.74
S1M	1,959	0.79	4,829	0.79	7,700	0.79
S1H	1,959	0.79	6,874	0.79	11,790	0.79
S2L	*2,203*	*0.60*	2,203	0.60	2,938	0.60
S2M	2,203	0.67	6,238	0.67	10,272	0.67
S2H	2,203	0.67	9,929	0.67	17,655	0.67
S3	*411*	*0.60*	*411*	*0.60*	411	0.60
S4L	*2,292*	*0.64*	2,292	0.64	3,173	0.64
S4M	2,292	0.70	6,287	0.70	10,283	0.70
S4H	2,292	0.70	9,950	0.70	17,609	0.70
S5L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
S5M	1,170	0.79	2,724	0.79	4,278	0.79
S5H	1,170	0.80	3,838	0.80	6,505	0.80
C1L	*2,350*	*0.74*	2,350	0.74	3,525	0.74
C1M	2,350	0.79	6,879	0.79	11,407	0.79
C1H	2,350	0.79	7,221	0.79	12,092	0.79
C2L	*3,085*	*0.67*	3,085	0.67	4,407	0.67
C2M	3,085	0.73	8,689	0.73	14,293	0.73
C2H	3,085	0.73	12,842	0.73	22,600	0.73
C3L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
C3M	1,170	0.79	3,259	0.79	5,347	0.79
C3H	1,170	0.80	3,588	0.80	6,005	0.80
PC1	*1,175*	*0.60*	1,175	0.60	1,175	0.60
PC2L	2,644	0.60	2,644	0.60	3,525	0.60
PC2M	2,644	0.67	7,029	0.67	11,414	0.67
PC2H	2,644	0.67	10,376	0.67	18,108	0.67
RM1L	*2,938*	*0.60*	2,938	0.60	3,915	0.60
RM1M	2,938	0.67	8,317	0.67	13,696	0.67
RM2L	*3,525*	*0.60*	3,525	0.60	4,698	0.60
RM2M	3,525	0.67	9,372	0.67	15,218	0.67
RM2H	3,525	0.67	13,811	0.67	24,097	0.67
URML	*506*	*0.66*	506	0.66	506	0.66

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta
URMM	506	0.67	1,884	0.67	3,261	0.67
MH	*33*	*0.60*	*33*	*0.60*	33	0.60

*Shaded italicized cells indicate damage states not required to characterize flow-related damage

Table 5-13 Baseline Values of Damage State Parameters for Evaluation of Damage to the Structure of Low-Code Seismic Design Specific Building Types due to Tsunami Flow

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta
W1	*247*	*0.74*	*247*	*0.74*	247	0.74
W2	*343*	*0.73*	*343*	*0.73*	343	0.73
S1L	*975*	*0.74*	975	0.74	1,465	0.74
S1M	975	0.79	2,413	0.79	3,850	0.79
S1H	975	0.80	3,415	0.80	5,855	0.80
S2L	*1,102*	*0.60*	1,102	0.60	1,469	0.60
S2M	1,102	0.67	3,127	0.67	5,152	0.67
S2H	1,102	0.67	4,965	0.67	8,828	0.67
S3	*206*	*0.60*	*206*	*0.60*	206	0.60
S4L	*1,146*	*0.64*	1,146	0.64	1,586	0.64
S4M	1,146	0.70	3,144	0.70	5,141	0.70
S4H	1,146	0.70	4,975	0.70	8,805	0.70
S5L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
S5M	1,170	0.79	2,724	0.79	4,278	0.79
S5H	1,170	0.80	3,838	0.80	6,505	0.80
C1L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
C1M	1,170	0.79	3,259	0.79	5,347	0.79
C1H	1,170	0.80	3,588	0.80	6,005	0.80
C2L	*1,542*	*0.67*	1,542	0.67	2,203	0.67
C2M	1,542	0.74	4,336	0.74	7,129	0.74
C2H	1,542	0.74	6,439	0.74	11,335	0.74
C3L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
C3M	1,170	0.79	3,259	0.79	5,347	0.79
C3H	1,170	0.80	3,588	0.80	6,005	0.80
PC1	*588*	*0.60*	588	0.60	588	0.60
PC2L	1,322	0.60	1,322	0.60	1,763	0.60

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta
PC2M	1,322	0.67	3,523	0.67	5,724	0.67
PC2H	1,322	0.67	5,188	0.67	9,054	0.67
RM1L	*1,469*	*0.60*	1,469	0.60	1,961	0.60
RM1M	1,469	0.67	4,159	0.67	6,848	0.67
RM2L	*1,763*	*0.60*	1,763	0.60	2,353	0.60
RM2M	1,763	0.67	4,686	0.67	7,609	0.67
RM2H	1,763	0.67	6,906	0.67	12,048	0.67
URML	*506*	*0.66*	506	0.66	506	0.66
URMM	506	0.67	1,884	0.67	3,261	0.67
MH	*33*	*0.60*	*33*	*0.60*	33	0.60

* Shaded italicized cells indicate damage states not required to characterize flow-related damage

Table 5-14 Baseline Values of Damage State Parameters for Evaluation of Damage to the Structure of Pre-Code Seismic Design Specific Building Types due to Tsunami Flow

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta
W1	*247*	*0.74*	*247*	*0.74*	247	0.74
W2	*343*	*0.73*	*343*	*0.73*	343	0.73
S1L	*975*	*0.74*	975	0.74	1,465	0.74
S1M	975	0.79	2,413	0.79	3,850	0.79
S1H	975	0.80	3,415	0.80	5,855	0.80
S2L	*1,102*	*0.60*	1,102	0.60	1,469	0.60
S2M	1,102	0.67	3,127	0.67	5,152	0.67
S2H	1,102	0.67	4,965	0.67	8,828	0.67
S3	*206*	*0.60*	*206*	*0.60*	206	0.60
S4L	*1,146*	*0.64*	1,146	0.64	1,586	0.64
S4M	1,146	0.70	3,144	0.70	5,141	0.70
S4H	1,146	0.70	4,975	0.70	8,805	0.70
S5L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
S5M	1,170	0.79	2,724	0.79	4,278	0.79
S5H	1,170	0.80	3,838	0.80	6,505	0.80
C1L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
C1M	1,170	0.79	3,259	0.79	5,347	0.79
C1H	1,170	0.80	3,588	0.80	6,005	0.80
C2L	*1,542*	*0.67*	1,542	0.67	2,203	0.67
C2M	1,542	0.74	4,336	0.74	7,129	0.74

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta
C2H	1,542	0.74	6,439	0.74	11,335	0.74
C3L	*1,170*	*0.74*	1,170	0.74	1,758	0.74
C3M	1,170	0.79	3,259	0.79	5,347	0.79
C3H	1,170	0.80	3,588	0.80	6,005	0.80
PC1	*588*	*0.60*	588	0.60	588	0.60
PC2L	1,322	0.60	1,322	0.60	1,763	0.60
PC2M	1,322	0.67	3,523	0.67	5,724	0.67
PC2H	1,322	0.67	5,188	0.67	9,054	0.67
RM1L	*1,469*	*0.60*	1,469	0.60	1,961	0.60
RM1M	1,469	0.67	4,159	0.67	6,848	0.67
RM2L	*1,763*	*0.60*	1,763	0.60	2,353	0.60
RM2M	1,763	0.67	4,686	0.67	7,609	0.67
RM2H	1,763	0.67	6,906	0.67	12,048	0.67
URML	*506*	*0.66*	506	0.66	506	0.66
URMM	506	0.67	1,884	0.67	3,261	0.67
MH	*16*	*0.60*	*16*	*0.60*	16	0.60

* Shaded italicized cells indicate damage states not required to characterize flow-related damage

Table 5-15 Baseline Values of Damage State Parameters for Evaluation of Damage to the Structure of Special High-Code Seismic Design Specific Building Types due to Tsunami Flow

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta
W1	*740*	*0.74*	*740*	*0.74*	740	0.74
W2	*2,057*	*0.73*	*2,057*	*0.73*	2,057	0.73
S1L	*5,872*	*0.74*	5,872	0.74	8,806	0.74
S1M	5,872	0.79	14,485	0.79	23,099	0.79
S1H	5,872	0.79	20,581	0.79	35,290	0.79
S2L	*6,610*	*0.60*	6,610	0.60	8,814	0.60
S2M	6,610	0.67	18,729	0.67	30,848	0.67
S2H	6,610	0.67	29,788	0.67	52,966	0.67
S3	*1,234*	*0.60*	*1,234*	*0.60*	1,234	0.60
S4L	*6,875*	*0.64*	6,875	0.64	9,519	0.64
S4M	6,875	0.70	18,861	0.70	30,848	0.70
S4H	6,875	0.70	29,890	0.70	52,905	0.70
S5L	*1,763*	*0.73*	1,763	0.73	2,642	0.73

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta
S5M	1,763	0.79	4,099	0.79	6,435	0.79
S5H	1,763	0.79	5,783	0.79	9,803	0.79
C1L	*7,046*	*0.74*	7,046	0.74	10,567	0.74
C1M	7,046	0.80	20,651	0.80	34,257	0.80
C1H	7,046	0.79	21,620	0.79	36,194	0.79
C2L	*9,254*	*0.67*	9,254	0.67	13,220	0.67
C2M	9,254	0.73	26,049	0.73	42,844	0.73
C2H	9,254	0.73	38,562	0.73	67,870	0.73
C3L	*1,763*	*0.73*	1,763	0.73	2,642	0.73
C3M	1,763	0.79	4,892	0.79	8,020	0.79
C3H	1,763	0.79	5,406	0.79	9,049	0.79
PC1	*3,525*	*0.60*	3,525	0.60	3,525	0.60
PC2L	7,932	0.60	7,932	0.60	10,576	0.60
PC2M	7,932	0.67	21,104	0.67	34,275	0.67
PC2H	7,932	0.67	31,128	0.67	54,325	0.67
RM1L	*8,814*	*0.60*	8,814	0.60	11,751	0.60
RM1M	8,814	0.67	24,967	0.67	41,120	0.67
RM2L	*10,576*	*0.60*	10,576	0.60	14,102	0.60
RM2M	10,576	0.67	28,132	0.67	45,689	0.67
RM2H	10,576	0.67	41,469	0.67	72,361	0.67
URML	*759*	*0.66*	759	0.66	759	0.66
URMM	759	0.67	2,825	0.67	4,892	0.67
MH	*49*	*0.60*	*49*	*0.60*	49	0.60

* Shaded italicized cells indicate damage states not required to characterize flow-related damage

Table 5-16 Baseline Values of Damage State Parameters for Evaluation of Damage to the Structure of Special Moderate-Code Seismic Design Specific Building Types due to Tsunami Flow

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta
W1	*555*	*0.74*	*555*	*0.74*	555	0.74
W2	*1,028*	*0.73*	*1,028*	*0.73*	1,028	0.73
S1L	*2,934*	*0.74*	2,934	0.74	4,403	0.74
S1M	2,934	0.79	7,242	0.79	11,549	0.79
S1H	2,934	0.80	10,289	0.80	17,645	0.80
S2L	*3,305*	*0.60*	3,305	0.60	4,407	0.60

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta
S2M	3,305	0.67	9,364	0.67	15,424	0.67
S2H	3,305	0.67	14,894	0.67	26,483	0.67
S3	*617*	*0.60*	*617*	*0.60*	617	0.60
S4L	*3,437*	*0.64*	3,437	0.64	4,759	0.64
S4M	3,437	0.70	9,431	0.70	15,424	0.70
S4H	3,437	0.70	14,964	0.70	26,491	0.70
S5L	*2,115*	*0.60*	2,115	0.60	2,820	0.60
S5M	2,115	0.67	5,628	0.67	9,140	0.67
S5H	2,115	0.79	14,413	0.79	26,711	0.79
C1L	*1,105*	*0.73*	1,105	0.73	1,655	0.73
C1M	1,105	0.79	2,437	0.79	3,770	0.79
C1H	1,105	0.80	9,601	0.80	18,097	0.80
C2L	*4,627*	*0.67*	4,627	0.67	6,610	0.67
C2M	4,627	0.73	13,025	0.73	21,422	0.73
C2H	4,627	0.74	19,281	0.74	33,935	0.74
C3L	*1,763*	*0.73*	1,763	0.73	2,642	0.73
C3M	1,763	0.79	4,892	0.79	8,020	0.79
C3H	1,763	0.79	5,406	0.79	9,049	0.79
PC1	*1,763*	*0.60*	1,763	0.60	1,763	0.60
PC2L	3,966	0.60	3,966	0.60	5,288	0.60
PC2M	3,966	0.67	10,552	0.67	17,138	0.67
PC2H	3,966	0.67	15,564	0.67	27,162	0.67
RM1L	*4,407*	*0.60*	4,407	0.60	5,876	0.60
RM1M	4,407	0.67	12,491	0.67	20,575	0.67
RM2L	*5,288*	*0.60*	5,288	0.60	7,051	0.60
RM2M	5,288	0.67	14,075	0.67	22,861	0.67
RM2H	5,288	0.67	20,752	0.67	36,216	0.67
URML	*759*	*0.66*	759	0.66	759	0.66
URMM	759	0.67	2,825	0.67	4,892	0.67
MH	*49*	*0.60*	*49*	*0.60*	49	0.60

*Shaded italicized cells indicate damage states not required to characterize flow-related damage

Table 5-17 Baseline Values of Damage State Parameters for Evaluation of Damage to the Structure of Special Low-Code Seismic Design Specific Building Types due to Tsunami Flow

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta	Median (ft³/s²)	Beta
W1	*370*	*0.74*	*370*	*0.74*	370	0.74
W2	*514*	*0.73*	*514*	*0.73*	514	0.73
S1L	*1,469*	*0.73*	1,469	0.73	2,201	0.73
S1M	1,469	0.79	3,630	0.79	5,791	0.79
S1H	1,469	0.79	5,146	0.79	8,822	0.79
S2L	*1,653*	*0.60*	1,653	0.60	2,203	0.60
S2M	1,653	0.67	4,682	0.67	7,712	0.67
S2H	1,653	0.67	7,430	0.67	13,207	0.67
S3	*308*	*0.60*	*308*	*0.60*	308	0.60
S4L	*1,719*	*0.64*	1,719	0.64	2,380	0.64
S4M	1,719	0.70	4,715	0.70	7,712	0.70
S4H	1,719	0.70	7,463	0.70	13,207	0.70
S5L	*1,763*	*0.73*	1,763	0.73	2,642	0.73
S5M	1,763	0.79	4,099	0.79	6,435	0.79
S5H	1,763	0.79	5,783	0.79	9,803	0.79
C1L	*1,763*	*0.73*	1,763	0.73	2,642	0.73
C1M	1,763	0.79	4,892	0.79	8,020	0.79
C1H	1,763	0.79	5,406	0.79	9,049	0.79
C2L	*2,314*	*0.67*	2,314	0.67	3,305	0.67
C2M	2,314	0.74	6,521	0.74	10,728	0.74
C2H	2,314	0.74	9,641	0.74	16,967	0.74
C3L	*1,763*	*0.73*	1,763	0.73	2,642	0.73
C3M	1,763	0.79	4,892	0.79	8,020	0.79
C3H	1,763	0.79	5,406	0.79	9,049	0.79
PC1	*881*	*0.60*	881	0.60	881	0.60
PC2L	1,983	0.60	1,983	0.60	2,644	0.60
PC2M	1,983	0.67	5,276	0.67	8,569	0.67
PC2H	1,983	0.67	7,764	0.67	13,545	0.67
RM1L	*2,203*	*0.60*	2,203	0.60	2,938	0.60
RM1M	2,203	0.67	6,238	0.67	10,272	0.67
RM2L	*2,644*	*0.60*	2,644	0.60	3,525	0.60
RM2M	2,644	0.67	7,029	0.67	11,414	0.67
RM2H	2,644	0.67	10,376	0.67	18,108	0.67
URML	*759*	*0.66*	759	0.66	759	0.66

SBT Name	Moderate Damage		Extensive Damage		Complete Damage	
	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta	Median (ft^3/s^2)	Beta
URMM	759	0.67	2,825	0.67	4,892	0.67
MH	*49*	*0.60*	*49*	*0.60*	49	0.60

* Shaded italicized cells indicate damage states not required to characterize flow-related damage

Table 5-18 Assumed SBT Values used to Develop Baseline Values of Damage State Parameters of Tsunami Flow Damage Functions

SBT Name	No. of Floors	Total Building Area (ft^2)	Avg. Unit Weight (w) (lb/ ft^2)	Total Seismic Design Weight (W) (kips)	Plan Dimension (B) (ft)
W1	1	1,600	30	48	40
W2	2	5,000	40	200	50
S1L	2	10,000	150	1,500	70
S1M	5	50,000	180	9,000	100
S1H	13	130,000	180	23,400	100
S2L	2	10,000	150	1,500	70
S2M	5	50,000	180	9,000	100
S2H	13	130,000	180	23,400	100
S3	1	2,500	60	150	50
S4L	2	10,000	180	1,800	70
S4M	5	50,000	200	10,000	100
S4H	13	130,000	200	26,000	100
S5L	2	10,000	180	1,800	70
S5M	5	50,000	200	10,000	100
S5H	13	130,000	200	26,000	100
C1L	2	10,000	180	1,800	70
C1M	5	50,000	200	10,000	100
C1H	12	120,000	200	24,000	100
C2L	2	10,000	180	1,800	70
C2M	5	50,000	200	10,000	100
C2H	12	120,000	200	24,000	100
C3L	2	10,000	180	1,800	70
C3M	5	50,000	200	10,000	100
C3H	12	120,000	200	24,000	100
PC1	1	40,000	100	4,000	200
PC2L	2	10,000	180	1,800	70
PC2M	5	50,000	200	10,000	100
PC2H	12	120,000	200	24,000	100

SBT Name	No. of Floors	Total Building Area (ft^2)	Avg. Unit Weight (w) (lb/ ft^2)	Total Seismic Design Weight (W) (kips)	Plan Dimension (B) (ft)
RM1L	2	10,000	180	1,800	70
RM1M	5	50,000	200	10,000	100
RM2L	2	10,000	180	1,800	70
RM2M	5	50,000	200	10,000	100
RM2H	12	120,000	200	24,000	100
URML	1	10,000	180	1,800	70
URMM	3	30,000	200	6,000	100
MH	1	600	20	12	50

5.5.2.3 Example Estimate of Tsunami Flow Damage State Uncertainty

The three primary sources of uncertainty in the median values of damage due to tsunami flow are:

- The uncertainty in building capacity, as defined by "pushover" strength of the building's structure
- The uncertainty in hydrodynamic loads due to debris impact and shielding effects
- The uncertainty in the plan dimension of the side of the building that faces tsunami flow

An estimate of the uncertainty in building capacity is based on the range of building strengths that the specific building type could possibly have. In this case, uncertainty in specific building type strength is estimated by the range of yield and ultimate strengths. For example, the larger wood (W2) specific building type designed for high-code seismic forces has yield strength of 60 kips and an ultimate strength of 150 kips. This range of strengths is assumed to represent two standard deviations and the corresponding uncertainty in building strength is calculated as, ln(150/60)/2, or a beta of about 0.46 due to uncertainty in building strength capacity.

An estimate of the uncertainty in hydrodynamic loads due to possible debris impact (which would increase hydrodynamic forces) and possible shielding of the building (which would decrease hydrodynamic forces) are based on the range of K_d values that encompass these possibilities. For example, the larger wood (W2) specific building type has K_d values that are assumed to be as large as 2.0 (assumed maximum increase due to potential debris impact) to as small as 0.5 (assumed maximum reduction due to potential shielding of other structures). This broad range of K_d values is assumed to represent plus or minus two standard deviations from the median, and the corresponding uncertainty in demand is estimated as ln(2.0/0.5)/4, or a beta of about 0.35.

An estimate of the uncertainty in the plan dimension (B) that defines the length of the side of the building that faces tsunami flow, is based on the range of plan dimensions that the building could reasonably have. For example, the larger wood (W2) specific building type (which has a nominal plan dimension of 50 feet), is assumed to have a plan dimension that could be as small as 30 feet, or as large as 75 feet. This range of plan dimensions is assumed to represent plus or minus one standard deviation from the median and the corresponding uncertainty in demand is estimated as ln(75/30)/2, or a beta of about 0.46.

The SRSS combination of the uncertainty in building capacity (0.46), the uncertainty in the K_d factor (0.35), and the uncertainty in plan dimension, B, defining the length of the side of the building facing tsunami flow (0.46) yields a total uncertainty of about 0.73, the value of beta given in Table 5-11 for Complete damage to nonstructural systems of the W2 specific building type.

5.6 Optimizing Damage State Probability Calculations

To rapidly estimate damage state probabilities, both the flood inundation depth and flood flow are represented by index values where the median values intersect the site of interest. For flood depth, index values (1-258) are assigned to building points in 0.10 feet increments from a depth of 0 to 10 feet, by 0.25 feet increments from 10 to 14 feet and then by 1-foot increments from 14 to 156 feet of flood depth. Likewise, flux index values (1-128) are assigned based on 10 ft^3/s^2 increments from 0 to 100 ft^3/s^2, 50 ft^3/s^2 increments from 100 to 2,000 $ft^3/s^2$and by 1,000 ft^3/s^2 increments from 2,000 to 82,000 ft^3/s^2. Depths and flows greater than these ranges will be assigned the highest index value; however, Complete damage to all building types are presumed at these levels.

5.7 Estimating Restoration Times for User-Defined Facilities

Beyond building damage categories, the Hazus Tsunami Model will also calculate restoration times and building functionality for individual user-defined facilities. Restoration functions, their associated methodology, and derived functionality are available throughout the Hazus Earthquake Model Technical Manual (FEMA, 2024), depending on facility type. In the Tsunami model, a lookup table was implemented in the Analysis Parameters database so that users do not need to locate and use the appropriate restoration functions as they would in the earthquake model. The Hazus Tsunami Model is not able to analyze as many building types or components as the earthquake model currently, therefore restoration and functionality values based on building damage state can be summarized in Table 5-19 Generic UDF Restoration Times For Tsunami, Table 5-20 and Table 5-21.

Table 5-19 Generic UDF Restoration Times For Tsunami (Days)

Building Type	Slight	Moderate	Extensive	Complete
Default UDF	Mean: 1	Mean: 3	Mean: 30	Mean: 120
	STD: 3	STD: 10	STD: 45	STD: 90

Table 5-20 UDF Restoration Look-Up Table

Restoration				
Building				
Days elapsed	Probability of being functional if slight damage	Probability of being functional if moderate damage	Probability of being functional if extensive damage	Probability of being functional if complete damage
1	0.500	0.421	0.260	0.093
3	0.748	0.500	0.274	0.097
7	0.977	0.655	0.305	0.105
10	0.999	0.758	0.328	0.111
14	1.000	0.864	0.361	0.119
30	1.000	0.997	0.500	0.159
60	1.000	1.000	0.748	0.252
90	1.000	1.000	0.909	0.369
120	1.000	1.000	0.977	0.500

Table 5-21 UDF Functionality Look-Up Table

Functionality for Different Flux Values					
Days elapsed	50	100	500	1000	2000
99.9	89.9	54.1	24.7	12.0	99.9
99.9	90.0	54.3	25.1	12.3	99.9
99.9	90.1	54.6	25.7	13.1	99.9
99.9	90.1	55.0	26.2	13.7	99.9
99.9	90.2	55.4	26.9	14.5	99.9
99.9	90.7	57.4	30.2	18.3	99.9
99.9	91.7	62.1	38.0	27.4	99.9
99.9	93.0	68.1	47.7	38.8	99.9
100.0	94.5	74.7	58.5	51.5	100.0

5.8 Evaluating Combined Earthquake and Tsunami Damages

This section describes the concepts and “Boolean logic” rules used to combine the probability of a given building damage state due to tsunami with probability of the same building damage state due to earthquake. Formulas based on these concepts and rules are summarized in the next section. It should be noted that tsunami damage state probabilities due to flood need not be combined with those due to tsunami flow, since tsunami flood and flow damage states are mutually exclusive (i.e., tsunami flood only affects nonstructural systems and contents, tsunami flow only affects the structure).

Tsunami building damage states are combined with earthquake building damage states assuming that the damage states are statistically independent, except as noted below:

1. *Probability of Complete Damage*: The probability of Complete damage also includes the joint probability of Extensive Damage due to tsunami and Extensive damage due to earthquake based on the assumption that Extensive damage due to tsunami occurring to a building that already has Extensive damage due to earthquake would result in Complete damage to the building. This concept applies to structure, as well as nonstructural and contents damage states.

2. *Probability of Extensive or Greater Damage*: The probability of at least Extensive damage also includes the joint probability of Moderate damage due to tsunami and Moderate damage due to earthquake. This assumes that Moderate damage from a tsunami occurring to a building that already has Moderate damage due to earthquake would result in Extensive damage to the building. This concept applies to structure, as well as nonstructural and contents damage states.

3. *Probability of Nonstructural and Contents Damage due to Complete Structure Damage*: The probability of nonstructural and contents damage also includes the probability of Complete structure damage, $P[C_{STR}|EQ+TS]$, based on the assumption that nonstructural systems and contents are completely damaged in a building that sustains Complete damage to the structural system. This concept applies to all nonstructural and contents damage states.

5.8.1 Formulas for Combining Damage State Probabilities – Earthquake with Tsunami

This section summarizes the formulas for calculating the combined probability of Complete (C), Extensive (E), Moderate (M), and Slight (S) damage states for building damage, using a combination of probabilities of damage states calculated in the tsunami (TS) model and building damage calculated in the earthquake (EQ) model.

It is important to note that the damage state of Slight is included in these sets of equations to represent the possible combination of less than moderate damage in a combined result. For example, if a probability of Slight damage is found in the earthquake analysis, but there is no probability of damage in the tsunami analysis, a combined probability will still include the probability of Slight damage from the earthquake. Users may observe that for non-combined results, such as tsunami-only GBS, the Slight category is omitted. Due to the physical nature of a tsunami, it does not typically produce Slight damage due to Hazus definitions. In most analyses damage state probabilities begin with None and continue at Moderate.

When working in the Hazus user interface, a user may also note that the results produced for combined damage state are probabilities, therefore each row in the Results table will total to 100%. This can be used to perform a simple validation that Hazus is combining probabilities correctly.

Formulas are provided for the structure (STR), nonstructural drift-sensitive systems (NSD), nonstructural acceleration-sensitive systems (NSA), and building contents (CON), recognizing that tsunami damage to nonstructural systems (NSS) does not distinguish between drift-sensitive and accelerations sensitive components.

5.8.1.1 Damage to Structure (STR)

Formulas for calculating combined probabilities of damage to the STR due to earthquake and tsunami (EQ+TS) hazards are given by Equation 5-18 through Equation 5-21 for Complete (CSTR), Extensive (ESTR), Moderate (MSTR), and Slight (SSTR) structure damage states:

For Complete (C_{STR}):

Equation 5-18

$$P[C_{STR}|EQ + TS] = P[C_{STR}|EQ] + P[C_{STR}|TS] - P[C_{STR}|EQ]\,P[C_{STR}|TS] + (P[\geq E_{STR}|EQ] - P[C_{STR}|EQ])\,(P[\geq E_{STR}|TS] - P[C_{STR}|TS])$$

For Extensive (E_{STR}):

Equation 5-19

$$P[\geq E_{STR}|EQ + TS] = P[\geq E_{STR}|EQ] + P[\geq E_{STR}|TS] - P[\geq E_{STR}|EQ]\,P[\geq E_{STR}|TS] + (P[\geq M_{STR}|EQ] - P[\geq E_{STR}|EQ])(P[\geq M_{STR}|TS] - P[\geq E_{STR}|TS])$$

For Moderate (M_{STR}):

Equation 5-20

$$P[\geq M_{STR}|EQ + TS] = P[\geq M_{STR}|EQ] + P[\geq M_{STR}|TS] - P[\geq M_{STR}|EQ]\,P[\geq M_{STR}|TS]$$

For Slight (S_{STR}):

Equation 5-21

$$P[\geq S_{STR}|EQ + TS] = P[\geq S_{STR}|EQ] + P[\geq M_{STR}|TS] - P[\geq S_{STR}|EQ]\,P[\geq M_{STR}|TS]$$

5.8.1.2 Damage to Nonstructural Drift (NDS) Sensitive Systems

Formulas for calculating combined probabilities of damage to NSD systems due to earthquake and tsunami (EQ+TS) hazards are given by Equation 5-22 through Equation 5-25 for Complete (C_{NSD}), Extensive (E_{NSD}), Moderate (M_{NSD}), and Slight (S_{NSD}) nonstructural drift- sensitive damage states:

For Complete (C_{NSD}):

Equation 5-22

$$P[C_{NSD}|EQ + TS] = P[C_{STR}|EQ + TS] + (1 - P(C_{STR}|EQ + TS)(P[C_{NSD}|EQ] + P[C_{NSS}|TS] - P[C_{NSD}|EQ]\,P[C_{NSS}|TS] + (P[\geq E_{NSD}|EQ] - P[C_{NSD}|EQ]\,P[\geq E_{NSS}|TS]) - P[C_{NSS}|TS])$$

For Extensive (E_{NSD}):

Equation 5-23

$$P[\geq E_{NSD}|EQ+TS] = P[C_{STR}|EQ+TS] + (1 - P(C_{STR}|EQ+TS)(P[\geq E_{NSD}|EQ] + P[E_{NSS}|TS] - P[\geq E_{NSD}|EQ]P[\geq E_{NSS}|TS] + P[M_{NSD}|EQ] - P[\geq E_{NSD}|EQ])P[\geq M_{NSS}|TS] - P[\geq E_{NSS}|TS])$$

For Moderate (M_{NSD}):

Equation 5-24

$$P[\geq M_{NSD}|EQ+TS] = P[C_{STR}|EQ+TS] + (1 - P[C_{STR}|EQ+TS])(P[\geq M_{NSD}|EQ] + P[\geq M_{NSS}|TS] - P[\geq M_{NSD}|EQ]\, P[\geq M_{NSS}|TS])$$

For Slight (S_{NSD}):

Equation 5-25

$$P[\geq S_{NSD}|EQ+TS] = P[C_{STR}|EQ+TS] + (1 - P[C_{STR}|EQ+TS])(P[\geq S_{NSD}|EQ] + P[\geq M_{NSD}|TS] - P[\geq S_{NSD}|EQ]\, P[\geq M_{NSD}|TS])$$

5.8.1.3 Damage to Nonstructural Acceleration-Sensitive (NSA) Systems

Formulas for calculating combined probabilities of damage to NSA systems due to earthquake and tsunami (EQ+TS) hazards are given by Equation 5-26 through Equation 5-29 for Complete (C_{NSA}), Extensive (E_{NSA}), Moderate (M_{NSA}), and Slight (S_{NSA}) nonstructural acceleration-sensitive damage states:

For Complete (C_{NSA}):

Equation 5-26

$$P[C_{NSA}|EQ+TS] = P[C_{STR}|EQ+TS] + (1 - P[C_{STR}|EQ+TS])\big(P[C_{NSA}|EQ] + P[C_{NSS}|TS] - P[C_{NSA}|EQ]\, P[C_{NSS}|TS] + (P[\geq E_{NSA}|EQ] - P[C_{NSA}|EQ])(P[\geq E_{NSS}|TS] - P[C_{NSS}|TS])\big)$$

For Extensive (E_{NSA}):

Equation 5-27

$$P[\geq E_{NSA}|EQ+TS] = P[C_{STR}|EQ+TS] + (1 - P[C_{STR}|EQ+TS])\big(P[\geq E_{NSA}|EQ] + P[\geq E_{NSS}|TS] - P[\geq E_{NSA}|EQ]\, P[\geq E_{NSS}|TS] + (P[\geq M_{NSA}|EQ] - P[\geq E_{NSA}|EQ])(P[\geq M_{NSS}|TS] - P[E_{NSS}|TS])\big)$$

For Moderate (M_{NSA}):

Equation 5-28

$$P[\geq M_{NSA}|EQ + TS] = P[C_{STR}|EQ + TS] + (1 - P[C_{STR}|EQ + TS])(P[\geq M_{NSA}|EQ] + P[\geq M_{NSS}|TS] - P[\geq M_{NSA}|EQ]\, P[\geq M_{NSS}|TS])$$

For Slight (S_{NSA}):

Equation 5-29

$$P[\geq S_{NSA}|EQ + TS] = P[C_{STR}|EQ + TS] + (1 - P[C_{STR}|EQ + TS])(P[\geq S_{NSA}|EQ] + P[\geq M_{NSA}|TS] - P[\geq S_{NSA}|EQ]\, P[\geq M_{NSS}|TS])$$

5.8.1.4 Damage to Building Contents (CON)

Formulas for calculating combined probabilities of damage to building CON due to earthquake and tsunami (EQ+TS) hazards are given by Equation 5-30 through Equation 5-33 for Complete (C_{CON}), Extensive (E_{CON}), Moderate (M_{CON}), and Slight (S_{CON}) contents damage states:

For Complete (C_{CON}):

Equation 5-30

$$P[C_{CON}|EQ + TS] = P[C_{STR}|EQ + TS] + (1 - P[C_{STR}|EQ + TS])\big(P[C_{CON}|EQ] + P[C_{CON}|TS] - P[C_{CON}|EQ]\, P[C_{CON}|TS] + (P[\geq E_{CON}|EQ] - P[C_{CON}|EQ])\,(P[\geq E_{CON}|TS] - P[C_{CON}|TS])\big)$$

For Extensive (E_{CON}):

Equation 5-31

$$P[\geq E_{CON}|EQ + TS] = P[C_{STR}|EQ + TS] + (1 - P[C_{STR}|EQ + TS])\big(P[\geq E_{CON}|EQ] + P[\geq E_{CON}|TS] - P[\geq E_{CON}|EQ]\, P[\geq E_{CON}|TS] + (P[\geq M_{CON}|EQ] - P[\geq E_{CON}|EQ])(P[\geq M_{CON}|TS] - P[\geq E_{CON}|TS])\big)$$

For Moderate (M_{CON}):

Equation 5-32

$$P[\geq M_{CON}|EQ + TS] = P[C_{STR}|EQ + TS] + (1 - P[C_{STR}|EQ + TS])(P[\geq M_{CON}|EQ] + P[\geq M_{CON}|TS] - P[\geq M_{CON}|EQ]\, P[\geq M_{CON}|TS])]$$

For Slight: (S_{CON}):

Equation 5-33

$$P[\geq S_{CON}|EQ + TS] = P[C_{STR}|EQ + TS] + (1 - P[C_{STR}|EQ + TS])(P[\geq S_{CON}|EQ] + P[\geq M_{CON}|TS] - P[\geq S_{CON}|EQ]\ P[\geq M_{CON}|TS])$$

5.8.1.5 Cumulative Probabilities

The equations above describe the cumulative probabilities (i.e., probability of greater than or equal to the damage state of interest). The discrete probabilities of other damage states are calculated as the difference in the probability of the damage state of interest and the next more severe damage state Users may also observe that both cumulative and discrete probabilities are reported in the Combined Results menu within Hazus. A detailed discussion of the methodologies for calculating cumulative versus discreet probabilities can be found in the *Hazus Earthquake Model Technical Manual (FEMA, 2024)*, Section 5.6.2. Note, the “cumulative” probability of Complete damage is also the probability of the Complete damage state since it is the most severe state of damage. Combined discreet probabilities are given by Equation 5-34 through Equation 5-36 for Extensive (E_{STR}), Moderate (M_{STR}), and Slight (S_{STR}) structure damage states:

For Extensive (E_{STR}):

Equation 5-34

$$P[E_{STR}\,|EQ + TS] = P[\geq E_{STR}\,|EQ + TS] - P[C_{STR}\,|EQ + TS]$$

For Moderate (M_{STR}):

Equation 5-35

$$P[M_{STR}\,|EQ + TS] = P[\geq M_{STR}\,|EQ + TS] - P[\geq E_{STR}\,|EQ + TS]$$

For Slight (S_{STR}):

Equation 5-36

$$P[S_{STR}\,|EQ + TS] = P[\geq S_{STR}\,|EQ\_TS] - P[\geq M_{STR}\,|EQ + TS]$$

Discrete damage state probabilities of nonstructural drift-sensitive systems, nonstructural acceleration-sensitive systems, and building contents are calculated in the same manner as that of the above equations for the structure.

Users may note that these equations describe only the combined probabilities for components of building damage, however in addition to building damage states, Hazus will produce combined results for the following (see also Table 8-1 in the *Hazus Tsunami Model User Guidance (FEMA, 2024)*):

- GBS: Building damage by square footage and direct economic loss
- UDF: Building functionality and building economic loss

These combined results are calculated using the tsunami-only methodology for the tsunami results, and the earthquake-only methodology for the earthquake results for each corresponding result type. For example, combined GBS direct economic loss is calculated using the tsunami-only methodology (Section 7 of this document), and the earthquake methodology for the same (Section 11 of the *Hazus Earthquake Model Technical Manual* (FEMA, 2024)). Results are then combined using the methodology described earlier in this section.

Section 6. Casualty Estimation

This section describes the methodology used to estimate casualty losses in the Hazus Tsunami Model. Casualty losses are provided by two measures: 1) the travel time for people to evacuate tsunami danger zones (called evacuation travel time in this model), and 2) the number of casualties for a given tsunami event. The evacuation travel time provides information on how long it could take for people to safely reach higher ground. This information is useful for identifying tsunami-risk areas within the coastal community. The evacuation travel time is determined once the location of a safe haven is identified without consideration of tsunami arrival times. However, consideration of the timing of tsunami warnings and arrival times must be evaluated when calculating casualties.

Compared to other natural hazards, human losses caused by tsunamis are especially difficult to estimate. In the event of an earthquake, human losses are directly related to the extent of damage to buildings and infrastructure, which is strongly correlated to the earthquake magnitude and built environment. With little or no forewarning time from an earthquake for evacuation, a majority of casualties result from crushing or suffocation associated with structure collapse. In contrast, there is lead-time for the prediction of a tsunami after detecting a seismic signal, possibly allowing for an effective warning and evacuation period. The lead-time can range from a few minutes for a local source tsunami to ten or more hours for a distant source tsunami. Tsunami warning lead-times are shorter than those of other natural hazards such as volcanic eruptions, hurricanes, and river floods.

6.1 Background

Suppasri et al. (2011) compiled data on fatality rate (fatality rate is the ratio of the number of people killed to the total population in the inundation area) for many historical tsunami events in Japan including the 2011 Tohoku Tsunami; as well as the 2004 Indian Ocean Tsunami in India, Thailand, and Indonesia; the 2006 Java Tsunami; and the 2010 Mentawai Tsunami. Observations from their analysis reveal that the tsunami's flow condition (represented by maximum runup heights) is not the controlling factor determining the fatality rate. Consider, for example, the 0.015% fatality rate data point at a 2.5-meter tsunami runup height.

At a similar runup height (3 ~ 3.5 meters), a data point exists showing the fatality rate at about 50%, an increase by more than three orders of magnitude. Another example is a comparison of nearly 100% fatality rate at the 5-meter tsunami runup height with the 0.06% fatality rate at the tsunami runup height of 31 meters. Evidently, tsunami runup height alone is not a good indicator when estimating fatality rate. The tsunami fatality rate diminishes when the maximum tsunami "height" is less than 1.5 meters. Note that tsunami runup "height" is the elevation from the sea level; the actual inundation "depth" at a location of interest is usually less than the "height:" see the definition sketch in Section 4, Figure 4-2, for the difference between "depth" and "height."

In the same paper, Suppasri et al. (2011) demonstrated better correlation between fatality rate and housing damage rate than the correlation between fatality rate and tsunami runup height. This trend makes sense because humans dwell in houses. Nonetheless, their results are for a specific tsunami event (the 2011 Tohoku Tsunami) in a specific locality (Miyagi Prefecture). Careful examination for each tsunami event presented in their research indicates such a correlation cannot be used for the prediction of a fatality rate in a different locality caused by a different tsunami event.

It is believed that critical factors for determining tsunami impacts on humans are a) prior knowledge and/or experience with tsunamis, b) effective education motivating people to evacuate in a timely manner, and c) effective tsunami warning systems. Age, and its associated mobility capacity, is also another critical factor. Therefore, temporal and spatial information about the tsunami runup is crucial. For example, warnings with more accurate tsunami information are possible when the tsunami arrival occurs a long time after the earthquake. Thus, a distant tsunami may have fewer casualties when compared with a similar tsunami from a local source. A shorter evacuation distance, to a safe haven, results in a better chance of survival.

Human behaviors and actions under strained conditions are difficult to predict. Nonetheless, one of the most systematic and logical methodologies for casualty estimation for a given tsunami scenario is agent-based modeling (Wood and Schmidtlein, 2011). In agent-based modeling, a system is modeled as a collection of autonomous decision-making entities called agents. Agents can be each evacuee or a group of evacuees. An individual agent evaluates the situation and makes decisions based on a set of rules. Agent-based simulations for tsunamis have been performed in the past, for the town of Owase, Japan (Katada et al., 2006), for Long Beach Peninsula, Washington (Yeh et al., 2009), and for the town of Cannon Beach, Oregon (Yeh and Karon, 2011). However, agent-based modeling requires detailed spatiotemporal data of tsunami inundation processes, in addition to geospatial data such as road networks, locations, and operations of warning transmissions (e.g., TV, radios, loudspeakers, and mobile warning vehicles), and demographic data. Also needed is social information for how people respond to the warning and interact with other evacuees (including tourists), and how people are killed and injured (casualty modeling). For Level 1 (Basic) and Level 2 (Advanced) Hazus Methodologies, the concept of agent-based modeling is implemented in a simplified manner. For Level 3 (Advanced) analysis, results from agent-based simulation models could be included as user input, but Hazus is not configured to make the best use of these data types. Hazus currently includes a Level 1 (Basic) Methodology utilizing a “roads only” network approach and a Level 2 (Advanced) Methodology using the travel time output from the USGS Pedestrian Evacuation Analyst (version EvacAnalystInstaller_20141023).

The Casualty Losses module estimates the evacuee travel times and statistics of the fatality and injury counts, and their spatial distribution for a community of interest. As shown in the tsunami loss estimation flow chart in Figure 6-1 (note that for distant events, the earthquake components can be bypassed), data of tsunami inundation processes are provided by the Tsunami Hazard Analysis module, and the Damage Assessment unit provides the effects of earthquake damage on human losses. It must be emphasized that the methodology presented here is as rational as possible even though the outcomes are strongly determined by human decision making and behaviors. Unlike physical laws governed in fluid flows and structural behaviors, human behaviors are not controlled by clear laws, but must be estimated by their tendencies (both based on empirical data and hypotheses). Because of the unavoidable uncertainties, the methodology is designed such that the users are allowed to make their own judgment calls for the characterization of a community and human behaviors of the residents and visitors.

Because of the complexity, only pedestrian evacuation is considered, and possibilities of other evacuation means such as automobiles, bikes, boats, etc. are excluded. In addition, the module includes the possibility of evacuation to tall and tsunami-resistant buildings, by using modified hazard zones or the USGS tool linked above. As noted earlier, an interface based on direct output from the Pedestrian Evacuation Analyst is available within Hazus for Level 2 Casualty modeling.

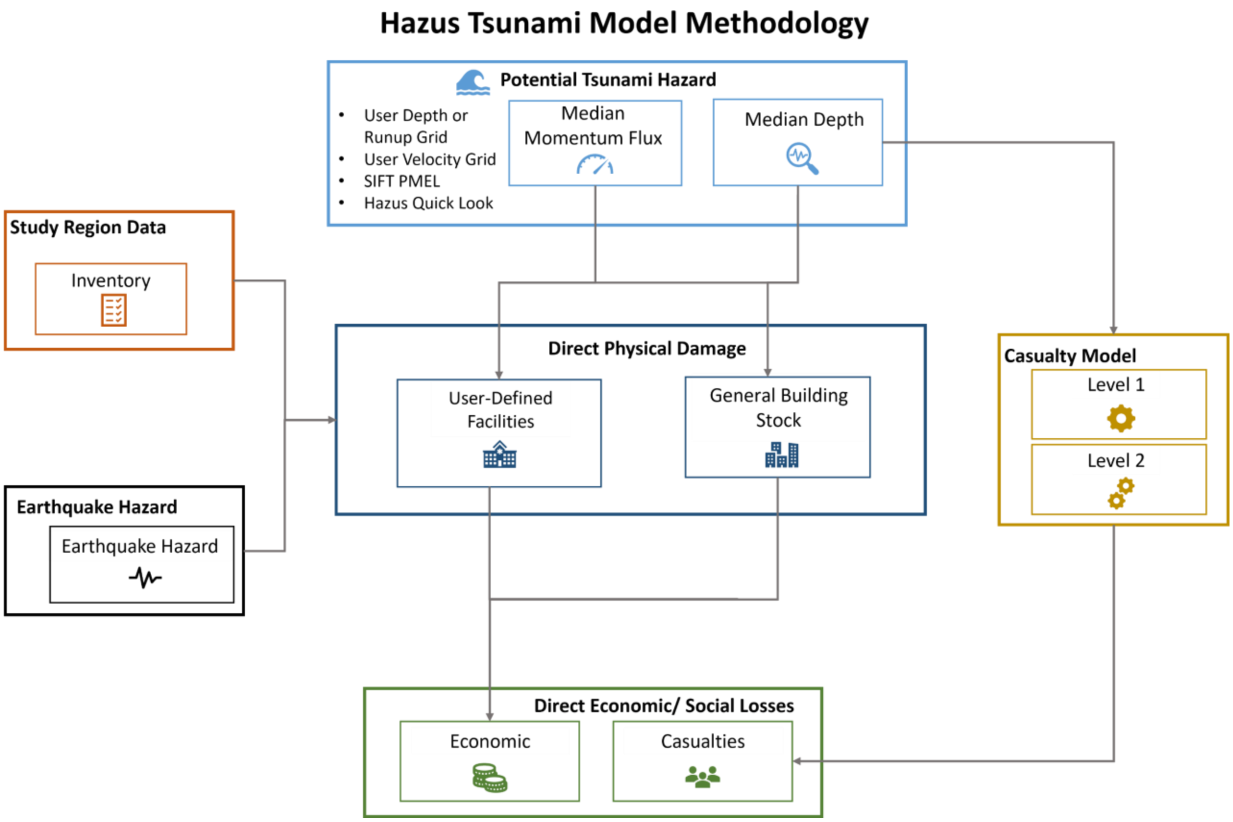

Figure 6-1 Hazus Tsunami Model Methodology Schematic

6.2 Input Requirements and Output Information

Input information and data include the following items for a given tsunami event from Tsunami Hazard Analysis (Section 4), combined earthquake and tsunami damage assessment (Section 5), and those prepared for this module. The input/output diagram is shown in Figure 6-2.

6.2.1 Input Data from User & Tsunami Hazard Analysis

- Maximum inundation locations X(x,y) (depth > 0, along the maximum runup contour line)
- Fatality boundary, where depth is greater than 2 meters and fatality rate is modeled as 99
- Arrival time of the leading tsunami, T_0
- Time of max runup, T_{max}

- Warning time, T_{warn}, after earthquake: this includes a natural cue (ground shaking, $T_{warn} = 0$) for a local tsunami

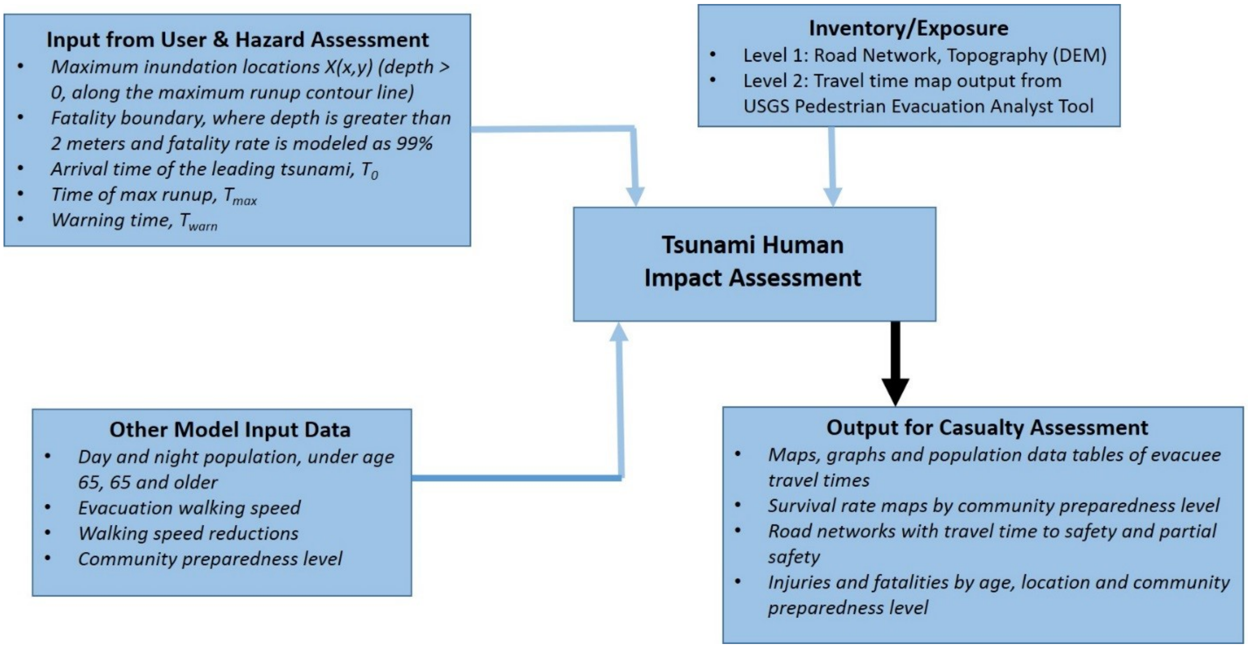

Figure 6-2 Flow Chart of Tsunami Loss Estimation Methodology

6.2.2 Levels of Analysis

Level 1 (Basic): The Hazus Level 1 casualty analysis integrates methodology from the USGS Pedestrian Evacuation Analyst Tool; however, it uses a "roads only" approach for evacuation. This approach helps ensure evacuation routing is not inadvertently placed across flooded or otherwise impassable areas, however, it may not be the fastest route to safety if across land routes are available. The Level 1 (Basic) Methodology calculates the path-distance using both a DEM and road-network provided by the user and applies the walking speeds selected by the user (Table 6-1). The module includes optional external download links for the U.S. Census Topologically Integrated Geographic Encoding and Referencing (TIGER) road network and the USGS National Elevation Datasets, or users can provide their own datasets.

Level 2 (Advanced): The Hazus Level 2 (Advanced) casualty analysis directly integrates the travel time map outputs from the USGS Pedestrian Evacuation Analyst Tool. Please visit this website to download the tool and run the tool to obtain these outputs. Both the travel time to safety (depth ≤ 0), T_{travel}, and travel time to partial safety (depth ≤ 2 meters), T^*_{travel}, are required as inputs for the Level 2 (Advanced) analysis. The Hazus interface with the USGS tool provides the capability to:

- Preprocess hazard zone and validate the safe zones to ensure slivers or erroneous areas determined as "safe" are removed.

- Utilize the entire Land-Cover, validating impassable areas, rather than just road network, to ensure the fastest least-cost routes are incorporated.

- Incorporate vertical evacuation structures into the analysis, including the ability to evaluate mitigation strategies (casualty reduction) associated with proposed structures.
- Validate population summaries and incorporate seasonal populations, such as beach goers and cruise ship populations into impacted blocks.

6.2.3 Input Data Prepared for This Module

- Population data are included with the NSI data as discussed in the *Hazus Inventory Technical Manual* (FEMA, 2024). These data include day and night population estimates for each structure, as well as estimates of under age 65, and 65 and older populations. These populations are distributed based on Census block level Longitudinal Employer and Household Data (LEHD) to specific Hazus occupancy types, except for school data that are based on a national dataset from Oak Ridge National Labs (ORNL) that include the numbers of students, teachers, and staff for each facility, that are used directly for peak day populations (see the *Hazus Inventory Technical Manual* (FEMA, 2024) for details). Although the population data and loss results are summarized by Census block, only the NSI point populations that are impacted by tsunami inundation are included in the casualty assessment.
- Community preparedness levels: Good, Fair, and Poor. These grades can be determined based, on the condition of shore-protection structures, emergency loudspeakers, preparation of evacuation routes and signs, community's risk management level, and/or the education level for tsunami awareness. The users may attempt to specify "good" for a tsunami-ready community designated by National Weather Service.

6.2.4 Input Data Considerations from Earthquake Damage Assessment

- The functionality status of evacuation routes and bridges from the Hazus Earthquake Model output can be used as input to adjust walking speed reductions (Table 6-2), remove roadway segments in Level 1 (Basic), or might be defined as impassable areas in the Level 2 (Advanced) analysis in the Hazus Tsunami Model.
- The casualties resulting from the earthquake could be considered in further reducing walking speeds because of rendering aid to the injured or for those directly injured by the earthquake.

6.2.5 Output Data

Output data are the graphical presentation of evacuee travel time and the statistics on the numbers of casualties (both fatalities and injuries). The casualty map shows both the total numbers and their spatial distributions. The results include:

- Day and night evacuee populations.
- Under age 65, and 65 and over evacuee populations.
- Travel time to safety and partial safety for under age 65, and 65 and over populations.

- Survival rates for under age 65, and 65 and over populations for each community preparedness level.
- Day and night injuries for under age 65, and 65 and over populations for each community preparedness level.
- Day and night fatalities for under age 65, and 65 and over populations for each community preparedness level.

Table 6-1 Pedestrian Walking Speeds (USGS Pedestrian Evacuation Analyst, meters per second)

Pedestrian Travel Speeds	(meters/second)
Slow walk	1.10
Fast walk	1.52
Slow run	1.79
Fast run	3.85

Table 6-2 Walking Speed Reduction Factors

Under 65	65 and Older
1.00	0.80

6.3 Methodology for Casualty Estimates

To avoid double counting casualties, the number of casualties caused by the preceding earthquake in each population block are first estimated and provided separately. The Hazus Methodology does not address a combined casualty model including the likelihood that earthquake injuries would likely increase tsunami casualties since evacuation would be made more difficult. Population in each block depends on time of day and season, population patterns would be different between daytime and nighttime and the presence of tourists. Casualty also depends on the vulnerability of people – age and gender (see for example, Doocy et al., 2007, 2009; Guha-Sapir et al., 2006; MacDonald, 2005; Nuemayer and Plümper, 2007; Prater et al., 2007; Yeh, 2010): this factor is included through evacuation walking speeds and reduction factors (Table 6-1 and Table 6-2). Drowning criteria based on physiology and tsunami dynamics (force balance) are not considered in the present methodology, although such criteria are often used in agent-based models.

As discussed earlier, earthquake casualties are directly related to earthquake intensity and building vulnerability because the severity of shaking determines whether buildings are collapsed or severely damaged, and the building collapse and damage kill and injure people. The strength of tsunamis (e.g., measured by tsunami runup height) is, however, not a good indicator for predicting casualty rates. The important factors are prior knowledge and experience with tsunamis (i.e., education) as well as timely and effective notification through tsunami warning systems. Consequently, temporal information on tsunami inundation (although no detailed flow depths and velocities are used here) is essential for estimating casualties. Table 6-3 summarizes the temporal parameters, and Figure 6-3 provides a flow chart of the Tsunami Casualty Module.

Table 6-3 Casualty Model Parameters

Casualty Parameter	Description
T_{travel}	Provided by T_{travel} time view summarized by Census block, using USGS Pedestrian Evacuation Analyst tool based on under age 65 walking speeds (1.00) and reduced for age 65 and older (0.80), summary view for population totals and travel time to safety in minutes is provided by analysis.
T^*_{travel}	Provided by T^*_{travel} time view summarized by Census block, using USGS Pedestrian Evacuation Analyst tool based on under age 65 walking speeds (1.00) to the area of partial safety (depth 0-2 meter) and reduced for 65 and older (0.80), summary view for population totals and travel time to partial safety in minutes. This should always be less than or equal to T_{travel}.
T_O (arrival time) Minutes	Estimated from Tsunami Travel Time maps for distant tsunamis and ***estimated by user*** for local tsunamis.
T_{MAX} (time to max runup) Minutes	***Estimated by user***, with a baseline value populated based on T_O plus 5 minutes, this always needs to be equal to or larger than T_O.
T_W (warning time) Time to Issue Warning in Minutes	***Estimated by user,*** baselines for distant (40 minutes) and local (10 minutes), *note provided to user to use 0 when warning cue is provided by earthquake ground shaking*, all user parameters are summarized before launching analysis and included in reporting. This may not be greater than T_O.
C_{PREP}	Community Preparedness Level (Good, Fair, or Poor) grading, baselines are 0.2, 0.6 and 1.0, respectively, and provided in an editable Analysis Parameter table (e.g., NWS TsunamiReady may be used for Good).
C_{STD}	Community Preparedness Level (Good, Fair, or Poor) proportionality constant (termed “betas” for consistency with Hazus Methodology), baselines are 0.3, 0.5 and 0.8, respectively, and provided in an editable Analysis Parameter table (e.g., NWS TsunamiReady may be used for Good).
T_{PREP}	Estimate in minutes for community to react to warning. Based on $C_{PREP}(T_O - T_W)$.
T_{CRIT}	Difference between the evacuation time and the time available to evacuate. Calculated from $T_{CRIT} = (T_{MAX} - T_W) - (T_{PREP} + T_{travel})$, 50% of population reaches safety at $T_{CRIT} = 0$.
Day or Night	Defines the starting population distribution as peak day or night. Both day and night results are provided.

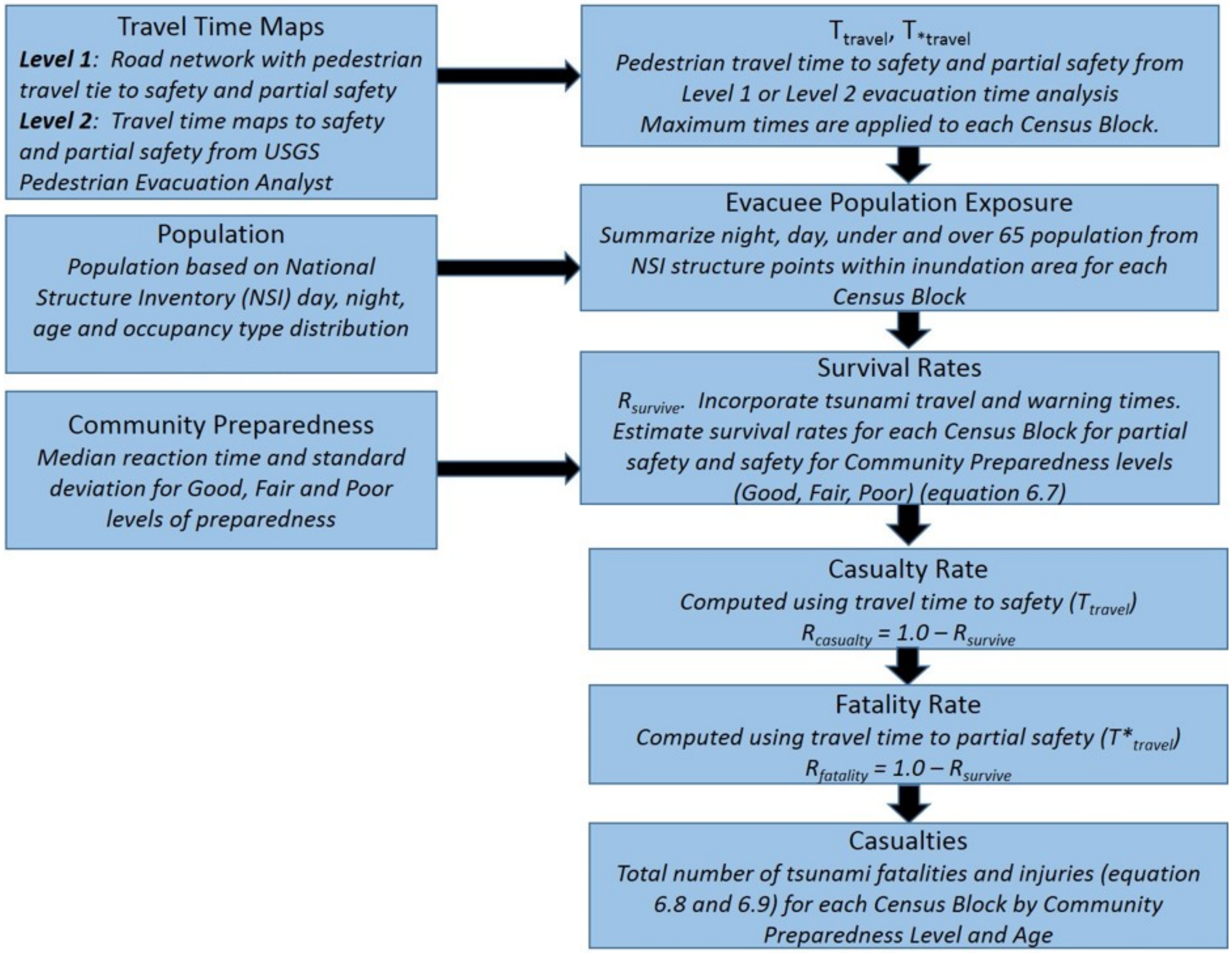

Figure 6-3 Flow Chart of Tsunami Loss Estimation Methodology

The critical time T_{crit}, which represents the time difference between the evacuation time and the available time to evacuate is determined as shown in Equation 6-1:

Equation 6-1

$$T_{crit} = T_{available} - T_{evacuation}$$

or more specifically,

$$T_{crit} = (T_{max} - T_w) - (T_{prep} + T_{travel})$$

Note that the FEMA (2013) methodology provided a special case formula for when the tsunami arrival at the shore is the evacuation cue, when tsunami warning is not issued or issued after its arrival, however, by requiring that the user-provided warning time is less than or equal to the tsunami travel time, $T_w \leq T_0$, (Table 6-3) the special case was not required.

If the evacuation travel time represents the median time for a given evacuee population, then, more than half of the population would travel beyond the inundation zone and thus be unharmed when the critical time $T_{crit} > 0$. When $T_{crit} < 0$, less than half would be unharmed, and when Tcrit = 0, then it is a 50/50 situation (50% of the evacuee population would reach the area beyond the maximum penetration of the tsunami).

It is important to recognize that when people receive tsunami warnings (either official warnings or natural cues), not everyone starts to evacuate at once: this is due to individuals' preparation behaviors, communication among their families and neighbors, and other various personal decision-making processes. The timing to initiate evacuation is the primary reason the evacuee pack spreads out from the initial population block. Assuming evacuees' population spread is skewed and is kept in the positive time (t > 0), the evacuees' initial distribution is modeled to be lognormal. It is pointed out that the choice of lognormal distribution is merely for convenience to form a skewed and 'smooth' distribution function of the evacuee population in t > 0. While the log function could imply some nonlinear effect of self-interactions, its physical justification is weak. With this caveat, the lognormal probability density function in terms of time, t can be written as:

Equation 6-2

$$P(t) = \frac{1}{s\sqrt{2\pi}t} \mathrm{Exp}(-(\ln t - M)^2/2s^2)$$

And the cumulative distribution function:

Equation 6-3

$$D(t) = \frac{1}{2}\left[1 + \mathrm{erf}\left((\ln t - M)/s\sqrt{2}\right)\right]$$

Where:

erf (*)	is the error function

The parameters s and M are related to the mean μ the variance σ^2 and the mode of the variable t:

Equation 6-4

$$\mu = \mathrm{Exp}\left(M + \frac{s^2}{2}\right); \sigma^2 = \mathrm{Exp}(s^2 + 2M)(\mathrm{Exp}(s^2) - 1);$$

$$\mathrm{mode} = \mathrm{Exp}(M - s^2); \mathrm{median} = \mathrm{Exp}(M)$$

Where:

s	is a parameter related to the mean
M	is a parameter related to the mean

In the Casualty Losses module, the evacuation preparation time T_{prep} is set at the mode of the lognormal distribution, which means that the parameter T_{prep} represents the most probable initial time for people to evacuate.

Because neither adequate empirical data nor reliable models for the behavior of humans to tsunami hazards are available, it is necessary to estimate the parameters by the user's expertise. Nevertheless, the methodologies in Hazus must be as rational as possible, including the consideration of several key elements described below. With the methodology framework in place, the development of human behavior modeling could be incorporated in the future.

The Methodology assumes that people tend to act quickly in a short interval of time by responding to a warning for a local tsunami (including severe ground shaking). Contrarily, their response spans a long period for a distant tsunami when they are told that the tsunami will not arrive for several hours. Therefore, people's response times are modeled to warnings as proportional to the time difference between the warning time and the tsunami arrival time. Hence, the standard deviation for the lognormal distribution is estimated as:

Equation 6-5

$$\sigma = C_{std}\ (T_0 - T_w)$$

The proportionality constant "betas" C_{std} = 0.3, 0.5, and 0.8 result in possible spreads in the evacuee distributions for the three community preparedness levels: good, fair, or poor for which Hazus provides results.

The value of the warning effectiveness and preparation time T_{prep} is not specified, but pre-assigned based on one of three grades of community preparedness. Recall that T_{prep} represents the most 'probable' time (i.e., mode) for people to initiate evacuation after a tsunami warning is received (including the natural cue: ground shaking). The mode of the evacuation initiation can be modified by the user and is set at the preparation time T_{prep}:

Equation 6-6

$$\text{mode} = T_{prep} = C_{prep}\ (T_0 - T_w)$$

in which C_{prep} = 0.2, 0.6, and 1 is used for the three grades of community preparedness (see Table 6-4). These parameters may be modified based on warning effectiveness and preparation time T_{prep} for the community, or as an option, the preparedness level results could be mixed for each Census block in the community. Note the values of C were modified slightly from FEMA (2013) based on performance testing summarized in Table 6-5 and Table 6-6 below. In addition, the case where tsunami travel time is less than warning time, $T_0 < T_W$, was removed by requiring $T_W \leq T_0$.

Table 6-4 Baseline Parameters to Determine the Initial Evacuee Spread Based on the Response to the Warning

Community Preparedness Level	Parameter to determine evacuation initiation time C_{prep} (Equation 6-6)	Parameter for the deviation of evacuation initiation C_{std}, which determines the spread (Equation 6-5)
Good	0.2	0.3
Fair	0.6	0.5
Poor	1	0.8

Figure 6-4 shows an example of probability density functions for the time to initiate evacuation with various values of C_{std} for both typical local-tsunami and distant-tsunami cases. The resulting distribution appears realistic but can be fine-tuned when better information is obtained. Also note that each distribution function in the figure represents the spread due to response to the warning only: effects of the pedestrian traveling process are not included, since that is provided directly from the USGS methodology.

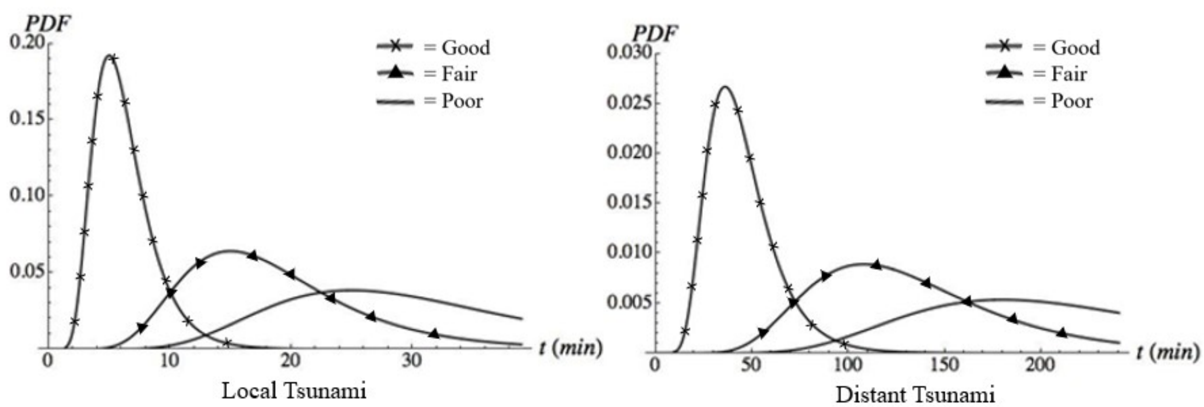

Figure 6-4 Example Probability Density Functions for Evacuation Times Based on Community Preparedness (Good, Fair, Poor)

The survival rate $R_{survive}$ is the value of the cumulative distribution at $t = T_{med} + T_{crit}$. The basis of this methodology implements a lognormal cumulative distribution to estimate the survival rate probabilities that can be implemented in a spreadsheet function and utilized as fast running SQL update statements in the Hazus program as follows:

Equation 6-7

$$R_{survive} = NORMDIST(\ln(T_{prep} + T_{crit}), \ln(T_{prep}), (C_{std}), 1$$

Where 1 represents the cumulative distribution function, yielding the casualty rate determined by $R_{casualty} = 1.0 - R_{survive}$. The spreadsheet implementation allowed for the computation of thousands of examples based on various tsunami travel and warning times (including $T_w = 0$ where the ground shaking provides a cue), as well as evacuation time combinations for each community preparedness level. Table 6-5 illustrates a summary of results, $R_{survive}$, for potential near-source events, while Table 6-6 provides a summary of results for distant-source events.

Table 6-5 Sampling of Survival Rates Based on Methodology – Near Source

Time in Minutes				Community Reaction Time (T_{prep}) in Minutes			Survival Rates Based on Community Preparedness Levels		
Tsunami Travel	Max Inundation Extent	Issue Warning	Pedestrian Evacuation	Good	Fair	Poor	Good	Fair	Poor
0	5	0	0	0	0	0	0%	0%	0%
5	10	5	3	0	0	0	0%	0%	0%
10	15	0	10	2	6	10	99.89%	35.77%	19.31%
15	20	0	15	3	9	15	95.57%	11.99%	8.48%
20	25	0	30	4	12	20	0%	0%	0%
25	30	0	15	5	15	25	99.99%	50.00%	26.16%
30	35	0	30	6	18	30	27.17%	0.52%	1.26%
35	40	10	15	5	15	25	99.99%	50.00%	26.16%
40	45	10	30	6	18	30	27.17%	0.52%	1.26%
45	50	10	15	7	21	35	100%	63.63%	33.70%
50	55	10	30	8	24	40	98.19%	17.36%	11.01%
55	60	10	15	9	27	45	100%	69.81%	37.67%

Table 6-6 Sampling of Survival Rates Based on Methodology – Distant Source

Time in Minutes				Community Reaction Time (T_{prep})			Survival Rates Based on Community Preparedness Levels		
Tsunami Travel	Max Inundation Extent	Issue Warning	Pedestrian Evacuation	Good	Fair	Poor	Good	Fair	Poor
60	65	10	60	10	30	50	0%	0%	0%
80	85	20	15	12	36	60	100%	74.44%	40.99%
100	105	20	60	16	48	80	93.16%	9.60%	7.30%
120	125	20	15	20	60	100	100%	79.13%	44.76%
140	145	20	60	24	72	120	99.96%	41.90%	22.17%
160	165	20	15	28	84	140	100%	80.88%	46.31%
180	185	40	60	28	84	140	99.99%	50.94%	26.64%
200	205	40	15	32	96	160	100%	81.40%	46.79%

Time in Minutes				Community Reaction Time (T_{prep})			Survival Rates Based on Community Preparedness Levels		
Tsunami Travel	Max Inundation Extent	Issue Warning	Pedestrian Evacuation	Good	Fair	Poor	Good	Fair	Poor
220	225	40	60	36	108	180	100%	61.50%	32.43%
240	245	40	15	40	120	200	100%	82.10%	47.44%
260	265	40	60	44	132	220	100%	67.23%	35.96%
280	285	40	15	48	144	240	100%	82.55%	47.88%

These tables represent reasonable survival rates that follow the logic described throughout this section regarding critical time and community preparedness levels. One rare exception is that for very low survival rates, the poorly prepared community may have a slighter higher rate (1.26% vs 0.52%, Rows 7 and 9 in Table 6-5) than the fair community. This is attributed to the relatively high standard deviation and wide distribution function associated with poor and is not expected to have a significant impact on casualty results.

The number of casualties consists of the numbers of injuries and fatalities. To distinguish a fatality from an injury, a criterion is set in terms of the inundation depth that assumes that 99% of people would be killed if they were caught in a depth of more than 2 meters. With the Evacuation Travel Time for fatality T^*_{travel} (to the boundary of the 2-meter depth), the foregoing calculations are repeated to obtain the fatality rate $R_{fatality}$. It is assumed the injury rate decreases linearly from 99% to nil from the point of 2-meter inundation depth toward the maximum inundation X (x, y). This logic is illustrated in Figure 6-5.

The total number of casualties for a given population block j can then be calculated by $N_j * R_{casualty}$, where N_j is the number of people in the population block j summarized from the population in structures that are in the inundation areas. Then, the number of fatalities for the population block j can be calculated by:

Equation 6-8

$$NF_j = N_j * \left(0.99\, R_{fatality} + {}^{1}/_{2}\left(R_{casualty} - 0.99\, R_{fatality}\right)\right)$$

And the number of injuries is:

Equation 6-9

$$NI_j = {}^{1}/_{2}\, N_j\left(R_{casualty} - 0.99\, R_{fatality}\right) = N_j * R_{casualty} - NF_j$$

Note that these equations are repeated for under age 65, 65 and over, as well as each community preparedness level. It should be emphasized that the foregoing estimate excludes potential survivors who have evacuated to tall, sturdy buildings.

Total numbers of fatalities and injuries for this community are the summations $\sum_j NF_j$ and $\sum_j NI_j$ respectively.

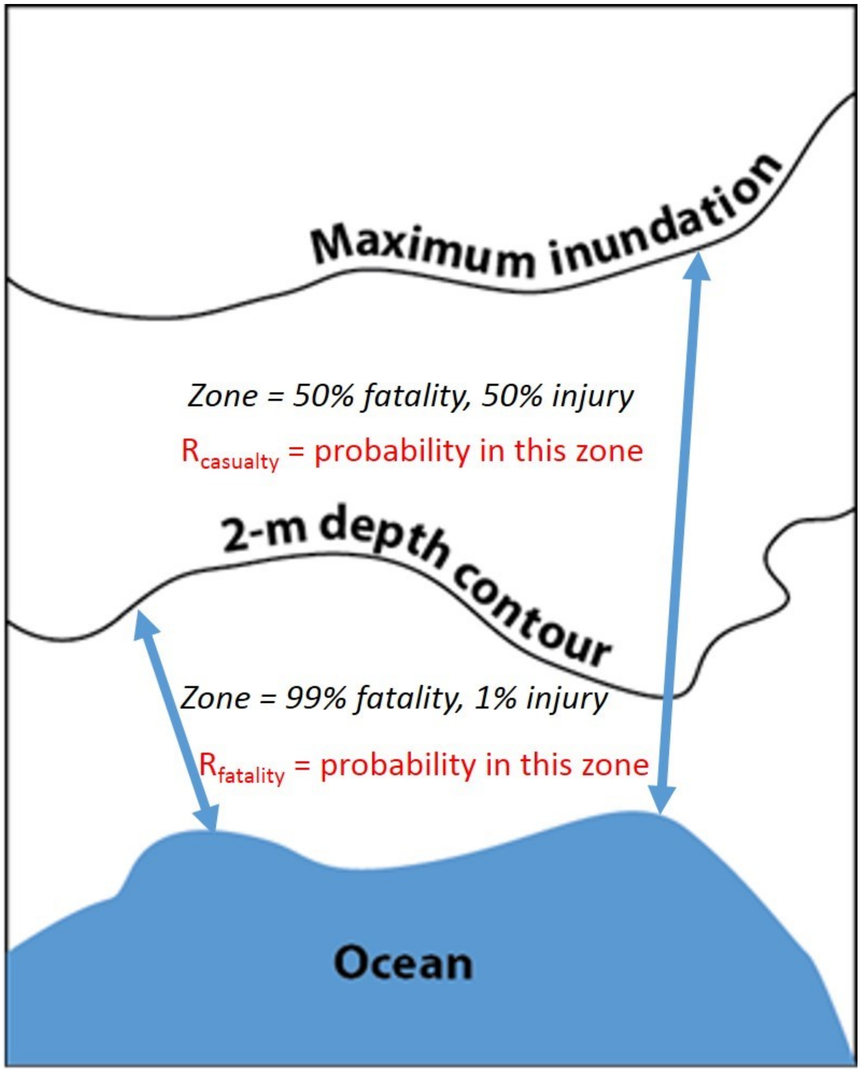

Figure 6-5 Illustration of Logic to Determine Fatality and Injury Rates

The FEMA (2013) example case with the conditions of preparation time T_{prep} = 10 minutes; tsunami arrival time T_0 = 25 minutes; time at maximum inundation T_{max} = 30 minutes; tsunami warning time T_w = 0 (essentially immediately upon occurrence of the earthquake); evacuee travel time T_{travel} = 18 minutes using the $R_{survive}$ probability Equation 6-7, yields a rate of 64.2% for the fair preparedness level community example. Consequently, the resulting casualty rate is 100% - 64.2% = 35.8%. If the Evacuation Travel Time T^*_{travel} to an inundation depth of 2 meters is assumed to be 17 minutes instead of 18 minutes, then Equation 6-7 yields 70.0%. Therefore, the probability of a 99% fatality rate would be 30.0%. For a given population block with 193 people, Equation 6-10 yields the estimated number of fatalities:

Equation 6-10

$$(193) * \{0.99\ (0.300) + ½\ (0.358 – 0.99\ (0.300))\} = 57 \text{ people}$$

and Equation 6-11 the number of injuries:

Equation 6-11

$$(193) * (0.358) - (57) = 12 \text{ people}$$

This compares well to the FEMA (2013) analysis of 56 fatalities and 13 injuries for this example case.

6.4 Future Enhancements

A future Level 3 (Advanced) analysis could use results from agent-based simulation models, although this option is not included for the present methodology development. Agent-based modeling for tsunami events has been performed in the past for the town of Owase, Japan (Katada et al., 2006), for Long Beach Peninsula, Washington (Yeh et al., 2009), and for the town of Cannon Beach, Oregon (Yeh and Karon, 2011).The FEMA (2013), as well as Yeh (2014), methodology recognizes that once people begin evacuating to a safe haven, they further disperse due to age and demographic factors incorporating a standard deviation that is included in the final cumulative distribution function. However, these assumptions were modified to leverage the evacuee travel times that are directly provided from the USGS Pedestrian Evacuation Analyst GIS-based approach. Outside methodologies also recognize that the level-based community preparedness approach has a larger influence on the calculation of survival rate. This potential dispersion of evacuees as a result of deviation in the walking speed assumptions could be incorporated into Hazus methodology in the future.

In addition, a methodology could be developed to better combine earthquake and tsunami casualties. Calculating these separately can result in an overestimation, however, fatality rates for earthquakes are exceptionally smaller than for those exposed to tsunami inundation. Therefore, it is more likely that the casualties caused by the earthquake could lead to additional tsunami casualties, by slowing evacuation because of those directly injured or those rendering aid to the injured.

Section 7. Direct Economic Losses

This section describes the conversion of damage state information, developed in previous modules, into estimates of economic loss.

The Hazus Methodology provides estimates of the structural and nonstructural repair costs caused by building damage and the associated loss of building contents and business inventory. Building damage can also cause additional losses by restricting the building's ability to function properly. To account for this, business interruption, including rental income losses, are estimated. These losses are calculated from the building damage estimates by use of methods described later in this section. The Hazus Methodology flowchart highlighting the Direct Economic Loss component is shown in Figure 7-1.

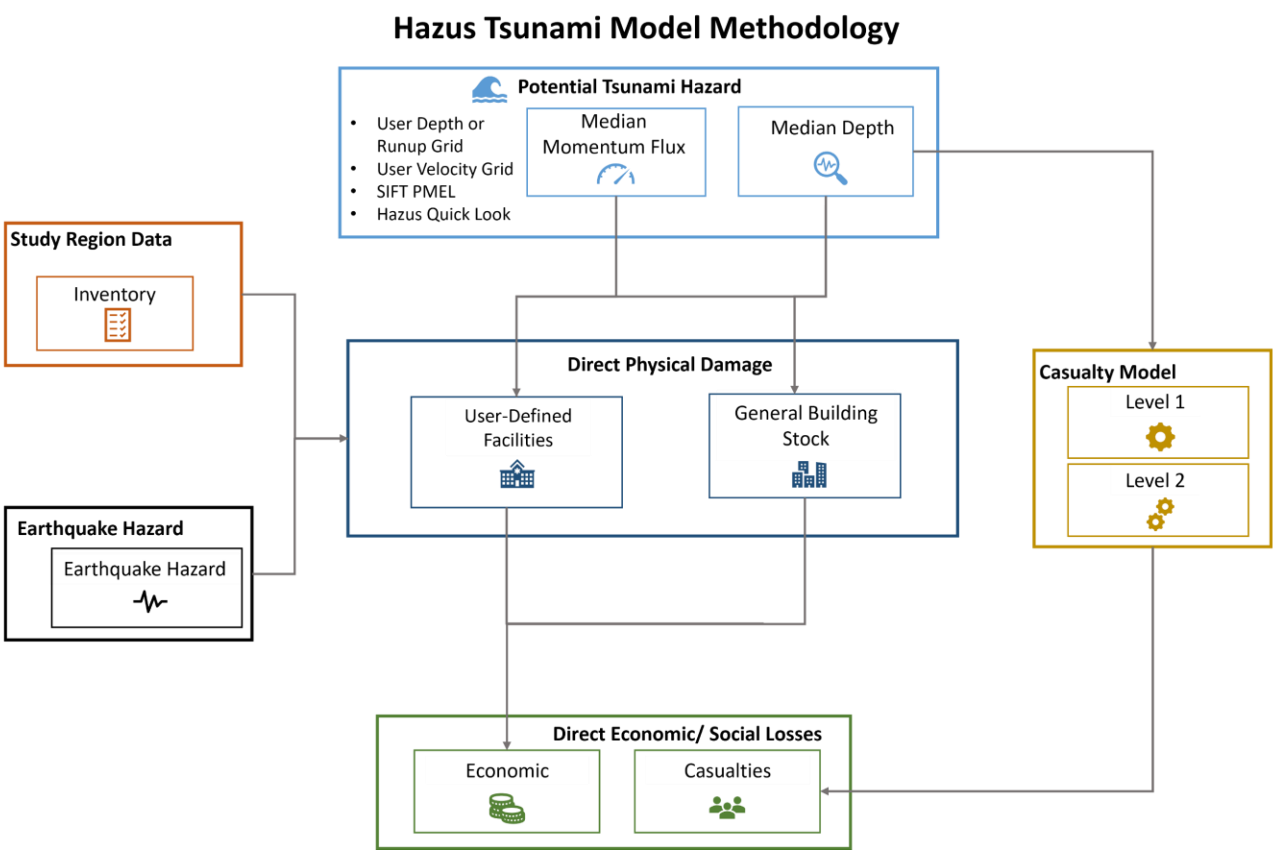

Figure 7-1 Direct Economic Losses Relationship to other Components of the Tsunami Loss Estimate Methodology

7.1 Scope

This section provides descriptions of the methodologies, the derivation of baseline data, and explanatory tables for a number of direct economic loss items, derived from estimates of building damage. For building-related items, methods for calculating the following dollar losses are provided:

- Building Repair and Replacement Costs

- Building Contents Losses
- Building Inventory Losses

To enable time-dependent losses to be calculated, baseline values are provided for:

- Building Recovery Time and Loss of Function (business interruption) time

Procedures for calculating the following time-dependent losses are provided:

- Relocation Expenses
- Proprietor’s Income and Wage Losses
- Rental Income Losses

7.2 Input Requirements

Input data for direct economic losses consists of building damage estimates from the direct physical damage module. The damage estimates are in the form of probabilities of being in each damage state, for each structural type or occupancy class. The building classification system is discussed in the *Hazus Inventory Technical Manual* (FEMA, 2024). Damage states are discussed in detail in Section 5 of this manual. Damage state probabilities are provided from the direct physical damage module for both structural and nonstructural damage. These damage state probabilities are then converted to monetary losses using inventory information and economic data. For Level 1 (Basic) Analysis, using baseline data values, the buildings are classified into three broad occupancy/use-related categories: residential, commercial/institutional, and industrial. These categories are used to determine the nonstructural element make-up of the buildings and the nature and value of their contents. Building replacement cost data is provided for each of the 33 occupancy classes can be found in the *Hazus Inventory Technical Manual* (FEMA, 2024).

7.3 Building Repair and Replacement Costs

To establish dollar loss estimates, the damage state probabilities must be converted to dollar loss equivalents. Losses will be due to both structural and nonstructural damage. For a given occupancy and damage state, building repair and replacement costs are estimated as the product of the floor area of each building type within the given occupancy, the probability of the building type being in the given damage state, and repair costs of the building type per square foot for the given damage state, summed over all building types within the occupancy.

For structural damage, losses are calculated as follows:

Equation 7-1

$$\mathrm{CS_{ds,i}} = \mathrm{BRC_i} * \sum_{i=1}^{33} \mathrm{PSBTSTR_{ds,i}} * \mathrm{RCS_{ds,i}}$$

Equation 7-2

$$\mathrm{CS_i} = \sum_{\mathrm{ds}=2}^{5} \mathrm{CS_{ds,i}}$$

Where:

$CS_{ds,i}$	is the cost of structural damage (repair and replacement costs) for damage state, ds, and occupancy, i
BRC_i	is the building replacement cost of occupancy, i
$PSBTSTR_{ds,i}$	is the probability of occupancy being in structural damage state, ds, see Section 5
$RCS_{ds,i}$	is the structural repair and replacement ratio for occupancy, i, in damage state, ds, see Table 7-1

The structural repair cost ratio for structural damage for each damage state and occupancy is shown in Table 7-2. Note that damage state None does not contribute to the calculation of the cost of structural damage, and thus the summation in Equation 7-2 is from Slight to Complete In addition, when the Tsunami Model is run without the Earthquake Model, the Slight damage state is not used for tsunami.

A similar calculation is performed for nonstructural damage. Nonstructural damage does not include the damage to contents such as furniture and computers; content loss is accounted for separately.

Nonstructural damage costs are calculated as follows:

Equation 7-3

$$\mathrm{CNS_{ds,i}} = \mathrm{BRC_i} * \mathrm{PONS_{ds,i}} * \mathrm{RC_{ds,i}}$$

Equation 7-4

$$CNS_i = \sum_{ds=2}^{5} CNS_{ds,i}$$

Where:

$CNS_{ds,i}$	is the cost of nonstructural damage (repair and replacement costs) for damage state, ds, and occupancy, i,
CNS_i	is the cost of nonstructural damage (repair and replacement costs) for occupancy, i
BRC_i	is the building replacement cost of occupancy, i
$PONS_{ds,i}$	is the probability of occupancy, i being in nonstructural damage state, ds,
$RC_{ds,i}$	is the nonstructural repair and replacement ratio for occupancy, i in damage state, ds (Equation 7-2).

The repair cost ratios for nonstructural damage for each damage state are shown in Table 7-2. The total cost of building damage (CBD_i) for occupancy class (i) is the sum of the structural and nonstructural damage.

Equation 7-5

$$CBD_i = CS_i + CNS_i$$

Finally, to determine the total cost of building damage (CBD),

Table 7-5 must be summed over all the occupancy classes.

Equation 7-6

$$CBD = \sum_{i} CBD_i$$

The following tables are from the *Hazus Earthquake Model Technical Manual* (FEMA, 2024) Tables 11-2 through 11-4.

Table 7-1 Structural Repair Cost Ratios (Percent of Building Replacement Cost)

Label	Occupancy Class	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
RES1	**Residential:** Single-Family Dwelling	0.5	2.3	11.7	23.4
RES2	**Residential:** Mobile Home	0.4	2.4	7.3	24.4
RES3a-f	**Residential:** Multi-Family Dwelling	0.3	1.4	6.9	13.8
RES4	**Residential:** Temporary Lodging	0.2	1.4	6.8	13.6
RES5	**Residential:** Institutional Dormitory	0.4	1.9	9.4	18.8
RES6	**Residential:** Nursing Home	0.4	1.8	9.2	18.4
COM1	**Commercial:** Retail Trade	0.6	2.9	14.7	29.4
COM2	**Commercial:** Wholesale Trade	0.6	3.2	16.2	32.4
COM3	**Commercial:** Personal and Repair Services	0.3	1.6	8.1	16.2
COM4	**Commercial:** Professional/Technical/ Business Services	0.4	1.9	9.6	19.2
COM5	**Commercial:** Banks/Financial Institutions	0.3	1.4	6.9	13.8
COM6	**Commercial:** Hospital	0.2	1.4	7.0	14.0
COM7	**Commercial:** Medical Office/Clinic	0.3	1.4	7.2	14.4
COM8	**Commercial:** Entertainment & Recreation	0.2	1.0	5.0	10.0
COM9	**Commercial:** Theaters	0.3	1.2	6.1	12.2
COM10	**Commercial:** Parking	1.3	6.1	30.4	60.9
IND1	**Industrial:** Heavy	0.4	1.6	7.8	15.7
IND2	**Industrial:** Light	0.4	1.6	7.8	15.7

Label	Occupancy Class	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
IND3	**Industrial:** Food/Drugs/Chemicals	0.4	1.6	7.8	15.7
IND4	**Industrial:** Metals/Minerals Processing	0.4	1.6	7.8	15.7
IND5	**Industrial:** High Technology	0.4	1.6	7.8	15.7
IND6	**Industrial:** Construction	0.4	1.6	7.8	15.7
AGR1	**Agriculture:** Agriculture	0.8	4.6	23.1	46.2
REL1	**Religion/Non-Profit:** Church/Membership Organization	0.3	2.0	9.9	19.8
GOV1	**Government:** General Services	0.3	1.8	9.0	17.9
GOV2	**Government:** Emergency Response	0.3	1.5	7.7	15.3
EDU1	**Education:** Schools/Libraries	0.4	1.9	9.5	18.9
EDU2	**Education:** Colleges/Universities	0.2	1.1	5.5	11.0

Note that the values in the last column (using corresponding rows of each occupancy class) of Table 7-1 and Table 7-2 must sum to 100 since the Complete damage state implies that the structure must be replaced. The replacement value of the building is the sum of the structural and nonstructural components.

Table 7-2 Nonstructural Repair Costs (Percent of Building Replacement Cost)

Label	Occupancy Class	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
RES1	**Residential:** Single-family Dwelling	1.5	7.7	33	76.6
RES2	**Residential:** Mobile Home	1.6	7.6	30.2	75.6
RES3a-f	**Residential:** Multi -family Dwelling	1.7	8.6	34.4	86.2
RES4	**Residential:** Temporary Lodging	1.8	8.6	34.6	86.4
RES5	**Residential:** Institutional Dormitory	1.6	8.1	32.4	81.2
RES6	**Residential:** Nursing Home	1.6	8.2	32.6	81.6

Label	Occupancy Class	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
COM1	**Commercial:** Retail Trade	1.4	7.1	26.7	70.6
COM2	**Commercial:** Wholesale Trade	1.4	6.8	25.6	67.6
COM3	**Commercial:** Personal and Repair Services	1.7	8.4	31.9	83.8
COM4	**Commercial:** Professional/Technical/ Business Services	1.6	8.1	30.8	80.8
COM5	**Commercial:** Banks/Financial Institutions	1.7	8.6	32.7	86.2
COM6	**Commercial:** Hospital	1.8	8.6	32.8	86
COM7	**Commercial:** Medical Office/Clinic	1.7	8.6	32.5	85.6
COM8	**Commercial:** Entertainment & Recreation	1.8	9	34.1	90
COM9	**Commercial:** Theaters	1.7	8.8	33.4	87.8
COM10	**Commercial:** Parking	0.7	3.9	15.2	39.1
IND1	**Industrial:** Heavy	1.6	8.4	27.7	84.3
IND2	**Industrial:** Light	1.6	8.4	27.7	84.3
IND3	**Industrial:** Food/Drugs/Chemicals	1.6	8.4	27.7	84.3
IND4	**Industrial:** Metals/Minerals Processing	1.6	8.4	27.7	84.3
IND5	**Industrial:** High Technology	1.6	8.4	27.7	84.3
IND6	**Industrial:** Construction	1.6	8.4	27.7	84.3
AGR1	**Agriculture:** Agriculture	0.8	5.4	17.6	53.8
REL1	**Religion/Nonprofit:** Church/Membership Organization	1.7	8	30.6	80.2

Label	Occupancy Class	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
GOV1	**Government:** General Services	1.7	8.2	31.2	82.1
GOV2	**Government:** Emergency Response	1.7	8.5	32.2	84.7
EDU1	**Education:** Schools/Libraries	1.6	8.1	34	81.1
EDU2	**Education:** Colleges/Universities	1.8	8.9	38.7	89

7.4 Other Costs

7.4.1 Building Contents

Building contents are defined as furniture, equipment that is not integral with the structure, computers, and other supplies. Contents do not include inventory or nonstructural components such as lighting, ceilings, mechanical and electrical equipment, and other fixtures.

The cost of contents damage is calculated as follows:

Equation 7-7

$$CCD_i = CRV_i * \sum_{ds=2}^{5} CD_{ds,i} * PSBTNS_{ds,i}$$

Where:

CCD_i	is the cost of contents damage for occupancy, i
CRV_i	is the contents replacement value for occupancy, i
$CD_{ds,i}$	is the contents damage ratio for occupancy, i, in damage state ds (Table 7-3)
$PSBTNS_{ds,i}$	is the probability of occupancy, i, being in content damage state, ds

Unlike earthquake, the contents damage ratios in Table 7-3 assume that at the Complete damage state for a tsunami, contents are not salvageable. The Earthquake Model assumes a 50% salvage rate for contents in a completely damaged structure.

Table 7-3 Contents Damage Ratios (Percent of Contents Replacement Cost)

Label	Occupancy Class	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
RES1	**Residential:** Single-family Dwelling	1	5	25	100
RES2	**Residential:** Mobile Home	1	5	25	100
RES3a-f	**Residential:** Multi-family Dwelling	1	5	25	100
RES4	**Residential:** Temporary Lodging	1	5	25	100
RES5	**Residential:** Institutional Dormitory	1	5	25	100
RES6	**Residential:** Nursing Home	1	5	25	100
COM1	**Commercial:** Retail Trade	1	5	25	100
COM2	**Commercial:** Wholesale Trade	1	5	25	100
COM3	**Commercial:** Personal and Repair Services	1	5	25	100
COM4	**Commercial:** Professional/Technical/ Business Services	1	5	25	100
COM5	**Commercial:** Banks/Financial Institutions	1	5	25	100
COM6	**Commercial:** Hospital	1	5	25	100
COM7	**Commercial:** Medical Office/Clinic	1	5	25	100
COM8	**Commercial:** Entertainment & Recreation	1	5	25	100
COM9	**Commercial:** Theaters	1	5	25	100
COM10	**Commercial:** Parking	1	5	25	100
IND1	**Industrial:** Heavy	1	5	25	100

Label	Occupancy Class	Slight Damage	Moderate Damage	Extensive Damage	Complete Damage
IND2	**Industrial:** Light	1	5	25	100
IND3	**Industrial:** Food/Drugs/Chemicals	1	5	25	100
IND4	**Industrial:** Metals/Minerals Processing	1	5	25	100
IND5	**Industrial:** High Technology	1	5	25	100
IND6	**Industrial:** Construction	1	5	25	100
AGR1	**Agriculture:** Agriculture	1	5	25	100
REL1	**Religion/Nonprofit:** Church/Membership Organization	1	5	25	100
GOV1	**Government:** General Services	1	5	25	100
GOV2	**Government:** Emergency Response	1	5	25	100
EDU1	**Education:** Schools/Libraries	1	5	25	100
EDU2	**Education:** Colleges/Universities	1	5	25	100

7.4.2 Business Inventory Losses

Business inventories vary considerably with occupancy. For example, the value of inventory for a high-tech manufacturing facility would be quite different from that of a retail store. Thus, it is assumed for this model that business inventory for each occupancy class is based on annual gross sales. Since losses to business inventory most likely occur from water damage to either the inundated stacks of inventory or from earthquake shaking collapsing inventory (for a local earthquake event), it is assumed, as it was with building contents, that nonstructural damage is a good indicator of losses to business inventory. As with structural and nonstructural losses, the Slight damage state is not considered for tsunami-only damages. Business inventory losses then become the product of the total inventory value (floor area times the percent of gross sales or production per square foot) of buildings of a given occupancy in each damage state, the percent loss to the inventory, and the probability of given damage states. The business inventory losses are given by the following expressions:

Equation 7-8

$$INV_i = FA_i * SALES_i * BI_i * \sum_{i=22}^{28} INV_i$$

Equation 7-9

$$INV = INV_{12} + INV_{13} + \sum_{i=22}^{28} INV_i$$

Where:

INV_i	is the value of inventory losses for occupancy, i
INV	is the total value of inventory losses (only the AGR, COM, and IND occupancies would have inventories, so the summation includes only these occupancies)
FA_i	is the floor area of occupancy group, i (in square feet)
$SALES_i$	is the annual gross sales or production ($ per square foot) for occupancy, i (see Table 6-10 in the Hazus Inventory Technical Manual (FEMA, 2024))
BI_i	is the business inventory as a percentage of annual gross sales for occupancy, i (see Table 6-11 in the Hazus Inventory Technical Manual (FEMA, 2024))

7.4.3 Loss of Income and Wage Loss

Business activity generates several types of income. One type is income associated with capital, or property ownership. Business generates profits, and a portion of this is paid out to individuals (as well as to pension funds and other businesses) as dividends, while another portion, retained earnings, is invested back into the enterprise. Businesses also make interest payments to banks and bondholders for loans. They pay rental income on property and make royalty payments for the use of tangible assets. Those in business for themselves, or in partnerships, generate a category called proprietary income, one portion of which reflects their profits and the other that reflects an imputed salary (e.g., the case of lawyers or dentists). Finally, the biggest category of income generated/paid is associated with labor. In most urban regions of the U.S., wage and salary income comprises more than 75% of total personal income payments.

Income losses occur when building damage disrupts economic activity. Income losses are the product of floor area, income realized per square foot, and the expected days of loss of function for each damage state. Proprietor's income losses are expressed as follows:

Equation 7-10

$$YLOS_i = (1 - RF_i) * FA_i * INC_i * \sum_{ds=2}^{5} POSTR_{ds,i} * LOF_{ds}$$

Where:

$YLOS_i$ is the income losses for occupancy class, i

FA_i is the floor area of occupancy class, i (in square feet)

INCi is the income per day (per square foot) for occupancy class, i (see

Table 7-5)

$POSTR_{ds,i}$ is the probability of occupancy, i, being in structural damage state, ds

LOF_{ds} is the loss of function time for damage state, ds

RF_i is the income recapture factor for occupancy, i (see Table 7-6).

The business-related losses can be recouped to some extent by working overtime after the event, and this is shown in the recapture factor. For example, a factory that is closed for six weeks due to directly caused structural damage or indirectly caused shortage of supplies may work extra shifts in the weeks or months following its reopening. It is necessary that there be a demand for its output (including inventory buildup), but this is likely to be the case as undamaged firms try to overcome input shortages, other firms that were temporarily closed try to make-up their lost production as well, and firms outside the region press for resumption of export sales to them.

Wage losses are calculated using the same equation by substituting wages per square foot per day for income (see Table 6-15 in the *Hazus Inventory Technical Manual* (FEMA, 2024)) and replacing the income recapture factor with the wage recapture factor (see Table 6-16 in the *Hazus Inventory Technical Manual* (FEMA, 2024)).

This ability to “recapture” production will differ across industries. It will be high for those that produce durable output and lower for those that produce perishables or “spot” products (examples of the latter being utility sales to residential customers, hotel services, entertainment). Even some durable manufacturing enterprises would seem to have severe recapture limits because they already work three shifts per day; however, work on weekends, excess capacity, and temporary production facilities all can be used to make up lost sales.

The recapture factors for the economic sectors used in the direct loss module are deemed appropriate for business disruptions lasting up to three months. As lost production becomes larger, it is increasingly difficult to recapture it for both demand-side and supply-side reasons. For more advanced studies, users may choose to adjust recapture factors downward for longer disruptions. For information on where these tables are located in Hazus, see the *Hazus Tsunami Model User Guidance* (FEMA, 2024).

7.4.4 Rental Income Losses

Rental income losses are the product of floor area, rental rates per square foot, and the expected days of loss of function for each damage state. Rental income losses include residential, commercial, and industrial properties. It is assumed that a renter will pay full rent if the property is in the damage state None or Slight. Thus, rental income losses are calculated only for Moderate, Extensive, and Complete damage states. It should be noted that rental income is based upon the percentage of floor area in occupancy i that is being rented (1 - %OOi).

Equation 7-11

$$RY_i = (1 - \%OO_i) * FA_i * RENT_i * \sum_{ds=3}^{5} POSTR_{ds,i} * RT_{ds}$$

Where:

RY_i	is the rental income losses for occupancy
$\%OO_i$	is the percent owner occupied for occupancy, i (see Table 6-14 of the *Hazus Inventory Technical Manual* (FEMA, 2024))
FA_i	is the floor area of occupancy group, i (in square feet)
$RENT_i$	is the rental cost (\$/ft^2/day) for occupancy (see Table 6-13 of the *Hazus Inventory Technical Manual* (FEMA, 2024))
$POSTR_{ds,I}$	is the probability of occupancy, i, being in structural damage state, ds
RT_{ds}	is the recovery time for damage state, ds

Rental rates vary widely with region and depend on local economic conditions including vacancy rate, the desirability of the neighborhood, and the desirability of the buildings. Regional and city rental rates are published annually by various real estate information services. The percentage rates given for owner occupancy are judgmentally based. For a given Study Region, Census data will provide a more accurate measure for residential numbers.

7.4.4.1 Relocation Costs

Relocation costs may be incurred when the level of building damage is such that the building or portions of the building are unusable while repairs are being made. While relocation costs may include a number of expenses, in this model, only the disruption costs that include the cost of shifting and transferring, and the rental of temporary space are considered. It should be noted that the burden of relocation expenses is not expected to be borne by the renter. Instead, it is assumed that the building owners will incur the expense of moving their tenants to a new location. It should also be noted that a renter who has been displaced from a property due to earthquake damage would cease to pay rent to the owner of the damaged property and only pay rent to the new landlord. Therefore, the renter has no new rental expenses. It is assumed that the owner of the damaged property will pay the disruption costs for their renter. If the damaged property is owner-occupied, then the owner will have to pay for disruption costs in addition to the cost of rent while the building is being repaired.

This model assumes that it is unlikely that an occupant will relocate if a building is in the damage states None or Slight. The exceptions are some government or emergency response services that need to be operational immediately after an earthquake. However, these are considered to contribute very little to the total relocation expenses for a region and are ignored. Finally, it is assumed that entertainment, theaters, parking facilities, and heavy industry (COM8, COM9, COM10, IND1) will not relocate to new facilities. Instead, they will resume operation when their facilities have been repaired or replaced. Relocation expenses are then a function of the floor area, the rental costs per day per square foot, a disruption cost, the expected days of loss of function for each damage state, the type of occupancy, and the damage state itself. These are given by the following expression:

Equation 7-12

$$\mathrm{REL_i} = \mathrm{FA_i} * \left[\begin{array}{c} (1 - \%\mathrm{OO_i}) * \sum_{ds=3}^{5} \left(\mathrm{POSTR_{ds,i}} * \mathrm{DC_i} \right) + \\ \%\mathrm{OO_i} * \sum_{ds=3}^{5} \left(\mathrm{POSTR_{ds,i}} * (\mathrm{DC_i} + \mathrm{RENT_i} * \mathrm{RT_{ds}}) \right) \end{array} \right]$$

Where:

REL_i	is the relocation costs for occupancy class, i (i = 1-18 and 23-33) FA_i floor area of occupancy class i (in square feet)
FA_i	is the floor area of occupancy class, i (in square feet)
$POSTR_{ds,i}$	is the probability of occupancy class, i being in structural damage state, ds
DC_i	are the disruption costs for occupancy, i ($/ft^2, see the *Hazus Inventory Technical Manual* (FEMA, 2024) for more information)
RT_{ds}	**is the recovery time for damage state, ds (see** Table 7-5)
%OO	is the percent owner-occupied for occupancy, i (see the *Hazus Inventory Technical Manual* (FEMA, 2024) for more information)
$RENT_i$	is the rental cost ($/ft^2/day) for occupancy, i (see the *Hazus Inventory Technical Manual* (FEMA, 2024) for more information).

7.4.4.2 Loss of Function

The damage state descriptions provide a basis for establishing loss of function and repair time, and the Methodology distinguishes between these. Loss of function is the time that a facility is not capable of conducting business. This, in general, will be shorter than repair time because business will rent alternative space while repairs and construction are being completed. The time to repair a damaged building can be divided into two parts: construction and clean-up time, and time to obtain financing, permits, and design completion. For the lower damage states, the construction time will be close to the real repair time. At the higher damage states, a number of additional tasks must be undertaken that typically will increase the actual repair time considerably. These tasks, which may vary considerably in scope and time between individual projects, include:

- Decision-making (related to business of institutional constraints, plans, financial status, etc.)
- Negotiation with FEMA (for public and nonprofit), Small Business Administration, etc.
- Negotiation with insurance company if insured
- Obtain financing
- Contract negotiation with design firm(s)
- Detailed inspections and recommendations
- Preparation of contract documents
- Obtain building and other permits
- Bid/negotiate construction contract
- Start-up and occupancy activities after construction completion

Building repair and clean-up times are presented in Table 7-4. These times represent estimates of the median time for actual cleanup and repair, or construction. These estimates provide the basis of the values presented in

Table 7-5 that are extended to account for delays in decision making, financing, inspection, etc., as outlined above, and represent estimates of the median time for recovery of building functions used by Hazus.

Table 7-4 Building Repair and Cleanup Times (Days) by Damage State

Occupancy	None	Moderate	Extensive	Complete
AGR1	0	10	30	60
COM1	0	30	90	180
COM2	0	30	90	180
COM3	0	30	90	180
COM4	0	30	120	240

Occupancy	None	Moderate	Extensive	Complete
COM5	0	30	90	180
COM6	0	45	180	360
COM7	0	45	180	240
COM8	0	30	90	180
COM9	0	30	120	240
COM10	0	20	80	160
EDU1	0	30	120	240
EDU2	0	45	180	360
GOV1	0	30	120	240
GOV2	0	20	90	180
IND1	0	30	120	240
IND2	0	30	120	240
IND3	0	30	120	240
IND4	0	30	120	240
IND5	0	45	180	360
IND6	0	20	80	160
REL1	0	30	120	240
RES1	0	30	90	180
RES2	0	10	30	60
RES3A	0	30	120	240
RES3B	0	30	120	240
RES3C	0	30	120	240
RES3D	0	30	120	240
RES3E	0	30	120	240
RES3F	0	30	120	240
RES4	0	30	120	240
RES5	0	30	120	240
RES6	0	30	120	240

Table 7-5 Building Recovery Time (Days) by Damage State

Occupancy	None	Moderate	Extensive	Complete
AGR1	0	20	60	120
COM1	0	90	270	360
COM2	0	90	270	360
COM3	0	90	270	360
COM4	0	90	360	480
COM5	0	90	180	360

Occupancy	None	Moderate	Extensive	Complete
COM6	0	135	540	720
COM7	0	135	270	540
COM8	0	90	180	360
COM9	0	90	180	360
COM10	0	60	180	360
EDU1	0	90	360	480
EDU2	0	120	480	960
GOV1	0	90	360	480
GOV2	0	60	270	360
IND1	0	90	240	360
IND2	0	90	240	360
IND3	0	90	240	360
IND4	0	90	240	360
IND5	0	135	360	540
IND6	0	60	160	320
REL1	0	120	480	960
RES1	0	120	360	720
RES2	0	20	120	240
RES3A	0	120	480	960
RES3B	0	120	480	960
RES3C	0	120	480	960
RES3D	0	120	480	960
RES3E	0	120	480	960
RES3F	0	120	480	960
RES4	0	90	360	480
RES5	0	90	360	480
RES6	0	120	480	960

Repair times differ for similar damage states depending on building occupancy: thus, simpler and smaller buildings will take less time to repair than more complex, heavily serviced, or larger buildings. It has also been noted that large, well-financed corporations can sometimes accelerate the repair time compared to normal construction procedures.

However, establishment of a more realistic repair time does not translate directly into business or service interruption. For some businesses, building repair time is largely irrelevant, because these businesses can rent alternative space or use spare industrial/commercial capacity elsewhere. These factors are reflected in Table 7-6, which provides multipliers to be applied to the values in

Table 7-5 to arrive at estimates of business interruption for economic purposes. The factors in Table 7-4,

Table 7-5, and Table 7-6 are judgmentally derived, using ATC-13 (1985), Table 9-11 as a starting point.

The times resulting from the application of the Table 7-6 multipliers to the times shown in

Table 7-5 represent median values for the probability of business or service interruption. For None and Slight damage, the time loss is assumed to be short, with cleanup by staff, but work can resume while slight repairs are done. For most commercial and industrial businesses that suffer Moderate or Extensive damage, the business interruption time is shown as short on the assumption that these concerns will find alternate ways of continuing their activities. The values in Table 7-6 also reflect the fact that a proportion of business will suffer longer outages or even fail completely. Church and Membership Organizations generally find temporary accommodation quickly, and government offices also resume operating almost at once. It is assumed that hospitals and medical offices can continue operating, perhaps with some temporary rearrangement and departmental relocation, if necessary, after Moderate damage, but with Extensive damage their loss of function time is also assumed to be equal to the total time for repair.

For other businesses and facilities, the interruption time is assumed to be equal to, or approaching, the total time for repair. This applies to residential, entertainment, theaters, parking, and religious facilities whose revenue or continued service is dependent on the existence and continued operation of the facility.

The modifiers from Table 7-6 are multiplied by extended building construction times as follows:

Equation 7-13

$$\mathrm{LOF_{ds}} = \mathrm{BCT_{ds}} * \mathrm{MOD_{ds}}$$

Where:

LOF_{ds} is the loss of function for damage state, ds

BCT_{ds} is the extended building construction and clean up time for damage state, ds (see

Table 7-5)

MOD_{ds} are the construction time modifiers for damage state, ds (see Table 7-6)

Table 7-6 Construction Time Modifiers by Damage State

Occupancy	None	Moderate	Extensive	Complete
AGR1	0	0.05	0.1	0.2
COM1	0.5	0.1	0.3	0.4
COM2	0.5	0.2	0.3	0.4
COM3	0.5	0.2	0.3	0.4
COM4	0.5	0.1	0.2	0.3
COM5	0.5	0.05	0.03	0.03
COM6	0.5	0.5	0.5	0.5
COM7	0.5	0.5	0.5	0.5
COM8	0.5	1	1	1
COM9	0.5	1	1	1
COM10	0.1	1	1	1
EDU1	0.5	0.02	0.05	0.05
EDU2	0.5	0.02	0.03	0.03
GOV1	0.5	0.02	0.03	0.03
GOV2	0.5	0.02	0.03	0.03
IND1	0.5	1	1	1
IND2	0.5	0.2	0.3	0.4
IND3	0.5	0.2	0.3	0.4
IND4	0.5	0.2	0.3	0.4
IND5	0.5	0.2	0.3	0.4
IND6	0.5	0.2	0.3	0.4
REL1	1	0.05	0.03	0.03
RES1	0	0.5	1	1
RES2	0	0.5	1	1
RES3A	0	0.5	1	1
RES3B	0	0.5	1	1
RES3C	0	0.5	1	1
RES3D	0	0.5	1	1
RES3E	0	0.5	1	1
RES3F	0	0.5	1	1
RES4	0	0.5	1	1
RES5	0	0.5	1	1
RES6	0	0.5	1	1

Section 8. Evaluation of Building Damage

This section incorporates information from the *Tsunami Methodology Technical Manual* (FEMA, 2013) Chapter 5 evaluation of the building damage functions, including comparison to building damage ratios from previous events. FEMA (2013) Chapter 5 evaluated the Hazus Tsunami Model building damage fragility curves and corresponding economic loss ratio curves for tsunami (assuming nil earthquake damage and loss) and compares estimated values of the loss ratio with observations of building damage from recent tsunamis. The loss ratio is defined as the cost of building damage repair or replacement divided by the full replacement value of the building or subsystem of interest. Estimated values of the loss ratio are compared to observed damage since the loss ratio represents the combined effects of damage to the structural system (due to flow) and nonstructural and contents damage (due to inundation). Observations of building damage typically mix structural and nonstructural damage in the same damage state (i.e., structural damage is not clearly distinguished from nonstructural damage), making it difficult to compare individual estimates of structural, nonstructural, and contents damage with observed damage.

Estimated values of the loss ratio are expressed in terms of the depth of water above the base of the building (H) since this is the hazard parameter commonly used by post-tsunami investigations to report and evaluate observed damage to buildings. As described in FEMA (2013), building damage functions define the probability of structure damage in terms of tsunami flow (momentum flux). Equation 6-6 of FEMA P-646 (FEMA, 2012) was used to convert structure damage expressed in terms of momentum flux to structure damage expressed in terms of water depth (H). Equation 6-6 defines momentum flux in terms of inundation height (R) and an assumed height of the building above sea level datum (z), where $H = R - z$ (see Figure 5-3). The examples of this section assume the value of z to be 20 feet (above sea level datum) and use values of R without the 1.3 increase suggested by FEMA P-646 for design. Note: Estimated probabilities of structure damage and associated values of the loss ratio expressed in terms of water depth, H, could be significantly different, if the relationship between momentum flux and water depth is substantially different from that of Equation 6-6 of FEMA P-646.

Loss ratio calculations are based on the methods and economic loss rates of Section 7. Economic loss rates are 100% economic loss for Complete damage, 50% economic loss for Extensive damage and 10% economic loss for Moderate damage. These rates apply to the structure, nonstructural systems, and contents of the building. Total building economic loss assumes that the structure represents 17%, the nonstructural systems represent 50%, and contents represent 33% of total model building replacement value (i.e., replacement value including all contents). These fractions of total building replacement value are generally representative of residential and commercial buildings.

8.1 Example Building Damage Loss Curves

Figure 8-1 through Figure 8-3 show the probability of damage to the structural system, nonstructural systems, and contents, and Figure 8-4 shows the associated loss ratio curves for older, Pre-Code (PC) one-story wood buildings (W1). Similarly, Figure 8-5 through Figure 8-7 show the probability of damage to the structural system, nonstructural systems, and contents, and Figure 8-8 shows the associated loss ratio curves for older, Pre-Code (PC) five-story concrete buildings (C2M). For both specific building types, the height of the first floor above the base of the buildings (h_F) is assumed to be 3 feet, corresponding to a height of 23 feet above sea level datum ($z + h_F$). Note: These fragility curves are derived from momentum flux-based fragility curves shown in Figure 5-2.

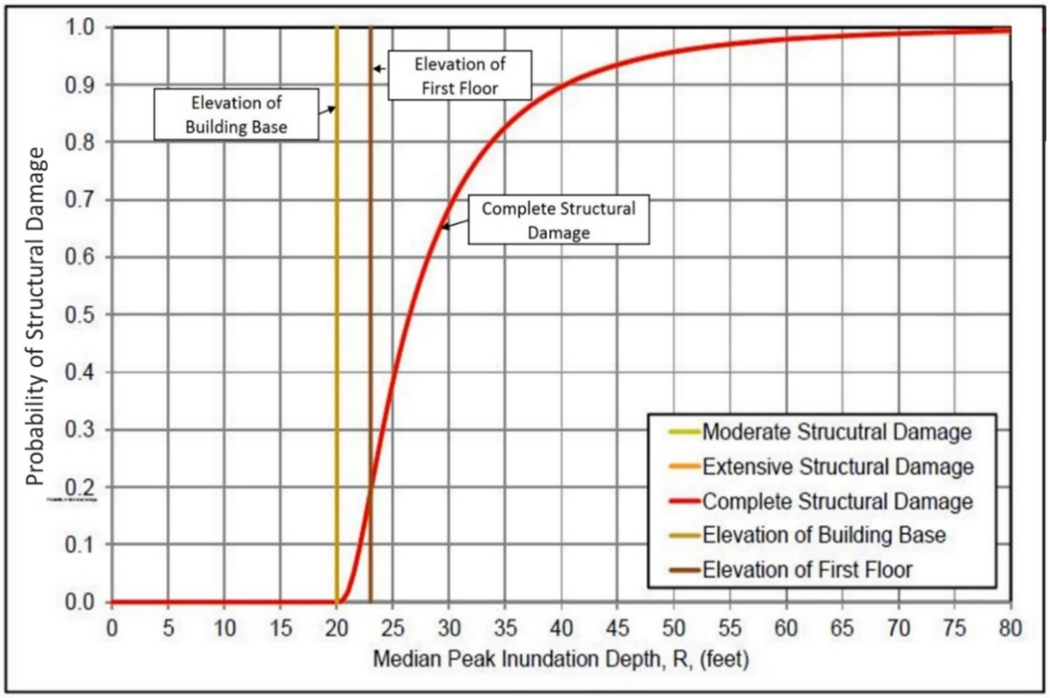

Figure 8-1 Example Fragility Curves for Structural Damage due to Tsunami Flow – Older One-Story Wood Buildings (W1 – PC)

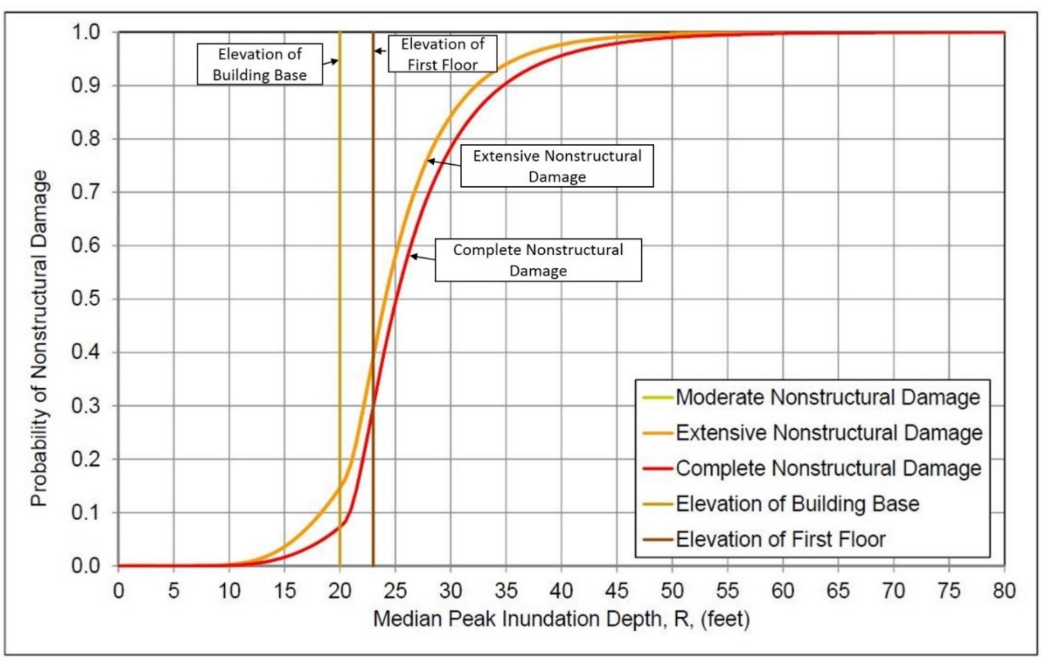

Figure 8-2 Example Fragility Curves for Structural Damage due to Tsunami Flood – Older One-Story Wood Buildings (W1 – PC)

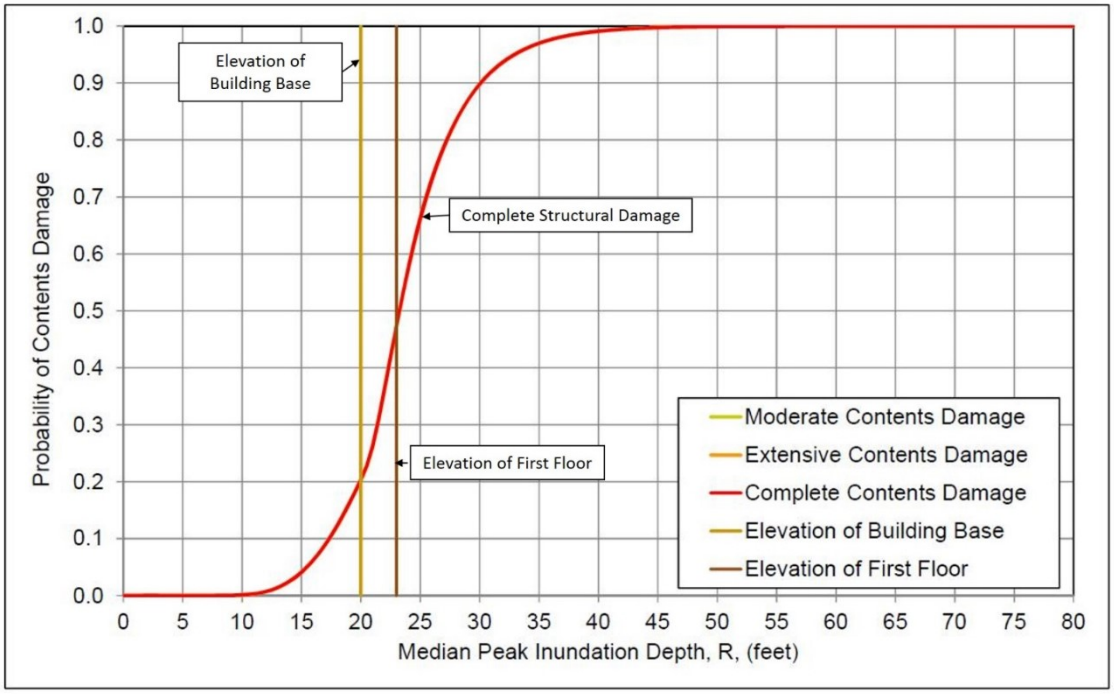

Figure 8-3 Example Fragility Curves for Contents Damage due to Tsunami Flood – Older One-Story Wood Buildings (W1 – PC)

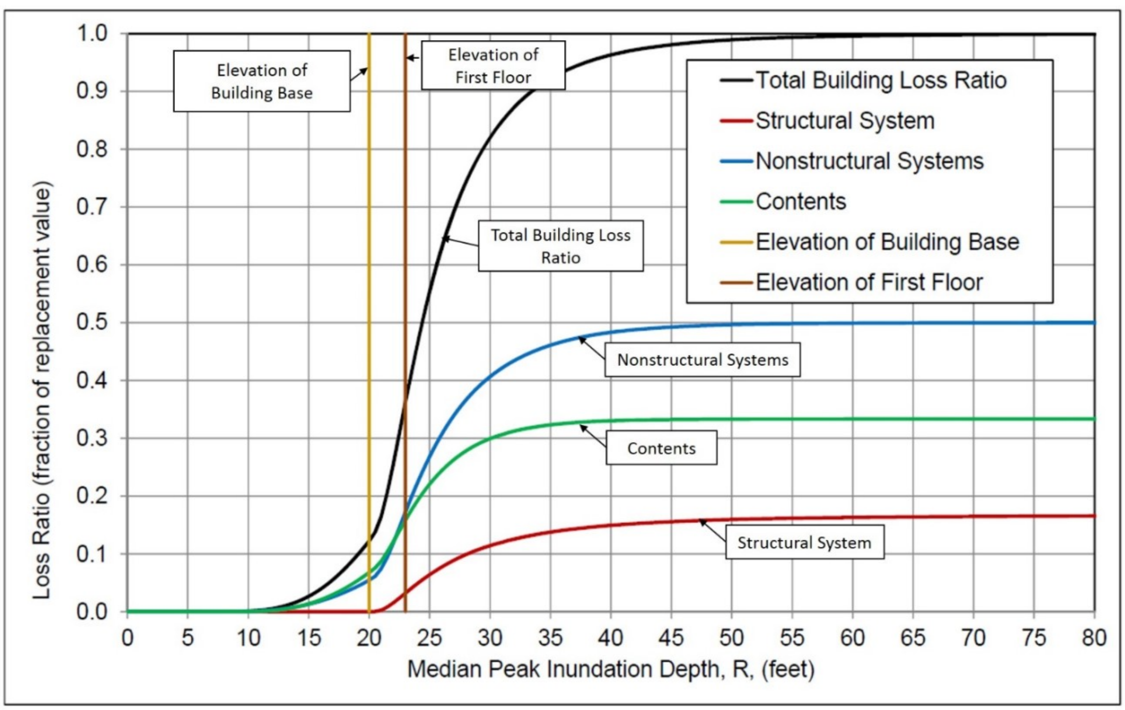

Figure 8-4 Example Loss Ratio Curves for Total Building, Structural System, Nonstructural Systems and Contents – Older One-Story Wood Buildings (W1 – PC)

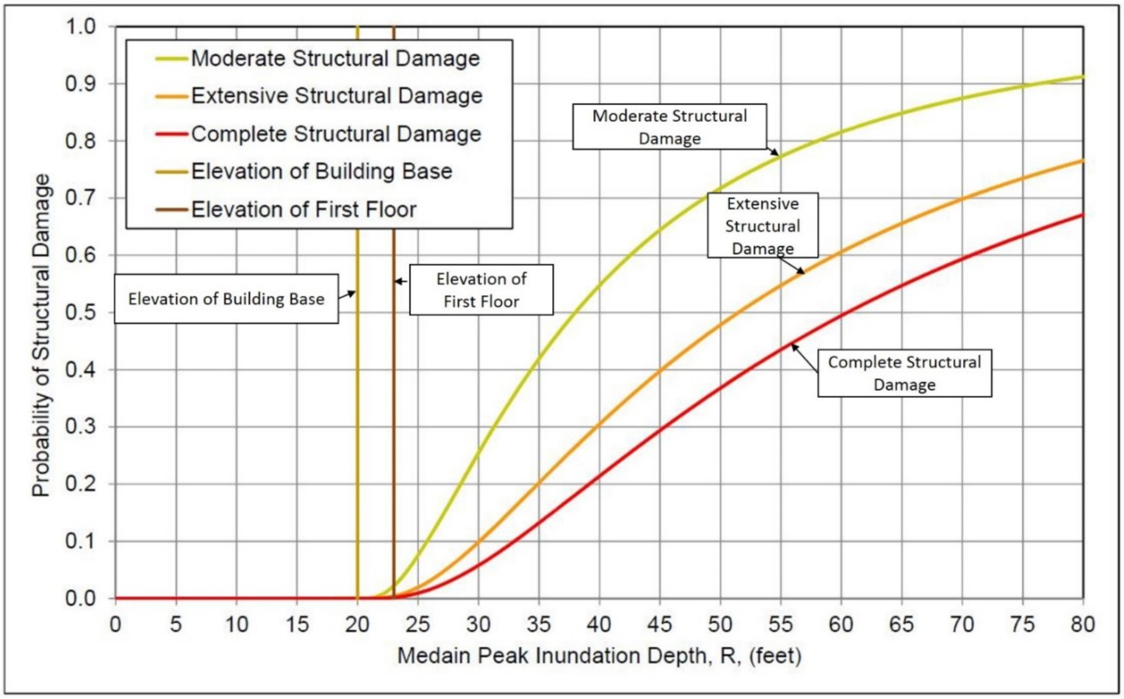

Figure 8-5 Example Fragility Curves for Structural System Damage Due to Tsunami Flow– Older Five-Story Concrete Buildings (C2M – PC)

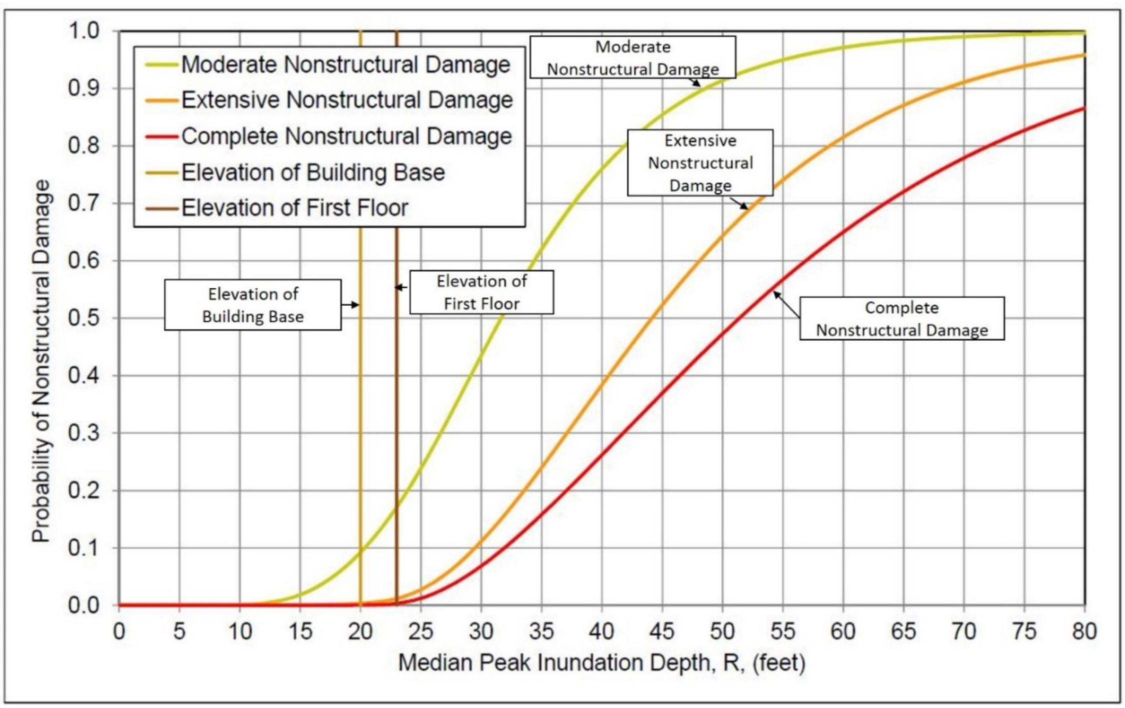

Figure 8-6 Example Fragility Curves - Probability of Nonstructural Damage Due to Tsunami Flood - Older Five-Story Concrete Buildings (C2M – PC)

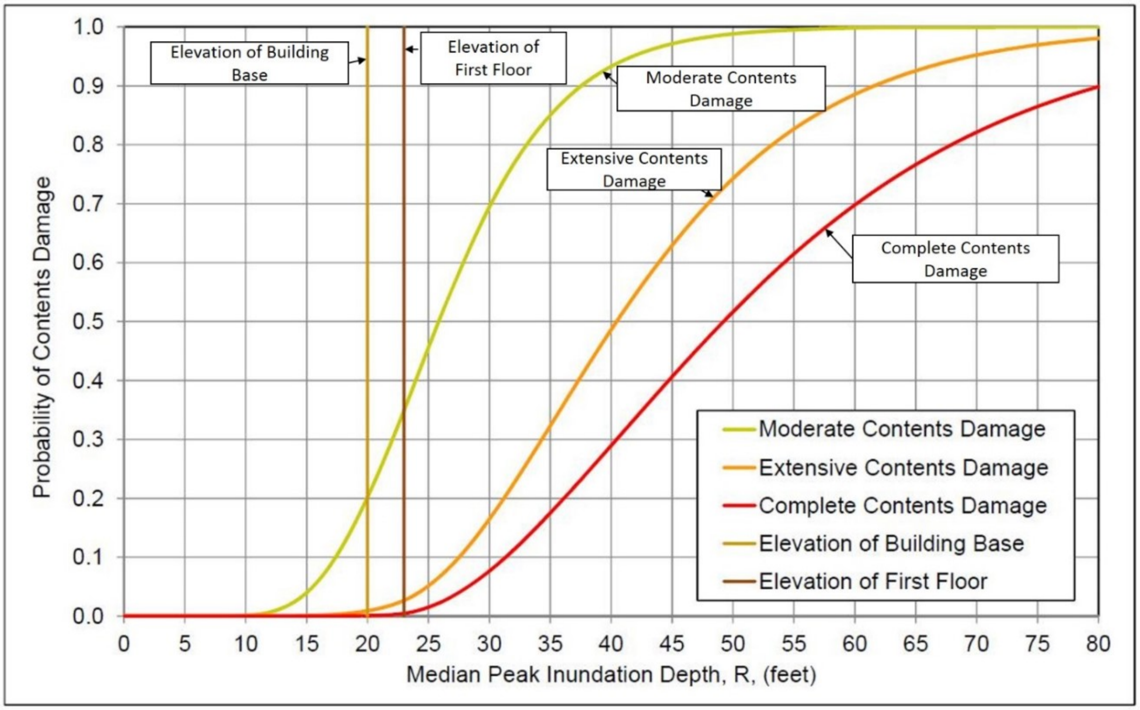

Figure 8-7 Example Fragility Curves for Contents Damage Due to Tsunami Flood – Older Five-Story Concrete Buildings (C2M – PC)

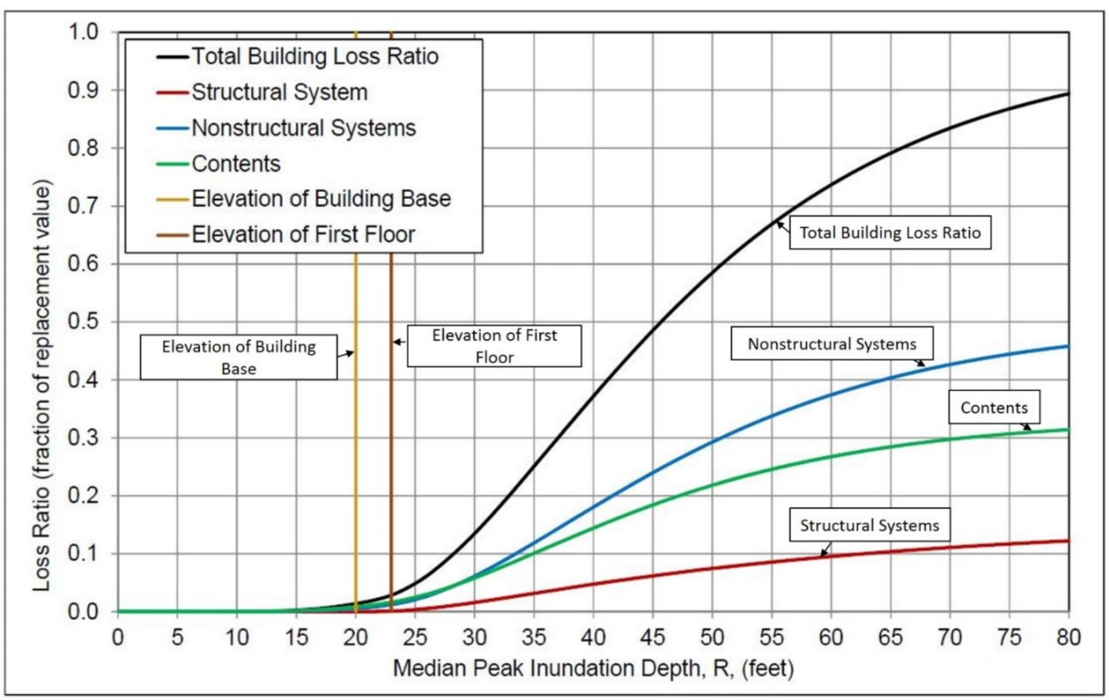

Figure 8-8 Example Loss Ratio Curves for Total Building, Structural System, Nonstructural Systems and Contents – Older Two-Story Concrete Buildings (C2L – PC)

In Figure 8-1 through Figure 8-3, fragility curves for Moderate damage and, in some cases, Extensive damage are not visible since they have the same properties as the next, more severe damage state (e.g., these curves are hidden by the Complete structural damage fragility curve in Figure 8-1). When Moderate or Extensive states are not required for the calculation of damage, their fragility values are, by definition, the same as those of the next, more severe damage state. In all cases, Slight damage is not shown since it is not used for calculation of tsunami damage and losses (i.e., presumed to have the same properties as Moderate damage).

In Figure 8-2, Figure 8-3, Figure 8-6, and Figure 8-7, the probabilities of nonstructural and contents damage incorporate the probability of Complete structural damage, in accordance with the logic and formulas of Section 5. The probability of Complete structure damage can significantly increase the probability of damage to nonstructural systems and contents of shorter buildings. For example, the nonstructural damage curves of one-story wood buildings, shown in Figure 8-2, emulate the shape of the Complete structural damage shown in Figure 8-1 (for depths of water above the base of the building).

Nonstructural and contents fragility curves shown in Figure 8-2, Figure 8-3, Figure 8-6, and Figure 8-7 incorporate flood-related hazard uncertainty assumed to be β_R = 0.3, in accordance with Equation 5-3 and structural fragility curves (prior to conversion from momentum flux to water depth) incorporate flow-related hazard uncertainty assumed to be β_F = 0.5, in accordance with Equation 5-4. The effect of incorporating hazard uncertainty is to modestly flatten fragility and loss curves and to accentuate non-zero estimates of nonstructural and contents damage and associated losses for median estimates of inundation depth at or less than the elevation of first-floor (i.e., values of $R \leq 23$ feet, in these figures). As discussed in Section 5, non-zero probabilities of damage and loss reflect the inherent uncertainty in the depth of water, that is water depth could be higher (or lower) than the estimate of the median value of inundation depth at the building of interest. Incorporation of hazard uncertainty is appropriate for estimation of damage and loss in future “scenario” earthquakes but would not be appropriate for estimation of damage and loss observed in past tsunamis for which water depths are reasonably well known.

Table 8-1 through Table 8-6 summarize the depths of water above the base of the building corresponding to loss ratios of 15% (15% LR), 50% (50% LR), and 85% (85% LR). In all cases, the base of the building is assumed to be 20 feet above sea level datum (z = 20 feet). In each table, the three loss ratios are provided for two lateral strength conditions of the specific building types: 1) building strength corresponding to modern (High-Code) construction in a high seismic region, and 2) building strength corresponding to older (Pre-Code) construction. Note: Specific building types (and depths) shown in shaded boxes with italics indicate older specific building types not permitted for use as modern construction.

The loss ratios provide a scale of tsunami consequences, ranging from significant economic loss (15% LR) and likely limited structural failures to extreme economic loss (85% LR) and likely structure failure. Since the loss ratio curves are inherently probabilistic, they never reach 100% loss. For all intents and purposes, 85% LR represents complete loss of the building, at least partial collapse, and should be considered comparable to post-event observations of tsunami damage characterized as “partial failure” or “collapse”.

Values of water depth given in Table 8-1 represent specific building types with the first floor located at 3 feet above the base of building (h_F), assume no debris impact or shielding effects (K_d = 1.0) and incorporate hazard uncertainty (β_F = 0.5 and β_R = 0.3), representing building properties that would be appropriate for evaluation of building damage due to a tsunami scenario. Water depths in Table 8-2 represent the same building conditions, except that they also include a nominal amount of debris impact (K_d = 2.0), illustrating the potential significance of debris impact on building damage and resulting losses.

Table 8-1 Water Depths Corresponding to Loss Ratios (LRs) for Specific Building Types: Above-Grade, Not Debris-Impacted, Incorporating Uncertainty

Specific Building Type	Modern High-Code Buildings			Specific Building Type	Older Pre-Code Buildings		
	15% LR	50% LR	85% LR		15% LR	50% LR	85% LR
MH	0	1	2.5	MH	0	0.5	2
W1	0.5	5.5	14	W1	0.5	4	11
URML	*1*	*6*	*14.5*	S3	0.5	4	9.5
S3	1	7	17	W2	1.5	5.5	14.5
PC1	1	9.5	23.5	URML	1	6	14.5
W2	2.5	10	24.5	PC1	1	6.5	14.5
C3L	*2*	*10*	*24.5*	S1L	2.5	10	24
S5L	*2.5*	*10.5*	*26*	C1L	2	10	24.5
C1L	2.5	14	36	C3L	2	10	24.5
S1L	3	15	37	S2L	2.5	10.5	23.5
C2L	2.5	15	38.5	S4L	2.5	10.5	24.5
PC2L	2.5	15	36.5	S5L	2.5	10.5	26
RM1L	2.5	15	37.5	PC2L	2.5	10.5	24
S2L	3	15.5	37	C2L	2.5	11	26
S4L	3	15.5	38	RM1L	2.5	11	25
RM2L	2.5	15.5	39.5	RM2L	2.5	11.5	26.5
URMM	*6.5*	*17*	*36.5*	URMM	6.5	17	36.5
S5M	*9*	*23*	*49.5*	S1M	8.5	22	48
C3M	*9*	*23*	*48.5*	S5M	9	23	49.5
C3H	*10.5*	*30*	*70.5*	C1M	9	23	48.5
S5H	*11.5*	*33*	*80.5*	C3M	9	23	48.5
C1M	13.5	33	68	PC2M	10.5	24.5	48.5
S1M	14	33.5	68.5	S2M	10.5	25	51
PC2M	14.5	34	68	S4M	10.5	25	51
C2M	14.5	34.5	71	C2M	10.5	25.5	52
RM1M	15	35	70.5	RM1M	11	25.5	51

Specific Building Type	Modern High-Code Buildings			Specific Building Type	Older Pre-Code Buildings		
	15% LR	50% LR	85% LR		15% LR	50% LR	85% LR
RM2M	15	35.5	72	RM2M	11	26.5	52.5
S2M	16	36.5	72.5	C1H	10.5	30	70.5
S4M	15.5	36.5	72.5	C3H	10.5	30	70.5
C1H	19	50.5	107.5	S1H	11	31	76.5
S1H	20	56	121.5	S5H	11.5	33	80.5
PC2H	24	58	117	PC2H	14	36.5	77.5
C2H	23.5	59	121.5	S2H	14.5	38	84.5
RM2H	24.5	60	121	S4H	14	38	85.5
S4H	25.5	65	132.5	C2H	14.5	39	85
S2H	26	65.5	131.5	RM2H	16	40.5	85

* Building types in shaded boxes with italics show specific building types that are not permitted for high-code seismic design. These are shown in table to highlight their relative ranking and damageability.

Table 8-2 Water Depths Corresponding to Loss Ratios (LRs) for Specific Building Types: Above-Grade, Debris-Impacted, Incorporating Uncertainty

Specific Building Type	Modern High-Code Buildings			Specific Building Type	Older Pre-Code Buildings		
	15% LR	50% LR	85% LR		15% LR	50% LR	85% LR
MH	0	0.5	2	MH	0	0	1
W1	0.5	4	11	W1	0.5	2.5	7.5
URML	0.5	4.5	10.5	S3	0.5	2.5	6
S3	1	5.5	12.5	W2	1	4	10
W2	2	7.5	19	PC1	0.5	4.5	11
C3L	2	8	19.5	URML	0.5	4.5	10.5
PC1	1	8	19	S1L	2	7.5	19
S5L	2	8.5	20.5	S2L	2	8	18.5
C1L	2.5	12	30	S4L	2	8	19
S1L	3	12.5	30	C1L	2	8	19.5
S2L	3	13	30	C3L	2	8	19.5
S4L	3	13	31	S5L	2	8.5	20.5
C2L	2.5	13	32	PC2L	2	8.5	19
PC2L	2.5	13	30	RM1L	2	8.5	19.5
RM1L	2.5	13	31	C2L	2	9	20.5
RM2L	2.5	13.5	32.5	RM2L	2	9	21

Specific Building Type	Modern High-Code Buildings			Specific Building Type	Older Pre-Code Buildings		
	15% LR	50% LR	85% LR		15% LR	50% LR	85% LR
URMM	5	13.5	29	URMM	5	13.5	29
S5M	6.5	17.5	40	S1M	6	16.5	38.5
C3M	7	18.5	40	S5M	6.5	17.5	40
C3H	8	22	55	C1M	7	18.5	40
S5H	8	23.5	60.5	C3M	7	18.5	40
S1M	11	28	58.5	S2M	8	19	41
C1M	11.5	28.5	58.5	S4M	7.5	19	41
PC2M	12.5	29.5	58	PC2M	8	19	39.5
C2M	12.5	30.5	61.5	C2M	8	20.5	43
RM1M	13	30.5	60.5	RM1M	8.5	20.5	41.5
S2M	13.5	31	61.5	RM2M	9	21	43.5
S4M	13	31	61.5	S1H	7.5	22	57.5
RM2M	13.5	31	62	C1H	8	22	55
C1H	14.5	40	88.5	C3H	8	22	55
S1H	15	42.5	98	S5H	8	23.5	60.5
PC2H	19	47	96.5	PC2H	10.5	27	60
C2H	19.5	50	104	S2H	10.5	27.5	63.5
S2H	19.5	51	107.5	S4H	10	27.5	64.5
S4H	19	51	108.5	C2H	11	29.5	67.5
RM2H	21	51.5	104.5	RM2H	12	31	67.5

* Building types in shaded boxes with italics show specific building types that are not permitted for high-code seismic design. These are shown in table to highlight their relative ranking and damageability.

Trends in the water depths shown in Table 8-1 and Table 8-2 are consistent with qualitative observations of tsunami damage. Taller buildings (i.e., mid-rise and high-rise specific building types) can have significant damage and economic loss (to lower floors) but are unlikely to have extensive structural damage or fail (unless tsunami inundation height is very high). It should be noted that the cost of repair of a high-rise building with a 15% LR (limited damage) is about twice the cost of replacement of a low-rise building with an 85% LR, since the high-rise building is more than 10 times larger and more valuable than the low-rise building.

Table 8-3 through Table 8-6 provide water depths for low-rise buildings based on hazard and building properties deemed to best represent observations of building damage due to a tsunami. Only low-rise specific building types are included in these tables, since low-rise buildings are the most vulnerable building types and observed damage is generally not available for taller buildings. In each of these tables, the hazard uncertainty is assumed to be nil for comparison with observed damage for which the water depth is assumed to be reasonably well known.

Table 8-3 and Table 8-4 provide values of the water-depth assuming no debris impact, which is possible, but unlikely for most buildings observed to have sustained significant damage in recent tsunamis. Table 8-3 assumes that the first floor of specific building types is 3 feet above grade (i.e., above the base of the building).

Table 8-4 assumes that the first floor of specific building types is at grade. Actual height of the first floor of buildings damaged by a tsunami is typically not reported, but likely to be somewhere between 0 feet (slab-on-grade construction) and 3 feet above grade (buildings with a crawl space). The height of the first floor is most important for water depths associated with a 15% LR, since smaller loss ratios are primarily due to damage to nonstructural components and contents. The height of the first floor is less important for water depths associated with an 85% LR, since larger losses are influenced by structural failure which is not dependent on first-floor height (i.e., force due to momentum flux is not a function of h_F). In general, the difference in water depths associated with 85% LR is not more than one foot for the same specific building type with the first floor 3 feet above grade and with the first floor at grade.

Table 8-3 Water Depths Corresponding to Loss Ratios (LRs) for Specific Building Types: Above-Grade, Not Debris-Impacted, Ignoring Uncertainty

Where: first-floors above grade (h_F = 3 ft.), not impacted by debris (K_d = 1.0) and ignoring hazard uncertainty (β_F = 0.0 and β_R = 0.0)

Specific Building Type	Modern High-Code Buildings			Specific Building Type	Older Pre-Code Buildings		
	15% LR	50% LR	85% LR		15% LR	50% LR	85% LR
MH	0.5	1	2.5	MH	0.5	0.5	1.5
W1	3	6	12.5	W1	2	5	9.5
URML	*3*	*6.5*	*12.5*	S3	2.5	5	8.5
S3	3.5	7.5	15	W2	2.5	6.5	13
PC1	4	9	21.5	URML	3	6.5	12.5
W2	4.5	10.5	22.5	PC1	3.5	7	13
C3L	*4.5*	*10.5*	*22.5*	S1L	4.5	10.5	22.5
S5L	*4.5*	*11.5*	*24*	C1L	4.5	10.5	22.5
C1L	5	14.5	33	C3L	4.5	10.5	22.5
C2L	5	15	35.5	S2L	5	11	22
S1L	5	15.5	34.5	S4L	5	11.5	23
PC2L	5	15.5	34	S5L	4.5	11.5	24
RM1L	5	15.5	34.5	C2L	4.5	11.5	24
RM2L	5	15.5	36.5	PC2L	4.5	11.5	22.5
S2L	5.5	16.5	34.5	RM1L	5	11.5	23
S4L	5.5	16.5	35.5	RM2L	5	12.5	24.5

* Building types in shaded boxes with italics show specific building types that are not permitted for high-code seismic design. These are shown in table to highlight their relative ranking and damageability.

Table 8-4 Water Depths Corresponding to Loss Ratios (LRs) for Specific Building Types: At-Grade, Debris-Impacted, Ignoring Uncertainty

Where: first-floors at grade (h_F = 0 ft.), impacted by debris (K_d = 2.0) and ignoring hazard uncertainty (β_F = 0.0 and β_R = 0.0)

Specific Building Type	Modern High-Code Buildings			Specific Building Type	Older Pre-Code Buildings		
	15% LR	50% LR	85% LR		15% LR	50% LR	85% LR
MH	0.5	1	2.5	MH	0	0.5	1.5
W1	1	4.5	11.5	W1	1	3.5	8.5
URML	*1*	*5*	*12*	S3	1	4	8
S3	1	6	14	URML	1	5	12
PC1	1	7	20.5	W2	1.5	5.5	12.5
W2	2.5	9.5	21.5	PC1	1	5.5	12
C3L	*2*	*9.5*	*21.5*	S1L	2.5	9.5	21.5
S5L	*2.5*	*10*	*23*	C1L	2	9.5	21.5
C1L	2	12.5	31.5	C3L	2	9.5	21.5
C2L	2	13	34	S2L	2.5	10	21
PC2L	2	13	32.5	S5L	2.5	10	23
RM1L	2	13	33.5	C2L	2	10	23
RM2L	2	13	35	PC2L	2	10	21
S1L	2.5	13.5	33	RM1L	2	10	22
S2L	2.5	14.5	33.5	S4L	2.5	10.5	22
S4L	2.5	14.5	34	RM2L	2	11	23.5

* Building types in shaded boxes with italics show specific building types that are not permitted for high-code seismic design. These are shown in table to highlight their relative ranking and damageability.

Table 8-5 and Table 8-6 provide values of the water depth assuming additional force on the structure due to a nominal amount of debris impact (Kd= 2.0). The effects of even a nominal amount of debris impact are significant for the lighter, low-rise structures. It is not possible to know the specific type and amount of debris, if any, which contributed to the observed building damage in past tsunamis. However, photos and videos tend to support the notion that it is more likely than not that debris impact contributed to observed building damage and loss, and likewise estimates of damage and loss to lighter buildings (W1 and W2) should include the effects of debris, even if very approximately.

Table 8-5 Water Depths Corresponding to Loss Ratios (LRs) for Specific Building Types: Above-Grade, Debris-Impacted, Ignoring Uncertainty

Where: first-floors above grade (hF = 3 ft.), impacted by debris (Kd = 2.0) and ignoring hazard uncertainty (βF = 0.0 and βR = 0.0)

Specific Building Type	Modern High-Code Buildings			Specific Building Type	Older Pre-Code Buildings		
	15% LR	50% LR	85% LR		15% LR	50% LR	85% LR
MH	0.5	0.5	1.5	MH	0	0	0.5
W1	2	5	9.5	S3	1.5	3	5.5
URML	*2.5*	*5*	*9.5*	W1	1.5	3.5	6.5
S3	3	6	11	W2	1.5	4	9
W2	3.5	8	17.5	URML	2.5	5	9.5
PC1	4	8	17	PC1	2.5	5.5	9.5
C3L	*3.5*	*8.5*	*18*	S1L	3.5	8.5	17.5
S5L	*4*	*9*	*19*	S2L	4	8.5	16.5
C1L	4.5	12.5	27.5	C1L	3.5	8.5	18
S1L	5	13	28	C3L	3.5	8.5	18
C2L	5	13.5	29.5	S4L	4	9	17.5
PC2L	5	13.5	27.5	S5L	4	9	19
S2L	5	14	28	PC2L	4	9	17.5
S4L	5	14	28.5	C2L	4	9.5	19
RM1L	5	14	28.5	RM1L	4	9.5	18
RM2L	5	14.5	30	RM2L	4.5	10	19.5

* Building types in shaded boxes with italics show specific building types that are not permitted for high-code seismic design. These are shown in table to highlight their relative ranking and damageability.

Table 8-6 Water Depths Corresponding to Loss Ratios (LRs) for Specific Building Types: At-Grade, Debris-Impacted, Ignoring Uncertainty

Where: first-floors at grade (hF = 0 ft.), impacted by debris (Kd = 2.0) and ignoring hazard uncertainty (βF = 0.0 and βR = 0.0)

Specific Building Type	Modern High-Code Buildings			Specific Building Type	Older Pre-Code Buildings		
	15% LR	50% LR	85% LR		15% LR	50% LR	85% LR
MH	0	0.5	1.5	MH	0	0	0.5
W1	1	3.5	8.5	W1	0.5	2.5	6
URML	*1*	*4*	*8.5*	S3	1	2.5	5
S3	1	4.5	10.5	W2	1	3.5	8.5
PC1	1	6	16	PC1	1	4	9

Specific Building Type	Modern High-Code Buildings			Specific Building Type	Older Pre-Code Buildings		
	15% LR	50% LR	85% LR		15% LR	50% LR	85% LR
W2	2	7.5	16.5	URML	1	4	8.5
C3L	*2*	*7.5*	*17*	S1L	2	7.5	16.5
S5L	*2*	*8*	*18*	C1L	2	7.5	17
C1L	2	11	26	C3L	2	7.5	17
S1L	2.5	11.5	27	S2L	2.5	8	16
PC2L	2	11.5	26.5	S4L	2.5	8	16.5
C2L	2	12	28	S5L	2	8	18
RM1L	2	12	27.5	PC2L	2	8	16.5
S2L	2.5	12.5	27	C2L	2	8.5	18
S4L	2.5	12.5	27.5	RM1L	2	8.5	17
RM2L	2	12.5	28.5	RM2L	2	9	18.5

* Building types in shaded boxes with italics show specific building types that are not permitted for high-code seismic design. These are shown in table to highlight their relative ranking and damageability.

8.2 Comparison of Estimated Building Loss and Observed Building Damage

Table 8-7 compares water depths based on tsunami building damage functions (estimated damage) with water depths of observed damage to buildings due to recent tsunamis (Section 8.3). Comparisons are made for Hazus specific building types for which observed tsunami damage is available for comparable types of construction. The specific building types include, light-frame wood and timber construction (W1 and W2), low-rise unreinforced masonry (URML), low-rise reinforced-concrete moment frames (C1L), low-rise reinforced-concrete shear walls (C2L), low-rise reinforced-concrete moment frames with masonry infill (C3L), and low- rise steel frames with cast-in-place concrete shear walls (S4L).

Estimated damage to the structure, nonstructural systems, and contents is characterized by water depths corresponding to an 85% loss ratio (i.e., damage requiring repair or replacement cost equal to 85% of the value of the building and contents). Loss ratio, rather than actual damage state fragility, is used in these comparisons with observed damage since it combines structural and nonstructural (and contents) damage that better represent observed damage states (which typically combine structural and nonstructural damage). Water depths corresponding to 85% loss are taken from Table 8-5 for lighter buildings (W1 and W2) which reflect some nominal amount of damage due to debris impact, and from Table 8-3 for other (heavier) buildings less susceptible to debris impact damage. Water depths are reported for both High-Code and Pre-Code model building strengths. In general, Pre-Code strength is the more appropriate of the two strengths for comparison with observed buildings damage.

Table 8-7 Comparison of Estimated and Observed Water Depths

Specific Building Type		Estimated Damage		Observed Damage		
Name	No. of Stories	High-Code Strength: 85% Loss Ratio (Table 8-3 and Table 8-5)	Pre-Code Strength: 85% Loss Ratio (Table 8-3 and Table 8-5)	2004 Indian Ocean SCHEMA Handbook (Tinti et al., 2010)	2009 Samoa Tsunami (Reese et al., 2011)	2011 Tohoku Tsunami (Suppasri et al., 2012)
W1	1	*9.5*	*6.5*	*8.5*	*5.3*	
W1	1&2					*13.5*
W2	2	*17.5*	*9.0*			*15.9*
URML	1		*12.5*	*13.0*	*8.2*	
C1L	2	33.0	*22.5*	*22.0*		
C2L	2	35.5	*24.0*		*24.0*	
C3L	2		*22.5*	*19.5*		
S4L	2	*35.5*	*23.0*	*31.0*		

Note: Shaded and italicized cells indicate the preferred strength level for comparison of water depths of estimated building damage with observed building damage. All estimated water depths are rounded to the nearest one-half foot.

Water depths of observed damage are available from the Scenarios for Hazard-induced Emergencies Management (SCHEMA) Handbook based largely on observations of building damage in Banda Aceh (Thailand) after the 2004 Indian Ocean Tsunami (Tinti et al., 2011) and from post-event surveys and evaluations of buildings damaged in American Samoa and Samoa due to the 2009 South Pacific (Samoa) Tsunami (Reese et al., 2011) and in the Miyagi and Fukushima prefectures of Japan due to the 2011 Tohoku Tsunami (Suppasri et al., 2012), as summarized in Section 8.3. Water depths are based on the damage state of each of the three sources that is deemed to best represent extreme damage corresponding to an 85% loss ratio. For all intents and purposes, 85% loss ratio represents full building loss, and likely partial or full building collapse. Accordingly, water depths were selected that correspond to the initiation of "Partial Failure" (Table 8-8), and the median values of "Collapse" damage fragility (Table 8-9 and Table 8-10). Note: Median values represent the hazard level for which 50% of the buildings would be expected to have collapsed.

As shown in Table 8-7, water depths corresponding to an 85% loss ratio (estimated damage) compare well with water depths of extreme (collapse) damage observed in recent tsunamis (observed damage).

8.2.1 Wood Specific Building Types (W1 and W2)

The 6.5 feet water depth estimated for the single-story light frame wood (W1) model building type with Pre-Code strength falls within the 5.3 feet to 8.5 feet range of water depths of observed failure and collapse of wood buildings in Banda Aceh and American Samoa/Samoa. The 9 feet (Pre-Code strength) and 17.5 feet (High-Code strength) water depths of the W2 specific building type bound the 15.9 feet water depth of observed collapse damage to mixed-use Japanese buildings. Similarly, the 9.5 feet (W1) and 17.5 feet (W2) water depths of wood buildings with High-Code strength bound the 13.5 feet water depth of observed collapse damage to one-story and two-story wooden Japanese residences.

8.2.2 Unreinforced Masonry Specific Building Type (URML)

The 12.5 feet water depth estimated for the single-story unreinforced masonry (URML) specific building type falls within the 8.2 feet to 13 feet range of water depths of observed failure and collapse of unreinforced masonry buildings in Banda Aceh and American Samoa/Samoa.

8.2.3 Reinforced-Concrete Specific Building Types (C1L, C2L, and C3L)

The 22.5 feet to 24 feet range of water depths estimated for low-rise reinforced concrete moment frame (C1L), shear wall (C2L), and frame with infill (C3L) specific building types with Pre-Code strength is essentially the same as the 19.5 feet to 24 feet range of water depths of observed failure and collapse of concrete buildings in Banda Aceh and American Samoa/Samoa.

8.2.4 Steel Frame with Concrete Shear Wall Specific Building Type (S4L)

The 23 feet (Pre-Code strength) to 35.5 feet (High-Code strength) range of water depths estimated for the low-rise steel frame with concrete shear wall specific building type bounds the 31 feet water depth of observed failure of similar construction in Banda Aceh.

8.3 Observed Building Damage Due to Tsunami – Post-Event Surveys

Post-event surveys have generated a considerable amount of information on the observed performance of buildings in recent tsunamis, and in some cases, researchers have developed damage functions (e.g., fragility curves) from observed damage. This section provides an overview of observed tsunami damage to buildings and a summary of derived fragility data, when available.

Observations of tsunami damage provide a valuable basis for a “sanity check” of the tsunami flood and flow building damage functions, but in general cannot be used directly to calibrate fragility parameters of the Hazus Tsunami Model, for the reasons discussed below.

1. *Combined Flood and Flow Damage*: Observed damage typically represents the combined effects of tsunami flood and tsunami flow and cannot be compared directly with Hazus functions that define either building damage due solely to flood or building damage due solely to flow. Further, most damaged buildings are smaller, shorter structures (e.g., one and two-story residences) for which Complete damage to the structure is dominated by tsunami force (flow effects), although observed damage to these buildings is typically expressed in terms of maximum depth of water, rather than maximum momentum flux (the hazard parameter used by the Hazus Tsunami Model to estimate damage to the structure due to tsunami flow).

2. *Maximum Water Depth:* The depth of tsunami inundation over a large, affected region can only be estimated approximately, and typically does not account for subtle, but important differences in the height of water affecting individual buildings due to likely differences in the base and/or first-floor

elevation of individual buildings. The elevation of the base and first floor are key parameters of the Hazus Tsunami Model building damage functions.

3. *Type of Construction:* Damage data are only available for buildings located outside the United States for which building design and construction may differ substantially from United States practice. The structural system (even if known) may not correspond to one of the Hazus specific building types and local building code requirements for lateral force design and are likely not the same as those of the United States (which are used to define the lateral strength of Hazus specific building types).

4. *Damage States:* Different research studies have typically used varying damage state definitions to develop fragility curves from observed data, all of which are to some degree different from the damage states of Hazus. In general, damage states of fragility curves based on observed data by others tend to mix damage to the structure with damage to nonstructural systems and contents, and express damage in terms of loss ratio (i.e., dollar loss as a fraction of replacement value). Whereas Hazus defines damage states separately for the structure, nonstructural systems, and the contents of the building in terms of the physical condition of each these building systems (e.g.,

5. Table 5-6).

The above points are made to avoid comparing the differing Hazus damage states with actual observed damage, not to suggest that actual observed damage (and loss) data should not be used to validate Hazus building damage functions for tsunami. Rather, to the extent applicable and to the degree of precision warranted by the data, the Hazus building damage functions should (and generally do) emulate actual observations of tsunami damage to buildings. For annotated summaries of papers and reports containing pertinent tsunami hazard and building damage data to the events discussed in this section, see the Appendix.

8.3.1 Building Damage Functions Derived from Observed Data

This section summarizes properties of building damage functions, including fragility curves, derived from observed damage due to the 2004 Indian Ocean Tsunami (Tinti et al., 2011), the 2009 South Pacific (Samoa) Tsunami (Reese et al., 2011), and the 2011 Tohoku Tsunami (Suppasri et al., 2012).

8.3.1.1 2004 Indian Ocean Tsunami

The "Handbook of Tsunami Hazard and Damage Scenarios," of the SCHEMA Project (Tinti et al., 2011) defines 11 building types, primarily residential and common coastal buildings, on the basis of their resistance capacity, as follows (from Table 4 of the SCHEMA handbook):

- Light construction of wood, timber, clay (A1) and rudimentary shelters (A2)
- *Unreinforced masonry:* plain brick, etc., (B1) and wooden timber/clay materials (B2)
- *Unreinforced concrete/masonry:* brick infill (C1), lava stone blocks/clay bricks (C2)
- *Unreinforced concrete:* larger residential/commercial (D)

- *Reinforced concrete (RC)/steel frame:* Up to three stories (E1), over three stories (E2)
- *Other:* Harbor, industrial, and hangar buildings (F)

For comparison with Hazus specific building types:

- *A1:* most like Hazus W1, Pre-Code strength, buildings
- *B1:* most like Hazus URML buildings
- *C1:* most like Hazus C3L, Pre-Code strength, buildings
- *D:* most like Hazus C1L, Pre-Code strength, buildings

"E1" is most like Hazus S4L, Pre-Code strength, buildings (although strength could be higher). Table 5 of the SCHEMA handbook defines five damage levels, as follows:

- *Light Damage:* No structural damage, minor nonstructural damage
- *Important Damage:* No structural damage, failure/collapse of nonstructural walls
- *Heavy Damage:* Structural damage that could affect building stability
- *Partial Failure*: Partial collapse, integrity of structure compromised
- *Collapse:* Complete collapse (washed away)

For comparison with Hazus building damage functions:

- *Important Damage:* most like Extensive/Complete nonstructural damage
- *Heavy Damage:* most like Hazus Extensive structural damage
- *Partial Failure and Collapse*: most like Hazus Complete structural damage

Table 8-8 (*from Table 6 of the SCHEMA handbook*) shows the range of water depths associated with each damage level for building classes A, B, C, D and E1. The range of water depths shown in Table 5-7 are based on damage functions derived (by the SCHEMA project) from empirical field observations collected in Banda Aceh after the December 26, 2004 Tsunami.

Table 8-8 Water Depth Range Based on Field-Observed Damage Levels Collected in Banda Aceh after 2004 Indian Ocean Tsunami

Building Type	Light	Important	Heavy	Failure	Collapse
Light Construction (A)	0 - 6	6 - 7	7 - 8.5	8.5 – 12.5	> 12.5
Unreinforced Masonry (B)	0 - 6.5	6.5 – 10	10 - 13	13 – 16.5	> 16.5
Unreinforced Concrete (C)	0 - 8	8 - 13	13 – 19.5	19.5 – 27	> 27
Unreinforced Concrete (D)	0 - 6.5	6.5 - 15	15 – 22	22 -30	> 30
RC/Steel Frame (E1)	0 - 10	10 - 20	20 - 31	31 - 41	> 41

* Taken from Table 6 of Tinti et at., 2011

8.3.1.2 2009 South Pacific (Samoa) Tsunami

The research paper, "Empirical building fragilities from observed damage in the 2009 South Pacific tsunami," (Reese, 2010) provides fragility data for masonry, concrete, and wood residential construction.

For comparison with Hazus specific building types:

- *Masonry Residential:* most like Hazus URML buildings
- *Reinforced-Concrete Residential:* most like Hazus C2L, Pre-Code strength, buildings
- *Timber (Wood) Residential:* most like Hazus W1, Pre-Code strength, buildings

Table 4 of the subject paper defines the following five damage states:

- *Light:* Nonstructural damage only
- *Minor:* Significant nonstructural, minor structural damage
- *Moderate:* Significant structural and nonstructural damage
- *Severe:* Irreparable structural damage (100% loss)
- *Collapse:* Complete structural damage

For comparison with Hazus building damage functions:

- *Minor damage:* most like Hazus Extensive nonstructural damage
- *Moderate damage*: most like Hazus Extensive structural and nonstructural damage
- *Severe and Complete damage*: most like Hazus Complete structure damage

Table 8-9 summarizes median and standard deviation values of lognormal fragility curves fit to empirical depth-damage data from the 2009 South Pacific tsunami (from Table 6, Reese et al. 2011).

Note: Residential masonry buildings are subdivided into groups representing shielded and unshielded conditions and groups with and without the effects of debris impact damage.

Table 8-9 Median Water Depths Based on Depth-Damage Data Collected in America Samoa and Samoa after the 2009 South Pacific Tsunami

Building Type	Median Water Depth (in feet) by Damage State (and logarithmic standard deviations):				
	Light	Minor	Moderate	Severe	Collapse
Generic	1.0 (0.43)	1.6 (0.49)	4.0 (0.58)	6.0 (0.62)	9.1 (0.55)
Masonry Residential	1.0 (0.46)	1.5 (0.40)	4.2 (0.35)	6.1 (0.41)	8.2 (0.40)
Shielded – Masonry Residential			4.5 (0.37)	10.2 (0.49)	12.8 (0.56)
Unshielded – Masonry Residential			3.8 (0.36)	4.7 (0.40)	7.4 (0.42)
Debris – Masonry Residential			3.0 (0.36)	4.7 (0.32)	
No Debris – Masonry Residential			4.5 (0.32)	6.4 (0.40)	
Reinforced-Concrete Residential			4.5 (0.56)	11.3 (0.54)	24 (0.93)
Timber (Wood) Residential			3.8 (0.38)	4.1 (0.40)	5.3 (0.28)

* Taken from Table 6 of Reese et at., 2011

8.3.1.3 2011 Tohoku Tsunami

The paper “Developing Tsunami Fragility Curves from the Surveyed Data of the 2011 Great East Japan Tsunami in Sendai and Ishinomaki Plains” (Suppasri et al., 2012) provides fragility data for wood residences and mixed-used occupancies.

For comparison with Hazus specific building types:

- *Wooden House (one-story):* most like Hazus W1, Moderate-Code strength, buildings
- *Wooden House (two-story):* most like Hazus W2, Moderate-Code strength, buildings
- *Mixed-Use:* most like Hazus W2, Moderate-Code strength, buildings

Table 2 of the subject paper defines the following five damage states:

- *Flood Only:* No structural damage
- *Minor:* Window is damaged, but no damage on wall

- *Moderate:* Window and one part of wall are damaged
- *Major:* Window and large part of wall are damaged
- *Collapse:* Window, wall and column are damaged

For comparison with Hazus building damage functions:

- *Major damage*: most like Hazus Extensive or Complete (W1) nonstructural damage
- *Collapse damage:* most like Hazus Complete structural damage

Table 8-10 summarizes median and standard deviation values of lognormal fragility curves fit to empirical depth-damage data from the 2011 Tohoku Tsunami (from Table 4, Suppasri et al., 2012).

Table 8-10 Median Water Depths Based on Depth-Damage Data Collected at 10 locations in Miyagi and Fukushima Prefectures Affected by the 2011 Tohoku Tsunami

Building Type	Median Water Depth (in feet) by Damage State (and logarithmic standard deviations):				
	Flood Only	Minor	Moderate	Severe	Collapse
Wooden House (One-story and Two-story, typical)	NA	7.8 (0.26)	9.3 (0.23)	12.3 (0.22)	13.5 (0.24)
Mixed-Type	NA	7.8 (0.32)	10.2 (0.32)	14.0 (0.29)	15.9 (0.29)

* Taken from Table 4 of Suppasri et at., 2011

8.3.1.4 Summary of Observed Damage

The damage ranges and fragility data based on observed damage show a wide variation building performance which cannot be explained solely on the basis of differences in the definitions of damage states and/or differences in building construction of the different regions. For example, based largely on buildings damaged in Banda Aceh by the 2004 Indian Ocean Tsunami, the SCHEMA Handbook (Tinti et al., 2011) shows over 12.5 feet of water is required to collapse light wood and timber construction (Table 8-8). In contrast, Reese et al. (2010) shows a median collapse depth of only 5.3 feet for timber (wood) residences damaged in the 2009 South Pacific (Samoa) Tsunami (Table 8-9). Finally, Suppasri et al. (2012) shows a median collapse depth of 13.5 feet for Japanese wooden houses damaged in the 2011 Tohoku Tsunami (Table 8-10). Arguably, Japanese residences are better built, on average, than similar types of wood buildings damaged in Banda Aceh and Samoa (and America Samoa), so higher water levels would be expected for collapse of Japanese residences.

One possible explanation for the wide variation in water depths observed to have caused collapse of similar types of wood construction is the likely difference in the hydrodynamic force (momentum flux) on the buildings in the areas affected by the three events. That is, the flow velocity of the water at the depth associated with collapse was likely not the same for the areas affected by each of the three tsunamis, and if substantially different could affect collapse performance of buildings characterized solely by inundation depth. The relatively low median values of collapse and other damage states of buildings in Samoa and America Samoa (Table 8-9) suggest that the water velocities in the areas where buildings were surveyed was likely greater, on average, than the water velocities in the areas of Banda Aceh (Thailand) surveyed after the 2004 Indian Ocean Tsunami, and the areas of the Miyagi and Fukushima prefectures of Japan surveyed after the 2011 Tohoku Tsunami.

Although limited to one event, detailed evaluations of damage to unreinforced masonry buildings in the 2009 Samoa Tsunami show the potential benefits of shielding provided by other building and structures, and the potential detrimental effects of debris impact. Shielding greatly reduced the likelihood of Severe damage (approximately a factor of 2 decrease in the median height of water depth for this damage state) and debris impact increased the likelihood of Severe damage (approximately a factor of 1.5 increase in the median height of water depth for this damage state).

Finally, while the observations of building damage in recent tsunamis provide a basis for a “sanity check” of Hazus building damage functions, they are not suitable for direct calibration of building fragility parameters and methods since:

- They have defined different damage states from those of Hazus (which tend to mix structural and nonstructural damage together)
- Only characterize damage in terms of water depth (rather than also considering momentum flux)
- Only apply to a limited number of Hazus specific building types

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Appendix A. Overview of Observed Building Damage in Recent Tsunamis

This section provides annotated summaries of papers and reports containing pertinent tsunami hazard and building damage data of the 2004 Indian Ocean Tsunami (Suppasri et al., 2011; Saatcioglu et al., 2006; Murty et al., 2006; Ruangrassamee et al., 2006; Tinti et al., 2011), the 2006 Java Tsunami (Reese et al., 2007), the 2009 South Pacific (Samoa) Tsunami (Robertson et al., 2010; Reese et al., 2011), and the 2011 Tohoku Tsunami (EERI 2011, MLIT 2011; Gokon et al., 2012; Suppasri et al., 2012).

2004 Indian Ocean Tsunami

Suppasri, A. S, Koshimura, F. Imamura, 2011. Developing tsunami fragility curves based on satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand, *Natural Hazards Earth System Sciences*, 11, 173-189, January 20, 2011.

> This paper summarizes development of tsunami fragility curves based on high-resolution satellite images of building damage in Thailand taken before and after the 2004 Indian Ocean Tsunami of December 26, 2004. Building damage is based on the number of buildings that have lost roofs (i.e., destroyed buildings) relative to the number of buildings in the area of interest, expressed as a function of estimated water depth, velocity, and hydrodynamic force, where values of these different hazard parameters were developed by a numerical model. Fragility curves are developed for three (undefined) damage states of RC structures, and for “structural destruction” of RC and “mixed” construction. The damage state corresponding to destruction of RC structures (height undefined) is shown as having a median inundation depth of about 5m (and about 2m for “mixed” construction).

Saatcioglu, M., Ghobarahm A., Nistor, I., 2006. Performance of Structures in Indonesia during the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami, *Earthquake Spectra,* Volume 22, No. S3, June 2006 (Oakland, CA: EERI).

> This paper summarizes reconnaissance conducted in Indonesia to investigate the effects of the December 26, 2004, earthquake and tsunami on buildings, bridges, and other physical infrastructure. The damaging effects of the tsunami were most pronounced in unreinforced masonry walls, nonengineered reinforced-concrete buildings, and low-rise timber-framed buildings. In some cases, engineered structures that survived tsunami forces showed evidence of extensive damage due to seismic forces. The majority of the seismic damage was attributed to poor design and detailing of nonductile buildings.

Murty, C.V.R., Rai, D., Jain, S., Kaushik, H., Mondal, G., and Dash, S. 2006. Performance of Structures in the Andaman and Nicobar Islands (India) during the December 2004 Great Sumatra Earthquake and Indian Ocean Tsunami, *Earthquake Spectra*, Volume 22, No. S3, June 2006 (Oakland, CA: EERI).

> This paper describes damage sustained by buildings and structures in the Andaman and Nicobar Islands area due to the earthquake and tsunami of December 26, 2004. On some islands, damage

was predominantly tsunami-related, while on others damage was primarily due to earthquake forces.

Ruangrassamee, A., Yanagisawa, H., Foytong, P., Lukkunaprasit, P., Koshimura, S., and Imamura, F. 2006. Investigation of Tsunami-Induced Damage and Fragility of Buildings in Thailand after the December 2004 Indian Ocean Tsunami, Earthquake Spectra, Volume 22, No. S3, June 2006 (Oakland, CA: EERI).

This paper describes damage to civil engineering structures, including buildings, along the west coast of southern Thailand due to the earthquake and tsunami of December 26, 2004. A database of 94 damaged reinforced-concrete buildings was developed and used to evaluate the relationship between the damage level measured by one of four structure damage states (no damage, secondary member damage, primary member damage, and collapse) and the distance of the building from the shoreline and inundation height (above the first floor).

Tinti, S., Tonini, R., Bressan, L., Armigliato, A., Gargi, A., Guillande, R., Valencia, N., and Scheer, S. 2011. Handbook of Tsunami Hazard and Damage Scenarios, SCHEMA Project, *JRC Scientific and Technical Report*s, EUR 24691 EN, 2011 (Joint Research Centre, Institute for the Protection and Security of the Citizen, Bologna, Italy).

This research report documents the results of the SCHEMA (Scenarios for Hazard- induced Emergencies Management) Project that illustrate the concepts and methods for producing tsunami scenarios, including damage functions and matrices for a number of common European building types. The report defines building types on the basis of their resistance capacity, five damage levels ranging from Light Damage to Collapse, and provides a range of flow depths for each damage level and building type derived from empirical field observations collected after the December 26, 2004 tsunami.

2006 Java Tsunami

Reese, S., Cousins, W. J., Power, W. L., Palmer, N. G., Tejakusuma, I. G., and Nurgrahadi, S., 2007. Tsunami vulnerability of buildings and people in South Java – field observation after the July 2006 Java tsunami, *Nat Hazards and Earth System Sciences*, 7, 573-589, October 15, 2007, (Copernicus Publications).

This paper describes the work of a reconnaissance team of New Zealand and Indonesian scientists who investigated the South Java area affected by the tsunami of July 17, 2006. The paper contains data acquired to calibrate models used to estimate tsunami inundation, casualty rates and damage levels. Damage ratios are estimated as a function of water depth (above floor) for four types of construction: 1) timber/bamboo, 2) brick traditional, 3) brick traditional with RC-columns, and 4) RC-frame with brick infill walls, distinguishing between “exposed” buildings, and buildings “shielded” by other buildings.

Damage ratios, defined as the (cost of repair)/(cost to replace) were derived from damage due to foundation and floor (15% of total cost), walls (50%), roof and ceiling (15%), and fittings and services (20%). At a water depth of 2 m, buildings made of timber and traditional brick (one story) had 70% to 100% loss, buildings made of traditional brick with RC columns had approximate 50% loss, when exposed, and 20% loss when shielded and buildings made of RC columns had low loss. Due to the relative valuation of building systems of this paper, these loss ratios reflect damage primarily to structural elements.

2009 South Pacific (Samoa) Tsunami

Robertson, I.N., Carden, L., Riggs, H.R., Yim, S., Young, Y.L., Paczkowski, K. and Witt, D., Reconnaissance following the September 29, 2009 tsunami in Samoa, University of Hawaii, Research Report UHM/CEE/10-01.

This report documents the work of a reconnaissance team from the University of Hawaii that investigated damage to coastal structures and buildings on Tutuila Island, American Samoa, and Upolu, Samoa due to the September 29, 2009 tsunami. The report provides descriptions and photos of typical damage to engineered and nonengineered buildings (as well as other infrastructure). The results of the survey indicate that most timber and masonry residential structures subjected to tsunami loads suffered significant damage or complete destruction. Engineered structures such as commercial buildings, schools, and churches (which are often built slightly elevated above the surrounding land) generally performed much better structurally than neighboring residential buildings.

Reese, S., Bradley, B., Bind, J., Smart, G., Power, W., Sturman, J. 2011. Empirical building fragilities from observed damage in the 2009 South Pacific tsunami, *Earth-Science Reviews*, Elsevier (National Institute of Water and Atmospheric Research).

This paper summarizes the work of a multi-disciplinary reconnaissance team that collected damage data and developed empirical fragility functions for buildings of coastal city sites in American Samoa and Samoa affected by the September 29, 2009, tsunami. Fragility functions were developed for a variety of building classes, including wood (timber) residences, masonry, and reinforced-concrete (RC) structures, including the effects of “shielding” and “entrained debris.” Fragility functions are developed solely on the basis of observed water depth due to the paucity of velocity or other hazard data.

2011 Tohoku Tsunami

EERI, 2011. The Tohoku, Japan, Tsunami of March 1, 2011: Effects on Structures, *EERI Special Earthquake Report,* Learning from Earthquakes – September 2011, (EERI: Oakland, CA).

This special earthquake report of Earthquake Engineering Research Institute (EERI) summarizes the work of the multi-disciplinary reconnaissance team of the ASCE accompanied by Japanese researchers and practitioners who visited over 45 towns and cities of the Tohoku coastline affected by the 2011 Tsunami. The report includes photos and descriptions of typical damage to buildings and other structures. A more detailed report of observations and findings is being published as an ASCE monograph (ASCE, 2012).

MLIT, 2011. Press Release, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 2011 (in Japanese).

Press release issued by the Japan Ministry of Land, Infrastructure, Transport and Tourism (MLIT) that summarizes inundation depth and building damage data (and other data) for coastal areas affected by 2011 Tohoku tsunami.

Gokon, H., and Koshimura, S., 2012. Mapping of Building Damage of the 2011 Tohoku Earthquake Tsunami in Miyagi Prefecture, Coastal Engineering Committee, Japan Society of Civil Engineers, *Coastal Engineering Journal*, Vol. 54, No. 1, March 24, 2012, (World Scientific Publishing Company: www.worldscientific.com).

This paper describes tsunami building damage for the cities of the Miyagi Prefectures affected by the 2011 Tsunami obtained from pre-event and post-event aerial photos. Buildings without roofs are classified as "Washed-away;" buildings with roofs are classified as "Surviving." The study found 47,655 (29.4%) of the 162,015 buildings in Miyagi Prefecture exposed to inundation to be Washed-away, noting that approximately one-half of the exposed buildings in the prefecture (82,754) are classified by the National Police Agency as "devastated."

Suppasri, A., Mas, E., Koshimura, S., Imai, K., Harada, K., Imahura, F., 2012. Developing Tsunami Fragility Curves from the Surveyed Data of the 2011 Great East Japan Tsunami in Sendai and Ishinomaki Plains, Coastal Engineering Committee, Japan Society of Civil Engineers, *Coastal Engineering Journal*, Vol. 54, No. 1, March 24, 2012, (World Scientific Publishing Company: www.worldscientific.com).

This paper describes field surveys of inundation depth and associated damage to buildings at 10 locations in the Miyagi and Fukushima prefectures affected by the March 11, 2011, Tsunami. Building damage was classified as either Flood only, Minor, Moderate, Major or Complete. Of the 189 buildings surveyed, 150 were wood residences, typically one story and two-story houses. Of the 150 wood residences, 57 houses (38%) had flood-only damage, 27 houses (18%) had Minor damage, 38 houses (25%) had Moderate damage, 11 houses (7%) had Major damage and 17 houses (12%) had Complete damage. The paper develops fragility functions of these damage states as a function of inundation depth and compares representative inundation depths of these damage functions with representative inundation depths of building damage due to the 2004 Indian Ocean Tsunami (Ruangrassamee et al. 2006, Suppasri et al., 2011) and the 2006 Java tsunami (Reese et al., 2007). These comparisons found that damage to wood houses surveyed in Miyagi prefecture after the 2011 tsunami to be associated with inundation depths that were roughly twice the inundation depths of previous tsunamis for comparable damage to wood residences. These findings are consistent with the observation that Japanese residential wood construction damaged in the 2011 Tohoku tsunami is generally much better built than the wood residences damaged in the 2004 Indian Ocean, 2006 Java and 2009 Samoa tsunamis.