EVACUATION PLANNING CONSIDERATIONS OF THE CITY OF HONOLULU FOR A GREAT ALEUTIAN TSUNAMI

G. Chock\textsuperscript{1} and R. Butler\textsuperscript{2}

ABSTRACT

The City and County of Honolulu is developing specific emergency evacuation route plans and updating its refuge area sites for Tsunami Warning notifications that will include the possibility of great \((M_w \geq 9)\) Aleutian earthquakes. It has become increasingly recognized that past inundation modeling for evacuations in Hawai‘i did not consider all possible sources of tsunamis. An effort is currently underway to evaluate the effects of a great earthquake on a presently quiescent section of the eastern Aleutian chain that would generate more substantial inundation that previously assumed from just the past 100 years of the historical record. Extensive study has been performed of the range of Aleutian events of \(M_w\) of 9 or greater that would significantly exceed current evacuation limits in Hawai‘i. A planning study completed in 2014 provides recommendations for evacuation route plans and tsunami evacuation signage plan for the island of Oahu, and will guide operational procedures for preparedness, response, and recovery actions to be implemented by the Honolulu Department of Emergency Management. A second “fallback” evacuation zone is being considered for this particular source region of great Aleutian earthquakes as plausible worst case tsunami scenarios for Hawai‘i. The operational consideration results in a second evacuation zone to be executed in warnings only when the Pacific Tsunami Warning Center DART and seismic-moment analyses discern this category of event in real-time. For other events of lesser magnitude from this region and all other events originating from other source regions, 2010-vintage evacuation zones would still apply. Therefore, future maps would identify the standard zone and the larger contingency evacuation extent as a second fallback line. Response planning is also underway to address community refuge area isolation due to the greater inundation of great Aleutian earthquakes.

Tsunami evacuation maps for Waikiki, Oahu also give the public an option of taking refuge in taller buildings. A baseline analysis was performed to evaluate what heights of prototypical reinforced concrete buildings could be capable of safely resisting the maximum tsunami impacting Waikiki. This analysis takes into account the past history of code criteria for Oahu multi-story buildings and typical construction practices relating to the structural systems utilized. A structural height of ten-stories or greater appears to provide the potential of sufficient strength of the lateral-load-resisting system to resist tsunami inundation in Waikiki.

\textsuperscript{1}\textit{President, Martin & Chock, Inc. Honolulu, Hawaii, USA 96734 and Chair of the ASCE 7 Tsunami Loads and Effects Subcommittee gchock@martinchock.com}
\textsuperscript{2}\textit{Director, Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i at Manoa, Honolulu, HI 96822 rgb@hawaii.edu}

Evacuation Planning Considerations of the City of Honolulu for a Great Aleutian Tsunami

G. Chock¹ and R. Butler²

ABSTRACT

The City and County of Honolulu is developing specific emergency evacuation route plans and updating its refuge area sites for Tsunami Warning notifications that will include the possibility of great ($M_w \geq 9$) Aleutian earthquakes. It has become increasingly recognized that past inundation modeling for evacuations in Hawai‘i did not consider all possible sources of tsunamis. An effort is currently underway to evaluate the effects of a great earthquake on a presently quiescent section of the eastern Aleutian chain that would generate more substantial inundation that previously assumed from just the past 100 years of the historical record. Extensive study has been performed of the range of Aleutian events of $M_w$ of 9 or greater that would significantly exceed current evacuation limits in Hawai‘i.

A planning study completed in 2014 provides recommendations for evacuation route plans and tsunami evacuation signage plan for the island of Oahu, and will guide operational procedures for preparedness, response, and recovery actions to be implemented by the Honolulu Department of Emergency Management. A second “fallback” evacuation zone is being considered for this particular source region of great Aleutian earthquakes as plausible worst case tsunami scenarios for Hawai‘i. The operational consideration results in a second evacuation zone to be executed in warnings only when the Pacific Tsunami Warning Center DART and seismic-moment analyses discern this category of event in real-time. For other events of lesser magnitude from this region and all other events originating from other source regions, 2010-vintage evacuation zones would still apply. Therefore, future maps would identify the standard zone and the larger contingency evacuation extent as a second fallback line. Response planning is also underway to address community refuge area isolation due to the greater inundation of great Aleutian earthquakes.

Tsunami evacuation maps for Waikiki, Oahu also give the public an option of taking refuge in taller buildings. A baseline analysis was performed to evaluate what heights of prototypical reinforced concrete buildings could be capable of safely resisting the maximum tsunami impacting Waikiki. This analysis takes into account the past history of code criteria for Oahu multi-story buildings and typical construction practices relating to the structural systems utilized. A structural height of ten-stories or greater appears to provide the potential of sufficient strength of the lateral-load-resisting system to resist tsunami inundation in Waikiki.

¹President, Martin & Chock, Inc. Honolulu, Hawaii, USA 96734, and Chair of the ASCE 7 Tsunami Loads and Effects Subcommittee gchock@martinchock.com
²Director, Hawai‘i Institute of Geophysics and Planetology, University of Hawai‘i at Manoa, Honolulu, HI 96822 rgb@hawaii.edu

Introduction

The Hawaiian Islands have a long history of destruction due to tsunamis and are particularly vulnerable to tsunamis originating from Alaska and Chile. Seismic regions with subduction boundaries such as Alaska and the Aleutian Islands, the countries of Chile and Japan, and Russia’s Kamchatka Peninsula, are common places of earthquakes that generate tsunamis that have affected Hawai`i in the past. The Hawaiian Islands have been subjected to large tsunamis in 1946, 1952, 1957, 1960, 1964 and 2011. Twenty-eight tsunamis with flood elevations greater than 3.3 ft (1 m) have affected the Hawaiian Islands during its short recorded history. This translates into a mean recurrence interval of one significant tsunami reaching Hawaiian shores about every 7 years [1].

The enduring lesson of recent devastating tsunamis is that historical records alone do not provide a sufficient precautionary measure of the potential runup elevations of future tsunamis. Since 2011, it has become increasingly recognized that past inundation modeling for Hawai`i have not considered all probable sources of future tsunamis [2]. In order to provide community resilience, it is not prudent to assume that only repeats of historical events will occur. In Hawai`i tsunami evacuation zone maps heretofore were essentially based just on re-created discrete historical tsunami events within the past 100 years, i.e., 1946 (Easternmost Aleutian), 1952 (Kamchatka), 1957 (Central Aleutian), 1960 (Southern Chile), and 1964 (Alaska). The past 100 years does not comprise all possible credible hazard threats; the approach taken in evaluating long-term risk is to utilize probabilistic tsunami hazard analysis. Moreover, from a conditional probability standpoint for tsunami evacuation planning for the near to intermediate timeframe, it is more likely that future subduction earthquakes will be different in location and magnitude and not identical events to those source mechanisms with tsunamigenic slip release in the recent past.

Largest Earthquake Scenarios for Worst Case Tsunami Evacuation Planning in Hawai`i

Tsunami energy is directed primarily perpendicular to the strike of the earthquake fault (e.g., Ward [3]). The largest historical tsunamis in Hawai`i were from the 1946 and 1957 Mw 8.6 earthquakes, which were focused east and west of the east Aleutian Islands, respectively (Figures 1 and 2). However, the region between these events is directionally focused at the Hawaiian Islands; and so tsunami from great earthquakes located here poses the most significant threat (Figure 3).

Butler [2] re-examined the potential for great earthquakes along the Aleutian Islands with respect to Hawai`i tsunami hazard. The Aleutian-Alaska megathrust subduction boundary between the Pacific and North American plates extends for over 3,400 km from the Alaska coast southeast of the Kenai Peninsula to the Near Islands east of Kamchatka. In the central region of this zone between the ruptures of the 1946 and 1957 great tsunamigenic earthquakes in the Aleutians, there is a ~700 km extent in the east Aleutian Islands without significant fault displacement in more than a century, which has the potential for a Mw 9.0–9.4 earthquake with a concomitant large tsunami. The tsunami travel time to Hawai`i would be no more than 4-1/2 hours after the earthquake.
Earthquakes centered on the eastern Aleutians direct substantial tsunami energy toward Hawaiʻi. For a broad range of the scenarios tested, the largest inundations in the islands were found for two basic scenarios. The first is a $M_w$ 9.29-“ab” event which concentrated large slip (a) near the trench, such as seen in the 2011 Tohoku earthquake (e.g., Shao et al. [4]), and less slip (b) further from the trench. The second basic scenario is an extended earthquake source with a $M_w$ of 9.6 from the east Aleutians through to the western edge of the 1964 Alaskan earthquake. These scenarios ($M_w$ 9.29ab and $M_w$ 9.6) are shown in Figure 4. It is perhaps not unusual that the largest tsunamis in Hawaiʻi would arise from scenarios comprised by a very broad event and one with narrow, large slip near the trench (Figure 4). The diverse and complex coasts of the Hawaiian islands interact with the tsunami. Some coasts are more affected by short wavelength tsunamis and others by longer wavelength events—this diversity is captured by the two largest scenarios.
Figure 3. Tsunami maximum ocean wave heights are shown for 4 tsunami events centered in the east Aleutians from great earthquakes with increasingly longer fault ruptures and concomitantly larger magnitudes. (The Hawaiian Islands are in the small white rectangle.)

Figure 4. Source slip characteristics of the Great Aleutian Tsunami scenarios with the most severe impact to Hawai‘i.
O‘ahu Coastal Communities Evacuation Planning Project -Planning Considerations for a Great Aleutian Tsunami (City and County of Honolulu, Hawai‘i)

In 2012, the City and County of Honolulu embarked on an enhanced Oahu Emergency Evacuation Plan to develop specific emergency evacuation route plans, with identifying refuge areas that will integrate and align with preparedness, response, and recovery actions to be implemented by the City and County of Honolulu Department of Emergency Management in the event of a Tsunami Warning notification. Hawai‘i has used tsunami evacuation zone maps since 1963; in fact, Hawai‘i was the first state to develop such maps and a comprehensive warning system after the 1960 Chile earthquake and tsunami. More recently, there have been several recent tsunamis in the Pacific that required coastal evacuations across the entire state in early February 2010 (Maule, Chile), March 2011 (Tohoku, Japan), and October 2012 (Haida Gwaii – Queen Charlotte Islands). In Hawai‘i, because of public awareness, there is a tendency for over-evacuation; that is, local residents outside of the official evacuation zones often leave as well as those within the zones. This leads to high traffic loads on highways. Based on that experience and further heeding the costly lesson of the “unexpectedly” severe inundation of the 2011 Tohoku Tsunami in Japan, where planners had discounted the possibility of very great regional megathrust slip events, Honolulu sought to improve the efficiency of evacuation routes, establish a sufficient number of viable local refuge areas able to accommodate evacuees arriving by vehicle, and to evaluate areas where post-tsunami isolation might result from highway erosion, debris, or bridge failures. The initial phase of the planning covered the coastline outside of the urban core of Honolulu because that is where evacuation routes are more limited and aligned along the coastline.

During this time, in order to evaluate the significance of Great Aleutian Tsunamis, State Civil Defense sponsored more detailed tsunami inundation analyses conducted by seismologist R. Butler of the Hawai‘i Institute of Geophysics and Planetology and tsunami modeler K. F. Cheung of the University of Hawai‘i (UH) School of Ocean Science and Technology. Also in 2012, a broad spectrum of emergency operations planners and first responder agencies considered the potential impacts of approximate tsunami inundation estimates from the preliminary analysis by R. Butler using the NOAA PMEL MOST model for an Aleutian M_w = 9.25 event.

Extensive study has been performed of the range of Aleutian events of M_w of 9 or greater that would significantly exceed current evacuation limits in Hawai‘i. Two independent tsunami simulation codes (NOAA MOST-SIFT and the UH-K. F. Cheung NEOWAVE models) were used to estimate tsunami inundation in the Hawaiian Islands from this tsunamigenic region [5]. Detailed independent analysis by the higher resolution K. F. Cheung NEOWAVE model produced similar results to inundation estimated by the MOST model. The Great Aleutian Tsunami scenarios produce greater inundation than the present-day evacuation zone maps (Figure 5). In Table 1, the difference in exposure to tsunami hazard is summarized for the present evacuation zones and for the Great Aleutian type scenarios.
Table 1. Direct Exposure of Oahu to Tsunami Hazard. (to be updated)

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Population at Direct Risk</th>
<th>Profile of Critical Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great Aleutian Tsunami</td>
<td>&gt;75,000 residents plus another 20,000 or more tourists and more than 700 buildings directly relating to the tourism industry;</td>
<td>An international airport, and 1 medium containership port, and 1 fuel refinery intake port, 1 regional power plant; ~145 government buildings $23 Billion of building inventory; 10,000 businesses with 135,000 employees</td>
</tr>
<tr>
<td>5 historical tsunami</td>
<td>~50,000 residents plus another or more 6,000 tourists</td>
<td>An international airport, 1 medium containership port, and 1 fuel refinery intake port; 28 government buildings $16 Billion of building inventory; 1,400 businesses with 21,000 employees</td>
</tr>
</tbody>
</table>

Figure 5. Inundation limits for Great Aleutian Tsunami scenarios developed by K. F. Cheung compared with the evacuation zone based on the 5 major historical events.

The planning study being completed in 2014 will provide a Geographical Information System
(GIS) -based evacuation route plan and tsunami evacuation signage plan for the island of Oahu, and will guide operational procedures for preparedness, response, and recovery actions to be implemented by the Honolulu Department of Emergency Management. A second “fallback” evacuation zone is being developed for just this particular source of great Aleutian earthquakes as plausible worst case scenarios for Hawaii. The operational consideration results in a second evacuation zone to be executed in warnings only when the Pacific Tsunami Warning Center DART and seismic-moment analyses discern this type of Mw 9 event in real-time. For other smaller events from this particular source as well as all events from other sources, 2010-vintage evacuation zones would still apply. Therefore, future maps would identify the standard zone and the larger contingency evacuation extent as a second line. There is also further planning relevant to community refuge area isolation due to the greater inundation of great Aleutian earthquakes.

**Vertical Evacuation Options in Waikiki**

Tsunami evacuation maps for Oahu give the public an option of taking refuge in buildings that are taller in height. Evacuation options for Waikiki have significant impacts on traffic planning for tsunami, since the state’s tourism resort center has an aggregate visitor lodging room count of over 40,000 as well as many high-rise condominiums and apartments that comprise an additional resident population of 23,000. Typically, such policy is predicated on the inventory having utilized high seismic design criteria that results in lateral-load-resisting systems with greater integrity and ability to accept extreme loading. However, Oahu is in a low to moderate seismic region and building codes historically adopted in Honolulu vary greatly as lateral load resisting capacity for seismic and wind effects. A baseline analysis was performed to evaluate what types of prototypical buildings could be capable of safely resisting maximum tsunamis. This analysis took into account the past history of code criteria for Oahu multi-story buildings and historical construction practices relating to the structural systems utilized for multi-story residential buildings.

Tsunami Vertical Evacuation Refuge Structures are a special use of buildings and structures within the tsunami evacuation zone providing alternative evacuation in communities where sufficiently high ground does not exist or where the time available after the tsunami warning is not deemed to be adequate for full evacuation prior to tsunami arrival. In the U.S., the Federal Emergency Management Agency published the *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis*, FEMA P-646 [7] as a set of guidelines for the siting, design, construction and operation of vertical evacuation refuges. The minimum elevation for a tsunami refuge floor level is taken as the maximum considered tsunami inundation elevation at the site determined by a site-specific inundation analysis, multiplied by 1.3, plus 1-story but not less than 10 ft, as indicated in Figure 6. The building structural height needs to provide sufficient lateral strength for the structure to withstand the hydrodynamic loadings created by the tsunami flow.

There are more than 600 significant buildings in Waikiki, but only about 190 of these are over 65 feet in height (Figure 7). The predominant proportion of these were designed and built during the time when the 1961 edition up to the 1973 edition *Uniform Building Code* applied. To examine the potential for vertical refuge use during a Great Aleutian Tsunami, prototypical reinforced concrete buildings of height greater than 65 feet within this design code regime were analyzed. (Modern buildings designed using the *International Building Code* would have about 150% to 200% more lateral strength than the typical Waikiki vintage period considered in the
Since the U.S. does not have any tsunami design requirements yet, the expected structural strength of the lateral-force-resisting system was based on the seismic design requirements of that era in Hawai‘i. Then, the prototypical building ultimate systemic strength inherently imparted by compliance with the seismic design requirements were evaluated for overall hydrostatic and hydrodynamic forces. A proposed Tsunami Loads and Effects chapter in ASCE 7-16 [6], Minimum Design Loads for Buildings and Other Structures, which would become the first national structural design provisions for tsunami resistance applicable to buildings and other structures, was utilized to develop these forces based on the flow depths determined from the K. F. Cheung NEOWAVE tsunami inundation analysis. An example of making such an evaluation is given in Chock, et al (2012) [8].

Figure 6. Tsunami Refuge Elevation Minimum Guidelines for Occupant Safety (Illustration by Chock based on the proposed ASCE 7-2016 tsunami provisions).

Figure 7. Building height distribution for Waikiki, Oahu, Hawai‘i.

In general, the structural seismic strength increases with building height (and mass),
since seismic design requirements are specified in terms of horizontal acceleration of the building mass. In other words, seismic strength of U.S. designed buildings is related to the total building weight. Tsunami hydrodynamic loads are typically related to the square of the flow depth multiplied by the building width. Accordingly, as building height increases, overall seismic strength for lateral forces eventually gains a margin over the overall tsunami lateral hydrodynamic loading. Also, as building height and mass increases, total building weight also gains a margin over hydrostatic uplift. The size and height of building necessary to acquire such a margin depends on the seismic design requirements of the location, i.e., the seismicity of the region as expressed in the seismic design standard of the code establishes the seismic strength that can be utilized against tsunami forces. This study identified the building typologies that could have the potential capacity to resist a Great Aleutian Tsunami in Waikiki, assuming the buildings strictly complied with the design code. In the case of Waikiki, it was found that the prototypical building typologies representing an average design vintage and size of the inventory started to have sufficient seismic strength at building structural heights of 10 stories or taller. Applying the guidelines of Figure 6, a reasonable minimum refuge level for Waikiki would be the 4th level or higher in reinforced concrete buildings that are 10 stories or taller.

However, tsunami loading or debris impacts on individual structural elements could still cause local failures that might initiate progressive collapse. Loads requiring specific evaluation on the individual building include hydrostatic and hydrodynamic forces on structural elements, waterborne debris impacts and flow stagnation effects on structurally enclosed areas and buoyant uplift effects on floors. Furthermore, the “picket fence” of buildings along the Waikiki shoreline modifies the tsunami flow, and may contribute to velocity-dependent scouring of building foundations from flows between buildings. Therefore, the acceptability of any proposed vertical evacuation refuge must still be based on a site-specific building evaluation of vulnerabilities. It is recommended that a standardized evaluation procedure should be developed to assess existing buildings to confirm tsunami refuge structural integrity.

Conclusions

In the aftermath of the March 11, 2011 Tohoku-Oki earthquake, a paradigm shift in emergency response and evacuation planning is developing in Hawai‘i. Rather than primarily relying on the historical events, a new effort has explored the largest potential tsunamigenic earthquakes in the Aleutian Islands that could impact Hawai‘i in about 4-1/2 hours’ time. Earthquakes centered on the eastern Aleutians direct substantial tsunami energy toward Hawai‘i. The Great Aleutian Tsunami scenarios produce greater inundation than the present-day evacuation zone maps. Such Great Aleutian Tsunami are being evaluated for updates in evacuation routing, location of refuge areas able to accommodate evacuees arriving by vehicle, and to evaluate areas where post-tsunami isolation might result from highway erosion, debris, or bridge failures. Preliminary engineering analysis of buildings in Waikiki indicate that the use of vertical evacuation refuge buildings is still a viable option that could reduce traffic issues for evacuation out of this high density urban resort area.

Acknowledgments

The work summarized in this paper was sponsored by the State Civil Defense Division of the
Hawai`i Department of Defense, the Department of Emergency Management - City and County of Honolulu, and the University of Hawai`i at Manoa - through the School of Ocean and Earth Science and Technology (SOEST) contribution no. 9038 and the Hawai`i Institute of Geophysics and Planetology (HIGP) contribution no. 2022.

References


