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Appendix G: Vulnerability of Hawaii Commercial Port

Please find supporting documentation at this link:
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Vulnerability of Hawaii Commercial Port and Harbor Facilities to Tsunamis and Hurricane Storm Surge and Wave Action

PROJECT REPORT
for
Hawaii Department of Transportation, Harbors Division

by

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This report is based on a series of field surveys performed at each of the commercial ports in Hawaii. The author wishes to thank the port managers for their willingness to provide information and time to show us their facilities and to discuss their response to hurricane and tsunami warnings. Thanks are also extended to Dr. Ron Riggs and graduate students Masoud Hayatdavoodi and Betsy Seiffert who participated in some of the field surveys. Dr. Riggs also provided useful input for this report, and reviewed the final copy.

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EXECUTIVE SUMMARY

Hurricane storm surge and wave action, and tsunami inundation, threaten all coastal areas of the Hawaiian Islands. This includes all commercial ports and harbors. Because of their remote location in the middle of the Pacific Ocean, the Hawaiian Islands are heavily dependent on their ports and harbors for delivery of essential produce to and between the islands. Closure of any of the Hawaiian commercial ports for more than a week due to storm or tsunami inundation would severely affect the health and safety of island residents and their ability to recover from the event.

This report summarizes a multi-year project to survey all commercial harbors in the State of Hawaii for their vulnerability to damage during future hurricane and tsunami events. The survey included Nawiliwili Harbor and Port Allen on Kauai, Honolulu Harbor and Kalaeloa Barbers Point Harbor on Oahu, Kahului Harbor on Maui, and Hilo and Kawaihae Harbors on Hawaii Island. Project team members met with harbor administrators of each commercial harbor to discuss current procedures for response to hurricane or tsunami warnings, and to survey the harbor facilities.

The team assessed the vulnerability of various aspects of port operations and facilities during the maximum considered hurricane and tsunami events. The scenario events considered for this assessment were a Category 4 hurricane making landfall at the worst location for each port, and a potential M_w 9.2 Great Aleutian Tsunami which would impact the State within 4 to 5 hours of the earthquake. The following are some of the more important findings and recommendations made as a result of this study.

Harbor Administration

The Harbor Administrator and all District Managers of commercial harbors in Hawaii are familiar with the potential consequences of hurricane or tsunami inundation. All harbors have procedures in place to respond to hurricane or tsunami warnings, including ship evacuation, shipping container and equipment handling, and personnel evacuation. All District Managers follow the same procedures; however, implementation of these procedures has not always gone smoothly during recent warning events.

Port Evacuation

Every effort should be made to evacuate all ships and barges to designated deep water anchor zones. Ships and barges that do not evacuate the harbor may break free from their moorings and become large floating debris. This may result in severe impact damage to piers, port facilities and neighboring structures, or sinking of the vessels in the harbor. This is particularly critical for non-seaworthy ships that are unable to leave the port.

Current ship evacuation procedures require that stevedores be available to assist with casting-off mooring lines before ships can evacuate. Pilots and tug boats are also generally required for large vessels to leave a harbor. During a hurricane warning there is generally sufficient time for these operations to run smoothly. However, if a tsunami warning occurs during non-working hours, these requirements can result in significant delays to the evacuation process.

If an evacuation is called, the decision to evacuate should not be left up to the ship captain or ship owner, and the evacuation should not be delayed in order to wait for non-essential crew members or cruise ship passengers stranded on land. Essential port personnel such as pilots and tug boat operators should have special identification passes that permit them to enter the evacuation zone during a warning. Such measures are already in place on Oahu. Activities that do not require land-based personnel, such as casting off, should be permitted under warning conditions so as to accelerate the evacuation process. Union rules governing these activities and potential liability issues will need to be addressed before a formal policy is adopted.

In order to gain a better understanding of the potential currents in selected critical ports, it is recommended that field instrumentation be developed and installed to monitor current and wave conditions during future tsunami and hurricane events. The data collected by this instrumentation could then be used to calibrate numerical models to simulate the hydrodynamic effects in the selected ports. An improved understanding of the anticipated harbor currents would allow for better decision making regarding the need to evacuate during minor or non-warning level events.

Before the all-clear can be given to allow evacuated ships and barges to re-enter the harbor, it will be necessary to verify that shipping containers and other floating debris have not sunk in the harbor channel or basin, thus reducing the available draft. Each harbor should have access to sonar or other equipment necessary to scan for sunken objects that might reduce the draft in the harbor channel or basin.

The vast majority of cargo handled by Hawaii's harbors is in the form of standard shipping containers. Whether empty or full, enclosed shipping containers will float given sufficient water levels. As large floating debris, they pose an impact hazard to cranes and other port equipment, buildings and neighboring structures. They are also likely to sink when water leaks into the container, resulting in potential loss of draft in the harbor.

Harbor procedures during a warning event should provide for evacuation of all shipping containers with hazardous materials, followed by those with livestock and perishable goods, to designated locations outside the inundation zone. Suitable locations for shipping container evacuation should be identified and Memoranda of Understanding (MOUs) should be established with the owners of each evacuation site. Harbor personnel required for shipping container evacuation should be provided with special identification passes that permit them to enter the evacuation zone during a warning. All container handling equipment that can leave the harbor should do so prior to anticipated inundation so that this equipment is available to assist with cleanup and post-event recovery.

Empty shipping containers that are left in the inundation zone will float if they are closed and the flow depth exceeds one foot. Consideration should be given to opening the doors of empty containers to avoid buoyancy forces, and restraining the containers with hold-downs or cables to prevent hydrodynamic loads from washing them into the harbor, where they would sink and reduce the available draft.

Cranes required to handle shipping containers will probably survive structurally, but water and impact damage to electrical and mechanical equipment at the base of the cranes will likely result in extended downtime. Alternative container handling procedures such as roll-on roll-off ramps, ship-mounted cranes and mobile land-based cranes may be required until the harbor cranes are repaired.

Harbor Piers, Equipment and Storage Facilities

Most existing piers are anticipated to perform well during future inundation events. However, designs of future piers should incorporate “pressure relief panels” to reduce the uplift pressures to which the piers might be subjected.

The majority of bulk handling facilities in Hawaii are located in Kalaeloa Barbers Point Harbor, while limited bulk handling operations exist at the other harbors. Potential water and debris impact damage to the mechanical and electrical components of this equipment is likely to result in considerable downtime before repairs can be made and bulk handling operations reinstated.

Fuel storage tank farms are often located within or adjacent to harbor facilities. These farms are typically surrounded by berms or walls that serve to contain fuel spills. These berms and walls will have been designed for internal hydrostatic pressure, but not necessarily for exterior hydrostatic and hydrodynamic loads that will occur during an inundation event. In addition, the height of these retention systems is controlled by the potential fuel spill, and not the anticipated exterior inundation. It is therefore to be anticipated that many of these berms or walls will be overtopped leading to potential large buoyancy uplift forces on the tanks, and potential for debris impact strikes, particularly from shipping containers that are often stored adjacent to the tank farms.

Enclosure walls that are structurally deficient or not tall enough to prevent overtopping during a design hurricane or tsunami event should be considered for strengthening or replacement. The addition of rock-fall protective fences to the top of structurally sound enclosure walls and berms could be considered as a measure to prevent debris (particularly shipping containers) from entering the fuel storage enclosure and damaging the tanks and piping. Fuel storage tanks should be kept as full as practical so as to reduce buoyancy forces if water overtops the protective wall or berm. Alternative fuel storage facilities outside of the inundation zone should be identified as backup supplies if the port fuel facilities are damaged or rendered inoperable.

Harbor Buildings and Adjacent Critical Facilities

No critical operations or equipment should be housed in substandard harbor buildings that are not expected to survive a design level hurricane or tsunami. Essential and critical buildings such as the Honolulu Harbor control tower, the HDOT harbors division Emergency Operations Center building on Pier 2, Matson control tower on Sand Island, and other buildings that will remain occupied during a warning event, must be evaluated structurally to ensure that they can withstand the anticipated hydrodynamic and debris impact loads. Important warehouse and other harbor buildings that are required to survive with only non-structural damage should be evaluated structurally.

Power plants located adjacent to Kahului and Honolulu harbors should be evaluated for their exposure to impact damage from floating shipping containers and other debris. Sand Island Wastewater Treatment plant should be evaluated for its ability to survive a design level hurricane or tsunami without resulting in sewage spills that could endanger rescue and recovery personnel.

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1 INTRODUCTION

Ports and harbors are of necessity built at sea level, making them particularly susceptible to damage due to tsunami wave loading, and hurricane storm surge and wave action. This report was developed on behalf of the Hawaii Department of Transportation as a preliminary overview of the vulnerability of Hawaii's commercial ports and harbors to damage during future tsunami and hurricane events.

The study involved site visits to all commercial ports in the Hawaiian Islands, and meetings with port administrators. Current port procedures in the event of a hurricane or tsunami warning were reviewed and evaluated in light of past experience during the 2010 Chile Tsunami, 2011 Japan Tohoku Tsunami, and Hurricane Iselle in 2014.

Potential hazards were considered during the field surveys and are summarized in this report. These include the potential impact damage from ships and other vessels in the harbor during the event, hazardous spills and impact damage from shipping containers, loss of draft due to sunken debris, and potential oil spills and fires due to damage to fuel storage facilities. The survey also included evaluations of bulk handling equipment, harbor piers, cranes, and buildings.

Chapter 2 of this report presents background information including damage caused to port facilities elsewhere in the US and around the World during past hurricane and tsunami events. Chapter 3 presents the hurricane and tsunami hazards that are considered in the evaluation of Hawaiian ports. Chapter 4 presents the observations made during visits to each of the seven commercial ports and harbors in the Hawaiian Islands, while Chapter 5 provides a summary, conclusions and recommendations based on these surveys.

2 BACKGROUND AND LITERATURE REVIEW

Considerable damage has been caused to port and harbor facilities during past hurricanes and tsunamis. The predominant damage to port facilities during past hurricanes has been due to storm surge and wave action, rather than the high speed winds. Tsunami waves have caused significant damage to ports and harbors throughout human history. Literally meaning “harbor wave”, damaging tsunamis have affected numerous ports and harbors during recent tsunamis in the Pacific Ocean.

This introduction discusses typical damage observed at port facilities during Hurricane Sandy in October 2012, Hurricane Katrina in September 2005, the Samoa Tsunami on September 29, 2009, the Chile Tsunami on February 27, 2010, and the Tohoku Tsunami in Japan on March 11, 2011. Similar damage during earlier tsunami and hurricane events is also presented, particularly where it relates to likely performance of current Hawaii port facilities.

2.1 Significant Past Hurricanes and Tsunamis

2.1.1 Hurricane Sandy

Hurricane Sandy caused “an extraordinary 14-foot storm surge into the Port of New York and New Jersey and surrounding communities” as it approached the northeast coast of the US in late October, 2012 (Sturgis et al. 2014). “The water swelled over the piers and quays, causing oil and hazardous materials incidents, sweeping debris into shipping channels and severely damaging 180 commercial waterfront facilities. Corrosive saltwater flooded the operations centers of marine terminals, destroying computers, security cameras, power transformers and cargo control systems. Crude oil refineries, bulk-oil holding facilities, and containership and passenger vessel terminal operations all came to a halt” (Sturgis et al. 2014).

In order to mitigate the effects of this storm, the US Coast Guard activated the Marine Transportation System Recovery Unit (MTS-RU) two days prior to the storm arrival. The ports were closed to marine traffic 24 hours before anticipated landfall, and all large commercial ships, including cruise ships, went to sea to weather the storm. Smaller vessels that remained in port had crew onboard to avoid having vessels swept onshore or grounded. Hurricane Sandy’s storm surge and wave action also damaged oil storage tanks and piping, resulting in approximately 500,000 gallons of heavy fuel oil being released into a local waterway (Sturgis et al. 2014).

According to Sturgis, et al. (2014), “the backbone of port recovery efforts was the MTS-RU, which worked successfully … because it relied on longstanding working relationships and trust … between members of the port community.”

2.1.2 Hurricane Katrina

Hurricane Katrina made landfall on the coastline of the Gulf of Mexico on August 29^{th}, 2005, as a category 3 hurricane, affecting the coastline from New Orleans, Louisiana, to Mobile, Alabama. Because of the local bathymetry and shape of the coastline, as well as the extended period as a category 5 hurricane over the Gulf of Mexico, the resulting storm surge exceeded 25 feet in some locations. Wind-driven waves on top of this storm surge added to the considerable damage caused to coastal buildings and other structures by hydrodynamic effects (Robertson, *et al*. 2006, 2007; FEMA 549, 2006; Mosqueda and Porter, 2007). In addition to considerable damage to communities all along the affected coastline, Gulfport Harbor suffered major damage due to hydrodynamic loading (Figure 2-1).

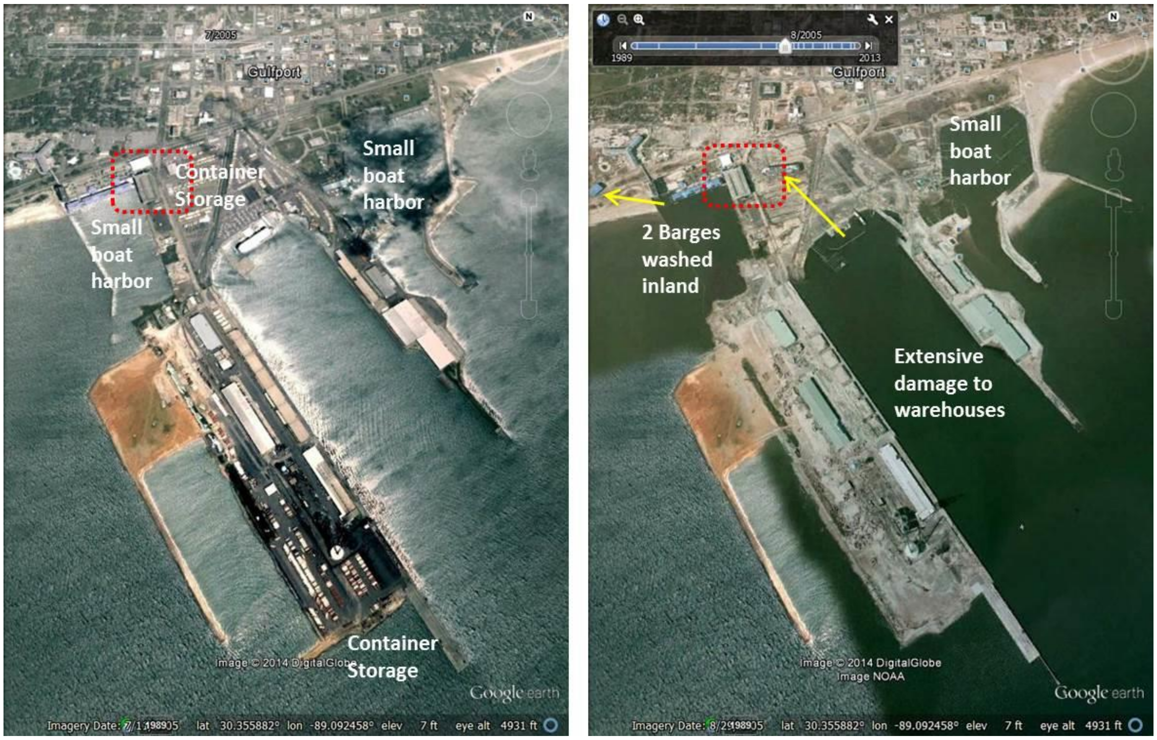

Figure 2-1: Google Earth images of Gulfport Harbor before (left) and after (right) Hurricane Katrina

2.1.3 Samoa Tsunami

The September 29th, 2009 tsunami affecting Samoa and American Samoa caused extensive damage in the main port of Pago Pago, American Samoa (Robertson, *et al.* 2010). This event was triggered by a magnitude 8.1 earthquake south of the Samoan Islands. Most of the damage occurred on the south shores of the island chain, but considerable wrap around damage was observed on east, west and even north shorelines of American Samoa.

2.1.4 Chile Tsunami

On February 27th, 2010 a magnitude 8.8 earthquake off the central coast of Chile caused a near source tsunami that resulted in considerable damage to the port of Talcahuano (EERI, 2010; Olsen, *et* al. 2012; Robertson, *et al*. 2012). Numerous coastal towns were also severely damaged by tsunami inundation. Figure 2-2 and Figure 2-3 show Google Earth images before and after the Chile Tsunami. Because the earthquake that caused the tsunami occurred at 3:34AM local time, very few of the ships in these harbors were able to evacuate. This resulted in numerous ships damaged, washed onshore, or sunk in the harbor basins.

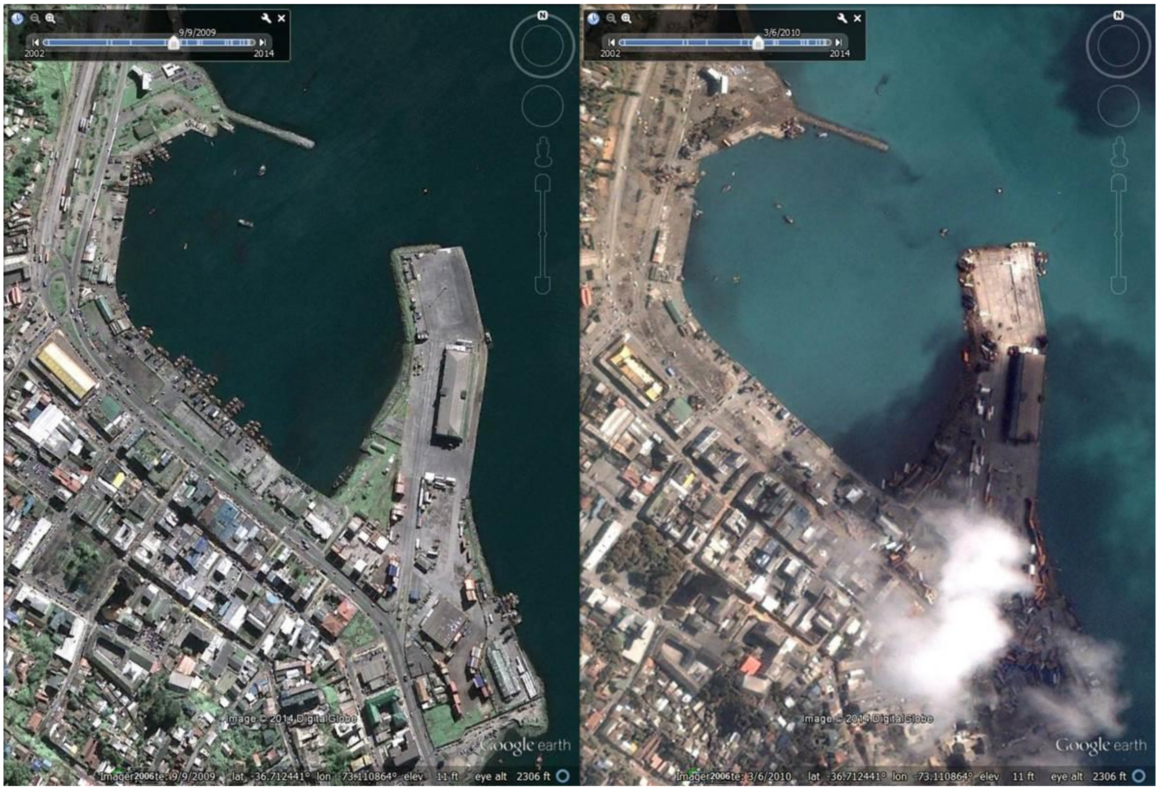

Figure 2-2: Talcahuano Harbor before (left) and after (right) the Chile Tsunami

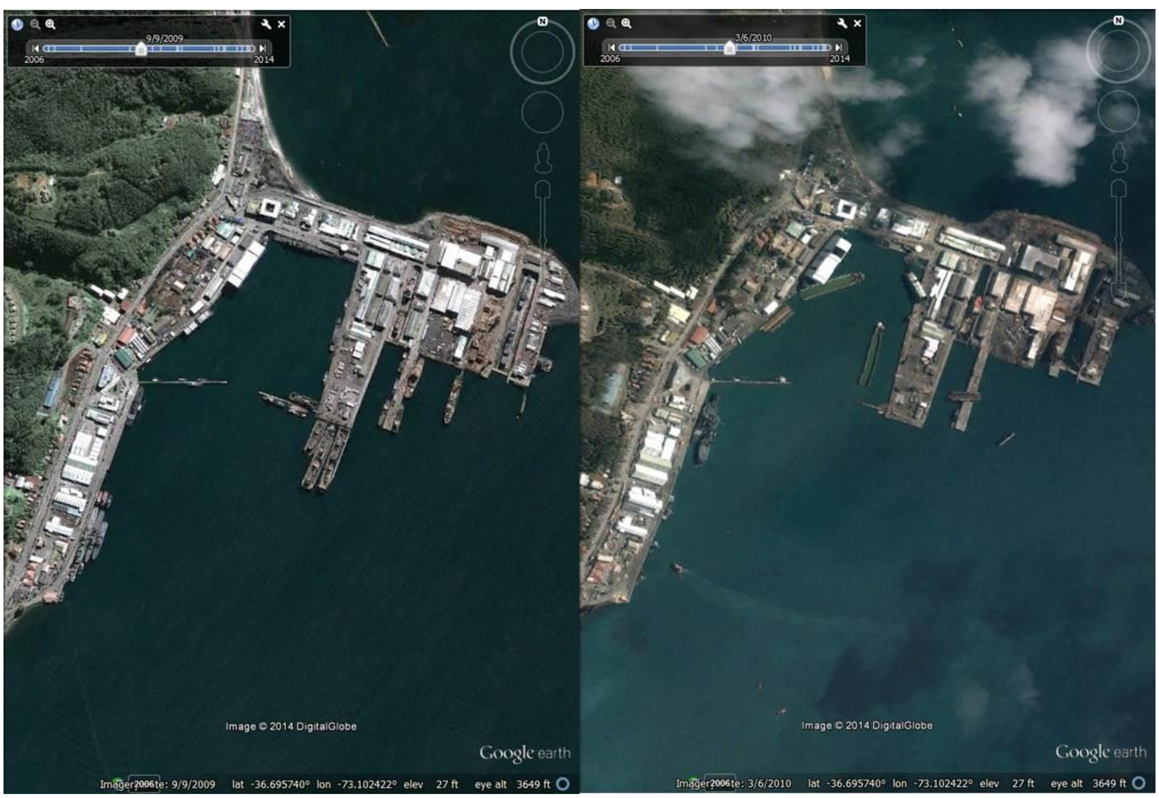

Figure 2-3: Talcahuano Naval Harbor before (left) and after (right) the Chile Tsunami

2.1.5 Japan Tohoku Tsunami

The March 11, 2011 Tohoku Tsunami off the Northeast coast of Honshu Island, Japan, caused tremendous damage to numerous ports all along the Tohoku coastline (Chock, et al. 2013a; Chock, et al. 2013b.). Many of these ports are still trying to recover from this disaster, while some are likely to cease functioning as port facilities for the foreseeable future. Figure 2-4 shows Google Earth images of Taro harbor before and after the Tohoku Tsunami. Similar comparisons for other ports along the Tohoku coastline are included in Appendix A.

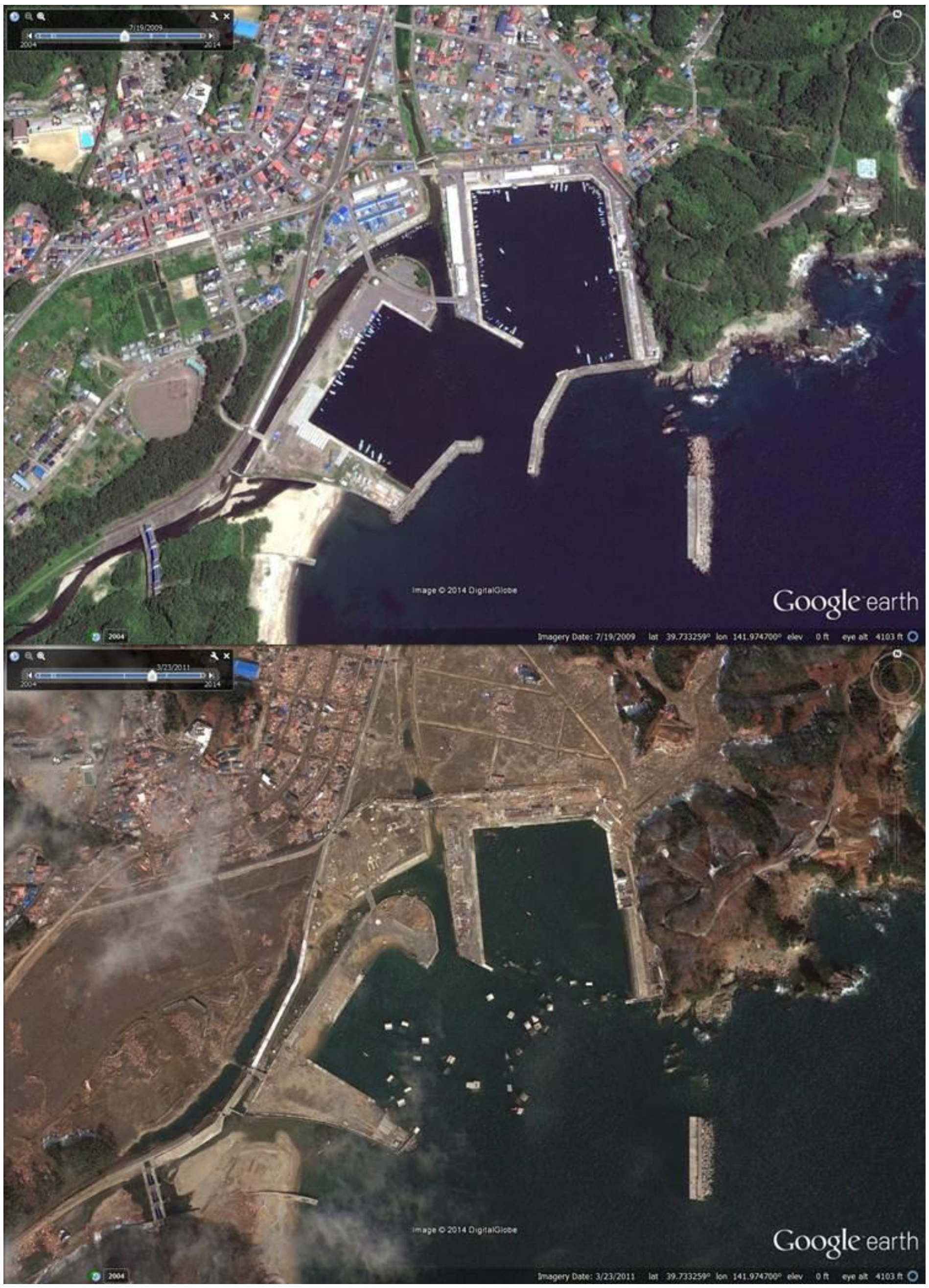

Figure 2-4: Google Earth images of Taro harbor before (top) and after (bottom) the Tohoku Tsunami

2.2 Port and Harbor Damage during past Hurricane and Tsunami Events

2.2.1 Ship and Barge Evacuation

During past hurricane and tsunami warnings, most of the affected ports and harbors have attempted to evacuate larger ships and barges to deep water prior to the event. Typically it is impossible to evacuate all vessels, particularly when warning times are short, or the vessels are not prepared to leave their moorings.

During the Tohoku Tsunami, most large ships were able to evacuate the harbors, even though the warning time was only between 30 and 60 minutes depending on the location. Hachinohe Harbor towards the North end of the Tohoku coastline was able to evacuate most of the deep ocean shipping vessels. Figure 2-5 shows numerous vessels that successfully evacuated the harbor and returned after the tsunami, along with a number that were trapped in the harbor and washed up onto the piers. Figure 2-6 shows two of these vessels stranded on the pier.

This port experienced tsunami flow depths on the order of 4-5 meters (12 – 16 feet), which are similar to what is anticipated for a major tsunami in Hawaii. This was sufficient to separate ships from their moorings and float them onto the adjacent piers, resulting in considerable disruption to port operations. Other ports in Japan experienced flow depths of up to 20 meters (60+ feet) but such extreme conditions are not anticipated at ports in Hawaii.

Figure 2-5: Hachinohe Harbor after the Tohoku Tsunami showing ships washed onshore (circled) and others that evacuated during the tsunami and have now returned.

Figure 2-6: Large fishing vessels washed onto the pier at Hachinohe Harbor, Japan.

A large fishing vessel in Kamaishi Harbor, Japan, broke free of its moorings during the Tohoku Tsunami and impacted a steel framed port building, causing considerable structural damage to the building and piled foundation (Figure 2-7). Based on video footage from an adjacent building, the ship was travelling at approximately 16 mph prior to impact. In Sendai Harbor, a cargo ship floated over the pier to impact a large cargo crane and adjacent warehouse causing considerable damage (Figure 2-8).

Figure 2-7: Ship impact damage to port building in Kamaishi, Japan.

Figure 2-8: Ship impact damage to cargo crane in Sendai Harbor, Japan

During Hurricane Katrina, a large amount of structural damage resulted from impact by large barge-mounted casinos. These barges broke free from their moorings and caused almost total destruction along their path. Figure 2-9 shows a barge-mounted casino in Biloxi, Mississippi, that broke its moorings, drifted inland and damaged a number of structures along the way. Figure 2-10 shows partial collapse of a prestressed concrete parking structure in Biloxi, Mississippi due to impact damage from a barge moored next to the structure.

Figure 2-9: Barge-mounted casino that drifted over Highway US90 in Biloxi, Mississippi, destroying a number of structures.

Figure 2-10: Partial collapse of prestressed concrete parking structure due to impact from barge moored adjacent to the structure

Similar barge damage to a harbor pier also occurred during the Samoa Tsunami, even though flow depths were relatively low. Figure 2-11 shows the damage caused to a pier in Pago Pago harbor due to uplift as the moored barge got caught below the pier during drawdown, and then rose with the incoming tsunami wave.

Figure 2-11: Barge uplift damage to concrete pier in Pago Pago Harbor, Samoa

2.2.2 Shipping Containers and Small Vessels

Debris impact due to floating shipping containers also caused considerable structural and non-structural damage. Figure 2-12 shows the result of floating shipping container impacts with structural steel columns in two buildings in Biloxi, Mississippi. Figure 2-13 shows the effect of impact and damming of water flow against shipping containers that floated into a series of precast concrete piles in a construction site.

Small boat harbors also pose a danger to nearby buildings due to impact from floating vessels (Figure 2-14).

Figure 2-12: Structural damage to steel columns due to shipping container impact

Figure 2-13: Damage to precast piles due to impact and damming effects of floating shipping containers in Biloxi, Mississippi

Figure 2-14: Small boat harbor debris in Ocean Springs, Mississippi

Shipping containers have also resulted in considerable damage to port facilities during recent tsunamis. Figure 2-15 and Figure 2-16 show the movement of shipping containers in the Sendai Harbor from their storage locations into the side of warehouse and other structures along the perimeter of the shipping container yard. Figure 2-17 shows the damage caused to a steel-framed warehouse impacted by these shipping containers.

Figure 2-15: Google Earth image of the shipping container storage area at Sendai Harbor after the Tohoku Tsunami

Figure 2-16: Shipping containers impacting port buildings in the Sendai Harbor after the Tohoku Tsunami

Figure 2-17: Damage to steel-framed warehouse in Sendai Harbor due to shipping container impact and damming effects

Figure 2-18 shows damage to a large light standard at the Sendai Harbor shipping container storage yard due to numerous shipping container impacts and damming effects.

Figure 2-18: Impact damage to large light standard in the Sendai Harbor shipping container yard.

Similar damage due to shipping container impact and damming effects was observed after the Chile Tsunami. Figure 2-19 and Figure 2-20 show shipping containers displaced by the Chile Tsunami in Talcahuano Harbor. Figure 2-21 shows the resulting damage to a steel-framed warehouse adjacent to the container storage yard.

Figure 2-19: Shipping containers at Talcahuano Harbor, Chile, displaced by the tsunami

Figure 2-20: Shipping containers washed up against buildings adjacent to Talcahuano Harbor, Chile

Figure 2-21: Damage to steel-framed warehouse due to shipping container impact and damming effects in Talcahuano Harbor, Chile.

2.2.3 Harbor Piers

Hydrodynamic loading caused considerable structural and non-structural damage to port facilities during Hurricane Katrina. Figure 2-22 shows damage to precast concrete deck slabs and the control tower at the Joint Cadet Marina in Biloxi, Mississippi. The precast concrete deck panels appear to have been lifted by storm surge and wave action, similar to numerous bridge failures along the same coastline. Figure 2-23 shows damage to concrete parking structures located adjacent to port facilities in Gulfport and Biloxi, Mississippi. The double-tee floor system in the precast concrete parking structure (Figure 2-23, left) failed due to buoyancy as air was trapped between the webs of the double-tees. The posttensioned cast-in-place concrete slabs in another parking structure (Figure 2-23, right) were damaged by uplift due to storm surge and wave action.

Figure 2-22: Hydrodynamic loading damage to concrete pier and steel harbor building at Joint Cadet Marina in Biloxi, Mississippi

Figure 2-23: Damage to precast parking structure in Gulfport (left) and prestressed cast-in-place parking structure in Biloxi due to hydrostatic and hydrodynamic uplift

During the 2004 Indian Ocean Tsunami, precast concrete piers at Kao Lak Harbor in Thailand were uplifted as the tsunami flow was blocked from passing under the piers (Figure 2-24). The lack of integral structural connection between the deck panels and the supporting concrete beams may have contributed to this failure mechanism.

During the Tohoku Tsunami, similar hydrodynamic uplift loads developed below piers at a number of harbors. The resulting pressure was sufficient to lift the concrete or steel grating panels placed between the pile-supported piers and the adjacent soil-supported wharf (Figure 2-25 and Figure 2-26). Analysis of these "breakaway panels" indicates that the tsunami-induced hydrodynamic uplift pressure required to lift these panels ranged from 150 to 250 psf.

Figure 2-24: Tsunami uplift damage to precast harbor piers in Kao Lak, Thailand

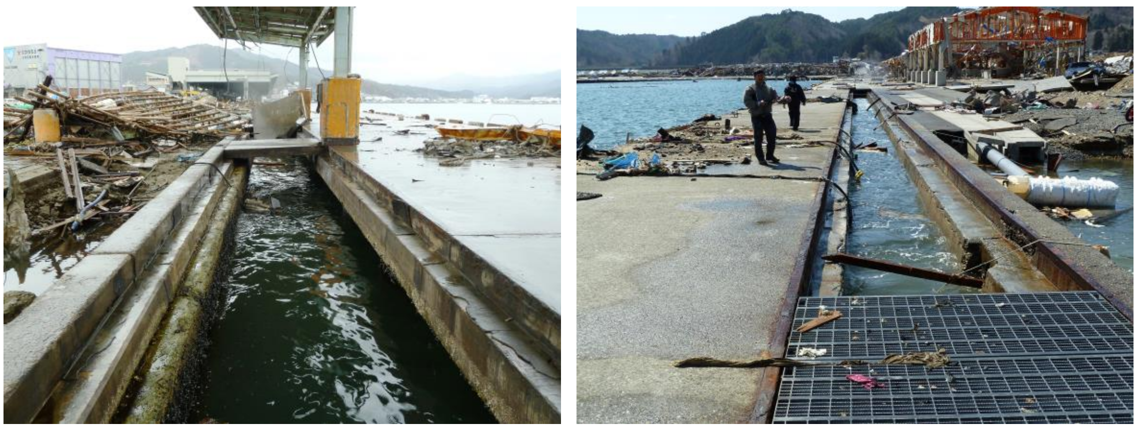

Figure 2-25: Concrete and steel grating "breakaway" panels uplifted by the Tohoku Tsunami in Kesennuma harbor (left) and Taro harbor (right)

Figure 2-26: Concrete "breakaway" panels uplifted by the Tohoku Tsunami in Ofunato harbor (left) and Yuriagi harbor (right)

2.2.4 Fuel Storage Facilities

Damage to fuel storage tanks was observed at a number of locations along the Gulf Coast. Figure 2-27 shows before and after satellite images of a tank farm on the shores of Back Bay behind Biloxi, Mississippi. The inundation depth exceeded the earthen berm around the tank farm and caused flotation of a number of the storage tanks, including one tank that moved out of the containment area. The level of contents in each tank is unknown, but it is presumed that the tanks that floated may have been empty while those that remained in place may have had sufficient contents to resist the buoyancy forces. It was estimated that 482,000 gallons of fuel was released at this location (Frye, 2005).

Figure 2-28 shows details of one of the tanks that moved off its foundations. It appears that the tank floated vertically by shearing the nuts from the top of the rusted anchor bolts. This relocation of the tank resulted in rupture of the pipes leading from the tank. Impact between the tanks also appears to have caused damage to the thin steel walls of this tank.

Figure 2-27: Google Earth images of tank farm in Biloxi Back Bay before (left) and after (right) Hurricane Katrina

Figure 2-28: Fuel storage tanks floated off their foundations in Biloxi Back Bay, Mississippi

Even more severe damage to fuel storage tanks occurred during the Tohoku Tsunami (Figure 2-29 and Figure 2-30). Because these tanks generally have very thin steel walls, they are easily puncture, allowing the tank contents to spill. Depending on the fuel being stored, there may be a significant potential for fires to start, even in the wet conditions during a tsunami. Figure 2-31 shows a number of fires that developed in the Sendai Harbor during the Tohoku Tsunami. It is not known if fuel spills contributed to these fires, but some appear to be in or adjacent to fuel storage tank farms.

Figure 2-29: Damage to fuel storage tanks at Kuji Port during the Tohoku Tsunami

Figure 2-30: One of many large fuel storage tanks in Kesennuma Harbor damaged during the Tohoku Tsunami

Figure 2-31: Fires in and around the fuel storage locations at Sendai Harbor immediately after the Tohoku Tsunami

Some fuel storage tanks were able to survive the Tohoku Tsunami. Figure 2-32 shows two fuel storage locations in Kamaishi where the tanks were undamaged during the Tohoku Tsunami. The Liquid Natural Gas tanks are spherical and have relatively thick steel shells to withstand the high pressure of the contents. They are also generally elevated as shown in Figure 2-32 (right) thereby giving them increased protection from tsunami loads. It is not known if any piping, pumps, or other equipment at these locations was damaged by the tsunami.

Figure 2-32: Undamaged fuel tanks (left) and LNG tanks (right) at Kamaishi Harbor after the Tohoku Tsunami

2.2.5 Bulk Material Handling Facilities

Other storage tanks were also damaged or relocated by the coastal inundation. Figure 2-33 shows a cement silo that collapsed and floated away from its original location.

Reports also indicate that underground fuel storage tanks at gas stations buckled, leading to breakage and fuel spills (Henderson, 2005).

Figure 2-33: Collapsed cement silo in Ocean Springs, Mississippi

During the Tohoku Tsunami, a number of bulk handling facilities were damaged by the inundation. However, some facilities were relatively undamaged, such as the elevated conveyor system at Kuji Port in Japan (Figure 2-34, left). However, damage to the associated warehouse (Figure 2-34, right) probably still meant considerable downtime before bulk handling operations could resume.

Figure 2-34: Conveyor system (left) and associated warehouse (right) at Kuji Port, Japan.

2.2.6 Harbor Buildings

Coastal buildings suffered varying degrees of damage during Hurricane Katrina. Figure 2-35 shows damage to the light sheet metal cladding on a warehouse due to hydrodynamic and debris impact loading. The structural steel frame with columns encased in concrete at the lower level survived intact. Some damaged girts, roller doors and cladding would need to be replaced to restore this warehouse to its original condition.

Figure 2-35: Damage to light sheet metal cladding on steel framed warehouse in Ocean Springs, Mississippi

More extensive warehouse damage was observed after the Tohoku Tsunami, such as the steel-framed port-side building shown in Figure 2-36. However, because the structural frame remained intact, this warehouse could be restored by adding new cladding as seen in the July 2013 image from Google Earth street view in Figure 2-37.

Similar cladding damage was observed at numerous other warehouses where the structural frame remained predominantly intact (Figure 2-38).

Figure 2-36: Cladding stripped from steel-framed warehouse in Taro Harbor.

Figure 2-37: Restoration of cladding on badly damaged warehouse building in Taro, Japan.

Figure 2-38: Port buildings with intact structural elements but extensive cladding damage; Kesennuma (left) and Taro (right)

A number of multi-story concrete and steel buildings in or near harbors experienced considerable damage to non-structural elements, but survived structurally (Figure 2-39). These buildings would be relatively easy to repair and put back into service after the tsunami. Unfortunately the two buildings shown in Figure 2-39 have not fared that well. The vertical evacuation building in Kesennuma Harbor has been demolished while the Taro hotel remains unrepaired over 2 years after the tsunami (Figure 2-40).

Figure 2-39: Multi-story buildings that survived inundation to the third floor level; Reinforced concrete vertical evacuation building in Kesennuma Harbor (left) and steel-framed hotel adjacent to Taro Harbor (right).

Figure 2-40: Demolition of Kesennuma vertical evacuation building in March 2013 (left) and unrepaired state of Taro Hotel from Google Earth street view July 2013 image (right).

Gulfport harbor suffered considerable damage during Hurricane Katrina. Figure 2-41 shows Google Earth satellite images before and after the hurricane. Extensive damage occurred to the steel-framed warehouses on both piers. Two barges broke free from their moorings and washed inland. All boats in the two small boat harbors were washed away, along with extensive damage to the dock systems. All shipping containers at the two storage yards were washed away, becoming floating debris for nearby structures. The container handling cranes remained intact, only experiencing water damage to electrical and mechanical components below the inundation level (Fritz, et al., 2008).

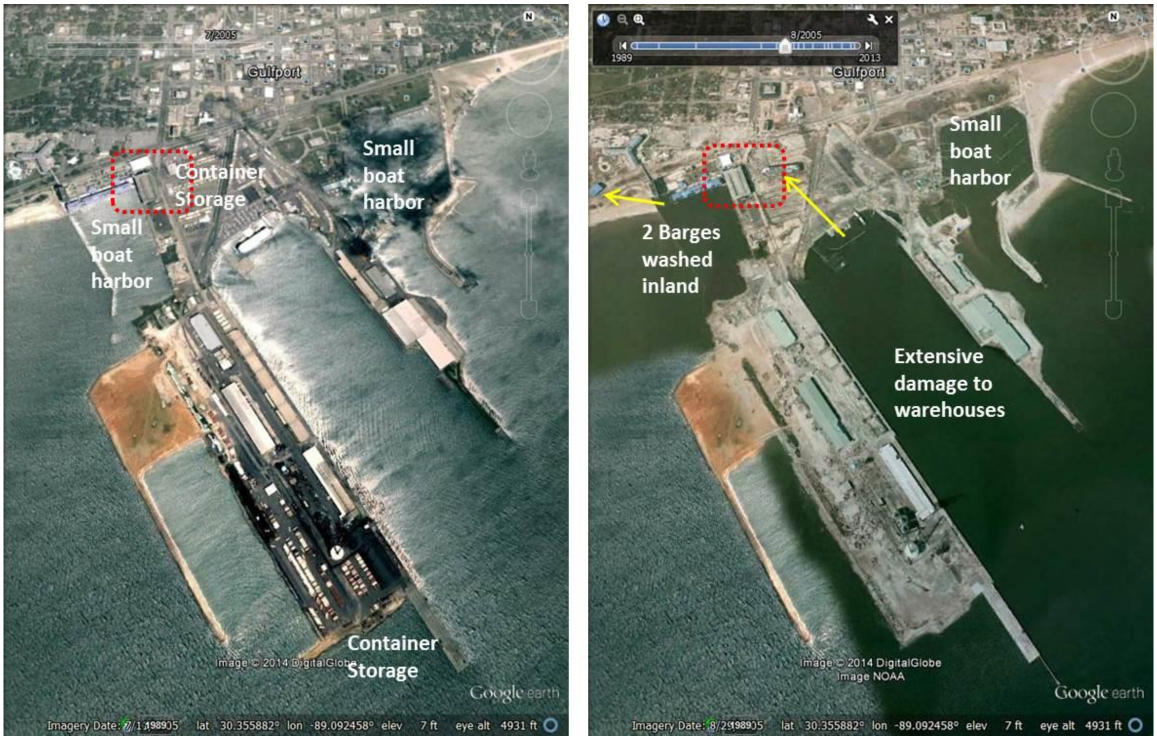

Figure 2-41: Google Earth images of Gulfport Harbor, Mississippi, before (left) and after (right) Hurricane Katrina

Figure 2-42: Google Earth images of portion of Gulfport Harbor before (left) and after (right) Hurricane Katrina showing shipping containers that impacted a parking garage

Figure 2-42 shows a portion of Gulfport Harbor with a concrete parking garage adjacent to a shipping container storage yard. Figure 2-43 shows damage to the lower levels of the precast concrete parking structure due to impacts from floating containers from the storage yard. Because of the relatively substantial nature of these columns and spandrel beams, most of the impact damage is superficial. The precast double-tee floor system supported by these spandrel beams collapsed due to buoyancy and hydrodynamic uplift (Figure 2-23, left).

Figure 2-43: Superficial impact damage to parking garage beams and columns at Gulfport Harbor, Mississippi

3 COASTAL HAZARDS

The Hawaiian Islands are exposed to both hurricanes and tsunamis. The most recent damaging hurricanes were Hurricane Iselle, which made landfall as a tropical storm on the Southeast coast of Hawaii Island on August 8th, 2014, Hurricane Iwa, which passed just North of Niihau and Kauai as a category 2 storm on November 23rd, 1982, and Hurricane Iniki, which made landfall as a category 4 storm on the South shore of Kauai on September 11th, 1992. The latter two hurricanes caused extensive damage to the Islands of Niihau and Kauai, and minor damage on Oahu. Hurricane Iselle caused power outages and limited damage to communities in Southeast Hawaii Island. Other hurricanes and tropical storms have impacted the State but without causing extensive damage.

Numerous damaging tsunamis have impacted the Hawaiian Islands during recorded history. In fact, tsunamis have resulted in more deaths in the Hawaiian Islands than all other natural disasters combined. According to Hawaiian Encyclopedia (2014), the following were the most damaging of the past tsunamis.

- On November 7th, 1837, an earthquake near Chile generated one of the first recorded tsunamis in the Hawaiian Islands, resulting in 15 deaths and damage to homes in Kahului and Hilo.
- On April 2nd, 1868, an earthquake on Hawaii Island, estimated at magnitude 8.0 on the Richter scale, caused a landslide and localized tsunami. Forty eight deaths in Puna are attributed to the 60 foot high tsunami wave.
- On May 9th, 1877, a large earthquake near Peru caused a tsunami that arrived in Hilo before dawn, killing 45 people.
- On April 1st, 1946 a tsunami originating from a magnitude 7.4 earthquake in the Aleutian Islands, caused 159 deaths and extensive damage on Hawaii Island, Maui, Oahu and Kauai.
- On May 23rd, 1960 a tsunami originating from a magnitude 9.5 earthquake off the coast of Chile, caused 61 deaths and extensive damage in Hilo.
- On November 29th, 1975 a local tsunami was generated by a 7.7 magnitude earthquake on the southeast shore of Hawaii Island, causing 2 deaths, but limited coastal inundation.
- On March 11th, 2011 the Great East Japan earthquake generated the Tohoku Tsunami which caused extensive damage in Japan, but also damage estimated at $40 million in Hawaii. Areas of Kahului harbor were inundated during this event.

3.1 Hurricane Storm Surge and Wave Height Predictions

Although only Kauai has experienced major damaging hurricanes in recent history, the scientific consensus is that all of the Hawaiian Islands are exposed to potential hurricane hazards, including high wind, storm surge and superimposed wind-driven high surf. Hurricane Iselle highlighted the risk of hurricane landfall on the other Hawaiian Islands. All commercial ports should therefore be prepared to withstand the effects of a category 4 hurricane making landfall at or near the port.

An extensive study by Kennedy et al. (2012) generated numerous simulations of hurricanes up to category 4 striking the Hawaiian Islands from various trajectories. The results of these simulations are provided in the Hawaii Storm Atlas, which is available online at https://www3.nd.edu/~swims/ (US Army Corps, 2014). The Atlas provides contour maps of storm surge and characteristic wave height for a wide spectrum of storm intensities and tracks. Samples from these predictions for the most severe storm levels are provided for each of the ports considered in this study.

3.2 Tsunami Flow Depth Predictions

Based on the history of tsunami activity in the Pacific Ocean, it is clear that the Hawaiian Islands will be affected by future tsunamis. Current tsunami evacuation zones are based on the worst effects of all historical tsunamis that affected Hawaii, as well as simulations of significant earthquakes near Japan, Chile, Samoa and the Cascadia Subduction zone off the northeast US. However, recent geophysical and paleontological research has identified the possibility of a more significant tsunami source mechanism in the central portion of the Aleutian Islands (Butler, 2011). This event would originate from the same region as the 1946 magnitude 7.4 earthquake in the Aleutian Islands, but with a magnitude as large as 9.2. This event is estimated to have a return period between 2000 and 4000 years. The resulting tsunami inundation in Hawaii would exceed anything observed during human presence on the islands.

Although this Great Aleutian Tsunami (GAT) has a long return period, or low probability of occurrence in any one year, it is a reasonable measure of the maximum considered tsunami for design of ports and coastal bridges. These components of the island infrastructure will be in existence for the foreseeable future, and will be essential to future inhabitants of the islands. It is therefore considered appropriate to utilize the results of simulations of this Great Aleutian Tsunami as estimates of the design level event for port disaster planning.

Computer simulations of the GAT have been performed by researchers at the School of Ocean Science and Technology, SOEST, at the University of Hawaii at Manoa. Inundation depths around all coastlines of the Hawaiian Islands have been provided for this study (Cheung, 2014).

4 HARBOR SURVEYS

4.1 Site visits

There are seven major commercial ports in the State of Hawaii, with numerous smaller harbors for interisland barge traffic, commercial and recreational fishing, and sailing vessels. This study focused only on the commercial ports identified in Table 4-1 and shown in Figure 4-1.

Site visits were performed to all commercial ports on the dates shown in Table 4-1. Discussions were held with the port administrator to determine current port procedures during a hurricane or tsunami warning. Feedback was also obtained relating to the port experience during recent tsunami and hurricane warnings. The following sections summarize the results of these discussions and the field observations at each port.

Table 4-1: Commercial Harbors in Hawaii

Island	Port	Contact	Date of Field Visit
Kauai	Nawiliwili Harbor	Robert Crowell	May 24, 2013
	Port Allen	Dwight Yama	May 24, 2013
Oahu	Honolulu Harbor		
	Initial Visit	Carter Luke	May 26, 2010
	Follow-up Visit	Raymond Bode	March 15, 2013
	Follow-up Meeting	Davis Yogi	March 19, 2013
	Kalaeloa - Barbers Point Harbor	Logan Williams	March 1, 2013
Maui	Kahului Harbor	Louis Nobriga	March 9, 2012
Hawaii	Hilo Harbor	Jeff Hood	May 4, 2012
	Kawaihae Harbor	Jeff Hood	May 4, 2012

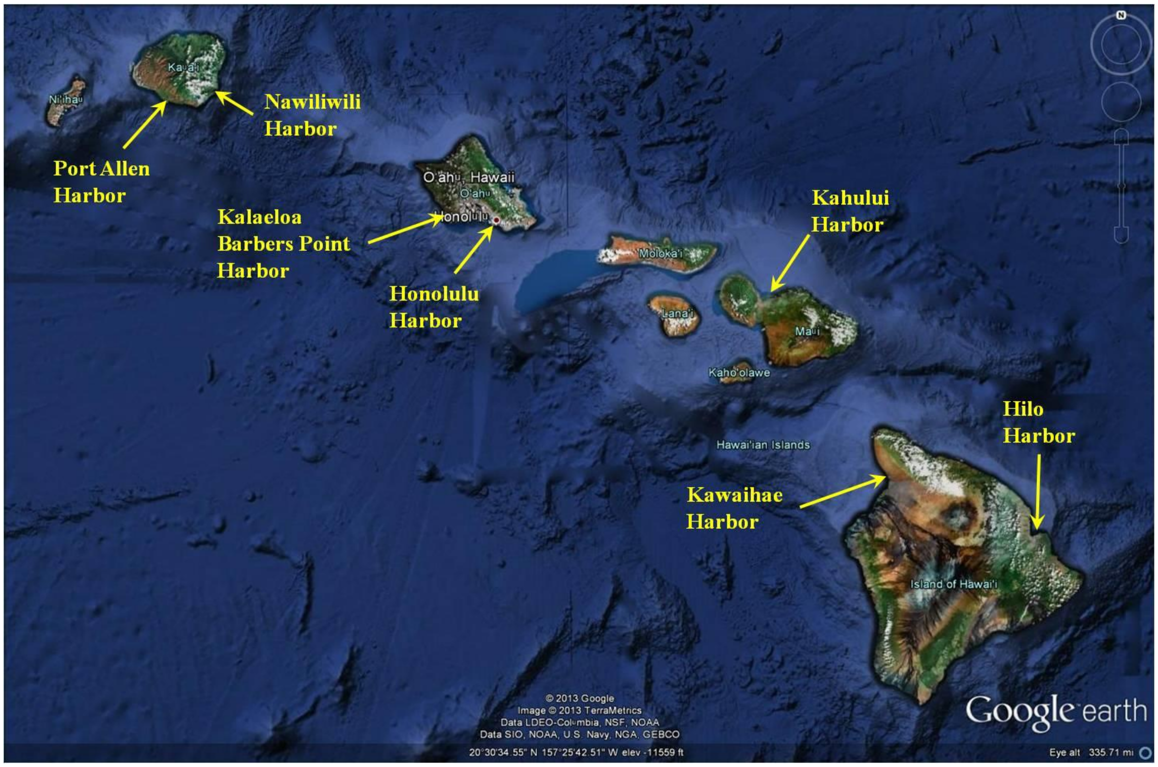

Figure 4-1: Hawaii Islands showing commercial harbors considered in this study

4.2 Nawiliwili Harbor, Kauai County

Nawiliwili Harbor is located on the SE side of the island of Kauai, just south of the county capital, Lihue (Figure 4-2). The entrance channel depth is 40 feet while the depth at pier side is 35 feet. Minimum depths within the harbor are around 32 feet. Three piers make up a total of 1,839 feet of berthing space, with almost 40 acres of container storage area (State of Hawaii, 2004).

Figure 4-2: Nawiliwili Harbor, Kauai

Based on the US Army Corps hurricane simulations, the worst storm surge and characteristic wave height at Nawiliwili harbor are generated by a storm following landfall track L6-D, with central pressure of 940 bars (CP940), radius of maximum winds of 45 km (R45), and forward speed of 22 knots (V22). This storm is designated as L6-D-CP940-R45-V22 on the Hawaii Storm Atlas (US Army Corps, 2014).

Figure 4-3 shows the storm surge and characteristic wave height generated by this storm for the western end of the Hawaiian Islands as the storm passes over Kauai. Figure 4-4 shows a close-up view of the predictions for Kauai, while Figure 4-5 shows the predictions for Nawiliwili Harbor and adjacent coastline. Storm surge in Nawiliwili Harbor is predicted to reach 6-7 feet, while the characteristic wave height in the harbor will be less than 5 feet. Immediately outside of the harbor breakwater, however, the wave heights rapidly increase to over 25-30 feet (Figure 4-5).

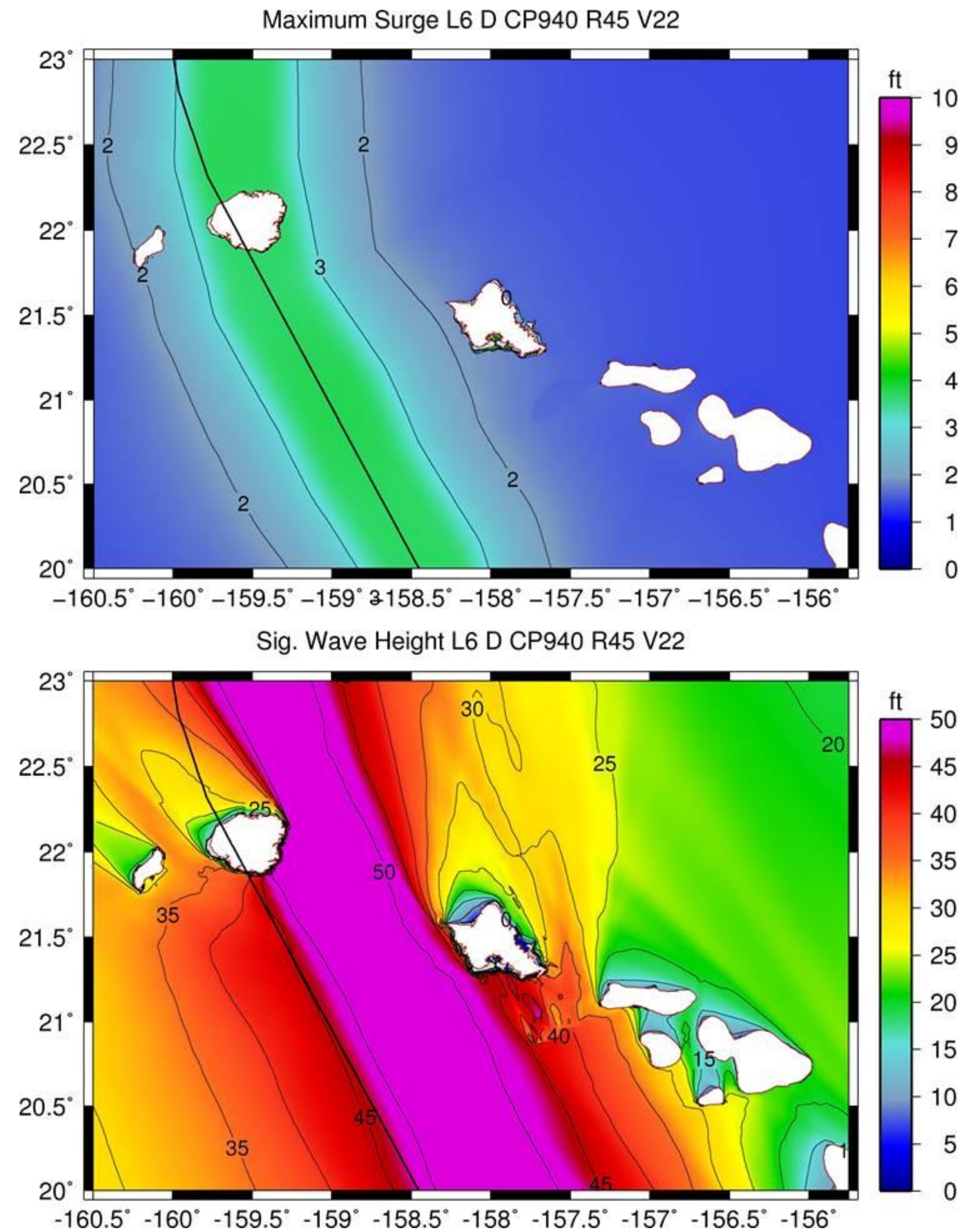

Figure 4-3: Storm surge and wave height predictions for storm L6-D-CP940-R45-V22 (US Army Corps, 2014)

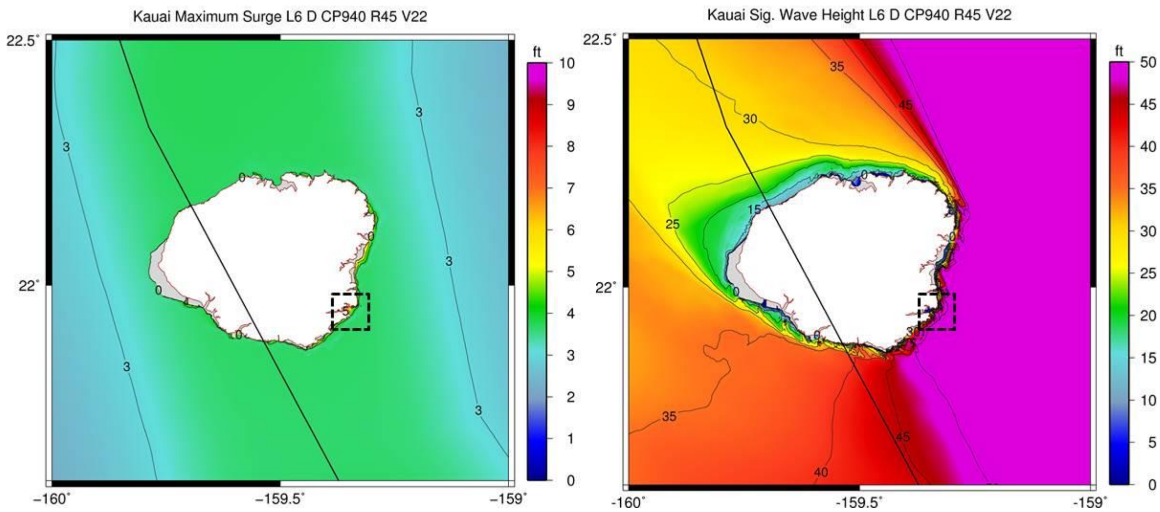

Figure 4-4: Storm surge and wave height predictions for Kauai for storm L6-D-CP940-R45-V22 (US Army Corps, 2014)

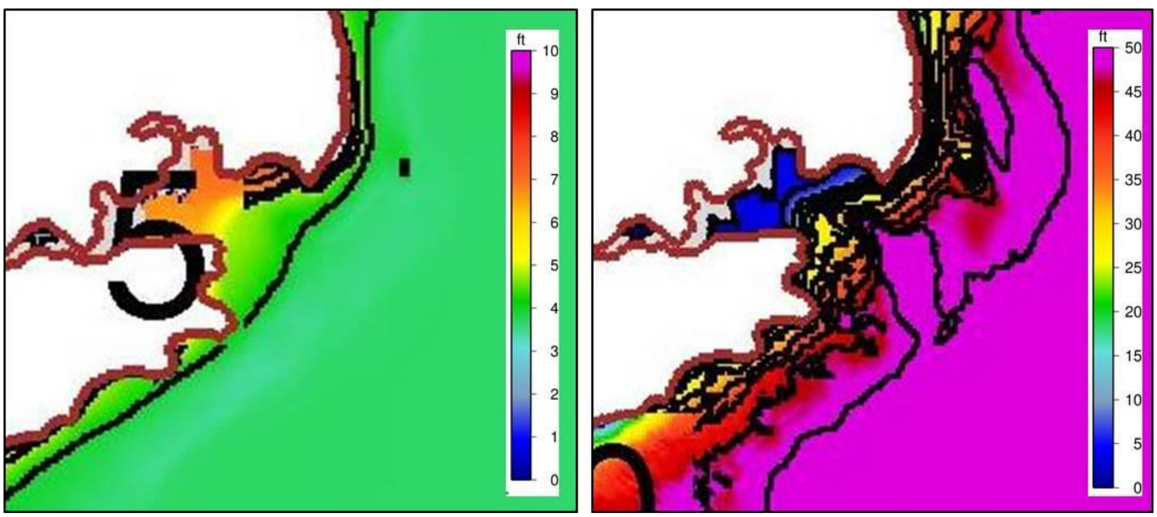

Figure 4-5: Storm surge and wave height predictions for Nawiliwili Harbor for storm L6-D-CP940-R45-V22 (US Army Corps, 2014)

Only portions of the harbor are included in the current Hawaii Tsunami Evacuation Maps (Figure 4-6). However, modeling of the Great Aleutian Tsunami indicates that the entire harbor and neighboring low-lying areas will be inundated with flow depths exceeding 26 feet in some areas (Figure 4-6) (Cheung, 2014). Because of the close proximity of high ground outside of the inundation zone, all individuals in danger should have ample time to evacuate to high ground, particularly during a hurricane or distant source tsunami warning. For local tsunamis, where warning times will be about 30 minutes, it should still be possible to evacuate all people from the inundation zone.

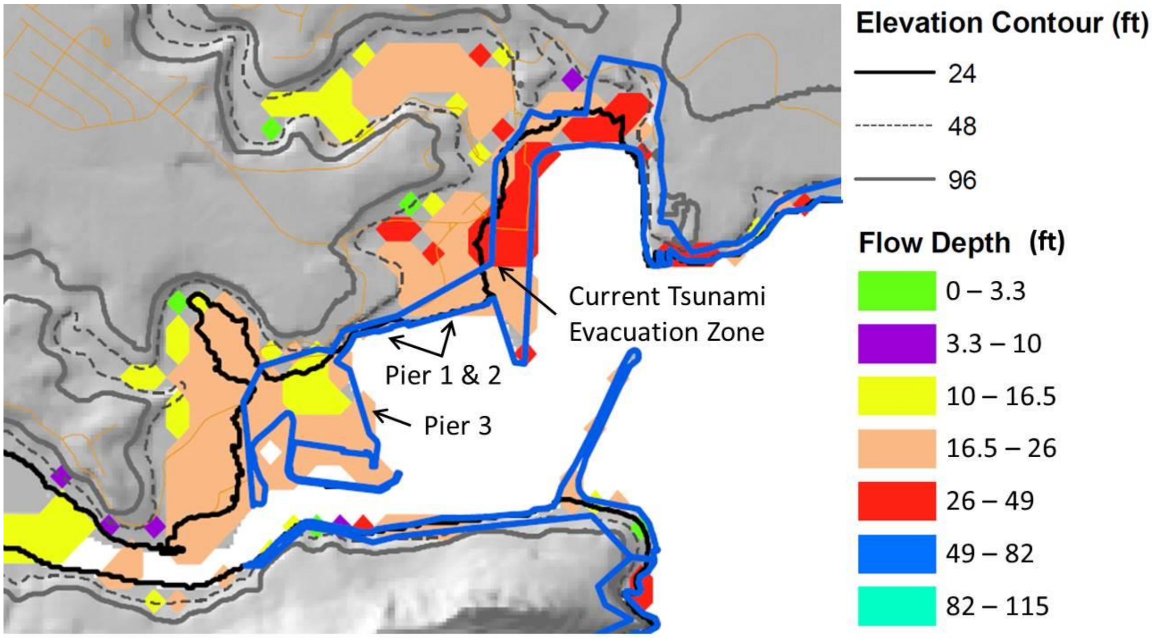

Figure 4-6: Nawiliwili Harbor Tsunami Inundation Predictions based on Great Aleutian Tsunami (Cheung, 2014)

4.2.1 Procedures during hurricane and tsunami warnings

Kauai District Manager, Robert Crowell, described the harbor procedures during a warning event as follows:

- The Captain of the Port makes a determination as to whether the harbor will be evacuated. The Coast Guard will oversee the evacuation and patrol the port until they need to move to deeper water.
- If an evacuation is ordered, all large ships are sent out of the harbor to deep water. However, there are generally no ship movements at night, so if a warning is issued at night it may not be possible to evacuate ships. During a past evacuation order, an NCL cruise boat was instructed to evacuated at 1:00AM, but elected to wait for passengers still on land.
- Barges with a tug attached will evacuate the harbor. They do not require pilot assistance to leave the harbor.
- Road blocks established to prevent people entering the evacuation zone will hamper dock workers needed to assist with evacuation.
- Both Matson and Young Brothers attempt to remove all containers with hazardous material and refrigerated containers from the harbor area.
- Additional full containers are removed as time allows.
- An informal agreement was in place for port equipment to be stored at Kauai High School. The Shopping Center parking area is also available. Formal agreements are required to ensure access to these locations during a warning.

- Large equipment cannot leave the harbor and is generally moved to the back end of the harbor prior to personnel evacuation.
- All personnel are evacuated from the harbor one hour before anticipated arrival time of the storm surge or tsunami. The harbor is then locked down and no more activity is allowed.
- During a tsunami or storm surge event, the harbor management and port personnel are located at the County EOC in Lihue.
- The Fire Department has a depth-measuring sonar to search for possible submerged containers and other objects in the harbor after the tsunami or hurricane event. Tugboats also have depth sonar than could be used to search for submerged objects.
- Immediately after the tsunami all-clear is given, on-land operations in the harbor can resume. However, water currents may not allow for safe operation in the water for some time after the event. This will delay operations to check water depths and clear any debris. The Port Captain has to issue an all-clear for water operations to resume. Ships that evacuated to deeper water may not be able to return to the port until water depths have been checked.
- The Island of Kauai cannot afford to have Nawiliwili harbor closed for more than 6 days.

4.2.2 Experience during Hurricane Iselle

A tropical storm watch was issued for Kauai County at 5PM local time on Wednesday, August 6, 2014, followed by a tropical storm warning issued at 5:00AM on Thursday, August 7. The warning was discontinued at 5PM on Friday, August 8. The Coast Guard informed the port captain on Thursday, August 7, that they intended to close both Nawiliwili and Port Allen as of 4:00AM Friday, August 8, however, this decision was reversed as the storm dissipated over Hawaii Island, and the Kauai ports were never officially closed.

Nevertheless, according to Harbor Administrator, Robert Crowell, the port followed its standard procedures in preparing for a possible tropical storm. An NCL cruise ship was in Nawiliwili Harbor all day Thursday, intending to stay overnight. The ship crew decided to depart the port at 7:00PM on Thursday so as not to be caught in the port if it were closed the next morning. Being a daylight port, the ship would not have been able to leave after dark. There were no barges in either Nawiliwili or Port Allen during the storm watch and warning.

All shipping container companies evacuated containers with hazardous materials, livestock and vehicles from the port. They also revised shipping schedules to delay incoming shipments of such materials so as to avoid having them in the port during the storm.

4.2.3 Harbor Piers

All three piers at Nawiliwili Harbor have both pile supported and soil supported sections. The pile supported sections are susceptible to hydrodynamic uplift during storm surge and wave action, and during tsunami inundation. In particular, the orientation of Pier 3 makes it most susceptible to incoming tsunami flow and hurricane wave action. Pier 3 was completed in 1994 and is constructed using closely spaced driven piles encased in large reinforced concrete beams supporting the reinforced concrete pier deck (Figure 4-7 and Figure 4-8). This integral construction provides superior resistance to the uplift forces and would be expected to survive anticipated hydrodynamic loading. However, drawings for the pier were not reviewed for this project, and no structural or hydrodynamic analysis was performed to verify the anticipated performance of this structure, or Piers 1 and 2, during future inundation events.

4.2.4 Shipping Container Storage Areas

The main shipping container storage areas are on Pier 1 and Pier 3 (Figure 4-8 and Figure 4-9). Both areas are directly exposed to inundation due to storm surge or tsunamis (Figure 4-2 and Figure 4-6). Containers with hazardous contents are stored on chassis ready for removal to high ground in the event of a hurricane or tsunami warning (Figure 4-9). Others are stacked without restraint, so would be expected to float during a major inundation event. They will then become floating debris with the potential for striking structures and other harbor facilities and causing considerable damage. Many of the containers will be washed off the piers and potentially sink in the harbor basin or entry channel, reducing the available draft. This would be a major concern that needs to be resolved prior to allowing ships into the harbor after a hurricane or tsunami.

Figure 4-7: Edge of Pier 3 showing closely spaced driven pile supports

Figure 4-8: Pier 3 container handling and pile support detail

Figure 4-9: Chassis-mounted containers on Pier 1

4.2.5 Fuel Storage Facilities

Two fuel storage tank farms are located adjacent to Nawiliwili Harbor (Figure 4-2). The first is a Midpac fuel storage facility directly inland from the container storage yard on

Pier 1 (Figure 4-10). The storage tanks do not appear to be secured to their foundations, and are surrounded by a small earthen berm for containment purposes (Figure 4-11). Other than self-weight, there does not appear to be any resistance to buoyancy of an empty or partially filled tank. In addition, the small earthen berm surrounding the tank farm will easily scour or be overtopped during storm surge or tsunami inundation, so it cannot be considered as protection for the tank farm. It is therefore highly likely that some or all of these tanks will be displaced during a major inundation event, potentially leading to fuel spills and fires.

The second fuel storage facility is the Aloha tank farm adjacent to Pier 2 (Figure 4-2). This facility is surrounded by a 6 foot high concrete wall (Figure 4-12). The top of the wall is approximately 14 feet above MSL. This wall was presumably designed as a containment wall, so would be able to resist internal hydrostatic pressure, but may not be adequate for external hydrostatic pressure due to storm surge, and may not be adequate to resist high velocity tsunami flow. Figure 4-6 shows that flow depths could exceed 16.5 feet at this location during a Great Aleutian Tsunami event. If the wall is overtopped by tsunami inundation, the tanks will be subject to potential flotation, buckling, or impact from floating debris. Resulting fuel spills could lead to fires that can spread with the water flow. A portion of the fire suppression system is located on the outside of the containment wall (Figure 4-13) and appears to be vulnerable to debris impact damage. This is also the case for the numerous fuel pipes both inside and outside the containment wall.

Figure 4-10: Midpac fuel storage tank farm at Nawiliwili Harbor

Figure 4-11: Midpac fuel storage tank base and containment berm

Figure 4-12: Containment wall around Aloha fuel storage facility at Nawiliwili Harbor

Figure 4-13: Aloha fuel storage facility at Nawiliwili Harbor

A Gasco Inc. propane storage facility is located adjacent to Pier 3 (Figure 4-2). This facility does not require a containment wall, so it is only surrounded by a security chain-link fence (Figure 4-14). This fence will not provide protection against floating shipping containers from Pier 3, or other debris impacts.

Figure 4-14: Gasco Inc. propane storage tanks adjacent to Pier 3 in Nawiliwili Harbor

Figure 4-15: Gas tank connection to concrete foundation.

The cylindrical and spherical storage tanks appear to be anchored to their concrete foundations (Figure 4-15), which will assist in preventing displacement due to buoyancy. However, the strength of the anchor bolts and size of the concrete foundations is unknown, so a complete evaluation of buoyancy potential could not be performed for this study. There is also potential for breakage of the pipes leading from these tanks due to floating debris strikes. Shutoff valves and other safety measures already in place at a gas storage facility should help to mitigate the potential for a gas leak and potentially explosive fire.

Although not part of the Nawiliwili Harbor property, these fuel storage facilities present a potential hazard to surrounding areas, including harbor property, if they are damaged during a coastal flooding event. Nawiliwili harbor procedures during a hurricane or tsunami warning call for power to the fuel storage facilities to be shut off and valves to be locked before the facilities are evacuated. Remediation against inundation would require an evaluation of the height of the containment berm and walls relative to anticipated storm surge and tsunami flow depths. The earthen berm at the Midpac storage facility will likely need to be replaced with a concrete wall in order to provide adequate protection against scour and debris impact. If the wall at the Aloha facility is not currently high enough to prevent inundation of the tank farm, it can be replaced with a higher wall. An alternative approach may be to add a retention fence to the top of the containment wall to prevent floating containers and other large debris from reaching the tanks.

4.2.6 *Bulk Handling Facilities*

The only bulk handling facility at Nawiliwili Harbor is the cement storage silos adjacent to the container storage yard at Pier 1 (Figure 4-2 and Figure 4-16). These silos are elevated above ground level, but are supported by relatively slender steel columns and cross-bracing. Debris impact damage to these supports, or to the piping and machinery used to operate the silos, could affect the availability of cement for reconstruction work after a major inundation event. Only limited cement supplies are stored at the concrete ready-mix companies on Kauai.

4.2.7 *Harbor Buildings*

The only major buildings in Nawiliwili Harbor are metal frame warehouses on Pier 1 and Pier 3 (Figure 4-17 and Figure 4-18). It should be anticipated that the exterior roller doors and sheet metal cladding on these buildings will be damaged during an inundation event. It is suggested that the roller doors be left fully open during future warnings so as to reduce damage to the doors. It is also possible that floating debris strikes could damage some of the structural columns and bracing members, but it is unlikely that the entire warehouse structures will be destroyed. These buildings are used for equipment and other storage purposes, as well as cruise boat loading and offloading, but are not essential for restoring harbor operations after an event.

The Harbor Master office is a single-story building elevated a few feet above grade (Figure 4-19). It is located near the entrance to the harbor (Figure 4-2) and will likely be severely damaged during a major inundation event. The Coast Guard facility near the back of the harbor (Figure 4-2 and Figure 4-20) will also be severely damaged. No critical equipment or functions should be maintained at these facilities because they will likely not be available after a major inundation event.

Figure 4-16: Cement Storage Silos at Nawiliwili Harbor

Figure 4-17: Warehouse on Pier 1

Figure 4-18: Warehouse on Pier 3

Figure 4-19: Nawiliwili Harbor Master office

Figure 4-20: Coast Guard facility in Nawiliwili Harbor

4.3 Port Allen, Kauai County

Port Allen Harbor is located on the Southern shore of Kauai Island (Figure 4-21). The entrance channel and pier 1 berthing depths are both 35 feet. Pier 1 provides 600 feet of berthing length and 1.5 acres of shed and open yard storage areas (State of Hawaii, 2004).

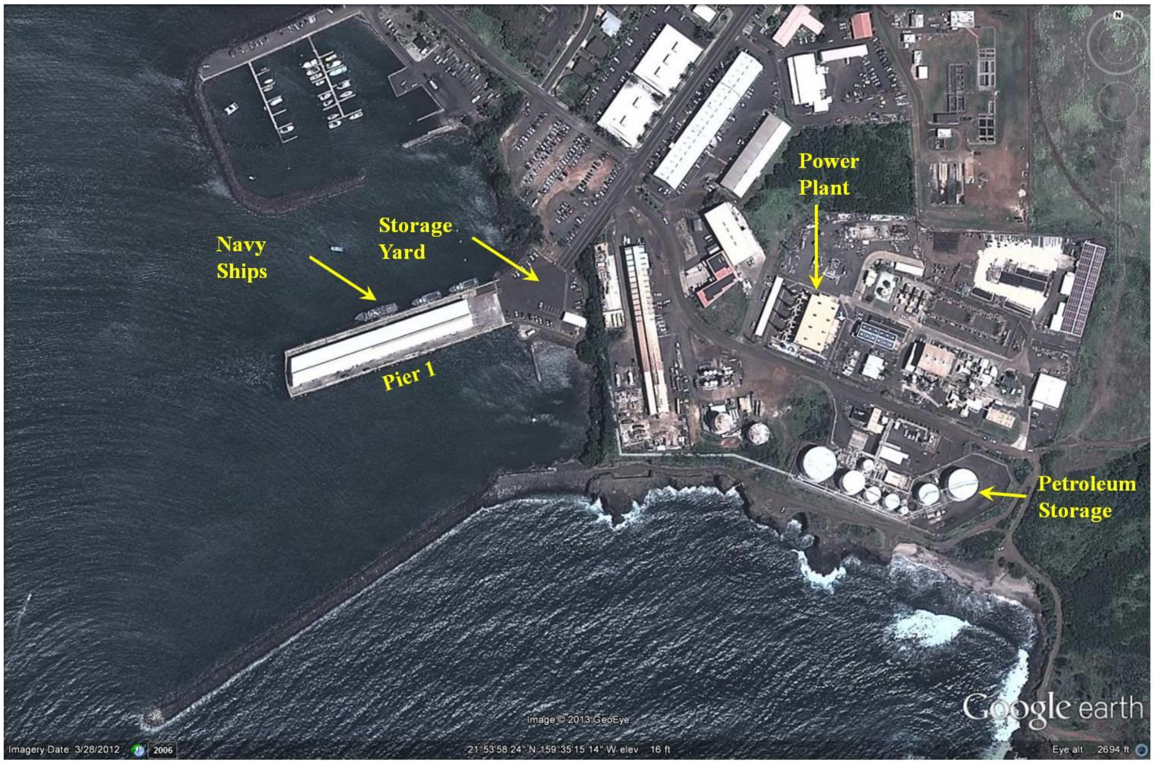

Figure 4-21: Port Allen Harbor, Kauai

Based on the US Army Corps hurricane simulations, the worst storm surge and characteristic wave height at Port Allen are generated by a storm following landfall track L7-D, with central pressure of 940 bars (CP940), radius of maximum winds of 60 km (R60), and forward speed of 22 knots (V22). This storm is designated as L7-D-CP940-R60-V22 on the Hawaii Storm Atlas (US Army Corps, 2014).

Figure 4-22 shows storm surge and characteristic wave height predictions for Kauai, while Figure 4-23 shows the predictions for Port Allen and adjacent coastline. Storm surge in Port Allen is predicted to reach 6-7 feet, while the characteristic wave height in the harbor could reach 10-15 feet. Immediately outside of the harbor the wave heights rapidly increase to as much as 50 feet (Figure 4-23).

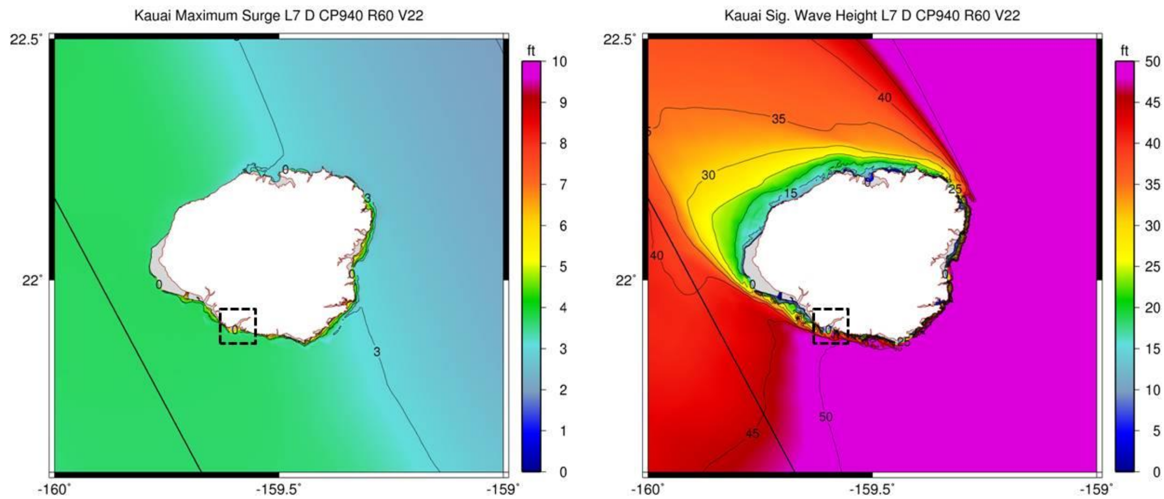

Figure 4-22: Storm surge and wave height predictions for Kauai for storm L7-D-CP940-R60-V22 (US Army Corps, 2014)

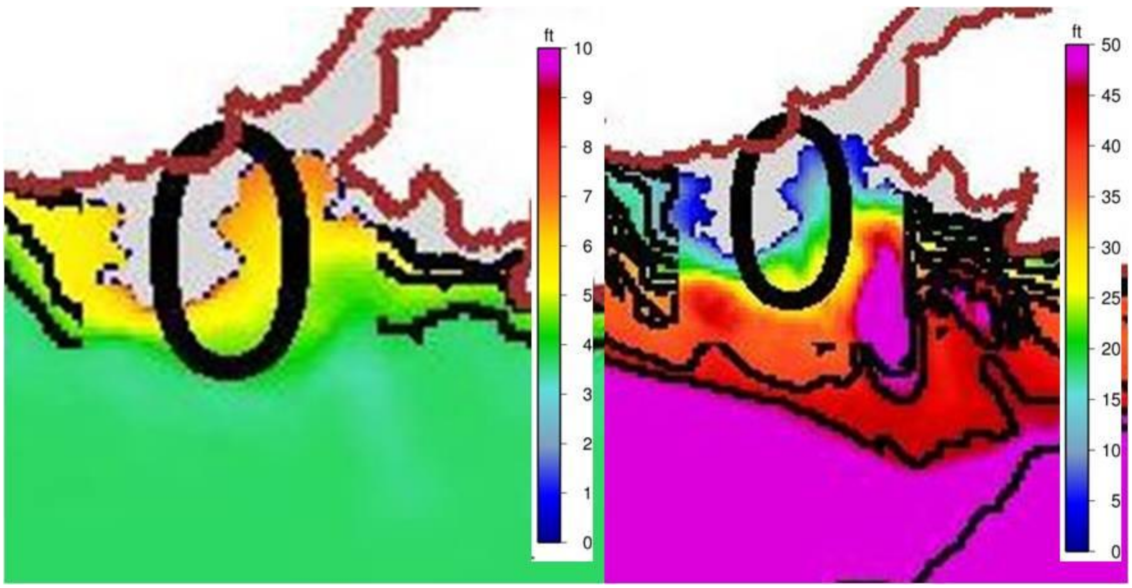

Figure 4-23: Storm surge and wave height predictions for Port Allen for storm L7-D-CP940-R60-V22 (US Army Corps, 2014)

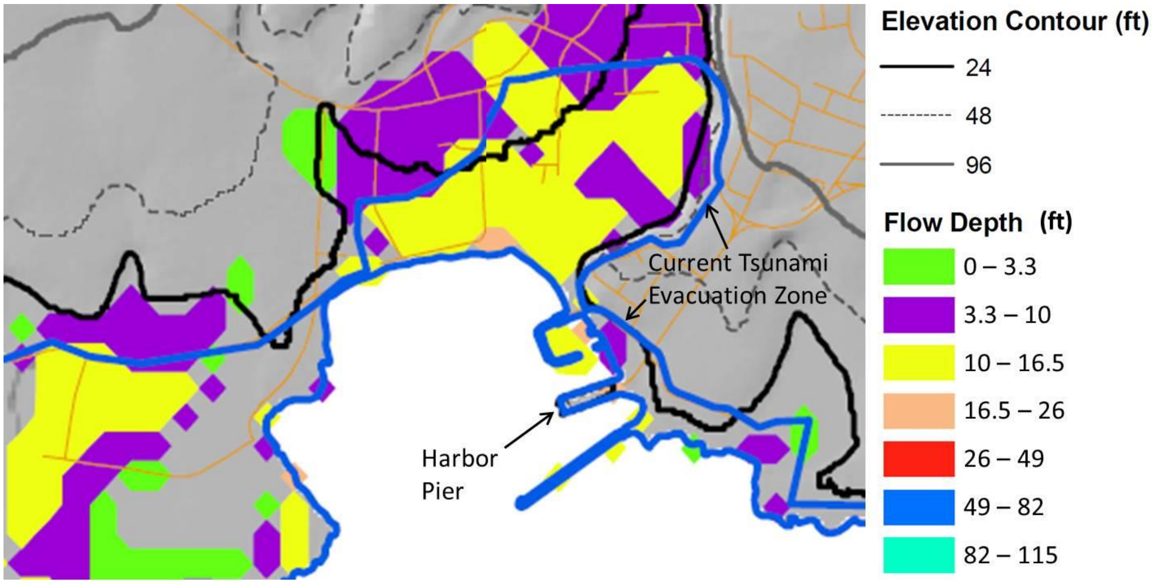

Figure 4-24: Port Allen Tsunami Inundation Predictions based on Great Aleutian Tsunami

All harbor facilities are included in the current Hawaii Tsunami Evacuation Maps (Figure 4-24), and modeling of the Great Aleutian Tsunami indicates that the location of the harbor pier will experience inundation up to 16.5 foot elevation above MSL (Cheung, 2014). Because of the close proximity of high ground outside of the inundation zone, all individuals in danger should have ample time to evacuate to high ground during hurricane or distant and near source tsunami warnings.

4.3.1 Procedures during hurricane and tsunami warnings

The harbor procedures during a warning event are as follows:

- The only major ship that enters the harbor is the fuel barge, which is in port approximately one day every two weeks. If a fuel barge is in the harbor during a warning, it is evacuated to deep water. The tug is always connected to the barge, and does not require pilot assistance to leave the harbor.
- US Navy ships using the North side of the pier follow their own procedures for evacuation during a warning.
- Operators of excursion boats that use Pier 1 make their own decisions as to whether or not to leave the harbor during a warning.
- There are no containers stored at this harbor.

4.3.2 Experience during Hurricane Iselle

A tropical storm watch was issued for Kauai County at 5PM local time on Wednesday, August 6, 2014, followed by a tropical storm warning issued at 5:00AM on Thursday, August 7. The warning was discontinued at 5PM on Friday, August 8. The Coast Guard informed the port captain on Thursday, August 7, that they intended to close both Nawiliwili and Port Allen as of 4:00AM Friday, August 8, however, this decision was reversed as the storm dissipated over Hawaii Island, and the Kauai ports were never officially closed.

No ships or barges were in Port Allen at the time of the storm. The recreational vessels that use the main pier, and the naval ships docked on the back side of the pier, all left for Nawiliwili Harbor, which would provide more protection from a storm predicted to pass south of the island. The harbor was therefore empty throughout the storm warning.

4.3.3 Harbor Piers

The single pier at Port Allen is approximately 10 feet above MSL and is supported entirely by driven pile foundations (Figure 4-25). Although the anticipated maximum storm surge will not exceed the pier elevation, the superimposed storm waves will well exceed the pier elevation. Tsunami inundation anticipated for the Great Aleutian Tsunami will also overtop the pier.

The piles supporting the pier are integral with large concrete beams supporting the concrete pier deck. This integral construction provides superior resistance to the uplift forces produced by hurricane waves and tsunami flow, and would be expected to survive anticipated hydrodynamic loading. However, drawings for the pier were not reviewed for this project, and no structural or hydrodynamic analysis was performed to verify the anticipated performance of this structure.

4.3.4 Fuel Storage Facilities

The only fuel storage tanks at Port Allen are in a Chevron facility located well above the anticipated inundation level (Figure 4-21 and Figure 4-26). No damage to these facilities or the adjacent power plant is anticipated because of their elevation above MSL. However, the pipes that lead from the harbor pier to the Chevron storage tanks may be damaged by debris impacts (Figure 4-27). Safety measures should be in place to prevent a fuel spill in case any of these pipes should be damaged during an inundation event.

4.3.5 Harbor Buildings

The only harbor building at Port Allen is the warehouse on Pier 1, which houses the harbor master office and various storage facilities for pier users (Figure 4-25 and Figure 4-28). Because the pier is elevated 10 feet above MSL, it is anticipated that inundation of the pier will only occur in an extreme hurricane or tsunami event. Damage to the warehouse exterior cladding and roller doors can be anticipated during such an event. Debris impact may also damage structural components of the warehouse frame, but it is likely that large portions of the warehouse will survive structurally. Most of the warehouse contents will be damaged or destroyed if the inundation exceeds the pier elevation. It is suggested that the roller doors be left open during hurricane or tsunami warnings so that they are less likely to suffer damage during the event. Security personnel can be located at the entrance to the port, which is outside the inundation zone, to secure the facility and warehouse contents for the duration of the warning.

Figure 4-25: Pile supported pier and warehouse at Port Allen

Figure 4-26: Chevron fuel storage facility located well above anticipated inundation levels

Figure 4-27: Pipes carrying fuel from Port Allen pier 1 to Chevron storage facility

Figure 4-28: Port Allen warehouse interior

4.4 Honolulu Harbor, Oahu

Honolulu Harbor on the South shore of Oahu is the primary lifeline for all goods and commodities moving in and out of the State of Hawaii. It also serves as the distribution point for the majority of cargo to and from the other Hawaiian Islands. As such, Honolulu Harbor is critical to the State's economy and its ability to recover after a natural disaster.

Honolulu Harbor offers over 200 acres of container yard and over five linear miles of mooring space at 30 major berths. The Main Channel has a depth of 45 feet while the harbor has a depth of 40 feet (State of Hawaii, 2004). The Kalihi Channel at the West end of the harbor is no longer used because Sand Island Access Road Bridge is no longer a drawbridge (Figure 4-29).

Sand Island is the primary container terminal and storage area, with the only access to the rest of Oahu via the Sand Island Access Road Bridge. Future expansion of the harbor includes development of a new container terminal on the land side of Sand Island Access Bridge (Figure 4-29).

More detailed aerial images of the harbor are shown in Figure 4-30 through Figure 4-32.

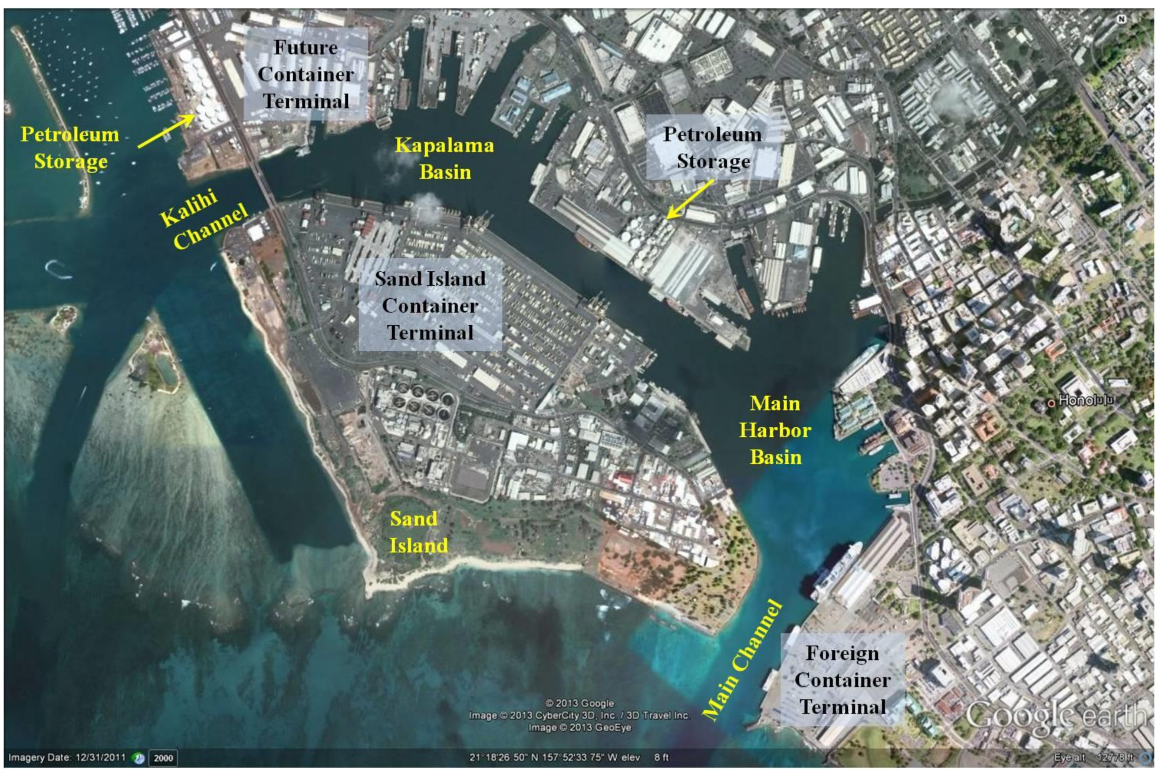

Figure 4-29: Honolulu Harbor, Oahu

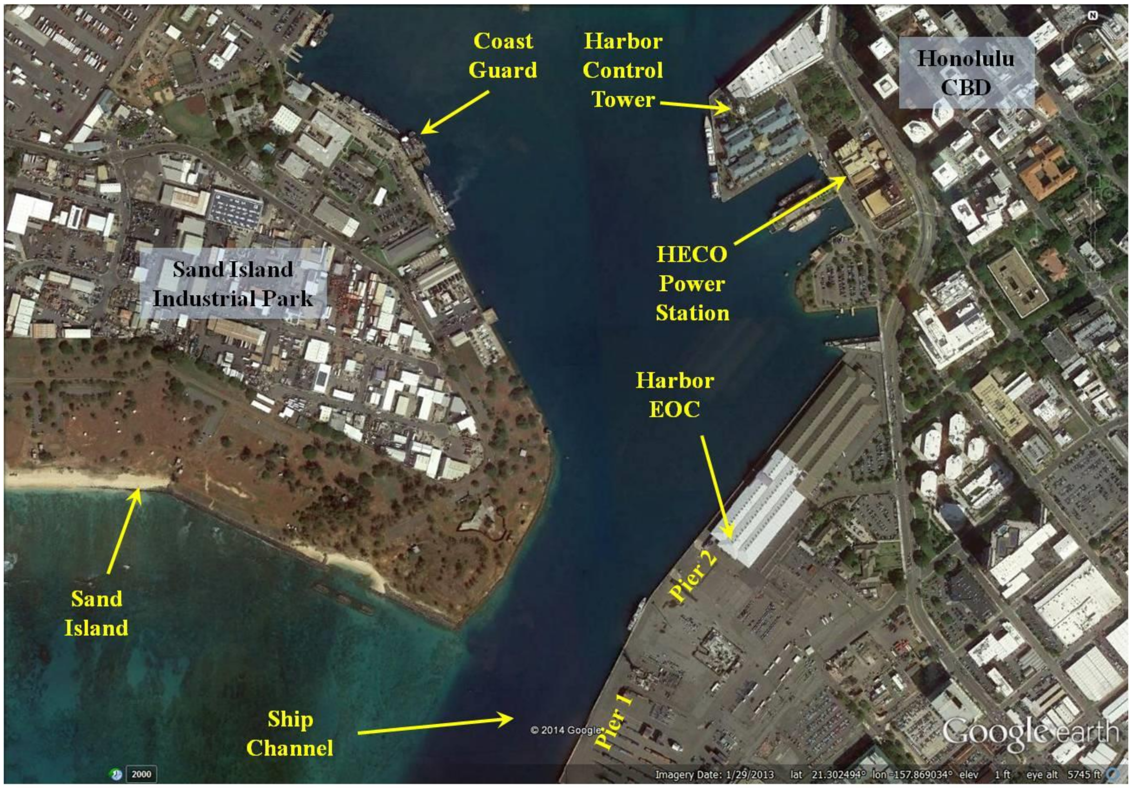

Figure 4-30: East end of Honolulu Harbor

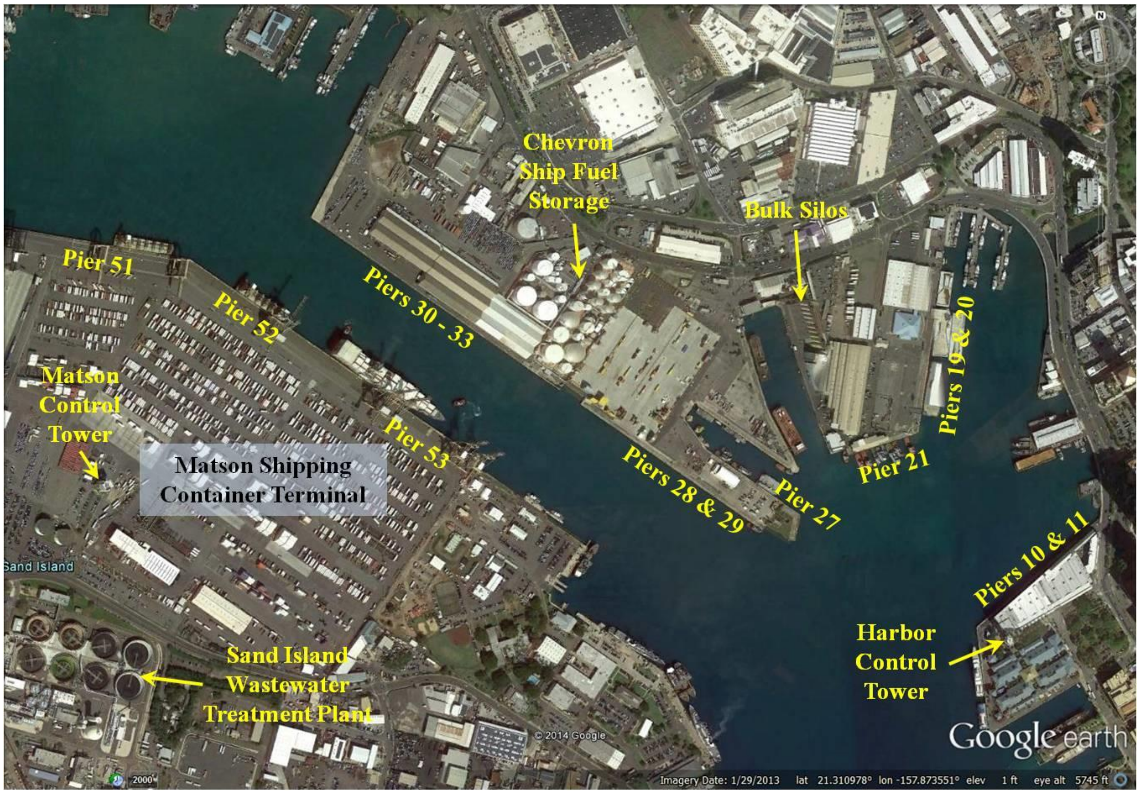

Figure 4-31: Center portion of Honolulu Harbor

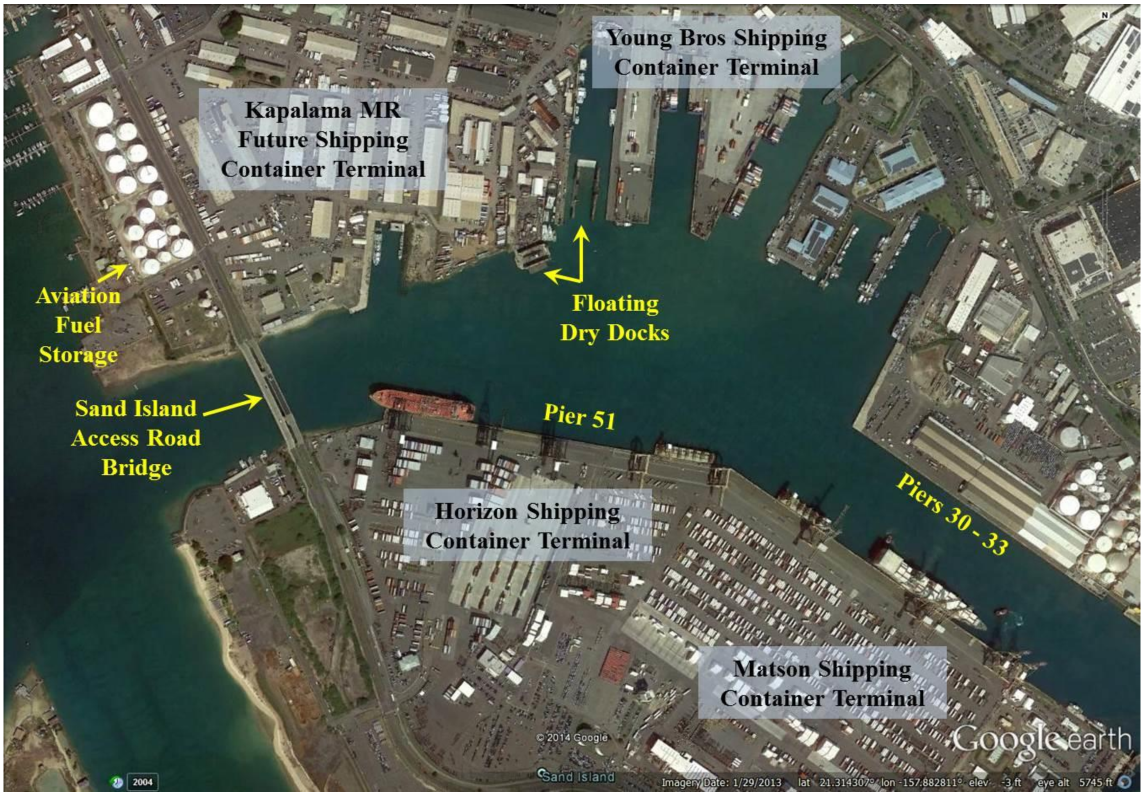

Figure 4-32: West end of Honolulu Harbor

Based on the US Army Corps hurricane simulations, the worst storm surge and characteristic wave height at Honolulu Harbor are generated by a storm following landfall track L2-C, with central pressure of 940 bars (CP940), radius of maximum winds of 60 km (R60), and forward speed of 22 knots (V22). This storm is designated as L2-C-CP940-R60-V22 on the Hawaii Storm Atlas (US Army Corps, 2014).

Figure 4-33 shows storm surge and characteristic wave height predictions for Oahu, while Figure 4-34 shows the predictions for Honolulu Harbor and adjacent coastline. Storm surge in Honolulu Harbor is predicted to reach 7-8 feet, resulting in partial inundation of Sand Island. The characteristic wave height in the harbor could reach 10 feet, particularly in the harbor entrance channel adjacent to Piers 1 and 2. Immediately outside of the harbor the wave heights rapidly increase to over 35 feet (Figure 4-34).

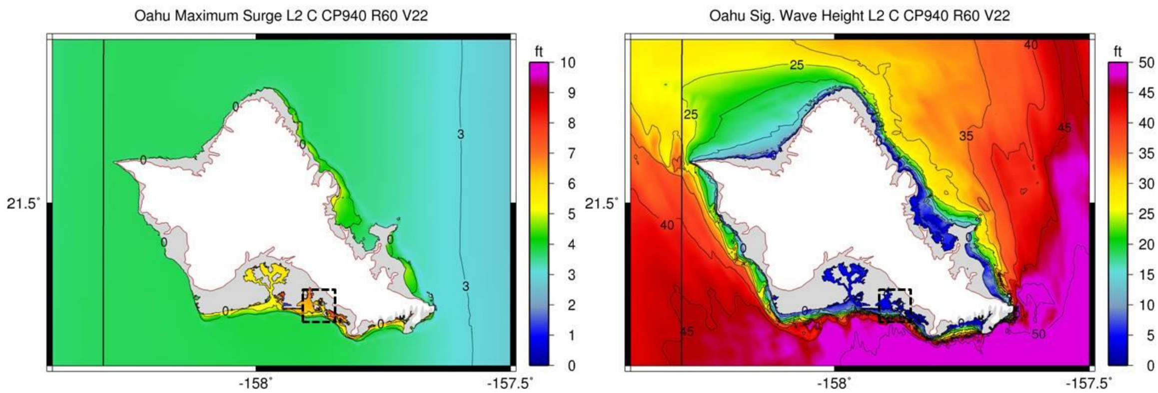

Figure 4-33: Storm surge and wave height predictions for Oahu for storm L2-C-CP940-R60-V22 (US Army Corps, 2014)

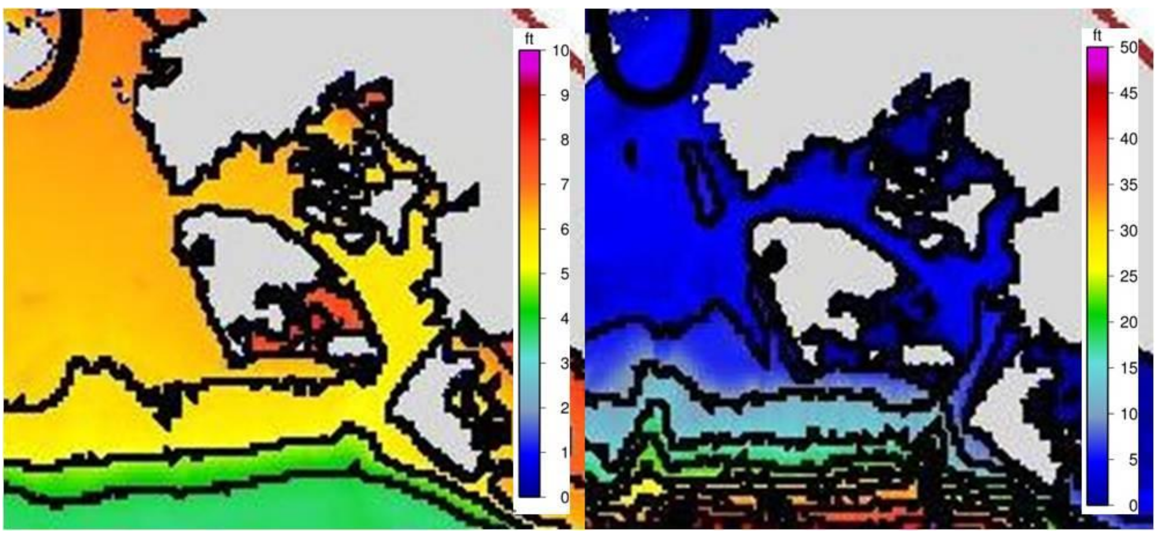

Figure 4-34: Storm surge and wave height predictions for Honolulu Harbor for storm L2-C-CP940-R60-V22 (US Army Corps, 2014)

Figure 4-35 shows the existing tsunami evacuation zone and the anticipated flow depth during the Great Aleutian Tsunami. All harbor facilities are within the current tsunami evacuation zone, and can anticipate flow depths up to 10 feet during the Great Aleutian Tsunami. Although the center of Sand Island is not currently in the tsunami evacuation zone, the GAT model predicts flow depths of 3 to 10 feet in this area.

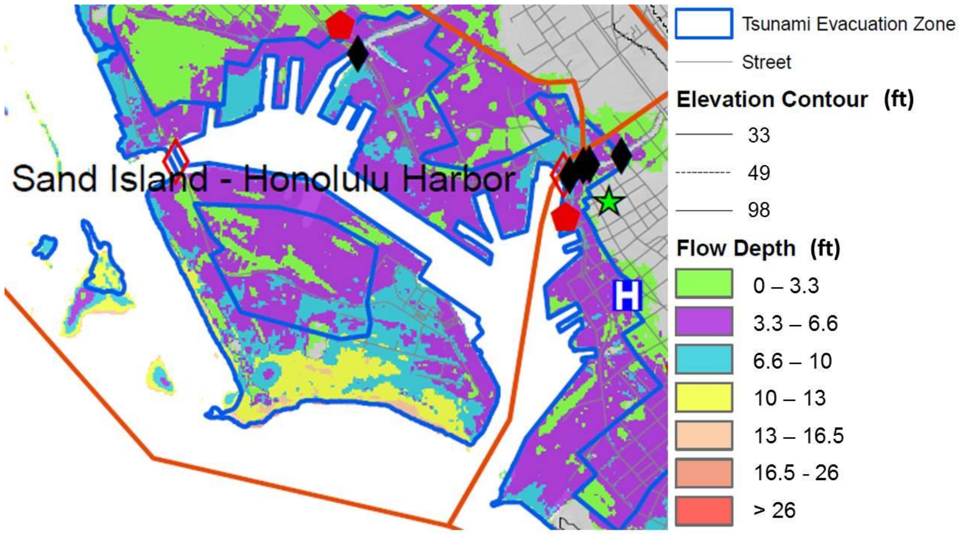

Figure 4-35: Honolulu Harbor Tsunami Inundation Predictions based on Great Aleutian Tsunami (Cheung, 2014)

Project team members met with Raymond Bode of Harbors Division on March 15, 2013, for a guided tour of Honolulu Harbor facilities. On March 19, 2013, the team met with HDOT Harbors Administrator, Davis Yogi, and Honolulu Harbor personnel to discuss harbor procedures during warning events.

4.4.1 Procedures during hurricane and tsunami warnings

When a warning is issued, the Coast Guard stationed on Sand Island (Figure 4-30) makes a determination as to whether or not to call for a mandatory evacuation of ships from Honolulu Harbor. Individual ships may decide to leave prior to the warning if they so choose. There are economic consequences to a mandatory evacuation because of the time and labor involved, and the delay in loading and unloading operations.

It is anticipated that a number of fishing vessels, floating dry docks and other moored barge vessels will remain in the harbor during the event (Figure 4-36). Some of these vessels will likely break their moorings because of the strong currents, resulting in potential grounding or impact with adjacent piers, buildings and other structures. In particular, non-seaworthy ships such as the Falls of Clyde cannot be evacuated and may sustain damage due to impact with piers and other vessels. They therefore pose an increased risk of sinking in the harbor.

During the 2010 Chile tsunami warning issued for all Hawaiian Harbors, ship evacuation at Honolulu Harbor took place from 7:15AM to 9:45AM on Saturday, February 27th. The first wave arrival was at 10:30AM. Evacuation requires linesmen, tug operators and pilots, all of whom need to be able to enter the harbor prior to or during the warning. It may also not be possible to fully secure all shipping containers on barges and ships prior to evacuation. It was suggested that table-top exercises of the evacuation operation would be beneficial. Makani Pahili exercises run annually by Hawaii Emergency Management Agency may provide a suitable platform for practicing harbor evacuation procedures.

Figure 4-36: Fishing and moored barge vessels that may remain in port during an inundation event

During a warning, port authorities are stationed at the Harbor Emergency Operations Center (EOC) on the second floor of the warehouse building on Pier 2, and the Harbor Control Office on the 9th Floor of the Aloha Tower (Figure 4-30). These locations are not evacuated during the event. Radio communications will be used between these centers and Honolulu City and County EOC and Hawaii Emergency Management Agency (Hi-EMA), formerly State Civil Defense. Coast Guard representatives are typically stationed at both EOCs.

Once the warning has passed, the Coast Guard will make the decision as to when it is safe for ships to return to the port.

4.4.2 Experience during Hurricane Iselle

A tropical storm watch was issued for Oahu at 5AM local time on Wednesday, August 6, 2014, followed by a tropical storm warning issued at 5PM the same day. The warning was discontinued at 3:28PM on Friday, August 8. The Coast Guard officially closed Honolulu Harbor on Thursday afternoon August 7. The Harbors Emergency Operations Center on Pier 2 was activated to coordinate response of all ports in the State. On the whole, operations went smoothly, though interagency communications could be improved, possibly through tabletop exercises. The all-clear was announced and the harbor opened to traffic at 4:00PM on Friday, August 8.

Because of the advance warning of possible effects from Hurricane Iselle, large ships were able to schedule their arrivals and departures from Honolulu Harbor to avoid the storm. Sause Brothers, which operates a series of tugs for towing barges between the Hawaiian Islands, was also able to evacuate all of their vessels prior to closure of the port. According to Brad Rimell, four of Sause Brothers' tugs were in Honolulu Harbor prior to arrival of the storm. All tugs evacuated with loaded barges well before closure of the port. Because of their relatively slow speed, the tug and barge combination is not able to outrun the storm. Some of the barges went well South of Oahu so as to be on the South side of the projected storm track, while another barge went North of Molokai, to avoid waves and wind associated with the storm. After the storm passed, the tugs continued to deliver the barges and their cargo to the appropriate ports on the neighbor islands.

Smaller passenger vessels that planned to ride out the storm in the harbor were required to submit mooring plans to the Coast Guard. These plans were then reviewed by the harbor master and either approved or returned for modifications within 24 hours. There were less than 12 such vessels that remained in the port, along with tugs, Coast Guard and other smaller vessels, without incident during the storm.

Because of the advance warning of the hurricane arrival, all companies handling shipping containers at Honolulu Harbor were able to ensure that containers with hazardous materials, livestock or perishable items were either delivered to clients or otherwise removed from the port.

There was no damage reported to any vessels, shipping containers, harbor equipment or buildings during this event.

4.4.3 Harbor Emergency Operations Center

The harbor EOC is currently located on the second floor of the reinforced concrete warehouse on Pier 2 (Figure 4-37). This location is approximately 12 feet above Pier 2, which should be adequate to avoid inundation during even the GAT event (Figure 4-35). The building is a relatively sturdy reinforced concrete frame building with infill masonry walls (Figure 4-38). Although there may be localized damage to the building due to impact from floating shipping containers, it is likely that the building will survive the anticipated flow depths of less than 10 feet above Pier 2. No evaluation has been performed of the tsunami capacity of this structure.

The emergency generator for this EOC is currently on the ground floor where it could be rendered inoperable by water damage. All emergency power generation and other critical equipment for this EOC should be located on the second level or roof to ensure continued functioning of the EOC during and after the event.

The Harbor Control Center on the 9^{th} floor of Aloha Tower will also remain occupied and active during a hurricane or tsunami event (Figure 4-30). This tower is a sturdy reinforced concrete structure that should survive the anticipated flow depths of less than 10 feet (Figure 4-39). No structural evaluation has been performed of the Aloha Tower to evaluate its tsunami resistance. Again, all emergency power generation and other critical equipment for the Harbor Control Center should be located above the 2^{nd} floor level of the Aloha Tower.

Figure 4-37: Honolulu Harbor EOC on second floor of warehouse building on Pier 2

Figure 4-38: Details of reinforced concrete framing for Honolulu Harbor EOC building

Figure 4-39: Aloha Tower with Harbor Control Center on 9th Floor level

4.4.4 Harbor Piers

Honolulu Harbor has over 50 numbered piers. Based on the Great Aleutian Tsunami simulation, all of these piers are expected to be inundated by flow depths from 3 to 10 feet (Figure 4-35). Many of the piers are pile supported, making them vulnerable to uplift due to hurricane storm surge and wave action, or tsunami inflow conditions. The primary piers for cargo delivery to Honolulu are those associated with shipping container terminals.

Pier 1 is currently used by Pasha Hawaii for roll-on roll-off container and vehicle shipping (Figure 4-30). Because of its proximity to the mouth of the harbor, and exposure to wave action during storms, this pier was constructed with a “pressure relieving precast panel” system (Figure 4-40). Based on the weight of the panels and the soffit area exposed to uplift pressure, these panels can be expected to lift when the pressure below the pier deck exceeds 175 psf. Once the relief panels have opened a gap at the back of the pier, the uplift pressure on the remaining pier deck will drop significantly, thereby reducing the potential for further damage to the pier.

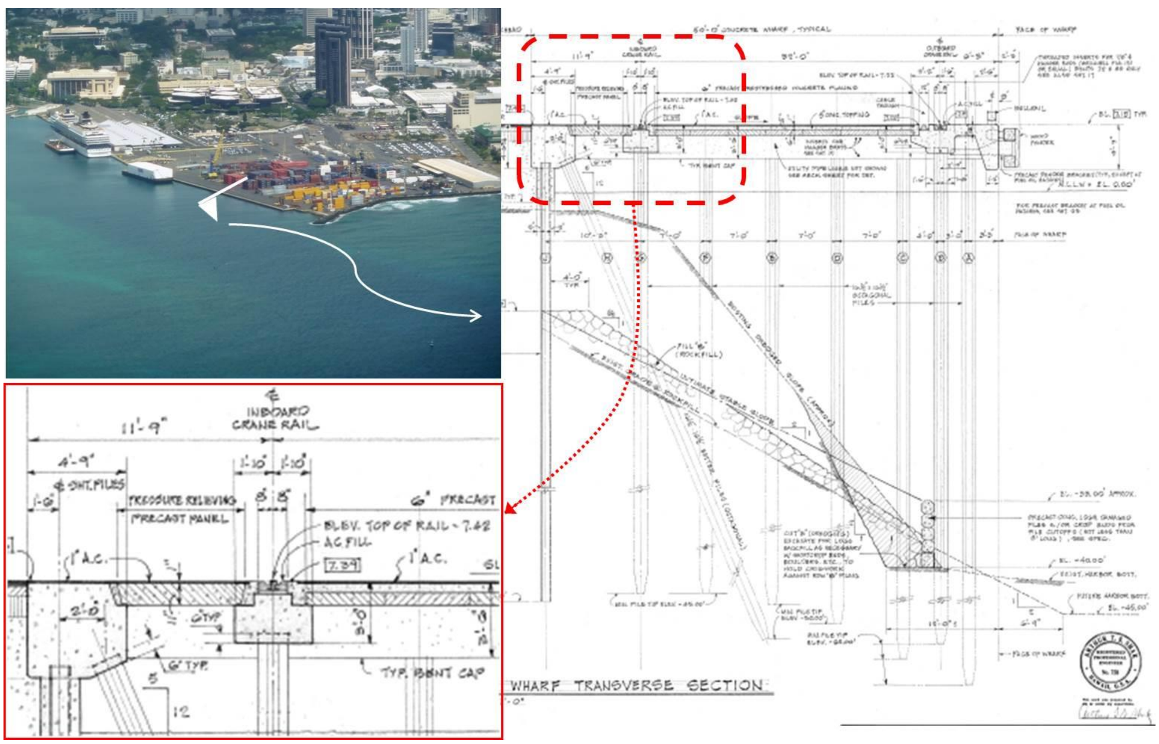

Figure 4-40: Drawing details of Pier 1 showing “pressure relieving precast panels”

The majority of trans-oceanic shipping container handling currently takes place at Pier 51 (Horizon Lines) and Piers 52 and 53 (Matson Shipping) on Sand Island (Figure 4-32). Figure 4-41 shows an end view of Pier 53, with closely spaced driven piles integrally connected to the deck beams and slab. These piers are designed to support significant gravity loads, including the cranes used to load and offload shipping containers. They are therefore relatively substantial and would not be expected to suffer any damage during a hurricane or tsunami.

Piers 39 through 41 are used by Young Brothers Shipping for interisland barge transport of shipping containers and pallet cargo (Figure 4-32).

The majority of the active piers at Honolulu Harbor are relatively recent construction and in good condition. However, there are some older piers that may suffer damage during an extreme event (Figure 4-42). Provided the functions served by these older piers are not critical to harbor operations, there is no need to strengthen them for hurricane or tsunami loads.

Figure 4-41: End view of Pier 53 with shipping container handling crane

Figure 4-42: Pier 21 (left) and Pier 27 (right) represent older pier construction in Honolulu Harbor

4.4.5 Shipping Container Storage Areas

Shipping containers are primarily handled and stored at five locations in Honolulu Harbor, namely:

- Pasha Hawaii and International Cargo at Pier 1
- Horizon Lines at Pier 51
- Matson Shipping at Piers 52 and 53
- Young Brothers at Piers 39 through 41
- Newly refurbished Pier 29

Shipping containers are generally stacked 3 to 4 high (Figure 4-43) without any restraint or interconnection between containers. With anticipated flow depths of 3 to 10 feet, all enclosed shipping containers would be anticipated to float and be displaced with the flow. A stack of four empty 40 foot containers requires less than 2 feet flow depth in order to float. A fully loaded 20ft container only requires 3 feet of inundation to float. A possible solution to this problem would be the use of open-sided containers at the bottom of container stacks to avoid buoyancy effects till the flow reaches the second layer of enclosed containers.

Containers with hazardous materials are generally not stored at the harbor, but are transported directly to their final destination. Similarly containers with perishable supplies do not stay in the harbor for extended periods. During a hurricane or tsunami warning, efforts will be made to remove containers with hazardous materials and perishable products. However, limited access to the main container areas on Sand Island, and long haul distances to suitable storage areas outside of the inundation zone make mass evacuation of shipping containers challenging.

Figure 4-44 shows three potential shipping container evacuation sites adjacent to Honolulu Harbor. These sites are at the Puuhale Elementary School, Kalakaua District Park and Farrington High School, located 2 miles, 2.5 miles and 3 miles, respectively, from the Sand Island container storage area. All of these sites have open field areas where containers could be stored during a warning. They are all outside of the anticipated inundation zone resulting from the Great Aleutian Tsunami (Figure 4-44, right).

The Harbor Administration is currently preparing for development of a new container storage facility at the existing Kapalama Military Reservation (Figure 4-32). This facility will have the advantage of being on the land-side of the Sand Island Access Road Bridge, but will still have relatively long haul distances to move containers to safe locations outside of the inundation zone. It also has the disadvantage that it is at the extreme end of the harbor basin, therefore requiring sonar location and removal of sunken debris for most of the harbor basin before ships can be allowed back to dock at this facility.

Figure 4-43: Container stacks at Matson facility on Sand Island

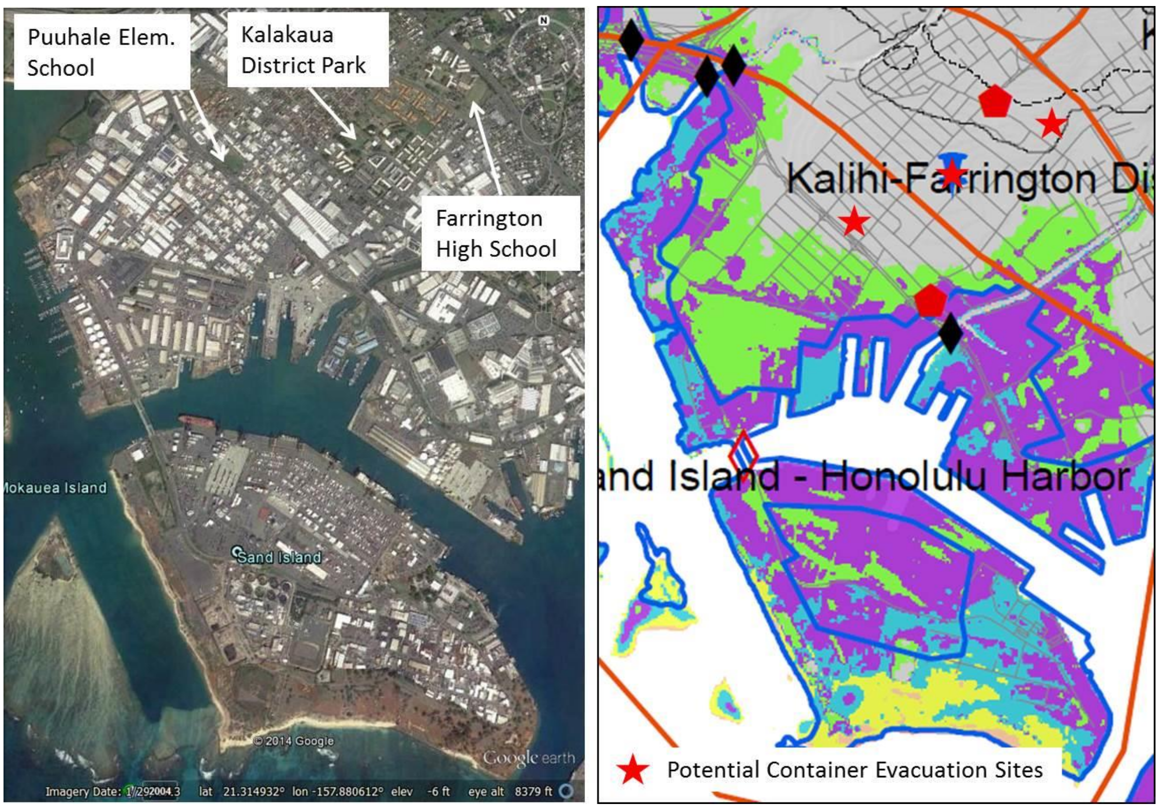

Figure 4-44: Potential shipping container evacuation sites adjacent to Honolulu Harbor

Shipping containers on Sand Island are offloaded using gantry cranes (Figure 4-45). These cranes will likely experience impact strikes from floating shipping containers during an inundation event. These impacts will only affect the lower sections of the crane legs, which are constructed as box columns using relatively thick steel plate. It is unlikely that the debris strikes will cause any structural damage to the crane framing elements. However, water and debris impact damage to electrical and other sensitive equipment located at the base of the cranes will likely make the cranes inoperable after an event (Figure 4-45).

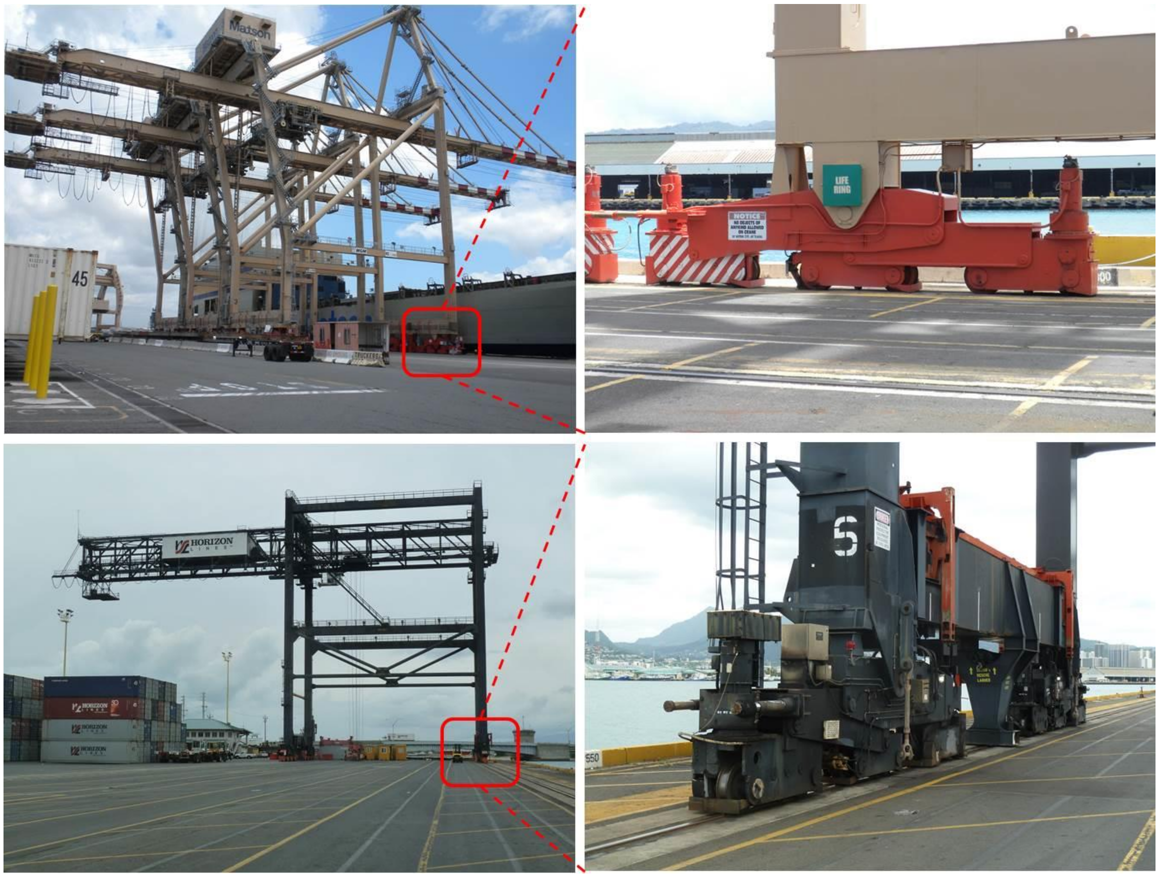

Figure 4-45: Container Cranes at Matson (top) and Horizon (bottom) on Sand Island

Shipping containers and other cargo at Young Brothers (Piers 39-41) is handled by mobile fork-lifts. These can be relocated outside of the inundation zone during a warning so that they are available for restacking and salvaging damaged shipping containers after the event.

On Pier 1, a mobile crane is used by Hawaii Stevedores Inc. to offload shipping containers (Figure 4-46). Although it is mobile, the crane cannot be moved from the pier because of its size and weight. It will likely suffer damage to electrical and mechanical equipment below the inundation level.

Matson has in the past used a roll-on roll-off facility at Pier 1, with no crane equipment. The ramp structures used in this operation could be damaged by impact from floating shipping containers, and may need repair after an inundation event (Figure 4-47).

In the event of a major inundation event at Honolulu Harbor, it is likely that a number of shipping containers will sink to the bottom of the harbor. Efforts are being made to acquire side sonar boats for this harbor (and neighbor island harbors) to scan for debris that might reduce draft in the harbor channel and basin. Extraction of this debris may pose concerns from an Environmental Protection Agency (EPA) standpoint, since handling and disposal of such debris would need to comply with EPA rules unless emergency conditions can override those requirements.

Figure 4-46: Hawaii Stevedores Inc. mobile crane at Pier 1

Figure 4-47: Ramp used for roll-on roll-off loading operations at Pier 1

Because of the potential for restricted capacity at Honolulu Harbor immediately after a disaster, the harbor administration has developed three alternatives for accepting incoming cargo.

- A Memorandum of Understanding (MOU) has been created between the State and the US Navy to facilitate an Alternate Port Concept. This will allow for the use of a pier in Joint Base Pearl Harbor Hickam (JBPHH) for emergency cargo handling after a disaster. A mobile crane has been procured to service cargo ships in JBPHH. In addition, ship-mounted cranes can be used to load and off-load cargo (Figure 4-48).

- Pier 1 and 2 could be used with Pasha Hawaii roll-on roll-off facilities, or with the HSI mobile crane if it is operational. Because these piers are close to the harbor entrance, they would be the first to become available after scanning for and clearing debris from the ship channel.
- Kalaeloa Barbers Point Harbor may not suffer the same damage as Honolulu Harbor, so it could be used for container handling in addition to the current bulk handling operations.

Figure 4-48: Container barge with crane for loading and unloading

4.4.6 Fuel Storage Facilities

There are two primary fuel storage locations within or near Honolulu Harbor. The first is a tank farm adjacent to Pier 30 where Chevron stores fuel for ships (Figure 4-31). This tank farm consists of three adjoining containment areas surrounded by reinforced concrete walls with heights of 3, 6 and 10 feet above the pier (Figure 4-49). With flow depths for the Great Aleutian Tsunami estimated at 3.3 to 6.6 ft. in this location (Figure 4-35), it is likely that the 10 ft. high wall will be sufficient to prevent inundation of the tanks in that enclosure. The 6 ft. high may also be adequate, but the 3 ft. high wall will likely be overtopped. This could lead to flotation of the tanks and damage to electrical and mechanical equipment in the tank enclosure. Because of the shipping container storage area adjacent to the tank farm, there is also a high potential for debris strikes on the tanks, piping and other equipment associated with the tank farm (Figure 4-50).

Figure 4-49: Chevron ship fuel storage tanks with 3 ft. and 10 ft. high containment walls

Figure 4-50: Proximity of Chevron tank farm to shipping containers on Piers 29 and 30

The second major fuel facility is the aviation fuel storage tank farm adjacent to Sand Island Access Road (Figure 4-32). This facility is on the shoreline of Keehi Lagoon and is surrounded by only a 3 ft. high containment wall (Figure 4-51 and Figure 4-52). Flow depths at this location during the GAT event are anticipated to exceed 6 ft. (Figure 4-35), meaning that these walls will be overtopped. The tank farm is also exposed to debris impact from the Keehi Lagoon Small Boat Harbor to the West (Figure 4-53), and shipping containers at the proposed new shipping container storage facility at Kapalama Military Reservation to the East (Figure 4-54).

Figure 4-51: Aviation Fuel Storage tank farm between Sand Island Access Road and Keehi Lagoon

Figure 4-52: Aviation Fuel Storage tank farm with 3 ft. high containment wall

Figure 4-53: Proximity of Aviation Fuel Storage tanks to Keehi Lagoon Small Boat Harbor

Figure 4-54: Proximity of Aviation Fuel Storage tanks to existing and proposed new shipping container storage facility at the Kapalama Military Reservation

Because of the critical nature of both fuel storage locations for ship and airplane refueling operations, it is important that these facilities be protected from damage during a major inundation event. Alternatively, fuel storage outside of the inundation zone might be able to serve as an emergency reserve. For example, fuel storage at the Red Hill underground tank farm for Joint Base Pearl Harbor Hickam could be used as a reserve location for both ship and aviation fuel. This would require a Memorandum of Understanding between the State and US Navy for shared use of this facility after a disaster.

4.4.7 Bulk Handling Facilities

The majority of bulk handling facilities on the Island of Oahu are located at Kalaeloa Barbers Point Harbor (See Section 4.5.5). However, bulk importation and storage of wheat is performed at the grain silos adjacent to Pier 23 in Honolulu Harbor (Figure 4-31 and Figure 4-55). Although it is unlikely that the reinforced concrete silos will be damaged by inundation, associated electrical and mechanical equipment will likely be inoperable due to submersion in salt water or impact from floating debris.

Figure 4-55: Grain Silos adjacent to Pier 23 in Honolulu Harbor

4.4.8 Harbor Buildings

A number of important buildings and various warehouses are located within the inundation zone anticipated for Honolulu Harbor during a Great Aleutian Tsunami event. The Harbor Office located in the Aloha Tower, and the EOC located in the warehouse building on Pier 2, were discussed earlier (see Section 4.4.3). The Coast Guard location on Sand Island (Figure 4-30) has a number of buildings that could be damaged during an event. These buildings were not inspected or evaluated for storm surge or tsunami inundation.

The following is a discussion of selected warehouse structures within Honolulu Harbor. It is not a comprehensive presentation of all harbor buildings, but gives an overview of some of the larger and more important structures. None of these buildings was evaluated structurally for storm surge and wave loading or tsunami loading.

The Matson container storage facility on Sand Island is controlled from a 6 story control tower (Figure 4-56). With anticipated flow depths less than 10 feet at this location, it is unlikely that this tower will be structurally compromised during an inundation event, even though it will be exposed to impact from floating shipping containers. No structural evaluation was performed to verify this assumption. It is anticipated that the control tower will remain occupied by a skeleton staff during an inundation event so as to speed cleanup and recovery operations.

A large reinforced concrete warehouse at Piers 10 and 11 is used for cruise ship loading and unloading, as well as housing the harbor operations offices (Figure 4-31). A portion of this structure is a reinforced concrete beam-slab elevated floor supported by concrete columns (Figure 4-57, left), while the rest of the structure consist of steel roof trusses supported on reinforced concrete columns (Figure 4-57, right). The flow depths at this location are not anticipated to reach the second level or roof framing, so would only affect the column and wall elements.

Figure 4-56: Control tower at Matson Shipping Container facility on Sand Island.

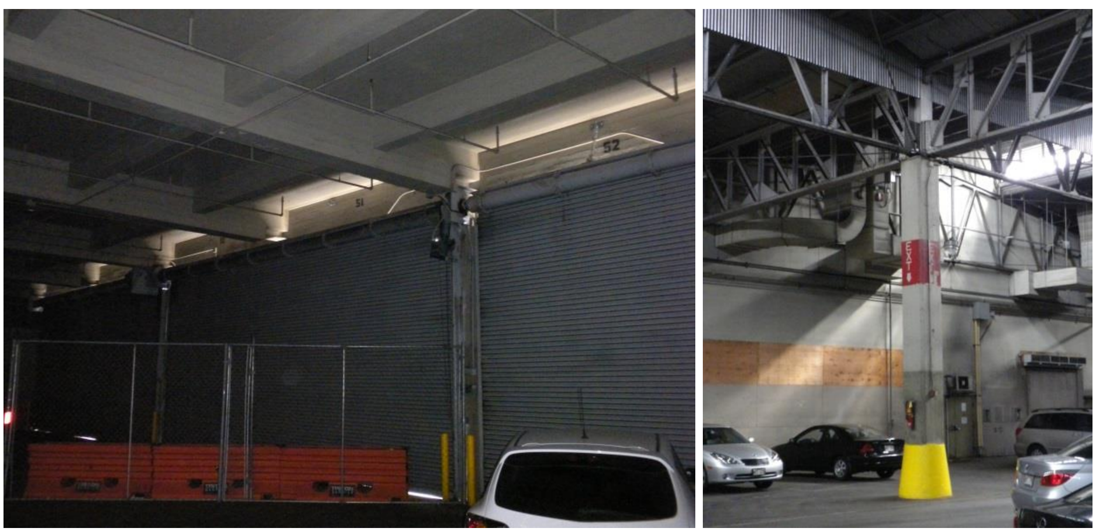

Figure 4-57: Structural framing members in warehouse on Piers 10 and 11.

A warehouse structure on Pier 19 was used in conjunction with the interisland ferry during its tenure (Figure 4-58). This steel framed building is clad with sheet metal, which is expected to suffer considerable damage during an inundation event. The steel columns are also susceptible to impact damage, even though they have been encased in concrete for the lower 3 feet. This warehouse currently has limited use and is probably not critical to harbor operations.

A large warehouse on Pier 22 is used for handling and storing pallet cargo and other non-containerized items (Figure 4-59). The building has a steel truss roof system supported on exterior walls consisting of reinforced concrete frames with infill masonry panels. These exterior masonry walls and relatively slender columns may be vulnerable to high velocity flow loading and debris impact damage. The contents of the building will also be exposed to water damage during an inundation event.

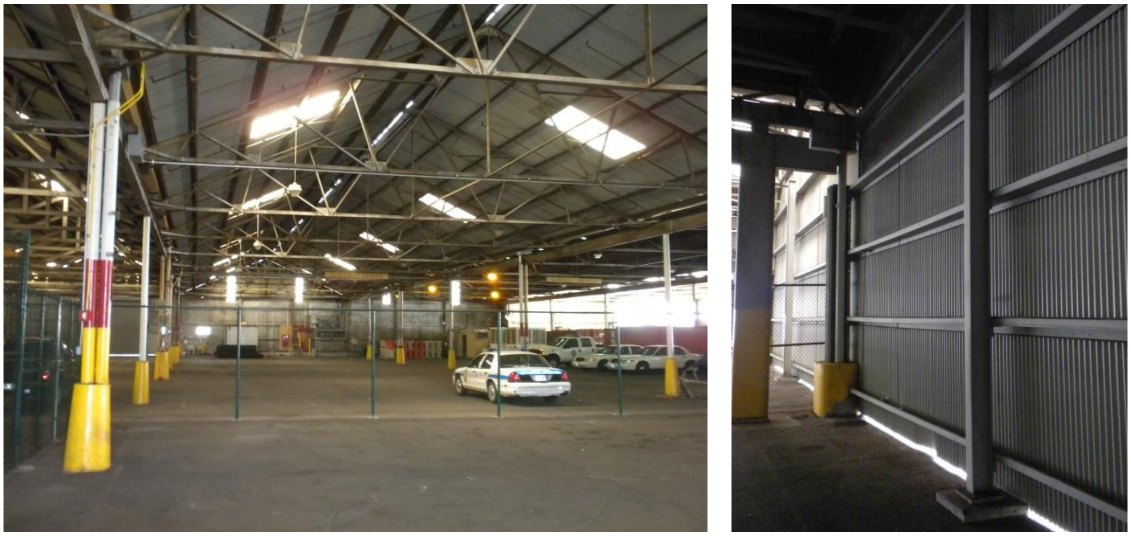

Figure 4-58: Interior views of warehouse on Pier 19

Figure 4-59: Interior and exterior views of warehouse on Pier 22

A large warehouse on Piers 31 to 33 is currently used for handling and storage of non-containerized cargo (Figure 4-60). Inundation will only affect the walls and columns of this structure. The steel columns are supported on concrete pedestals (Figure 4-61, left). The exterior wall is either sheet metal on girts (Figure 4-61, center) or concrete frame with infill masonry walls (Figure 4-61, right). All of these elements, including the cross-bracing, could be damaged by hydrodynamic flow and debris impacts.

Two large warehouses in the Matson shipping container facility on Sand Island also consist of steel framed buildings with sheet metal cladding (Figure 4-62). Damage to the sheet metal and localized impact damage to the lower extents of the columns can be anticipated during an inundation event.

Figure 4-60: Steel framed warehouse on Piers 31 to 33

Figure 4-61: Details of framing members in warehouse on Piers 31 to 33

Figure 4-62: Pre-manufactured steel framed warehouses on Sand Island

4.4.9 Adjacent Critical Facilities

Honolulu Harbor is located at the edge of the Honolulu central business district (Figure 4-30 and Figure 4-63). Hawaiian Electric Company (HECO) also maintains an emergency backup power plant immediately adjacent to the harbor (Figure 4-63). In addition to hydrodynamic flow loads, the first row of these buildings will be exposed to potential impacts from floating debris from the harbor, including potentially large barges, boats and fishing vessels. Nimitz highway, a major artery that runs along the North edge of the harbor, is also exposed to potential impact loads and debris accumulation during an inundation event (Figure 4-64).

Figure 4-63: View from Aloha Tower looking East, showing Central Business District and HECO power plant (yellow structure in center)

Figure 4-64: Nimitz highway running around the North side of Honolulu Harbor

The main wastewater treatment plant for Honolulu is located adjacent to the port facilities on Sand Island (Figure 4-31). During a major inundation event, much of the electrical and mechanical equipment at this facility will be damaged and rendered inoperable (Figure 4-65). There is potential for large sewage spills that affect Sand Island and the harbor basin. This will create hazardous conditions for first responders and early recovery efforts in and around the harbor. This plant treats the majority of wastewater from Honolulu. Extended downtime will result in discharge of untreated sewage directly into the ocean with serious health and environmental consequences.

Figure 4-65: Sand Island Wastewater Treatment Plant

4.5 Kalaeloa Barbers Point Harbor, Oahu

Being close to Campbell Industrial Park at the Southwest end of Oahu, Kalaeloa Barbers Point Harbor serves the function of bulk material handling not possible at Honolulu Harbor. This includes a coal bulk unloader system and a pneumatic cement pump system. This harbor also handles all scrap metal transported out of Hawaii. The harbor is not currently used for container handling or storage. The harbor channel is 42 feet deep while the depth adjacent to the piers is 38 feet (State of Hawaii, 2004).

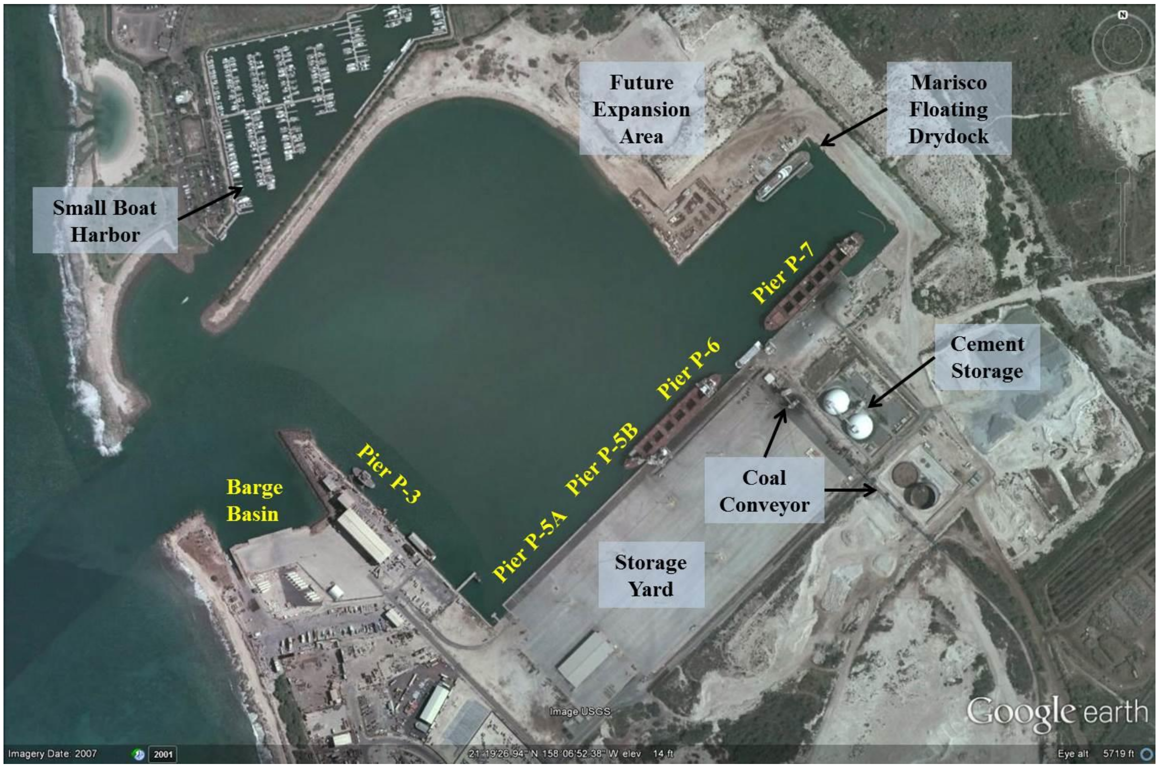

Figure 4-66: Kalaeloa Barbers Point Harbor, Oahu

Based on the US Army Corps hurricane simulations, the worst storm surge and characteristic wave height at Kalaeloa Barbers Point Harbor are generated by a storm following landfall track L4-A, with central pressure of 940 bars (CP940), radius of maximum winds of 45 km (R45), and forward speed of 22 knots (V22). This storm is designated as L4-A-CP940-R45-V22 on the Hawaii Storm Atlas (US Army Corps, 2014).

Figure 4-67 shows storm surge and characteristic wave height predictions for Oahu, while Figure 4-68 shows the predictions for Kalaeloa Barbers Point Harbor and adjacent coastline. Storm surge in Kalaeloa Barbers Point Harbor is predicted to reach 6-7 feet, while the characteristic wave height in the harbor could reach 8 feet, with slightly larger waves in the harbor entrance channel. Immediately outside of the harbor the wave heights rapidly increase to 50 feet (Figure 4-68).

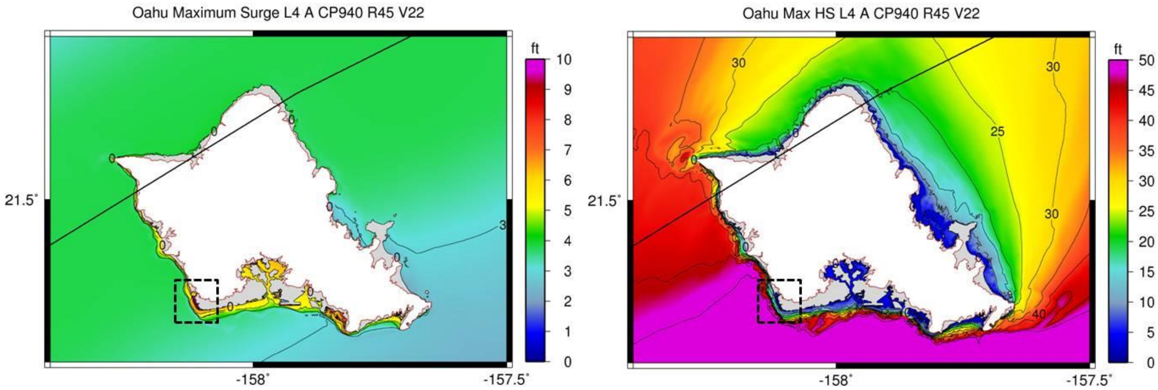

Figure 4-67: Storm surge and wave height predictions for Oahu for storm L4-A-CP940-R45-V22 (US Army Corps, 2014)

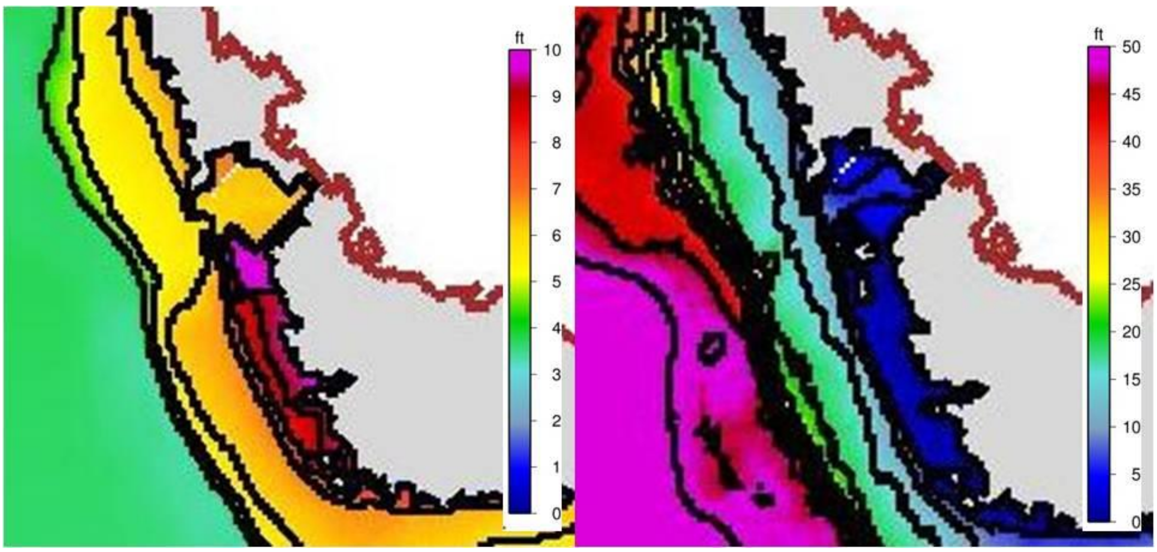

Figure 4-68: Storm surge and wave height predictions for Kalaeloa Barbers Point Harbor for storm L4-A-CP940-R45-V22 (US Army Corps, 2014)

Only the barge basin and Pier P-3 are currently inside the tsunami evacuation zone (Figure 4-69). However, based on the Great Aleutian Tsunami scenario, all harbor facilities will be inundated by flow depths exceeding 16 feet (Chueng, 2014).

Team members met with harbor aggent, Logan Williams, on March 1, 2013. After a discussion of harbor procedures during hurricane and tsunami warnings, and the performance of these procedures during recent tsunami events, the team was taken on a tour of the port facilities.

4.5.1 Procedures during hurricane and tsunami warnings

Harbor Administrator Williams described the harbor procedures during a warning event as follows:

- Large ships are expected to leave the harbor for deep water, but the decision is sometimes left up to the ship owner and/or captain.

- If three or more large ships are in port at the time of a warning, there is not sufficient time and personnel to evacuate them all to deep water. Stevedores and pilots are required for ships to cast-off and leave the harbor.
- Marisco Shipyard maintains a floating dry dock opposite Pier P-7 (Figure 4-70). This dry dock will not be evacuated during a warning, so may break loose from its moorings and present a large debris impact hazard during the event.
- The two resident tugs, and any inter-island barges in the harbor, will be evacuated to deep water when a warning is announced.

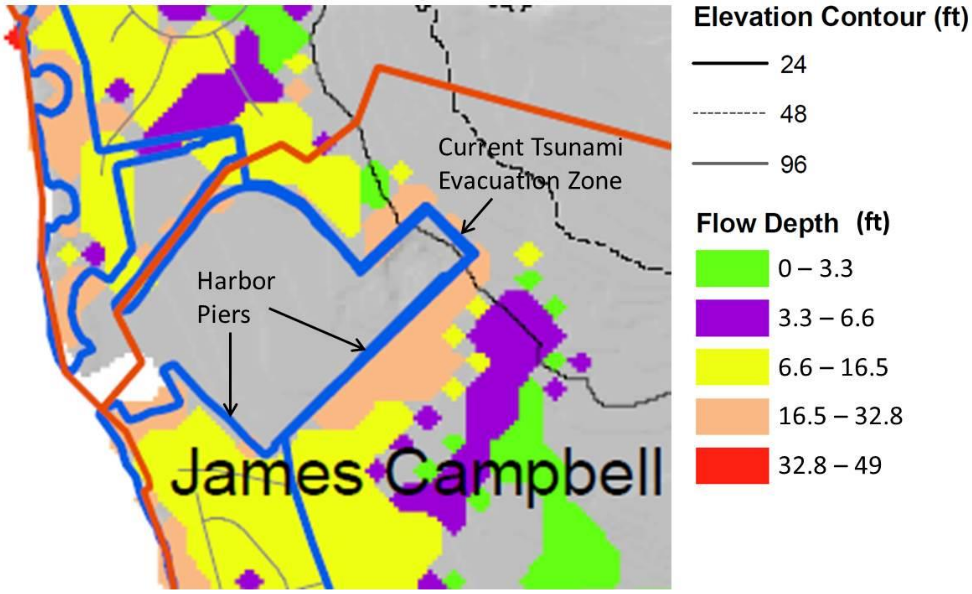

Figure 4-69: Kalaeloa Barbers Point Harbor Tsunami Inundation Predictions based on Great Aleutian Tsunami (Cheung, 2014)

Figure 4-70: Marisco Shipyard floating dry dock opposite Pier P-7

4.5.2 Experience during Hurricane Iselle

A tropical storm watch was issued for Oahu at 5AM local time on Wednesday, August 6, 2014, followed by a tropical storm warning issued at 5PM the same day. The warning was discontinued at 3:28PM on Friday, August 8. The coast guard closed Kalaeloa Barbers Point harbor on the evening of Thursday, August 7, and reopened the port at 4:00PM on Friday, August 8.

The only vessels in the port during the storm were the interisland cement barge and the Marisco floating drydock, both of which homeport at this location. Mooring plans for these vessels had been pre-approved and were implemented well before the effects of the storm were felt. The harbor master was in constant contact with the harbors' EOC in Honolulu throughout the event. All non-essential personnel were evacuated from the port for the duration of the closure, and no damage to facilities or vessels occurred as a result of the storm.

4.5.3 Harbor Piers

All piers at Kalaeloa Barbers Point harbor are relatively new construction (Figure 4-71). They consist of pile supported reinforced concrete beams and deck, with integral connections between the piles and deck. The closely spaced piles provide significant resistance to uplift of the pier during storm surge and wave action, or tsunami inundation. It is not anticipated that the piers will be damaged by hydrodynamic loading. However, damage due to impact from large ships is possible, particularly if the ships cannot be evacuated to deep water prior to inundation.

Figure 4-71: Ship berthed at Pier P7 at Kalaeloa Barbers Point Harbor

4.5.4 Shipping Container Storage Areas

There are currently no active large scale container handling operations at Kalaeloa Barbers Point Harbor, though there are some containers stored in and adjacent to the storage yard (Figure 4-66).

4.5.5 Bulk Handling Facilities

One of the major functions of Kalaeloa Barbers Point Harbor is to provide bulk handling facilities for Campbell Industrial Park and the rest of Oahu. The following bulk materials are handled on a regular basis:

- Coal – transported via conveyor belt to AES Power Plant in Campbell Industrial Park
- Fuel – transported via underground pipeline to Chevron and Tesoro refineries
- Cement – stored in dome facility on port property prior to transport to Hawaii Cement
- Steel - both incoming fabricated steel and outgoing scrap steel for recycling
- Sand and stone from British Colombia as aggregate for the local construction industry
- Lumber from mainland and other sources for local construction industry

Many of these materials are then transported by inter-island barges to the other Hawaiian Islands. Loss of use of Kalaeloa Barbers Point Harbor would have devastating effects not only on Oahu, but on all Hawaiian Islands, because the vast majority of incoming bulk handled items rely entirely on this harbor. Even though incoming ships could be redirected to other ports, they would not have the equipment required to efficiently offload, store and distribute the bulk materials.

The first three items listed above are critical to operation of power plants, vehicular traffic and the construction industry on Oahu and throughout the Hawaiian Islands.

Coal Handling Equipment

Approximately 650,000 tons of coal is offloaded annually using the bucket/screw lift shown in Figure 4-72. It is then transported by a 1.6 mile long conveyor belt system to the AES power plant in Campbell Industrial Park. Both the offloading equipment and conveyor belt are exposed to potential floating debris impacts. Electronic components of the equipment will also be damaged if submerged in seawater during the event. It is likely that a major inundation event will result in an extended breakdown on this coal bulk handling equipment, leading to downtime for the AES power plant. This power plant generates about 11% of Oahu’s commercial electricity supply (Wikipedia, 2014), so provided other power generation facilities are still operational, the island electrical grid could likely be maintained without power from the AES plant.

Figure 4-72: Bulk coal handling equipment at Pier P-6

Fuel Handling and Distribution

The majority of liquid fuels are delivered via off-shore transfer stations located South of Campbell Industrial Park. However, a considerable amount of fuel is also delivered at Piers P-5A and P-5B. This fuel is transported via underground pipelines to the Chevron and Tesoro refineries in Campbell Industrial Park. Damage to the off-shore transfer stations during a hurricane or tsunami would make this Kalaeloa Barbers Point Harbor fuel handling capability vital to power generation and vehicular transportation on Oahu and the other Hawaiian Islands. Because the majority of the pipeline is underground, it is protected from hydrodynamic loading and floating debris strikes. However, any electronic equipment and pumps required to transport the fuel may be at risk of water damage during inundation.

Cement Handling and Storage

Kalaeloa Barbers Point Harbor is the only harbor in Hawaii that can accept bulk deliveries of cement in ocean-going ships. Equipment at Pier P-6 is dedicated to this task (Figure 4-73). The cement is transported pneumatically to large storage domes adjacent to Pier P-6 (Figure 4-74). It is then either transported to the Hawaii Cement facility in Campbell Industrial Park for use on Oahu, or transported by barge to the other Hawaiian Islands.

Water damage to the electronics or motors operating the offloading and pneumatic transport equipment could potentially lead to extended downtime for this bulk cement handling capability. An interim solution would be the importation of cement in super-sacks until the bulk handling equipment could be repaired. A large earthen berm surrounding the cement storage domes will help to prevent water damage to the stored cement and any ground level equipment at this storage site (Figure 4-74).

Figure 4-73: Bulk cement handling equipment at Pier P-6

Figure 4-74: Cement storage facility adjacent to Pier P-6

4.5.6 Harbor Buildings

The harbor administrators office is a simple timber framed office that will likely be severely damaged during a major hurricane or tsunami event (Figure 4-75). All personnel and important equipment should be evacuated from this office during a warning. The nearby steel-framed warehouse on Pier P-5A (Figure 4-75) is only used to store equipment and is not critical to port functionality after an inundation event. It is likely to experience damage to the sheet metal siding and roller doors, and possibly debris impact damage to steel columns and bracing members. Keeping the roller doors open during an inundation event would help to protect them from damage.

Figure 4-75: Harbor administration building and Pier P-5A warehouse

4.5.7 Small Boat Harbor

The Ko'Olina Small Boat Harbor to the North of Kalaeloa Barbers Point Harbor shares the port entrance channel (Figure 4-66). During a hurricane or tsunami it is unlikely that all of the small boats and yachts will be removed to deep water by their owners. It is therefore likely that some of these boats will break loose from their moorings. There is also a potential that entire floating docks will break loose and become floating debris in the main harbor channel. Any of these boats, yachts or docks that sink in the harbor entrance channel will reduce the available draft and may have to be removed prior to opening the harbor to incoming vessels.

4.6 Kahului Harbor, Maui County

Kahului Harbor is located on the North shore of the Island of Maui, and is the only commercial port for this second most populous Hawaiian Island (Figure 4-1). The harbor channel is 40 feet deep while the basin varies from 18 to 35 feet deep. The harbor has three piers with a total berth length of 3000 feet, and over 30 acres of container and cargo handling yard area (State of Hawaii, 2004). Figure 4-76 and Figure 4-77 show the harbor layout.

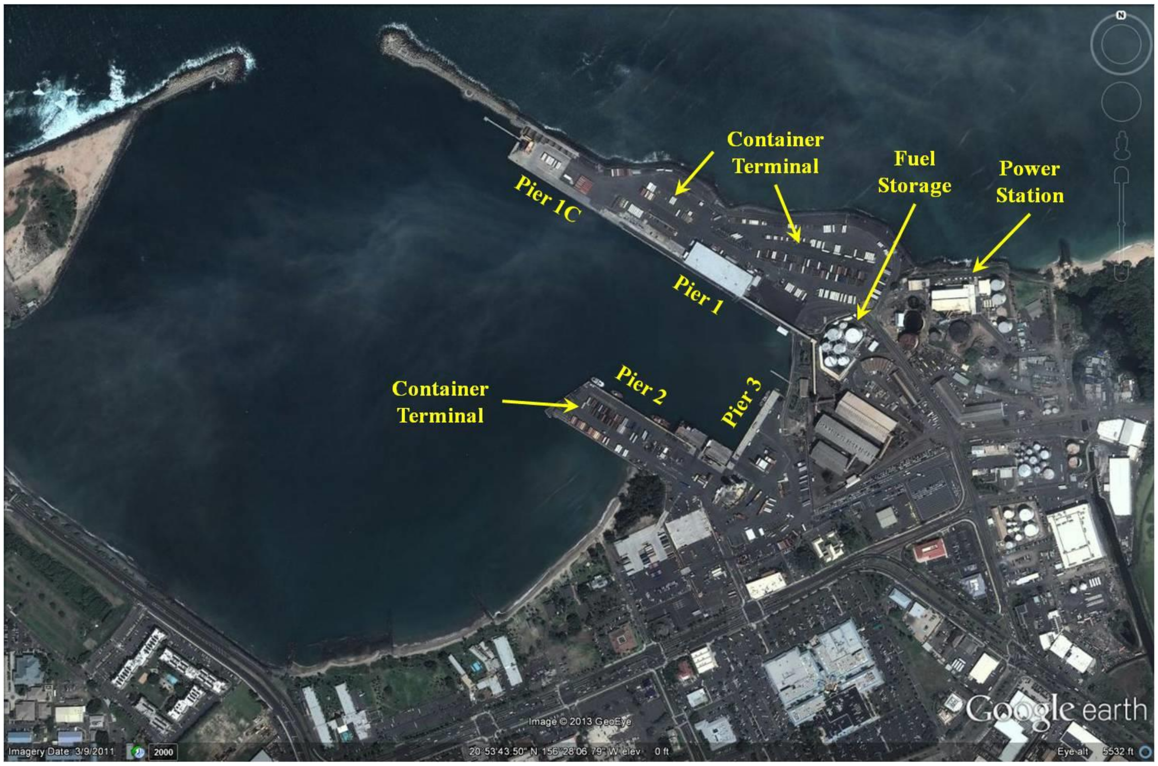

Figure 4-76: Kahului Harbor, Maui

Based on the US Army Corps hurricane simulations, the worst storm surge and characteristic wave height at Kahului Harbor are generated by a storm following landfall track B9-E, with central pressure of 940 bars (CP940), radius of maximum winds of 60 km (R60), and forward speed of 22 knots (V22). This storm is designated as B9-E-CP940-R60-V22 on the Hawaii Storm Atlas (US Army Corps, 2014).

Figure 4-78 shows storm surge and characteristic wave height predictions for Maui, while Figure 4-79 shows the predictions for Kahului Harbor and adjacent coastline. Storm surge in Kahului Harbor is predicted to reach 5-6 feet, while the characteristic wave height in the harbor could reach 15 feet, particularly in the harbor entrance channel. Immediately outside of the harbor wave heights of 25 to 30 feet are anticipated (Figure 4-79).

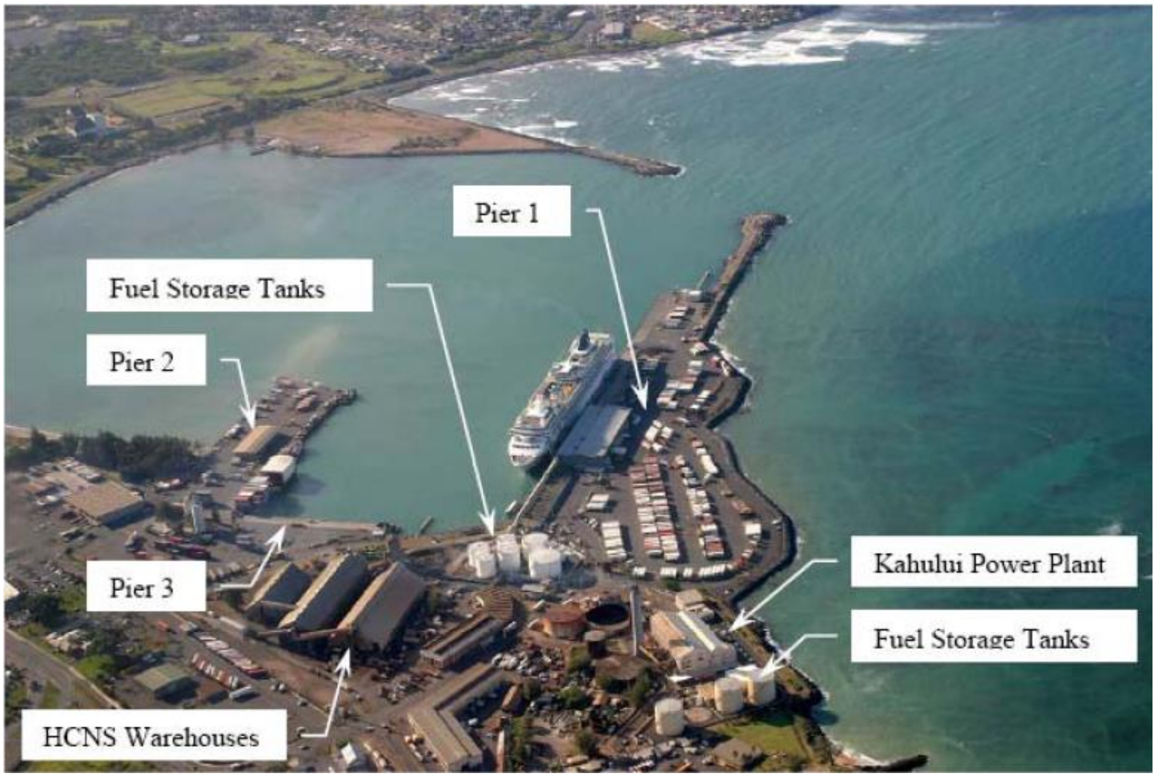

Figure 4-77: Aerial view of Kahului Harbor from "County of Maui Multi-Hazard Mitigation Plan, 2010" (Martin & Chock, Inc.)

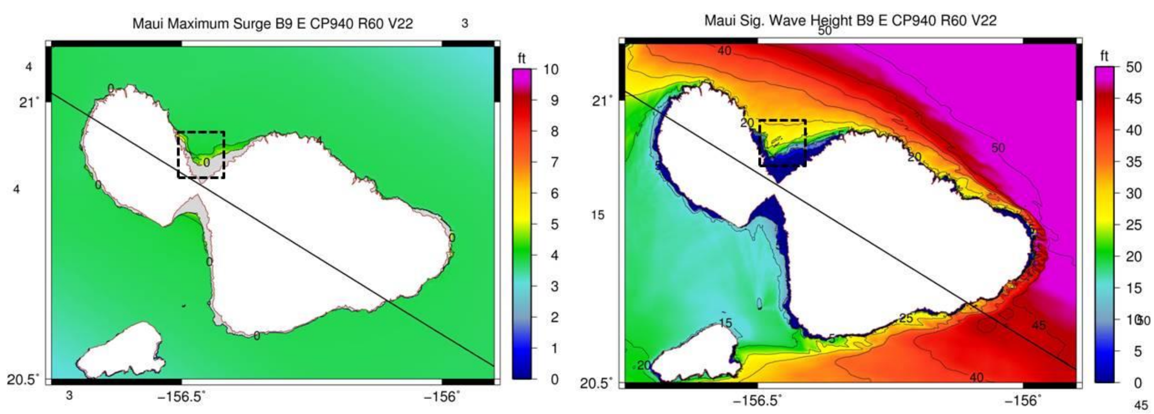

Figure 4-78: Storm surge and wave height predictions for Maui for storm B9-E-CP940-R60-V22 (US Army Corps, 2014)

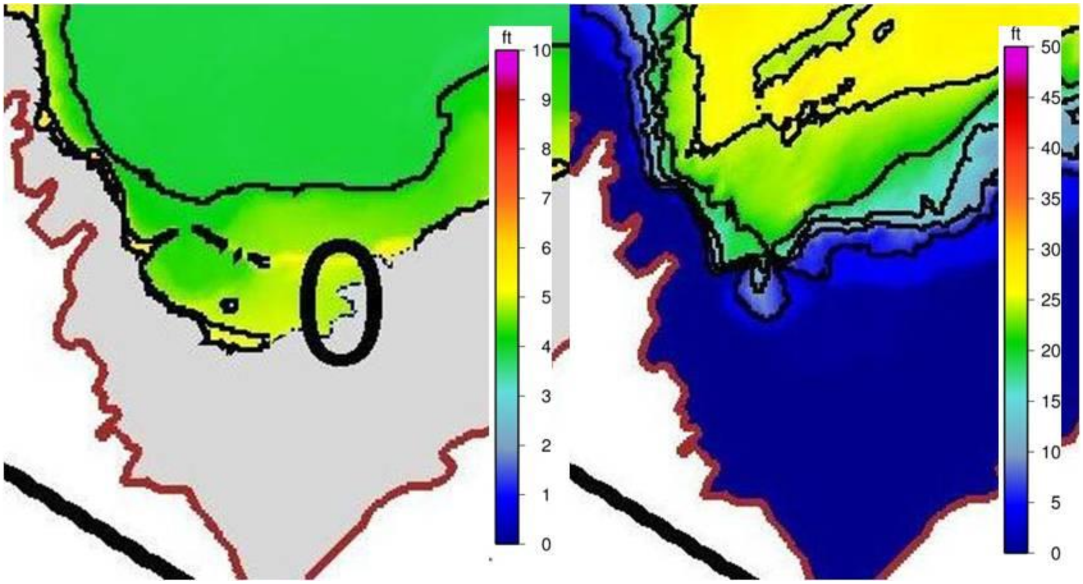

Figure 4-79: Storm surge and wave height predictions for Kahului Harbor for storm B9-E-CP940-R60-V22 (US Army Corps, 2014)

Figure 4-80 shows that inundation depths resulting from the Great Aleutian Tsunami are expected to exceed 16.5 feet throughout the harbor, with the main piers and container storage yards experiencing depths in excess of 32 feet (Cheung, 2014). The adjacent power plant, fuel storage tanks and neighboring warehouses are all anticipated to be inundated and damaged during this extreme event. Even based on current tsunami evacuation maps, all of the harbor facilities are in the evacuation zone (Figure 4-80).

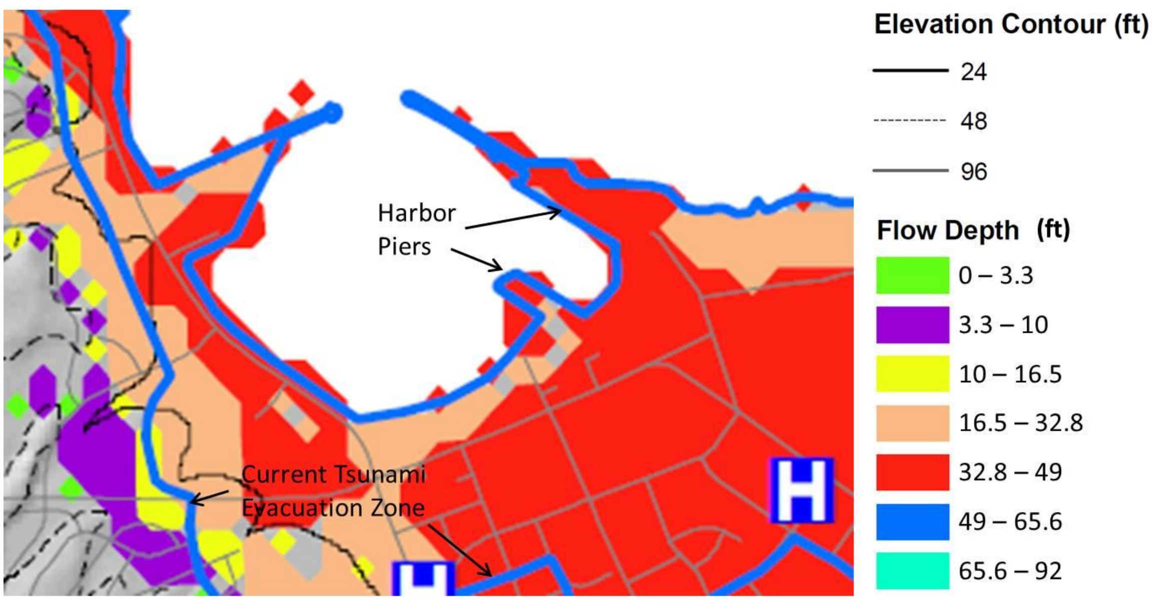

Figure 4-80: Kahului Harbor Tsunami Inundation Predictions based on Great Aleutian Tsunami (Cheung, 2014)

Team members met with harbor manager, Louis Nobriga, on March 30, 2012. After a discussion of harbor procedures during hurricane and tsunami warnings, and the performance of these procedures during recent tsunami events, the team was taken on a tour of the port facilities.

4.6.1 Procedures during hurricane and tsunami warnings

Harbor Administrator Nobriga described the harbor procedures during a warning event as follows:

- All large ships are sent out of the harbor to deep water.
- All containers with hazardous material are removed from the harbor.
- Additional full containers are removed as time allows.
- Empty containers are stored towards the end of pier 1C. It was estimated that 40% of the containers are empty. Of all containers in the harbor, the approximate distribution of 20ft, 40ft and 45ft containers is 25%, 50% and 25% respectively.
- Hazardous and full containers are generally stored on chassis (Matson) and container stacks (Young Brothers) closer to the harbor exit for easier evacuation during an emergency.

4.6.2 Experience during Tohoku Tsunami

The harbor was inundated during the March 11, 2011 Tohoku Tsunami. The basin water elevation exceeded the pier elevations resulting in sand deposition on all piers and storage areas. Young Brothers container yard had a few containers that floated, but caused no damage. Water levels did not exceed the 8 foot high protective wall around the Tesoro fuel storage tanks. Water levels did not exceed the height of the protective berm around the Power Station and its fuel storage tanks. These tanks are usually maintained at least 50% full to avoid fuel shortages in the event of delays in barge fuel delivery. Māʼalaea Power Station on the South side of the island is the major power supply for Maui providing approximately 80% of the island's power. More recently, wind turbines are contributing about 11% of the island's power needs.

4.6.3 Experience during Hurricane Iselle

A tropical storm watch was issued for Maui County at 11PM local time on Tuesday, August 5, 2014, followed by a tropical storm warning issued at 11AM on Wednesday, August 6. The warning was discontinued at 3:28PM on Friday, August 8. The Coast Guard officially closed Kahului Harbor on Thursday evening, August 7. All barges and larger vessels had already vacated the port on Wednesday, so the only vessels left in port were two assist tugs and two 45ft Coast Guard operations boats. These were all moored at Pier 1 and weathered the storm successfully.

Matson and Young Brothers reduced most container stacks to one or two high. Some container stacks were left at three to four high, but were lashed together to prevent toppling due to high wind.

All personnel evacuated the port with the harbor manager stationed at Maui County EOC. Two roving security guards were told to seek safe haven around midnight on Thursday, August 7. There was no damage to any harbor facilities or vessels during this event.

4.6.4 Harbor Piers

All three piers at Kahului Harbor have both pile supported and soil supported sections. The pile supported sections are susceptible to hydrodynamic uplift during storm surge and wave action, and during tsunami inundation. The main pier (Pier 1) is constructed using driven piles encased in large reinforced concrete beams supporting the reinforced concrete pier deck (Figure 4-81). This integral construction provides superior resistance to the uplift forces and would be expected to survive anticipated hydrodynamic loading. However, drawings for the pier were not reviewed for this project, and no structural or hydrodynamic analysis was performed to verify the anticipated performance of this structure during future inundation events.

Piers 2 and 3 are older piers and are less robust. Figure 4-82 shows the structural system for Pier 3 currently undergoing repair due to excessive reinforcement corrosion. In addition, because of their orientation, these piers have greater exposure to wave action during a hurricane and uplift due to tsunami surge than Pier 1. Piers 2 and 3 should be assumed to be susceptible to damage during a major hurricane or tsunami event.

Figure 4-81: View of Pier 1 structural system

Figure 4-82: View of Pier 3 showing ongoing repair work

4.6.5 Shipping Container Storage Areas

The main container storage areas are on Pier 1 and Pier 2 (Figure 4-76). Both areas are directly exposed to inundation due to storm surge or tsunami. Containers with hazardous contents are stored on chassis ready for removal to high ground in the event of a hurricane or tsunami warning (Figure 4-83). Others are stacked without restraint, so should be expected to float during a major inundation event (Figure 4-84). They will then become floating debris with the potential for striking structures and other harbor facilities and causing considerable damage. Many of the containers will be washed off the piers and potentially sink in the harbor basin or entry channel, reducing the available draft. This would be a major concern that needs to be resolved prior to allowing ships into the harbor after a hurricane or tsunami.

Figure 4-83: Chassis mounted containers on Pier 1 ready for removal to high ground

Figure 4-84: Container stacking on Pier 3

4.6.6 Fuel Storage Facilities

Two tank farms are located adjacent to Kahului Harbor (Figure 4-77). The first is a Tesoro fuel storage facility directly inland from the container storage yard on Pier 1 (Figure 4-85). The storage tanks are secured to concrete foundations by means of anchor bolts as shown in the insert in Figure 4-85. This will help to prevent uplift during inundation, but may not be able to resist the potential buoyancy of an empty tank with significant inundation. The relatively thin steel walls of empty tanks may also tend to buckle due to the external water pressure.

This facility is surrounded by a concrete wall varying in height from 8 to 10 feet. The top of the wall is therefore approximately 14 to 16 feet above MSL. This wall was presumably designed as a containment wall, so would be able to resist hydrostatic pressure due to storm surge, but may not be adequate to resist high velocity tsunami flow.

If the wall is overtopped by either storm surge and wave action, or tsunami inundation, the tanks will be subject to potential flotation, buckling, or impact from floating debris. Resulting fuel spills could lead to fires that can spread with the water flow. The current fire suppression system is located on the outside of the wall (horizontal red pipe in Figure 4-85) and is exposed to potential damage from debris strikes.

Figure 4-85: Tesoro fuel storage tank farm at Kahului Harbor

The second fuel storage facility is associated with the Kahului Power Station (Figure 4-86). Both the power station and tanks are protected from wave action by a berm with top elevation approximately 16 feet above MSL. The berm is built of earthen fill with the ocean face lined with boulders. The berm is not continuous around the power station and fuel storage area, so would not provide protection during a significant hurricane storm surge or tsunami inundation. The Kahului Power Station produces approximately 13% of the power generated on Maui (Wikipedia, 2014), but may be decommissioned in the future.

Figure 4-86: Kahului Power Station and fuel storage tanks behind earthen berm

Although not part of the Kahului Harbor property, both of these fuel storage tank farms present a potential hazard to surrounding areas, including harbor property, if they are damaged during a coastal flooding event. Remediation against inundation would require an evaluation of the height of the containment walls relative to anticipated storm surge and tsunami flow depths. If the walls are not currently high enough to prevent inundation of the tank farm areas, then they can be replaced with higher walls. An alternative approach may be to leave the walls in their current condition but prevent buoyancy and tank wall buckling by maintaining the tanks at least half full. A retention fence should be added to the top of the containment walls to prevent floating containers and other large debris from reaching the tanks.

Because both the Kahului Power Station and the Ma’alaea Power Station are in the tsunami evacuation zone, the port should have contingency plans for operating without power from Maui Electric Company for some time after a major coastal flooding event.

4.6.7 Bulk Handling Facilities

Kahului Harbor has a bulk handling system for loading sugar onto ships at Pier 1. The conveyor system is supported by timber trestles (Figure 4-87) leading to the loading facility in the warehouse on Pier 1. Although the trestle legs are well secured to their concrete foundations (inset in Figure 4-87), they are still susceptible to impact damage from floating shipping containers. Based on the number of trestles and their location relative to the shipping container storage yard, it should be assumed that there will be sufficient damage to make the bulk handling system inoperable after a major inundation event.

There is also a Hawaiian Cement bulk handling facility for cement on Pier 2, which is planned for relocation to the existing Harbors Maui District Office.

Figure 4-87: Bulk handling conveyor system for sugar export

4.6.8 Harbor Buildings

The only major warehouse in the harbor is on Pier 1 (Figure 4-88). It houses the sugar bulk loading system and services cruise ship passengers, but it is no longer used for pallet mounted material handling. The structure has not been evaluated for high velocity flow conditions, but it is likely that the main steel columns and roof structure would survive while the infill walls may be damaged (Figure 4-89). Roller doors, windows and any sheet metal cladding at the lower elevations would likely be damaged during a flooding event.

Figure 4-88: Warehouse on Pier 1

Figure 4-89: Interior of Pier 1 Warehouse and typical column base (inset)

The harbor office building shown in Figure 4-90 is elevated 10 feet above grade, and approximately 14 feet above MSL. It was therefore not damaged during the Tohoku Tsunami inundation. It is not known if the masonry walls and columns supporting this structure were designed for high velocity tsunami flow or hurricane wave loading, but elevation of the building will certainly provide better continuity of services after an event. This building should still be evacuated during a tsunami or hurricane warning.

Figure 4-90: Kahului Harbor office

4.7 Hilo Harbor, Hawaii County

Hilo Harbor is located on the East shore of Hawaii Island and predominantly serves communities on the East and South sides of the island. It is protected by a 10,000 foot breakwater. Three piers make up the 2600 lineal feet of berth, accompanied by 22 acres of storage yard (Figure 4-91). The main channel is 35 feet deep while the alongside depth at each pier is between 33 and 35 feet (State of Hawaii, 2004).

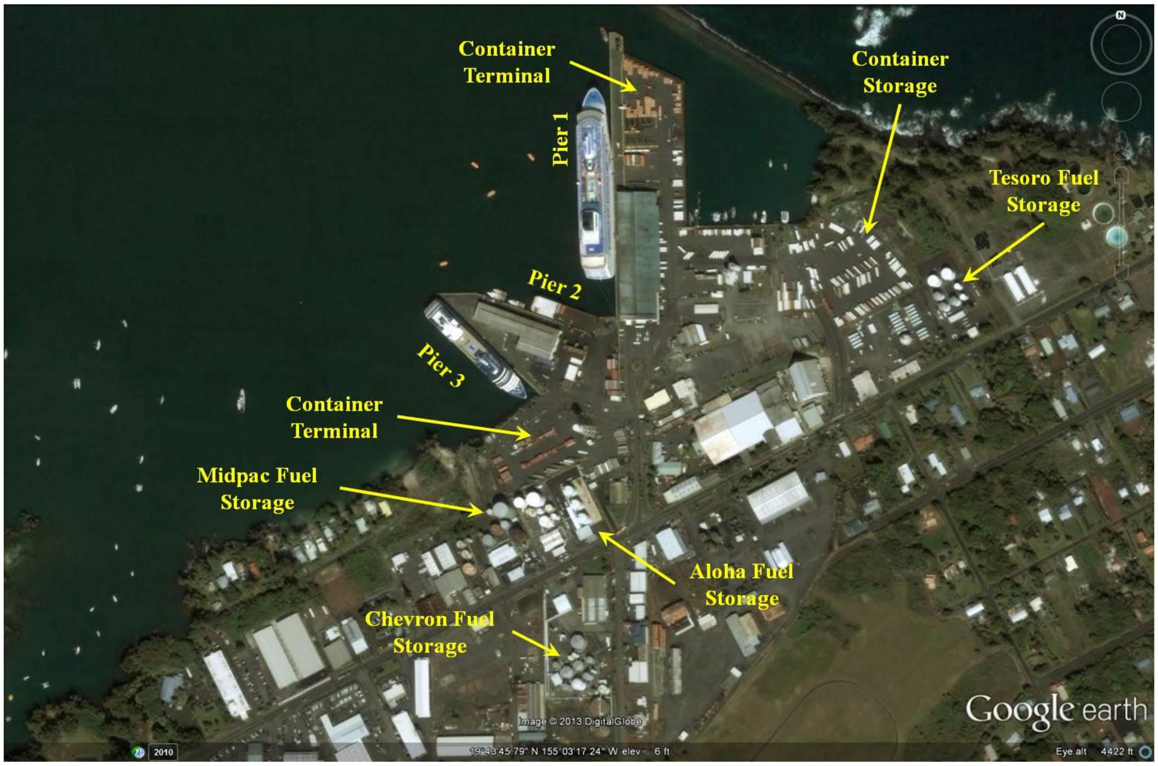

Figure 4-91: Hilo Harbor, Hawaii Island

Based on the US Army Corps hurricane simulations, the worst storm surge and characteristic wave height at Hilo Harbor are generated by a storm following landfall track B9-D, with central pressure of 940 bars (CP940), radius of maximum winds of 60 km (R60), and forward speed of 22 knots (V22). This storm is designated as B9-D-CP940-R60-V22 on the Hawaii Storm Atlas (US Army Corps, 2014).

Figure 4-92 shows storm surge and characteristic wave height predictions for Hawaii Island, while Figure 4-93 shows the predictions for Hilo Harbor and adjacent coastline. Storm surge in Hilo Harbor is predicted to reach 4-5 feet, while the characteristic wave height in the harbor could reach 15 feet, particularly at the West end of the harbor basin that is not protected by the breakwater. Immediately outside of the harbor the wave heights rapidly increase to 30 feet (Figure 4-93Figure 4-34).

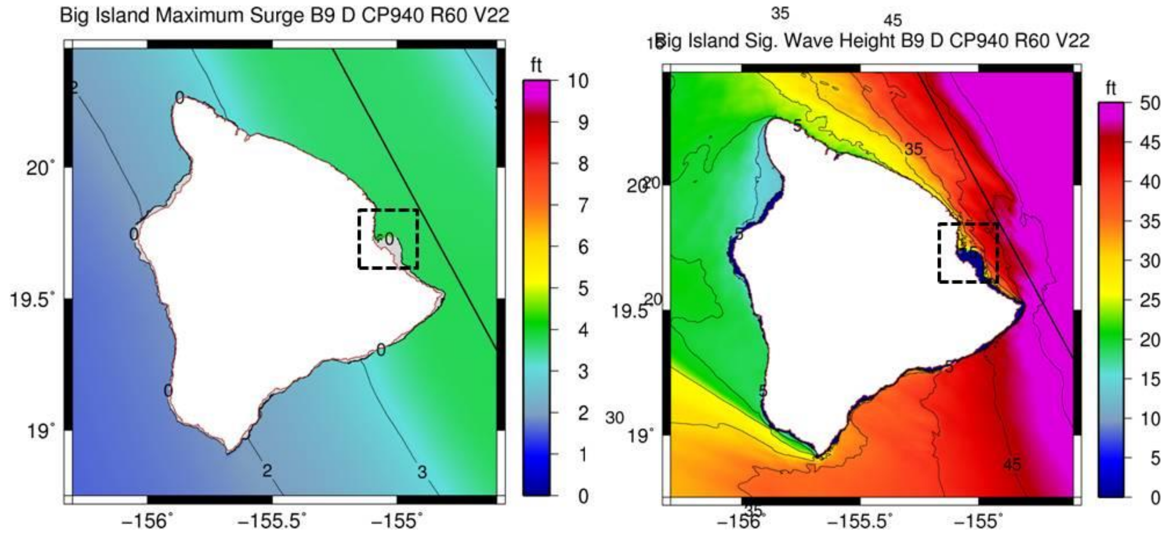

Figure 4-92: Storm surge and wave height predictions for Hawaii Island for storm B9-D-CP940-R60-V22 (US Army Corps, 2014)

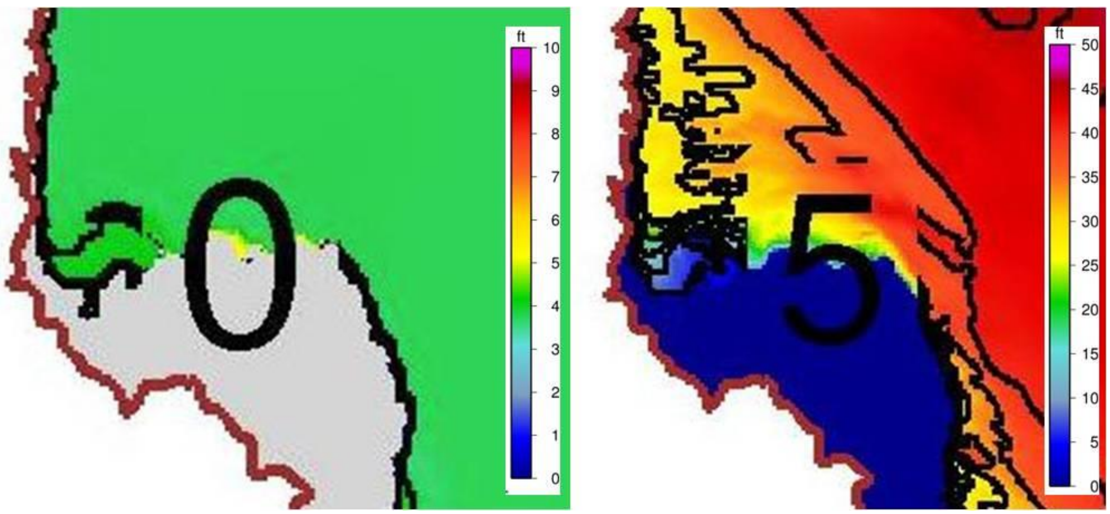

Figure 4-93: Storm surge and wave height predictions for Hilo Harbor for storm B9-D-CP940-R60-V22 (US Army Corps, 2014)

Figure 4-94 shows that all harbor facilities are within the current tsunami evacuation zone. Based on the Great Aleutian Tsunami scenario, flow depths within the harbor are expected to exceed 32 feet (Cheung, 2014). The adjacent fuel storage tanks and neighboring warehouses are all anticipated to be inundated and damaged during major hurricane and tsunami events.

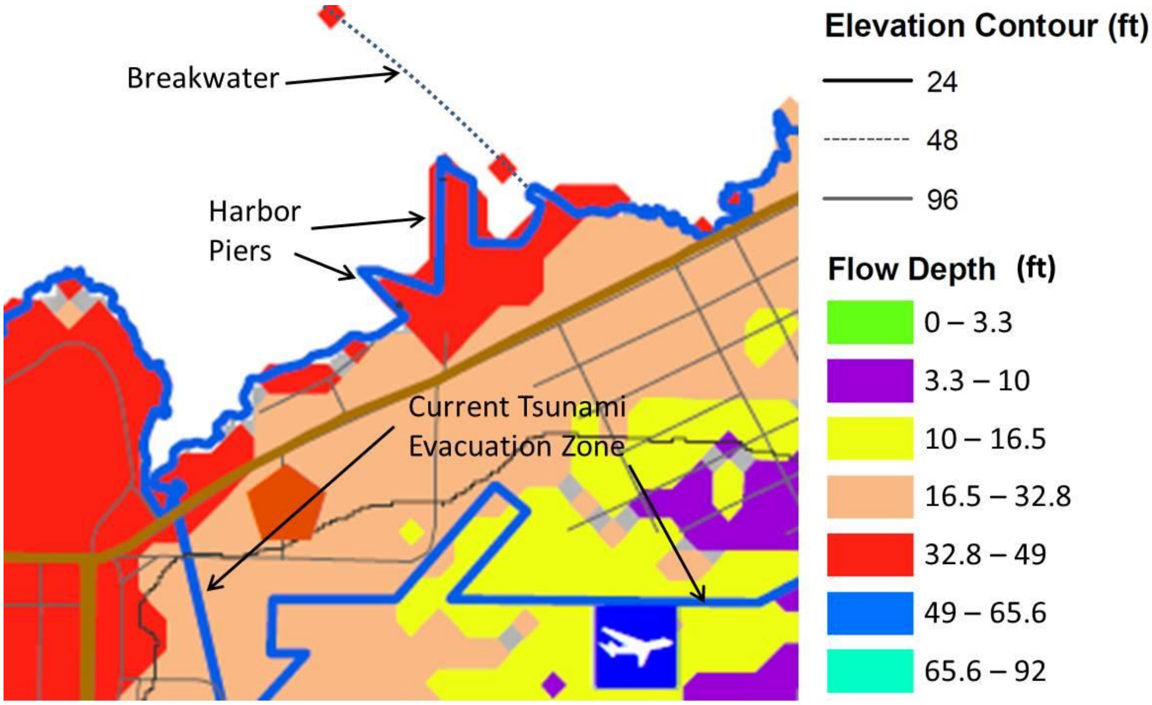

Figure 4-94: Hilo Harbor Tsunami Inundation Predictions based on Great Aleutian Tsunami (Cheung, 2014)

Team members met with harbor administrator, Jeff Hood, on May 4, 2012. After a discussion of harbor procedures during hurricane and tsunami warnings, and the performance of these procedures during recent tsunami events, the team was taken on a tour of the port facilities.

4.7.1 Procedures during hurricane and tsunami warnings

Harbor Administrator, Jeff Hood, described the harbor procedures during a warning event as follows:

- All large ships are sent out of the harbor to deep water.
- All containers with hazardous material are stored in a selected area and are removed from the harbor during a hurricane or tsunami warning.
- Additional containers, particularly those with food, are removed as time allows.

Because Hawaii Island has two commercial ports, Hilo Harbor and Kawaihae Harbor, if one harbor is damaged but the other is still operational, cargo can be transported across the island by truck. This was the case after the Kiholo Bay earthquake in 2006 when Kawaihae Harbor was closed to ship traffic until the piers were inspected for damage.

Currently Hilo Harbor handles approximately 60% of cargo for Hawaii Island, while Kawaihae Harbor handles 40%. Hilo Harbor receives two Matson ships and two Young Brothers barges every week, as well as cruise boat traffic.

4.7.2 Experience during Tohoku Tsunami

The harbor was not inundated during the March 11, 2011 Tohoku Tsunami. Even though the warning was at night, all hazardous material containers and some cargo containers with food were removed from the harbor to high ground. All harbor personnel were evacuated prior to tsunami arrival.

4.7.3 Experience during Hurricane Iselle

A tropical storm watch was issued for Hawaii County at 11AM local time on Tuesday, August 5, 2014, followed by a hurricane warning issued at 10:55AM local time on Wednesday, August 6, 2014. The hurricane warning lasted until 5:00AM local time on Friday, August 8, 2014, when it was changed to a tropical storm warning, which was discontinued at 2PM on the same day.

The Coast Guard officially closed Hilo harbor at 10:00PM local time on Thursday, August 7, 2014. The only vessels in the harbor at that time were the two station tugs, which rode out the storm at their moorings with no damage. A cruise ship left the port at 6:00PM, while a barge left the port earlier in the day to avoid the storm.

All shipping containers with hazardous materials were removed from the port by the three shipping companies, Young Brothers, Matson and Pasha Hawaii. In addition, Young Brothers and Matson lowered their container stacks to single containers instead of the normal 4 container stacks so as to reduce the potential for toppling during high winds.

The port experienced a maximum storm surge estimated at 4 feet, which did not result in any pier overtopping since the lowest pier freeboard is 7 feet.

The port captain opened the port to shore side operations once the winds had subsided to less than 30mph around midday Friday. The Coast Guard opened the port to ocean traffic late Friday evening. No damage was reported to any port facilities or vessels.

4.7.4 Harbor Piers

All three piers are partly supported on piles and partly on fill material. The pile supported piers are built integrally from driven piles to girder to deck slab, providing good resistance to potential hydrodynamic uplift. Piers 2 and 3, and portion of Pier 1, were constructed in the 1920s, while the end of Pier 1 is newer construction. Portions of Pier 2 deck slab have failed under forklift wheel loads, and the piers cannot support mobile cranes during an emergency.

The newer Pier 1 construction (Figure 4-95) is anticipated to survive future inundation events. It is likely that Pier 2 and 3 (Figure 4-96), and the older portion of Pier 1, will also survive future inundation events, though contingency plans should incorporate possible collapse or damage to portions of these older piers.

A new Pier 4 is currently being planned to the West of Pier 3. This pier should be designed for uplift forces anticipated from tsunami inundation and storm wave loading. Inclusion of breakaway panels to relieve the uplift pressures should be considered for this new pier.

Figure 4-95: Pier 1 newer construction with view of pile to deck connection (inset)

Figure 4-96: Older pier construction

4.7.5 Shipping Container Storage Areas

Containers are stored at various locations in the harbor, including in the large storage area adjacent to the fuel storage tanks shown in Figure 4-91. Containers with hazardous materials and perishable cargo such as food are stored on chassis for easy evacuation (Figure 4-97). Empty containers and those containing regular cargo are stacked in the storage and handling areas.

Figure 4-97: Shipping containers stored on chassis

4.7.6 Fuel Storage Facilities

There are four fuel storage facilities adjacent to or near the Hilo Harbor. Containment walls of various heights surround the storage tanks, most constructed of concrete masonry unit (CMU) walls. Tesoro storage tanks are surrounded by a 4ft high CMU wall (Figure 4-98), while the Aloha storage tanks have a 5.5 ft high CMU containment wall (Figure 4-99). The Midpac storage tanks are surrounded by a 10 ft high reinforced concrete wall topped by 5 ft of CMU wall (Figure 4-99).

The tall reinforced concrete and CMU walls at the Midpac facility are likely strong enough to survive moderate velocity flow, however the lower CMU walls at the other storage tank sites should be expected to fail or suffer overtopping during a major inundation event.

Many of the storage tanks are not secured to the ground (Figure 4-100), so they should be expected to float during inundation, resulting in damage to pipe connections and potential impact and puncturing of the tank wall.

A gas storage facility adjacent to the container handling yard is also exposed to impact damage due to floating debris (Figure 4-101).

Figure 4-98: Tesoro storage tank facility

Figure 4-99: Aloha (left) and Midpac (right) storage tank facilities

Figure 4-100: Tank bases resting on concrete slab without uplift restraint

Figure 4-101: Gas storage facility adjacent to shipping container yard

4.7.7 Bulk Handling Facilities

The only bulk handling facility at Hilo Harbor is the cement delivery and storage. Loss of this facility could impact construction during the critical early construction phase after a disaster. Alternative cement delivery systems, such as super-sacks, are available that could be used on a temporary basis if necessary. The elevated nature of the cement silos and the sturdy construction should provide improved resistance to damage, though the piping systems may need repair after an inundation event.

4.7.8 Harbor Buildings

Two major warehouses on Piers 1 and 2 are no longer fully utilized. The warehouse on Pier 2 may be considered for removed when Pier 4 construction is completed, while the North half of the warehouse on Pier 1 is also scheduled for removal.

Harbor control and management offices are not elevated above the anticipated flood level, and so should be assumed a total loss during a major hurricane or tsunami event.

Due to Pier 1 shed modifications occurring within Hilo Harbor, the steel truss-supported water tank is being evaluated for its purpose and use. Potential damage to the support legs or bracing from debris impact could create a falling hazard (Figure 4-102).

Figure 4-102: Unused water tower

4.8 Kawaihae Harbor, Hawaii County

Kawaihae Harbor is located on the Northwest shore of Hawaii Island and predominantly serves communities on the North and West sides of Hawaii Island. Two piers provide 1500 lineal feet of berth with water depths of 35 feet. Adjacent storage areas total 45 acres, used primarily for interisland container handling and storage. The harbor channel is 40 feet deep (State of Hawaii, 2004).

Figure 4-103: Kawaihae Harbor, Hawaii County

Based on the US Army Corps hurricane simulations, the worst storm surge and characteristic wave height at Kawaihae Harbor are generated by a storm following landfall track B6-A, with central pressure of 940 bars (CP940), radius of maximum winds of 45 km (R45), and forward speed of 22 knots (V22). This storm is designated as B6-A-CP940-R45-V22 on the Hawaii Storm Atlas (US Army Corps, 2014).

Figure 4-104 shows storm surge and characteristic wave height predictions for Hawaii Island, while Figure 4-105 shows the predictions for Kawaihae Harbor and adjacent coastline. Storm surge in Kawaihae Harbor is predicted to reach 15-20 feet, while the characteristic wave height in the harbor could reach 25 feet, particularly because of the low breakwater which will be overtopped by the storm surge. Immediately outside of the harbor the wave heights rapidly increase to over 35 feet (Figure 4-105).

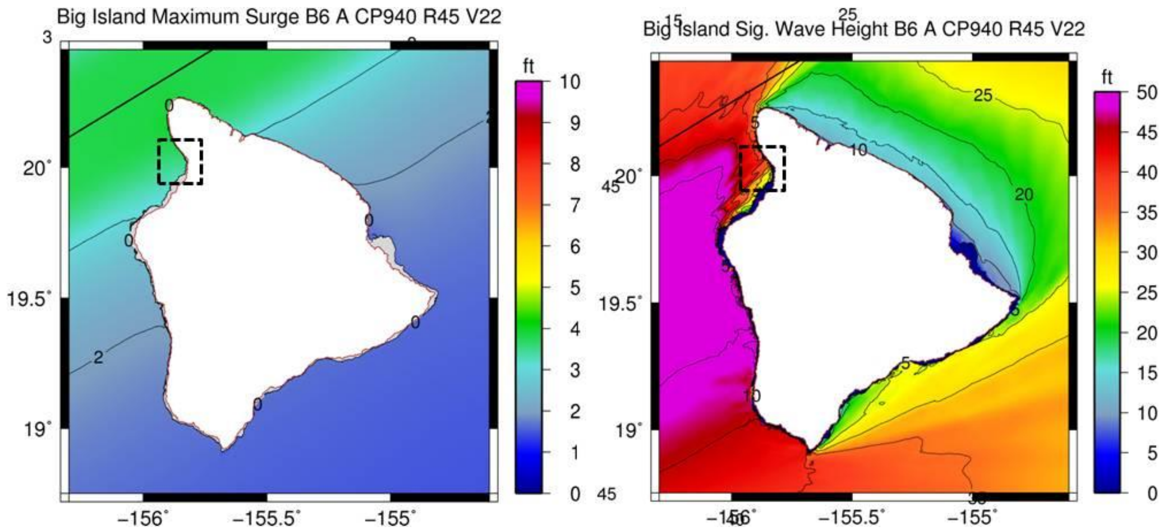

Figure 4-104: Storm surge and wave height predictions for Hawaii Island for storm B6-A-CP940-R45-V22 (US Army Corps, 2014)

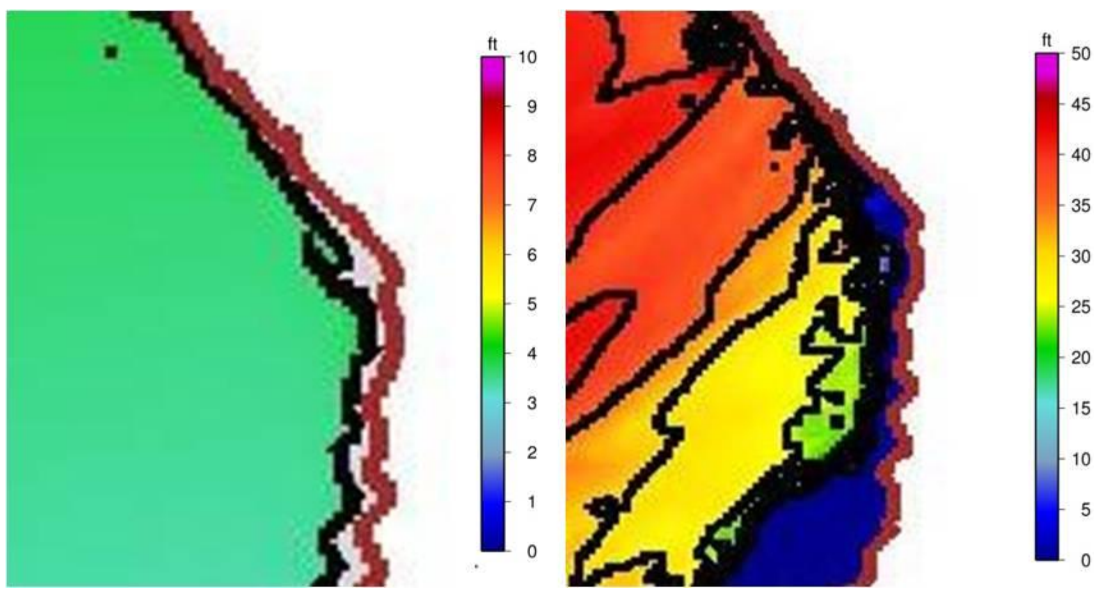

Figure 4-105: Storm surge and wave height predictions for Kahului Harbor for storm B6-A-CP940-R45-V22 (US Army Corps, 2014)

The entire harbor facility is within the current tsunami evacuation zone, and predictions of flow depths during a Great Aleutian Tsunami are in the 10-16.5 feet range (Figure 4-106).

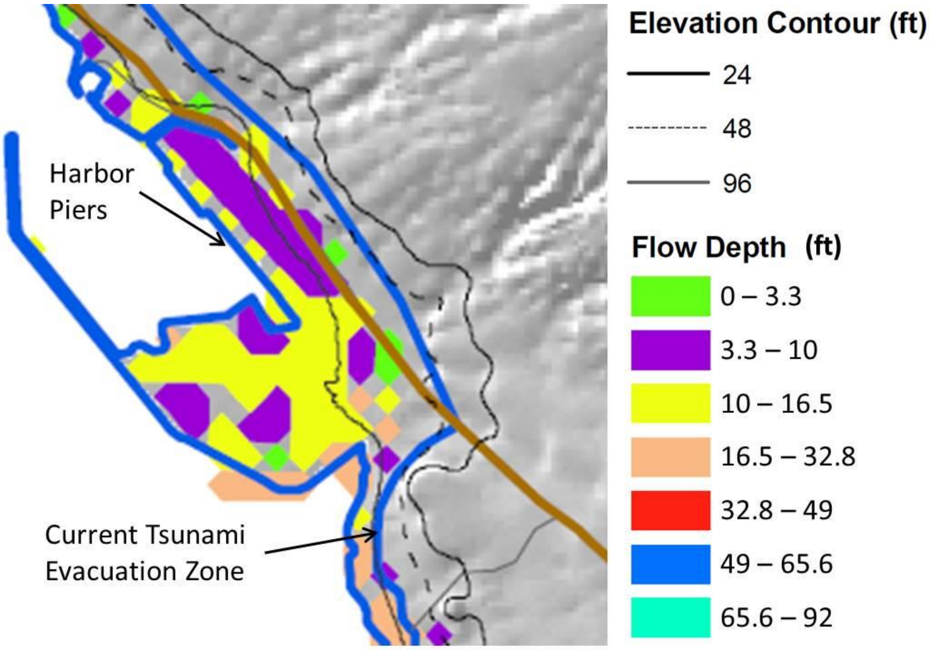

Figure 4-106: Kawaihae Harbor Tsunami Inundation Predictions based on Great Aleutian Tsunami (Cheung, 2014)

Team members met with the assistant harbor manager on May 4, 2012 for a tour of the port facilities.

4.8.1 Procedures during hurricane and tsunami warnings

The following procedures are followed during a warning event:

- All ships and barges are sent out of the harbor to deep water.
- All containers with hazardous material are removed from the inundation zone.
- Other cargo and empty containers are unstacked and placed close together in a single layer.

Because Hawaii Island has two commercial ports, Hilo Harbor and Kawaihae Harbor, if one harbor is damaged but the other is still operational, cargo can be transported across the island by truck. This was the case after the Kiholo Bay earthquake in 2006 when Kawaihae Harbor was closed to ship traffic until the piers were inspected for damage. Currently Kawaihae Harbor handles approximately 40% of cargo for Hawaii Island, most of which arrives by barge from Honolulu Harbor.

4.8.2 Experience during Tohoku Tsunami

The harbor was not inundated during the March 11, 2011 Tohoku Tsunami. Even though the warning was at night, all hazardous material containers were removed from the harbor to high ground. All harbor personnel were evacuated prior to tsunami arrival.

4.8.3 Experience during Hurricane Iselle

A tropical storm watch was issued for Hawaii County at 11AM local time on Tuesday, August 5, 2014, followed by a hurricane warning issued at 10:55AM local time on

Wednesday, August 6, 2014. The hurricane warning lasted until 5:00AM local time on Friday, August 8, 2014, when it was changed to a tropical storm warning, which was discontinued at 2PM on the same day.

The Coast Guard officially closed Kawaihae harbor at 10:00PM local time on Thursday, August 7, 2014. There were no vessels in the port at the time.

All shipping containers with hazardous materials were removed from the port and container stacks were lowered to single containers instead of the normal 4 container stacks so as to reduce the potential for toppling during high winds.

The port captain opened the port to shore side operations once the winds had subsided to less than 30mph around midday Friday. The Coast Guard opened the port to ocean traffic late Friday evening. No damage was reported to any port facilities or vessels.

4.8.4 Harbor Piers

Pier 1 is the oldest pier while Pier 2 consists of two sections built at different times (Figure 4-103). Pier 1 was damaged during the Kiholo Bay earthquake in 2006 and was out of commission for some time while repairs were made. It may be anticipated to experience damage during future tsunami or hurricane events.

Pier 2 is a more robust construction (Figure 4-107) and would be expected to survive a major inundation event without significant damage.

Figure 4-107: Pier 2 - concrete deck on piles (inset)

4.8.5 Shipping Container Storage Areas

Containers are stored adjacent to Pier 1. Containers with hazardous materials are stored on chassis for easy evacuation (Figure 4-108). Empty containers and those containing regular cargo are stacked in the storage and handling areas (Figure 4-109), but are unstacked and packed against each other during a disaster warning.

Figure 4-108: Chassis mounted containers in storage area

Figure 4-109: Stacked containers

4.8.6 Fuel Storage Facilities

There are two fuel storage yards at Kawaihae Harbor, both of which are adjacent to container storage areas (Figure 4-110 and Figure 4-111). The storage tanks are filled by a barge every 4 weeks. The 5 foot high containment wall is designed for the contents of the largest tank plus 25 year rainfall. The tanks are located at an elevation of approximately 5 feet, and therefore the top of the wall is approximately 10 feet above MSL (Figure 4-112). The tanks are not connected to the concrete foundations, so inundation of the tank farm could lead to floatation and damage of the piping connections (Figure 4-113).

Figure 4-110: Midpac fuel storage facility

Figure 4-111: Fuel storage facility

Figure 4-112: CMU wall surrounding Midpac fuel storage facility

Figure 4-113: Base support and piping in Midpac tank farm

4.8.7 Bulk Handling Facilities

The only bulk handling facility at Kawaihae Harbor is the cement delivery and storage (Figure 4-103 and Figure 4-114). Loss of this facility could impact construction during the critical early construction phase after a disaster. Alternative cement delivery systems, such as super-sacks, are available that could be used on a temporary basis if necessary. The elevated nature of the cement silos and the sturdy construction should provide improved resistance to damage, though the piping systems may need repair after an inundation event.

Figure 4-114: Cement Silos at Kawaihae Harbor

4.8.8 Harbor Buildings

Most harbor activities occur in the open container handling areas. However, there are two older warehouse structures on Pier 1, the harbor manager's office, and ancillary buildings in the harbor area. None of these structures has been elevated to prevent inundation during a flooding event. These buildings and their contents should all be assumed to be a total loss after a major inundation event.

5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Hurricane storm surge and wave action, and tsunami inundation, threaten all coastal areas of the Hawaiian Islands. This includes all commercial ports and harbors. Because of their remote location in the middle of the Pacific Ocean, the Hawaiian Islands are heavily dependent on their ports and harbors for delivery of essential produce to and between the islands. Closure of any of the Hawaiian commercial ports for more than a week due to storm or tsunami inundation would severely affect the health and safety of island residents and their ability to recover from the event.

This report summarizes a multi-year project to survey all commercial harbors in the State of Hawaii for their vulnerability to damage during future hurricane and tsunami events. The survey included Nawiliwili Harbor and Port Allen on Kauai, Honolulu Harbor and Kalaeloa Barbers Point Harbor on Oahu, Kahului Harbor on Maui, and Hilo and Kawaihae Harbors on Hawaii Island. Project team members met with harbor administrators of each commercial harbor to discuss current procedures for response to hurricane or tsunami warnings, and to survey the harbor facilities. Based on observations from past damaging hurricane and tsunami events, the team assessed the vulnerability of various aspects of port operations resulting in the following conclusions and recommendations.

5.2 Conclusions

In general, all administrators of commercial harbors in Hawaii are familiar with the potential consequences of hurricane or tsunami inundation. Some have experience of past flooding events at their harbors. All harbors have procedures in place to respond to hurricane or tsunami warnings, including ship evacuation, shipping container and equipment handling, and personnel evacuation. However, the procedures sometimes differ between harbors, and implementation of these procedures has not always gone smoothly during recent warning events.

Harbor administrator offices at many of the harbors are unlikely to survive a major inundation event. Harbor management staff will therefore have to evacuate to a safe location during the event. Potential loss of these offices and their contents must not present a major hurdle to reinstatement of harbor operations after the all-clear is announced.

Every effort should be made to evacuate all ships and barges to deep water prior to a warning level event. Ships and barges that do not evacuate the harbor may break free from their moorings and become large floating debris. This may result in severe impact damage to piers, port facilities and neighboring structures, or sinking of the vessels in the harbor.

Current ship evacuation procedures require that stevedores be available to assist with casting-off mooring lines before ships can evacuate. Pilots and tug boats are also generally required for large vessels to leave a harbor. If a warning occurs during non-working hours, these requirements can result in significant delays to the evacuation process.

Although it is recommended that all vessels be evacuated during a warning event, there are likely to be a number of smaller or less mobile vessels that will have to remain in port. An understanding of the anticipated currents in the harbor is critical to deciding on the ideal location for these vessels, and developing adequate mooring criteria so that they are restrained throughout the event. An improved understanding of the anticipated harbor currents would also allow for better decision making regarding the need to evacuate during minor or non-warning level events, which may still produce appreciable currents.

In order to gain a better understanding of the potential currents in selected critical ports, it is recommended that field instrumentation be developed and installed to monitor current and wave conditions during future tsunami and hurricane events. This instrumentation would consist of video cameras, current sensors and water level monitors located to capture critical information about the flow depth, velocity and wave heights during both tsunamis and hurricanes. The data collected by this instrumentation could then be used to calibrate numerical models to simulate the hydrodynamic effects in the selected ports. No such field instrumentation has been implemented in the past, so existing numerical models have had to rely on the results of small scale laboratory experiments for calibration.

Before the all-clear can be given to allow evacuated ships and barges to re-enter the harbor, it will be necessary to verify that shipping containers and other floating debris have not sunk in the harbor channel or basin, thus reducing the available draft. The US Army Corps of Engineers, USACE, has the authority to remove a vessel and other object that “restricts or obstructs general navigation within a defined channel” (United States Code, 2006). Activation of this authority immediately after a warning event will allow for rapid removal of sunken debris and other obstructions.

The vast majority of cargo handled by Hawaii’s harbors is in the form of standard shipping containers. Whether empty or full, enclosed shipping containers will float given sufficient water levels. As large floating debris, they pose an impact hazard to cranes and other port equipment, buildings and neighboring structures. They are also likely to sink when water leaks into the container, resulting in potential loss of draft in the harbor.

Cranes required to handle shipping containers will probably survive structurally, but water and impact damage to electrical and mechanical equipment at the base of the cranes will likely result in extended downtime. Alternative container handling procedures such as roll-on roll-off ramps, ship-mounted cranes and mobile land-based cranes may be required until the harbor cranes are repaired.

The majority of bulk handling facilities in Hawaii are located in Kalaeloa Barbers Point Harbor, while limited bulk handling operations exist at most of the other harbors. Potential water and debris impact damage to the mechanical and electrical components of this equipment is likely to result in considerable downtime before repairs can be made and bulk handling operations reinstated.

Fuel storage tank farms are often located within or adjacent to harbor facilities. These farms are typically surrounded by berms or walls that serve to contain fuel spills. These berms and walls will have been designed for internal hydrostatic pressure, but not for exterior hydrostatic and hydrodynamic loads that will occur during an inundation event. In addition, the height of these retention systems is controlled by the potential fuel spill, and not the anticipated exterior inundation. It is therefore to be anticipated that many of these berms or walls will be overtopped leading to potential large buoyancy uplift forces on the tanks, and potential for debris impact strikes, particularly from shipping containers that are often stored adjacent to the tank farms.

5.3 Recommendations

Based on the results of the harbor surveys performed during this study, the following recommendations are made to improve harbor resilience during future hurricane and tsunami events.

5.3.1 Harbor Procedures

- All District Managers have standardized procedures to follow during either a hurricane or tsunami warning. Although individual ports may require special items on their warning event procedures, the basic policies should be applied consistent throughout the State.
- The harbor procedures identify the chain of command and decision-making protocol during a warning event for each individual harbor. These procedures should be rehearsed through table-top exercises such as Makani Pahili on an annual basis.
- Each harbor should have a designated safe location for District Managers to evacuate to during a warning event. These locations should have radio or other forms of communication with the individual County Emergency Operations Center (EOC), the State Emergency Management Agency (Hi-EMA, formerly State Civil Defense) and the HDOT Harbor Division EOC in Honolulu Harbor, at all times during the warning and subsequent event.
- The harbor procedures must clearly identify conditions under which the all-clear can be issued for land-based operations to resume. They must also identify the procedures to be followed to ensure it is safe for evacuated ships and barges to return to the harbor. This will involve ensuring currents in the harbor have reduced to acceptable levels, and verifying adequate draft is available for vessels to enter and dock in the harbor. Landside operations at State piers can only proceed after landslide surveys have been performed by the Coast Guard and DOT Harbors.
- Each harbor should have access to sonar or other equipment necessary to scan for sunken objects that might reduce the draft in the harbor channel or basin.
- Based on the experience during recovery from Hurricane Sandy, it is recommended that the Hawaii Marine Transportation Systems Recovery Unit (MTSRU) and Harbor Users Groups (HUGS) programs be continued and enhanced so that all harbor users and emergency responders are able to develop the relationships and trust necessary to allow for quick and flexible decision making during the clean-up and recovery process.

5.3.2 Ship and Barge Evacuation

- Evacuation of large ships and barges to deep water should be a priority once a tsunami warning is announced.
- Evacuation of large ships and barges during a hurricane warning may not be necessary if the wind conditions are not expected to exceed category one storm conditions at the port. Vessel evacuation should be performed if wind conditions equivalent to category two or higher are anticipated at the port.
- If an evacuation is called, the decision to evacuate should not be left up to the ship captain or ship owner, and the evacuation should not be delayed in order to wait for non-essential crew members or cruise ship passengers stranded on land.
- Essential port personnel such as pilots and tug operators should have special identification passes that permit them to enter the evacuation zone during a warning.
- Activities that do not require land-based personnel, such as casting off, should be permitted under warning conditions so as to accelerate the evacuation process. Union rules governing these activities should be waived during warnings so as not to delay vessel evacuation.
- Suitable deep water anchor zones should be identified off-shore from each harbor for evacuating vessels to use until the all-clear is given.
- Many smaller vessels, floating drydocks and platforms, older non-navigable vessels and similar floating objects will likely have to remain in the harbor during the event. It should be anticipated that some of these vessels will break free from their moorings and damage nearby piers, buildings and other facilities in and around the harbor. They may also sink in the harbor, resulting in channel blockage and reduced draft. Additional restraints should be considered to limit the potential for these vessels to break free. These restraints would need to be designed to allow for the anticipated water level changes, waves and currents induced by the event.
- In order to gain a better understanding of the potential currents in selected critical ports, it is recommended that field instrumentation be developed and installed to monitor current and wave conditions during future tsunami and hurricane events. The data collected by this instrumentation could then be used to calibrate numerical models to simulate the hydrodynamic effects in the selected ports.

5.3.3 Harbor Piers and Wharfs

- Most existing piers are anticipated to perform well during future inundation events. However, designs of future piers should incorporate “pressure relief panels” to reduce the uplift pressures to which the piers might be subjected. Laboratory research should be performed to establish the optimal design criteria for the dimensions and details of these pressure relief panels.
- Soil-supported wharfs may experience liquefaction due to earthquake ground shaking or scour due to water inundation and withdrawal, resulting in potential damage to paved cargo handling areas. New wharf construction should incorporate soil stabilization measures to limit the potential for liquefaction.

5.3.4 Shipping Container Storage Yards

- Harbor procedures during a warning event should provide for evacuation of all shipping containers with hazardous materials, followed by those with perishable goods, to designated locations outside the inundation zone.
- Suitable locations for shipping container evacuation should be established and Memoranda of Understanding (MOUs) should be established with the owners of each evacuation site. These MOUs will need to be renewed or modified if ownership of the evacuation site changes.
- Harbor personnel required for shipping container evacuation should be provided with special identification passes that permit them to enter the evacuation zone during a warning.
- Consideration should be given to opening the doors of empty containers left in the inundation zone to avoid buoyancy forces. These open containers should also be restrained with hold-downs or cables to prevent hydrodynamic loads from washing them into the harbor, where they would sink and reduce the available draft.
- All container handling equipment that can leave the harbor should do so prior to anticipated inundation so that this equipment is available to assist with cleanup and post-event recovery.

5.3.5 Fuel Storage Facilities

- Enclosure walls and earthen berms surrounding fuel storage facilities should be reviewed to determine whether or not they will be overtopped during a design level hurricane or tsunami event.
- Enclosure walls should also be reviewed structurally to determine their ability to withstand external hydrostatic and hydrodynamic pressure due to storm or tsunami inundation. They are typically only designed for internal pressure due to a fuel spill.
- Enclosure walls that are structurally deficient or not tall enough to prevent overtopping during a design hurricane or tsunami event should be considered for strengthening or replacement.
- The addition of rock-fall protective fences to the top of structurally sound enclosure walls and berms could be considered as a measure to prevent debris (particularly shipping containers) from entering the fuel storage enclosure and damaging the tanks and piping.
- Fuel storage tanks should be kept as full as practical so as to reduce buoyancy forces if water overtops the protective wall or berm.
- Alternative fuel storage facilities outside of the inundation zone should be identified as backup supplies if the port fuel facilities are damaged or rendered inoperable.

5.3.6 Bulk Handling Facilities

- Where possible, electrical and mechanical components of bulk handling equipment should be elevated above the anticipated inundation level, or waterproofed and protected against water and debris impact damage.
- Alternative stockpiles of critical bulk materials such as cement, coal and fuel located outside of the inundation zone should be identified. These stockpiles should be

maintained at a level that allows for continued operation of island services even if the harbor bulk handling equipment is out of commission for up to a month.

- The fuel transfer station off-shore of Campbell Industrial Park should be reviewed for its likely performance during a design level hurricane or tsunami. The loss of this transfer facility would greatly hamper fuel deliveries to Oahu and the other islands.
- Alternative bulk handling equipment and procedures available on island should be identified to provide even limited handling capabilities during downtime of the primary bulk handling facility.

5.3.7 Harbor Buildings

- No critical operations or equipment should be housed in substandard harbor buildings that are not expected to survive a design level hurricane or tsunami.
- Essential and critical buildings such as the Honolulu Harbor control tower, the HDOT harbors division Emergency Operations Center building on Pier 2, Matson control tower on Sand Island, and other buildings that will remain occupied during a warning event, must be evaluated structurally to ensure that they can withstand the anticipated hydrodynamic and debris impact loads.
- Important warehouse and other harbor buildings that are required to survive with only non-structural damage should be evaluated structurally.
- During hurricanes, it is recommended that warehouse roller doors be kept closed to reduce the potential for internal wind pressurization. During tsunamis, it is recommended that roller doors be kept fully open so as to reduce damage to the doors if water inundates the wharf.

5.3.8 Adjacent Critical Facilities

- Power plants located adjacent to Kahului and Honolulu harbors should be evaluated for their exposure to impact damage from floating shipping containers and other debris.
- Sand Island Wastewater Treatment plant should be evaluated for its ability to survive a design level hurricane or tsunami without resulting in sewage spills that could endanger rescue and recovery personnel.

6 REFERENCES

Bulter, R., 2011. “Re-examination of the potential for great earthquakes along the Aleutian island arc with implication for tsunamis in Hawaii”, *Seismological Research Letters*, 81(1), pp. 30-39.

Cheung, K.F., 2014. “Preliminary Tsunami Inundation Maps for the Great Aleutian Tsunami”, *Draft Copy*

Chock, G., Carden, L., Robertson, I.N., Olsen, M.J., and Yu, G., 2013a. “Tohoku Tsunami-induced Building Failure Analysis with Implications for U.S. Tsunami and Seismic Design Codes”, *Earthquake Spectra*, Vol. --, No. --, Date, p. ---.

Chock, G., Robertson, I.N., Kriebel, D., Francis, M., and Nistor, I., 2013b. “Tohoku Japan Tsunami of March 11, 2011 – Performance of Structures”, *American Society of Civil Engineers, Structural Engineering Institute,* pp 346.

EERI, 2010. “The Mw 8.8 chile Earthquake of February 27, 2010”, *EERI Special Earthquake Report*, June 2010, EERI Newsletter, pp. 20.

Federal Register, 2013. “Safety Zones; Hawaiian Island Commercial Harbors, HI”, *Federal Register*, Vol. 78, No. 96, May 17, 2013.

FEMA 549, 2006. “Hurricane Katrina in the Gulf Coast”, FEMA MAT Report

Fritz, H.M., Blount, C., Sokoloski, R., Singleton, J., Fuggle, A., McAdoo, B.G., Moore, A., Grass, C., and Tate, B., 2008. “Hurricane Katrina Storm Surge Reconnaissance”, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, May, pp. 644-656.

Frye, E., 2005. “Tanks in the Wake … A Postmortem of Katrina, Rita, Wilma”, L.U.S.T.Line Bulletin 51, Dec., pp. 2-6.

HawaiianEncyclopedia.com, 2014. “Tsunamis”, website accessed July 9, 2014, http://www.hawaiianencyclopedia.com/tsunamis.asp

Henderson, K., 2005. “The Case of the Buckled Steel Tanks on Mississippi Highway 90”, L.U.S.T.Line Bulletin 51, Dec., pp. 8-9.

Kennedy, A.B., Westerink, J.J., Smith, J.M., Hope, M.E., Hartman, M., Taflanidis, A.A., Tanaka, S., Westerink, H., Cheung, K.F., Smith, T., Hamann, M., Minamide, M., Ota, A., and Dawson, C., “Tropical cyclone inundation potential on the Hawaiian Islands of Oahu and Kauai”, Ocean Modelling, 52-53, Elsevier Ltd., pp. 54-68.

Mosqueda, G., and Porter, K.A., 2007. “Damage to Engineered Buildings and Lifelines from Wind, Storm Surge and Debris in the Wake of Hurricane Katrina”, MCEER Special Report Series, Hurricane Katrina Vol. 4, pp. 64.

Olsen, M.J., Cheung, K.F., Yamazaki, Y., Butcher, S., Garlock, M., Yim, S.C., Piaskowy, S., Robertson, I.N., Burgos, L., and Young, Y.L., 2012. “Damage Assessment of the 2010 Chile Earthquake and Tsunami using Ground-based LIDAR”, *Earthquake Spectra*, Vol. 28, No. S1, pp. S179-S197, June.

Robertson, I. N., Riggs, H. R., Yim, S. C. S., and Young, Y. L., 2006. “Lessons from Katrina”, *Civil Engineering*, American Society of Civil Engineers, April, pp. 56-63.

Robertson, I. N., Riggs, H. R., Yim, S. C. S., and Young, Y. L., 2007. “Lessons From Hurricane Katrina Storm Surge on Bridges and Buildings”, *Journal of Waterway, Port, Coastal and Ocean Engineering*, Vol.133, No.6, American Society of Civil Engineers, Nov/Dec.

Robertson, I.N., Carden, L., Riggs, H.R., Yim, S., Young, Y.L., Paczkowski, K., and Witt, D., 2010. "Reconnaissance Following the September 29, 2009 Tsunami in Samoa", *University of Hawaii Research Report UHM/CEE/10-01*, Jan. pp. 145, http://www.cee.hawaii.edu/reports/UHM-CEE-10-01.pdf

Robertson, I.N., Chock, G., and Morla, J., 2012. "Structural Analysis of Selected Failures Caused by the 27 February 2010 Chile Tsunami", *Earthquake Spectra*, Vol. 28, No. S1, June, p. S1-S29.

State of Hawaii, 2004. "Port Hawaii – Commercial Harbors System Handbook", Hawaii Department of Transportation, Harbors Division, pp. 44.

Sturgis, L.A., Smythe, T.C., and Tucci, A.E., 2014. "Port Recovery in the Aftermath of Hurricane Sandy," *Voices from the Field*, August 2014, Center for a New American Security, Washington, DC.

United States Code, 2006. "33 U.S.C. 409 – Obstruction of Navigable Waters by Vessels; Floating Timber; Marking and Removal of Sunken Vessels," *United States Code*, 2006 Edition, Supplement 5, Title 33, Section 409, January 3, 2006.

US Army Corps, 2014. "Hawaii Storm Atlas", https://www3.nd.edu/~swims/, website accesses on July 11, 2014.

Wikipedia, 2014. "Hawaiian Electric Industries", http://www.wikipedia.org/wiki/Hawaiian_Electric_Industries, accessed July 22, 2014.

7 Appendix A

Additional Google Earth aerial before and after images of ports and harbors damaged by the Tohoku Tsunami.

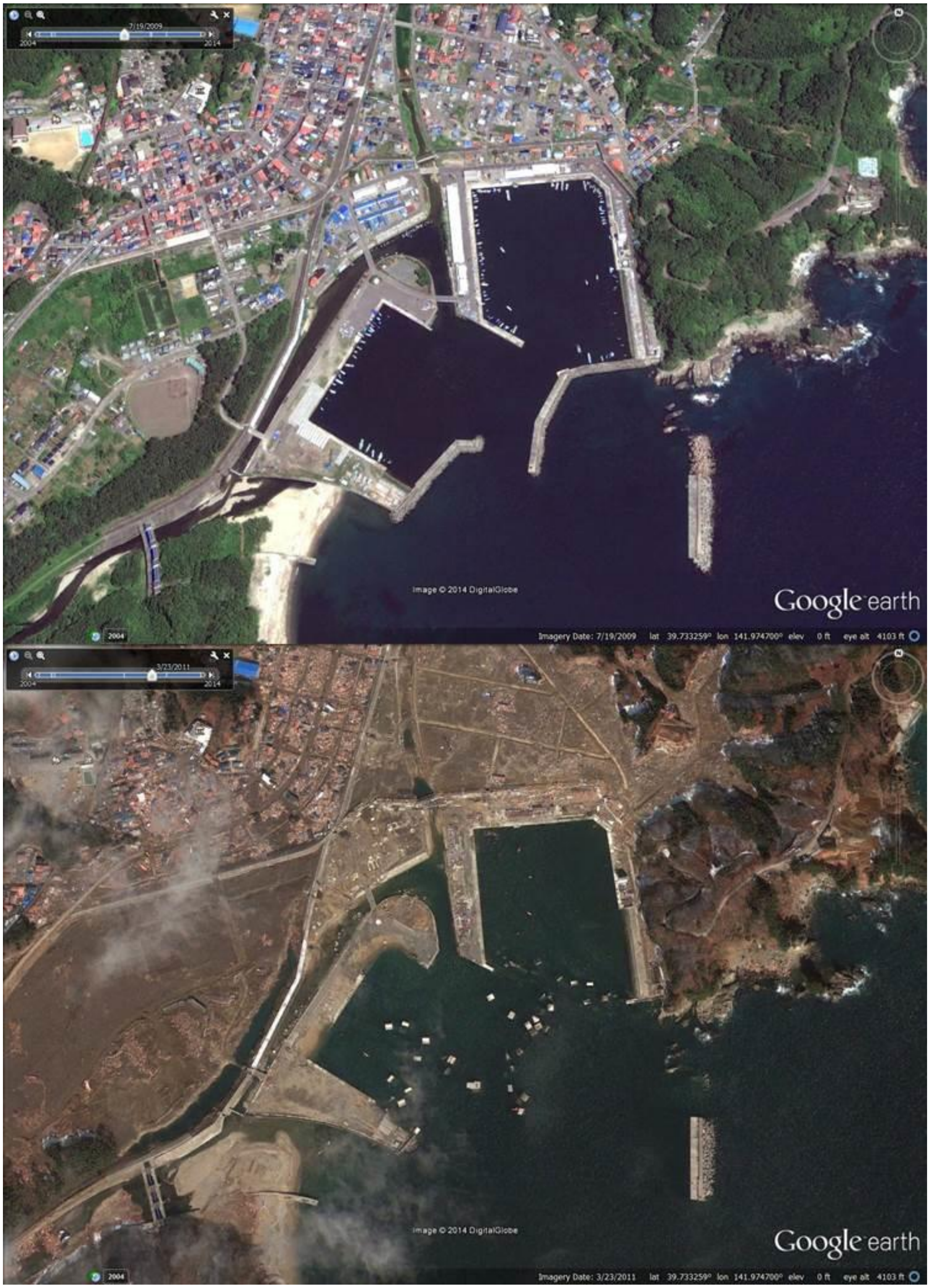

Figure 7-1: Taro Port before (top) and after (bottom) the Tohoku Tsunami

Figure 7-2: Yamada Port before (top) and after (bottom) the Tohoku Tsunami

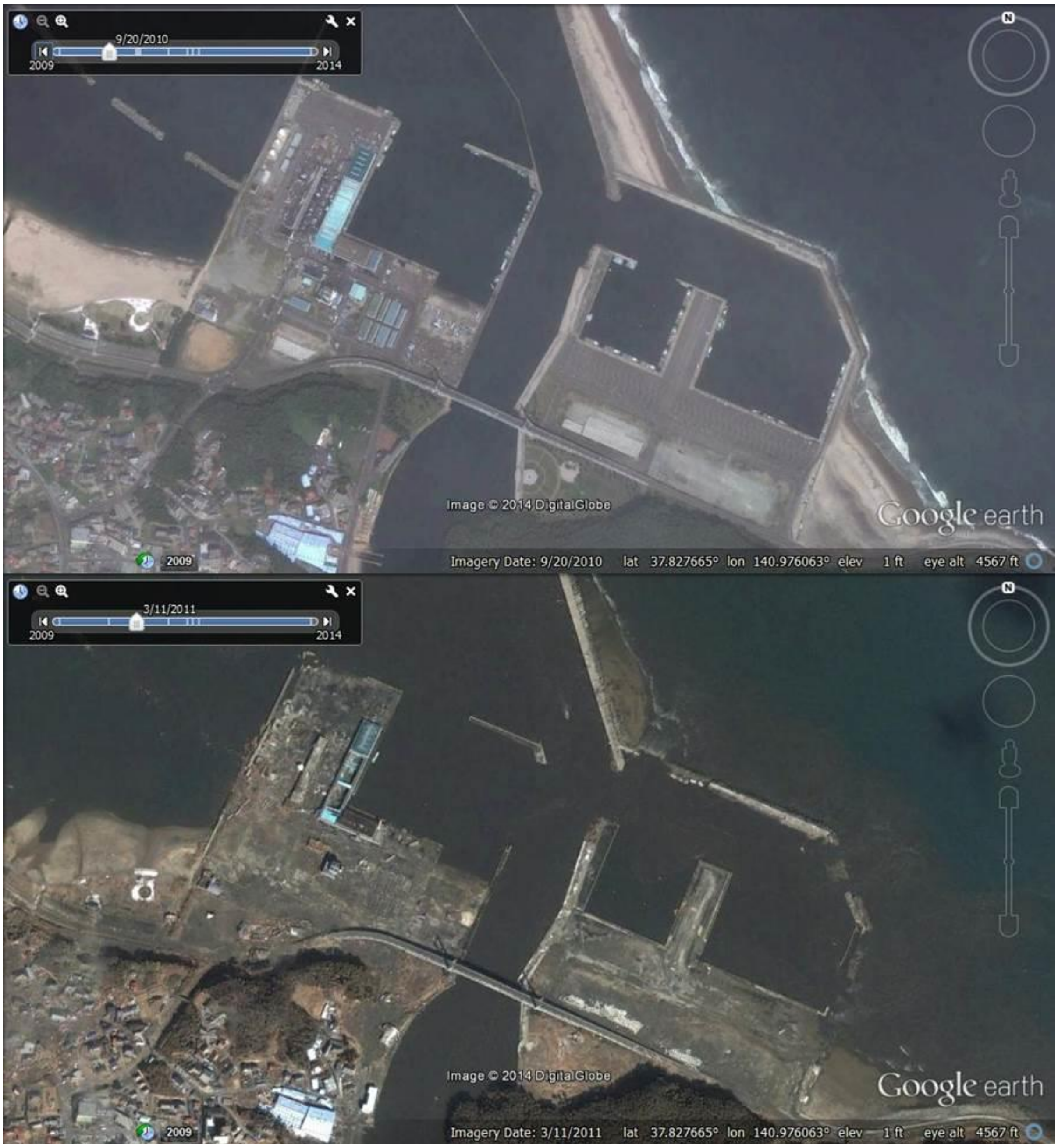

Figure 7-3: Soma Port before (top) and after (bottom) the Tohoku Tsunami

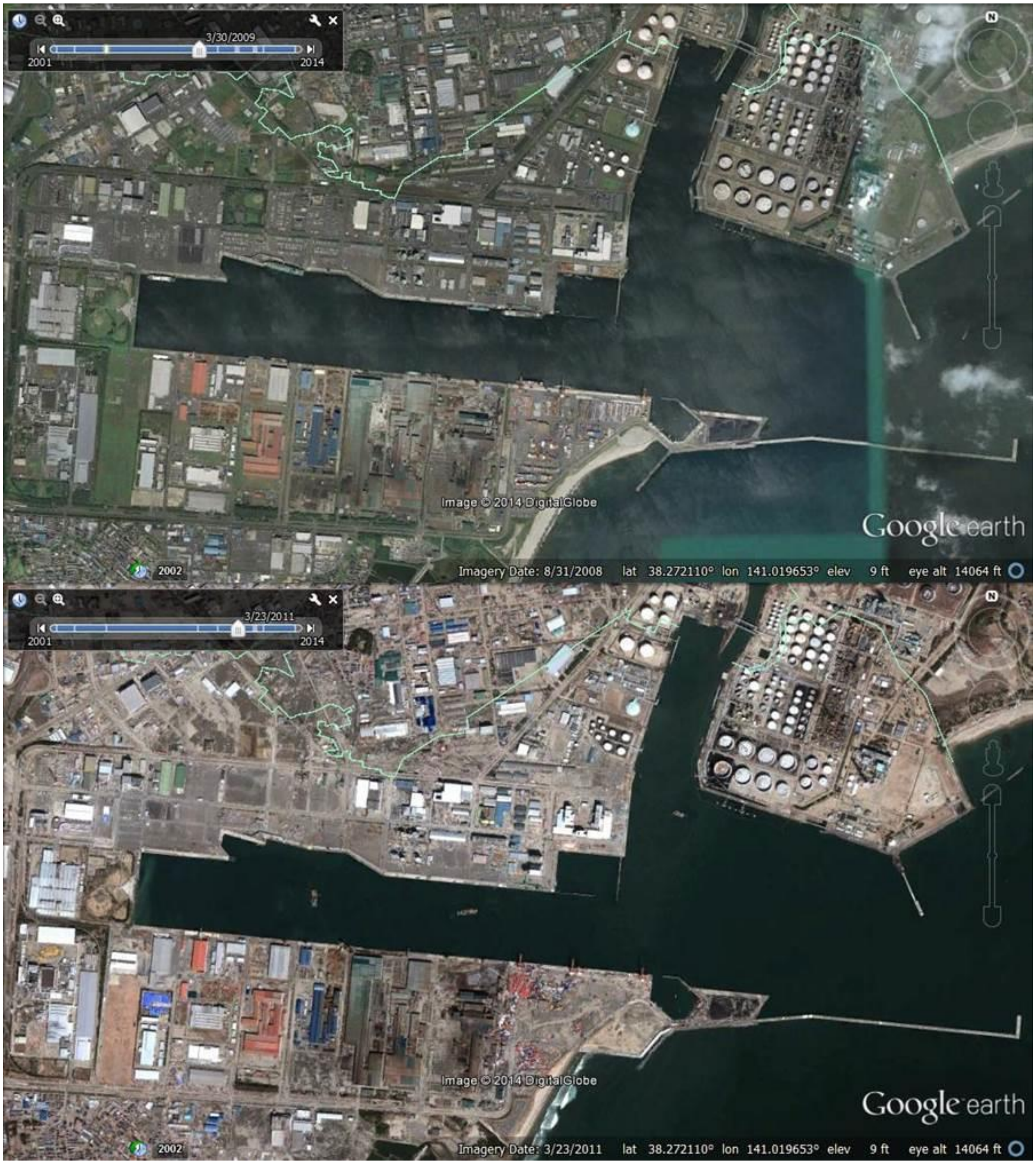

Figure 7-4: Sendai Harbor before (top) and after (bottom) the Tohoku Tsunami

Figure 7-5: Otsuchi Port before (top) and after (bottom) the Tohoku Tsunami

Figure 7-6: Kamaishi Harbor before (top) and after (bottom) the Tohoku Tsunami

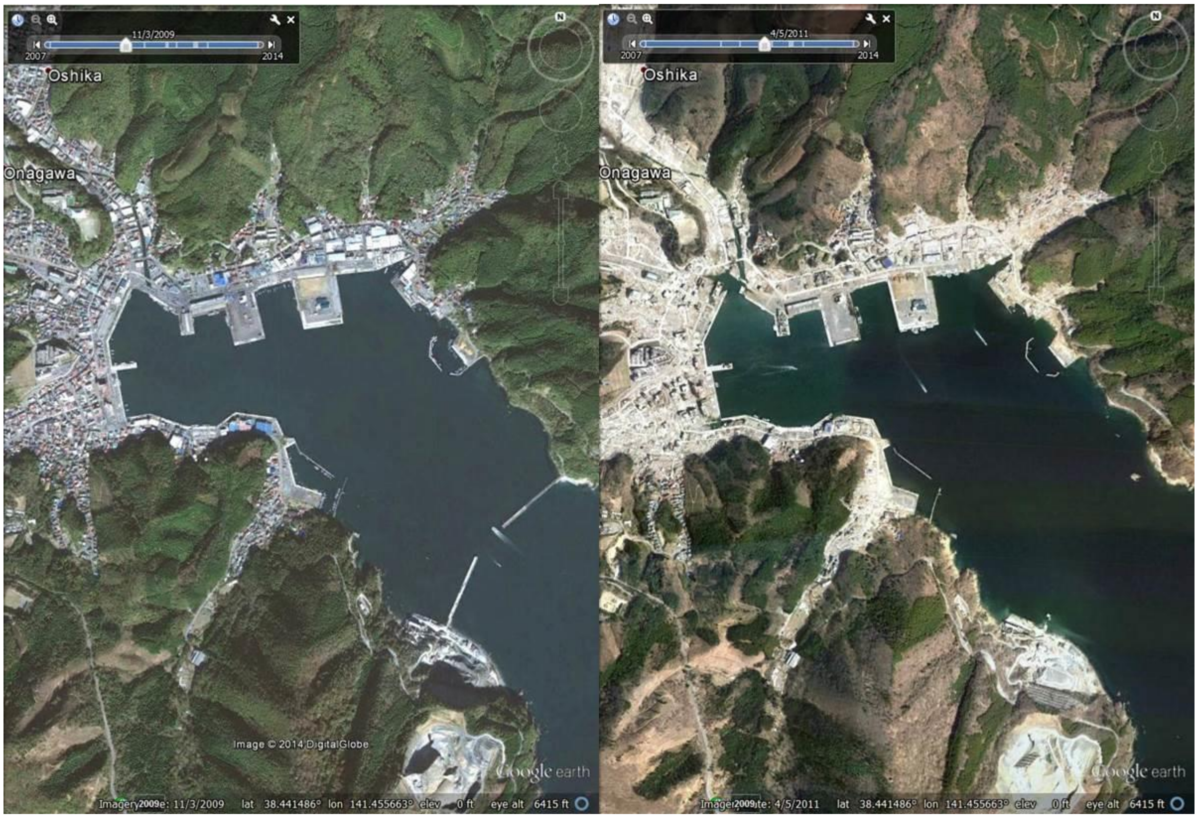

Figure 7-7: Onagawa Harbor before (left) and after (right) the Tohoku Tsunami