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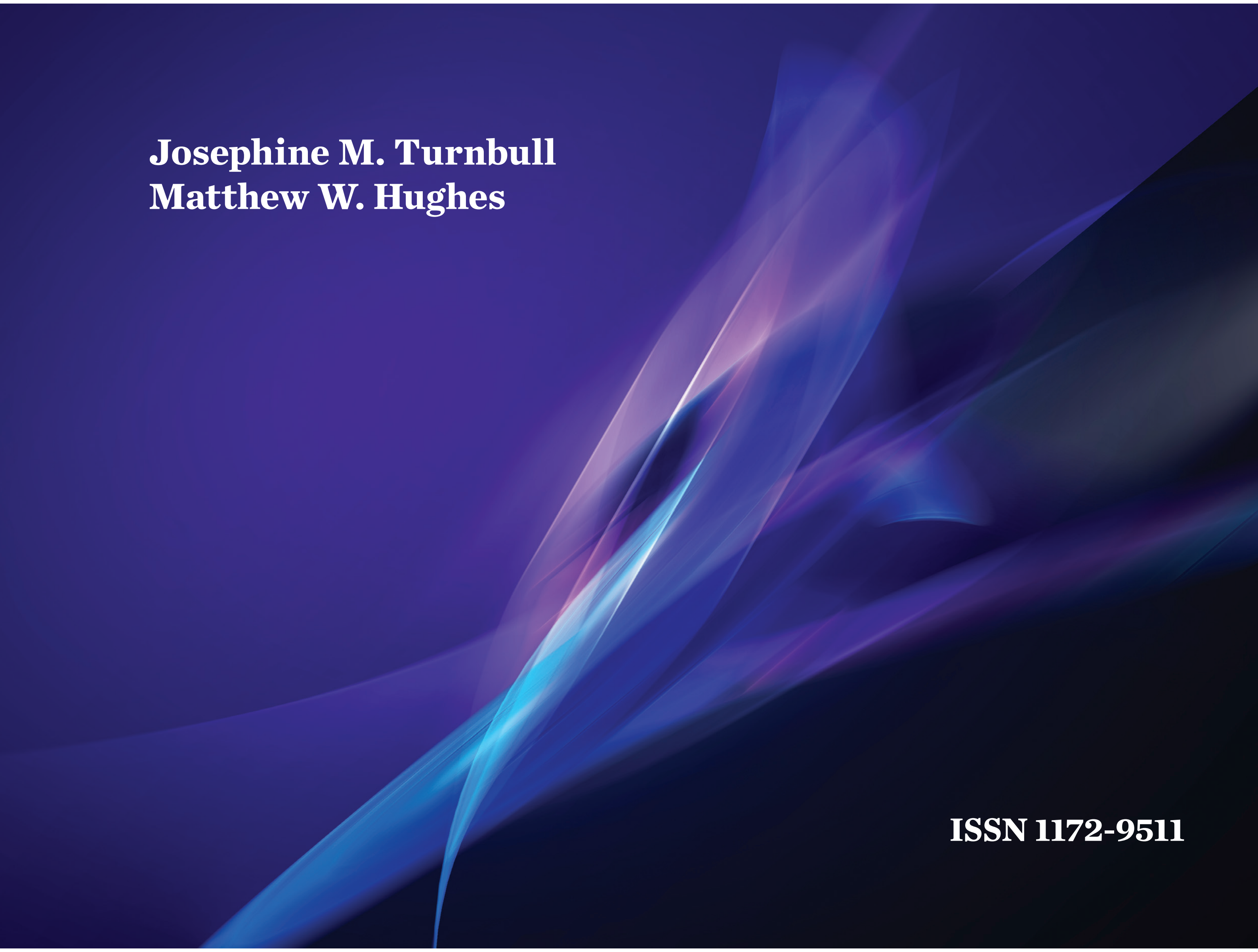
ANTICIPATING TSUNAMI IMPACTS IN PORT MARLBOROUGH



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Anticipating tsunami impacts in Port Marlborough

IMPLICATIONS FOR PORT OPERATION AND HARBOUR NAVIGABILITY

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1.0 Introduction

Ports play a crucial role in facilitating a nation's ability to trade internally and with external markets, and many countries such as New Zealand rely heavily on export and import trade for their economy. Ports also provide services to many other sectors, and constitute critical nodes in infrastructure lifeline networks.

The operation of ports and harbour navigability can be compromised by primary and secondary tsunami impacts (Power et al. 2013; Admire et al. 2014). Ports are extremely vulnerable to both inundating and non-inundating tsunamis due to strong currents, which can persist up to 24 hours after the initial tsunami arrival (Okal et al. 2006b; Okal et al. 2006c; Okal et al. 2006a; Wilson et al. 2013; Admire et al. 2014; Borrero et al. 2015a). The hazard presented by strong currents remains an underappreciated and under-communicated risk in the port and maritime community, which along with other tsunami impacts may have implications for the movement of vessels and goods through and around ports (Wilson et al. 2013; Borrero et al. 2015b; Borrero et al. 2015a).

New Zealand's ports are exposed to tsunami hazards from distant, regional and local sources, that vary in travel time from >3 hours to <60 minutes, respectively (De Lange et al. 1986; Power et al. 2007; Power et al. 2013). In the Marlborough Sounds and Cook Strait there are numerous active faults, which have the potential to rupture vertically and causing local tsunami (Power et al. 2013).

Port Marlborough is one of the busiest ports in New Zealand, with >7,500 large vessel movements annually (Port Marlborough New Zealand (PMNZ) (n.d.). It runs diverse port and marina facilities, including scenic cruising by all manner of vessels, and is the South Island terminal for inter-island passenger and freight ferries. The wider Marlborough Sounds is home to the largest residential population in New Zealand accessible only by boat. Therefore there is a need to understand potential tsunami impacts their effects on port operations and harbor navigability. This study focuses on the Marlborough Port area and Queen Charlotte Sound only, and excludes Pelorus and Kenepuru Sounds.

2.0 Method

This assessment is based on the following:

1. Literature review of recent peer-reviewed scientific literature.
2. Literature review of other publically available reports, journal articles, books and other documents.
3. Discussions with Port Marlborough and Marlborough District Council CDEM personnel (meeting 28th February 2017).
4. Exposure analysis of infrastructure to tsunami inundation scenarios using Geographic Information Systems (GIS).

3.0 Results

3.1 New Zealand's tsunami environment

Many historically tsunamis of varying magnitude from distant, regional and local sources have been recorded throughout New Zealand (Table 1) (Appendix 5.1a) (De Lange et al. 1986; Power et al. 2013; Borrero et al. 2015b; GNS (n.d.). Because the travel time is generally consistent with the sources, distant, regional and local sources can be classified based on travel times to the New Zealand coastline (Power et al. 2013; Williams 2016);

- Distant source – >3 hours travel time
- Regional source – 1-3 hours travel time
- Local source – 0-60 minutes to the nearest New Zealand coast (most sources are <30 minutes and vary in arrival time throughout New Zealand)

Sources such as Chile, Peru and Ecuador pose a higher risk than others to New Zealand because higher energy waves propagate in the direction perpendicular to the strike of the fault (Appendix 5.1b) (Okal et al. 2006b; PIANC 2010). Therefore the location of the source and orientation of the strike of the fault relative to New Zealand is important because it will affect the directivity of high-energy tsunami waves and the time it will arrive.

The far field effects from a large tsunami from South America in New Zealand could be analogous to effects from the 2011 Tohoku tsunami in California (Borerro et al. 2015b). Both the orientation and the distance between California relative to the Japan subduction zone are similar to the distance and orientation and distance between New Zealand relative to the South American subduction zone (Appendix 5.2) (Borerro et al. 2015b).

3.1.1 Port Marlborough tsunami hazard

Tsunamis have been historically recorded in the Marlborough sounds at Picton, Wairau River/Bar, and The Grove (GNS (n.d.; Table 2). In a 100-year return period the Marlborough Sounds and Tasman Bay in Cape Jackson have an expected maximum tsunami height in the 50th and 84th percentile of 2-4 m (Appendix 5.3) (Power et al. 2013; Power et al. 2014). Power et al. (2014) suggest an increase in maximum tsunami height to 4-6 m in the 50th and 84th percentile of a 500-year return period scenario (Appendix 5.3).

The location of the source relative to Port Marlborough will have an effect on the travel time, and therefore the available time to effectively communicate the tsunami hazard to the port and maritime community reduce the exposure and vulnerability of people, vessels and mobile infrastructure.

Table 1. Locations of potential local, regional and distant tsunami sources for New Zealand based on travel time. Maximum run-ups recorded from around New Zealand. Tsunami run-ups actually recorded in New Zealand are in bold and modelled estimates of the maximum run-up are in italic. Sources (Power et al., 2007; Borerro et al., 2013; Power et al., 2013; Borerro et al., 2015; GNS (n.d.).

	Travel time	**Location**	**Max. run-up in NZ**
Distant	>3 hours	South America: Chile;	**4**
		South America: Peru;	**4**
		Mexico and central America;	n/a
		Cascadia subduction zone;	*1-3*
		Alaska and the Aleutians,	**2**
		Kurile Islands, Kamchatka;	**>1**
		Japan;	**1**
		Solomon Islands, Papua New Guinea;	**0.5**
		Northern New Hebrides;	n/a
		Krakatau, Indonesia;	**1.8** (peak to trough)
Regional	1-3 hours	Southern New Herbrides;	*1-5*
		Tonga Trench;	negligible
		Kermadec Trench;	*15-20*
		South of New Zealand (including Macquarie Ridge);	**<0.5**
		Volcanoes along the Taupo-Kermadec arc;	n/a
Local	<1 hour	Kermadec Trench;	n/a
		Offshore eastern North Island & Hikurangi subduction zone ;	**10**
		bay of plenty faults;	n/a
		faults near Auckland;	*2>*
		faults in Cook Strait and offshore Marlborough;	**10**
		faults in western Cook Strait and offshore Manawatu;	n/a
		faults in southern South Island;	n/a
		Mayor island and White island volcanoes;	n/a

Table 2. Table showing tsunamis historically recorded in the Marlborough sounds. Source (GNS (n.d.).

Year	**Source**	**EQ Magnitude**	**Impact location**	**Approx. travel time**
1855	Wairarapa	MW8.2-8.4	Wairau River/Bar	0.2-0.3h
1868	Southern Peru	MW9.1	Picton The Grove	16.5h 16.5h
1868	Cape Farewell, NZ	MW7.2-7.6	Picton	>1h
1877	Northern Chile	MW9.0	Wairau River/Bar	15h
1883	Krakatoa, Indonesia	Volcanic eruption	Wairau River/Bar	n/a
1960	Chile	MW9.5	Picton	14.5h
1964	Prince William Sound, Alaska	MW9.2	Picton	15.5h

3.2 Primary and secondary direct tsunami impacts

Power et al. (2013) place tsunami damage in two categories: 1) Primary impacts – impacts directly from the flow of water e.g. hydrostatic and hydrodynamic forces; 2) Secondary impacts – impacts from objects or contaminants within the flow. The main forces present during a tsunami that cause damage are described by Ewing et al. (2013), Chock et al. (2013), Palermo et al. (2013) and Horspool et al. (2016), and are summarised as:

1. Primary:
   - **a)** *Hydrostatic:* forces arising from a difference in water levels on opposite sides of a structure.
   - ***b)*** *Hydrodynamic (drag)*: forces due to the flow of the tsunami around a structure, the forces can impose uplift on horizontal members due to the rapidly rising water level or due to a vertical component in the flow.
   - ***c)*** *Buoyancy and uplift*: forces generated on structures when fully or partially submerged, these forces can induce stability failures through reductions in the resistance to sliding and overturning.
   - ***d)*** *Impulsive*: short-duration forces from the leading edge of the tsunami flow.
   - ***e)*** *Gravity*: Gravity forces will result if water is retained on horizontal structural flooring systems during the receding phase of the tsunami.
2. Secondary:
   - ***a)*** *Debris impact and damming*: Debris impacts are short-duration forces that occur from objects transported by the flow e.g. vehicles, vessels, containers. Debris accumulation in front of structures leads to a damming affect where the surface area exposed to the flow increases, resulting in an increase in hydrodynamic forces imposed on the structure.

Debris transport is governed by the size of the debris, topographic gradient, flow depth, flow direction and the surrounding building layout (Naito et al. 2014). Flow depth will determine what debris can be picked up and entrained in the flow, e.g. for a container to float over a building the inundation depth minus the draft of the container must be more than the building height (Table 3) (Appendix 5.4) (Naito et al., 2014). If flow depth is small or reduced and with lower flow velocities, the impact forces become less significant as debris contacts the ground (Naito et al. 2014). Distances that debris will be dispersed is a function of flow depth and building height, building spacing and construction material (Appendix 5.4). It is important to consider debris strikes from multiple directions due to both inundating and receding waves.

Direct primary and secondary tsunami impacts observed in historical tsunamis, and described in experiments, are summarised in Tables 4-5).

Table 3. Types of debris that can be entrained, suspended and deposited from tsunami depending on flow depth, extracted from Evan et al. (2011).

Flow depth (m)	**Debris type suspended and deposited**
<1 m	Sand, silt and light vegetation
1-2 m	Cobbles, wood and buoyant objects
>2 m	Large boulders, storage tanks, cars, boats, building debris etc.

Table 4. Summary of primary direct tsunami impacts on port infrastructure and navigation.

Asset	**Type of impact**	**Citations**
	Port infrastructure	
Piles	Damage by impulsive forces; Structure washed away by hydrodynamic forces; Scouring around the base of foundations therefore increasing the likelihood of structural collapse; Pinning of floating docks to their pilings may allow water to overtop	(Bell et al. 2005); (Borrero et al. 2013); (Wilson et al. 2013); (Borrero et al. 2015a)
Wharf, quay and pier decks	Damage by impulsive forces; Lifting of the decks off piles due to buoyancy and uplift forces; Structure or components of failed structure washed and carried away by hydrodynamic forces; Relevant telecom, gas lines, power lines and/or water pipelines may be destroyed; Fire from gas leak or electricity; Separation of deck slabs from their footings; Removal of concrete blocks; Sedimentation in-between and beneath docks; Shearing of decks off their piles	(Lander et al. 1989); (Bell, 2005); (Edwards 2006); (PIANC 2010); (Barberopoulou et al. 2011); (Takahashi et al. 2011); (Wilson et al. 2012); (Chock et al, 2013); (Edge, 2013); (Wilson et al. 2013); (Borrero et al. 2015b); (Horspool et al. 2016)
Cranes	Damage by impulsive forces; Lifting of the cranes due to buoyancy and uplift forces; Structure washed away by hydrodynamic forces; Inundation causing failure of mechanical equipment and electrical control circuits; Fire from gas leak or electricity	(Edwards 2006);
Mooring dolphins, bollards and pontoons	Damage by impulsive forces; Structure or components of failed structure washed and carried away by hydrodynamic forces; Structural damage due to hydrostatic forces	(Edwards, 2006); (Okal et al. 2006a); (Power, 2013)

Table 4 continued

Mooring lines	Damage by impulsive forces; Breaking of mooring lines due to increased tension from buoyancy and hydrodynamic forces	(Lander et al. 1989); (Okal et al. 2006a); (Okal et al. 2006b); (Okal et al. 2006c); (PIANC 2010); (Takahashi et al. 2011); (Chock et al, 2013); (Wilson et al. 2013); (Edge, 2013); (Borrero et al. 2015a); (Borrero et al. 2015b)
Seawalls	Damage by impulsive forces; Lifting of failed components of seawall due to buoyancy and uplift forces; Structure or components of failed structure washed and carried away by hydrodynamic forces; Scouring around the base of foundations therefore increasing the likelihood of structural collapse; Tilting and rotating of seawall by hydrodynamic forces and/or scouring	(Bell et al. 2005); (PIANC 2010); (Chock et al, 2013); (Edge, 2013); (Ewing et al. 2013); (Takahashi et al. 2011)
Breakwater	Damage by impulsive forces; Lifting of failed components of breakwaters due to buoyancy and uplift forces; Structure or components of failed structure washed and carried away by hydrodynamic forces; Scouring around the base of foundations therefore increasing the likelihood of structural collapse	(PIANC 2010); (Takahashi et al. 2011) (Chock et al, 2013); (Ewing et al. 2013)
Containers	Damage by impulsive forces; Lifting of containers from original position or stacks due to buoyancy and uplift forces; Containers washed and carried away by hydrodynamic forces; Containers may be subject to motion if their storage facility is damaged; Subject to motion if the wharf, barge or platform they are sitting on is uplifted or rotated even if the containers themselves are not inundated; Dangerous good potentially exposed; Damage to goods inside the containers	(PIANC 2010); (Takahashi et al. 2011); (Chock et al, 2013); (Edge, 2013); (Palermo et al. 2013); (Cox et al. 2014); (Borrero et al. 2015a)
Timber logs	Damage by impulsive forces; Lifting of utility logs from original position or stacks due to buoyancy and uplift forces; Logs washed and carried away by hydrodynamic forces; Logs may be subject to motion if their storage facility is damaged; Subject to motion if the wharf, barge or platform they are sitting on is uplifted or rotated even if the logs themselves are not inundated	(PIANC 2010); (Chock et al, 2013); (Borrero et al. 2015a)

Table 4 continued

Vessels	Damage by impulsive forces; Hydrodynamic forces rotating vessels causing potential collision with other vessels and structures with or without breaking its mooring lines; Large wave amplitudes or hydrodynamic forces causing vessels to capsize and possibly sink; Vessels unable to navigate through strong currents; Vessels may get caught in turbulent coherent structures (TCS) and uncontrollably spin; Water damage from inundation; Fire from gas leak or electricity; Floating and depositing inland; Vessels may have harbor entry restricted to certain portions of the tidal cycle if the draft has been significantly been reduced; Vessel damage during ground contact with receding waves	(Lander et al. 1989); (Okal et al. 2002); (Bell et al. 2005); (Fritz & Borrero 2006); (Okal et al. 2006a); (Okal et al. 2006b); (Okal et al. 2006c); (PIANC 2010); (Fritz et al. 2011); (Takahashi et al. 2011); (Chock et al, 2013); (Edge, 2013); (Wilson et al. 2013); (Borrero et al. 2015a); (Borrero et al. 2015b)
Other shipping goods	Damage by impulsive forces; Water damage from inundation; Dangerous good potentially exposed	(Horspool et al. 2016)
Buoys	Damage by impulsive forces; Scouring causing the mooring buoy anchor to move	(Edge, 2013); (Borrero et al. 2015a)
Boat ramps and jetties	Damage by impulsive forces; Unable to use the boat ramp due to strong currents and inundation; Scouring around the base of the ramp causing collapse, settling or rotation of the ramp; Sediment deposition in the direct vicinity may make the boat ramp inaccessible	(Borrero et al. 2013); (Edge, 2013)
Buildings	Damage by impulsive forces; Lifting of buildings from original position or foundations due to buoyancy and uplift forces; Structure or components of failed structure washed and carried away by hydrodynamic forces; Structural damage due to hydrostatic forces; Scouring around the base of foundations therefore increasing the likelihood of structural collapse; Inundation causing failure of mechanical, electrical and communication equipment; Water damage to exterior, interior and stored goods from inundation; Washout of light structures e.g. light steel and timber; Relevant telecom, gas lines, power lines and/or water pipelines may be destroyed; Fire from gas leak or electricity; Flooding of power generators; Pumps for water and wastewater getting clogged with sand	(Okal et al. 2002); (Edwards 2006); (Goff et al. 2006); (Okal et al. 2006a); (Okal et al. 2006b); (Okal et al. 2006c); (Fritz & Borrero 2006); (Fritz et al. 2011); (Takahashi et al. 2011); (Chock et al, 2013); (Edge, 2013); (Palermo et al. 2013); (Cox et al. 2014); (Borrero et al. 2015a); (Borrero et al. 2015b);

Table 4 continued

Vehicles	Damage by impulsive forces; Water damage from inundation; Fire from oil leaks; Floating and deposition inland	(Edwards, 2006); (Fritz & Borrero 2006); (Goff et al. 2006); (Okal et al. 2006a); (Okal et al. 2006b); (Okal et al. 2006c); (Fritz et al. 2011); (Borrero et al. 2013); (Chock et al, 2013)
Pavement	Damage by impulsive forces; Extensive scouring causing damage and settlement; Lifting and removal of large concrete slabs	(Bell et al. 2005); (Edwards, 2006); (Goff et al, 2006); (Okal et al. 2006a); (Okal et al, 2006c); (Chock et al, 2013); (Edge, 2013); (Ewing et al. 2013); (Borrero et al. 2015b); (Horspool et al. 2016)
<u>Harbor Navigation</u>		
Seabed	Erosion and scouring of seabed; Sedimentation and siltation; Disturbance of marine habitat	(Bell et al. 2005); (PIANC 2010); (Takahashi et al. 2011); (Wilson et al. 2012); (Borrero et al. 2013); (Wilson et al. 2013); (Admire et al. 2014); (Borrero et al. 2015a); (Horspool et al. 2016)
Shoreline	Loss of coastlines, dunes, soil and beaches due to erosion and scouring; Uprooting of trees; Disturbance of terrestrial habitats; Fish and shellfish thrown ashore with possible consequent contamination; Contamination of groundwater; Burial of debris on the shoreline from sedimentation	(Bell et al. 2005); (Edwards, 2006); (Fritz & Borrero 2006); (Goff et al. 2006); (Okal et al. 2006b); (Fritz et al. 2011); (Chock et al, 2013); (Edge, 2013); (Ewing et al. 2013); (Horspool et al. 2016)

Table 4 continued

Waterways	Changes in water depth and available draft due to the erosion and deposition of sediment; Strong currents and high or low water levels may make navigation difficult or impossible and impede vessel traffic; Strong currents may exist for hours even if there is no visible amplified wave activity; Turbulent coherent structures (TCS) may form and drag anything floating in the water towards it and increase the ability of the flow to carry debris	(Okal et al. 2006a); (Okal et al. 2006b); (Okal et al. 2006c); (PIANC 2010); (Barberopoulou et al. 2011); (BBC, 2011); (Takahashi et al. 2011); (Lynett et al. 2012); (Wilson et al. 2012); (Borrero et al. 2013); (Hinwood et al. 2013); (Wilson et al. 2013); (Admire et al. 2014); (Borrero et al. 2015a); (Borrero et al. 2015b)
Marine farms	Damage by impulsive forces; Structure or components of failed structure washed and carried away by hydrodynamic forces; Disturbance of marine habitats; Damage to farmland and yield; Low water levels may cause marine farm moorings to become tangled; Wash-away of salmon far superstructures	(PIANC 2010); (Takahashi et al. 2011); (Borrero et al. 2013);

Table 5. Summary of secondary direct tsunami impacts on port infrastructure.

Asset	Type of impact	Citations
Port infrastructure		
Piles	Structural damage by debris impact; Fire from waterborne flammable materials; Structural damage by debris damming	(PIANC 2010)
Wharf, quay and pier decks	Structural damage by debris impact; Fire from waterborne flammable materials; Structural damage by debris damming; If not destroyed, could be extensively covered with debris; Drifting or rotation of vessels moored to the structure causing damage during collision; Severing of relevant telecom, gas lines, power lines and/or water pipelines by debris strike	(Edwards, 2006); (PIANC 2010); (Chock et al, 2013); (Edge, 2013); (Wilson et al. 2013); (Borrero et al. 2015a); (Borrero et al. 2015b); (Horspool et al. 2016)
Cranes	Structural damage by debris impact; Removal of crane from original position by debris impact; Cranes in mid-operation with lost power may be damaged when unloading vessels move; Structural damage by debris damming; Lifting, tilting or destruction of the structure the cranes sit on; Fire from gas leaks or electricity	(Okal et al. 2006a); (PIANC 2010); (Chock et al, 2013); (Edge, 2013); (Borrero et al. 2015a); (Horspool et al. 2016)
Mooring dolphins, bollards and pontoons	Structural damage by debris impact; Structural damage by debris damming; Drifting or rotation of moored vessels causing damage during collision	(PIANC 2010); (Edge, 2013);
Mooring lines	Severing of lines by debris impact	(Wilson et al. 2013)
Seawalls	Structural damage by debris impact; Structural damage by debris damming; Subsequent movement from original position from debris impact	(PIANC 2010); (Chock et al, 2013); (Ewing et al. 2013)
Breakwaters	Structural damage by debris impact; Structural damage by debris damming	(Okal et al. 2006c); (PIANC 2010); (Chock et al, 2013); (Borrero et al. 2015a)

Table 5 continued

Containers	Structural damage by debris impact; Subsequent movement from original position from debris impact; Impacted and moved by other debris; Lifting, tilting or destruction of the structure the containers sit on; Structural damage by debris damming; Damage to the container as its carried in the waves and impacted with other debris and/or structures; Dangerous good potentially exposed	(PIANC 2010); (Chock et al, 2013); (Palermo et al. 2013); (Cox et al. 2014); (Riggs et al. 2014); (Borrero et al. 2015a)
Timber logs	Subsequent movement from original position from debris impact; Fire from waterborne flammable materials; Lifting, tilting or destruction of the structure the logs sit on	(PIANC 2010); (Palermo et al. 2013); (Cox et al. 2014); (Riggs et al. 2014)
Other shipping goods	Fire from waterborne flammable materials; Dangerous good potentially exposed	
Vessels	Structural damage by debris impact; Fire from waterborne flammable; Fire from gas leak or electricity; Damage to the vessel as its carried in the waves and impacted with other vessels, the ground, debris and/or structures	(Fritz & Borrero 2006); (Okal et al. 2006c); (PIANC 2010); (Takahashi et al. 2011); (Chock et al, 2013); (Palermo et al. 2013); (Wilson et al. 2013); (Borrero et al. 2015a); (Borrero et al. 2015b); (Horspool et al. 2016)
Buoys	Breaking of buoy anchor lines from debris impact; Vessels and propellers getting caught in the ropes	(Borrero et al. 2015a)
Boat Ramps and jetty's	Damage by debris impact; Extensive debris cover	
Pavement	Structural damage by debris impact; Extensive debris cover	(Edwards, 2006); (Horspool et al. 2016)
Buildings	Structural damage by debris impact; Fire from waterborne flammable materials; Structural damage by debris damming; Fire from gas leak or electricity; Severing of relevant telecom or power poles or gas, water pipelines by debris strike	(Cox et al. 2014); (PIANC, 2010); (Edwards, 2006); (Fritz & Borrero 2006); (Goff et al. 2006); (Palermo et al. 2013); (Edge, 2013); (Chock et al, 2013); (Horspool et al. 2016); (Takahashi et al. 2011); (Bell et al. 2005)
Vehicles	Structural damage by debris impact; Fire from waterborne flammable materials; Damage to the vehicle as its carried in the waves and impacted with other vehicles, the ground, debris and/or structures	(Chock et al, 2013); (Fritz et al. 2011); (Takahashi et al. 2011); (Bell et al. 2005)

Table 5 continued

Harbor Navigation		
Seabed	Debris sunken and scattered on the seabed, possibly reducing the available draft and leading to contamination	(Takahashi et al. 2011)
Shoreline	Buildup of debris scattered on the shoreline; Oil spills from damaged storage tanks, vehicles, vessels, heaters or pipes; Contamination from sewerage; Severing of relevant telecom or power poles or gas, water pipelines by debris strike	(Edwards, 2006); (Fritz & Borrero 2006); (Goff et al. 2006); (Okal et al. 2006c); (Fritz et al. 2011); (Takahashi et al. 2011)
Waterways	Submerged, floating or sunken debris scattered in waterways; Contamination of near shore environment; Oil spills from storage tanks, vehicles, vessels, heaters or pipes; Contamination from sewerage; Deposition of sediment in waterways could reduce the hydraulic capacity and cause flooding in the future; Debris in the intertidal zone is subject to remobilization; Water level fluctuations may have implications for the minimum safe depths for vessel evacuation; Partially or fully submerged debris may delay harbor navigation or make it unviable until removed	(Edwards 2006); (Goff et al. 2006); (Takahashi et al. 2011); (Lynett et al. 2012); (Edge, 2013); (Borrero et al. 2015b)
Marine farms	Structural damage by debris impact; Structural damage by debris damming	

Note: some damage described in the literature did not explicitly say whether or not the tsunami damage was from primary or secondary impacts, so it was assumed that any impact would have had to have some component of hydrodynamic and/or hydrostatic forces initially or throughout the duration of the tsunami. Therefore lots of damage has been classified as primary when it is most likely that many impacts scenarios discussed had components of both primary and secondary impacts e.g. buoyancy, scour and debris impact that contributed to the failure or damage.

Any structures that survive the preceding earthquake and the initial tsunami arrival are subject to secondary impact from debris, which if severe enough may cause failure of individual structural or non-structural elements and contribute additional tsunami debris (Chock et al. 2013; Naito et al. 2014; Naito et al. 2016; Williams 2016).

Engineered structures commonly performed better than non-engineered structures constructed from timber, concrete, with brick masonry infill walls and light steel being susceptible to debris strike damage (Goff et al., 2006; Chock et al., 2013; Palermo et al., 2013). Individual sections of steel and reinforced concrete structures also frequently suffered damage in which walls parallel to the shoreline were commonly pushed in (Appendix 5.5) (Bell et al., 2005; Fritz & Borerro, 2006). Structures that perform better during inundation and debris strike provide an obstruction to the flow and reduce the dispersal of large amounts of debris inland, and as a result buildings sheltered by more competent buildings have a decreased likelihood of debris strike (Goff et al., 2006; Naito et al., 2014). Therefore, depending on the construction material of buildings near potential debris sources at ports, they could either limit or facilitate debris dispersal and related damage (Appendix 5.5; Chock et al. 2013).

There are many historical observations of strong tsunami-induced currents and their effects on moored and navigating vessels. Interestingly, many incidents of breaking mooring lines differ in the timing of initial rupture relative to the arrival time of the tsunami, indicating hazardous conditions are not only defined by the tsunami arrival (Okal et al., 2006b; Okal et al., 2006c; Okal et al., 2006a). For far-field events the largest wave amplitudes are usually delayed for several hours after the initial arrival of the tsunami (Borrero et al., 2015b; Borrero et al., 2013). In the hours and days after a tsunami, harbour navigation can be made difficult and sometimes unviable by elevated current velocities (Appendix 5.6a; Borrero et al. 2013; Wilson et al. 2013; Admire et al. 2014).

The following points summarise the main direct tsunami impacts observed in ports and harbours:

1. Damage to wharfs and piers from hydrodynamic forces, buoyancy and uplift forces, scouring and debris impact (Figure 1).
2. Breaking of vessel mooring lines, capsizing and sinking of vessels, and drifting of vessels inland and in currents that typically lasted for up to 24 hours after initial tsunami arrival; vessels have potential to become large and damaging debris (Figure 2).
3. Scouring around piers, breakwater, seawalls, building corner and along the shoreline, often causing structural collapse (Figure 3).
4. Damage to structures from debris strike, and also damage to/fragmentation of debris itself (vessels, tanks, vessels) as it impacts other debris, structures and the ground (Appendix 5.7; Figure 4).

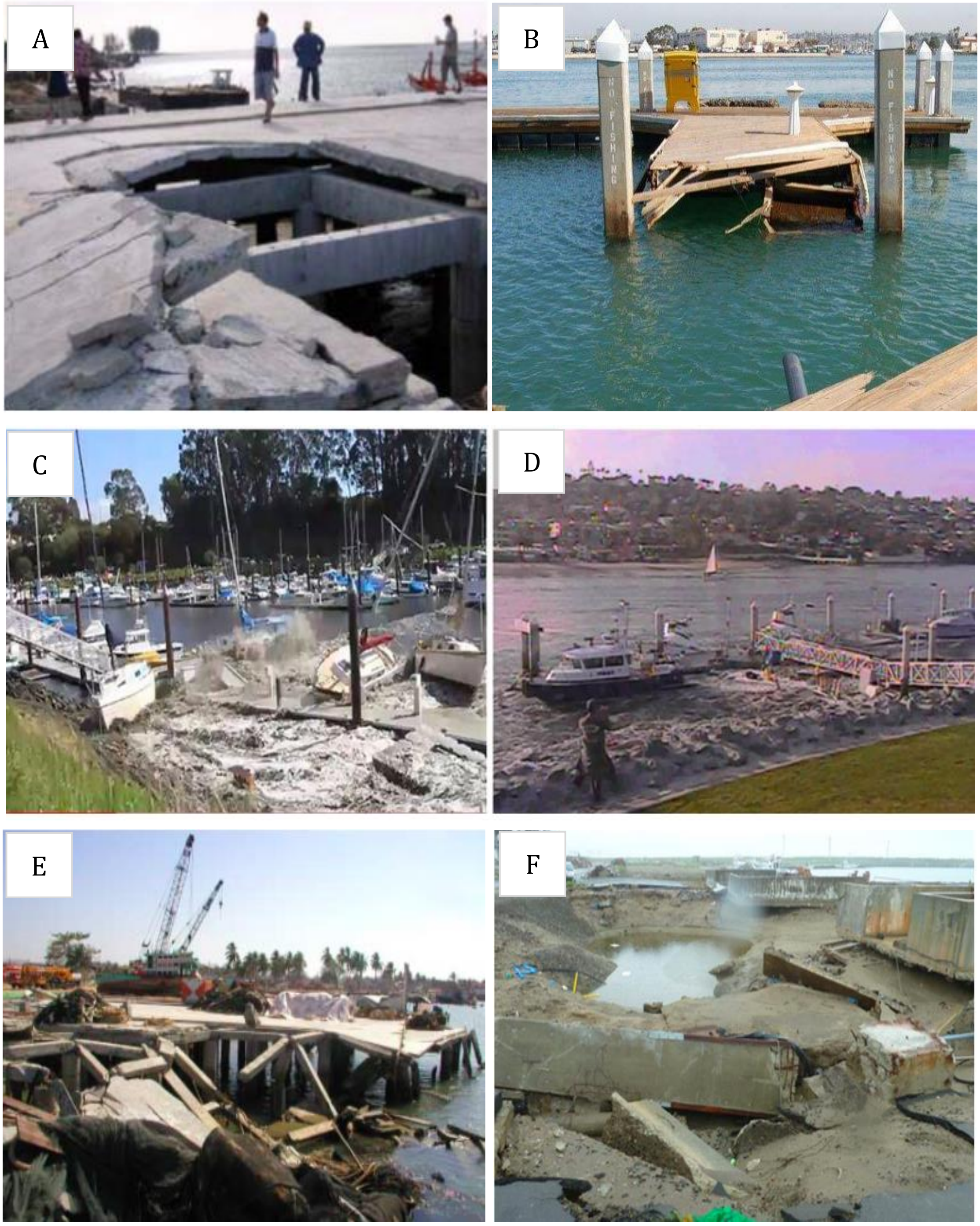


Figure 1. A) Damage to a wharf deck in Thailand after the December 26th 2004 tsunami from vertical buoyancy forces. Source (Horspool et al., 2016). **(B)** Damage to a dock and a water pipe under the dock in Shelter Island, San Diego Bay, from hydrodynamic and impulsive forces exhibited by the 2010 Chile Tsunami. Source (**http://www.sandiegouniontribune.com/sdut-tsunami-severs-shelter-island-dock-2010mar02-story.html**)**. (C)** Damage to the docks and vessels in Santa Cruz Harbour, California from a travelling bore during the March 11, 2011 Chile tsunami. Source (Wilson et al., 2013). **(F)** Sinking vessels and damage in Southern Shelter Island, Diego Bay. Source (Wilson et al., 2013). **(E)** Severe damage to the wharf piles and topping at Ban Nam Kem fishing port in Thailand. The tsunami height recorded in this area was 9 metres. Source (Bell et al., 2005)**. (F)** Scour and collapsed reinforced concrete columns of the wharf and associated buildings at Yuriage, Miyagi, Japan, in the Great East Japan Tsunami. (Horspool et al., 2016).

Figure 2. (A) Large vessel that has been potentially damaging debris is left on the roof of a tourist hotel in Otsuchi, Japan after the 2011 Japan tsunami. Source (http://www.ibtimes.co.uk/2011-earthquake-tsunami-60-powerful-photos-disaster-that-hit-japan-five-years-ago-1548255). **(B)** A vessel washed inland to a street in Talcahuano, Chile after the 2010 Chile Tsunami. Source (http://archive.boston.com/bigpicture/2010/03/chile_three_days_later.html). **(C)** Oil leaks from capsized and sunken vessels in Fudai Village, Iwate Prefecture, Japan after the 2011 Japan tsunami. Source (http://www.ibtimes.co.uk/2011-earthquake-tsunami-60-powerful-photos-disaster-that-hit-japan-five-years-ago-1548255). **(D)** An example of a drifting ship causing damage during collision with a crane in Sendai Port, Japan during the 2011 Japan Tsunami. Source (Chock et al., 2013). **(E)** Large fishing vessel transported 750m inland from a port in Kesennuma, Japan after the 2011 Japan Tsunami. Source (https://www.researchgate.net/figure/282949701_fig3_Fig-4-At-Kesennuma-Japan-during-the-2011-Tsunami-This-large-fi-shing-boat-the-330-t).

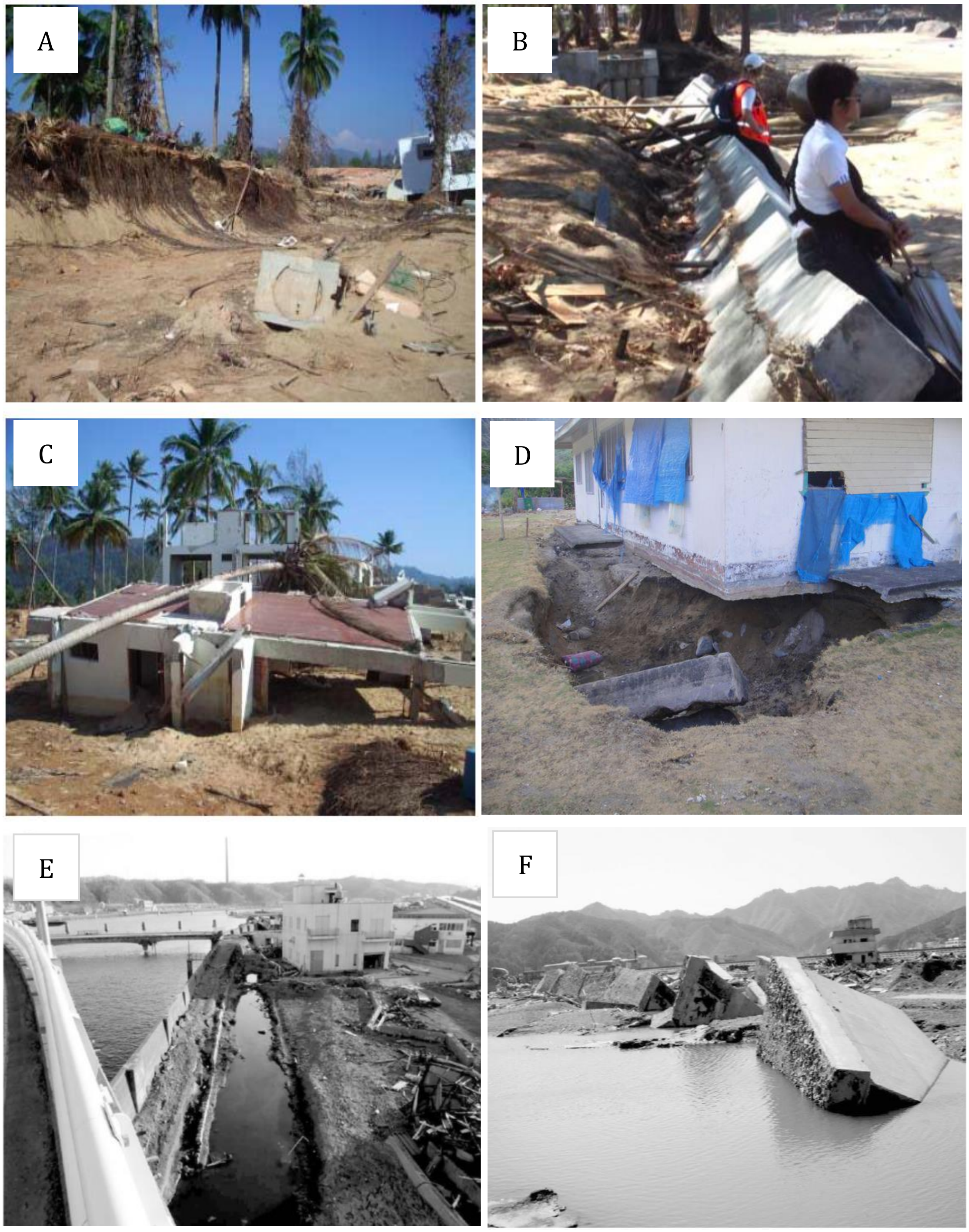


Figure 3. (A) Receeding waters after waves from the 26th December 2004 tsunami scoured channels with dimensions up to 50m wide and up to 3m deep shown here, in Khao Lak, Thailand. Source (Bell et al. 2005). **(B)** Receding waters from the December 26th 2004 tsunami causing the collapse and tilting of most seawall defences on the Andaman Coast, Southern Thailand due to scouring on the landward side. Source (Bell et al. 2005). **(C)** Extensive scour from the 26th December 2004 tsunami completely undermining nearby resort buildings in Khao Lak, Thailand, source (Bell et al. 2005). **(D)** Tsunami induced scour around the corner of buildings in Masefau, American Samoa during the 2009 Samoa tsunami. Source (https://walrus.wr.usgs.gov/news/samoareports.html). **(E)** Scour trench formed on the landward side of a flood wall in Miyako, Japan after the 2011 Japan tsunami. Source (Chock et al. 2013). **(F)** Damage to a concrete gravity seawall with shallow foundations in Otsuchi Port, Japan, due to a deep scour trench forming on the landward side of the structure, resulting in collapse and dispersal of monolithic concrete blocks up to 70m inland. Source (Chock et al. 2013).

Figure 4. (A) Extensive mounds of debris in Natori, Miyagi prefecture, Japan after the 2011 Japan tsunami. Source (http://www.ibtimes.co.uk/2011-earthquake-tsunami-60-powerful-photos-disaster-that-hit-japan-five-years-ago-1548255). **(B)** An example of timber log debris in port buildings at Ofunato, Japan after the 2011 Japan tsunami. Source (Chock et al, 2013). **(C)** A coconut palm tree entrained by the December 26th 2004 Tsunami, see here penetrating through a roof and internal ceiling of a hotel room on Koh Phi, Thailand. Source (Bell et al. 2005). **(D)** A building has become unseated from its foundations and been transported in the flow as large and potentially damaging debris and finally rested ontop of another building in Minamisanriku, Miyagi prefecture, Japan. Source (http://www.ibtimes.co.uk/2011-earthquake-tsunami-60-powerful-photos-disaster-that-hit-japan-five-years-ago-1548255). **(E)** An example of damage to the debris (shipping container) due to strikes with other containers or structures. Source (Chock et al. 2013). **(F) .** A damaged storage tank that has been removed and transported from its original position in Kesennuma, Japan, during the Great East Japan Tsunami. Note the buckling and/or impact damage to the side of the tank nearest the road. Source (Horspool et al. 2016).

3.3 Indirect impacts

The direct effects from a tsunami have further adverse effects on infrastructure lifelines, the economy and society (Table 6). Because of the interdependency of lifelines (e.g. wastewater operations and telecommunications are affected by power outages), the effects on disrupted services can be prolonged (Horspool et al. 2016). In addition, it is not just the businesses in the inundation zone that suffer the consequences from tsunami impact. Bell et al. (2005) noted that tourism and business in tourism related sectors such as taxis and hospitality decreased significantly.

Table 6. Summary of potential indirect tsunami impacts on infrastructure, society, lifelines and the economy.

	Impacts
Infrastructure	Disruption of networks; Loss of production and services; Cost of cleaning up debris; Costs of demolition and removal of damaged structures; Increased operating and distribution costs; Increase cost for water and sanitation services; The cost of communication services throughout the recovery phase
Social	Delayed delivery of services and goods; Increase in the need for medical treatment and care facilities; Cost for families to relocate and for accommodation; Increased debt; More people put out of their homes; Increased likelihood of poverty; Loss of jobs and livelihoods; Loss of basic services such as cultural and education based ones; The cost of services e.g. power, food will go up; Loss of land value; Jobs created in clean up and reconstruction process
Social	Delayed delivery of services and goods; Increase in the need for medical treatment and care facilities; Cost for families to relocate and for accommodation; Increased debt; More people put out of their homes; Increased likelihood of poverty; Loss of jobs and livelihoods; Loss of basic services such as cultural and education based ones; The cost of services e.g. power, food will go up; Loss of land value; Jobs created in clean up and reconstruction process

3.4 Exposure analysis

We present a preliminary exposure analysis of infrastructure throughout Queen Charlotte Sound to 0-5 m and >5 m inundation scenarios modelled by GNS. The study area encompasses all of Queen Charlotte Sound, as debris has the potential to be distributed for large distances in tides and currents, and these waterways are important navigation routes for recreational and commercial vessels.

3.4.1 Datasets

- Digital Elevation Model (DEM) – https://data.linz.govt.nz/layer/1768-nz-8m-digital-elevation-model-2012/
- Property - http://data-marlborough.opendata.arcgis.com/datasets/b961702a70184113bf9377cf2b998dab_19
- Building points - http://data-marlborough.opendata.arcgis.com/datasets/bd716e2478574941af4fcab207166190_3
- Tsunami inundation layer - Provided by Malcolm Jacobson, GIS Analyst from the Marlborough District (as used in - https://maps.marlborough.govt.nz/smaps/?map=61a36a29276b4d4888306321f4448b83)
- Foreshore structures (lines) - Interpreted as jetties, pontoons, slipways, linkspans, ramp, retaining wall, decks, landings, cables (sub-aqueous), outfalls, breakwaters, groynes, walkways, pipelines, tramway, steps etc - http://data-marlborough.opendata.arcgis.com/datasets/0b3eda298b1c46d98e67e1b88ecd4b9a_1
- Marine farms – http://data-marlborough.opendata.arcgis.com/datasets/f235b09866a3448689e0a319d4694583_12
- Moorings - http://data-marlborough.opendata.arcgis.com/datasets/d18320eb891c42c2ac5a18ba97d70576_13
- Aerial photos - https://data.linz.govt.nz/layer/1909-marlborough-04m-rural-aerial-photos-2011-2012/

3.4.2 Outputs produced

- Determine the impacted area under 2 different inundation scenarios:
  - 0 –5 m
  - >5 m
- Lengths of affected foreshore infrastructure in each scenario
- Numbers of affected buildings under each scenario
- Numbers of affected properties under each scenario
- Numbers of affected moorings under each scenario
- Affected area of marine farms under each scenario

3.4.3 Background

In the inundation modelling done by GNS for the Marlborough District Council, 3 zones were developed:

a) *The red zone*: A shore exclusion zone which can be designated off limits in the event of any expected tsunami, no matter the amplitude. The red zone is to be evacuated in response to the 0.2-1 m threat level warning.

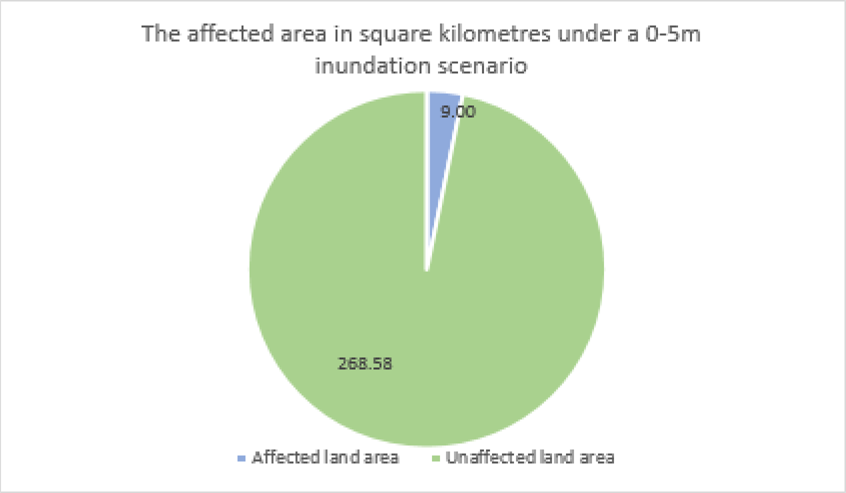
b) *The orange zone*: The area to be evacuated in most if not all distant and regional source official warnings. The orange zone is inclusive of the red zone and is to be evacuated in response to 1-3 m and 3-5 m threat level warnings.

c) *The yellow zone*: A zone taking into account the worst case scenario from modelling and known tsunami deposits, and has been designed to encompass the area inundated by the tsunami with a 2,500 year return period at the 84% confidence level (Power, 2013). This area should be evacuated if there are natural or informal warning from a local source event. The yellow zone is inclusive of the orange and red zone.

In this analysis, red and orange zones have been grouped into one zone (0-5 m elevation) and the yellow zone is >5 m elevation.

3.4.4 Results

The Queen Charlotte Sound study area covers 541 km^2, with 277 km^2 of that area being land. Figure 5 shows the land area in square kilometers affected by each inundation scenario. Because of the steep topographic gradient throughout Queen Charlotte Sound, a small proportion of land area is inundated in both scenarios. However, because settlement has occurred in low-lying coastal areas and in pockets with a shallower topographic gradient, the areas where the worst inundation occurs are also the most populated. This results in the exposure of a significant amount of infrastructure to the hazard (Figure 6).



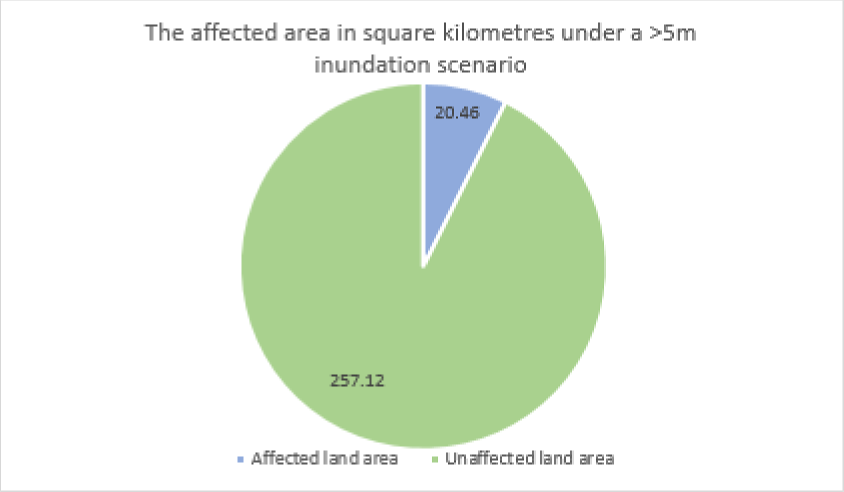


Figure 5. The cumulative affected area in square kilometers in each inundation scenario in Queen Charlotte Sound.

In a 0-5 m inundation scenario, 22% or 1099 buildings are inundated, and in a >5 m inundation scenario, 50% or 2520 buildings are inundated (Appendix 5.9.2). This is a significant number of buildings exposed directly to the hazard considering the small inundation footprint. Depending on the hydrodynamic and hydrostatic forces, and also the ability of the flow to carry debris upslope and throughout the entire inundation zone, all buildings throughout the inundation zone could be considered potential debris sources. Not only are the buildings themselves subject to inundation, but the interior goods are subject to damage and mobilisation in the flow. In total, >1440 or 35% of properties in Queen Charlotte Sound are affected in a 0-5 m inundation scenario. This number increases to 2650 or 65% in a >5 m inundation scenario (Appendix 5.9.3). Objects such as kayaks, dingies, and rainwater tanks may be present on some properties and have the potential to become debris.

Nearly all foreshore infrastructure, marine farms and moorings are inundated in both scenarios (Appendix 5.9.4-6). Because these types of infrastructure are directly in or above the water they are most likely going to be exposed to the strongest hydrodynamic and hydrostatic forces. A total of 5.79 km^2 of marine farms are affected, and 1752 moorings. Hundreds of private and public jetties which are utilised throughout the area for boat docking and mooring are affected in both inundation scenarios (Appendix 5.9.4 & 5.9.6). Nearly 69 km of foreshore infrastructure is affected in a >5 m inundation scenario, although this does not take into account piles underneath jetties, nor the total area of the decks, which also have the potential to generate debris.

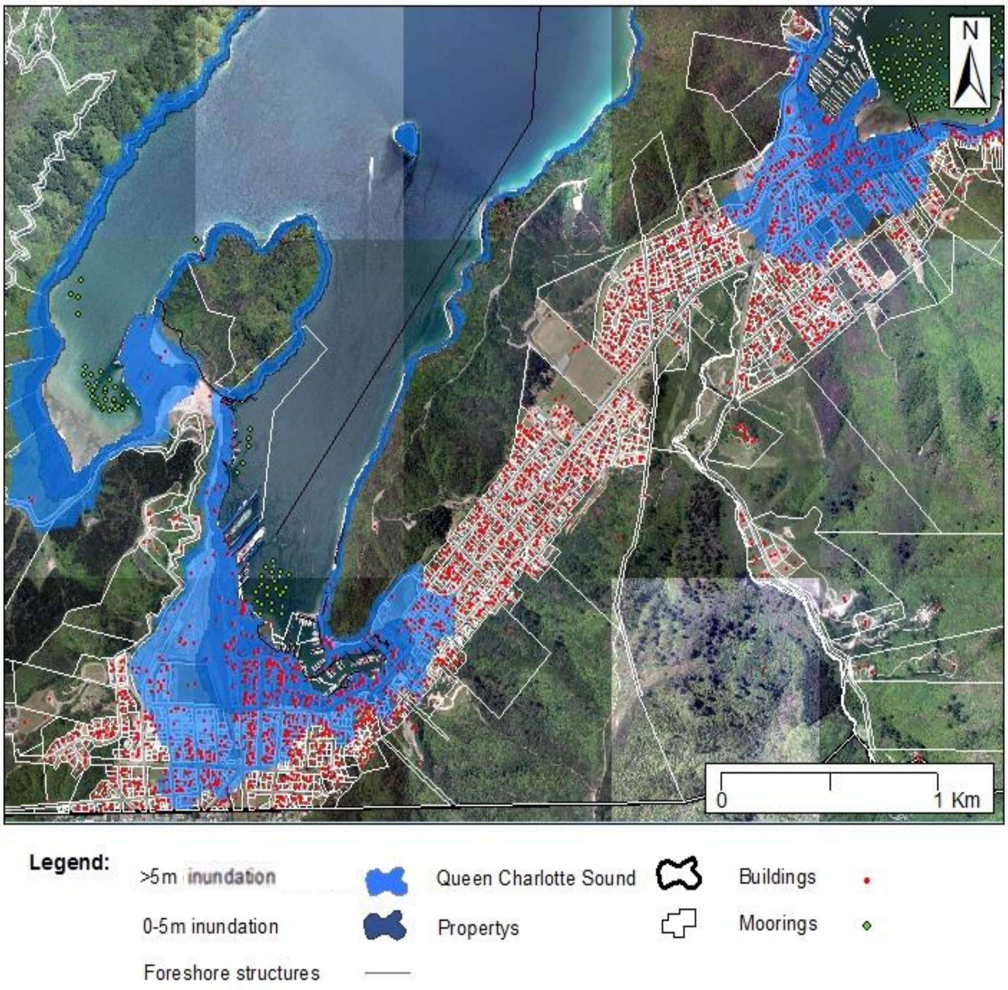


Figure 6. The affected area and affected infrastructure in a 0-5 m and >5 m inundation scenario in Picton, Shakespeare Bay and Waikawa.

3.5 Mitigation

Tsunami impacts in ports and harbors can be mitigated in two ways:

1. Decreasing exposure and vulnerability through the evacuation of vessels and people.
2. Taking structural countermeasures by reinforcing existing port infrastructure, constructing tsunami defenses, and improving or constructing evacuation facilities (PIANC 2010).

When thinking about direct and indirect tsunami damage, mitigation measures should consider human safety, economic loss and business continuity. Taking into consideration the earthquake effects from a local-source tsunami is important too, as they may delay the time it would normally take to complete simple tasks such as moving around the port. Significant uplift and subsidence from a local source earthquake may impacts navigation in channels marinas.

3.5.1 Decreasing exposure

Decreasing the exposure of people and vessels in the port is possible with an audible early warning and advisory system that explains the estimated tsunami amplitude and the estimated arrival time, to allow for sufficient evacuation time (Chock et al., 2013). It is important that not only the arrival of the tsunami is communicated but also the duration that hazardous conditions in navigation pathways may exist (Okal et al., 2006c; Borrero et al., 2015b). All people working in ports and navigating around the port should understand the possibility of a tsunami event and the potential inundation and current velocities that could be reached.

Warnings should be disseminated from the port authority to all people in the port, including those in vessels in and around the port. Evacuation safe places should be located in the port or within 15 minutes walking distance, and should have the capacity to accommodate the expected number of people (PIANC 2010; Chock et al., 2013). Potential evacuation facilities could be stairways to high ground; vertical evacuation towers or artificial high grounds could be constructed within the port (Figure 7; PIANC, 2010). Routes to the buildings and the buildings themselves should be earthquake resistant and be clearly indicated and identifiable (Edge et al., 2013).

For the evacuation of vessels the timing of the evacuation is important, because it is difficult for vessels to navigate in strong currents (Okal et al., 2006b; Wilson et al., 2013). The evacuation of vessels is important as it reduces damage to the vessels themselves and reduces the risk of them impacting other port structures. Evacuation safe depths can be obtained where there is no chance of vessel grounding, there is negligible wave steepness, and navigable currents can be reached (Appendix 5.8; Wilson et al., 2013; Lynett et al., 2014; Borrero et al., 2015b).

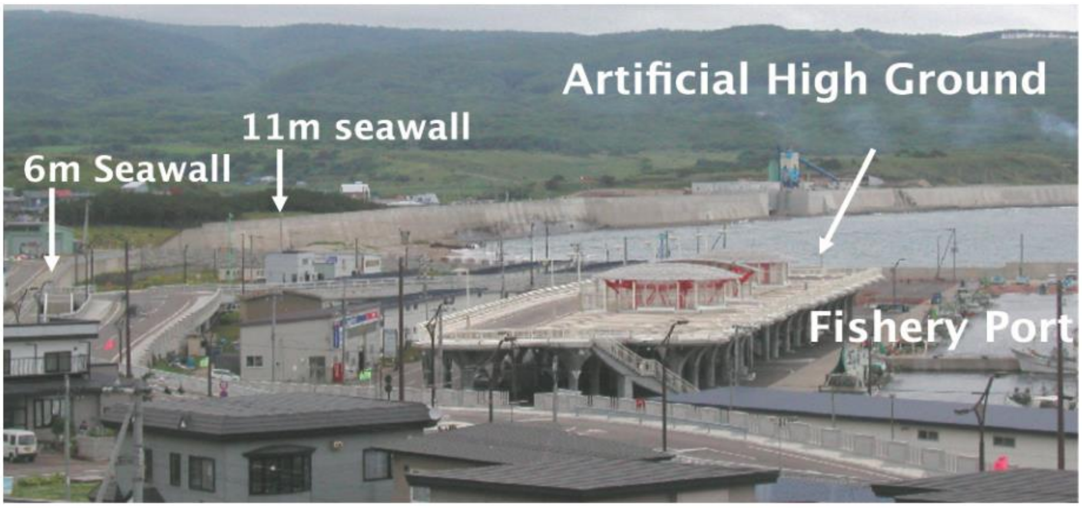


Figure 7. Artificial high ground in a fishery port. Workers can work daily on the first floor and use the second floor for evacuation purposes during a tsunami. Source (PIANC. 2010)

The Japan Association of Marine Safety proposes a series of actions for vessels to undertake depending on the tsunami amplitude, available time before arrival, size of the vessel and the state of the ship (Appendix 5.10). If evacuation before the time of arrival is not viable then reinforcement of the mooring system is the best option. PIANC (2010) suggests the reinforcement of mooring lines can be done in two ways;

1. Increase the strength of the mooring system by using high-strength rope or by increasing the number of ropes.
2. Reinforce the mooring system by loosening the mooring ropes to counteract against rapid increase and decrease in water elevation.

Actions taken by vessels in and around Port Marlborough will be subject to the source location and the available time before initial tsunami arrival. It is suggested that Port Marlborough develops different evacuation and vessels action plans based on 3 travel time scenarios: 1. Distant source - >3 hours travel time; 2. Regional Source- 1-3 hours travel time; 3. Local Source- 0-60 minutes. These can be used as a basis for developing mitigation measures that can be executed safely by port staff, local residents and boat owners in the available time frame.

3.5.2 Structural countermeasures

Using observations of impacts from recent tsunamis and modelling, we can understand common impacts and failure modes, which infrastructure and mitigation methods commonly performed well, and which infrastructure failed commonly and why. This in turn allows successful and informed structural countermeasures to be put in place to meet target levels of human safety, economic loss and business continuity. All structures whose failure would be considered unacceptable losses such as designated evacuation shelters, port control towers and other facilities critical to the ports operation should be designed to withstand expected primary and secondary tsunami loads.

Prior to the 2004 Indian Ocean Tsunami, many port buildings were designed to withstand debris impact loads of 454 kg debris weight, which is appropriate for timber logs and drift-wood (Palermo et al., 2013). However from observation we know that this grossly underestimates the debris impact loads imparted on structures from larger debris such as vessels, shipping containers and vehicles, which commonly caused the failure of critical load-bearing elements in buildings and caused progressive collapse (PIANC, 2010; Chock et al., 2013; Edge et al., 2013; Palermo et al., 2013; Naito et al., 2014; Riggs et al., 2014; Borerro et al., 2015a;). These types of debris were commonly observed displaced far inland and distributed widely across inundation zones (Bell et al., 2005; Fritz & Borerro, 2006; PIANC, 2010; Chock et al., 2013; Edge et al., 2013; Palermo et al., 2013; Horspool et al., 2016). Ports in particular should consider debris impacts loads from larger debris such as vessels and containers if there is potential for these sources of debris to become mobilised and transported.

Robustness of infrastructure building materials plays a role being able to withstand hydrodynamic and hydrostatic forces and also debris impact. Although all building material types are susceptible to debris impact and progressive collapse, engineered structures commonly performed better during inundation, with exterior glazing units and interior water damage as the main damage type (Edge et al. 2013; Chock et al. 2013; Palermo et al 2013). Non-engineered structures constructed in light timber or concrete frame with brick masonry infill walls had widespread damage due to sliding and unseating of roofs and second story levels, punching in of walls and partial or complete collapse of load bearing elements (Figure 8; Bell et al. 2005; Fritz & Borerro 2006; Goff et al. 2006; PIANC 2010; Chock et al. 2013; Palermo et al. 2013). Light industrial and recreational steel also had widespread failure. However, mid to high rise concrete building with robust shear walls and steel buildings performed well in their lower storeys, indicating these structures could be evacuation structures (Chock et al. 2013; Ewing et al. 2013). Chock et al. (2013) suggest that buoyancy and uplift in the corners of foundations and in the design of the buildings should be considered where there should be sufficient openness in buildings to alleviate buoyancy effects. Timber and light steel buildings performed poorly in many tsunami scenarios, so the reinforcement of these buildings with industrial steel is recommended to prevent wall failure and the mobilisation of interior goods in the flow.

Figure 8. (A-B) Sliding and unseating of storey levels in Dichato, Chile after the 27th February 2010 Chile Tsunami. Source (Palermo et al. 2013) **(C)** Widespread damage timber homes in Dichato, Chile after the 27th February 201 Chile Tsunami resulting in extensive timber debris. Source (Palermo et al. 2013)

Scouring around building foundations from accelerated, turbulent or converging flow, particularly around solid 90 degree corner walls was predominant, especially in sandy soils and native sands which experienced widespread scour (Appendix 5.11) (Okal et al. 2002; Bell et al. 2005; Edwards 2006; Fritz & Borerro 2006; Goff et al. 2006; Chock et al. 2013; Edge et al. 2013; Borerro et al. 2015a; Horspool et al. 2016). Scour depth was not linearly proportional to the inundation depth where in some cases water depths of >10m had mild scour and 3m water depth resulted in a 10m diameter scour channel (Chock et al., 2013). Infrastructure with rounded foundations, scour resistant foundations, surface paving around the structure, surrounding vegetated areas and structures that were pile supported, performed better and were better able to withstand scouring without structural failure. Sites with hard ground (e.g. pavement or rock) had more severe scour adjacent to the hard ground because they focused the flow energy. To reduce scouring around the base of buildings, raising the superstructure above the elevation of a 100-year-flood elevation and using scour resistant foundations is recommended (Chock et al. 2013; Palermo et al. 2013).

Figure 9. The front of a damaged earth filled and concrete lined seawall at Noda, Japan after the 2011 Tohoku tsunami. The seawall had a parapet lining the crest but failed in many locations due to the loss of internal earth fill from scouring. Failure also appeared to be concentrated at the junctions between adjoining segments of seawall, resulting in a large number of armour units being displaced inland. Source (Chock et al. 2013)

Tsunami defenses such as breakwaters and seawalls were susceptible to severe scour on the landward side of the structure once overtopped and as a result experienced the structural failure typically at the ends in earth berms and between joined segments with poor continuity (Chock et al. 2013). It was common to see the failure of both concrete lined earth barriers, which appeared to be the weakest form of protection. The failure of wharf sheet pile retaining walls resulted in the loss of retained soil and settlement of the backlands (Chock et al. 2013. Plunging scour often resulted in the destruction of the upslope dike, or paved berms, shearing and uplift of paved sections and the scattering of small and large surface armoring’s far distances inland (Figure 9). Seawall segments often failed by rotation, tilting, sliding, overturning and debris impact. Due to the prevalence of failure between adjoining segments in seawalls, the strength of the continuity between units should be revised so it can function as a continuous unit. Seawalls that were not overtopped experienced little structural damage and ones that were overtopped and remained intact successfully reduced the flow velocity and momentum. This highlights the importance of the consideration of tsunami impacts in the design of structures and in particular tsunami barriers. An adequately designed tsunami barrier can serve its purpose, but failed barriers contributed debris to the flow. Failure often initiated with intensive scour, which can be reduced by using deepened piles and scour aprons, or using adequate pile foundations. Scour protection needs to be considered on both the landward and seaward side of the structure and the resilience to overtopping scour also needs to be considered.

Scouring around gravity-type piers, wharves and quays and also floating type and pile type piers, wharves and quays caused some failures in the structures (PIANC 2010; Chock et al. 2013). However, gravity-type piers, wharves and quays appear much more resilient to tsunamis than floating type and pile type piers, wharves and quays which more frequently received damage, especially from tsunami currents and water level oscillations (Appendix 5.12) (PIANC 2010). Docks often failed from buckling, tearing away from its concrete piles, shearing off of the decks from its piles and lifting of the decks off its piles (Wilson et al. 2013). Concrete and steel pile supported structures with concrete decks performed well (Chock et al. 2013). Bulkhead walls were subject to lateral failure due to soil erosion or loss of restraint wall stiffness due to scour at tieback anchorages (Chock et al. 2013). Scour commonly caused damage to sheet pile-supported quay wall structures and often resulted in the exposure of tie backs and quay support sheet pile systems (Figure 10) (Chock et al. 2013). Pressure relief grating and/or small concrete access panels served as a breakaway element between pier and wharf sections lessening damage to both. Chock et al. (2013) found that piers and quays were less susceptible to debris impact because the initial leading edge of a tsunami at the waterfront contains little debris, and a combination of the limited vertical exposure and the high inundation levels experienced in Japan in 2011 meant large debris often floated overtop of these structures. The overall design of piers wharves and quays should prevent total loss of sections of pier wharf walls and their tiebacks and restrain selected breakaway panels to provide post tsunami access.

Figure 10. Significant scour behind the sheet pile-supported quay wall structures exposing the quay support sheet pile system in Otsu Fishing port, Ibaraki prefecture, Japan. Source (Chock et al. 2013)

Structures should be constructed around buoyant cargo such as containers, timber logs and ferry vehicle carparks, as these were frequently observed drifting the flow and causing damage from debris strike (Bell et al. 2005; Edwards, 2006; PIANC 2010; Chock et al. 2013; Edge et al. 2013; Palermo et al. 2013; Horspool et al. 2016). Green belts or perforated fences could be suffice, however green belts provided inadequate protection in past tsunamis during high flow velocities and when the inundation depth exceeded the height of the trees, the failure resulted in additional debris to the flow and the trees also facilitated debris damming (Fritz et al. 2011; Ewing et al. 2013). Often tanks containing hazardous and flammable goods were damaged or moved during the tsunami, and empty tanks were more susceptible to displacement compared to full tanks (Appendix 5.13) (Chock et al. 2013). Dangerous goods such as oil storage tanks should be elevated high in the port and should be reinforced to avoid fatal failure and fire, or the leakage of oil or chemicals into the ground or water.

Damage to docks was frequently caused by the movement of moored vessels into and away from docks, strong currents, and inundation and the related buoyant forces (Wilson et al. 2013). Edge et al. (2013) recommends the use of one line per bollard and the consideration of mooring hooks with mechanical releases where possible. If a vessel rotates even slightly there is an unequal transfer of the increased drag force on the mooring lines and the tie down anchor which could result in the breaking of mooring lines or damage to the tie down anchor (Figure

11) (Lynett et al. 2012). However, the drag force on a mooring ship is reduced when the ship is moored parallel to the direction of the current (PIANC 2010). Mooring lines strengths need to be revised as vessels may not always be able to evacuate before the arrival of a tsunami.

Figure 11. Uprooting of a steel-concrete mooring in Talcahuano, Chile, after the 27th February 2010 Chile. Source (Palermo et al. 2013)

Coastal roads were commonly eroded leading to minor to major damage and should be protected by erosion by using walls and riprap, this is especially important in low lying areas where the flow concentrates (Edwards 2006). Roads typically built native sands were highly susceptible to erosion, so should be constructed on full pavement sections (Edwards 2006).

Damage to cranes from vessel drift and debris strike, water damage, and the loss of power which resulted in damage from the evacuation of vessels that were using the crane during the earthquake and tsunami (Appendix 5.14) (Chock et al. 2013; Edge et al. 2013; Borerro et al. 2015b).

Lynett et al. (2014) found a correlation between current velocities and observed damage during tsunamis using numerical modeling (Appendix 5.15). According to Lynett et al. (2014), damage to floating docks and vessels initiates with currents of 3 knots (1.5 ms^{-1} approx.). When current velocities are increased to around 6-9 knots (3.1-4.6 ms^{-1} approx.) harbour assets are subject to moderate and major damage. The damage thresholds are sensitive to the structural capacity of the infrastructure, which is dependent on the age and extent of deterioration. It will also be affected by the accuracy of the predicted currents in the model, which are influenced by bathymetry and numerical errors in the model. This correlation allows guidelines to be set for the development and design of infrastructure around the harbor and port based on the current velocities expected in various inundation scenarios.

3.6 Implications for Port Marlborough

The implications for Port Marlborough will be relevant to what infrastructure and facilities are present in the port and its navigation pathways. Like every other port, Port Marlborough is a lifeline that is still vulnerable to non-inundating tsunami due to potential impact from strong currents. Unnecessary closing of the port or evacuating vessels can cause adverse economic effects, so it is important to understand the hazard and potential impacts to the port in various tsunami scenarios for informed and accurate decision making.

Debris sources are concentrated at major settlements within Queen Charlotte Sound e.g. Picton and Waikawa, and at or within the vicinity of buildings. Potential debris sources ranged from fixed or moored things such as vessels, boat sheds, boat ramps, wharves, jetties, breakwaters, pontoons etc. to loose things such as kayaks, row boats, outdoor furniture, outdoor appliances (fridges, freezers, barbeques; Figure 12). Other identifiable debris sources located across the shoreline were fallen tree logs and branches, and loose boulders which will affect the available draft (Figure 12). Overall, sediment seafloor dynamics controlling the erosion and deposition of sediment and debris, and floating and semi-submerged debris are the main concern in terms of navigation.

Figure 7. Examples of potential debris sources identified throughout Queen Charlotte Sound.

A major hazard is posed from dangerous goods moving through the ports despite the short transit time. They have the potential to cause major issues in terms of contamination, and also cleanup and remedial efforts/ costs. It is recommended that storage of dangerous goods occurs in places out of the inundation zone if possible or in an area where they could be easily moved or secured with extremely short notice.

In terms of potential debris, salmon farms consist of significant superstructure above and below water and have the potential to break up into smaller components; this is in comparison to mussel farms, which predominantly consist of moorings. The bungy arrangement on mussel farm moorings may be helpful to calibrate models by using tensions recorded in previous tsunamis and comparing it to modelled tsunami forces and known breaking strains. Understanding the forces exerted from tsunamis on infrastructure is crucial in understanding the vulnerability of all types of debris to fail and contribute debris.

The time of the day and the time of year will affect the extent of exposure and also the availability of people to undertake mitigation measures on their belongings at short notice. Many recreational boat users in the Marlborough Sounds may not be live in the area and may be unable to strengthen or loosen mooring lines for example. If a far field tsunami was to occur and there was ample time for people to travel from the likes of Christchurch to come and protect their belongings and properties, it may make other tasks more difficult from the influx of people. It is therefore important to educate and communicate with local residents and recreational boat users on how they can reduce damage to their personal belongings and property. Creating plans within marinas on who will undertake mitigation measures is important because if individual vessel owners all come to the shore to secure their vessels, the number of people exposed to the hazard substantially increases. In a short time frame it may not be an option to strengthen or loosen all mooring lines on every individual vessel within the marina. It could be an option to accept that time is to short and damage will occur and to simply deploy tsunami resistant netting or mechanisms in the harbour to constrain the damaged piers, decks, piles and vessels to the within marina. This will incur high economic costs in terms of damage but from a recovery and response perspective, restricting debris from entering the main waterway passages will increase the efficiency of both the movement of vessels throughout Queen Charlotte Sound and also the cleanup post tsunami.

It is recommended that the local residents, port personnel and recreational boat users are provided with a holistic outline of three different source location scenarios based on the available time before tsunami arrival and are recommended actions to take in terms of mitigation and evacuation. It is important that this is only used as an outline, as the available time before arrival will vary with the source location, which can be communicated if communication lines remain operable after an earthquake for example. If communication lines are down before a preceding tsunami people may refer to the proposed actions, therefore it is extremely important that special precaution is taken in the proposed actions for a local source tsunami as travel time can vary from a few minutes to 1 hour.

4.0 Conclusions, future research directions and recommendations

This review provides insight to Port Marlborough's tsunami hazard and highlights potential impacts a tsunami could have on port operations and harbor navigability. Tsunami effects on ports can be highly variable depending on the source location, factors affecting the propagation of waves and site-specific factors affecting the development and amplification of waves. Therefore ports require accurate and detailed modeling to provide information on the extent, duration and onset of tsunami induced currents and inundation to fully characterise the hazard, impacts and the flow-on effects on port operations and harbor navigability. Understanding the tsunami hazard at Port Marlborough is economically important because it allows for effective hazard planning and mitigation that is driven by exposure and vulnerability. This lowers the long-term risk of Port Marlborough to tsunamis making it more resilient to future events and more cost-efficient to operate. Everyone involved in securing the safety of ports must understand the characteristics of tsunamis and the types of damage that can occur by learning from past experiences in ports around the world.

Future recommendations are as follows:

- Include current velocity estimates in addition to inundation in hazard modelling, as ports are vulnerable in even non-inundating tsunamis due to strong currents.
- Incorporating current velocity time series to show the duration strong currents may exist in navigation pathways for (Appendix 5.6b). This can help identify current velocities, how long and where current speeds will be elevated, and where sediment erosion and deposition will occur as a result. The may help inform decision making in terms of where vessels are evacuated to or positioned during a tsunami, long-term infrastructure planning, and when vessels may again be able enter particular navigation routes.
- Making sure warning messages are not solely focused on the initial arrival time of the tsunami, and that they include how long hazardous conditions in the port and harbor may continue.
- Tsunami warnings and evacuation routes need to be clearly communicated and in the absence of any definitive warning, port authorities should have a protocol to have vessels and staff leave the port following a strong earthquake, take into account and assume that conventional communication lines could be cut off including land lines, cell phone and radio/television.
- Including multilingual information for general tsunami education and information e.g. maps and signs showing coastal areas with a tsunami hazard, evacuation pathways and evacuation safe places.

- Incorporating tsunami arrival times in hazard maps if possible, this particularly relevant if a local tsunami is generated and shaking can be felt in Port Marlborough because the tsunami arrival time will be fast. This will give individuals holistic time frames to effectively evacuate in and undertake mitigation measures.
- There was an absence of literature describing debris clean up methods in waterways. Following a tsunami, fully or partially submerged debris of varying sizes may be dispersed throughout the Marlborough Sounds, which may have major implications for the movement of vessels. Therefore it is recommended that some research is done looking at the dispersion of debris in strong currents and clean up methods of fully and partially submerged debris.
- Take special precaution of the location of dangerous goods and critical port infrastructure e.g. control towers and software programs, or vehicles such as cranes, diggers and forklifts to minimize tsunami damage as these may be very important components in the response and recovery phase after a tsunami. If possible avoid areas of potential inundation and where flow could be concentrated or accelerated.
- Protect existing infrastructure and facilities from tsunami losses through redevelopment and structural countermeasures.
- Exposure of potential debris source throughout the Queen Charlotte Sound can be characterised, but there is a need to understand vulnerability of the potential debris sources to failure and to contribute debris. It would be helpful to run an analysis to identify the forces that the identified debris (e.g. timber logs, small and large vessels) may impart on structures in and around the port, and whether these forces are large enough to cause structural failure and the addition of more debris.
- Incorporate floating and submerged debris into the inundation and current model to understand how debris will move and where it will end up. Understanding the seafloor dynamics will identify areas where deposition or erosion of debris and sediment will occur, which will have implications on the available draft. Understanding where floating debris moves will be key in understanding the implications on navigation pathways (e.g. will debris in small bays adjacent to the main channels actually move out or will it be constrained to the bays, therefore only providing implications for residents within the bay?).
- Develop different action plans based on the source location and travel time.

5.0 Appendix

5.1 New Zealand tsunami hazard

5.1a Tsunamis recorded in New Zealand between 1835-2011

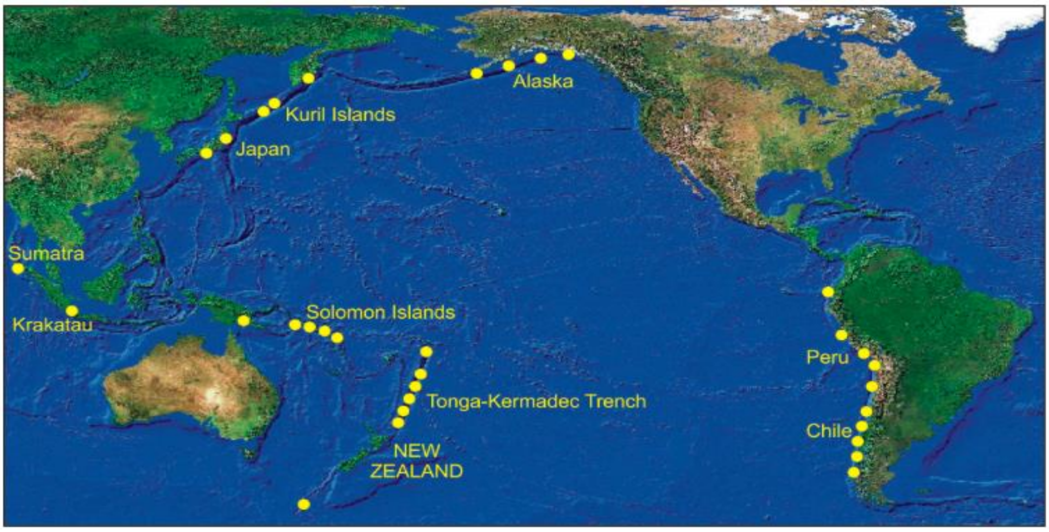


Figure 8. Yellow dots show the distant sources where tsunamis were generated that reached New Zealand between 1835 and 2011 (each dot represents the approximate location of a source event not an accurate epicenter). All events were earthquakes, except Krakatau, which was a volcanic eruption. (GNS, *DATE* http://data.gns.cri.nz/tsunami/index.html)

5.1b The effect of source location as a function of wave directivity

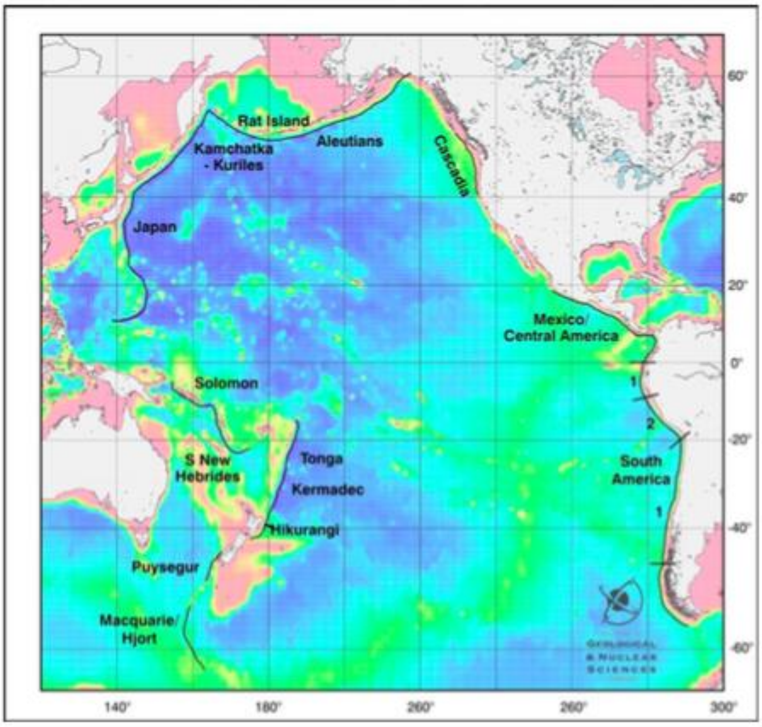
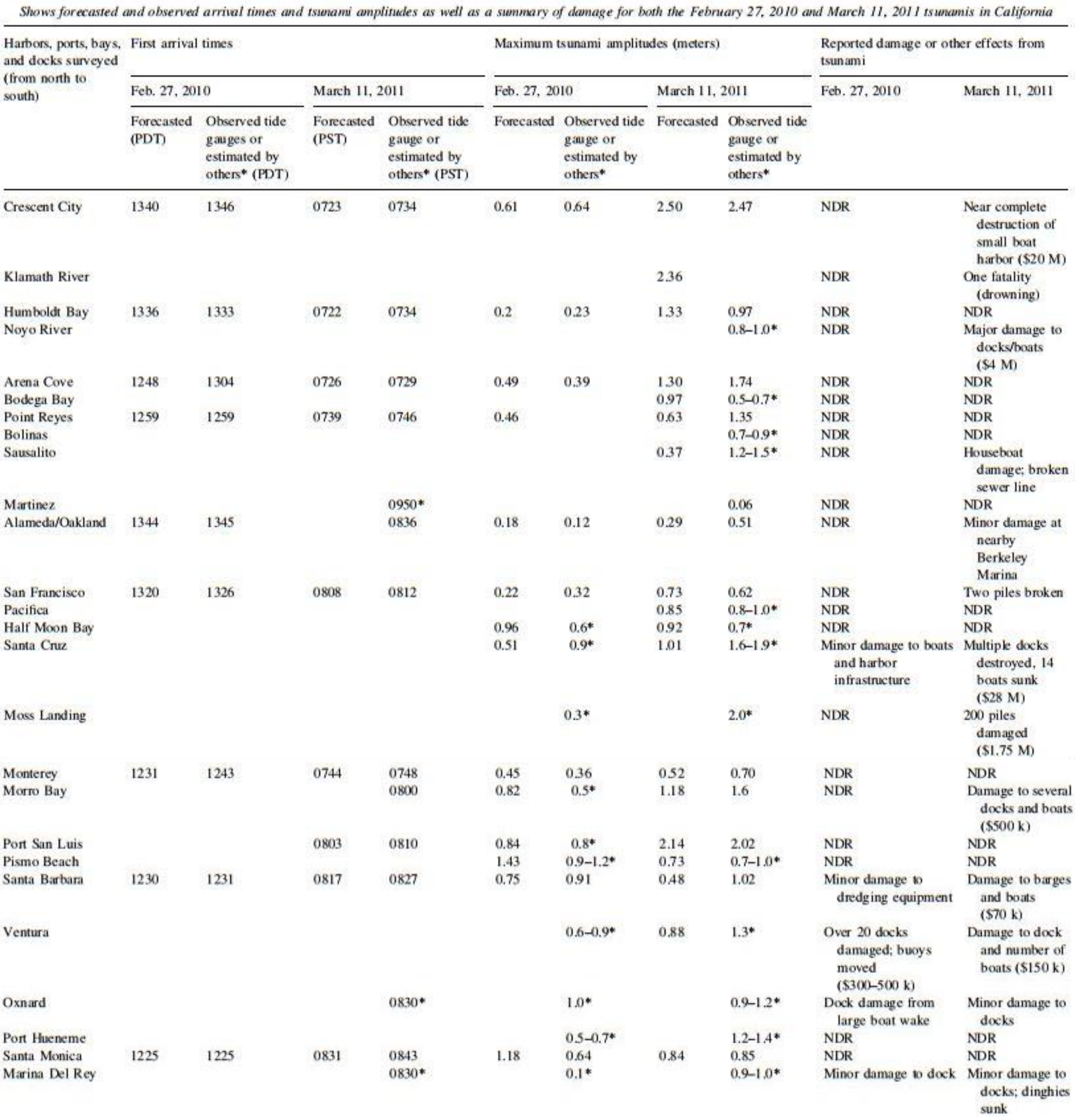


Figure 9. Subduction margins in the circum-Pacific region. The South American coastal margin can be partitioned into regions that propagate tsunami either south-westward toward eastern New Zealand (region 2), or direct tsunami further northward, thus more strongly affecting the north Pacific (region 1). The 1868 tsunami was generated in region 2, while the larger but less damaging (in New Zealand) 1960 tsunami originated in region 1. Source (Power et al. 2013).

5.2 Effects in the California during the 2010 Chile tsunami and the 2011 Japan tsunami

Both the orientation and the distance between California relative to the Japan subduction zone is similar to the distance and orientation and distance between New Zealand relative to the South American subduction zone. Therefore the effects in California from the far field 2011 Tohoku tsunami can be used to help understand how a large tsunami from South America may affect New Zealand. Below is an example of the damage to areas along the California coastline from far field tsunamis in 2010 and 2011.



Shows forecasted and observed arrival times and tsunami amplitudes as well as a summary of damage for both the February 27, 2010 and March 11, 2011 tsunamis in California

Harbors, ports, bays, and docks surveyed (from north to south)	First arrival times				Maximum tsunami amplitudes (meters)				Reported damage or other effects from tsunami	
	Feb. 27, 2010		March 11, 2011		Feb. 27, 2010		March 11, 2011		Feb. 27, 2010	March 11, 2011
	Forecasted (PDT)	Observed tide gauges or estimated by others* (PDT)	Forecasted (PST)	Observed tide gauge or estimated by others* (PST)	Forecasted	Observed tide gauge or estimated by others*	Forecasted	Observed tide gauge or estimated by others*		
Crescent City	1340	1346	0723	0734	0.61	0.64	2.50	2.47	NDR	Near complete destruction of small boat harbor ($20 M)
Klamath River							2.36		NDR	One fatality (drowning)
Humboldt Bay	1336	1333	0722	0734	0.2	0.23	1.33	0.97	NDR	NDR
Noyo River								0.8–1.0*	NDR	Major damage to docks/boats ($4 M)
Arena Cove	1248	1304	0726	0729	0.49	0.39	1.30	1.74	NDR	NDR
Bodega Bay							0.97	0.5–0.7*	NDR	NDR
Point Reyes	1259	1259	0739	0746	0.46		0.63	1.35	NDR	NDR
Bolinas								0.7–0.9*	NDR	NDR
Sausalito							0.37	1.2–1.5*	NDR	Houseboat damage; broken sewer line
Martinez				0950*				0.06	NDR	NDR
Alameda/Oakland	1344	1345		0836	0.18	0.12	0.29	0.51	NDR	Minor damage at nearby Berkeley Marina
San Francisco	1320	1326	0808	0812	0.22	0.32	0.73	0.62	NDR	Two piles broken
Pacifica							0.85	0.8–1.0*	NDR	NDR
Half Moon Bay					0.96	0.6*	0.92	0.7*	NDR	NDR
Santa Cruz					0.51	0.9*	1.01	1.6–1.9*	Minor damage to boats and harbor infrastructure	Multiple docks destroyed, 14 boats sunk ($28 M)
Moss Landing						0.3*		2.0*	NDR	200 piles damaged ($1.75 M)
Monterey	1231	1243	0744	0748	0.45	0.36	0.52	0.70	NDR	NDR
Morro Bay				0800	0.82	0.5*	1.18	1.6	NDR	Damage to several docks and boats ($500 k)
Port San Luis			0803	0810	0.84	0.8*	2.14	2.02	NDR	NDR
Pismo Beach					1.43	0.9–1.2*	0.73	0.7–1.0*	NDR	NDR
Santa Barbara	1230	1231	0817	0827	0.75	0.91	0.48	1.02	Minor damage to dredging equipment	Damage to barges and boats ($70 k)
Ventura						0.6–0.9*	0.88	1.3*	Over 20 docks damaged; buoys moved ($300–500 k)	Damage to dock and number of boats ($150 k)
Oxnard				0830*		1.0*		0.9–1.2*	Dock damage from large boat wake	Minor damage to docks
Port Hueneme						0.5–0.7*		1.2–1.4*	NDR	NDR
Santa Monica	1225	1225	0831	0843	1.18	0.64	0.84	0.85	NDR	NDR
Marina Del Rey				0830*		0.1*		0.9–1.0*	Minor damage to dock	Minor damage to docks; dinghies sunk

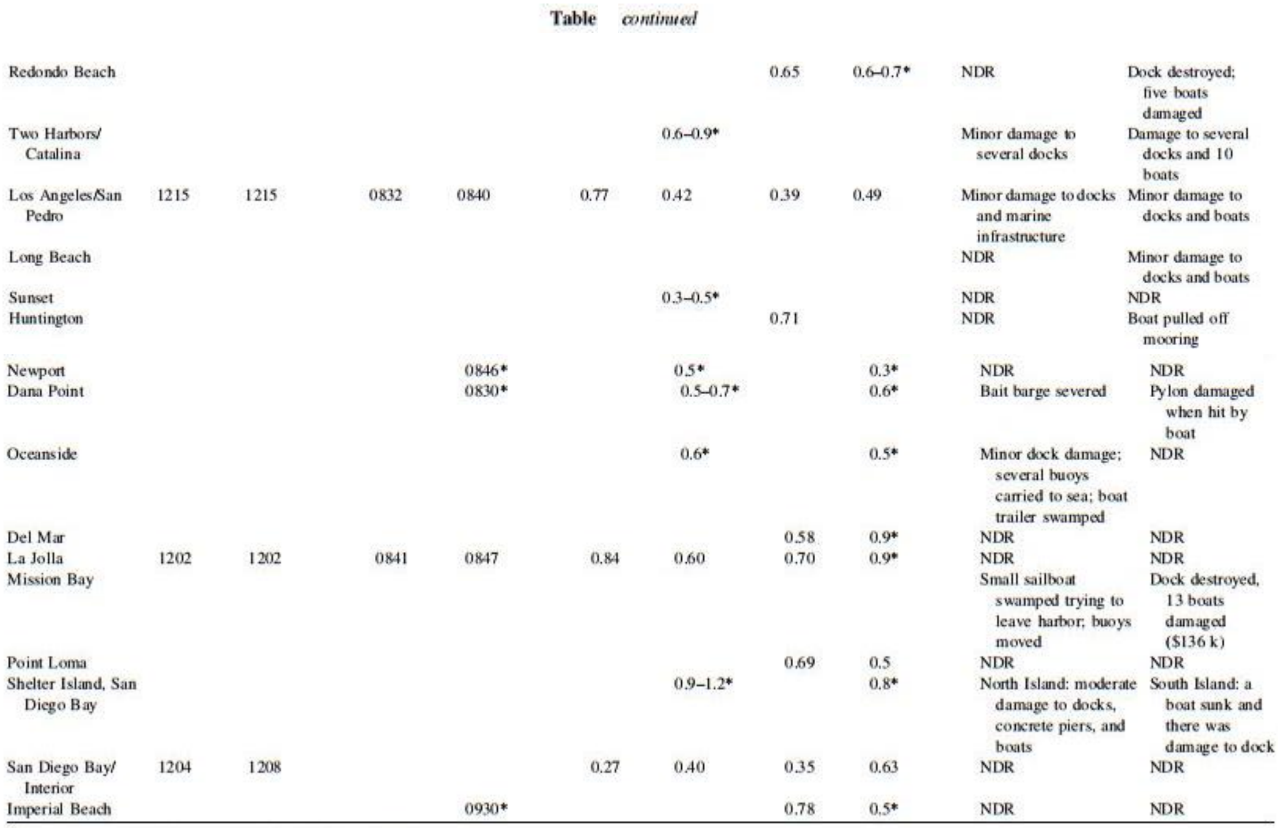


Table *continued*

Redondo Beach							0.65	0.6–0.7*	NDR	Dock destroyed; five boats damaged
Two Harbors/ Catalina						0.6–0.9*			Minor damage to several docks	Damage to several docks and 10 boats
Los Angeles/San Pedro	1215	1215	0832	0840	0.77	0.42	0.39	0.49	Minor damage to docks and marine infrastructure	Minor damage to docks and boats
Long Beach									NDR	Minor damage to docks and boats
Sunset						0.3–0.5*			NDR	NDR
Huntington							0.71		NDR	Boat pulled off mooring
Newport				0846*		0.5*		0.3*	NDR	NDR
Dana Point				0830*		0.5–0.7*		0.6*	Bait barge severed	Pylon damaged when hit by boat
Oceanside						0.6*		0.5*	Minor dock damage; several buoys carried to sea; boat trailer swamped	NDR
Del Mar							0.58	0.9*	NDR	NDR
La Jolla	1202	1202	0841	0847	0.84	0.60	0.70	0.9*	NDR	NDR
Mission Bay									Small sailboat swamped trying to leave harbor; buoys moved	Dock destroyed, 13 boats damaged ($136 k)
Point Loma							0.69	0.5	NDR	NDR
Shelter Island, San Diego Bay						0.9–1.2*		0.8*	North Island: moderate damage to docks, concrete piers, and boats	South Island: a boat sunk and there was damage to dock
San Diego Bay/ Interior	1204	1208			0.27	0.40	0.35	0.63	NDR	NDR
Imperial Beach				0930*			0.78	0.5*	NDR	NDR

Figure 10. This table provides a summary of measured or observed tsunami amplitudes, and a description of the damage that occurred in harbors and bays. NDR= no damage reported. The asterisk indicates values were obtained from observers (not tidal gauges). Table extracted from (Wilson et al. 2013)

5.3 Modelled New Zealand tsunami hazard

Power et al (2013) developed a probabilistic tsunami hazard model covering New Zealand's coastlines. The coast lines were divided into 268, approximately 20km sections to run the analysis. The output shows the expected maximum tsunami amplitudes which should be interpreted as the maximum tsunami height measured at the location within each coastal section where it is the highest. It is important to note that this maximum height will vary considerably within each individual coastal section and the median tsunami height within an individual section may be considerably lower than the maximum height. Power et al. (2013) also breaks down the relative contribution of each fault source to the median hazard in each coastal section.

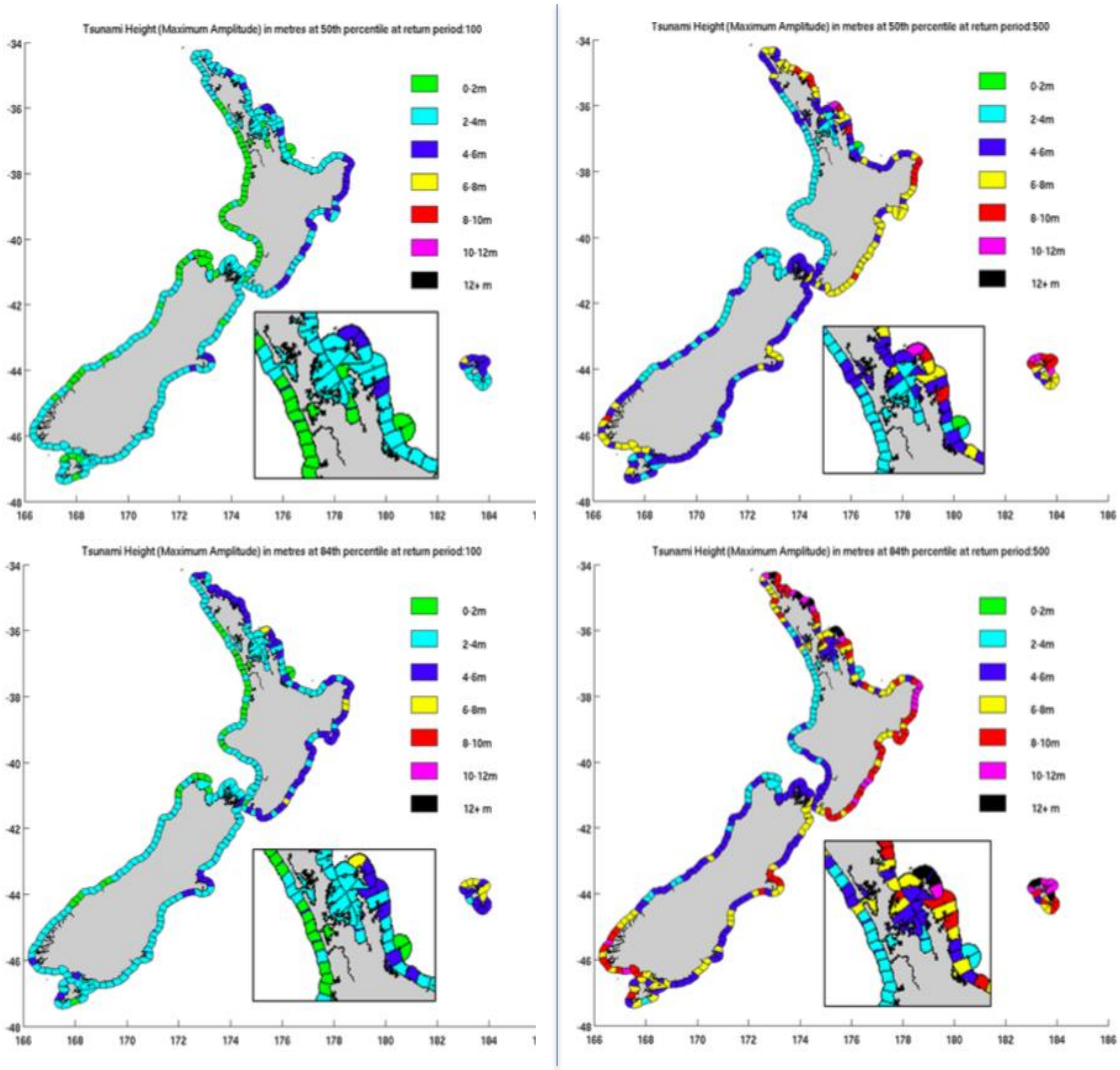


Figure 11. Expected maximum tsunami height in metres at 100 year return period, shown at median (50th percentile) and 84th percentile of epistemic uncertainty. Source (Power et al. 2014). **(right)** Expected maximum tsunami height in metres at 500 year return period, shown at median (50th percentile) and 84th percentile of epistemic uncertainty. Source (Power et al. 2014)

5.4 Debris dispersal patterns from the 2011 Tohoku tsunami

Figure 12. Looking at container dispersal from container storage facilities following the 2011 Tohoku tsunami. (a) Sendai region and port. (b) Small container facility at Sendai port before and after the tsunami. (c) Large container facility at Sendai Port before and after the tsunami. (d) Ofunato region and port. (e) Ofunato container facility before and after the tsunami. Source (Naito et al. 2014).

After the 2011 Tohoku tsunami, Naito et al. (2014) looked at the dispersal patterns of shipping containers from a large container facility in Ofunato, Japan and two container facilities in Sendai, Japan. Shipping containers were chosen because they have an identifiable origin unlike most debris such as wood, rubble and vehicles. The observed dispersal patterns of the containers from the storage facilities show good examples of how building construction type and how the height of the surrounding buildings compared to the inundation height control debris dispersal.

At both Sendai storage facilities, containers from both storage facilities did not disperse inland and were confined to the storage site or in the case of the large storage facility, were washed out to sea and dispersed up to 4164m along the coast. When containers are washed out to open ocean they can move effectively with minimal obstruction and disperse over a wide area which may have implications for the movement of vessels along the coast. Naito et al. (2014) attributed the lack of dispersal at Sendai to the steel construction of the buildings surrounding the facility and also the inundation height compared to the building height. For a container to float over a building, the inundation depth minus the draft of the container must be greater than the building height. Both storage facilities at Sendai had average building heights of 6.4m with the inundation height being marginally higher than the building height at the small facility and lower at the larger facility. Both factors contributed to ceasing of containers moving and dispersing inland.

However at Ofunato storage facility, containers dispersed outside the facility and inland up to 520m, forming large and potentially damaging debris as they were entrained in the flow. The dispersal of the containers at Ofunato was attributed to the wooden-framed surrounding building layout and also the high inundation height. Naito et al. (2014) states that generally in areas of light framed construction and where inundation height is a storey or more higher, it can be assumed that the building will collapse. However steel and concrete construction are better able to withstand the hydrodynamic forces generated by the tsunami so are able to act as barriers to debris transport. The average surrounding building height at Ofunato was also lower than the average inundation depth minus the draft meaning even if the buildings remained standing the containers had the capability of floating overtop.

5.5 Examples of typical lateral wall failures

Walls parallel to the shoreline or perpendicular to the flow in many tsunamis were frequently punched in. If hydrodynamic or hydrostatic forces cause the failure of a load bearing wall, it could initiate progressive building collapse (Bell et al. 2005; Chock et al. 2013; Palermo et al. 2013).

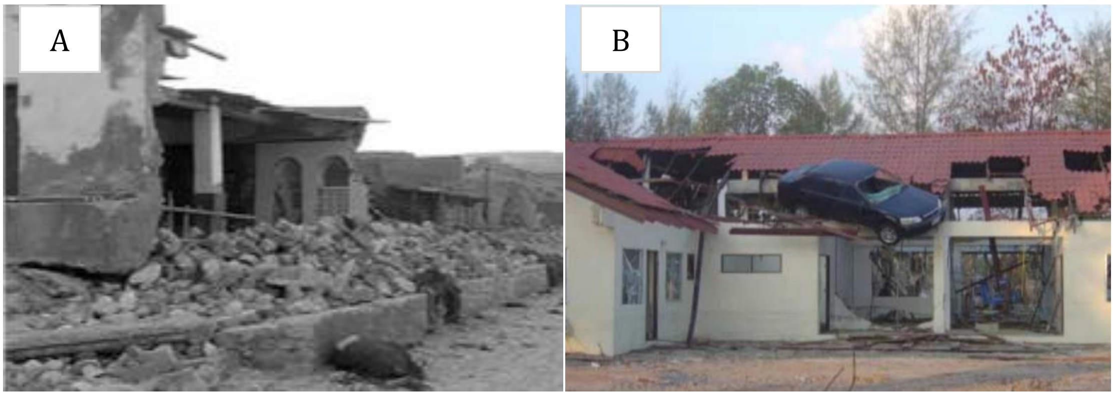


Figure 13. (A) Far-field effects from the 26th December 2004 tsunami in Bandarbeyla Somalia, blowout failure of walls parallel to the shoreline. Source (Fritz & Borerro 2006). **(B)** Failure of walls parallel to the shoreline in Khao Lak, Thailand after the 2004 Sumatra tsunami. The removal of roof tiles and the vehicle resting on the roof indicate inundation heights on the order of 2-storeys high. Source (Bell et al. 2005)

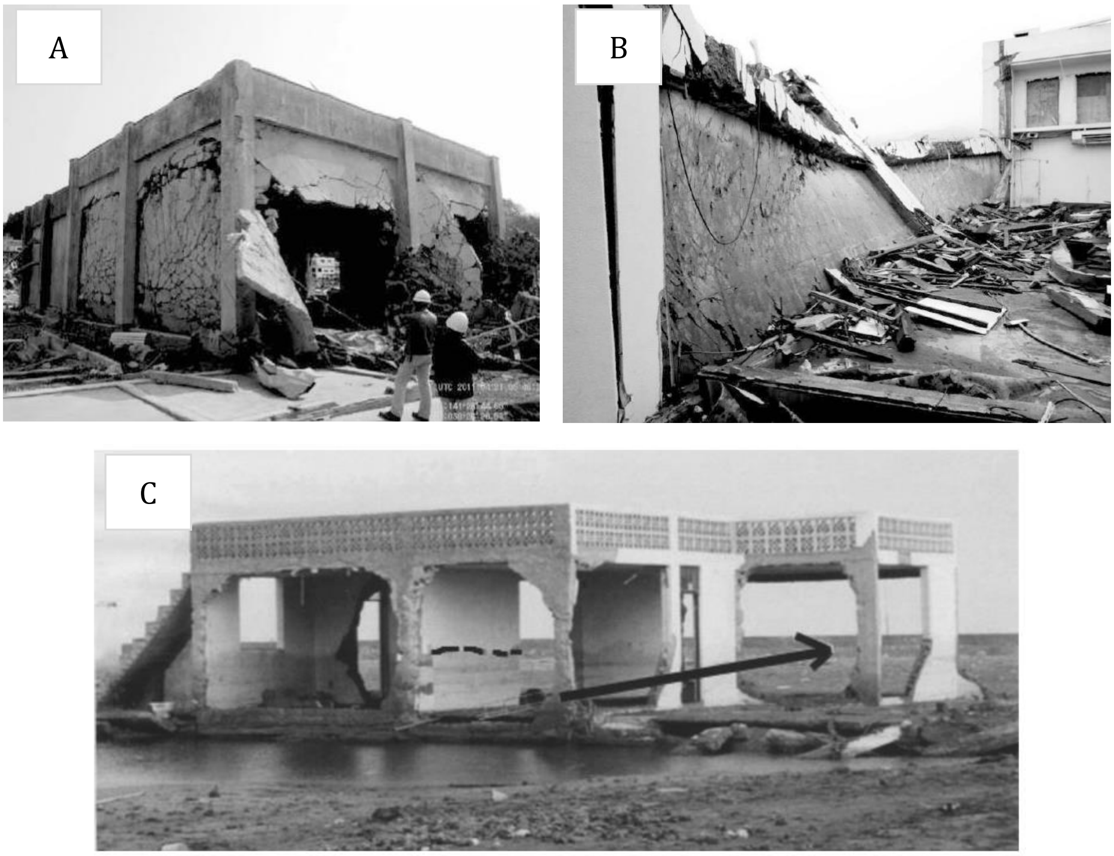


Figure 14. (A) Shear walls blown outward in a reinforced concrete building in Onagawa, Japan from the flow returning to the ocean during the 2011 Tohoku tsunami. Source (Chock et al. 2013). **(B)** Collapse of a steel framed multi-barrel vaulted roof due to the failure of load bearing walls (reinforced concrete pilasters and attached concrete shear walls infilled below the arch) from fluid lateral forces in Rikuzentakata, Japan. Source (Chock et al. 2013)**. (C)** Damaged summer home in La Punta, Peru. Walls perpendicular to the direction of flow (black arrow) or parallel to the shoreline failed. Dashed lines show the stagnant water mark. Source (Okal et al. 2002)

5.6 Strong Currents

5.6a Observation of strong currents

Strong currents may not necessarily be visible turbulent coherent structures but channels or specific regions of elevated current velocities. Modelling by Lynett et al. (2014), Borerro et al. (2015a) and Admire et al (2014) showed that often the strongest currents in the direct vicinity of the port occur at the tips of breakwaters and jetties, alongside wharves and docks, through the harbor entrance and along shorelines (Appendix 5.6b) (Borerro et al. 2015b). In conclusion it seems that when the flow is constricted or interacts with coastal infrastructure the flow is often accelerated, so it is important to consider the effects of strong currents when designing coastal infrastructure to increase its resilience.

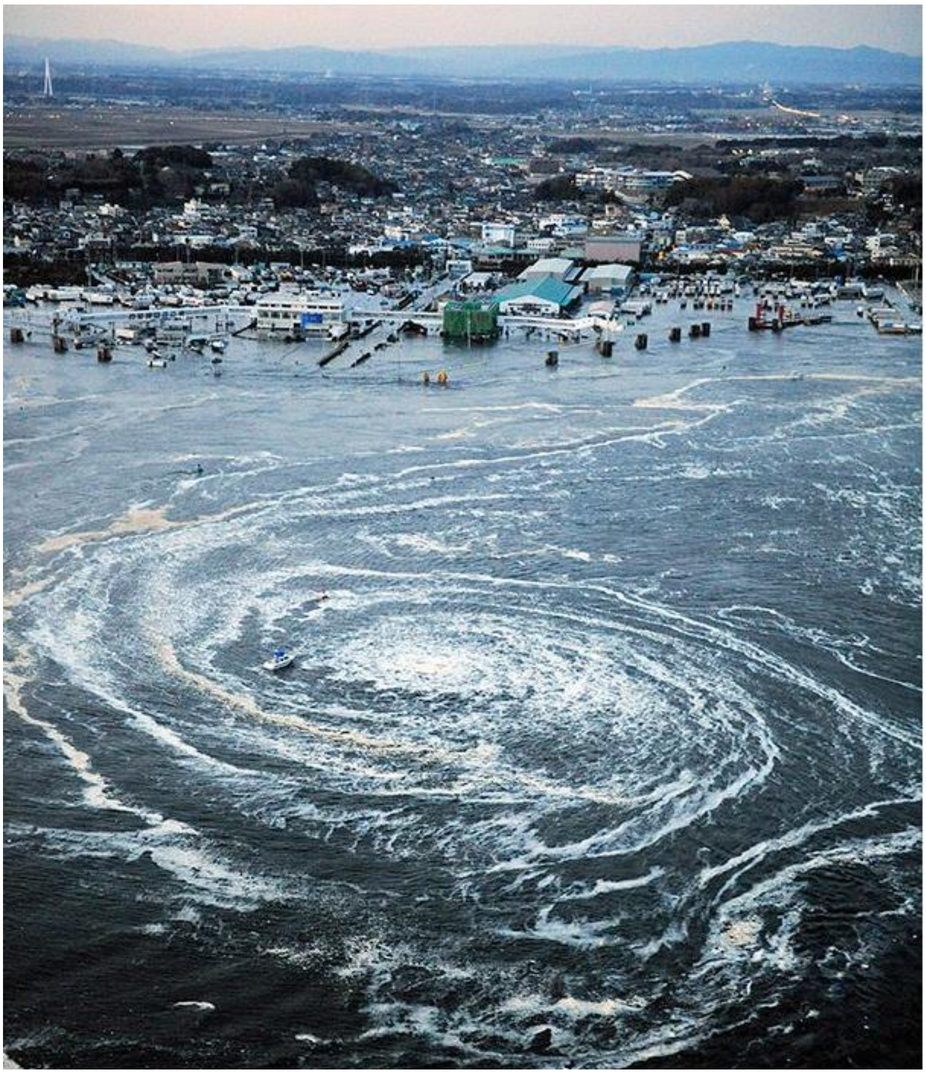


Figure 15. A huge turbulent coherent structure (TCS) is visible in the Pacific Ocean off the coast of Oarai, Ibaraki prefecture, Japan during the 2011 Tohoku tsunami. A vessel near the centre is captured trying to navigate in the TCS. Source (http://www.ibtimes.co.uk/2011-earthquake-tsunami-60-powerful-photos-disaster-that-hit-japan-five-years-ago-1548255).

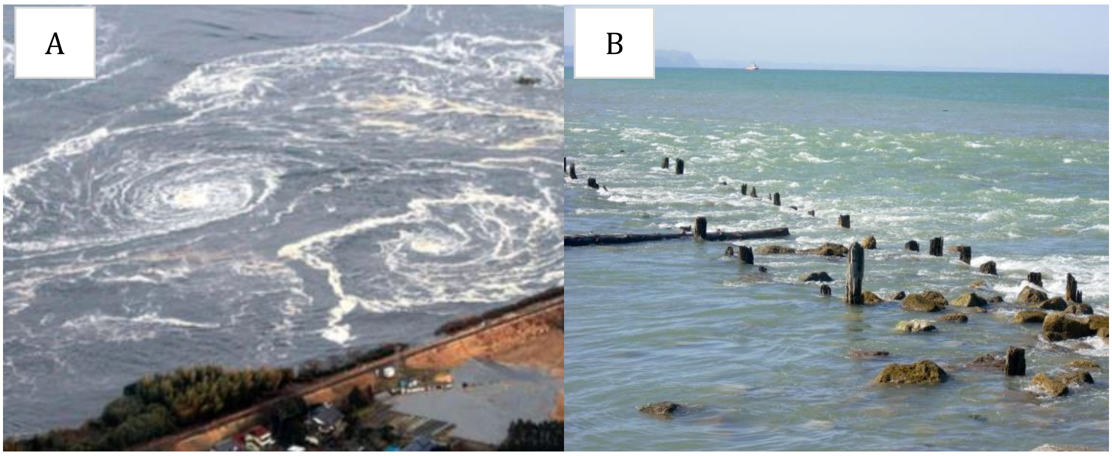


Figure 20. (A) Counter-rotating turbulent coherent structure near Iwaki city, Japan during the 2011 Tohoku tsunami. Source (Borerro et al. 2015a). **(B)** Strong currents from the far field 2010 Chile tsunami in the Port of Napier, New Zealand. Source (http://www.civildefence.govt.nz/resources/photo-library/tsunami/).

Figure 21 is an example of the tsunami flow regime in Crescent City during the 2011 Japan tsunami. The erosional and non-erosional currents highlight where sediment erosion and deposition may occur within the harbor which may have future implications on the movement of vessels and have major remediation costs.

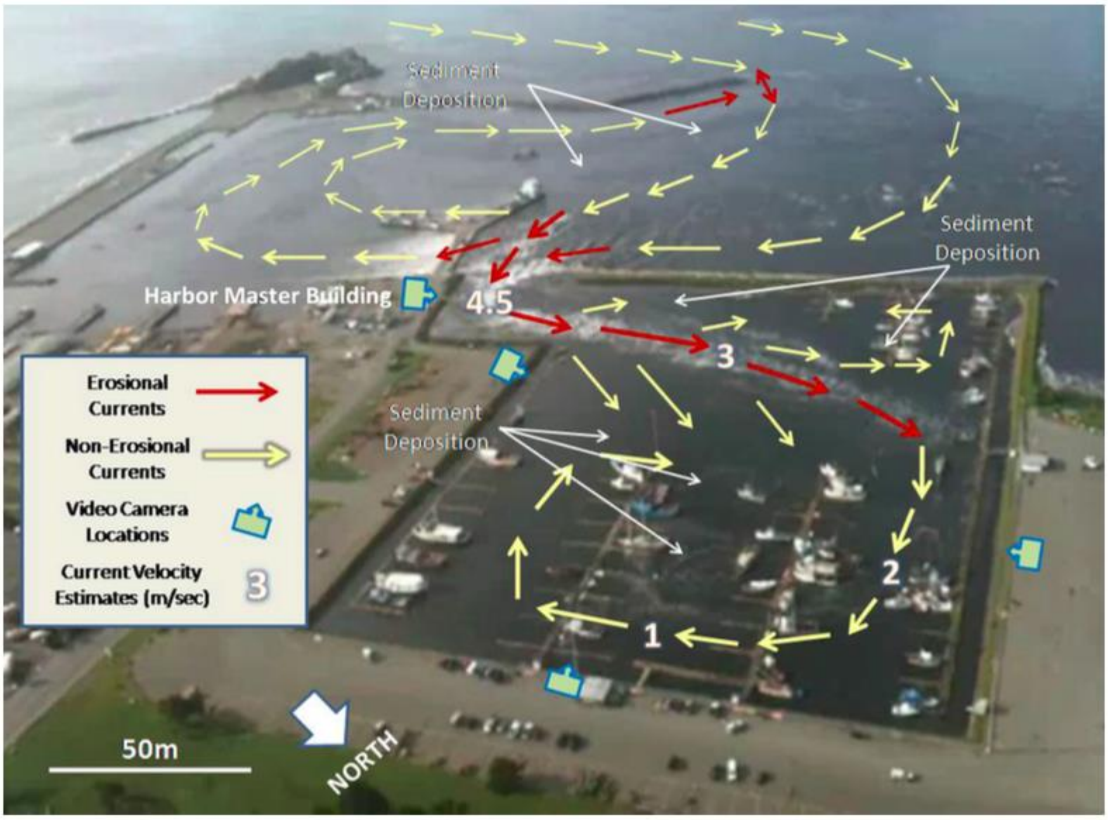


Figure 16. Tsunami in-flow regime map for Crescent City Harbor showing the maximum observed tsunami current velocity values over the span of the first 3.5h of the 2011 Tohoku tsunami. Numbers show estimated surface velocities (m/s), and arrows indicate flow direction based on 14 ground-level and aerial videos taken of the event. Source (Admire et al. 2014).

5.6b Modelling of currents

Lynett et al. (2014) produced simulations of current speeds in Crescent City based on the 2011 Tohoku tsunami and a hypothetical scenario from an Alaskan tsunami. The simulations show the maximum current speed with each colour band representing a current speed e.g. less than 3 knots, 3-6 knots or 9 knots and above which correspond to the damage threshold maps also produced by Lynett et al. (2014) (Appendix 5.14). Lynett et al. (2014) found that the zonation from the current maps, match well with the observations of currents and damage in Crescent City Harbour during the 2011 Tohoku tsunami. Time-threshold maps were also produced to show the extent that particular current velocities will exist for after a tsunami. For example a 6-knot time threshold map which shows a 3.4h value for a particular location within the harbor indicates that at that location, flow speeds of 6 knots are not exceeded after 3.4h after the arrival of the tsunami. These simulations provide ports and harbours with valuable information on the extent and duration that hazardous conditions may exist for and combined with the damage threshold map in Appendix 5.14, it is possible to predict areas where infrastructure damage is most likely to occur.

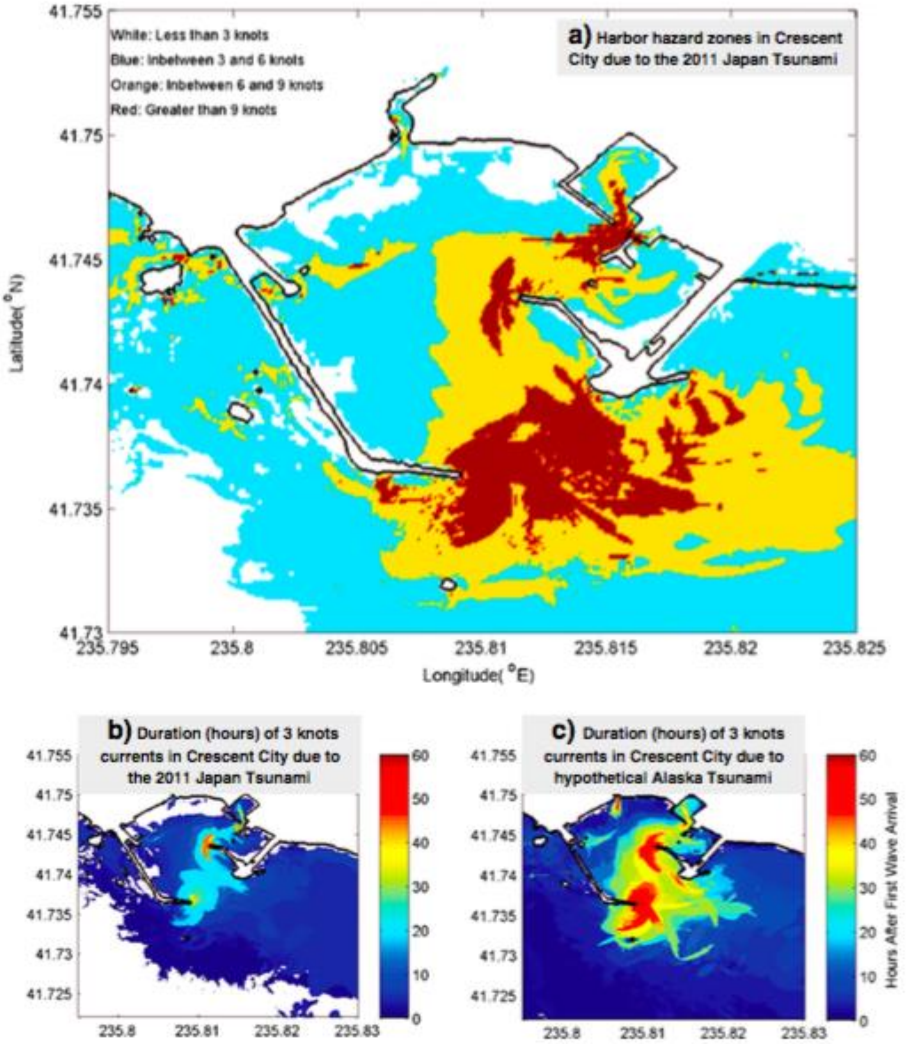


Figure 17. Examples of uses of the simulation in produced by Lynett et al. (2014) in Crescent City, California. (a) Current speed hazard zones for <3/3-6/6-9/9< knot zonation. (b-c) Time threshold maps for two different tsunami sources. Source (Lynett et al. 2014).

5.7 Damage to debris

As debris such as vessels, tanks, vehicles and containers are transported in the flow they have the potential to cause damage to structures from debris strike. However the debris itself can also sustain damage as it impacts with structures, other debris or the ground. Depending on the type of debris and the sustained damage to things such as forklifts, cranes and other heavy machinery, this could have major implications in terms of response and recovery after a tsunami disaster.

Figure 18 (over the page). (A) Fire truck (*left*) and automobile (*right*) in Otsuchi, Japan after the 2011 Tohoku tsunami. Source (Chock et al. 2013). **(B) .** Bus in Tarau, Japan (*left*) and in Natori, Japan (*right*) after the 2011 Tohoku tsunami. Source (Chock et al. 2013). **(C)** Damage shipping containers at Sendai Port, Japan after the 2011 Tohoku tsunami. Source (Chock et al. 2013). **(D)** Large storage tankers as floating debris in Kesennuma, Japan after the 2011 Tohoku tsunami. Source (Chock et al. 2013).

5.8 Evacuation safe depths

Evacuation safe depths are an option for vessels during regional and far-field tsunamis depending on the travel time and the time information takes to be processed and distributed. Lynett et al. (2014) used a current model to produce a scatterplot of current velocities in near shore and offshore areas of Northern California as a function of water depth. Mean and maximum current velocities can be depicted from this plot. This plot aims to provide vessel with “safe” evacuation depths which is classified as no chance of vessel grounding, negligible wave steepness and readily navigable currents. Lynett et al. (2014) found that maximum tsunami currents of 1 knot (0.5m/s) are expected at a depth of 100 fathoms (~180m). Up to depths of 25 fathoms (~45m) the maximum current speed is highly variable indicating that this is the greatest depth that large eddies or jets might extend to. Once depths greater than 30 fathoms are reached (~55m) it will generally be safe, particularly for dispersed and larger vessels.

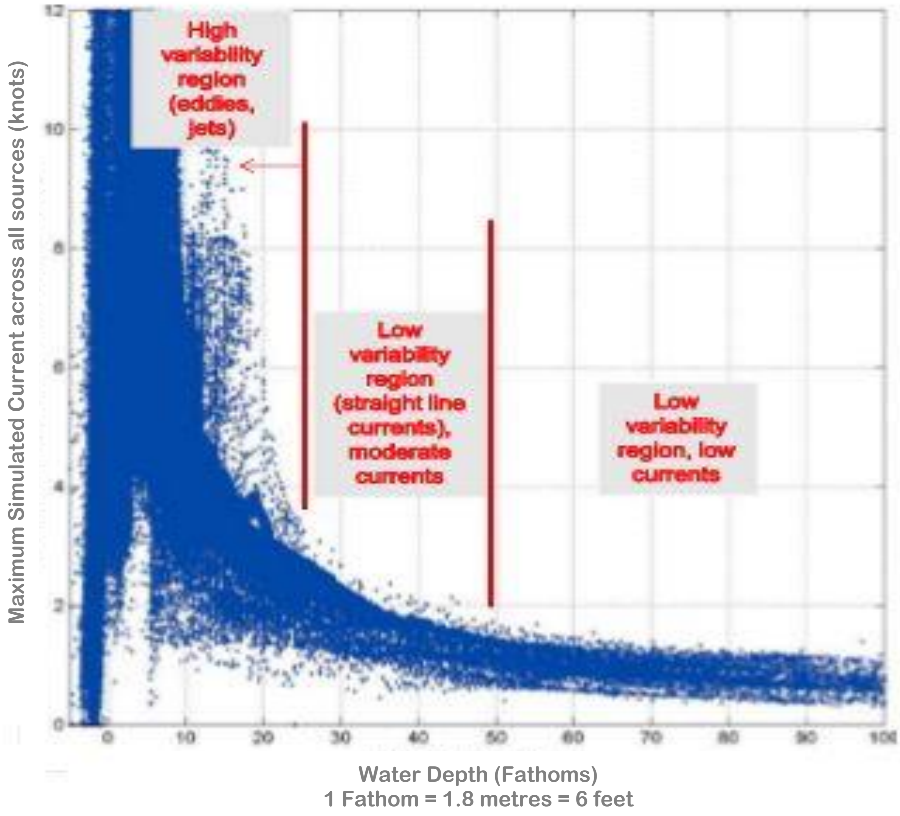


Figure 19. Scatterplot of maximum simulated current speeds as a function of water depth for all sources, all grid resolutions and all models. Source (Lynett et al. 2014).

5.9 GIS analysis

5.9.1 Appendix A

Tables and maps showing each inundation scenario and the corresponding area (in square kilometres) that it affected.

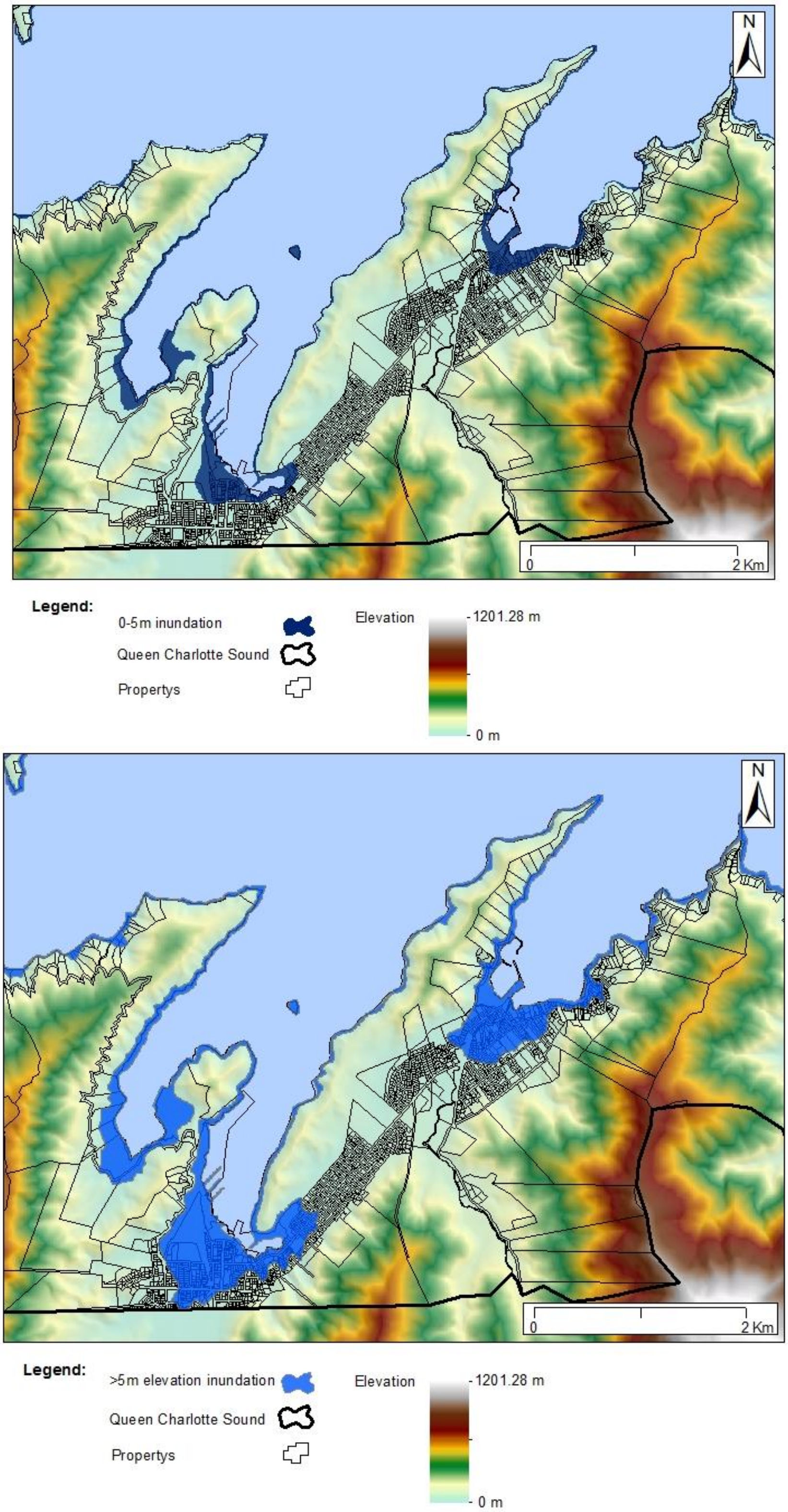
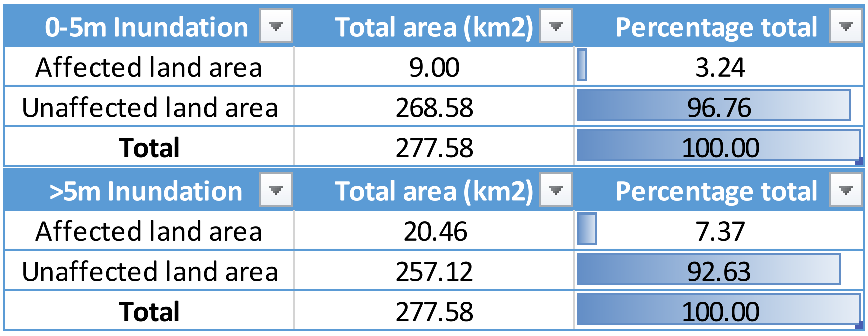


Figure 20. (TOP) 0-5m inundation scenario for Picton, Waikawa and Shakespeare Bay. **(BOTTOM)** >5m inundation scenario for Picton, Waikawa and Shakespeare Bay.



0-5m Inundation	Total area (km2)	Percentage total
Affected land area	9.00	3.24
Unaffected land area	268.58	96.76
Total	277.58	100.00

>5m Inundation	Total area (km2)	Percentage total
Affected land area	20.46	7.37
Unaffected land area	257.12	92.63
Total	277.58	100.00

5.9.2 Appendix B

Tables and maps showing each inundation scenario and the corresponding buildings that it affected.

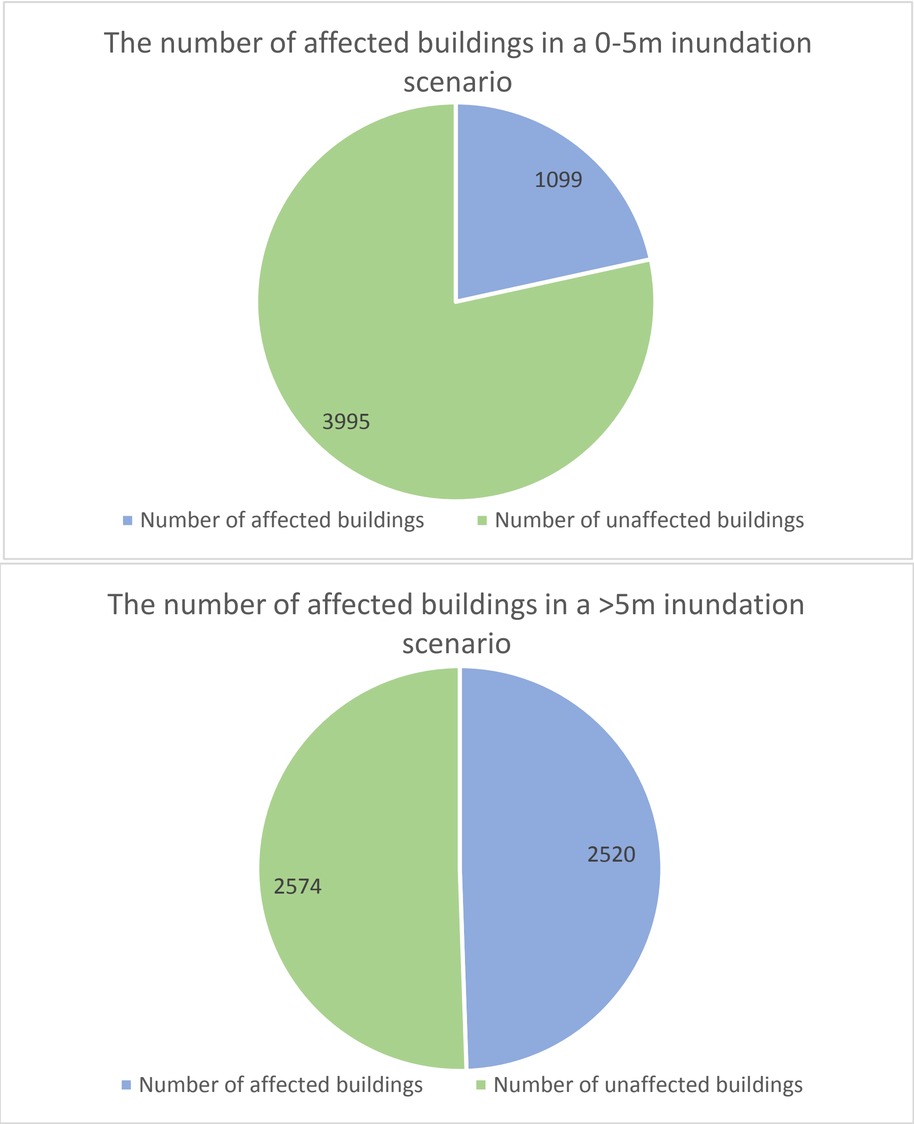


Figure 21. The cumulative number of affected buildings under each inundation scenario in Queen Charlotte Sound

0-5m Inundation	Total number of buildings	Percentage total
Number of affected buildings	1099	21.57
Number of unaffected buildings	3995	78.43
Total	5094	100.00

>5m Inundation	Total number of buildings	Percentage total
Number of affected buildings	2520	49.47
Number of unaffected buildings	2574	50.53
Total	5094	100.00

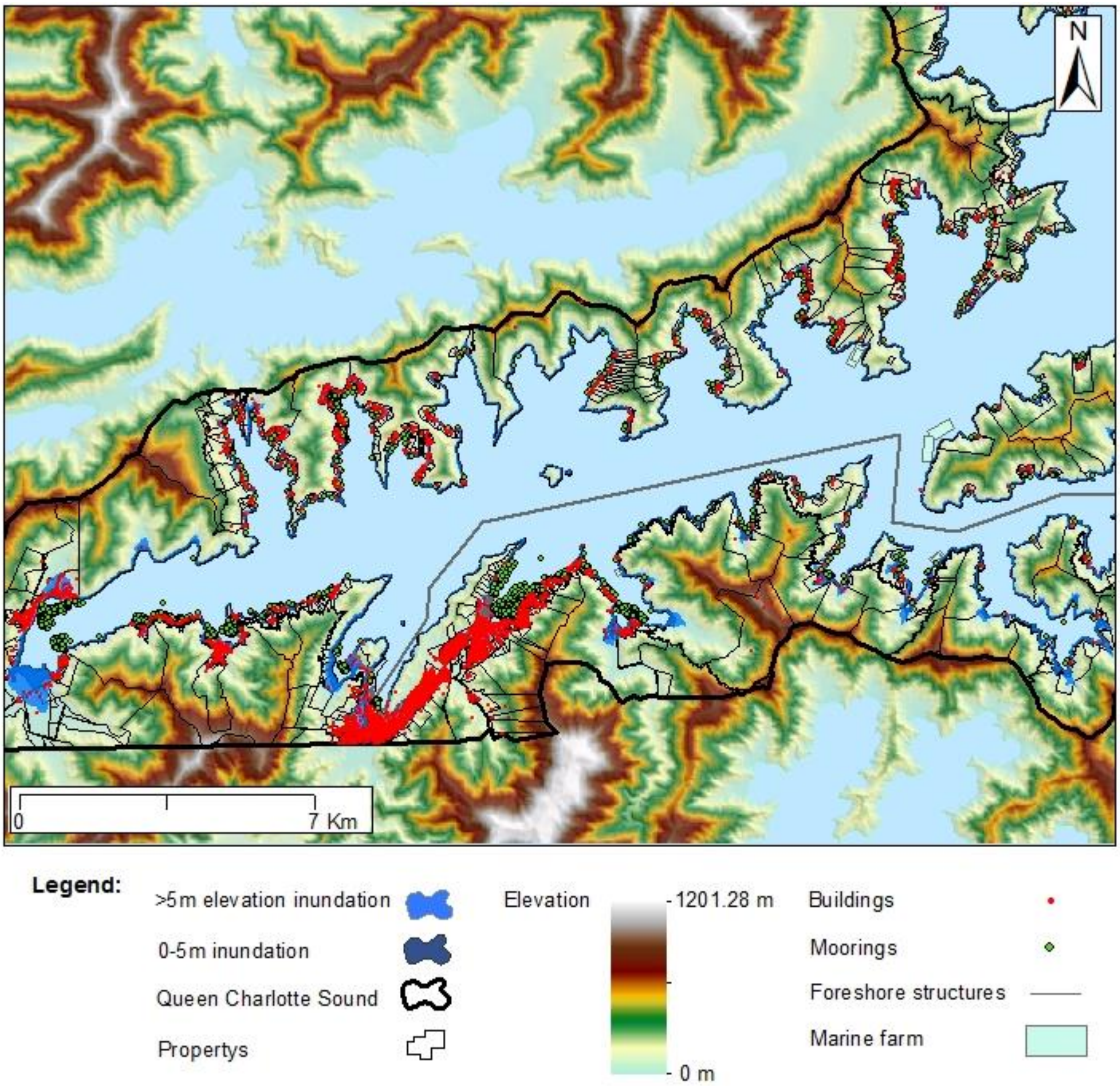


Figure 22. The location of all types of infrastructure throughout Queen Charlotte Sound under 0-5m and >5m inundation scenarios. The grey foreshore structure line is an underwater pipeline but also outline the route of the Inter islander ferry. Note the cluster of buildings in low lying coastal areas.

5.9.3 Appendix C

Tables and maps showing each inundation scenario and the corresponding lengths (in kilometres) of foreshore structures that it affected.

0-5m Inundation	Total Length (km)	Percentage total
Affected length of foreshore structures	68.29	98.04
Unaffected length of foreshore structures	1.36	1.96
Total	69.65	100.00

>5m Inundation	Total Length (km)	Percentage total
Affected length of foreshore structures	68.82	98.81
Unaffected length of foreshore structures	0.83	1.19
Total	69.65	100.00

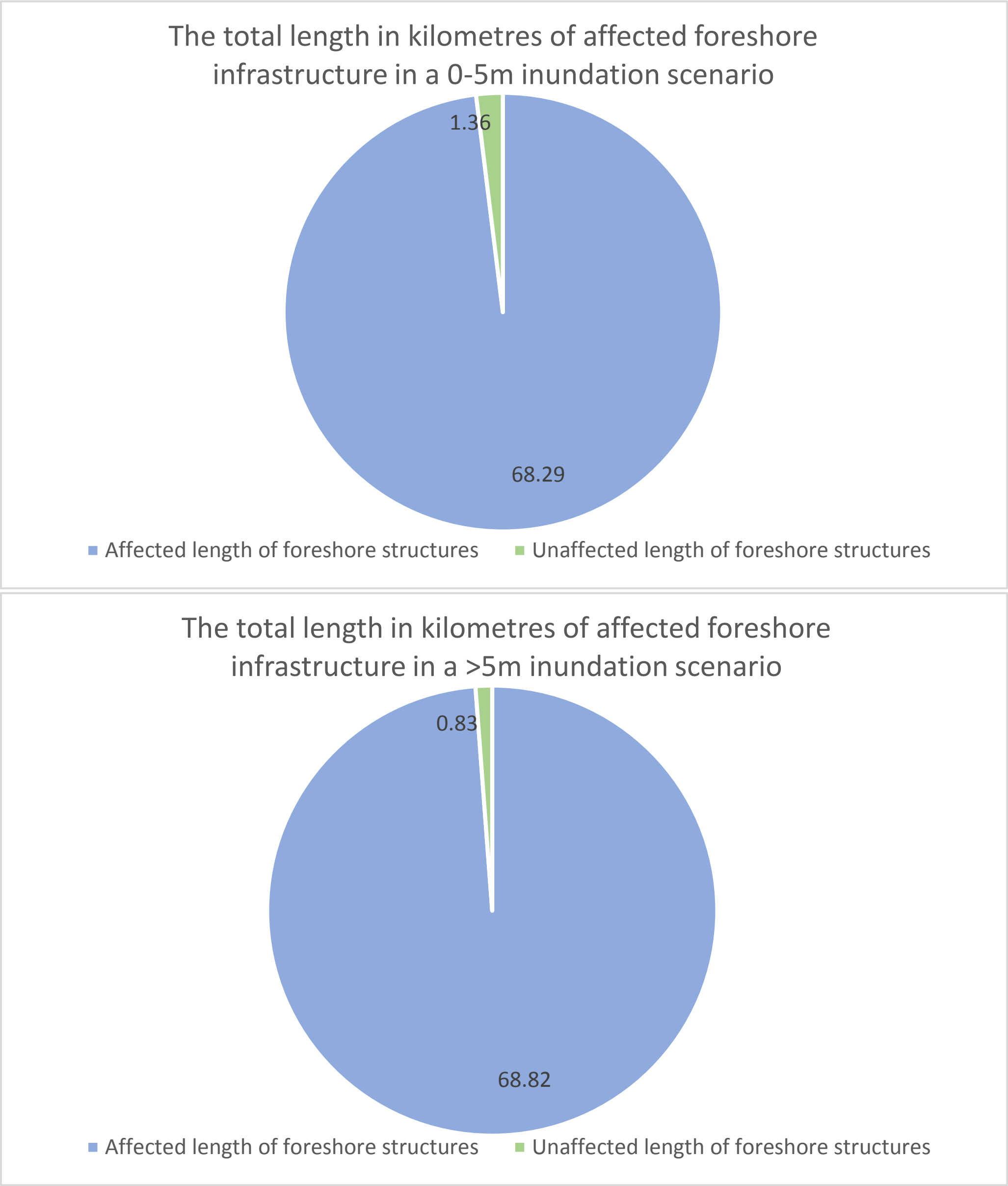


Figure 23. The cumulative affected length in kilometres of foreshore infrastructure in the Marlborough Sounds.

5.9.4 Appendix D

Tables and maps showing each inundation scenario and the corresponding number of properties that it affected.

0-5m Inundation	Total number of properties	Percentage total
Number of affected properties	1440	35.21
Number of unaffected properties	2650	64.79
Total	4090	100.00

>5m Inundation	Total number of properties	Percentage total
Number of affected properties	2650	64.79
Number of unaffected properties	1440	35.21
Total	4090	100.00

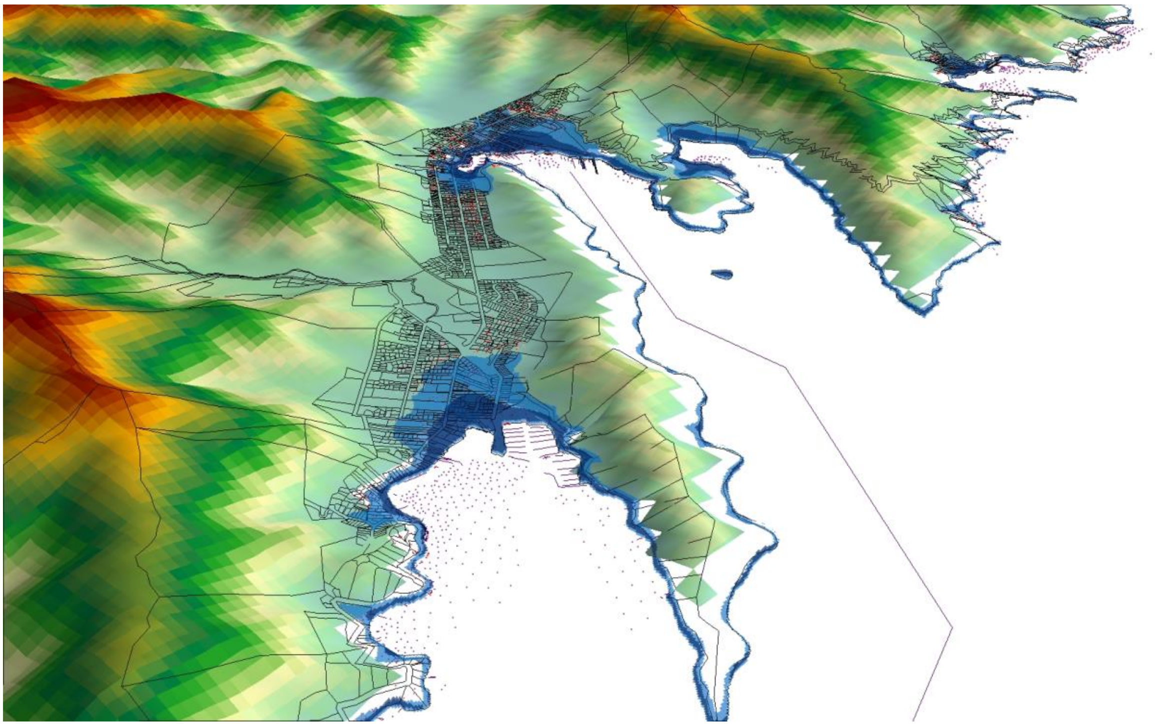


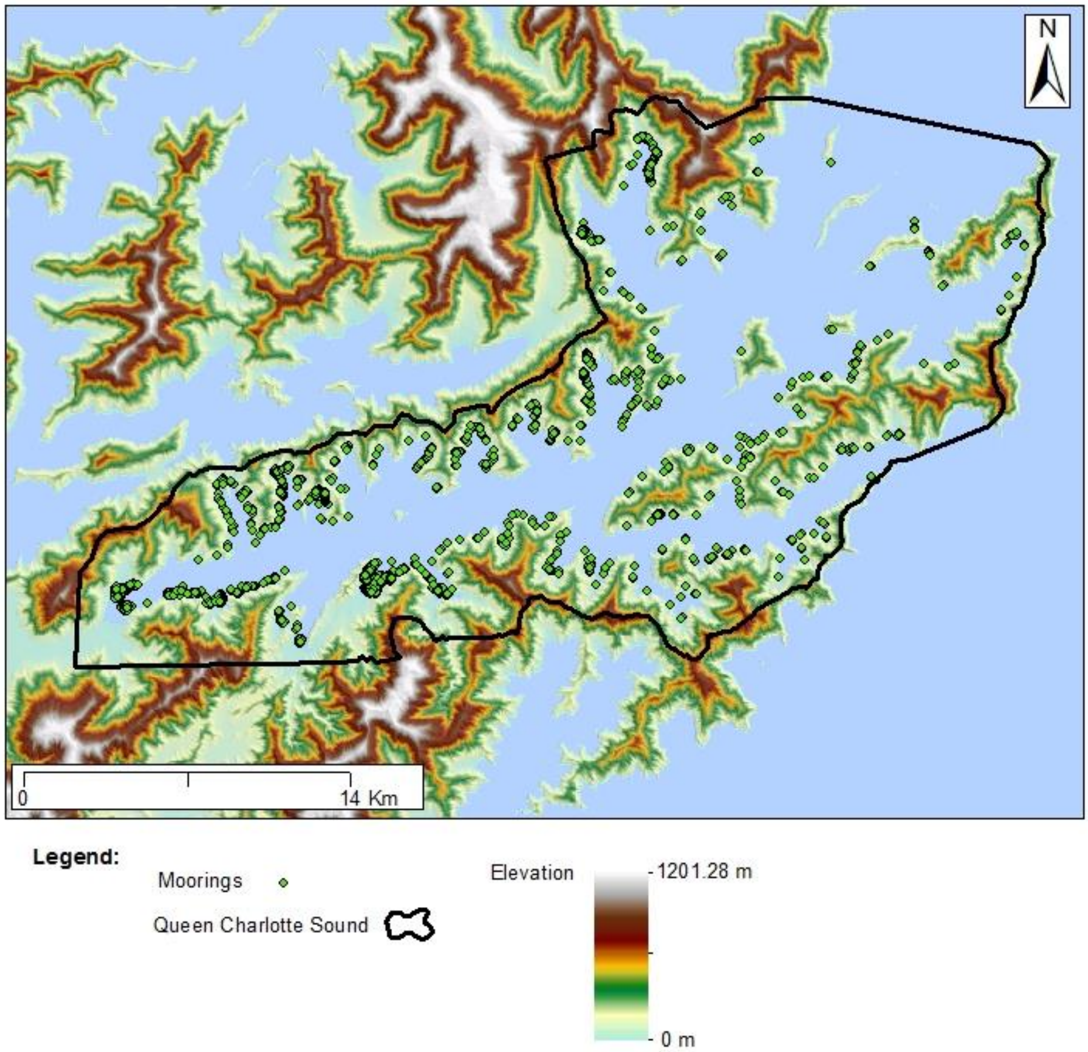
Figure 24. A screenshot from ArcScene looking towards Picton, Waikawa and Shakespeare Bay, showing the 0-5m inundation layer (Dark blue) and the >5m inundation layer (Light blue). Properties are outlined in black, mooring locations are in green and the locations of building are depicted with red dots.

5.9.5 Appendix E

Tables and maps showing each inundation scenario and the corresponding area (in square kilometres) of marine farms that it affected.

0-5m Inundation	Total Area (km 2)	Percentage total
Affected area of marine farms	5.75	99.83
Unaffected area of marine farms	0.01	0.17
Total	5.76	100.00

>5m Inundation	Total Area (km 2)	Percentage total
Affected area of marine farms	5.76	100.00
Unaffected area of marine farms	0.00	0.00
Total	5.76	100.00



route.

5.9.6 Appendix F

Tables and maps showing each inundation scenario and the corresponding number of moorings (private and public) that it affected.

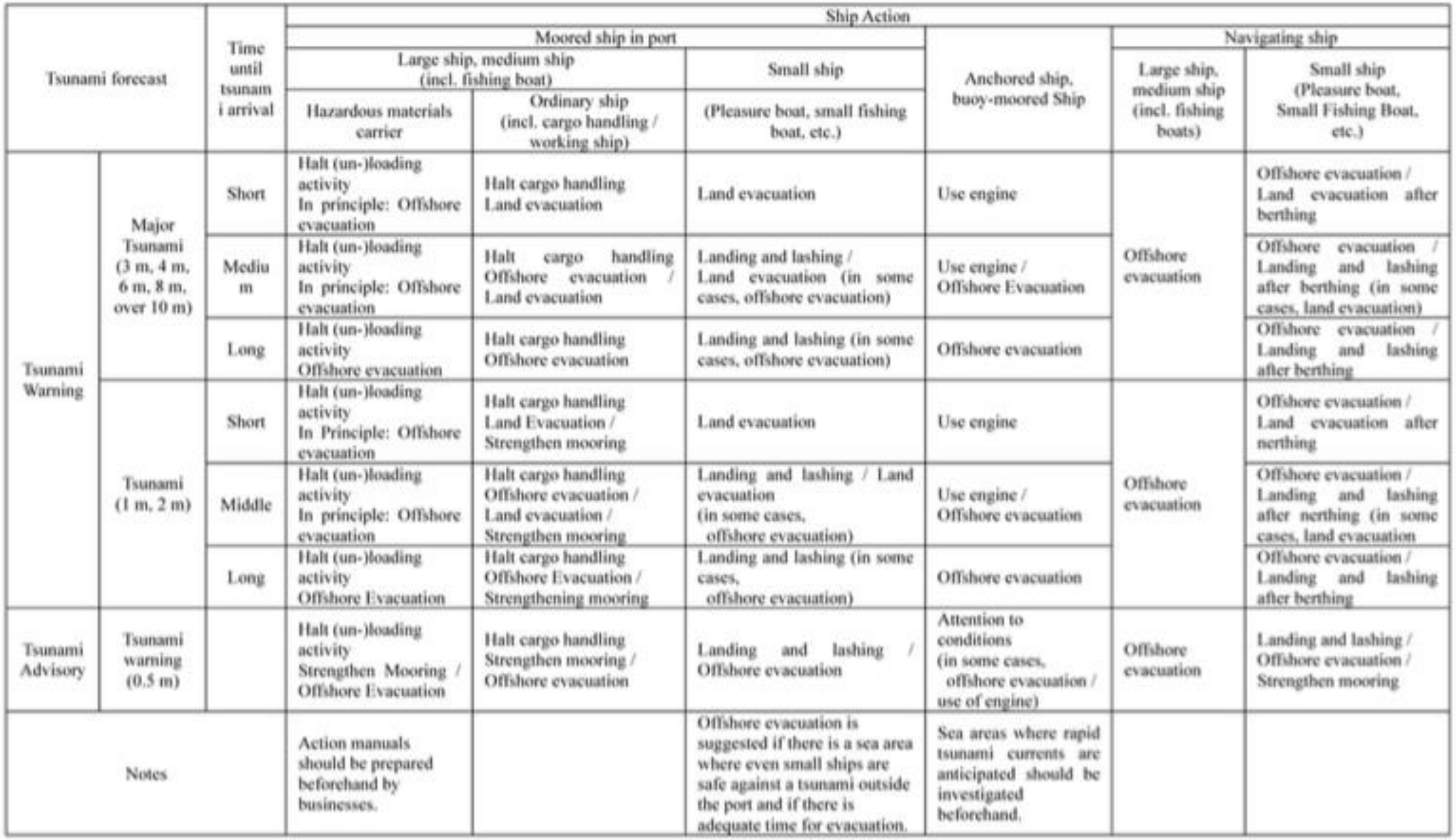
0-5m Inundation	Total number of moorings	Percentage total
Number of affected moorings	1752	99.89
Number of unaffected moorings	2	0.11
Total	1754	100.00

>5m Inundation	Total number of moorings	Percentage total
Number of affected moorings	1752	99.89
Number of unaffected moorings	2	0.11
Total	1754	100.00

Even if the damage to moorings specifically may not be significant in terms of the port operation and harbor navigation, the damage to vessels which may be moored at these locations could have significant implications during the recovery and response phase after a tsunami.

5.10 Ship action policy against tsunami

A table of ship actions proposed by the Japan Association of Marine Safety for actions vessels should take during a tsunami based on the tsunami height, available time, ship size and state of the ship (PIANC 2010).



Tsunami forecast		Time until tsunami arrival	Ship Action					
			Moored ship in port			Anchored ship, buoy-moored Ship	Navigating ship	
			Large ship, medium ship (incl. fishing boat)		Small ship		Large ship, medium ship (incl. fishing boats)	Small ship (Pleasure boat, Small Fishing Boat, etc.)
			Hazardous materials carrier	Ordinary ship (incl. cargo handling / working ship)	(Pleasure boat, small fishing boat, etc.)			
Tsunami Warning	Major Tsunami (3 m, 4 m, 6 m, 8 m, over 10 m)	Short	Halt (un-)loading activity In principle: Offshore evacuation	Halt cargo handling Land evacuation	Land evacuation	Use engine	Offshore evacuation	Offshore evacuation / Land evacuation after berthing
		Medium	Halt (un-)loading activity In principle: Offshore evacuation	Halt cargo handling Offshore evacuation / Land evacuation	Landing and lashing / Land evacuation (in some cases, offshore evacuation)	Use engine / Offshore Evacuation		Offshore evacuation / Landing and lashing after berthing (in some cases, land evacuation)
		Long	Halt (un-)loading activity Offshore evacuation	Halt cargo handling Offshore evacuation	Landing and lashing (in some cases, offshore evacuation)	Offshore evacuation		Offshore evacuation / Landing and lashing after berthing
	Tsunami (1 m, 2 m)	Short	Halt (un-)loading activity In Principle: Offshore evacuation	Halt cargo handling Land Evacuation / Strengthen mooring	Land evacuation	Use engine	Offshore evacuation	Offshore evacuation / Land evacuation after nerthing
		Middle	Halt (un-)loading activity In principle: Offshore evacuation	Halt cargo handling Offshore evacuation / Land evacuation / Strengthen mooring	Landing and lashing / Land evacuation (in some cases, offshore evacuation)	Use engine / Offshore evacuation		Offshore evacuation / Landing and lashing after nerthing (in some cases, land evacuation
		Long	Halt (un-)loading activity Offshore Evacuation	Halt cargo handling Offshore Evacuation / Strengthening mooring	Landing and lashing (in some cases, offshore evacuation)	Offshore evacuation		Offshore evacuation / Landing and lashing after berthing
Tsunami Advisory	Tsunami warning (0.5 m)		Halt (un-)loading activity Strengthen Mooring / Offshore Evacuation	Halt cargo handling Strengthen mooring / Offshore evacuation	Landing and lashing / Offshore evacuation	Attention to conditions (in some cases, offshore evacuation / use of engine)	Offshore evacuation	Landing and lashing / Offshore evacuation / Strengthen mooring
Notes			Action manuals should be prepared beforehand by businesses.		Offshore evacuation is suggested if there is a sea area where even small ships are safe against a tsunami outside the port and if there is adequate time for evacuation.	Sea areas where rapid tsunami currents are anticipated should be investigated beforehand.		

Time until tsunami arrival:
Long: Adequate time is available for evacuation after a tsunami warning (until a ship is under safe conditions such as offshore evacuation, landing and lashing, etc.).
Short: Little time is available for evacuation after a tsunami warning (until a ship is under safe conditions such as offshore evacuation, landing and lashing, etc.).
Medium: Between 'Long' and 'Short'
Small ship: The ships, which can be landed in a port, such as pleasure boats and fishing boats (excluding landing in a shipbuilding yard).
Land evacuation: Crew members take refuge in a high land area because evacuation by ship is anticipated to involve a high degree of risk. They also prevent the outflow of ships and exercise safety precautions regarding dangerous goods.
Offshore evacuation: Ships evacuate to deep and wide offshore area outside a port (if there is no time for offshore evacuation, ships should wait in an emergency evacuation area inside the port).
Attention to conditions: Although crew members do not take evacuation measures, they pay attention to changing conditions and take measures for ship safety until the cancellation of tsunami advisory.
Landing and lashing: Crew members land small ships, such as pleasure boats and fishing boats, and lash them to prevent them from being washed away by a tsunami.
Use of engine: Crew members start the engine of an anchored ship to drive it against the tsunami if necessary.
Note: The above table shows the standard ship actions. Countermeasures should be examined on the basis of the features of each port area.

5.11 Typical scour observations

Scour is characterized by sustained shear flow around obstacles and includes plunging scour during seawall overtopping (Chock et al. 2013). The most predominant scour from past tsunamis is corner scour around foundations resulting in structural failure in some cases and also plunging scour on the landward side of tsunami barriers as they are overtopped.

Figure 137. Examples of corner scour: (a) damage to a home in Dichato, Chile. Source (Edge et al. 2013). **(b)** Far-field effects from the 26th December 2004 tsunami in Xaafun, Somalia showing scour damaged a house corner. Source (Fritz & Borerro 2006). (c-d) 1.4m deep scour pit below a buildings foundations behind a failed seawall in Tarou, Japan. Source (Chock et al. 2013).

5.12 Damage to floating docks

Figure 138. A 66-foot floating dock from the Port of Misawa, Japan drifted across the Pacific Ocean and beached 15 months later on Agate Beach in Oregon, US after the 2011 Tohoku Tsunami. Source (https://usresponserestoration.wordpress.com/2012/12/

5.13 Damage to tanks

The spread of accidental spills from storage tanks is stopped by retention walls which are usually built around storage tanks, however these retention walls typically aren't built to prevent tsunami inundation. If the inundation depth around the storage tank exceeds the level of the contents uplift and buoyancy forces will develop, therefore tanks filled with less goods are more susceptible to uplift and buoyancy forces and subsequent movement than full tanks (Chock et al. 2013).

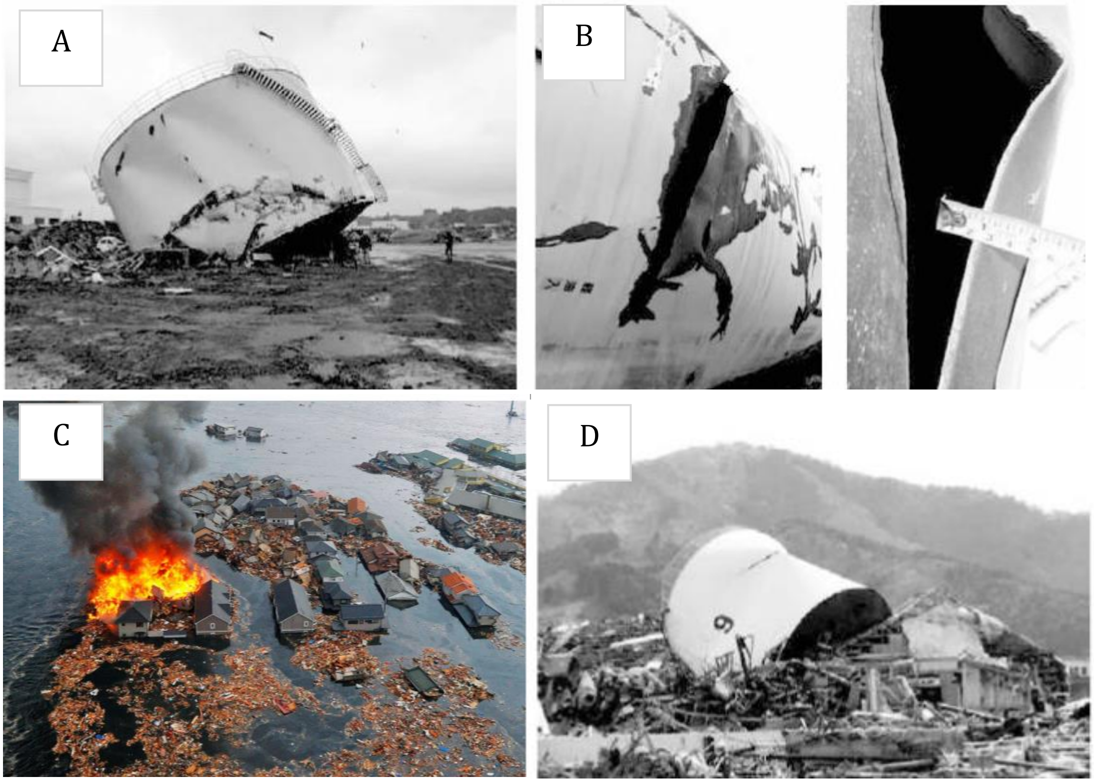


Figure 195. (A-B) A storage tank in Kesennuma with multiple ruptures of its 4mm steel wall after being moved from its original position. Source (Chock et al. 2013). **(C)** An example of a fire breaking out in houses and debris that was swept out to sea by the tsunami in Natori, Fukushima prefecture, Japan. Source (http://www.ibtimes.co.uk/2011-earthquake-tsunami-60-powerful-photos-disaster-that-hit-japan-five-years-ago-1548255). **(D)** Large storage tank as floating debris in Onagawa, Japan after the 2011 Tohoku tsunami. Source (Chock et al. 2013)

5.14 Crane damage

During the 2010 Chile earthquake and tsunami commercial power was lost at the Port of San Antonio in Chile and the emergency generators lacked sufficient power to operate the container cranes. As a result container cranes were frozen in place and evacuating vessels caused damage to the cranes, crane spreader bar, cables or containers. Damage to crane arms, buckling in legs, derailment and buckling throughout the frame all contributed to the damage of many cranes on several different berths. Each crane is estimated to cost US $7-8 million to replace, not including the costs of the removal and demolition of damaged cranes which may significantly increase the remediation costs. Cranes are an important aspect of port recovery and operation after a disaster so techniques to minimize tsunami damages to them must be considered for the port to function after a tsunami disaster.

5.15 Observed damage and current velocity correlation

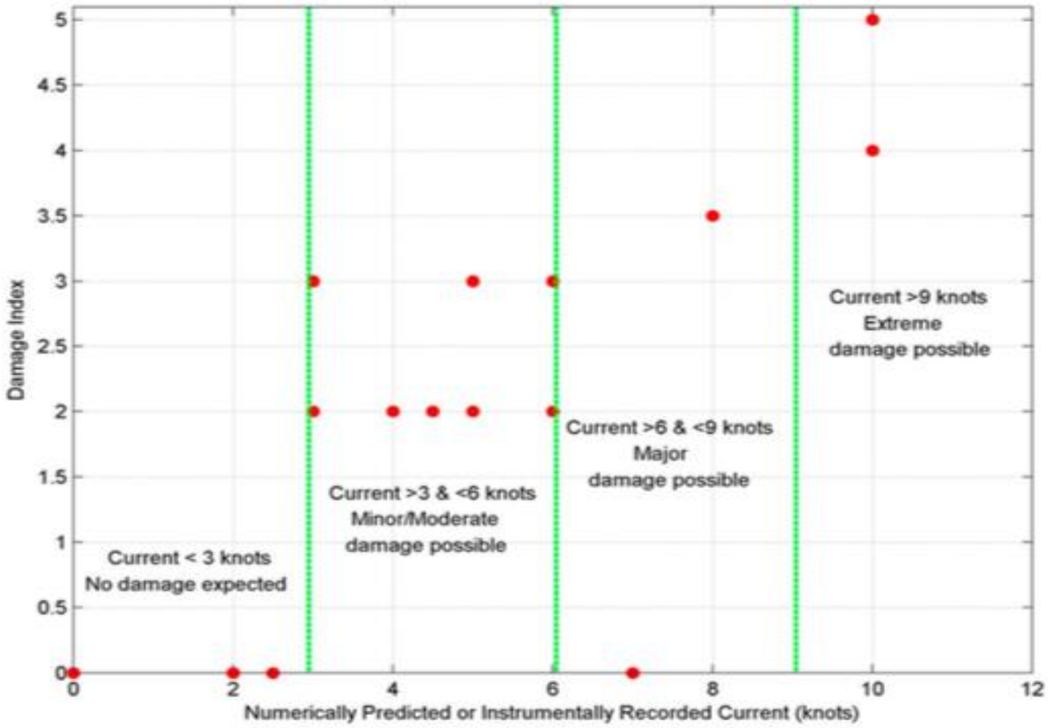


Figure 243. Scatter plot of observed damage indicies and their corresponding tsunami induced current.

Lynett et al. (2014) found a correlation between current velocities and observed damage during tsunamis using numerical modeling (Appendix 5.15). According to Lynett et al. (2014), damage to floating docks and vessels initiates with currents of 3 knots (1.5ms-1 approx.). When current velocities are increased to around 6-9 knots (3.1-4.6ms-1 approx.) harbour assets are subject to moderate and major damage. The damage thresholds are sensitive to the structural capacity of the infrastructure, which is dependent on the age and extent of deterioration. It will also be affected by the accuracy of the predicted currents in the model, which are influenced by bathymetry and numerical errors in the model. This correlation allows guidelines to be set for the development and design of infrastructure around the harbor and port based on the current velocities expected in various inundation scenarios. It also provides a good basis for reducing damage and losses in ports and harbours from tsunamis via improved understanding and forecasting.

5.16 examples of tsunami mitigation in ports

5.16a Susaki Port, Japan

During the 1960 Chile tsunami houses in the direct vicinity of the timber yards were affected by debris strike when parts of the embankment failed and seawater flooded the yards (PIANC 2010). To prevent further disaster breakwaters and seawalls have been constructed. The local government has provided all local citizens with tsunami hazards maps, which show potential inundation zones during a tsunami, evacuation routes and highlight evacuation "safe places". The public also has access to tsunami-lecture meetings and evacuation drills. Tsunami information is also cleverly displayed using evacuation signs in the streets and an electrical bulletin board.

5.16b Kamaishi Port, Japan

Kamaishi Port has suffered considerable damage to infrastructure and many casualties from 3 tsunami events in the past: 1) 1896, Meiji Sanriku Earthquake Tsunami; 2) 1933, Show Sanriku Earthquake Tsunami; 3) 2010, Chilean Tsunami. Collectively, the events have caused damage to over 400 vessels, inundated over 450 homes and damaged over 3000 homes (PIANC 2010). A breakwater has been constructed at the mouth of the Kamaishi Bay to minimize the ports risk to tsunamis.

5.16c Okushiri Port, Japan

After the 10m Okushiri tsunami hit Okushiri Island and swept houses from the inundation zone into the fishing port, several mitigation measures have been put in place. Firstly, both land reclamation to create higher elevations and also naturally occurring topographic highs were utilized to move severely damaged homes to these areas (PIANC 2010). Secondly, an artificial hard ground was created, this allows workers to commence daily operations on the first level and use the second floor for evacuation. Thirdly, a seawall has been constructed in front of reclaimed land.

5.16d United States

Over the last 230 years, the United States has been affected by 80 significant tsunamis, inflicting over $180 million in port, vessel and property related damage (PIANC 2010). Following many tsunamis, few false warnings and concerns from coastal residents, it prompted the establishment of the National Tsunami Hazard Mitigation Program (NTHMP) in 1996. A focus on improving tsunami warning and detection systems, establishing tsunami hazard assessments and initiating mitigation plans to a state and local level is executed collaboratively by the United States Geological Society (USGS), the Federal Emergency Management Agency (FEMA), and the five states along the west coast (Alaska, California, Hawaii, Oregon, and Washington) (Borerro et al, 2005).

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Cover Picture

Fisherman in the port of Iquiqe, Chile try to salvage their boats and navigate through extensive floating and semi-submerged debris in the aftermath of the April 2nd, 2014 Iquique earthquake. Source. (https://www.theatlantic.com/photo/2014/04/the-aftermath-of-chiles-earthquake/100709/)