Tsunami Loads and Effects

Guide to the Tsunami Design Provisions of ASCE 7-16

Ian N. Robertson, Ph.D., S.E.

ASCE PRESS

Tsunami Loads and Effects

Other Titles of Interest

ASCE 7 Hazard Tool. (ASCE, 2016). Delivers a quick, efficient way to look up key design parameters specified by Standards ASCE/SEI 7-10 and 7-16 through a web-based application that retrieves load data for each of seven hazards, visualizes them on a map, and generates a unified report of results. (http://ascetools.online)

***Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE/SEI 7-16** (ASCE Standard, 2016). Provides requirements for general structural design and includes means for determining dead, live, soil, flood, wind, snow, rain, atmospheric ice, tsunami, and earthquake loads and their combinations that are suitable for inclusion in building codes and other documents. A detailed commentary of explanatory and supplementary information is included. (ISBN 978-0-7844-1424-8)

***Significant Changes to the Minimum Design Load Provisions of ASCE 7-16*, by Gary Chock, P.E., D.CE.; S. K. Ghosh, Ph.D.; Michael O'Rourke, Ph.D., P.E.; and T. Eric Stafford, P.E.** (ASCE Press, 2018) Describes the revisions to the minimum design load requirements set forth in Standard ASCE/SEI 7-16. (ISBN 978-0-7844-1457-6)

***Wind Loads: Guide to the Wind Load Provisions of ASCE 7-16*, by William L. Coulbourne, P.E., and T. Eric Stafford, P.E.** (ASCE Press, 2020) Sets forth a detailed and authoritative interpretation of the wind load provisions of *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, Standard ASCE/SEI 7-16. (ISBN 978-0-7844-1526-9)

***Snow Loads: Guide to the Snow Load Provision of ASCE 7-16*, by Michael O'Rourke, Ph.D., P.E.** (ASCE Press, 2017) Supplies a detailed, authoritative explanation of the snow load provisions contained in *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, Standard ASCE/SEI 7-16. (ISBN 978-0-7844-1456-9)

***Seismic Loads: Guide to the Seismic Load Provisions of ASCE 7-16*, by Finley A. Charney, Ph.D., P.E.; Thomas F. Heausler, P.E., S.E.; and Justin D. Marshall, Ph.D., P.E.** (ASCE Press, 2020) Provides clear, authoritative explanations of the seismic design provisions contained in *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, Standard ASCE/SEI 7-16 (ISBN 978-0-7844-1550-4)

***Rain Loads: Guide to the Rain Load Provisions of ASCE 7-16*, by Michael O'Rourke, Ph.D., P.E., and Aaron R. Lewis, P.E.** (ASCE Press, 2020). Provides a comprehensive overview of the rain load provisions in *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, Standard ASCE/SEI 7-16. (ISBN 978-0-7844-4155-3)

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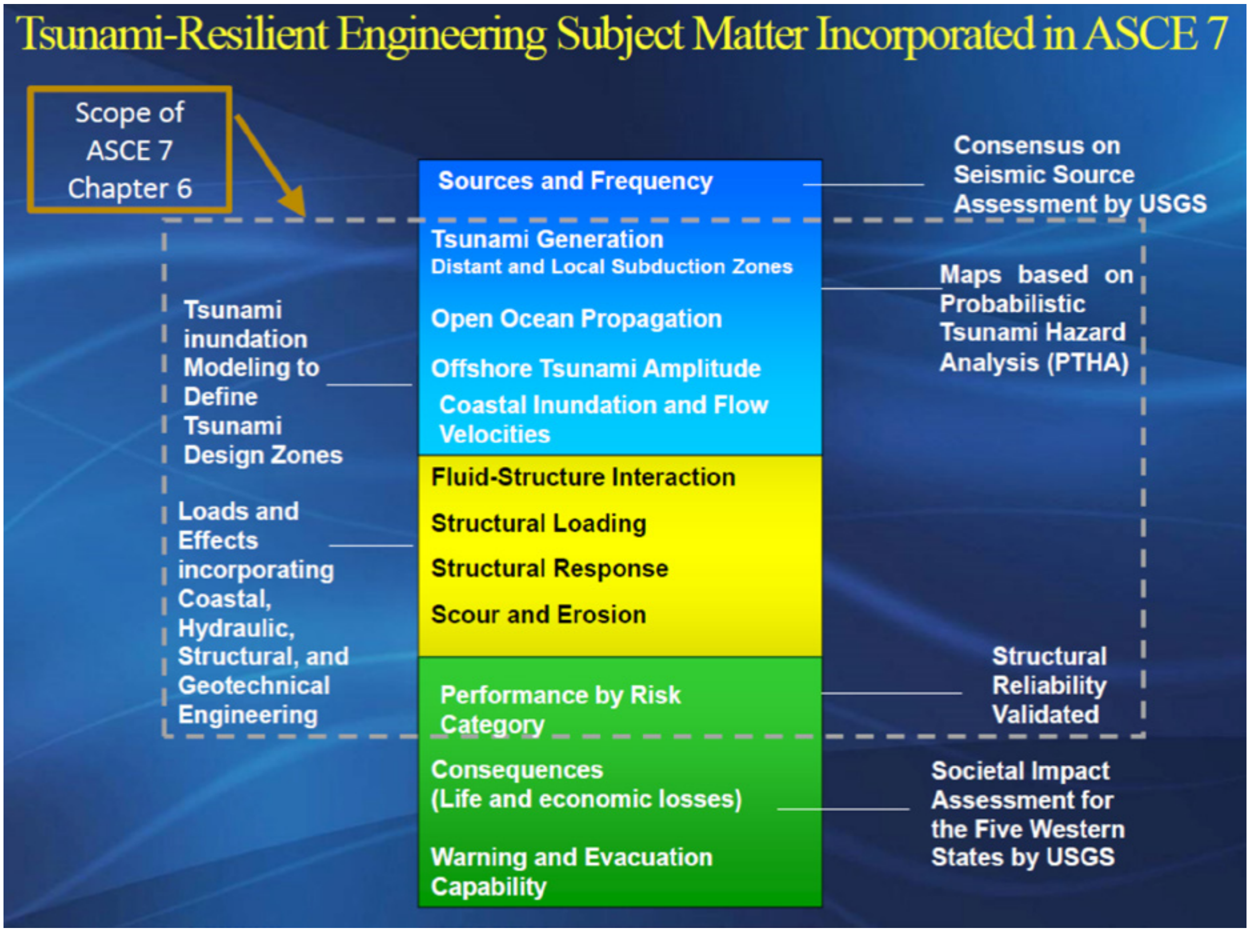
Foreword

The design of a structure to resist tsunami loads and effects should be undertaken with the most serious intent because of the very high mortality rate of tsunami events. In high tsunami hazard regions, tsunami loading on structural components can be extreme, and inundation depths can amount to tens of feet of water flowing at high velocity. As we have witnessed in past tsunamis, under such conditions people unable to leave the tsunami inundation zone almost certainly become fatalities unless they can seek refuge in robust structures of sufficient height. Therefore, when engaged in the design of any building that falls within the scope of ASCE 7-16, Chapter 6, engineers should bear in mind at all times that their work is to create the sanctuary that may be the only means of survival against otherwise nearly impossible odds. It is recommended that the beginning of every designer's involvement include meeting the community in person to emphasize this relationship. Furthermore, the design professionals should also give serious study of past events, such as the 2004 Indian Ocean tsunami and the 2011 Tohoku Japan tsunami, to gain a further understanding of the effects of tsunamis on structures; that will serve as visualization when working through the design requirements intended to defend against the many mechanisms of possible failure.

The ASCE 7 Tsunami Loads and Effects Subcommittee (TLESC) that was charged in February 2011 to develop the design requirements included experts that comprised the diversity of knowledge of seismology, probabilistic tsunami hazard analysis and inundation modeling, coastal, hydraulic, structural, and geotechnical engineering, and structural reliability analysis. The ASCE 7 tsunami design provisions are the timely culmination of more than a decade of recent engineering research, including that of the author, Ian Robertson of the University of Hawai'i, which was particularly aimed to produce practical design applications for structural loadings.

This multi-disciplinary insight was brought to bear on the reconnaissance of the March 11, 2011, Great East Japan Earthquake and Tsunami, where detailed investigations of structures were targeted based on remote sensing and nationwide damage surveys conducted immediately after the event by 300 Japanese researchers coordinated as the 2011 Tohoku Earthquake Tsunami Joint Survey Group. The ASCE tsunami reconnaissance began in April of



Tsunami-Resilient Engineering Subject Matter Incorporated in ASCE 7

Scope of
ASCE 7
Chapter 6

Sources and Frequency

Tsunami Generation
Distant and Local Subduction Zones

Open Ocean Propagation

Offshore Tsunami Amplitude

Coastal Inundation and Flow Velocities

Fluid-Structure Interaction

Structural Loading

Structural Response

Scour and Erosion

Performance by Risk Category

Consequences
(Life and economic losses)

Warning and Evacuation Capability

Tsunami inundation Modeling to Define Tsunami Design Zones

Loads and Effects incorporating Coastal, Hydraulic, Structural, and Geotechnical Engineering

Consensus on Seismic Source Assessment by USGS

Maps based on Probabilistic Tsunami Hazard Analysis (PTHA)

Structural Reliability Validated

Societal Impact Assessment for the Five Western States by USGS

2011 in collaboration with tsunami researchers mostly affiliated with Dr. Tomoya Shibayama of Waseda University and the Japan Society of Civil Engineers, Kyoto University, the Tokyo Institute of Technology, the University of Tokyo, Yokohama National University, and Saitama University. The ASCE tsunami reconnaissance team performed a series of investigations that included field measurements and material samples sufficient to comprise independent validation case examples of structural failure mechanisms for the anticipated tsunami design formulations. A second group from the University of Hawaiʻi and Oregon State University, funded by a National Science Foundation RAPID grant, used ground-based LiDAR capabilities to collect detailed three-dimensional (3D) structural data for specific structures, which were then used as input for the structural nonlinear analysis modeling that was compared against the actual structural damage and deformations.

In combination with past reconnaissance from 2005 onward conducted by members of the ASCE TLESC, the ASCE 7 tsunami design provisions were subjected to a series of structural analysis case studies together with numerical modeling and reliability analysis for validation prior to being presented for ultimate approval by the ASCE Standards Committee accredited consensus process. Subsequently, it was approved for incorporation into the 2018 International Building Code that is used as the model code for all states in the United States.

Presently, the tsunami design requirements apply to the five western states of Alaska, Washington, Oregon, California, and Hawai‘i.

The reader will find this book to be an excellent companion to ASCE 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. It is intended to provide guidance to structural engineers and other design professionals charged with an actual project. The ASCE 7-16 standard includes an extensive commentary to the provisions of Chapter 6, “Tsunami Loads and Effects.” Nevertheless, Ian Robertson has composed much needed additional discusion and design examples to explain the requirements. It would be an effective practice to refer to the ASCE 7-16 Commentary while reading this book to garner a comprehensive context to the requirements of the provisions.

As chair of the ASCE 7 Tsunami Loads and Effects Subcommittee, I commend the dedicated work of its members that resulted in the first national, consensus-based standard for tsunami-resilient design, and I particularly recommend this work of Ian Robertson that provides a truly useful design guide for practitioners engaged in the defense of our vital coastal communities and critical facilities.

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Preface

Although there have been devastating tsunamis throughout recorded history, it was the Indian Ocean tsunami of December 26, 2004, that raised the profile of tsunami research in the general population around the world. For decades, Japan had been designing and constructing coastal defensive structures to resist tsunami loads because of their long and painful history of loss of life and property due to tsunami inundation. Researchers around the world had also been studying the generation and open ocean propagation of tsunamis with the intent of improving warning systems and public awareness. However, it took the enormous loss of life and infrastructure damage caused around the Indian Ocean for other countries to take note and begin to address the tsunami hazard in earnest.

In the United States, Honolulu City and County was the only jurisdiction that required any consideration of tsunami loads and effects in the design of coastal buildings (Honolulu City & County 1984). These provisions were rather rudimentary and were based on research performed in the 1970s (Dames & Moore 1980). These provisions also lacked any tsunami hazard maps, so there were very few actual applications of the provisions. A workshop held in Tacoma, Washington, in November 2002 was one of the first attempts to include structural engineering in tsunami research in the United States (Walsh et al. 2002). A preliminary study stemming from that workshop came to the conclusion that properly engineered buildings and other structures could survive the effects of a major tsunami with damage only to nonstructural elements below the flow level (Yeh et al., 2005).

In 2004, FEMA funded a project through the Applied Technology Council of Redwood City, California, to develop *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis*. First published as FEMA P-646 in 2008, this document was updated subsequent to the Tohoku tsunami of March 11, 2011, with the second edition published in 2012 (FEMA 2012). These guidelines were written specifically for the design of designated vertical evacuation structures but made no attempt to address the general building stock. As such, the provisions could deliberately err on the conservative side without jeopardizing the cost of coastal construction in general. This document was not written in mandatory language, so it was not amenable to implementation in legally binding building codes.

Following the 2004 Indian Ocean tsunami, considerable laboratory experimentation and computational research has been funded in the United States and elsewhere. Field surveys of damaged and surviving structures after the Indian Ocean tsunami and more recent Samoa tsunami (2009) and Chile tsunami (2010) provided additional insight into fluid-structure interaction during coastal inundation resulting from tsunamis. Based on the results of this laboratory research and the post-tsunami field investigations, a group of 30 researchers and engineers collaborated to form a new ASCE 7 Tsunami Loads and Effects Subcommittee (TLESC). In February 2011, this group, under the leadership of Gary Chock, was formally accepted as a fully functioning subcommittee of ASCE 7. At the time, Standard ASCE/SEI 7-16, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, considered seismic, wind, rain, flood, snow, live, dead, and other loads, but had no provisions requiring design for tsunami loads.

Only one month later, the Great East Japan Earthquake with a moment magnitude of 9.2 generated a tsunami that devastated many communities along the northeast (Tōhoku) coast of Honshu Island, commonly referred to as the Tohoku tsunami. ASCE funded seven members of TLESC to travel to the affected areas one month after the tsunami to gather as much information as possible to aid in development of the design provisions. Analysis of buildings and other structures damaged during the Tohoku tsunami contributed significantly to the subcommittee's work on the tsunami design provisions (Chock et al. 2013a, b; Carden et al. 2015).

The TLESC worked for three and a half years to develop a draft chapter on tsunami loads and effects for incorporation in ASCE 7-16. After multiple internal subcommittee ballots, this draft chapter was submitted to the ASCE 7 Main Committee for its first ballot in July 2014. After a total of eight main committee ballots and a period for public comment, the consensus-based document of requirements and accompanying commentary was accepted into ASCE 7-16 as Chapter 6, "Tsunami Loads and Effects," on March 11, 2016, exactly five years after the Tohoku tsunami.

This guide serves as a companion document to the new ASCE 7-16, Chapter 6 on "Tsunami Loads and Effects." Since this is the first exposure to tsunami design in the United States for the majority of structural and geotechnical engineers, architects, building officials, contractors, and others involved in the building design and construction process, this companion manual was developed to guide new users through the application of tsunami design to coastal buildings and other structures. The target audience for this book is therefore structural and geotechnical engineers, architects, building officials, and others who currently use ASCE 7. It is my intent to help the reader understand the background to the code provisions while also providing clear and detailed examples demonstrating the application of the provisions to typical coastal buildings.

The examples presented in the guide often refer to sections, equations, tables, and figures in ASCE 7-16. All such items are referred to directly, without specific reference to ASCE 7-16. For instance, a specific example might contain the statement, "The illustration is provided in Table 6.12-1 of the standard."

References to sections, equations, tables, and figures that are unique to the guide are always preceded by the letter G and use bold text. For example, the text may state that the distribution of forces along the height of the structure is provided in Table G12-3 and illustrated in Figure G12-5. In this citation, the number 12 is the guide chapter number, and the number after the dash is the sequence number of the item (i.e., third table or fifth figure).

Overview of Contents

This guide describes the basis for all provisions in the new ASCE 7-16 Chapter 6 on “Tsunami Loads and Effects” and demonstrates by example how each of the provisions applies to prototypical coastal buildings. Chapter 1 of this guide provides an overview of the background for development of the tsunami design provisions in ASCE 7-16. It describes many of the observations made during past tsunamis that contributed to development of particular design provisions, as well as a brief history of the development of tsunami design in the United States. Chapter 2 introduces the prototypical buildings that are used throughout the rest of the manual as example applications of the design provisions. Chapter 3 covers the first three sections of ASCE 7-16 Chapter 6, “General Requirements, Definitions, and Symbols and Notation.” The remaining chapters of this manual are numbered to correspond to the ASCE 7-16 Chapter 6 subsections, as follows:

Chapter 4 – ASCE 7-16 Section 6.4	Tsunami Risk Categories
Chapter 5 – ASCE 7-16 Section 6.5	Analysis of Design Inundation Depth and Flow Velocity
Chapter 6 – ASCE 7-16 Section 6.6	Inundation Depths and Flow Velocities Based on Runup
Chapter 7 – ASCE 7-16 Section 6.7	Inundation Depths and Flow Velocities Based on Site-Specific Probabilistic Tsunami Hazard Analysis
Chapter 8 – ASCE 7-16 Section 6.8	Structural Design Procedures for Tsunami Effects
Chapter 9 – ASCE 7-16 Section 6.9	Hydrostatic Loads
Chapter 10 – ASCE 7-16 Section 6.10	Hydrodynamic Loads
Chapter 11 – ASCE 7-16 Section 6.11	Debris Impact Loads
Chapter 12 – ASCE 7-16 Section 6.12	Foundation Design
Chapter 13 – ASCE 7-16 Section 6.13	Structural Countermeasures for Tsunami Loading
Chapter 14 – ASCE 7-16 Section 6.14	Tsunami Vertical Evacuation Refuge Structures
Chapter 15 – ASCE 7-16 Section 6.15	Designated Nonstructural Components and Systems
Chapter 16 – ASCE 7-16 Section 6.16	Non-Building Tsunami Risk Category III and IV Structures

It is assumed that the reader has a copy of ASCE 7-16 available for reference while using this guide. References to sections and equations in ASCE 7-16 are prefaced with “ASCE 7,” whereas references to the ASCE 7-16 Commentary are prefaced with “ASCE 7 Commentary.” References without these prefaces are to sections within this guide.

Because the ASCE 7-16 Chapter 6 “Tsunami Loads and Effects” provisions are new and likely to be unfamiliar to the user, extra effort was made by the subcommittee to develop a detailed commentary. The reader is strongly encouraged to read the commentary relating to each code provision to gain a better understanding of the code requirements.

Read the Commentary!

The reader is strongly encouraged to read the ASCE 7-16 Commentary relating to each code provision to gain a better understanding of the code requirements.

Unit Conversions

US customary units	International System of Units (SI)
1 inch (in.)	25.4 millimeters (mm)
1 foot (ft)	0.3048 meter (m)
1 statute mile (mi)	1.6093 kilometers (km)
1 square foot (ft^2)	0.0929 square meter (m^2)
1 cubic foot (ft^3)	0.0283 cubic meter (m^3)
1 foot per second (ft/s)	0.3048 meter per second (m/s)
1 slug (sl) (mass)	0.4536 kilogram (kg)
1 pound (lb) (force)	4.4482 newtons (N)
1 pound per lineal foot (lb/ft, plf)	0.0146 kilonewtons per lineal meter (kN/m)
1 pound per square foot (lb/ft^2, psf)	0.0479 kilonewton per square meter (kN/m^2, kPa)
1 pound per cubic foot (lb/ft^3)	0.157 kilonewtons per cubic meter (kN/m^3)
1 slug per cubic foot (sl/ft^3)	512.6 kilograms per cubic meter (kg/m^3)

1

Introduction

1.1 Past Tsunamis

Trans-oceanic tsunamis are generated regularly by large subduction zone earthquakes. Over the last 70 years (1950–2020), 24 trans-oceanic tsunamis have occurred around the world but primarily in the Pacific Ocean (Wikipedia 2020b). All these tsunamis resulted in coastal inundation locally near the source with associated loss of life and property. Many were also large enough to result in inundation on distant shores. Most notably, the Indian Ocean tsunami caused by a 9.1-magnitude earthquake off the west coast of northern Sumatra resulted in more than 225,000 deaths in countries bordering the Indian Ocean (Wikipedia 2020c). This was a wake-up call that led to development of tsunami warning systems throughout the Pacific and Indian Oceans, as well as the Caribbean and other tsunami-prone coastlines. Subsequent damaging tsunamis affecting Samoa in 2009 (189 fatalities), Chile in 2010 (507 fatalities and $15 to $30 billion in losses), and Tohoku Japan in 2011 (more than 18,000 fatalities and approximately $360 billion in losses) (Wikipedia 2020b) reinforced the need for improved tsunami preparedness both in terms of warning systems and evacuation planning and in the form of enhanced resilience of coastal communities. By improving the performance of critical and essential facilities and all buildings that are taller than the anticipated flow depth, a coastal community can reduce the number of deaths and casualties, limit the extent of structural damage, reduce the financial losses, and facilitate more rapid recovery after a damaging tsunami.

Post-tsunami reconnaissance has gathered valuable information regarding the performance of engineered and nonengineered structures when subjected to high-velocity tsunami flow. In particular, the Tohoku tsunami demonstrated the potential devastating effects of a major tsunami on coastal communities and their economies.

During past tsunamis, most timber-framed residential structures that experienced flow depths more than 8 ft either floated or were destroyed (**Figures G1-1, G1-2, and G1-3**). Unreinforced and lightly reinforced masonry structures commonly experienced out-of-plane wall failures (**Figure G1-4**). Some reinforced concrete, reinforced masonry, and structural steel-framed buildings were also destroyed during the Tohoku tsunami (**Figures G1-5 and G1-6**).