An Analysis of Tsunami Impacts to Lifelines

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CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX FIGURES

APPENDIX TABLES

ABSTRACT

Recent tsunami events across Asia, the Pacific and South America have demonstrated the destructive potential of tsunami to the built environment. While devastating for the countries impacted, these events provide an opportunity for other countries to learn lessons from the disasters and to better prepare for future tsunami. The impacts of tsunami on the four major lifelines sectors (water, transport, energy and telecommunications) can be significant and can cause major disruptions to services, which in turn can delay emergency response and recovery efforts. However, actions can be taken to reduce the impacts through mitigation activities that increase the resilience of lifelines to tsunami. These include options such as response and recovery planning, engineering solutions to increase the performance of lifelines, or improved site selections to reduce exposure to tsunami. New Zealand has a very high tsunami hazard with local, regional and distant tsunami sources potentially affecting the country. It is therefore critical that key lifelines are resilient from the threat of tsunami.

Recent events in Indonesia, Samoa, Chile and Japan have resulted in a significant amount of literature that describe tsunami damage to lifelines, however these studies are usually event specific and prove difficult to draw out general observations on the performance of lifelines. The quantity and quality of information available on the results of tsunami is variable across the different sectors, with more information available for the transport and water sectors, and a lack of information available for the electricity sector. This has limited the information that can be included in this report for that sector. Furthermore, due to the lifeline networks and the manner in which information was gathered following major tsunami, more information has been available from the Japan tsunami than any other event. This means that much of this report relies on information from Japan, supplemented by information from other events. Further, of the information that is available, it is sometimes not clear as to whether damage to infrastructure was caused by the initial earthquake or the following tsunami. Only information directly attributed to tsunami action has been included in this report. This report is a review that consolidates the current state of knowledge of tsunami impacts to lifelines and a) summarises the damage and failure models of lifelines impacted by tsunami, b) describes what recovery actions were taken following recent tsunami by lifeline operators, and c) outlines what actions can be taken to increase the resilience of lifelines to future tsunami.

The findings of this review highlight that all lifelines can be impacted to some level by tsunami. Furthermore, the interdependency between lifelines can compound the disruption of services. For example, power outages impact wastewater operations, telecommunications and some transportation services such as airports and trains. Having operational transportation and telecommunications networks are also critical in being able to respond and recover from tsunami impacts.

Transportation networks, such as roads, bridges, and rail will likely be damaged disrupted by even small tsunami (tsunami depths ~ 1m) due to scouring and deposition of debris. Airports that are in tsunami inundation zones will be inundated, however services can be restored quickly once debris from the runway has been cleared.

Wastewater and potable water networks are particularly vulnerable to tsunami at their facility buildings and pipe intake and outflow sites. Damage to building structures or electrical equipment can cause significant service disruptions, while repairs are undertaken. Furthermore, contamination of drinking water supplies or sewerage containment ponds can occur with even small amounts of intrusion of seawater from a tsunami. Less data is available regarding the susceptibility of buried pipelines to tsunami, however it appears that such infrastructure is less vulnerable to tsunami than the above facilities.

Telecommunications networks will most likely be disrupted locally due to damage to buildings and electrical equipment at exchanges. Failure of cellular sites can occur at stand alone towers that are toppled by debris strikes or scouring, as well as those located on buildings that are damaged. Again, little information is available regarding the performance of buried cables in tsunami, however it appears that buried cables are less susceptible from tsunami than overhead lines.

Energy networks, particularly electricity, will be impacted due to shorting of buried cables if they become exposed to the water and have pre-existing casing damage. Also, overhead lines are susceptible to failure by toppling of poles, which can be damaged by debris strikes. Petroleum and gas terminals, often located in coastal areas may suffer damage to their pipe networks and tank farms in tsunami depths of 2m or greater.

A salient observation across all lifeline sectors was that often back-up services, such as generators, were often located on the ground outside of buildings, on ground floors or in basements. Such locations put this critical equipment in the direct path of even small tsunami. It is recommended that back-up generators be raised above ground level or located on at least the second floor of buildings. Furthermore, tsunami damage ‘hot spots’ were identified where multiple lifeline damage and failure can occur. Bridges are a lifeline component that are vulnerable to tsunami and often have co-location of other lifeline services, which if damaged can cause failure of these other lifeline services. Hotspots also occurred on coastal roads, where culverts or wastewater outflows run beneath roads and through sea walls. These water channels are a site of high scour, which often results in scouring of the seawall, roadway and any underground or overhead services. Identifying and increasing the resilience of these tsunami ‘hot spots’ should be a priority for lifeline operators.

Information is given in the report sections on how recovery of lifelines from tsunami was carried out from other events. Further, information is given on potential mitigation actions that can be taken by lifeline organisations to lessen the likelihood of damage and service disruption from tsunami.

Recommendations on areas for future study include analysing the vulnerability of energy lifelines and buried services using physical or analytical experimental methods, in order to fill in the gaps of empirical data described in this report. During post-event surveys, it is recommended that a more systematic approach should be adopted that surveys all lifeline types, as well as both undamaged and damaged infrastructure, in order to better quantify and describe tsunami damage to lifelines.

KEYWORDS

Tsunami, lifelines, damage, risk, infrastructure

1.0 INTRODUCTION

1.1 PROJECT BRIEF

The Auckland Lifelines Group (ALG) and the Wellington Lifelines Group (WeLG) commissioned GNS Science to capture knowledge from existing research of tsunami impacts on infrastructure. The brief noted that there is significant research available from recent events that can inform the New Zealand lifeline utilities, it is not in a readily digestible or usable format.

The deliverable from this project will be a report (this document) and a tsunami damage look-up table (Appendix 2) that draw on existing national and international literature on historic tsunami events, as well as reconnaissance surveys by the authors (to the 2011 Japan and 2015 Chile events) to achieve the specific outputs detailed below.

The analysis needed to include (where existing information makes possible):

- The probable impacts of varying size and duration tsunami on different lifeline utility infrastructure asset types, considering relevant factors such as materials/age/ condition/design/construction methods. Lifeline asset types include from the transport, energy, telecommunications and water sectors.
- Recommendations on the most resilient materials and design/construction methods for different asset types across all lifeline utility sectors, whether above or below ground.
- Any other relevant lessons learnt for lifeline utility providers from recent tsunami events that may be useful in asset planning, design and general tsunami preparedness.
- Guidance on the impact of varying depths and tsunami velocities on different asset types/materials.

1.2 LIFELINE TYPES CONSIDERED

The review considered tsunami impacts to the main four lifelines sectors:

- Water – including storm water, wastewater and potable (drinking) water;
- Energy – including natural gas, petroleum and electricity;
- Transport – including roads, bridges, rail, airports, ports and harbours;
- Telecommunications – including landlines, cellular networks and the Internet.

New Zealand lifelines often have variable asset types, for example electricity, internet and landlines can be overhead or buried, as well as a range of material and construction methods. All variations are considered in the analysis.

1.3 TSUNAMI EVENTS

The 2004 Indian Ocean tsunami sparked interest worldwide on the destructive potential of tsunami. It also marked a decade of large tsunamigenic earthquakes across the subduction zones in the Pacific and Indian oceans. These events provided an opportunity for scientists and engineers to record and document the impact of tsunami on the built environment. The majority of the literature reviewed in this analysis is from events in the past 10 years, due to the increased focus on tsunami impacts and post-tsunami recording of damage in this time. This includes:

- The 26 December 2004 Indian Ocean tsunami (impacts in India, Sri Lanka, Thailand and Indonesia);
- The 29 September 2009 Samoa tsunami (impacts in Samoa and American Samoa)
- The 27 February 2010 Maule, Chile tsunami (impacts in Chile);
- The 11 March 2011 Great East Japan (or Tōhoku) tsunami (impacts in Japan);
- The 16 September 2015 Illapel, Chile tsunami (impacts in Chile).

1.4 LITERATURE SOURCES

The analysis includes a review of existing literature from a number of sources, which include:

- Published peer-reviewed scientific literature;
- Published scientific conference proceedings (often not peer-reviewed);
- Reports from post-tsunami survey teams (e.g., American Society of Civil Engineers, ASCE; Earthquake Engineering Field Investigation Team , EEFIT; or Earthquake Engineering Research Institute, EERI);
- Reports from lifeline companies;
- Damage data from the Japanese Ministry of Land, Infrastructure Transport and Tourism (MLIT, 2012);
- Other researchers from overseas that have first hand experience in tsunami field investigations.

1.5 INFORMATION AND DATA GAPS

The available information and data on tsunami impacts to lifelines varies both in quantity and relevance for this review. This is due to a number of reasons. Some lifelines, for example roads and bridges, are well documented because they are easy to access in a post-tsunami survey and often have significant damage so are a point of interest, whereas others, such as electricity substations or water treatment plants, are often difficult to access due to security issues. Further, some lifeline companies have published useful information on the performance of their network and what actions were taken to repair and reinstate services. A good example of this is the telecommunications network in Japan, or the Ministry of Land Infrastructure and Tourism (MLIT) that published data on road and rail network damage. Some sectors, such as energy, presumably have security concerns and do not want to publish information about their network. These barriers mean that there are data and information gaps for some lifelines. Table 1 highlights the gaps in available information in this review for each lifeline sector and provides a means of identifying what areas could be improved in the future, and also for the reader to understand that when information may be missing, this is often due to limited information being available. Furthermore, many reports and papers on impacts to lifelines do not differentiate between earthquake tsunami damage. This makes it difficult to identify the failure mechanism, and therefore these types of observations were excluded in this review.

Table 1 Information and data gaps identified in the literature review. Green: sufficient information is available. Orange: limited information is available. Red: little to no information is available.

Lifeline Sector	**Damage and Failure Models**	**Recovery Actions**	**Increasing Resilience**
Water	🟩	🟧	🟩
Telecommunications	🟧	🟩	🟩
Transport	🟧	🟧	🟧
Energy	🟧	🟥	🟥

1.6 REPORT FORMAT AND INTENDED USE

The report is structured into lifeline sectors. For each lifeline sector, we report on observed and documented *damage descriptions and modes of failure from tsunami* for that sector, then outline the *recovery actions* that were taken by lifeline operators or emergency responders following the various tsunami events[1], and finally present actions that may be taken to *increase the resilience* of lifelines.

It is assumed that New Zealand lifelines will use this information to better understand the types of damage that could be experienced and for mitigation and recovery planning. It is therefore not explicit in advice as to how New Zealand lifelines should react to such an event.

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[1] But with a focus on Japan as that is where most of the information is from.

2.0 TSUNAMI

A tsunami is a natural phenomenon consisting of a series of waves generated when a large volume of water in the sea, or in a lake, is rapidly displaced. Tsunami are known for their capacity to violently inundate coastlines causing devastating property damage, injuries, and loss of life. The principal sources of tsunami are:

- Large submarine or coastal earthquakes (in which significant uplift or subsidence of the seafloor or coast occurs);
- Underwater landslides (which may be triggered by an earthquake, or volcanic activity);
- Large landslides from coastal or lakeside cliffs;
- Volcanic eruptions (e.g., under-water explosions or caldera collapse[2], pyroclastic flows[3] and atmospheric pressure waves);
- Meteor (bolide) splashdown, or an atmospheric airburst over the ocean.

In a tsunami, the whole water column from the ocean floor to its surface is affected, the initial disturbance creating a series of waves radiating outwards, until the waves either dissipate or collide with a shoreline. Tsunami waves can arrive at nearby shores within minutes, or travel across the deep ocean basins at speeds in excess of 500 kilometres per hour (km/hr.). Very large sources (disturbances) are required to cause tsunami that are damaging at great distances from the source. For example, the 1960 magnitude[4] (M) 9.5 Chile earthquake, which had a rupture length of several hundred kilometres, produced a 25 metre (m) high tsunami locally, over 10 m in Hawaii and nearly 4 m in New Zealand. On the other hand, tsunamis that are generated locally do not need such a large source to be large and damaging at nearby shores. For example, the 1947 M7.1 earthquake off Gisborne affected 120 km of coastline, with a tsunami of 10 m maximum height occurring along tens of kilometres of coast north of Gisborne. The amplitude of tsunami waves[5] in deep water is generally less than one metre, producing only a gentle rise and fall of the sea surface that is not noticed by ships, nor able to be seen by aircraft, although new satellites with sea-surface elevation technology can detect large tsunami in the deep ocean. When tsunami waves reach shallower waters, their speed decreases rapidly from their deep-ocean values, and at the same time their height increases (as the front of each wave slows down and the back of the wave, which is moving faster, catches

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[2] CALDERA COLLAPSE refers to the formation of a large depression when the underlying magma chamber of a volcano collapses during or following an eruption or explosion. The collapse needs to occur suddenly to cause a tsunami.

[3] A PYROCLASTIC FLOW is a ground-hugging avalanche of hot ash, pumice, rock fragments, and volcanic gas that rushes down the side of a volcano at hundreds of km/hr, and can have temperatures greater than 500°C. In a coastal setting, such flows cause tsunami when they enter the sea. Pyroclastic flows can also occur from underwater volcanoes.

[4] The MAGNITUDE of an earthquake is a measure of its energy. There are several methods for estimating the magnitude, which often give slightly different results. At present the most widely used form of the magnitude is the moment magnitude M_W.

[5] TSUNAMI HEIGHT (m) is the vertical height of waves above the tide level at the time of the tsunami (offshore it is approximately the same as the AMPLITUDE). It is far from constant, and increases substantially as the wave approaches the shoreline, and as the tsunami travels onshore. The term “WAVE HEIGHT” is also often used, but there is a potential ambiguity as many scientists define WAVE HEIGHT as the peak-to-trough height of a wave (approximately twice the amplitude).

up on the front, piling the water higher). A tsunami wave that is only half a metre high in the open ocean can increase to a devastating 10 m high wave travelling at 10–40 km/hr at impact with the shore.

Tsunami waves differ from the usual waves we see breaking on the beach or in the deep ocean, particularly in the distance between successive waves, because tsunami waves occupy the whole ocean depth and not just the top few tens of metres as in storm waves. Both of these factors contribute to the huge momentum of water in a tsunami at the coast. The distance between successive tsunami waves (‘wavelength’) can vary from several kilometres to over 400 km, rather than around 100 metres for normal waves at the beach. The time between successive tsunami wave crests (‘period’) can vary from several minutes to a few hours, rather than the few seconds usual for beach waves. Hence, when tsunami waves reach the shore, they continue to flood inland over many minutes, and then the waves may retreat over as many minutes, before the arrival of the next wave. The waves may come in at irregular intervals, often without complete withdrawal of the inundating water from previous waves due to retardation of the outflow and impoundments. The first wave to arrive may not be the largest wave.

New Zealand’s location astride a plate boundary means that it experiences many large earthquakes. Some cause large tsunami. New Zealand’s coasts are also exposed to tsunami from submarine and coastal landslides, and from island and submarine volcanoes. In addition, tsunami generated by large earthquakes at distant locations, such as South America, or western North America and the Aleutians in the north Pacific Ocean, can also be damaging in New Zealand.

Tsunami with run-up heights[6] of a metre or more have occurred about once every 10 years on average somewhere around New Zealand, a similar frequency to Hawaii and Indonesia, but about one third that in Japan. Smaller tsunami occurs more frequently, the smallest of which are only detectable on sea-level recorders.

New Zealand can expect tsunami in the future. Some coasts are more at risk than others because of their proximity to areas of high local seismic activity, or exposure to tsunami from more distant sources. No part of the New Zealand coastline is completely free from tsunami hazard.

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[6] Run-up height is the maximum elevation a tsunami reaches, measured above mean sea level.

2.1 TSUNAMI DAMAGE

Tsunami damage and casualties are usually from four main factors:

- Impact of swiftly flowing torrent (up to 40 km/hr.), or travelling bores[7], on vessels in navigable waterways, canal estates and marinas, and on buildings, infrastructure and people where coastal margins are inundated. Torrents (inundating and receding) and bores can also cause substantial erosion and scouring both of the coast and the sea floor. They can scour roads and railways, land and associated vegetation. The receding flows, when a large tsunami wave recedes are often the main cause of drowning, as people are swept out to sea. Hydrostatic forces generated by tsunami are dependent on the flow depth and result in upward or buoyancy forces on structures. Hydrodynamic forces are from the integration of the flow depth and flow velocity and act as a lateral force on objects. These two forces are the main cause of flow related damage to structures.
- Debris impacts – many casualties and much damage to structures and infrastructure arise from the high impulsive impacts of floating debris picked up and carried by the in-rush (inundating) and out-rush (receding) flows. The debris density and load usually increases during the course of the tsunami inundation as more buildings and objects are damaged and then suspended by the tsunami flow.
- Fire and contamination – fire may occur when fuel installations are floated or breached by debris, or when home heaters are overturned. Breached fuel tanks, and broken or flooded sewerage pipes or works can cause contamination. Homes and many businesses contain harmful chemicals that can be spilled.
- Inundation and salt-water contamination by the ponding of potentially large volumes of seawater will cause medium- to long-term damage to buildings, electronics, fittings, and to farmland.

2.2 TSUNAMI HAZARD IN NEW ZEALAND

To provide some context to the level of tsunami hazard that could be experienced in New Zealand, Figure 1 to Figure 3 show the National Tsunami Hazard Maps from Power (2013). Figure 1 shows the maximum expected height at the 50th and 84th percentile (i.e., median and median plus one standard deviation) for the 100 year return period, or a 1 in 100 chance of being exceeded in any given year. Figure 2 is the 500 year return period, and Figure 3 is the 2500 year return period. These will provide some context when tsunami inundation depths are discussed in following sections. Although, note that Figure 1 to Figure 3 are tsunami height at the coast and this is different to tsunami inundation depth which is the flow depth on land.

Due to the local-source tsunami hazard on the east coast of the North Island, it should be noted that the tsunami impacts on lifelines described here may follow shortly after strong ground shaking that is likely to damage lifelines through ground motion, liquefaction, and co-seismic subsidence or uplift at the coast prior to tsunami arrival.

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[7] Tsunamis often form bores in harbours, man-made waterways, and in coastal rivers and streams. A bore can be a smooth or turbulent, non-breaking step-like increase in water height resulting in wall-like change in water levels from normal to some higher level. They can travel three or more kilometres up a river with the water many metres above the normal level, sometimes well over the bank height, causing damage to bridges and wharves, and causing water to flood nearby flat areas.

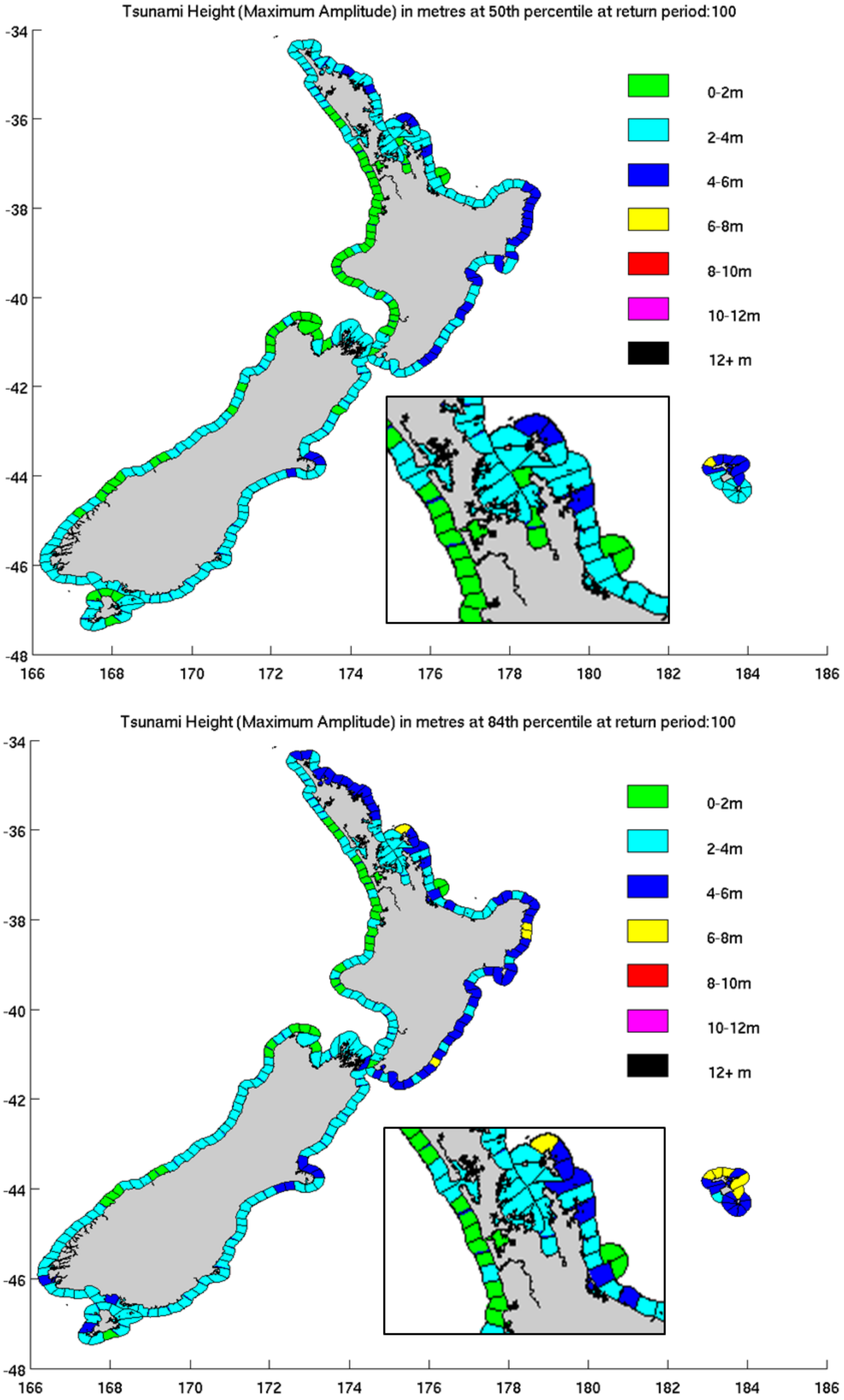


Figure 1 Expected maximum tsunami height in metres at 100 year return period, shown at median (50th percentile) and 84th percentile of epistemic uncertainty. Source: Power (2013).

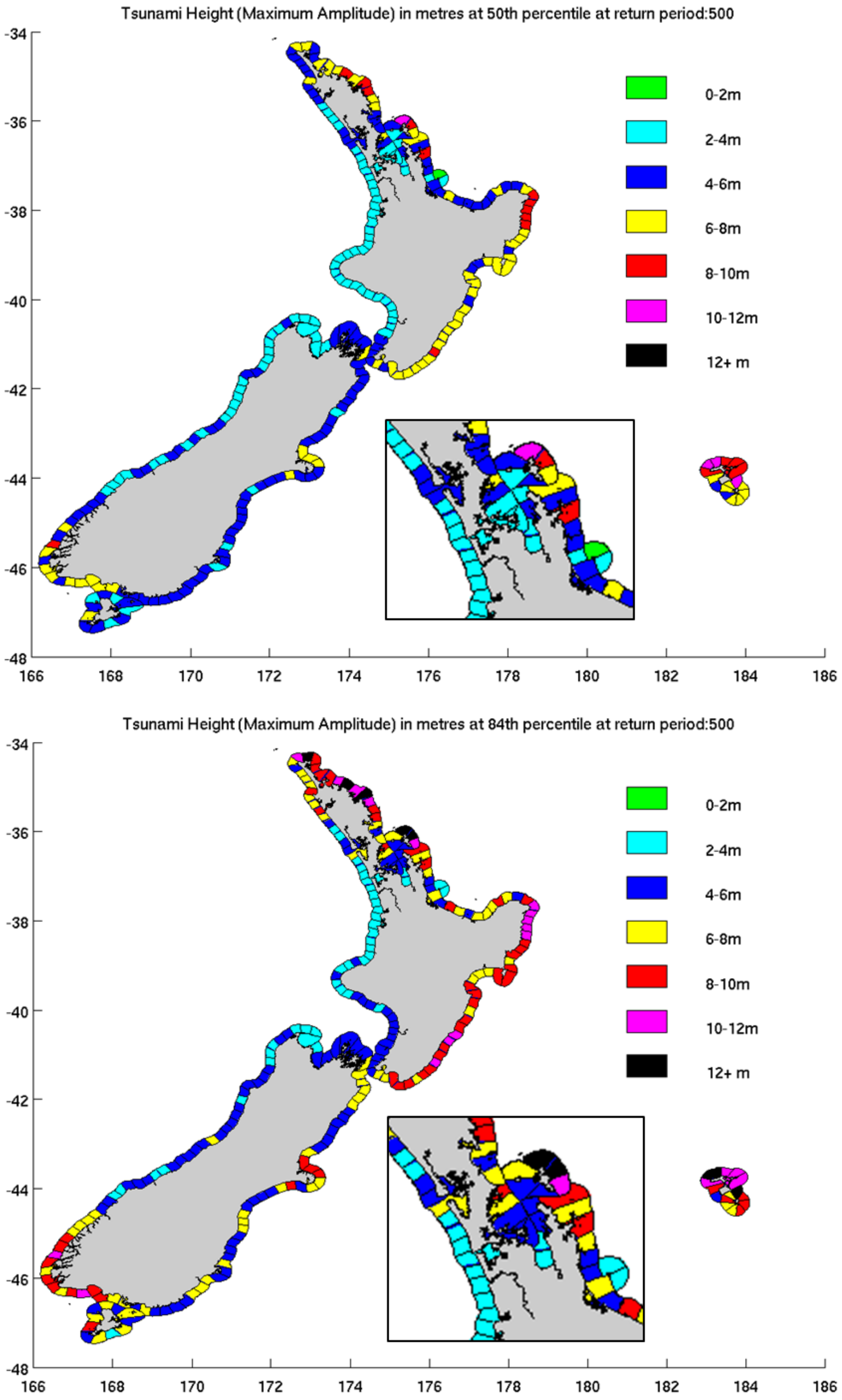


Figure 2 Expected maximum tsunami height in metres at 500 year return period, shown at median (50th percentile) and 84th percentile of epistemic uncertainty. Source: Power (2013).

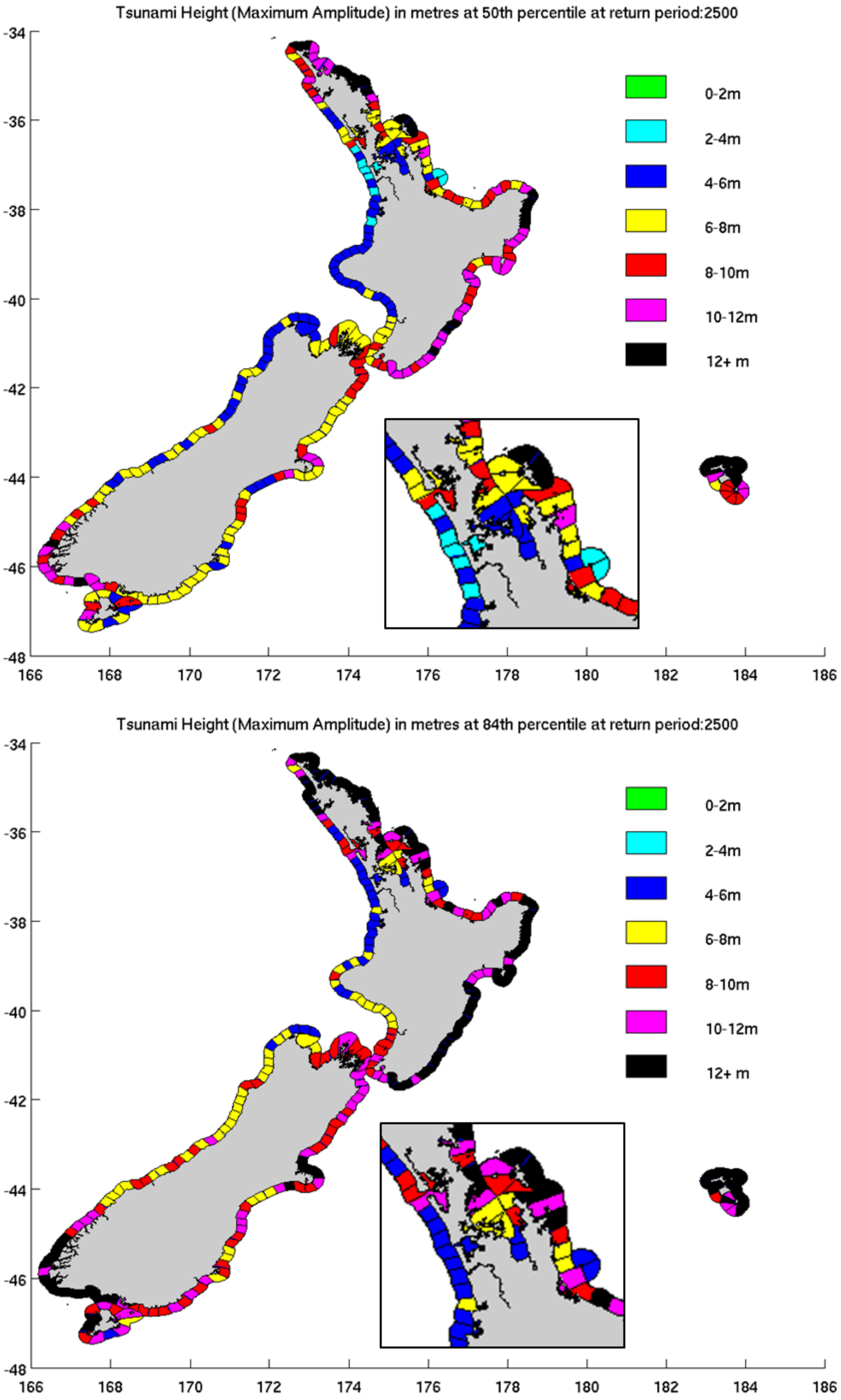


Figure 3 Expected maximum tsunami height in metres at 2500 year return period, shown at median (50th percentile) and 84th percentile of epistemic uncertainty. Source: Power (2013).

3.0 TRANSPORT

Transport networks are one of the most vulnerable lifelines to tsunami because transport routes are often located along coastal areas. However, they are also one of the most important for response and recovery actions. Without access routes, it is difficult for first responders to reach impacted communities and, in the subsequent days, to supply water and food to these communities. Therefore transport is considered a priority lifeline in the aftermath of a tsunami. Lessons learnt from the Great East Japan tsunami in particular can help increase the resilience of transport networks both from a mitigation and a scenario planning perspective, such that key transport routes can be reinstated soon after a tsunami event.

Transport lifelines in Japan, Chile, Indonesia, Thailand, and Samoa were studied in this analysis. Transport lifelines included in the analysis are roads, bridges, rail, airports, ports, and harbours. The majority of the networks have close similarities with those in New Zealand in terms of structure types and type of components, so lessons from their performance in tsunami elsewhere can be transferred to New Zealand. Bridges have been the most studied transport lifelines as they are often high-cost assets and one of the most vulnerable and also easily accessed following an event, followed by roads, ports, and harbours.

3.1 ROADS

Road networks are often located in tsunami inundation zones. This is due to the convenient topography of coastal plains or river flood plains. In New Zealand, some of the key state highways are located in tsunami inundation zones (e.g., SH1 and 2 between Wellington and Lower Hutt, SH1 on the northern side of the Auckland harbour bridge, and SH1 north of Kaikoura). Most roads that were surveyed in the literature were well engineered with compacted bases, which is also typical of New Zealand roads. However, in Thailand and Indonesia, some roads were asphalt laid straight on top of sand. Roads often have co-located lifelines such as buried or overhead pipes and cables which can result in damage to these other services if the road is scoured.

Damage and Failure Modes

Damage to roads consisted of two types; scouring (including peeling of the road surface) and debris damage. Scouring occurred on most roads to some degree and was more pronounced if the road was elevated or located in areas of topographic relief, for example along drainage channels and at the base of slopes (Francis, 2006). Furthermore, if the road base was exposed or constructed of weak material (e.g., sand) then often the road was totally destroyed and washed away (Edwards, 2006). Scouring is a process that often occurs in the receding waves as the water rushes back out (Bell, 2005). Therefore, when considering the scouring hazard to road networks it is important to consider the number of waves that may inundate a road, as this will increase the risk of scouring (Francis, 2006). The severity of scouring is also related to the flow velocity, which is often highest near the coast, along drainage channels and in areas of low surface roughness (Francis, 2006). Therefore roads that are most vulnerable are those located: 1) near the shoreline, 2) adjacent to drainage channels/rivers/culverts, 3) on elevated ridges, and 4) are formed of asphalt laid on a poorly compacted base (Figure 4). Roads that are inundated will also be unpassable due to surface water throughout the duration and immediate aftermath of the tsunami. During the 2015 Chile Tsunami, most major road damage was near the coast and at sites where culverts or pipes intersected the road and these were identified as damage hot spots in the network. Away from the coast, damage was limited to minor peeling or deterioration of the road surface (Horspool et al., 2016).

Using damage data from Miyagi Prefecture in Japan, fragility curves have been developed that show the probability of experiencing road damage as a function of tsunami flow depth. The road construction practices (i.e., engineered road base) and material are considered similar to that of New Zealand, which makes this fragility model applicable in New Zealand.

Figure 4 Upper Left: Peeling off of road surface in Iwate Prefecture (Unjoh, 2012), Upper Right: Scouring of road in Iwate Prefecture (Unjoh, 2012). Lower: Scouring of a raised coastal road and scour pit on the landward side of the road caused by the receding wave. (Horspool et al, 2016).

The MLIT (2012) post-tsunami survey data included spatial information on damaged roads. Roads that were damaged were assigned a damage state according to the degree of damage. This ranged from Damage State 1 (DS1), which consisted of minor damage but the road was still operating, Damage State 2 (DS2) where one lane had been damaged and that lane was impassable, and Damage State 3 (DS3) where the entire carriage way was damaged and the road was impassable. MLIT note that the types of damage most common were peeling off of the road surface or scouring of road base. Using this damage data fragility curves for each damage state were developed (Figure 5). See Appendix 1 for details on how the fragility curves were developed. This is based on data from Miyagi and Iwate prefecture, which were two of the regions that were impacted the most severely.

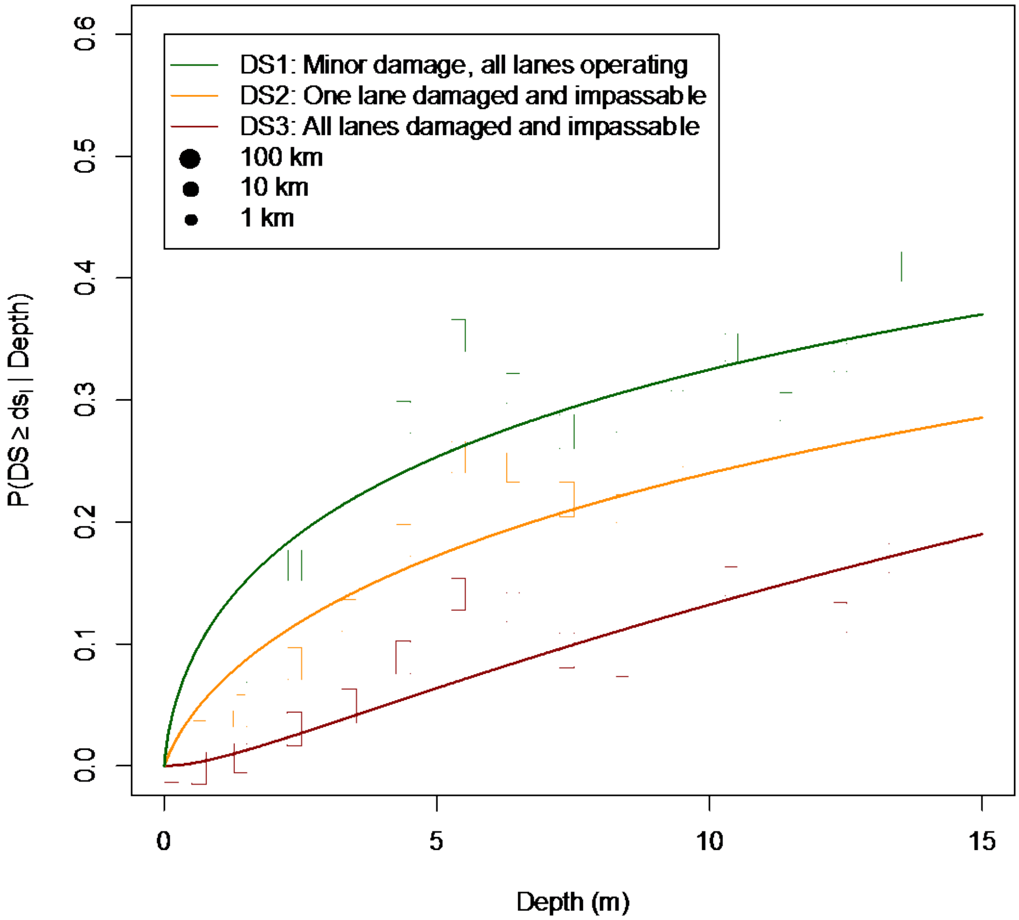


Figure 5 Fragility curve for roads, based on MLIT (2012) data from Miyagi and Iwate Prefecture. Each curve defines the probability of being in that damage state or greater as a function of tsunami inundation depth (m). For example at 5m flow depth there is a 65% probability of no damage, 25% probability of experiencing at least Damage State 1,17% probability of experiencing Damage State 2 or greater, and a 5% probability of experiencing Damage State 3. The size of the data points indicates the length of road at that depth and damage state level in the database. See Appendix 1 for details on how the fragility curves were developed.

The second type of damage to roads from tsunami is from debris. Tsunami are very high energy waves and have the ability to suspend large loads and then deposit these many kilometres from the shoreline (Shoji, 2012). This is evident from some striking photos from recent tsunami events (Figure 6). In most cases damage to roads from debris is superficial, with debris being deposited on the road surface and requiring clean up. This size of debris that can be deposited is related to the flow depth (Evans, 2011) and Table 2 describes the debris type and size that can be expected as a function of tsunami flow depth. Generally, flow depths of greater than 2 m can suspend most objects. At flow depths over 2 m, damage to most types of building increases significantly (Suppers, et al. 2013a; MLIT, 2012), increasing the amount of debris that is being mobilised and deposited, and creating a snowball effect by then causing more damage to other buildings. It was noted in Japan, that in areas of severe inundation (i.e., >2 m), roads often have coincident scouring and disposition (Shoji, 2012). In addition to debris, some areas that are low lying and poorly drained may have ponding of water that can remain for days following a tsunami (Horspool et al., 2016).

Figure 6 Photos of debris on roads in Iwate Prefecture, Japan. Excavators clearing a road (top left), example of debris from destroyed timber frame buildings blocking a main road (top right) (Source: theatlantic.com) and example of ponded water in Coquimbo during that remained for a few days following the 2015 Chile Tsunami (Horspool et al, 2016).

Table 2 Debris type that can be suspended and deposited from tsunami for given flow depths (Source: Evans, 2011).

Flow Depth (m)	Debris Type Suspended and Deposited
< 1 m	Sand, silt and light vegetation
1–2 m	Cobbles, wood, buoyant objects
> 2 m	Large boulders, storage tanks, cars, boats, building debris etc.

Recovery Actions

The response and recovery actions for scouring and debris deposition are quite different but will often apply to coincident stretches of roads (Shoji, 2012). For debris deposition, clearing of debris will be the priority. For small amounts of debris (sand, silt, and vegetation), this can often be done by hand to clear the way for vehicles. However, heavy machinery will be needed when the debris consists of large objects (e.g., boulder, vehicles, etc.) (Ghobarah, 2006; Edwards, 2006). In Japan, pre-existing arrangements between road network managers (the equivalent of New Zealand Transport Agency, NZTA, and local councils) and companies operating heavy machinery helped facilitate a rapid deployment of heavy machinery to clear roadways for first responders and supply trucks (Shoji, 2012; Figure 6 and Figure 7). In some areas of Japan and in other tsunami events (e.g., Indian Ocean tsunami), where recovery plans had not been undertaken prior to the tsunami, there were delays of many days in deploying heaving machinery to clear critical roads (Edwards, 2006; Shoji, 2012). Damage to roads from scouring varied from small holes to entire stretches washed away. For minor damage, holes can be filled with whatever fill is available. In areas where stretches of roads have been washed away, it may take weeks to repair the road. In some instances, four-wheel drive access may be possible for initial access before roads are opened to all traffic (Francis, 2006). During the 2015 Chile tsunami, quick repairs were undertaken on a major local coastal road 1-2 weeks after the tsunami, however the repairs consisted of dumping poorly consolidated sand that was available at the beach to reconstruct the washed-out sections of the road. While a quick fix that enabled the road to be opened 2 weeks after the event, this would need to remediated for a long-term solution.

Figure 7 First responders blocked by debris on roads. Source: telegraph.co.uk

Increasing Resilience

Road networks are critical for response and recovery activities following a tsunami. Therefore they are considered a priority lifeline. There are a number of measures that can be undertaken to increase the resilience of road networks. These include:

- Introducing redundancy into a road network. Multiple access routes to communities increase the chance of having access following an event. It also allows the least damaged route to be prioritised for response;
- Developing rapid response plans. Prearranged contracts with civil engineering or heavy machinery operators will assist in deploying resources immediately after an event. Ideally, these will be located out of inundation zones. Rapid response plans will also identify road routes at risk of tsunami and to prioritise them for damage identification and response;
- Using well-compacted bases. Roads that had well compacted bases with strong material are more resilient to scouring and performed better than those with thin or loose sand bases. Most New Zealand roads have well compacted bases, but roads located in areas that have soils with a high sand content are more at risk;
- Protect coastal roads from scour by installing sea walls, riprap or other measures;
- Carry out tsunami inundation modelling (e.g., Power, 2013) to understand the nature of potential tsunami hazard, and the likelihood of scouring during inundation.

3.2 BRIDGES

Bridges are the weak point in any transportation network during a tsunami event yet they are also critical in ensuring a functioning transportation network for response and recovery following an event (Bell, 2005; Edwards, 2006). Further, bridges often have other lifelines (e.g. telecommunications, water, electricity) attached to them, and if the bridge is damaged or washed away then the service of the dependent lifelines will also be disrupted. Some bridges span waterways and that puts them in direct exposure to tsunami, often in areas that have high flow velocity. There are many post-tsunami surveys that focus on damage to bridges, particularly from the Indian Ocean tsunami and Great East Japan tsunami. Most of the observations and lessons learnt in these events can be applied to New Zealand.

Damage and Failure Modes

Damage to bridges can be classified into three main types:

1. Scouring and erosion of fill around abutments, wing walls and piers (Figure 8);
2. Minor-moderate damage to bridge superstructure, mostly from debris impacts. In such cases the bridge is still standing but the superstructure may have shifted slightly (Figure 9);
3. Complete washout of bridge superstructure (Figure 10).

Many studies noted that scouring and erosion nearly always occurred when a bridge was located in the tsunami inundation zone (Ballantyne, 2006; Evans, 2011; Horspool et al., 2016). Scouring of fill around abutments, wing walls and piers was extremely common. It often occurred during the receding wave when velocities are highest (Bell, 2005). In most cases the bridge was still operational following repairs to fill in the lost material. Bridges that had deep foundations were less susceptible to scouring. In New Zealand, bridges are designed according to their importance level (New Zealand Transport Authority, 2013) and this includes designing for scour due to flood waters, although this may not include the increased scouring risk due to higher velocity flows that occur in tsunami.

When a tsunami reaches the height of the bridge deck and superstructure, the bridge is subject to hydrodynamic (lateral) and buoyancy (vertical) forces (Kosa, 2012). Further, the bridge structure is also exposed to debris impact. These three forces can cause significant damage to the bridge. Hydrodynamic forces affect the substructure and superstructure of the bridge, while buoyancy forces mainly affect the superstructure (i.e., bridge deck).

There is evidence from Banda Aceh in Indonesia and in Japan that flow velocities as low as 3 m/s can cause unseating of a bridge superstructure, although this was noted as occurring in bridges that had poor connections between the piers and superstructure. In most cases, velocities of 6–20 m/s increased the probability of unseating (Iemura, 2005; Kosa, 2012). There were many observations of tsunami heights exceeding bridge deck height by many metres, and the bridge remaining undamaged (Francis, 2006). In Japan and Sumatra it was noted by Kosa (2012) that reinforced concrete bridges performed much better than steel or steel truss bridges as shown in Figure 11 where a higher proportion of steel and steel truss bridges had total washout of the superstructure. However, this data is not correlated with tsunami flow depths so it is difficult to know if all bridges experienced the same tsunami heights.

A general finding from studies in Japan was that bridges that had been seismically strengthened performed much better than those that hadn’t due to little confinement and inadequate development of reinforcement into adjacent members (Yashinsky, 2012). It is unclear if this due to any pre-existing damage to bridges by the earthquake that may have weakened the bridge prior to tsunami strike.

Debris impact mainly caused superficial damage to bridges. For example debris impacts often severely damaged guardrails or any services that were attached to the bridge, but not the bridge structure itself. There were a few cases of large debris strikes in Banda Aceh causing some lateral displacement of a few sections of the bridge deck (Iemura, 2005).

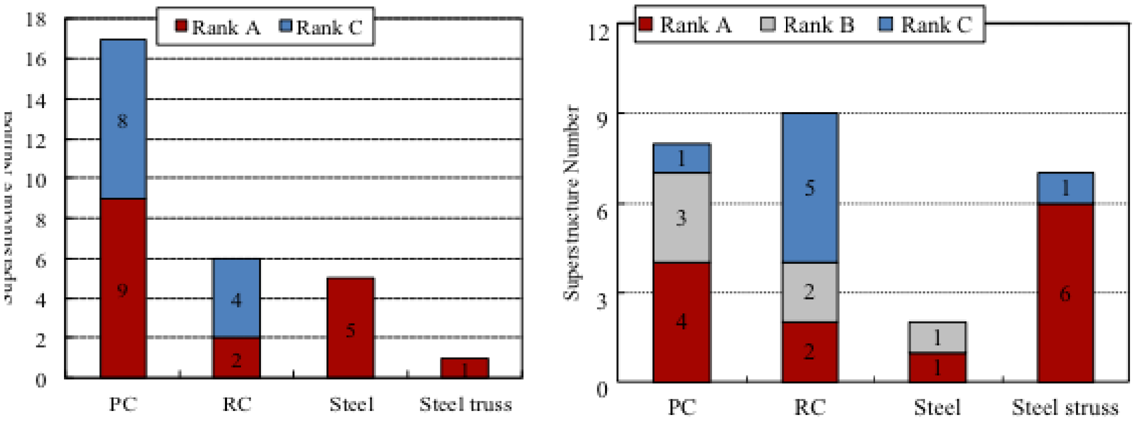
Bridges are also infrastructure that are co-located with other lifelines networks such as water and telecommunications. During the 2015 Chile tsunami, minor erosion of an unprotected abutment caused collapse and failure of a large water main. This required urgent repairs to reinstate the towns water supply (See Section 4).

Figure 8 Bridge in Sumatra, Indonesia located on a river entrance, with complete scouring of one riverbank (right side of photo). Source: Francis, 2006.

Figure 9 Bridge in Japan with minor-moderate damage of the superstructure and some minor scouring in the foreground. Source: Structural Engineers Association of Washington.

Figure 10 Bridge in Japan with complete wash out of the superstructure with only the piers remaining. Source: Structural Engineers Association of Washington.

To develop fragility curves for bridges, data from MLIT (2012) from Miyagi and Iwate Prefectures, as well as data from the 2004 Indian Ocean Tsunami from Indonesia and Sri Lanka (Shoji, 2007) were analysed. The method for developing the fragility curves is described in Appendix 1. Three damage states were assigned to bridge damage data by MLIT (2012) and Shoji (2007); Damage State 1, where the bridge suffered minor but easily repairable damage to the superstructure (e.g. Figure 9), Damage State 2, where the superstructure was heavily damaged and may have moved slightly of its seating, and Damage State 3, where the superstructure was completely washed away (e.g. Figure 10). The fragility curves (Figure 12) from the 2004 Indian Ocean Tsunami, which have information on bridge type, show that reinforced concrete performs better than precast concrete, with steel performing the worst. It can be seen that the probability of experiencing at least Damage State 1 increases dramatically as the flow depth exceeds 1-4 m above the base of the bridge deck, and at flow depths exceeding 6-8 m above the base of the deck, PC and Steel bridges will likely be in Damage State 3 (complete washout) where as RC bridges only have a 25% probability of being in DS3. The data from Japan (Figure 12: Upper Left) has nearly five-times as many bridges as that of the Indian Ocean Tsunami data but does not have information on the bridge type. It can be seen from the upper two panels of Figure 12 that DS2 and DS3 are very similar between these data sets. Where as the probability of being in DS1 is much higher for the RC bridges from the Indian Ocean Tsunami compared to all the bridges in Japan. This could be due to differences in construction practices between Japan and Indonesia and Sri Lanka.



A. Damage in East Japan

B. Damage in Sumatra

Figure 11 Damage data for different bridge types in Japan (A) and Sumatra (B). Rank A is complete destruction of superstructure, Rank B is where the superstructure has moved but not been washed away, and Rank C is minor or no damage. PC = precast concrete, RC=reinforced concrete. Note that this data does not show the damage rank (class) as a function of tsunami flow depths. The numbers on the bars indicate the number of bridges in each damage rank. Note that Rank A = Damage State 3, Rank B = Damage State 2 and Rank C = Damage State 1.

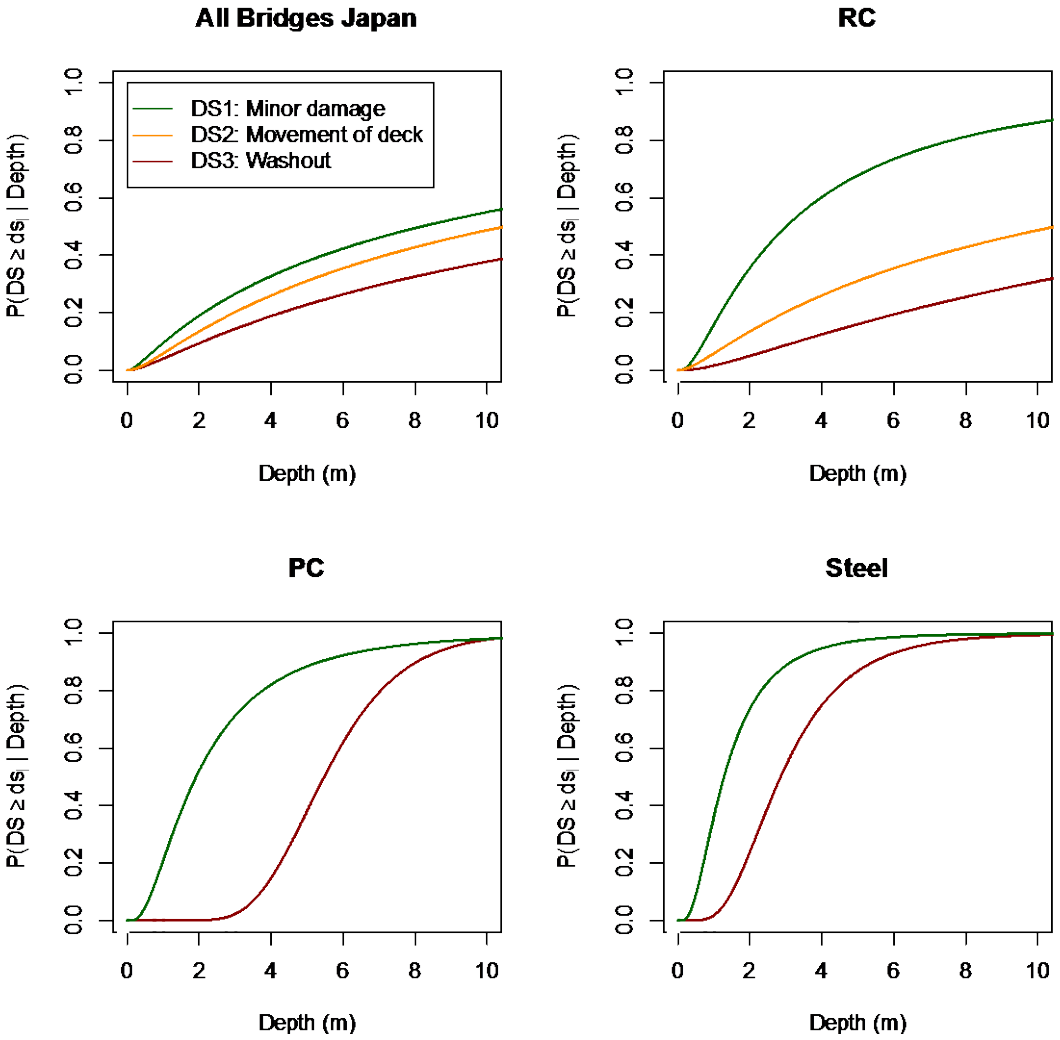


Figure 12 Fragility curve for bridges, based on MLIT (2012) data from the 2011 Japan Tsunami in Miyagi and Iwate Prefectures and the 2004 Indian Ocean Tsunami in Sri Lanka and Indonesia from Shoji (2007). Each curve defines the probability of being in that damage state or greater as a function of tsunami inundation depth (m) above the base of the bridge deck. See Appendix 1 for details on how the fragility curves were developed. Upper Left Panel: All bridge data from the 2011 Japan Tsunami (note the data did not detail bridge construction type), Upper Right Panel: Reinforced Concrete bridge data from the 2004 Indian Ocean Tsunami, Lower Left Panel: Precast Concrete from the 2004 Indian Ocean Tsunami, Lower Right Panel: Steel bridges from the 2004 Indian Ocean Tsunami. Note that for PC and Steel bridges there was not enough data at Damage State 2 to be included in the analysis.

Recovery Actions

In most cases bridge recovery and repair was prioritised depending on their criticality to transport routes. Those that were essential for access to communities were addressed first. For minor damage such as debris covering the bridge or scouring of backfill, the bridge was reopened in hours to a few days once it was stabilised. When the superstructure was significantly damaged or washed away, the most common recovery strategy was to erect a temporary bridge adjacent to the original bridge. There were no reported cases of using the original piers, as these were often considered unstable.

Increasing Resilience

There are a number of measures that can be undertaken to increase the resilience of bridges to tsunami:

- Scouring is the most likely cause of damage in any tsunami and can be reduced by having deep foundations and erecting erosion protection measures around abutments, wing walls and piers. There was also evidence that longer wing walls were less susceptible to scouring (Kosa, 2012). Tsunami have much higher flow velocities than floods, so these will need to exceed the design of flood protection measures;
- Ensure seismic strengthening of the bridge. Bridges that were seismically strengthened often suffered little or no damage from the earthquake and tsunami. This is because seismic and tsunami loads are very similar. It was noted in Japan that if bridges were built slightly higher than code in the vertical direction then this would address the slightly higher vertical loads from buoyancy forces of tsunami. Some design features of note are: to ensure continuity of superstructure as this provides redundancy benefits for vertical and horizontal loading; use monolithic connections which provide resilience to tsunami effects (similar to superstructure continuity); raise superstructure elevation depending on the modelled tsunami hazard; have an aerodynamic profile to reduce hydrodynamic drag; and install strong uplift and longitudinal restrainers;
- Some researchers noted that installing “vents” in the bridge deck will reduce vertical buoyancy forces (CalTrans, 2010) but this approach is also revoked by others (Yashinsky, 2012). Further research is needed on this topic;
- Use reinforced concrete designs rather than steel or steel truss.

3.3 RAIL

Rail networks were significantly impacted during the Indian Ocean tsunami and Great East Japan tsunami. Rail lines often run along coastal plains exposing them to high velocity tsunami flow.

Damage and Failure Modes

Damage to rail networks can be classified into four distinct classes:

1. Damage to rail tracks and ballast (Figure 13) and debris deposited on tracks;
2. Damage to railway bridges;
3. Damage to trains (Figure 14);
4. Damage to overhead lines;
5. Damage to stations and facilities.

During the Great East Japan tsunami, of all the affected components of the rail network, 82% of the damage (by number) was to rail tracks, embankments (ballast), and associated features, and 18% was to stations, facility buildings and electrical and mechanical equipment (Shimamura, 2012). There were 1780 sites of damage Shimamura (2012) along approximately 325 km of track that was located in the inundation zone. This equates to a site of damage on average every 190m of track.

The most vulnerable components of a rail network to tsunami are the tracks and ballast. These may be located on elevated ridges made of coarse gravel (ballast) and sometimes sand, which are prone to scouring. If tsunami flow depth exceeds the ballast height, then there will likely be extensive scouring which leaves the tracks susceptible to total washout (Francis, 2006). In Coquimbo, Chile during the 2015 tsunami, a coastal rail track was moved laterally in flow depths less than 1m and as the depths approached 2 m and greater it was washed out (Figure 13, Horspool et al., 2016). At tsunami heights lower than the ballast, then minor scouring may occur in areas of focused flow (Figure 13). In areas of low flow depths, rail embankments were shown to have a mitigating impact on damage by restricting flow and blocking floating debris (EEFIT, 2011). Damage also occurred to many rail bridges in the Great East Japan and Indian Ocean tsunami. Refer to Section 3.2 for information on bridge damage.

Figure 13 Scouring of rail ballast in Ofunato City, Japan, 2011 (Source: S. Fraser), and lateral movement and washout of a track in Coquimbo, Chile during the 2015 Tsunami (Horspool et al., 2016).

There is limited amount of information on damage to overhead lines, but it is expected that the poles could be washed away, similar to that of overhead power lines, in flow depths of 1–2 m, due to scouring of the base of the pole or from debris strikes. If the tsunami height reaches the overhead lines or other auxiliary electrical equipment, then it will likely short.

Shimamura (2012) used detailed observations of the floating behaviour of trains during the 2011 Great East Japan tsunami and determined that trains began floating when inundation depth reached ~1.7 m. Further, Shimamura (2012) also deduced that when the inundation depths dropped to ~1.1 m the trains no longer floated and fell out of suspension. In some instances, trains floated hundreds of metres from their original location (Figure 14). This analysis does not consider the tsunami flow velocity which will likely control where the train is deposited and high velocities would most likely decrease the depth at which the train is suspended. This type of information can also be used to assess the risk to human life when a passenger train is struck by a tsunami.

Figure 14 A train that has been suspended and carried ~200 m from its original location at a station in the Great East Japan tsunami (Shimamura, 2012).

Widespread damage to stations was also observed in Japan. These were typically local stations made of masonry or reinforced concrete. Generic building fragility curves, such as those developed by Suppasri, et al. (2013b) and presented in Section 5.2 can therefore be used to model the vulnerability of these facility buildings. In addition to damage to the station or facility buildings, platforms were damaged, and electrical and mechanical equipment was often totally destroyed if it was located in the inundation zone.

Recovery Actions

Recovery of the rail network was a priority for JR East, the company that runs most of the network in the affected areas. They focussed first on reinstating the Shinkansen fast trains, which were located outside of the tsunami inundation zones. They then focussed on the regional networks by prioritising areas with the least damage or the most important transport routes (especially since travel by rail is a popular mode in Japan). While this is not relevant for New Zealand, it highlights that JR East prioritised reinstating their major intercity networks to allow people and goods to flow between unaffected and affected regions. This speeds up recovery as relief supplies and spare parts and heavy machinery could be dispatched to the impacted areas quicker and in larger volumes than by road alone.

Recovery of railway services in New Zealand would require likely removal of debris from tracks, excavation and relaying of ballast and tracks, repair of bridges, and reinstatement of overhead lines and associated electrical equipment. In relaying track, new drainage systems, track level and grade may have to be established following scour and/or co-seismic subsidence. Recovery and replacement of stranded/damaged engines and rail carriages is likely to be required. At railway lines running along the shoreline, reinstatement of coastal protection would be required to protect ballast from further erosion. These recovery actions will require large amounts of spare parts. If these are located at the rail yards in tsunami inundation zones then they will also be damaged and unusable. Therefore it is important to stockpile spare parts outside of the tsunami inundation zone, or have plans to bring spare parts in from unaffected areas. However, the latter approach will be reliant on other transportation networks, which may also be affected.

Increasing Resilience

In Japan the first priority for the rail network is the safety of passengers. All trains are fitted with tsunami alert systems that notify the driver of a tsunami. Following an alert the train is stopped and passengers disembark and evacuate to higher ground (or the nearest vertical evacuation structure). While many trains were washed away by the tsunami it appears there were few fatalities of train passengers. The alerting system is obviously critical to ensure rapid evacuation of train passengers when a tsunami warning occurs.

In addition to a focus on life safety through an alerting system the following actions can be taken to increase the resilience of the rail network:

- Strengthen rail bridges as described in Section 3.2;
- Have tsunami evacuation plans and routes inland or to high ground for passengers and crew. At present in New Zealand, evacuation should be based on natural warnings for a local tsunami and official warnings for a distant tsunami. Train drivers should be trained to know what to do in the event of a tsunami and where to evacuate a train at points along the route;
- Have machinery available and spare electrical equipment stockpiled to facilitate rapid repairs of the network.

3.4 AIRPORTS

The Indian Ocean and Great East Japan tsunami both inundated airports. In Thailand, the Phuket airport, a major regional hub was inundated with flow depths of 0.5–1 m. In Japan, the Sendai Airport, located only a few hundred metres from the coast was inundated with flow depths of 4–5 m. All of these examples provide excellent examples of damage expected to airports during small to large tsunami events.

Damage and Failure Modes

In Thailand, the Phuket airport was inundated with low flow depths, on the order of 0.5–1 m (Bell, 2005). A coastal seawall helped protect the airport from more inundation than was actually observed. The water flooded parts of the runway and caused damage to the runway lighting system. No other damage was observed and the airport was reopened later that day.

The Sendai Airport in Miyagi Prefecture suffered more extensive damage to due tsunami with flow depths of 4–5 m. The tsunami initially came as a thin layer with a depth of <1 m, and within minutes was a fast flowing torrent that increased to its peak of 4–5 m within 5–10 minutes (Figure 15). This caused inundation up to the second level of the passenger terminal. All operations were immediately stopped following the earthquake and passengers and staff were evacuated to the upper levels (2–4) of the passenger terminal, which was of sufficient height. The tsunami inundated the whole airport facility (Figure 15) and left a large amount of debris (silt, sand, vehicles and wood) on the runway. The damage to the terminal structural components was superficial and minor, however the water damaged and destroyed all electrical equipment and machinery that was located below level 2 (Suppasri and Mas, 2013). For fragility curves of terminal buildings, see reinforced concrete fragility curves in Section 5.2.

Figure 15 The first wave of the tsunami inundating the Sendai Airport. Note the large amount of debris being carried through the car park. Source: telegraph.co.uk

Figure 16 Sendai Airport when inundated by the tsunami. This is taken near the peak tsunami height (4–5 m). Source: Reuters.

No large planes were on the tarmac at the time of the earthquake and tsunami (EEFIT, 2011). Sendai is a regional airport with six air-bridges (Figure 16). If planes had been present they could have acted as large flotsam and caused significant impact damage to the terminal or adjacent buildings. They could also have been suspended and deposited somewhere else on the tarmac or runway and since they would likely suffer damage, heavy machinery would be needed to remove them to open access to the runway.

Recovery Actions

In the Great East Japan tsunami, recovery took place as follows. Five days after the tsunami, the Japanese Self-Defence Force, with assistance from the US Military (who parachuted into Sendai Airport), removed enough debris from the runway to allow a C-130 Hercules to land. This brought in extra supplies, such as water-pumps to help drain the rest of the water from the runway. Nine days after the tsunami the airport was open as a transit site for relief and recovery supplies. The airport was reopened to commercial air traffic on the 13th April 2011, over one month after the tsunami. The airport passenger terminal also served as an evacuee shelter for the first 3 days following the tsunami.

Recovery actions for New Zealand airports, if damaged in a similar manner, will likely take a similar period of time (1–2 weeks) for first operations, and 2–6 weeks for reinstatement of commercial operations. However this does depends on the damage to the runway, terminal building and other equipment. While no large aircraft were at Sendai Airport during the tsunami, some New Zealand airports are much busier, and if aircraft are floated and mobilised by the tsunami it may take longer to reopen the runway if the damaged aircraft need to be moved by heavy machinery.

Increasing Resilience

Airports are critical lifelines for the transport of supplies to an affected area. For cities such as Wellington that may be isolated during a large earthquake and tsunami due to vulnerable roads in and out of the city, the airport may provide a key transport node. The recovery phase will likely be two staged. The first priority will be to clear the runway of debris to allow aircraft with emergency supplies to land, and repair the runway in case of scouring or earthquake-induced damage to the surface. This will be the focus for the first 7 days in a large tsunami (or first day in a small tsunami). The second stage will be to reinstate commercial flights. In a larger tsunami this will require repairs/replacement to key electrical equipment or machinery, as well as repairs to the terminal and air bridges if they suffered damage. The impacts on airports by tsunami in Thailand and Japan indicate that the main way to increase the resilience of an airport is through recovery planning by;

- Developing a plan to get immediate access to heavy machinery to clear debris from the runway. This will be the priority to allow aircraft to land. For small tsunami that may inundate an airport with flow depths of less than 1 m, clean up will be quick and may be able to be done by hand. However, for higher flow depths that may deposit large debris then reinstatement times will increase.
- Having quick access to spare electrical parts or machinery needed for reinstatement of general airport operations through stockpiles located inside or outside of tsunami affected areas.

3.5 PORTS AND HARBOURS

Port and harbours are inherently at risk from tsunami due to their coastal location. They are also one of the few lifelines that are vulnerable to non-inundating tsunami due to the potential impact of severe currents.

Damage and Failure Modes

Damage in ports and harbours from tsunami can be summarised as:

1. Damage to wharfs from buoyancy and/or hydrodynamic forces;
2. Scouring of piers and breakwaters;
3. Damage to structures, including wharfs and port buildings, from debris strikes;
4. Damage to vessels.

Damage to ports and harbours can occur in all tsunami, regardless of whether a significant tsunami height is experienced, or not, and whether the tsunami is from a local or distant source. Tsunami can have high velocity flow and often create eddies (circular currents) in harbours and ports where narrow entrances and shallow channels constrict tsunami flow (Admire et al., 2014; Wilson et al., 2013). There are ample observations of strong currents from tsunami even thousands of kilometres away from the source. The Indian Ocean tsunami caused significant damage in ports around the Indian Ocean due to strong currents, even though the tsunami heights were less than 1 m in many places (PIANC, 2009). There was strong tidal response in harbours and ports in New Zealand following the 2010 Chile tsunami however, no damaged was reported (Borrero and Greer, 2013). Crescent City, California has sustained damage to wharfs and vessels in several recent tsunami (Wilson et al., 2013). As yet, there are relatively few detailed analyses of tsunami currents in harbours, but Lynett et al. (2014) have developed a relationship between current speed and damage level based on recorded and simulated currents.

Due to the high currents, damage to the wharf substructure can occur from scouring of the seabed, including material around wharfs and piers (e.g., Lekkas, 2011; Figure 17). This can weaken the piers and in extreme cases cause collapse of wharf structures. This is difficult to observe and generally requires divers to survey any damage. Scour combined with hydrodynamic and hydrostatic forces caused collapse of substantial breakwaters and sea walls in Kamaishi and Ofunato, Japan, scattering caissons in the harbours (Takahashi, 2011). Aligned with scour and erosion of sediment, tsunami can also deposit significant volumes of sediment in ports and navigation channels (Takahashi et al., 2011; R. Wilson, Davenport & Jaffe, 2012).

Many reinforced concrete wharf decks were washed away or damaged during the Indian Ocean tsunami due to poor connections between the deck and piers (Figure 20). This was often caused by high vertical buoyancy forces when the tsunami height was greater than that of the deck. This also occurred in the Great East Japan tsunami, but to a lesser degree due to better design and seismic strengthening of wharfs (Tomita, 2012). During the Great East Japan tsunami, tsunami heights at the main ports along the coast ranged from 5–10 m (PARI, 2011) and caused significant damage to both the wharfs and port facilities (warehouses and tanks). In the 2015 Chile tsunami, reclaimed areas of the Coquimbo fishing wharf where concrete panels were placed on compacted dirt were washed away in tsunami of 4 m flow depth (Horspool et al, 2016). Wharfs are generally not designed for resisting large lateral loads and debris strikes can cause significant damage. Once a vessel has broken from its moorings it will be uncontrollable and then turns into debris that can strike wharfs and other vessels. Further, if a tsunami is large enough and causes inundation, the debris field increases in density as it picks up debris from damage structures or other material. When the wave withdraws the debris can flow back through the port and harbour causing further damage. During the Great East Japan tsunami thousands of containers were picked up by the tsunami from container ports and entrained in the debris field (Figure 19 and Takahashi et al., 2011) and this was also observed at the Coquimbo port during the 2015 Chile tsunami (Horspool, et al, 2016). Containers can then become water-borne debris, causing further damage (Ko, Cox, Riggs & Naito, 2014). Once containers are mobilised, their contents will likely be dislodged and may move inside the container, which may cause significant damage to the contents. If there are dangerous goods inside the container, then mobilisation of containers could be a source of fire, explosion or pollution.

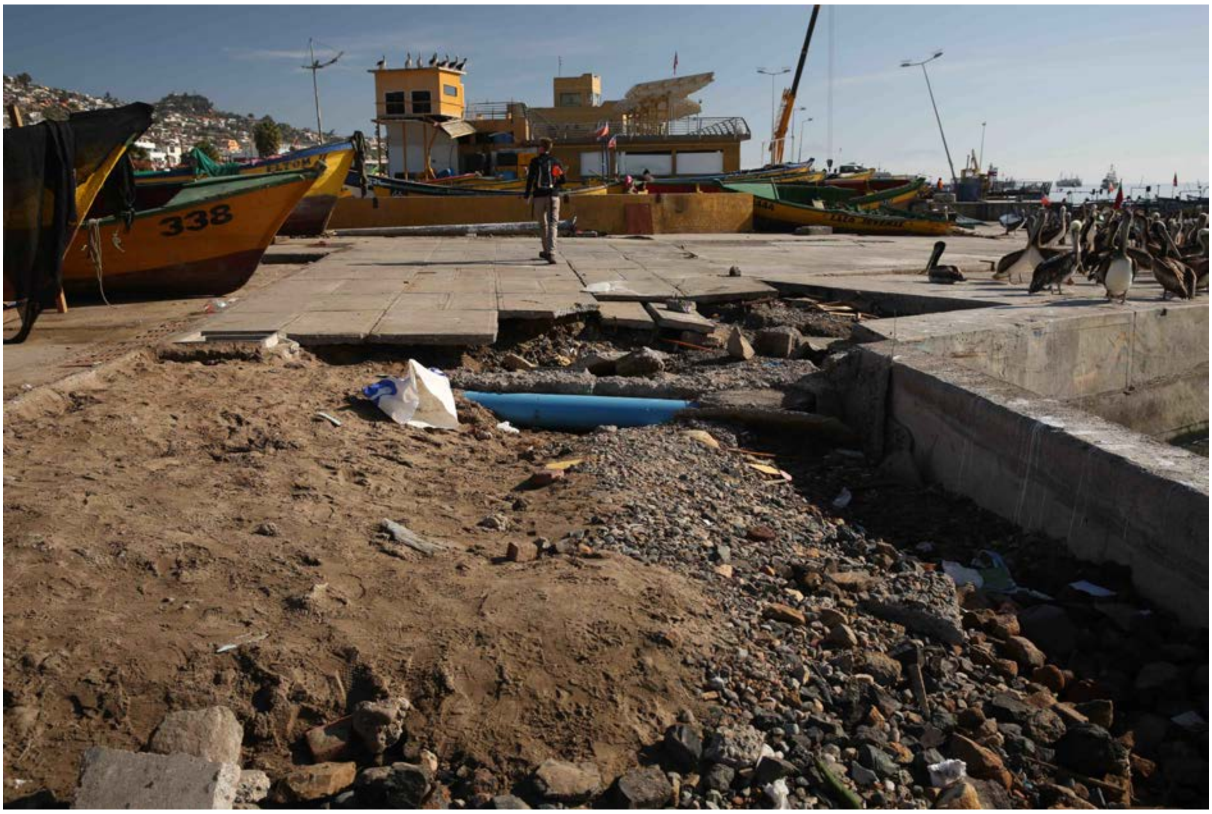


Figure 17 Bottom: scour, and collapsed reinforced concrete columns of the wharf and associated buildings at Yuriage, Miyagi, Japan, in the Great East Japan tsunami. Source: S. Fraser. Top: washout of some untied concrete tiles at Coquimbo wharf in the 2015 Chile tsunami (Horspool, et al., 2016).

In local-source tsunami, co-seismic subsidence may leave wharfs at a lower elevation than prior to the tsunami, resulting in the wharf being submerged entirely or subjecting it to repeated flooding at high tide. This was the case in a number of cities in Japan, e.g., Onagawa, Ishinomaki, Kamaishi, and Ofunato, in 2011, where 0.5–1.2 m of subsidence resulted in wharfs and developed areas being flooded (EEFIT, 2011; Figure 18).

In high velocity flows vessels can break from their moorings and become uncontrollable (PIANC, 2009). Large ships were stranded many hundreds of metres inland in Japan, potentially destroying structures in their path, with some coming to rest on the top of buildings, and causing oil spillage (Takahashi, 2011). Figure 21 shows an example of destruction of gantry cranes and wharf structures from a debris strike by a large vessel. However, there is little information on what tsunami flow depth would shift gantry cranes off their rails. During the 2015 Chile tsunami, there was no damage to medium sized gantry cranes at Coquimbo port which had tsunami flow depths of 3 – 4 m (Horspool, et al., 2016). Even smaller boats can cause significant damage to lighter steel and timber structures. In Miyako City, Japan in 2011, fishermen reported evacuating the harbour in their boats to mitigate damage to their fleet (Fraser et al., 2012). A group of boats gathered in deep water overnight as they could not return immediately to shore through the debris field, but many boats were not equipped to cope with winter weather conditions at sea. It was reported that many other boats were still trying to leave the harbour when strong currents arrived (Fraser et al., 2012).

Figure 18 Subsidence reduced ground elevation, resulting flooding land in Onagawa, Japan. Taken six months after the Great East Japan tsunami, new roads have been constructed at a higher elevation. Source: S. Fraser and G.S. Leonard.

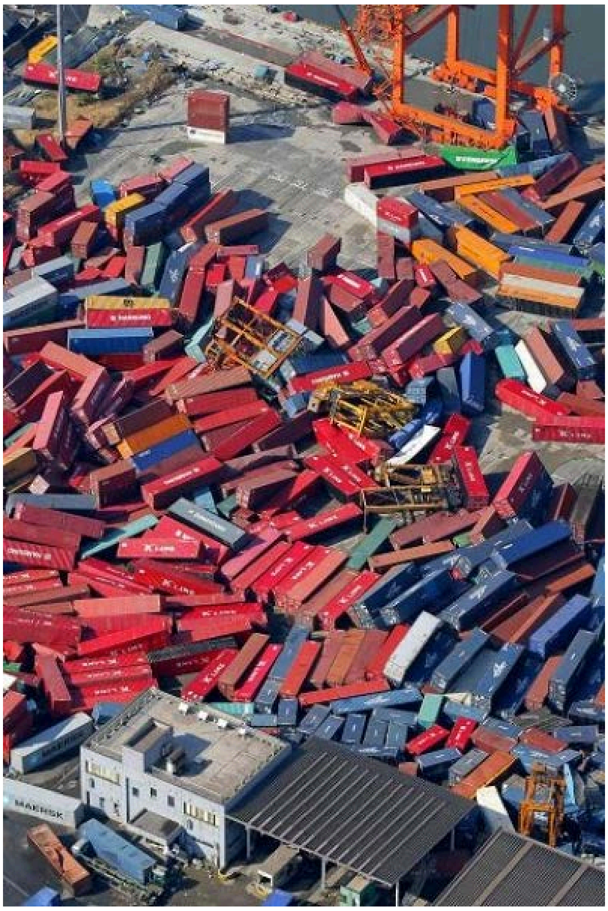


Figure 19 Containers lifted and transported by the tsunami in Japan. Source: PARI, 2012.

Figure 20 Damage to a wharf deck in Thailand from vertical buoyancy forces. Source: PARI, 2009.

Figure 21 Example of damage to a gantry crane from debris strike by a large ship. Source: S. Fraser, 2011.

Recovery Actions

Response and recovery actions at ports and harbours involves repair of wharfs and breakwaters, and clean up of debris to allow the port service to recommence. This may be important in some locations such as Wellington, where roads may be unpassable and emergency supplies and crews may need to be brought in by boat. However, strong currents may continue in ports and harbours for several days, potentially delaying emergency response, debris clearance, return of vessels at sea, or assessment and repair of damaged wharfs.

Due to subsidence, wharfs may require rebuilding at a higher elevation to prevent repeated flooding. Salvage or break-up of boats and ships deposited onshore will be required, in addition to salvage of large debris (e.g., breakwater caissons, shipping containers or vessels) sunk in the harbour and shipping channels. Due to potential sediment deposition in the port and shipping channels, in some cases dredging may be required to remove excess sediment and facilitate access for large ships. There may also be a requirement for extensive replacement or repair of vessels.

Increasing Resilience

There are two main actions that can be taken to increase the resilience to tsunami for ports and harbours:

- Develop appropriate response plans if a tsunami warning occurs (natural or official). This may involve moving some vessels to deeper water to reduce the risk of being broken from moorings and striking the wharfs. In some cases in Japan, this actually occurred as the first wave arrived. Modelling indicates that evacuating harbours by taking vessels to a water depth of approximately 55 m or greater may be sufficient to mitigate damage to vessels (Lynett et al., 2014). Evacuation of this sort may only be possible in regional and distant-source tsunami, where a period of several hours is available before strong currents occur;
- Designing wharf structures to withstand tsunami forces. This would be similar to seismic design but have a higher design load for vertical buoyancy forces. It is thought that designing for debris impact of a large vessel is not practically reasonable for a wharf. However, “bumpers” could be installed to reduce the forces (Eskijan, 2012).

4.0 WATER SYSTEMS

Water systems consist of two key elements; the pipe network and the accompanying facilities. Pipe networks are normally buried services with varying pipe types, backfill and burial depths. Pipe networks commonly cross waterways along bridges. Facilities are structures such as pump stations, in/out-takes, treatment plants and tanks and pools that are used to process and pump the water.

Two main types of water systems were considered for analysis based on available information and they are potable (drinking) water, and wastewater and stormwater.

4.1 POTABLE WATER

Damage and Failure Modes

In general, buried pipes for potable water supply performed well in most recent tsunami. Often scouring exposed pipes but there was often little damage even when the pipe was covered with heavy debris (Bell, 2005; Strand, 2005; Edwards, 2006; Miyajima, 2012). Takada et al. (2010) suggested buried water pipes up to 200 m from the shore were destroyed by debris strike in Nam Kem, Thailand in 2004, but noted that damage was also caused after the tsunami by excavators, confusing the picture somewhat. A key point of weakness in pipe networks is when they are above ground. This typically occurs when a pipe section crosses a waterway and the pipe either spans the waterway in isolation, supported by piers if the span is wide, or the pipe is attached to the side or underside of a bridge for support. Most pipe network failures in tsunami occurred at these locations (Bell, 2005; Strand, 2005; Edwards, 2006; Scawthorn et al., 2006; Miyajima, 2012). The water supply network also suffered damage at entry points into homes, including damage to household water meters (Takada et al., 2010).

In regard to pipe construction material, observations were recorded to pipes made of plastic (HDPE and PVC), and steel. In most cases pipes that had been seismically strengthened (usually made of HDPE and steel) were the best performing pipes, as they were flexible enough to move once the surrounding material had been scoured. Note that most buried pipe damage documented in the post-tsunami surveys was from prior damage due to liquefaction. There is no mention of how different backfill material influences the vulnerability of pipes in any of the surveys, however it can be assumed that material less resistant to scour will be the most resilient.

During the 2015 Chile tsunami, a water main servicing Coquimbo was severed where it crossed a low-lying reinforced concrete bridge at the coast. The bridge superstructure was undamaged, but there was significant erosion of the unprotected abutment, which resulted in a pipe node collapsing into the estuary and severing the steel/HDPC pipe (Figure 22). The tsunami was only about 2-3 m in height at this site. Furthermore, along the same stretch of pipe, there was severe scouring which caused the pipe to float to the surface, which required temporary remedial action (piles of sand dumped on the pipe) to hold down it down as it was gravity fed (Horspool et al., 2016).

During the Samoa, 2009 tsunami there were observations of floatation of small above ground concrete storage tanks (S. Fraser, pers. Comm.) in flow depths of a few metres. It is expected that polyethylene tanks, common in residential properties in New Zealand, would float at lower flow depths than concrete. The threshold of floatation will depend on how full the tank is, with tanks with lower water levels being more susceptible to floatation. New Zealand has many large concrete water reservoirs. These will likely be susceptible to floatation particularly if they are below half full. However, most of these are located in elevated areas and therefore outside of tsunami inundation zones.

Figure 22 Top: Severed water main where it crosses a bridge in Coquimbo, Chile caused by erosion of the abutment. Bottom: severe scouring that exposed the same water main and caused it to float to the surface. (Horspool et al, 2016).

Potable piped water services were significantly affected by the Great East Japan tsunami. In the first week, 2.2 million people did not have piped water, this dropped to 1.2 million after two weeks, and 0.6 million by the third week. This is due to a combination of earthquake damage to large transmission water pipes, and tsunami damage to local water facilities.

At the time of the Indian Ocean tsunami in Thailand, India, and Indonesia, many communities relied on artesian wells for water supplies. In nearly all cases, if a well was located within the inundation zone the well became contaminated with salt water (Tang et al., 2006; Edwards, 2006), and required pumping to restore the fresh water supply (Ballantyne, 2006). In some cases, large areas of the aquifer were severely affected as well due to dense salt water displacing the fresh water. This caused significant disruption to water supplies and in the immediate aftermath, drinking water was supplied by truck (Strand, 2005).

While there is little information available on the description of damage to potable water facilities, MLIT (2012) collected damage data of water treatment facilities (Figure 23), which highlight that potable water facilities are likely to be vulnerable to tsunami flooding. While there is no information on buildings that were undamaged or on facility construction type, it can be seen in Figure 23 that even at low inundation depths (i.e., < 2 m) significant damage can occur. Damage level 1 is mainly due to submersion of electrical and mechanical equipment, which can occur at low inundation levels, and can be costly to repair.

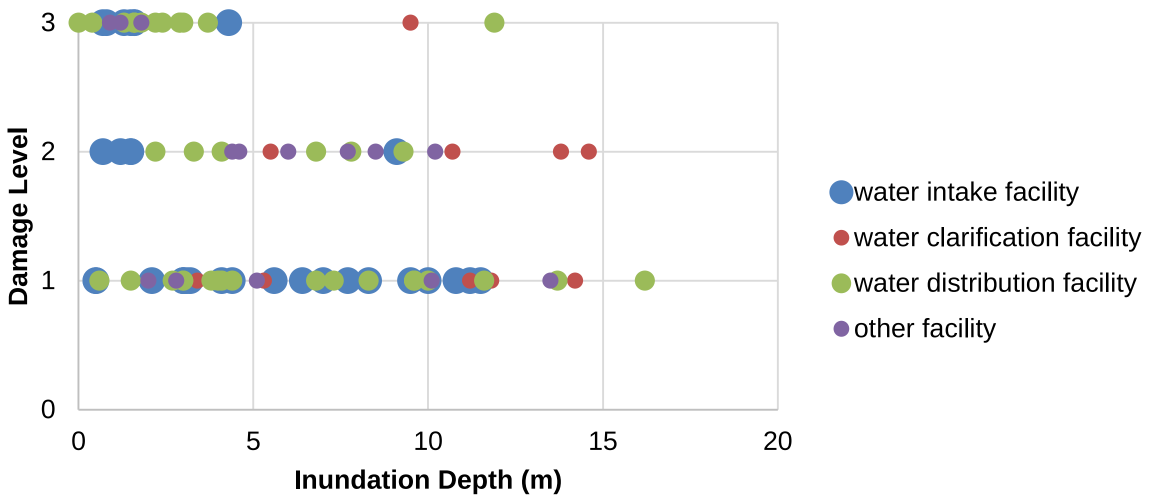


Figure 23 Damage level as a function of inundation flow depth (m) for various potable water facilities where damage level 3 is severe/extensive damage, level 2 is moderate damage, and damage level 1 is minor damage. Note that severe damage states can be reached in relatively shallow inundation depths (< 2m). Data source: MLIT (2012).

For fragility curves of some facility buildings, see the fragility curves of Suppasri (2013a) presented in Section 5.2.

Recovery Actions

The first response in Japan was to reinstate a drinking water service to affected areas. Due to the extensive damage, this was accomplished by shipping in drinking water with trucks from regions outside the affected areas. The water authorities dispatched 300 water trucks to areas with no service. The aim was to deliver 3L/per person/per day for first 3 days, then 20L/pp./pd. until 10 days, then 100L/pp./pd. until 21 days after the event (Miyajima, 2012).

In cases where pipes were destroyed where they crossed waterways, the following are two possible recovery actions. The first is to lay a new pipe with its own temporary support. The second option is to wait until a temporary bridge is erected (if any) and to then attach the new pipe to the bridge. The water service provider can undertake the first option, as long as they have equipment available to do this. The second option relies on road network managers.

Contaminated wells were either abandoned, or in some cases pumps were used to attempt to pump out the salt water, which is a time consuming process (Strand, 2005).

Increasing Resilience

The following actions can be taken to increase the resilience of potable water systems to tsunami:

- Where possible, locate water supply and treatment facilities outside of tsunami inundation zones;
- Construct facility buildings using reinforced concrete and either ensure areas containing power systems are watertight, or locate electrical equipment at height to minimise damage to key electrical components;
- Install sealed lids on pumps and tanks to stop contamination by saltwater, sediment, and debris;
- Bury pipes across water crossings or attach to earthquake strengthened reinforced concrete bridges, preferably with protection buffers to reduce damage from debris impacts;
- Replace old pipes with more seismic resilient pipes (e.g., HDPE) to increase the resilience, particularly if the pipe is vulnerable to scouring;
- Maintain a supply of spare parts outside tsunami inundation areas;
- Ensuring water wellheads are watertight to prevent surface salt water entering drinking water wells.

4.2 WASTEWATER / STORMWATER

Damage and Failure Modes

The performance of the wastewater pipe network in recent tsunami was similar to that of the potable water supply, due to its similar structure and placement (Section 4.1). In addition to minor pipe damage, most of the impact to wastewater systems was confined to intakes/outtakes and treatment facilities. Damage was caused either by wave force or submersion. Wave forces often destroyed buildings or facilities, while submersion caused contamination to, or damage, to electrical circuits. In Thailand during the Indian Ocean tsunami, a wastewater treatment plant was inundated with small flow depths (tens of centimetres), which caused salt-water infiltration into the pumps and filters, resulting in malfunction. The salt water also inundated treatment ponds, killing bacteria used in for treating sewerage. In this case, the operation of the treatment plant was disrupted for a few months as a result of the damage and contamination (Edwards, 2006; Bell, 2006). At another treatment plant in Thailand that had higher inundation levels (1–2 m flow depth) the main damage was to the electrical circuits (Edwards, 2006). These were shorted and needed replacement, however spare parts were in short supply and resulted in the plant being out of operation for many months.

During the 2015 Chile tsunami a pump station located 200 m from the coast was inundated by flow depths of around 3 m and suffered complete damage. The structure housing the pump, all electrical equipment and most mechanical equipment was destroyed. The only remaining mechanical components were some of the in-ground filters (Figure 24). The pump station was reinstated to 80% capacity within 2 weeks, which required new parts to be shipped in and a mobile generator on site (Horspool et al, 2016).

Figure 24 Pump station near Coquimbo port that was inundated by a tsunami with a flow depth of ~3 m. This destroyed most of the pump station with only in-ground filters surviving semi intact (Horspool et al., 2016).

Damage to electrical circuitry also occurred in many pump stations in the inundation zone in the 2011 Great East Japan tsunami, where the size of the tsunami meant that most wastewater facilities were totally destroyed. MLIT (2012) collected information on water facility buildings (Figure 25) and this has been converted into a fragility function for facility buildings. The data generally did not have information on non-damaged buildings in the inundation zone so there is the problem of under-coverage of the data, nevertheless, a fragility curves for extensive-complete damage was derived (Figure 26). Most of the facility buildings were constructed with masonry or concrete block, or concrete tilt slab. As shown in Figure 26, once the flow depth exceeds ~5 m, there is a high probability of extensive or complete damage. For information on fragilities of generic reinforced concrete or timber framed buildings, refer to Section 5.2.

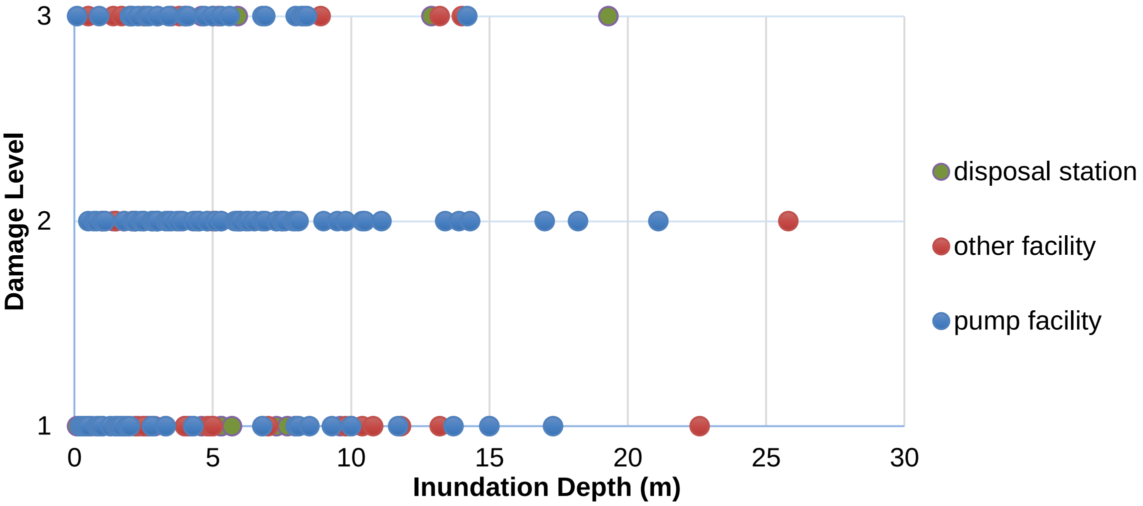


Figure 25 Damage level as a function of inundation flow depth (m) for various wastewater facilities where damage level 3 is the severe/extensive damage, level 2 is moderate damage, and damage level 1 is minor damage. Data source: MLIT.

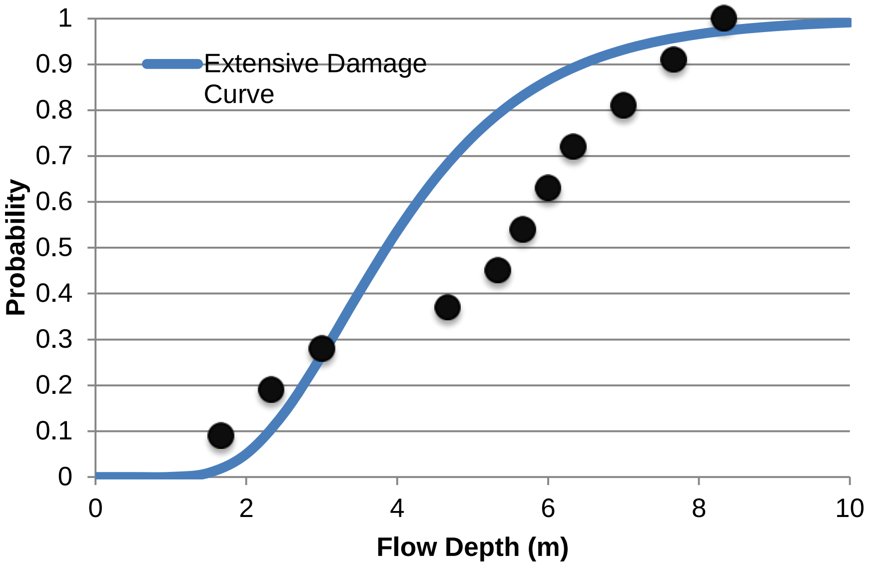


Figure 26 Fragility curve for extensive-complete damage state for generic wastewater facility buildings (mostly reinforced concrete). This fitted curve (blue line) shows the probability of being in the extensive-complete damage state as a function of tsunami flow depth (m). The black circles are observed data from the Great East Japan tsunami. Data source: MLIT.

Damage to stormwater assets was observed during the 2015 Chile tsunami. During this event most drains in the inundation zone were blocked with fine silt, sand and debris which also caused blockages of the stormwater pipe network (Figure 27). The drains were cleared out by hand which gave access to the pipes which were then flushed out (Horspool et al., 2016). If not cleared, blockage of the stormwater network could lead to flooding if heavy rain occurred in the days after the event. Many stormwater culverts and outfalls were damaged near the coast during this event. Damage mainly consisted of scouring and erosion around the concrete casing (Figure 27) or blockages due to debris (Horspool et al., 2016).

Figure 27 Left: Stormwater drain blocked by silt and sand in Coquimbo, Chile during the 2015 Chile tsunami. Right: Culvert/outfall at the coast in Coquimbo that was eroded during the 2015 Chile tsunami (Horspool et al., 2016).

Recovery Actions

In Thailand, the waste water systems were operational very quickly after the tsunami in most cases. This was due to most of the key facilities (i.e., treatment plants) being located outside the inundation zone (Edwards, 2006). In cases where facilities such as pump stations were damaged, recovery took many months while spare parts were sourced. In Japan, due to the sheer scale of the disaster, recovery of the waste water system occurred at the same time as rebuilding of areas. In most cases, this involved building new treatment facilities and pump stations. Most buried pipe networks were still in place and could be restored. Pipes that were destroyed or damaged crossing waterways were replaced. For areas with minor damage to a few facilities, restoration of services resumed within a few weeks. For heavily damaged areas where facilities and treatment plants were totally destroyed, service was restored 2 years after the event (Kuwata, 2012).

In New Zealand, reinstatement of services will require repair of damaged facilities such as pipes, buildings and processing plants. The time of this will be dependent on the extent of damage as well as the availability of service crews and spare parts. Given recent lessons from the Christchurch earthquakes, recovery of wastewater systems could take weeks to months.

Increasing Resilience

The following measures can be undertaken to increase the resilience of wastewater networks to tsunami:

- Locate key facilities outside of the inundation zone. This is the most effective way of reducing interruption, although this may not be possible for some pump stations that need to be located near outlets;
- Maintaining a supply of spare parts to expedite restoration;
- Locate any electrical boards at height and/or insulate from water to increase the resilience of the facility;
- Install sealed lids on pumps and tanks to stop contamination and ingress of sediment and debris;
- Install covers on outlets and inlets to minimise the amount of debris that can enter the system (sand will still likely enter but is difficult to prevent). This may only be applicable for distant tsunami when sufficient warning times (>6 hr) are available to cover outlets.

5.0 TELECOMMUNICATIONS

Telecommunications networks are a critical lifeline in the immediate aftermath of a disaster. They are required for a range of uses, from initially communicating the extent of damage to centralised response centres and then amongst recovery decision makers. However, the greatest demand is usually from the general public seeking assistance, or eager to contact family members or friends. The latter puts huge loads on communications networks. Telecommunications networks are dependent on power supply for most of their operations (Kwasinski, 2013).

5.1 WIRELESS

The Great East Japan tsunami is the best documented event for impacts to wireless (cellular) communications. There is one main company, NTT, which operates the telecommunications network in Japan (NTT, 2011; NTT, 2012). While this business model is different to New Zealand, which has several operators, the lessons learnt could be implemented by any of the New Zealand service providers.

Damage and Failure Modes

Loss of service for wireless communications arose from four main factors (Figure 28):

1. Damage to cellular sites;
2. Damage/outages to exchanges that caused issues with switching functions;
3. Power outages to cell sites;
4. Damage to radio communications.

In Japan, most cell sites are located on buildings, with a small proportion as stand-alone towers. Therefore the vulnerability of sites located on buildings was dependent on the building performance. In most cases, buildings made of reinforced concrete that were four or more stories high survived the tsunami, along with the cell sites (Kwasinski, 2014). However, stand-alone towers were often severely damaged or destroyed in tsunami flow depths of more than 2 m. It was most commonly damage to surface electrical equipment or scouring at the base of the tower, which weakened the structure. The towers were often destroyed by large debris strike as they were not designed to withstand such large horizontal forces (Kwasinski, 2013; Scawthorn et al., 2006). Scawthorn (2006) noted that a 70 m high radio tower collapsed (but others nearby remained standing) but unfortunately did not describe the tsunami height or the failure mechanism at the tower. There are no fragility models developed for cell towers. For cell towers located on buildings, fragility curves for the building type can be used (e.g., Suppasri, et al. 2013b), see Section 5.2.

In addition to damage to the cell towers, there was often significant damage to telephone exchange buildings (NTT, 2011; Kwasinski, 2013). These are used as switching facilities for wireless networks and so are an important node in a wireless network. If one exchange cannot be reached, often the packet of information (or call) will be redirected to another. However, in the Great East Japan tsunami, many exchanges failed which caused a total loss of service in some areas (Kwasinski, 2013). In Japan, exchanges are often housed in 2–3 storey reinforced concrete buildings, which are the most resilient to structural damage in tsunami, but the contents such as the electrical equipment were vulnerable to inundation. There were also reports of damage to fibre optic cables where they entered the building as this was a location that is often prone to scouring. Please see section 5.2 for more information on fragilities of exchange buildings.

By far the most common failure mode of the wireless network was due to loss of power at cell sites (Kwasinski, 2013). This includes both sites inside and outside the inundation zone. This occurred to both cell sites located on buildings, which rely on the building power, but also stand-along towers, which have battery packs to provide backup power for 8 hours (NTT, 2011). However, power outages lasted days in some areas and so these sites were out of service until power was restored. Further, many back-up generators for cell sites were located at ground level and were inundated by the tsunami causing failure of the back-up power source.

There is little information available about damage to radio communications infrastructure in Japan. It appears that most radio infrastructure is located on elevated positions, or inland, both of which are outside of the inundation zone, so these types of facilities may not have been exposed to tsunami. It is expected that radio towers would be vulnerable to large tsunami where significant amounts of debris could damage the structure, or from high velocity flows where scouring could destabilise the foundation of the tower.

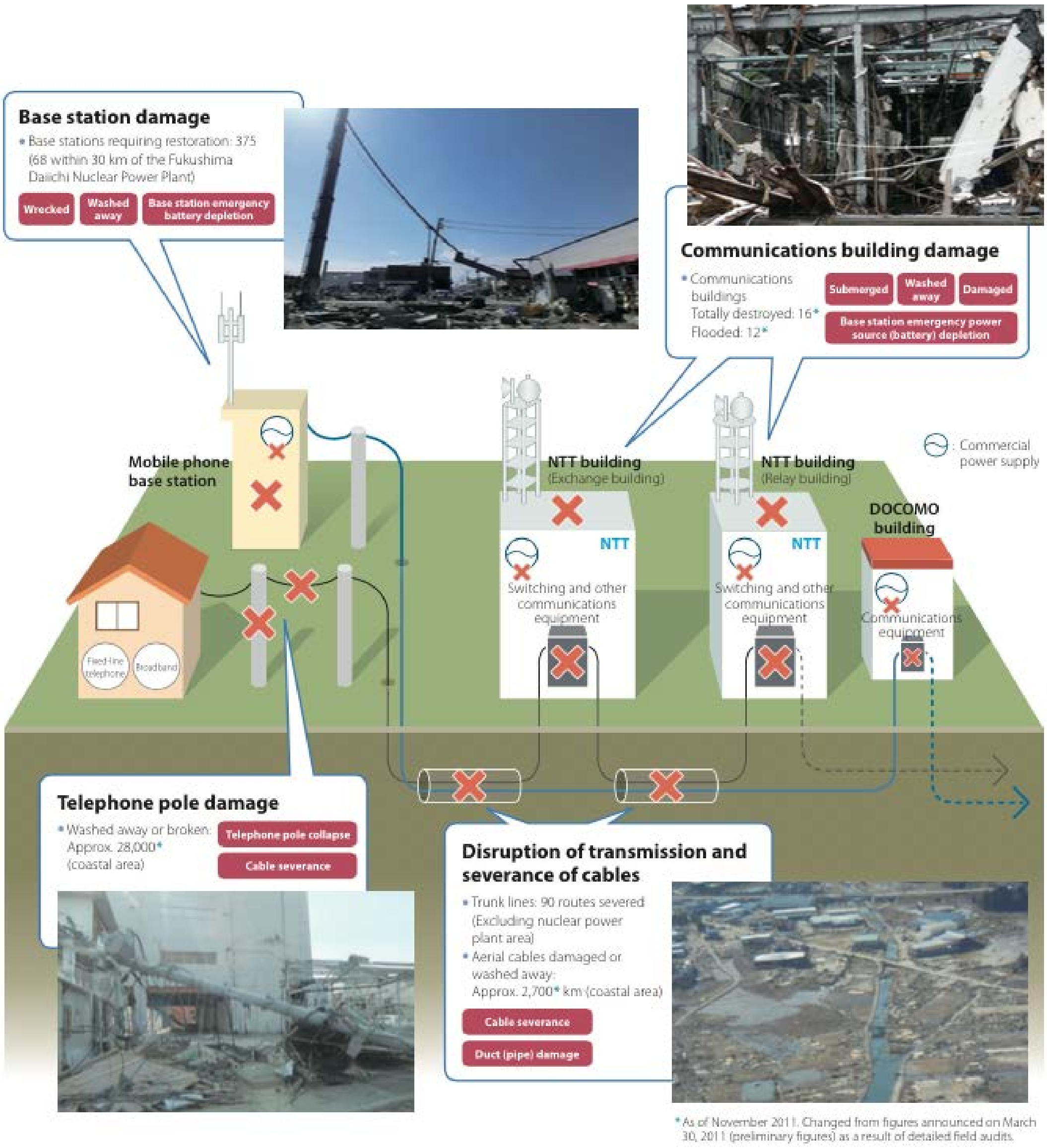


Figure 28 Summary of different types of damage and outages to the wireless and landline communications network during the Great East Japan tsunami. Note that some of the damage was due to the earthquake (e.g., disruption to underground services by liquefaction induced damage). Source: NTT (2011).

Recovery Actions

NTT, the company that run the national telecommunications network infrastructure in Japan, had a comprehensive recovery and service restoration plan that was put into action straight away (NTT, 2011; Figure 29). This included:

- Deploying mobile generators to undamaged cell sites that lost power;
- Deploying mobile cell sites mounted on trailers: cells on wheels (COWs);
- Redirecting more traffic to sites with good coverage that were undamaged;
- Increasing the size of the radius of radio repeater zones to cover the areas without coverage;
- Deployment of microwave repeater temporary stations to transmit between the cell towers and exchanges;
- Using satellite links to transmit to a remote undamaged exchange if local exchanges were all damaged;
- Using a voice message system where users could record a message and it would then be sent to the destination. This was done to allow NTT to balance the load.

Recovery was slowed by two main interdependency issues; road access and power. NTT did not have sufficient mobile generators to cover all sites, so had to prioritise deployment until power was restored. Further, many badly affected areas did not have road access and so deployment of the mobile equipment was delayed until road access was reinstated.

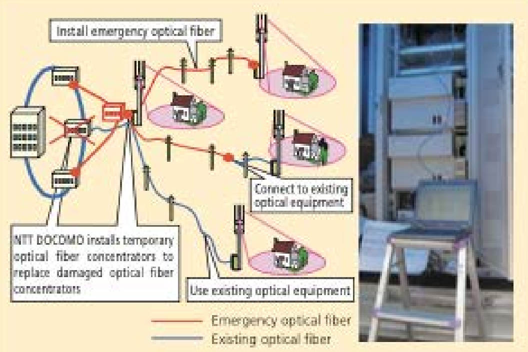


Figure 2 Facilities recovery using optical fiber/emergency optical fiber cable

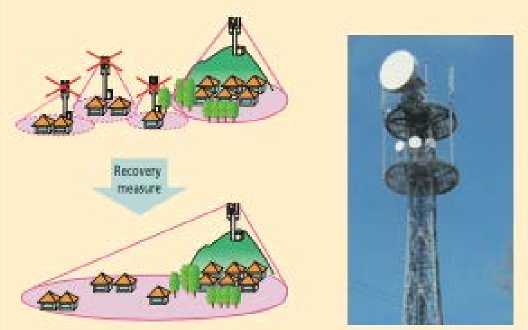


Figure 3 Facilities recovery by increasing zone size

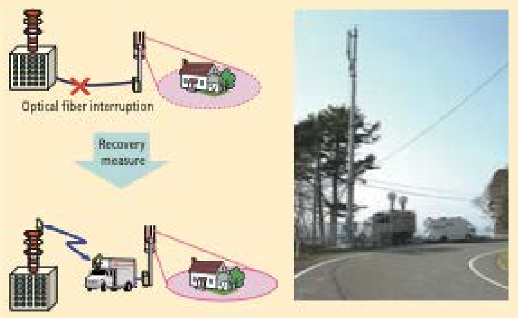


Figure 4 Facilities recovery using microwave-entrance

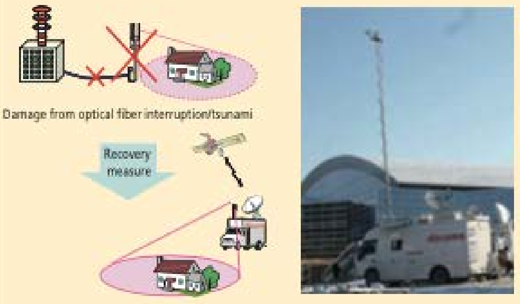


Figure 5 Facilities recovery using satellite entrance link

Figure 29 Recovery actions from NTT during the Great East Japan tsunami for various outages of the wireless network. Source: NTT.

Increasing Resilience

Telecommunications are a critical service before, during and after a tsunami event. Some warning systems, such as siren, SMS (text) and radio/TV based warnings are reliant on operating telecommunications and so continuation of service during an event is very important. Furthermore, during a response phase, telecommunications are needed to coordinate response and recovery. Therefore, a robust and resilient telecommunications network is a way to reduce impacts from tsunami. Following the Japan event, NTT noted further improvements they could make to increase the resilience of their wireless networks (NTT, 2012). Interestingly, these improvements are focussed on response and recovery not necessarily preventing damage. However, based on NTT's recommendations as well as other observations the following actions could be taken:

- Relocate exchanges out of tsunami inundation zones or place them in multi-storey reinforced concrete buildings;
- If the above is not possible, ensure critical electrical equipment and switches are waterproofed and located on higher levels;
- Locate cell towers on buildings to reduce the chance of damage from tsunami;
- Install large radio base stations outside of inundation zone with 360 degree coverage and long range (e.g., 7 km) to use as back up when exchanges are down;
- Increase battery life on cell sites and exchanges, possibly setting up alternate power sources (e.g., solar, wind etc.);
- Locate back-up generators above ground level and ideally above the expected tsunami height;
- Have a stockpile of mobile cell sites, generators and radio repeaters that can be deployed to areas with service outages;
- Develop short voice message system to send voice messages through the network to still allow contact between families and friends;
- Deploy mobile WIFI hotspots that use satellite links;
- Develop a system to visualise real-time service maps to visualise spatially where outages are and when service is expected to be reinstated. Share these with the public and emergency managers.

5.2 LANDLINES

Landlines, or wired networks, comprise of three main components: overhead wires and cables mounted on poles, underground wires and cables, and exchange buildings. Wires and cables can be made of copper or glass/plastic (fibre optic) and are housed in a protective sheath (often plastic). For both types of cable, it is critical that the core is protected from water. There are good observations on the performance of landline networks in the Indian Ocean tsunami (mainly overhead wires) and the Great East Japan tsunami (overhead and buried services, and exchanges). While the observational data is quite useful, there are no fragility models or systematic surveys of damage for these networks.

Damage and Failure Modes

Overhead cable services are extremely vulnerable to tsunami. Complete damage can occur to poles by impact forces from debris (Kwasinski, 2014) and scouring of the base of the pole that weakens the pole further (Francis, 2006). During the Great East Japan tsunami, some 28,000 overhead line poles were destroyed (NTT, Figure 28). It appears from the various observations, that poles can be destroyed in water depths of less than half their height, and damage is more likely with an increase in debris content in the tsunami (Edwards, 2006; GEER, 2009; Kwasinski, 2013). Failure of overhead services can also occur if wires are submerged in water, which is often the case in low velocity flows where the pole is still standing but the wires become submerged (Horspool et al., 2016).

There is little documented evidence of damage to underground services from tsunami. As noted in Section 4.0 on water systems, tsunami scouring often exposed underground services but they often remained undamaged. NTT reports extensive damage to underground services from liquefaction or landslides, but there are few observations on tsunami damage (NTT, 2011). There are, however, reports of tsunami damage to fibre optic cables at the point where they enter the exchange buildings. This often occurred where the foundation of the building had been scoured, exposing the cables. In these instances, the cables were damaged because the housing of the cables was weak or in poor condition which allowed water to enter the cable and damaged the core. This process could also possibly occur at other points in a fibre optic cable network, but there are few reports of this.

Any of the underground or overhead services that cross bridges will also be very susceptible to complete damage as noted in Section 3.2 on performance of services attached to bridges. These are often weak points in a lifeline network that is impacted by tsunami.

NTT report that 16 exchanges were destroyed by the tsunami and 12 more were flooded such that the equipment failed (Figure 28). Damage to exchange buildings and contents is dependent on the performance of the building as well as the height at which the main electrical equipment is located. In many of the exchanges, most switches are located on the second floor, however the tsunami height often exceeded this and destroyed the equipment. Further, exchanges located in reinforced concrete buildings were less likely to have been destroyed than those in wood buildings (Suppasri, et al. 2013a). The fragility models of Suppasri (2013a) shown below can be used to estimate the damage to exchange buildings constructed of wood or reinforced concrete (Figure 30 – Figure 33). The damage states are described in Table 3.

Table 3 Description of damage states (DS) from Suppasri (2013a). These relate to the building fragility curves.

Damage State (DS)	Description
DS1: Minor	Minor flooding, no significant damage to structure
DS2: Moderate	Slight damage to non-structural components and contents
DS3: Major	Heavy damage to some walls but not columns
DS4: Complete	Heavy damage to walls and some columns
DS5: Collapsed	Destructive damage to more than half of walls and columns
DS6: Washed Away	Structure washed away with only foundation remaining

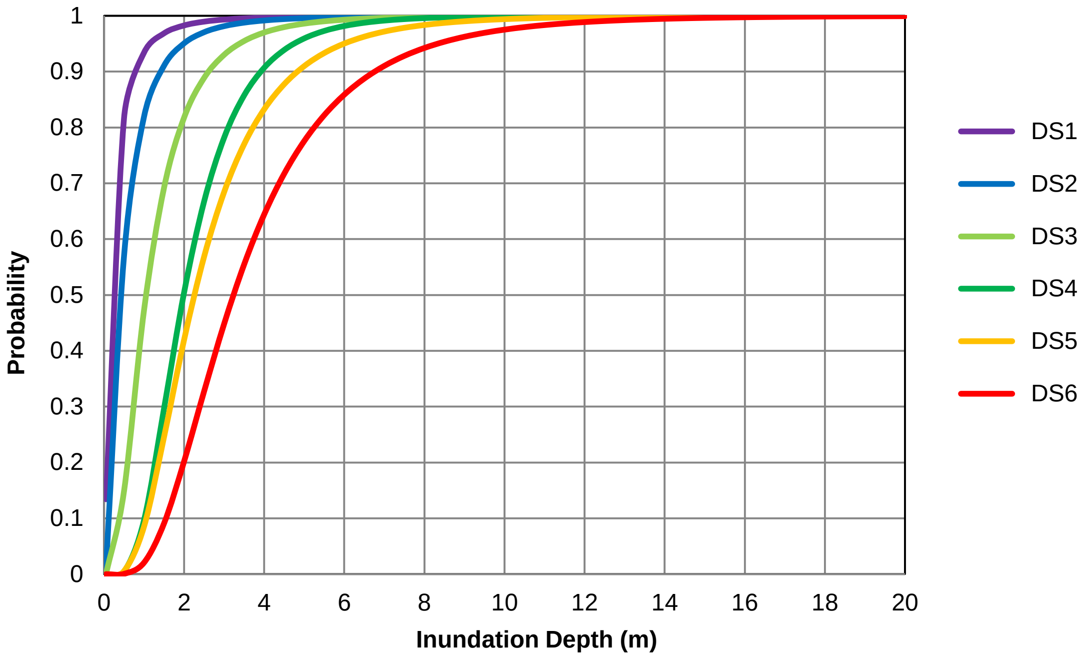


Figure 30 Fragility curve for 1-storey timber frame buildings. Source: Suppasri (2013a).

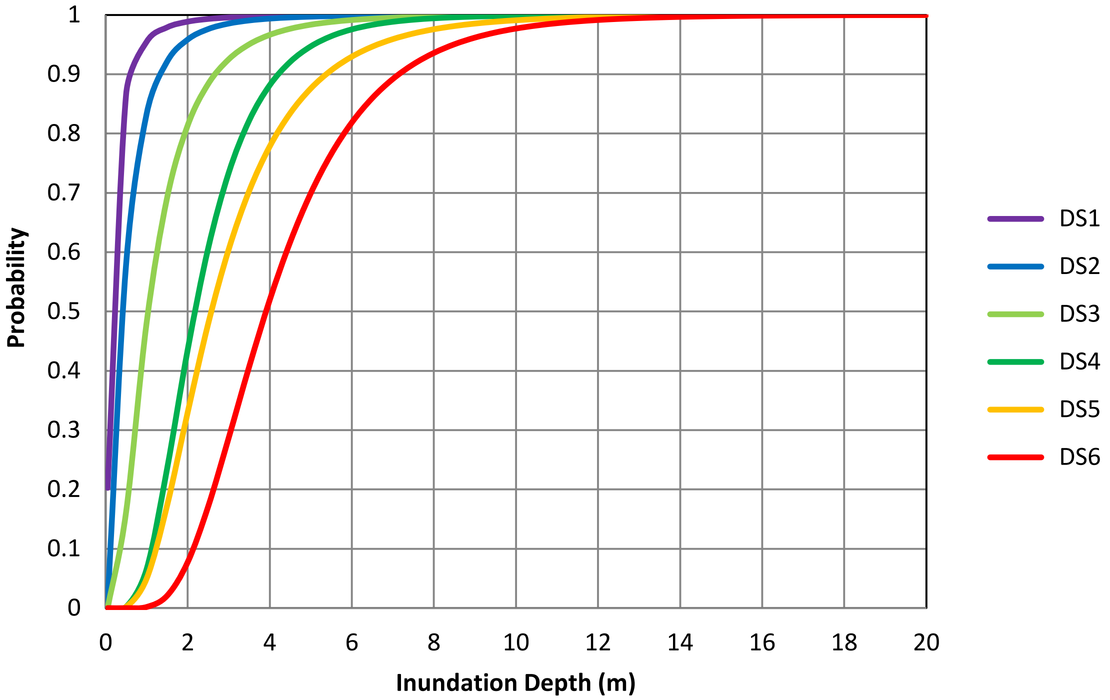


Figure 31 Fragility curve for 2-storey timber frame buildings. Source: Suppasri (2013a).

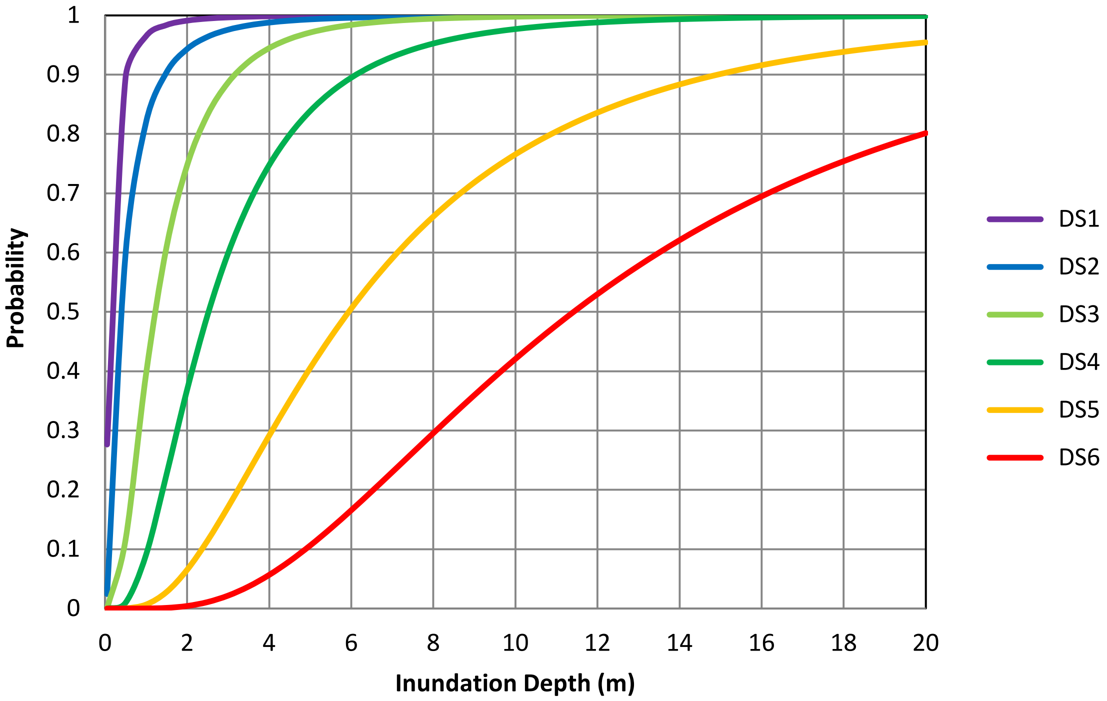


Figure 32 Fragility curve for 1–2 storey reinforced concrete building. Source: Suppasri (2013a).

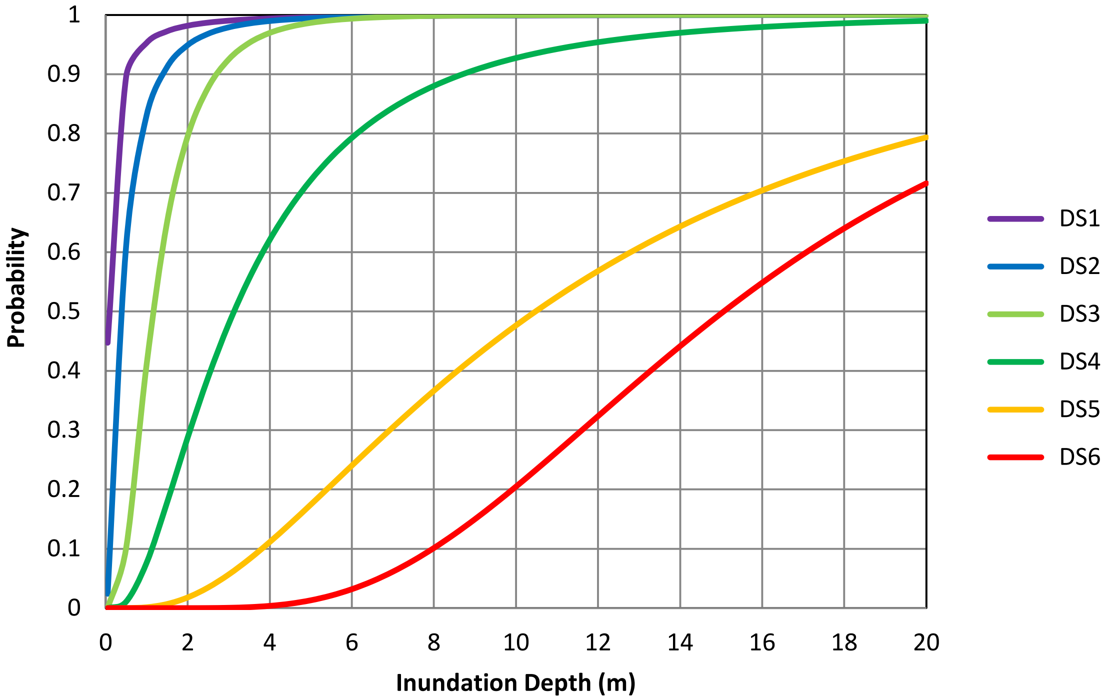


Figure 33 Fragility curve for 3+ storey reinforced concrete building. Source: Suppasri (2013a).

Recovery Actions

As noted in Section 5.1, NTT had a well-prepared action plan for response and recovery (Figure 29). Further to the recovery actions listed in Section 5.1, the following activities relate more to recovery of landlines and exchanges. NTT decided not to restore landline services to areas that were severely damaged. This was due to the fact that most people had been evacuated and the entire town had been heavily damaged and there was no demand for landlines. Instead, they focussed on areas where people were still living or where landline communications were important for local government or recovery operations. Once debris had been removed from roads and other areas, NTT erected temporary or new poles to replace overhead lines. This was accomplished with some 2,000 extra employees who were brought in from unaffected areas. For damaged or destroyed exchanges, temporary exchanges located in shipping containers were deployed at the original exchange site. For exchanges with minor damage or power outages, repairs were made and mobile generators were deployed.

Increasing Resilience

A number of measures can be taken to reduce the impact to telecommunications systems from tsunami:

- Relocate overhead services to underground. It appears underground services performed better than overhead services due to the high vulnerability of poles and overhead lines. However further work is needed to analyse the trade-off moving services underground and the potential impact from other perils (e.g., earthquake);
- Relocate exchanges out of tsunami inundation zones or place them in multi-story reinforced concrete buildings;
- If the above is not possible, ensure critical electrical equipment and switches are waterproofed and located on higher levels, this includes critical back-up equipment such as generators;
- Develop a stockpile of mobile exchanges that can be rapidly deployed to damaged exchanges;
- Develop a stockpile of spare poles, wires and other critical equipment so overhead lines can be reinstated soon after the event.

5.3 INTERNET

The only observations of performance of the internet network in a tsunami are from Japan. The lessons from Sections 5.1 and 5.2 apply to the copper or fibre optic Internet network. This section describes the performance of the trunk infrastructure.

Damage and Failure Modes

There was little drop in performance of the Internet in and out of Japan following the tsunami. There was damage as described in Sections 5.1 and 5.2 to local networks, but the main network was unaffected. There was damage to one of the three submarine cables that have landing sites in eastern Japan. These three sites were all located within 200 km of the earthquake epicentre and located in areas affected by the tsunami (Kwasinski, 2013). Although one cable failed, the other two picked up the load. It is unclear what the cause of the failure was, but this could be due to a submarine landslide, or strike from debris in the tsunami.

In our literature review, there was no information available on roadside Internet switch boxes that are common in New Zealand. It is expected that since these are located at ground level and are housed in a weak non-watertight structure that they will be damaged even in small flow depths.

Recovery Actions

The Internet network in Japan has a lot of redundancy. This allowed network operators, NTT, to reroute internet traffic around damaged areas.

Increasing Resilience

Lessons from Japan include:

- Those listed in Sections 5.1 and 5.2 for local network cables;
- Developing a network with redundancy and the ability to reroute traffic away from affected areas so the rest of the country is not affected.

6.0 ENERGY

There is little documentation in the way of impacts and performance of energy lifelines to tsunami. These following observations are made from the 2010 Chile tsunami and the 2011 Great East Japan tsunami. Most of the focus of available literature is on storage tanks located at oil terminals. The impact on energy networks from tsunami is critical as power is a key lifeline that many other lifelines depend on. The lack of observations and data is surprising and is highlighted as a sector that needs further research, perhaps from an expert-judgement or analytical approach.

6.1 NATURAL GAS

Damage and Failure Modes

Observations on the performance of gas networks in recent tsunami are limited to data from Japan, on the damage state of gas facility buildings (MLIT, 2012). MLIT subdivided the facility use into manufacturing, storage or "other" buildings. There is also no description about the construction type or material of the facility buildings. Figure 34 shows the observed data for natural gas facilities. Unfortunately, the number of undamaged infrastructure was not recorded so there is a problem with under sampling and it is difficult to draw conclusions from this data. However, Figure 34 does shows that even at small inundation depths (i.e., <2 m) damage (e.g., Damage Level 1 and 2) can occur to these facilities.

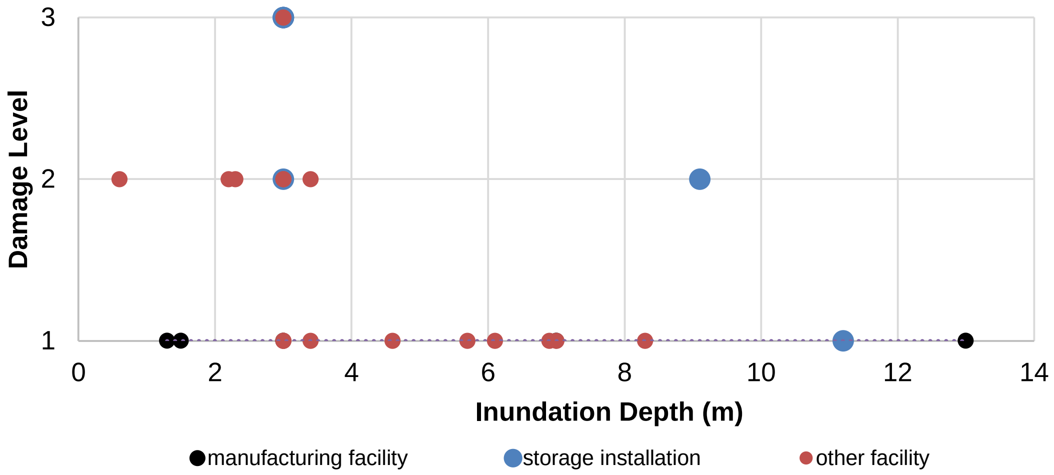


Figure 34 Observed damage data to gas facilities as a function of tsunami inundation depth (Damage Level 1: Minor damage, 2: Moderate damage, 3: destroyed). Source: MLIT (2012).

Recovery Actions

In our literature review we were unable to find any information on the recovery actions of gas network operators following tsunami.

Increasing Resilience

It is difficult to draw conclusions on how to increase resilience of gas networks from the available literature and data. This is an area that needs further research.

6.2 PETROLEUM

Damage and Failure Modes

Tsunami damage to petroleum facilities consisted mainly of damage to storage tanks that are often located near the coast at oil terminals, and associated pipelines and facilities. Tanks can be damaged from hydrostatic forces, which often cause buckling of the tank near the base (TCLEE, 2010), from buoyancy forces that cause tanks to slide or float, or from scouring at the base of the foundations (Hatayama, 2014). Tanks may be transported away from their original site and cause damage by striking structures (Figure 36). Hatayama (2014) collated an excellent dataset of the performance of storage tanks at oil terminals (Figure 37). Hatayama (2014) found that at flow depths less than 1 m, there was little or no damage to tanks, and for flow depths greater than 7 m there was always damage, with 1–7 m being a transition zone between the two (Figure 38). At depths of 2 m or more, damage to pipework occurred. A third of the storage tanks at the Kreung Raya deep-water port in Banda Aceh in 2004 were mobilised by floatation forces and damaged. It was found that those that floated were less than half full, while those that did not move were nearly full (Scawthorn et al., 2006). It appears from the observational data that smaller tanks and those that are less than half full are more susceptible to sliding and floatation than larger capacity and full tanks (Figure 37 and Figure 38).

Fires are a common hazard in tsunami. The spillage of combustible liquids such as petroleum from coastal industrial facilities, combined with transportation of the liquid on the surface of the water can spread fire rapidly over a wide area. Such fires were observed to exacerbate damage in the industrial facilities and neighbouring residential areas after the 1964 Niigata, Japan earthquake and tsunami (Iwabuchi, 2006), and occurred in Banda Aceh, 2004 (Borrero, 2005), and in several cities in Japan, 2011 (EEFIT, 2011).

During the 2015 Chile tsunami a single petrol station was located in the inundation zone in Coquimbo, Chile (Figure 35). The tsunami flow depth at the site was 1 – 2 m which caused damage to the pumps and backup generators which required replacement with new pumps and a mobile generator (while the distribution lines were still being repaired). The station was out of operation for 10 days while new pumps and electrical equipment was installed. The retail building was destroyed and a temporary wooden structure was built to keep operations going. The underground tanks were undamaged (Horspool et al., 2016).

Figure 35 COPEC petrol station in Coquimbo, Chile damaged during the 2015 Chile tsunami. This photo taken 12 days after the tsunami shows the newly installed pumps and temporary retail building under construction (Horspool et al., 2016).

Figure 36 A damaged storage tank that has been deposited away from its original site in Kesennuma during the Great East Japan tsunami. Note the buckling and/or impact damage to the side of the tank nearest the road. Source: S. Fraser.

Recovery Actions

In our literature review we were unable to find any information on what recovery actions were taken at oil terminals in recent tsunami.

Increasing Resilience

- To increase the resilience to tsunami, the following actions could be taken:
- Use larger capacity storage tanks that are more resistant to sliding and floatation;
- Relocate tanks to higher ground;
- Raise the foundation of tanks to increase their effective height against tsunami flooding;
- Construct scouring resistant foundations with riprap or other material;
- Construct tanks to earthquake design standards to better withstand lateral tsunami forces.

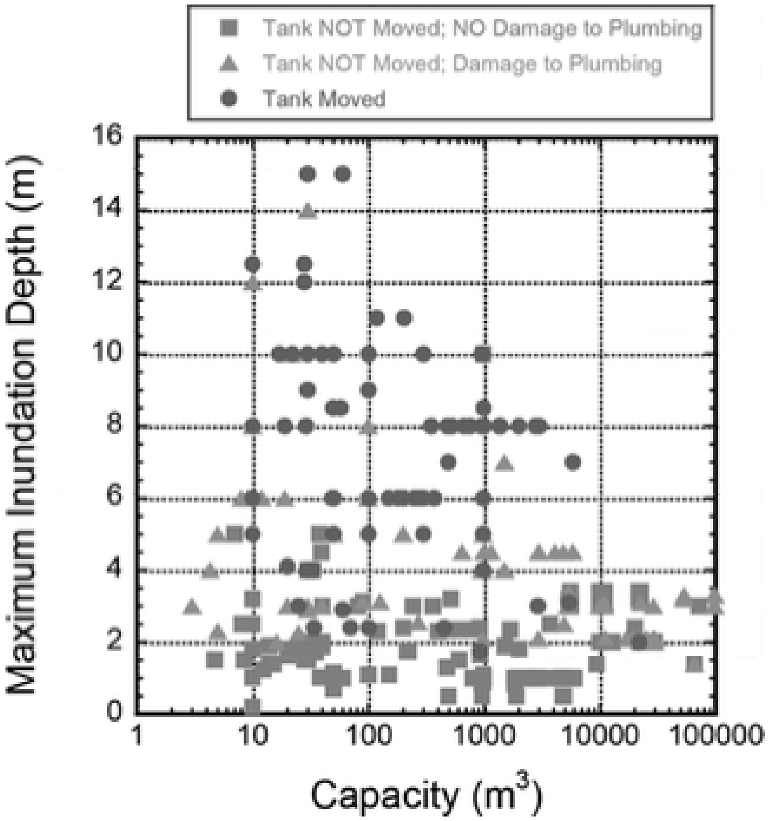


Figure 37 Observations of damage to storage tanks as function of inundation depth (m) and storage capacity. This shows damage to plumbing can occur at ~2m inundation depth, and tank movement at 2–3 m of inundation depth. Source: Hatayama (2014).

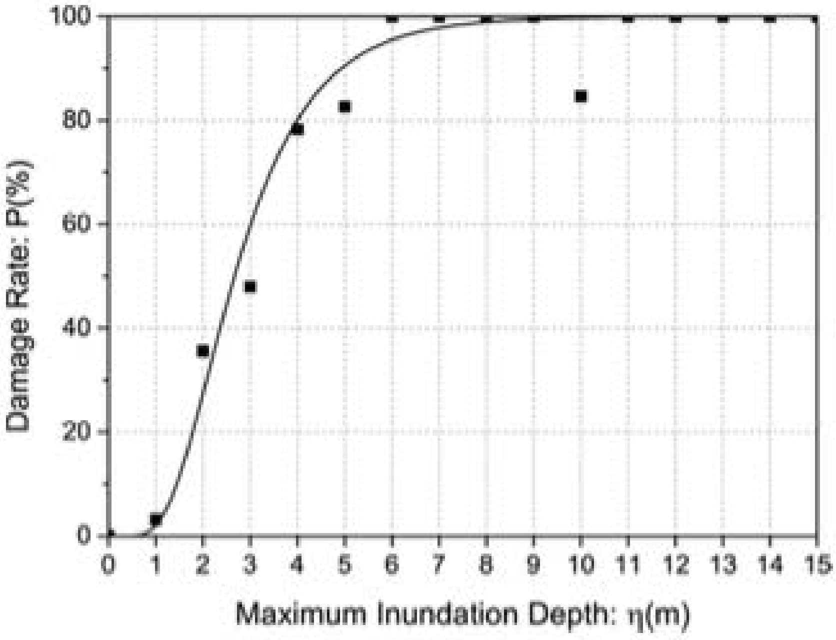


Figure 38 Fragility curve for generic storage tanks. This shows the probability of a tank being damaged as a function of inundation depth (m). The probability of damage increases significantly between 1 m and 5 m inundation depth and reaches 100% at 9 m inundation depth. Source: Hatayama (2014).

6.3 ELECTRICITY

In our review of the literature, there is limited data available on tsunami damage to the electrical systems and their components. This may be due to concerns about security of electricity networks by operators that has resulted in a lack of post-tsunami surveys at electrical infrastructure sites, or publication of reports by electricity providers. Most of the observations were from the 2015 Chile tsunami in Coquimbo (Horspool et al., 2016). However, we can draw some conclusions from damage information to similar infrastructure. To address the data gap, fragility curves for electricity infrastructure (poles and substations) were derived from expert judgement combined with the limited observations from post-tsunami surveys.

Damage and Failure Modes

Scawthorn (2011) reported that the Great East Japan tsunami affected some coastal substations, and transmission and distribution lines, but that its major impact was on power generation at stations along the coast. However, there is no further information on the type of damage at these sites. Damage to the distribution system can occur due to:

- Damage to utility poles and overhead lines (e.g., Tang, 2006; TCLEE, 2010), from hydrodynamic forces, scouring of pole foundations or debris strikes (e.g. Figure 39 to Figure 42);
- Damage to buried services if they are exposed and their cable housing is compromised (from earthquake damage);
- Damage to substations from flooding or debris strikes.

Tang (2006) noted that in the Andaman Islands during the 2004 Indian Ocean Tsunami tens of kilometres of overhead lines came down due to damage to utility poles from the tsunami. In addition, in many cases the pole remained standing but pole mounted transformers (Figure 39 and Figure 42) were inundated and they were rendered inoperable and needed to be replaced due to salt-water intrusion.

Figure 39 Example of damage to utility poles in Sri Lanka. In this example the poles have been moderately damaged and the tsunami inundated above the height of the pole mounted transformer, which later needed replacement. This would correspond to Damage State 1. (Source: Tang, 2006)

Reese (2007) also noted that during the 2009 Samoa Tsunami a number of wooden utility poles were leaning or washed away by the tsunami, with tsunami inundation depths on the order of 3-10 m.

During the 2015 Chile tsunami, many overhead lines and utility poles were damaged where flow depths ranged between 1-5 m. Damage to the poles was mainly due to lateral forces, debris strikes or scouring of foundations (Figure 40 and Figure 42). Damage from lateral hydrodynamic forces and debris strike was very random, where one pole would be washed away and the next was undamaged. The damage would often consist of a shearing at the base of poles that had a base plate causing total washout, or if the pole was set in a foundation, then often the pole would remain leaning at a high angle (Horspool et al., 2016). Scouring of foundations primarily occurred near the coast and where the pole was set in soil (Figure 40). Overhead lines were severed or washed away when the tsunami height reached the height of the lines, which in Coquimbo was ~3 m (Horspool et al., 2016). Figure 41 shows a utility pole stripped of the overhead lines.

Figure 40 Example of damage to utility poles by shearing due to lateral forces or debris strike (left) and scouring of base (right) in Coquimbo during the 2015 Chile tsunami (Horspool et al., 2016).

In the review, there was no information available on the performance of buried lines. Drawing on observations from tsunami damage to other buried lifelines, it is expected that tsunami will cause very little damage to buried lines (Miyajima, 2012; NTT, 2011). In some cases scouring may expose the line, but the cable will often remain intact. Weak links in the network such as entry points to buildings (where severe scouring and high velocities can occur) or where a line crosses a waterway on a bridge will most likley be the points where a cable may be broken or damaged. However, if the integrity or watertightness of the cable housing is damaged in the preceeding earthquake and the cable is exposed from scouring, then damage will likely occur due to salt-water infiltration and the cable will need to be replaced.

Figure 41 Example of damage to overhead lines in Coquimbo during the 2015 Chile tsunami (Horspool et al., 2016).

Tsunami can significantly impact other key infrastructure such as substations due to debris strike, inundation, and deposition of salt-water and sediment onto electrical equipment (Scawthorn, 2011). When electrical equipment is inundated, complete damage may occur from corrosive effects of salt water (Tang, 2006).

Tsunami can also result in a significant reduction in national power generation capacity where power stations or major transmission networks are taken offline due to damage, as occurred in Japan 2011. In New Zealand, the absence of major power stations at the coast means a major reduction in power supply is less likely to occur. The more likely effect of tsunami damage to the electricity system is due to failure of local distribution systems and local blackouts until the system is restored.

Figure 42 Damage to local electricity transmission lines from the 2011 Japan Tsunami. This would correspond to Damage State 1 in the analysis and Figure 43 below. (Source: TCLEE, 2010).

Given the lack of and non-specific information on damage to the electricity sector, fragility curves were developed for utility poles and substations based on a combination of limited anecdotal observations of damage from post-tsunami reports (e.g. Tang, 2006, Reese, 2007; TCLEE, 2010) and expert judgement from Natural Hazard Risk Engineers at GNS Science. Fragility curves were developed for substations and poles and overhead lines (Figure 43 and Figure 44).

It is expected pre-cast concrete utility poles will perform better underdebris strikes and hydrodynamic loads than wood, and this is reflected in the fragility curves (Figure 43). It is expected that once the height of the pole is reached by the tsunami the pole will be in at least Damage State 1 and have a high probability of being washed away (Damage State 2). At low flow depths (e.g. flow depth half of the pole height), some poles may topple due to scouring of their base or from debris impacts.

Substations are vulnerable components of an electricity network due to their sensitivity to water and their set up, which often includes components being located outdoors with no protection (apart from a lighweight wire fence). As such, substation components located outside are more vulnerable than those located inside facility buildings. Facility buildings are often constructed from reinforced columns with masonry infill walls or pre-cast concrete panels. This construction type provides good resistance to tsunami flows at low to moderate depths (i.e. less than the height of the building). Minor flooding damage will usually occur at similar levels for both indoor and outdoor components as the building are not designed to be water tight, whereas moderate or complete damage (washed away) will occur at lower depths for outdoor components than indoor components. This is due to the facility building acting as a barrier for debris strikes or reducing the flow velocity of the tsunami, both of which will minimise the probability of moderate or complete damage. However, if the facility building has suffered pre-existing damage from an earthquake (in the case of local tsunami), such as wall failure or collapse (particularly for masonry infill wall types), then it is expected the indoor substation components will have the same vulnerabiity as outdoor substation components.

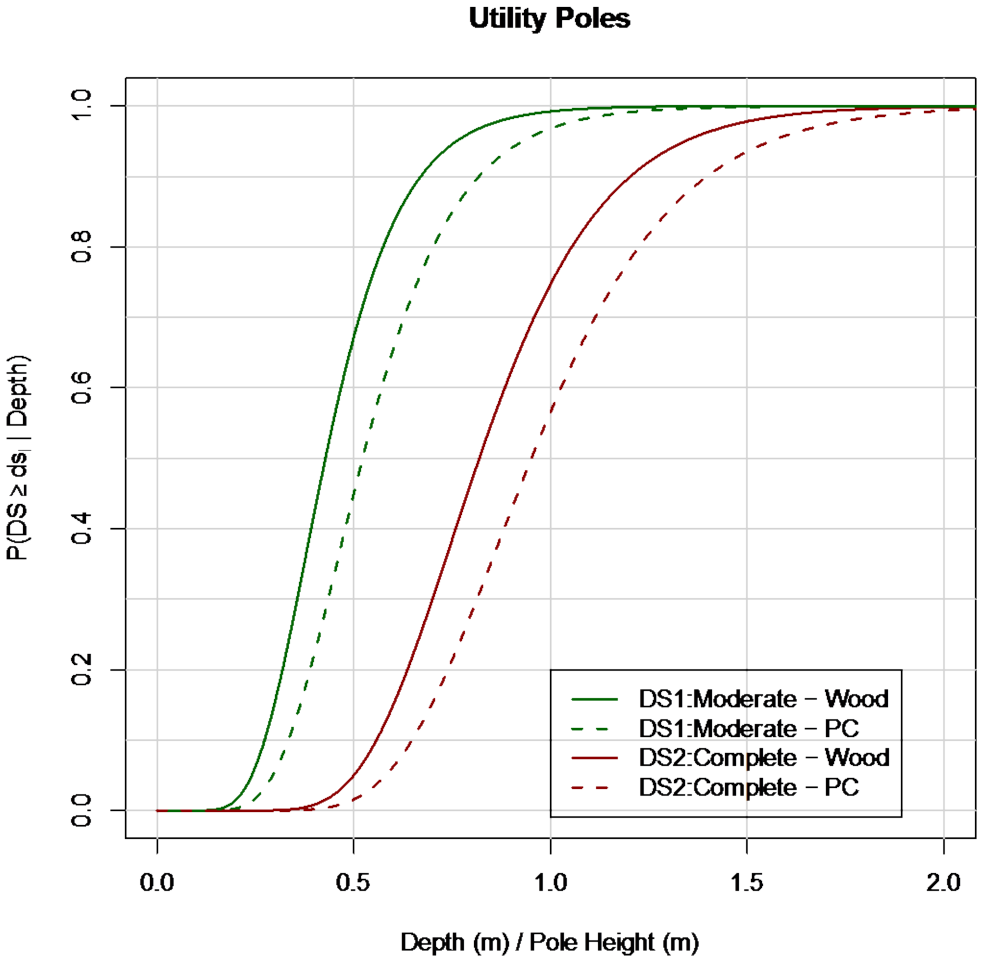


Figure 43 Fragility curve for utility poles constructed from wood or precast concrete (PC) derived from expert judgement and from observations from post-tsunami surveys. The curves show the probability of being in a given damage state or greater as a function of tsunami depth. Damage State 1 (DS1) is defined as damage to the pole such that it is leaning or may need repair, but the pole is still standing. Damage State 2 (DS2) is complete damage where the pole has been washed away.

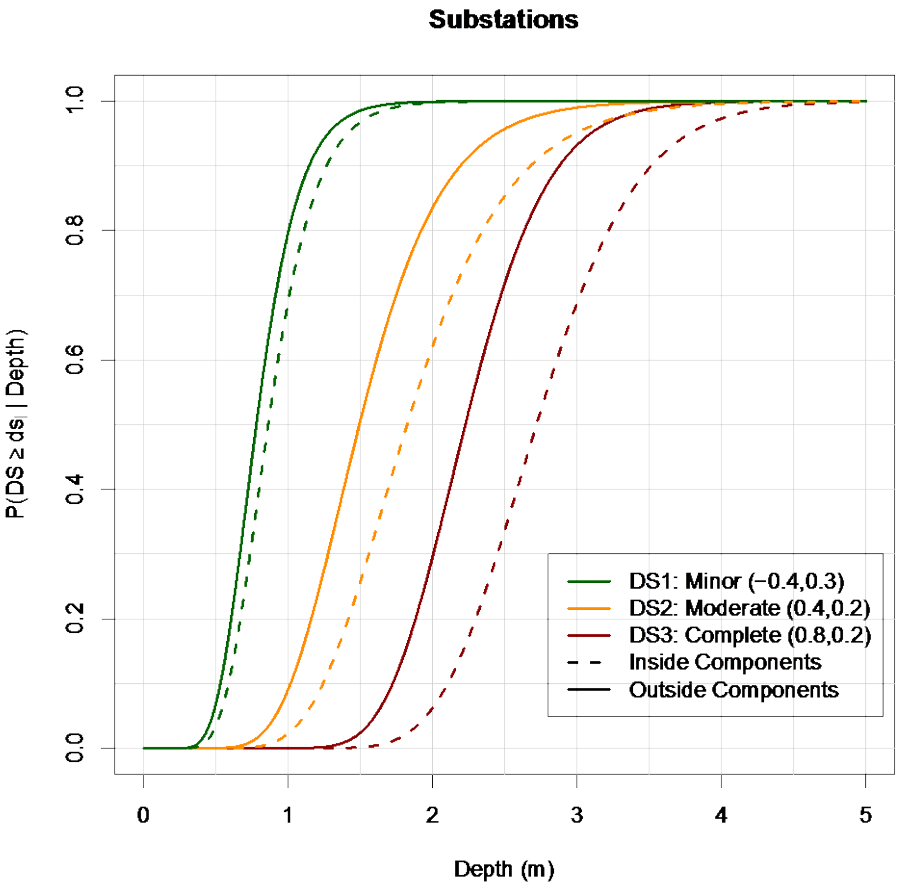


Figure 44 Fragility curves for electrical substations derived from expert judgement and observations from post-tsunami surveys. Each curve shows the probability of being in a given damage state or greater as a function of tsunami inundation depth. Fragility curves are developed for indoor components, usually housed in a small concrete or masonry building and outdoor components in a yard. Damage State 1 (DS1) is minor water damage to substation components with repairs required. Damage State 2 (DS2) is moderate damage where some components have had structural damage and may need replacement. Damage State 3 (DS3) is complete damage where components have been washed away. Loss of service is expected even at damage state 1 due to shorting of the substation.

Recovery Actions

Recovery actions comprise the repair and replacement of inundated and damage components, to bring power systems back online. During the Great East Japan tsunami, 70% of customers had service outages following the event. This dropped to 12% within 3 days, and only 4% were still without power 8 days after the event (Kuwata, 2012). Between the two main power companies (Tohoku-EPC and TEPCO), nearly 10,000 personnel were deployed to repair substations and transmission lines (Kuwata, 2012). This highlights that the speed of recovery for electricity networks will rely heavily on the availability of spare parts and teams to make repairs.

In Japan temporary electricity poles (Figure 45) were erected within days of the tsunami to reinstate electricity services to key facilities such as hospitals, relief centres, telephone exchanges etc., which was followed by transmission lines to households (Araki, 2012). In some cities, the reinstatement of power poles required roads or land to be first built-up to above water level due to co-seismic subsidence. Furthermore for critical sites, mobile generators (truck or container mounted) were deployed by the facility operators within 24 hours.

Figure 45 Example of utility poles being erected in the early stages of the recovery process following the 2011 Japan Tsunami. In this coastal location the majority of utility poles were washed away by the tsunami. Source: USA Today.

Increasing Resilience

The actions that can be taken to increase the resilience of electricity networks to tsunami are:

- Locate substations outside of tsunami inundation zones; The United States National Tsunami Hazard Mitigation Program (NTHMP) includes substations under the category of ‘critical facilities’. Under their principles for designing and planning for tsunamis, they recommend that substations should located outside of the inundation zone, with relocation of these facilities an ‘integral part of any tsunami mitigation plan’ (NTHMP, 2001, p. 26).
- Where electrical systems cannot be located outside inundation zones, robust tsunami-resistant design, e.g., flood defence walls, raised equipment, housing components in strong buildings, should be employed.
- Build in redundancy to key distribution networks.
- Stockpile spare parts (e.g. poles) for rapid repairs and restoration of service;
- Stockpile mobile generators (and substations) for rapid deployment to critical sites;
- Develop pre-existing contracts to deploy personnel to repair the network as soon as possible following a tsunami.

7.0 RECOMMENDATIONS FOR FUTURE RESEARCH

This literature review highlighted some large gaps in the knowledge of how various lifelines will perform in a tsunami. It also identified issues with how damage data was collected to allow fragility models to be developed that can be used for loss modelling purposes. The following are areas that could be addressed in future research, or be a focus in future post-tsunami surveys:

- More research is needed on the performance of energy lifelines. This sector is under-represented in the literature even though other sectors are heavily dependent on power supplies for their operations;
- Further work should focus on buried services. There is little information on the performance of these in regard to casing material and backfill type;
- More information is needed on the vulnerability to different construction and material types across most lifelines. This type of information needs to be collected during post-tsunami surveys;
- The vulnerability of roads requires more quantitative information, particularly on scouring damage;
- Develop a series of information posters for different lifeline sectors;
- Develop improved post-tsunami data collection methods. Many post-tsunami surveys attempted to cover all lifelines but in very little detail. This results in very little useable information to understand how different materials or construction practices performed (apart from bridges). Furthermore, where damage data was collected (e.g., MLIT, 2012) there was often under sampling as no data was collected on undamaged structures. This means that useable fragility models cannot be developed as they require the proportion of undamaged structures at different hazard (tsunami depth) levels to be defined. Studies such as that by Kwasinski (2013, 2014) are examples of a good studies that focus on a single lifeline sector (telecommunications) and describes the performance, recovery and mitigation measures in detail. The study by Hatayama (2014) is also a good example of a study that develops fragility models for storage tanks from damage data (which included data for both damaged and undamaged tanks);
- Further research on linking damage state with repair cost (damage ratios) and downtime is required. There is little information available in the literature on the repair cost to lifelines following tsunami damage. This is most likely because it is held by lifeline operators or insurance companies and is confidential information. However, to facilitate lifelines loss modelling, this information is needed. Work by Graf (2014) is aiming to develop damage ratios for tsunami for the HAZUS software (U.S.) and these could potentially be adopted for New Zealand once they are implemented. Information on downtime could be sourced from lifeline operators in countries such as Japan or from local lifeline operators who may be able to estimate downtime given a certain damage state of the network.

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9.0 GLOSSARY

ALG	Auckland Lifelines Group
ASCE	American Society of Civil Engineers
Bore	A bore can be a smooth or turbulent, non-breaking step-like increase in water height resulting in wall-like change in water levels from normal to some higher level.
Caldera Collapse	Catastrophic collapse of a volcanic cone. If the debris collapses into a body of water (sea or lake etc.) then a tsunami can be generated.
Damage State/Grade/Rank	Categories that describe different levels of physical damage to a structure often assigned during a post-tsunami survey. Damage states can be linked to repair cost or down-time to model the recovery process.
EEFIT	Earthquake Engineering Field Investigation Team
EERI	Earthquake Engineering Research Institute
Flow Depth (Inundation Depth)	Depth of water above ground surface during tsunami inundation (m).
Flow Velocity	Speed of tsunami flow (m/s)
Fragility Curve	A model that describes the probability of being in a given damage state or greater as a function of hazard intensity (e.g. tsunami inundation depth)
MLIT	Japan Ministry of Land Infrastructure and Tourism.
NTT	Japan’s major telecommunications operator.
Run Up	Maximum elevation (above mean sea level) that a tsunami flow reaches
TEPCO	Japan’s major electricity provider.
WeLG	Wellington Engineering Lifelines Group.

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APPENDICES

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A1.0 APPENDIX 1: DEVELOPMENT OF FRAGILITY CURVES

This appendix outlines the method for developing fragility curves for roads, bridges and electricity network components.

A1.1 TRANSPORT SECTOR

Data sourced from the Japan Ministry of Land Infrastructure and Transport (MLIT, 2012) from the 2011 Japan Tsunami was used in conjunction with information on bridge damage from the 2004 Indian Ocean Tsunami (Shoji, 2007) to develop empirical fragility curves for roads and bridges.

A1.1.1 Road Fragility Curves

A database was provided by MLIT (2012) which contained information on all damaged roads within the tsunami inundation zone. MLIT defined the length of road affected and assigned a damage state to this road segment. The damage states were defined as shown in Table A1.

Table A1 Damage state definitions for roads from MLIT (2012) data.

Damage State	Damage	Serviceability
Damage State 1 (DS1)	Minor damage to road surface	All lanes passable
Damage State 2 (DS2)	Major damage to one lane	One lane impassable
Damage State 3 (DS3)	Major damage to whole carriageway	All lanes impassable

However, to use this data to develop fragility curves, the undamaged roads must be included in the analysis. Therefore, all roads within the inundation zone were extracted from OpenStreetMap[8] or were digitized from aerial imagery. All road segments not included in the MLIT dataset were assumed to be undamaged and assigned a damage state of none. By adding the undamaged roads, the dataset now comprised all roads in the inundation zone with an assigned damage state of none, DS1, DS2, or DS3 (Table A1, Figure A1).

Tsunami inundation depth maps that were also provided by MLIT (2012) and were used to assign tsunami inundation flow depths to each road segment in the database. Using flow depth bins of 1 m (i.e. 0.0 – 1.0 m, 1.0 – 2.0 m….) the total length (in km) of road in each depth bin and in each damage state was tabulated. This was used to create a damage probability matrix that defines the probability of being in each damage state for each flow depth bin (e.g. Figure 41). Next, for each flow depth bin, the probability of being in DS1 or greater, DS2 or greater and DS3 were calculated. These were then plotted as points as shown in Figure 5. Finally, a lognormal cumulative distribution function (CDF) curve was fitted to the data points for each damage state using the maximum-likelihood method within the R software package[9]. The cumulative lognormal curve was chosen as it is often used for fitting fragility functions for tsunami and earthquake damage states (e.g. Suppasri, 2013b).

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[8] http://www.openstreetmap.org

[9] http://www.r-project.org

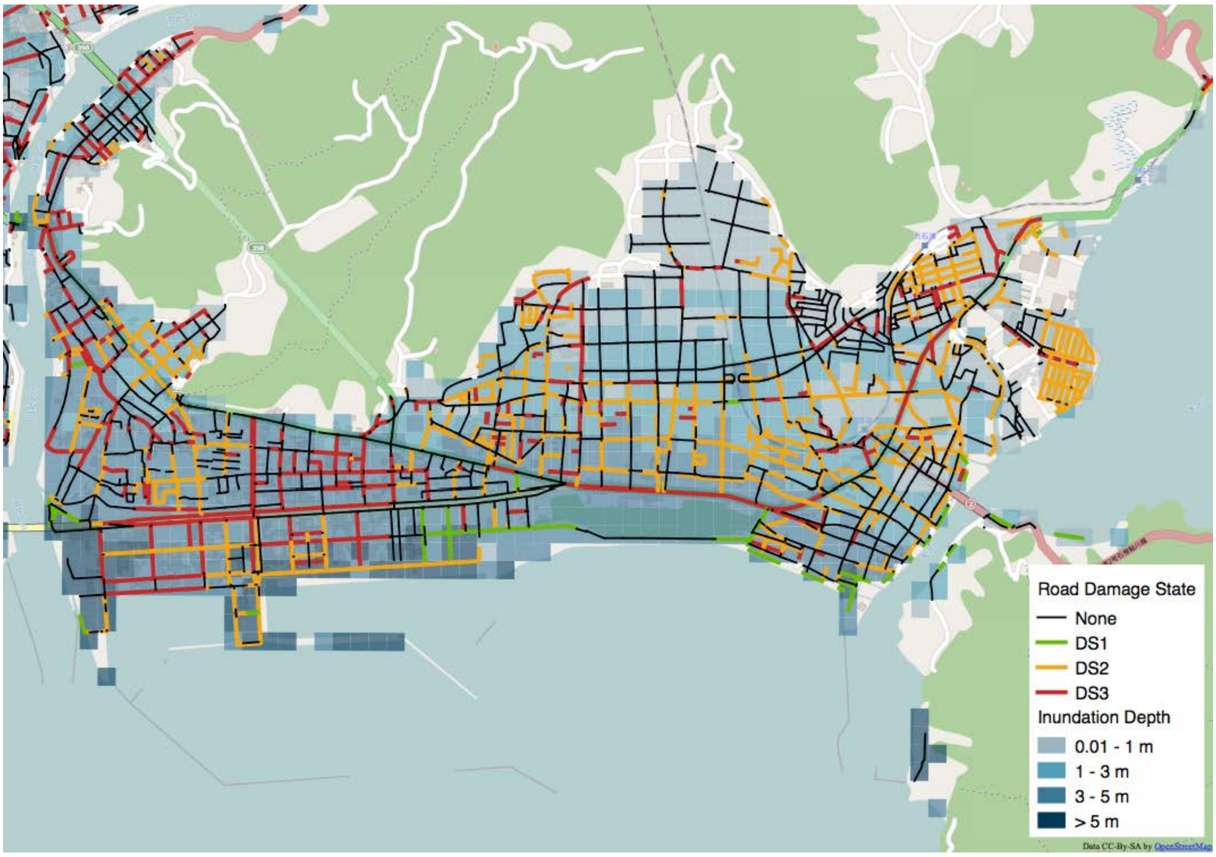

Figure A1 Map showing location of roads and their assigned damage states overlayed on mapped inundation depths for Ishinomaki, Miyagi Prefecture.

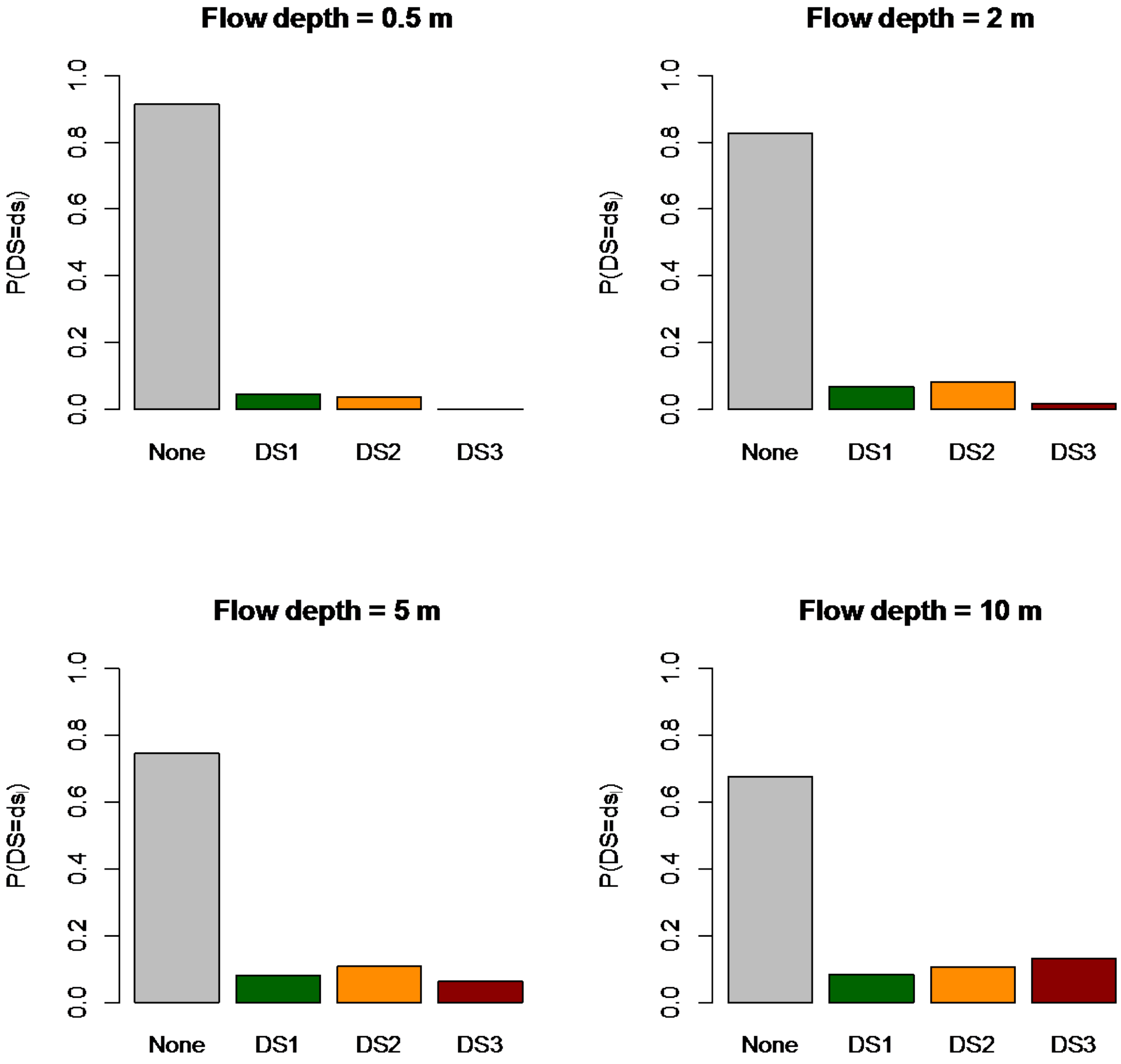

Figure A2 Damage state probability plot for roads. Each plot shows the probability of being in a given damage state for flow depths of 0.5 m, 2 m, 5 m and 10 m. This information was extracted from the fragility curves shown in Figure 5.

A1.1.2 Bridge Fragility Curves

To derive fragility curves for bridges two datasets were used; the MLIT (2012) dataset for bridges which comprised of data from the 2011 Japan Tsunami for Iwate and Miyagi Prefectures, and data from Shoji (2007) that includes bridges surveyed following the 2004 Indian Ocean Tsuanmi in Indonesia and Sri Lanka. The Shoji (2007) dataset includes bridges that were undamaged as well as damaged, and also assigned a bridge construction type (Precast concrete=PC, Reinforced Concrete=RC, Steel). The MLIT (2012) data set includes multiple bridge types (vehicle, rail and pedestrian), but only includes damaged bridges. Furhter, the bridge deck height and bridge construction material type is not included in the dataset. To use the MLIT (2012) data to develop fragility curves, the undamaged bridges are required. Data from OpenStreetMap and imagery from Google Maps before the tsunami were used to identify bridges that were not in the damaged data set (e.g. Figure 41). All bridges that were mapped but not included in the MLIT datset were assumed to be undamaged and assigned a damage state of ‘none’ and a deck height of 5 m. The tsunami inundation flow depth map used in the road analysis was also used to assign flow depths to each bridge. The flow depth assigned is recalculated so that it is relative to the base of the bridge deck (i.e. a flow depth of 0.0 m is at the base of the bridge deck). The damage state definitions used for both the MLIT (2012) and Shoji (2007) data sets are similar and are described in Table A2.

Table A2 Damage state definitions for bridges from MLIT (2012) and Shoji (2007).

Damage State	Description	Serviceability
Damage State 1 (Rank C)	Minor damage, often from impacts, to the superstructure.	Operating as normal, needs minor repairs
Damage State 2 (Rank B)	Major damage to superstructure but still in place on piers. Superstructure may have been shifted.	Operating under speed and load restrictions or not operating if superstructure has shifted. Requires moderate-major repairs. If superstructure has moved bridge may need to be demolished.
Damage State 3 (Rank A)	Complete washout of superstructure	Not operating. Bridge will need to be rebuilt on new piles.

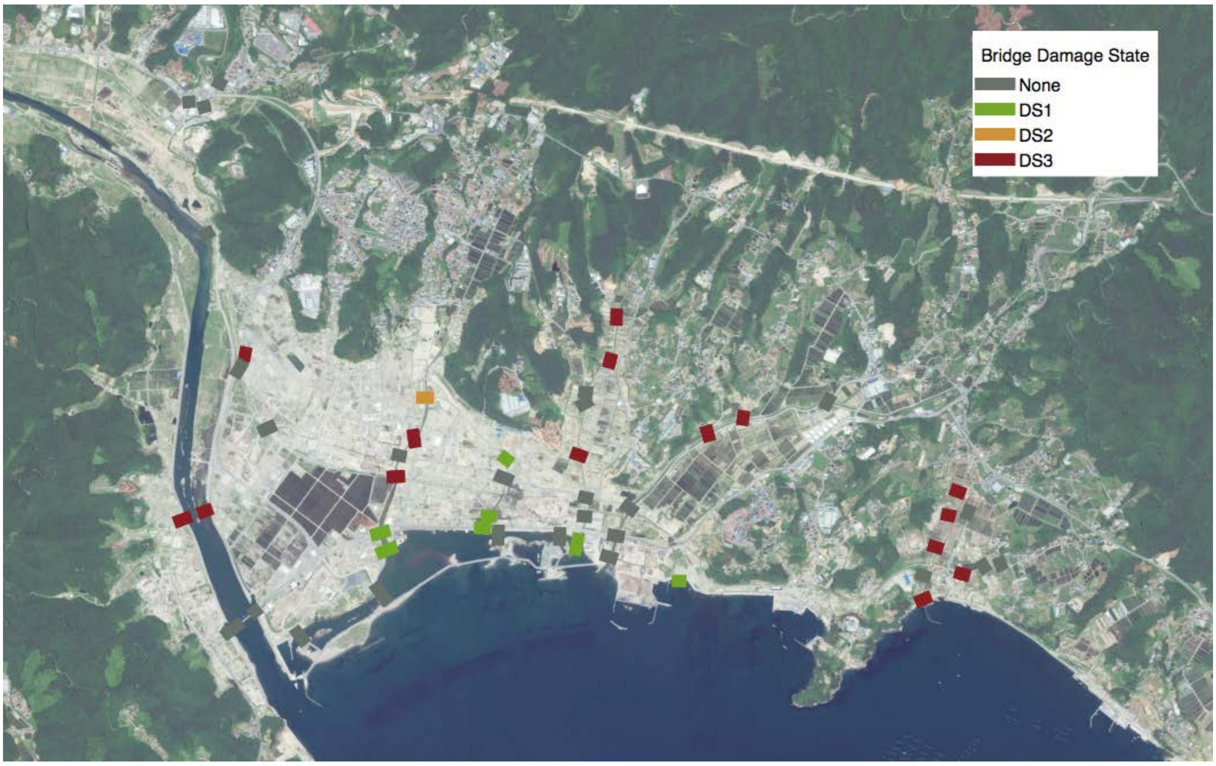

Figure A3 Map showing the location of bridges and their damage states for Rikuzentakata, Iwate Prefecture.

Similar to the method for developing road fragility curves, the number of bridges in each damage state for a series of flow depths bins were tabulated, and the probability of being in a given damage state or above were calculated. Fragility curves were derived by fitting a cumulative lognormal curve to the bridge data (Figure 12). This was undertaken seperately for each of the datasets. The Japan data can be used to define generic fragility curves for bridges, where as the Shoji (2007) data was used to define fragility curves for RC, PC and Steel bridges construction types. Note that there was not enough data for bridges in DS2 for PC and Steel bridges to define a curve, and as a result this data was excluded from the analysis. The Japan data has the largest data set, around 5 times as many bridges as the Indian Ocean Tsunami dataset. However, since it does not have any information on bridge construction type, the analysis is limited to developing a generic fragility curve. If any data is becomes available on bridge type from the Japan data, then fragility curves for each type could be constructed.

A1.2 ELECTRICITY SECTOR

As mentioned earlier in this report, there is very little empirical data available on tsunami damage to electricity network infrastructure. A few post-tsunami surveys note damage to some components such as utility poles or substation (e.g. Tang, 2006; Reese, 2007; EEFIT, 2011; TCLEE, 2012;), however the information provided lacks any detail of the mechanism and type of damage and is often only observed at a few sites. This lack of comprehensive survey data restricts developing empirical fragility curves. However, the damage descriptions can be combined with expert judgement to develop "expert-judgement" based fragility curves. These have much more uncertainty than empirical or analytical fragility curves but nonetheless provide a means of modelling tsunami impacts when no other data exists. If new empirical or analytical data becomes available it should replace the expert derived fragility curves.

A similar expert-judgement based approach was used by Nayerloo (2014) to derive vulnerability functions (repair cost as a function of tsunami flow depth) for electricity infrastructure for the Wellington region.

To develop fragility curves for the electricity sector the components are divided into the following:

5. Substations (high and low voltage). In New Zealand substations components are either located outside or inside of buildings so two classes are defined; 1) Outside, when the main transformer and circuit breakers are located outside, and the circuit boards and electrical equipment is inside a building and 2) where all components are located inside a building.
6. Overhead poles, including lines and transformers.

Expert-based fragility curves for substation components and utility poles were developed by GNS Science Risk Engineers through a workshop process. First, three damage states were developed for substation components (Table A3) and two for utility poles (Table A4).

Table A3 Damage state definitions for substation components.

Damage State	Damage	Serviceability
Damage State 1 (DS1)	Minor damage to components, mainly from shallow, low velocity water intrusion. Similar to flooding damage.	Shorting and loss of service. Minor repairs needed.
Damage State 2 (DS2)	Moderate damage where components have flooding damage and some may have had structural damage and may need replacement.	Shorting, and loss of service, major repairs or replacement of parts.
Damage State 3 (DS3)	Complete damage where components have been washed away.	Loss of service and major replacements or rebuild required.

For each component and each damage state (e.g. Damage State 1 for utility poles), the flow depth at which this damage level would likely occur (i.e. probability > 0%) and always occur (i.e. probability = 100%) were defined by the expert panel. These flow depth levels were then used to constrain the end points (i.e. 0 and 100% probability) in the fragility curves shown in Figure 37 and Figure 38. A lognormal curve was then fitted between these points to define the fragility function.

Table A4 Damage state definitions for utility poles.

Damage State	Damage	Serviceability
Damage State 1 (DS1)	Minor damage to pole and overhead services. Pole may be leaning and services most likely have experienced water damage.	Shorting and loss of service. Minor repairs needed and pole realignment. Some components may need replacing due to salt-water intrusion.
Damage State 2 (DS2)	Complete damage, pole and services washed away.	Replacement needed.

Lifeline Component	Flow Depth < 0.5m		Flow Depth 0.5m – 2m		Flow Depth >2m		Information Quality	Sources
	Probability of Damage	Damage Type	Probability of Damage	Damage Type	Probability of Damage	Damage Type		
Transportation								
Roads								
Pavement	Low	Silt and light debris coverage, ponding	Medium	Debris & sediment coverage, scour of weak base materials and near culverts, removal of signage and markings, ponding.	Medium-High	Debris strikes, scour of base materials and near culverts, lifting of carriage-way, removal of barriers and signage, cracking of pavement, liquefaction of base materials, ponding, debris and sediment coverage.	High	(American Society of Civil Engineers, 2005; AON Benfield, 2011; Auckland Engineering Lifelines, 2014; Robert; Bell et al., 2005; Edwards, 2006; Eguchi, Eguchi, Bouabid, Koshimura, & Graf, 2013; Francis, 2006; Ghobarah, Saatcioglu, & Nistor, 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Kim, Marshall, & Pal, 2014; Lekkas, 2011; Okal et al., 2010; PIANC Working Group 53, 2009; Suppasri, Mas, & Imamura, 2013; Tang & Edwards, 2012; Unjoh, 2012; Yeh, Sato, & Tajima, 2013)
Bridges	Negligible-Low	Superficial debris strikes	Medium	Some bank/abutment/wingwall erosion, superficial debris strikes, sediment deposition, scour of footings, corrosion, washout of light timber structures	High	Debris and sediment deposition, erosion of adjoining banks/abutments/wingwalls, loss of signage and markings, side barriers bent or sheared, debris strikes, scour of footings, aggradation of waterway, widening of waterway separation of deck from footings, lateral distortion of super structure, separation of girders, washout of superstructure, corrosion, damage to utilities across bridge	High	(Akiyama, Frangopol, Arai, & Koshimura, 2013; American Society of Civil Engineers, 2005; AON Benfield, 2011; Auckland Engineering Lifelines, 2014; Robert Bell et al., 2005; Edwards, 2006; Eguchi et al., 2013; Evans & McGhie, 2011; Francis, 2006; Frangopol & Bocchini, 2012; Ghobarah et al., 2006; Horspool & Fraser, 2015; Horspool et al., 2016;Iemura, Harris, & Yoshikazu, 2005; Kazama & Noda, 2012; Kim et al., 2014; Kosa, 2012; Lekkas, 2011; LRFD, 2010; Number, Lamichhane, Marin-artieda, & Engineering, n.d.; PIANC Working Group 53, 2009; Saatcioglu, 2007; Sagara & Ishiwatari, 2012; Tang & Edwards, 2012; University of Hawaii, 2015; Unjoh, 2012)
Lighting	Low	Damage to electrical components	Medium-High	Debris strikes, inundation of electrical components, tilting or shearing of supports	High	Complete washout, Debris strikes, inundation of electrical components, tilting or shearing of supports	Low	(American Society of Civil Engineers, 2005; Francis, 2006; Horspool & Fraser, 2015; Kazama & Noda, 2012; Scawthorn, Ono, Iemura, Ridha, & Purwanto, 2006)
Vehicles	Low	Damage to electrical components	High	electrical short, floating, debris strikes, impact damage	High	Electrical short, floating, debris strikes, impact damage	Low	(American Society of Civil Engineers, 2005; Nakanishi, Black, & Matsuo, 2014; Okal et al., 2010; PIANC Working Group 53, 2009; Suppasri et al., 2013; Tomita, Yeom, Tatsumi, Okamoto, & Kawai, 2011)
Rail								
Tracks	Low	Sediment deposition, minor scour of ballast	Medium-High	Scour of ballast, lateral movement of tracks, debris and sediment deposition, disruption to signage and lighting	High	Scour of ballast, , debris and sediment deposition, loss of signage and lighting, distortion, lateral movement or washout of track	Medium	(American Society of Civil Engineers, 2005; Francis, 2006; Goff et al., 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Lekkas, 2011; Sagara & Ishiwatari, 2012; Tang & Edwards, 2012)
Bridges	Low	Superficial debris strikes	Medium	Some bank erosion, superficial debris strikes, sediment deposition, scour of footings, corrosion, washout of light timber structures	High	Debris and sediment deposition, erosion of adjoining banks, loss of signage and markings, side barriers bent or sheared, debris strikes, scour of footings, aggradation of waterway, widening of waterway separation of deck from footings, lateral distortion of super structure, separation of girders, washout of superstructure, corrosion, loss of utilities across bridge	Medium	(Akiyama et al., 2013; American Society of Civil Engineers, 2005; AON Benfield, 2011; Auckland Engineering Lifelines, 2014; Robert Bell et al., 2005; Edwards, 2006; Eguchi et al., 2013; Evans & McGhie, 2011; Francis, 2006; Frangopol & Bocchini, 2012; Ghobarah et al., 2006; Horspool & Fraser, 2015; Iemura et al., 2005; Kazama & Noda, 2012; Kim et al., 2014; Kosa, 2012; Lekkas, 2011; LRFD, 2010; Number et al., n.d.; PIANC Working Group 53, 2009; Saatcioglu, 2007; Sagara & Ishiwatari, 2012; Tang & Edwards, 2012; University of Hawaii, 2015; Unjoh, 2012)
Stations/Depots	Low	Water damage to interiors	High	Water damage to interiors wall washout, short circuiting of electrical components and machinery, corrosion, debris strikes	High	Water damage to interiors, wall collapse, short circuiting of electrical components and machinery, corrosion, debris strikes, washout	Medium	(American Society of Civil Engineers, 2005; Horspool & Fraser, 2015; Reese et al., 2011; Sagara & Ishiwatari, 2012; Tang & Edwards, 2012)
Overhead lines	Low	Scour of support foundations, shorting of low lying electrical equipment	High	Scour of support foundations, distortion of supports, collapse, debris strikes, shorting of low lying electrical equipment	High	Scour of support foundation, distortion of supports, collapse, short circuiting, debris strikes , washout of poles, removal of overhead lines (if water level reaches lines)	Low	(Francis, 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Sagara & Ishiwatari, 2012)
Trains	Negligible	Negligible	Low - High	Derailment, debris strikes, floating, impact damage	High	Derailment, debris strikes, floating, impact damage	Low	(American Society of Civil Engineers, 2005; AON Benfield, 2011; Goff et al., 2006; Horspool & Fraser, 2015; Kazama & Noda, 2012)
Ports								
Wharves and piers	Negligible-Low	Debris strikes, scour of foundations	Medium	Sediment and debris deposition, debris strikes, scour of seabed, debris in waterways, scour of foundations, lifting of wharf slabs if poorly tied	High	Aggradation/erosion of sea bed, separation of deck slabs from footings, removal of concrete blocks, subsidence, collapse, complete washout, debris in waterways	Medium	(American Society of Civil Engineers, 2005; Auckland Engineering Lifelines, 2014; Robert; Bell et al., 2005; Evans & McGhie, 2011; Francis, 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Lekkas, 2011; PIANC Working Group 53, 2009; Saatcioglu, 2007; Sagara & Ishiwatari, 2012; Scawthorn et al., 2006; Tang & Edwards, 2012; Tomita et al., 2011)

Lifeline Component	Flow Depth < 0.5m		Flow Depth 0.5m – 2m		Flow Depth >2m		Information Quality	Sources
	Probability of Damage	Damage Type	Probability of Damage	Damage Type	Probability of Damage	Damage Type		
Buildings	Low-Medium	Water damage to interiors & stored goods	High	Water damage to interiors & stored goods, short circuiting of electrical components, washout of lightweight structures (timber and light steel)	High	Water damage to interiors & stored goods, short circuiting of electrical components, washout of lightweight structures and non-structural damage reinforced concrete buildings	High	(American Society of Civil Engineers, 2005; Auckland Engineering Lifelines, 2014; Evans & McGhie, 2011; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Lekkas, 2011; PIANC Working Group 53, 2009; Reese et al., 2011)
Plant Machinery	Low	Water damage to electrical components	High	Water damage to electrical components, debris strikes, floatation of equipment	High	Water damage to electrical components, debris strikes, washout	Medium	(American Society of Civil Engineers, 2005; Auckland Engineering Lifelines, 2014; Robert; Bell et al., 2005; Graf, Lee, & Eguchi, 2014; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012)
Vessels	Negligible-Low	Broken moorings, debris strikes, impact damage	Medium-High	Broken moorings, debris damage, impact damage, floated inland	High	Broken moorings, debris damage, impact damage, floated inland, capsized, submerged	High	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Cruz, Franchello, & Krausmann, 2009; Fritz et al., 2011; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Kurian, Prakash, & Baba, 2007; Lekkas, 2011; Leone, Lavigne, Paris, Denain, & Vinet, 2011; PIANC Working Group 53, 2009; Saatcioglu, 2007; Scawthorn et al., 2006; Tang & Edwards, 2012; Tomita et al., 2011)
Containers	Negligible	Negligible	Medium	Floating of container, impact damage, debris strikes, water & impact damage to goods, dangerous goods exposed, carried inland	High	Floating of container, carried inland, impact damage, debris strikes, water & impact damage to goods, dangerous goods exposed, distorted, crushed	Medium	(American Society of Civil Engineers, 2005; Cruz et al., 2009; Fritz et al., 2011; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Lekkas, 2011; PIANC Working Group 53, 2009; Tang & Edwards, 2012; Tomita et al., 2011)
Airports								
Runway	Low	Silt & light debris coverage, ponding, shorting of low lying electronic components	High	Damage to lighting, debris coverage, ponding, shorting of electronic components	High	Damage to lighting, debris coverage, ponding, shorting of electronic components	Low	(American Society of Civil Engineers, 2005; AON Benfield, 2011; Robert; Bell et al., 2005; Horspool & Fraser, 2015; McClelland, 2011; Sagara & Ishiwatari, 2012; Tang & Edwards, 2012)
Buildings	Low	Silt infiltration, water damage to interiors	High	Silt infiltration, water damage to interiors, wall washout, scour of foundations	High	Debris strikes, water damage to interiors, structural collapse, scour of foundations, wall washout, complete washout,	High	(American Society of Civil Engineers, 2005; AON Benfield, 2011; Francis, 2006; Horspool & Fraser, 2015; Reese et al., 2011; Sagara & Ishiwatari, 2012; Suppasri et al., 2013; Tang & Edwards, 2012)
Plant Machinery	Low	Water damage to electrical components	High	water damage to electrical components, debris strikes	High	water damage to electrical components, debris strikes, impact damage, washout	Low	(American Society of Civil Engineers, 2005; Auckland Engineering Lifelines, 2014; Robert; Bell et al., 2005; Graf et al., 2014; Horspool & Fraser, 2015; Kazama & Noda, 2012)
Planes	Negligible	Negligible	High	Small planes floated, debris strikes, impact damage	High	Planes floated, debris strikes, impact damage, fuel tanks breached	Low	(Horspool & Fraser, 2015)
Energy								
Electricity								
Overhead Power Lines	Negligible	Negligible	Low-Medium	Lines severed from pulling of utility poles, shorting of inundated transformers	High	Debris strikes, lines severed and washed away if reached by water, short circuiting, water damage, shorting of transformers	Medium	(American Society of Civil Engineers, 2005; Edwards, 2006; Evans & McGhie, 2011; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012)
Buried Power Lines	Negligible - Low	Water infiltration of compromised cable housing	Low	Scour at building entry points, scour of backfill, exposure, water infiltration of compromised cable housing , ducting & cables across waterways or below bridges severed	Low-Medium	Scour at building entry points, scour of backfill, exposure, water infiltration of compromised cable housing , ducting & cables across waterways or below bridges severed, ducting & cables severed	Low	(Auckland Engineering Lifelines, 2014; Francis, 2006; Horspool & Fraser, 2015; Horspool et al., 2016)
Utility Poles	Negligible	Negligible	Low-Medium	Some debris strikes causing leaning or washout, scour of foundations (more if set in soil), shorting of inundated transformers	High	Debris strikes causing leaning or washout, scour and liquefaction of foundations (more if set in soil), shorting of inundated transformers, tilting, shearing of base, washout	Medium	(American Society of Civil Engineers, 2005; Francis, 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Scawthorn et al., 2006)
Sub-stations	Negligible-Low	Shorting of low lying electrical components, silt coverage	Medium-High	Salt water contamination to electrical components & structures, debris and sediment cover, debris strikes, non-structural collapse to building, washout of some outdoor components	High	Salt water contamination to electrical components and structures, debris and sediment cover, debris strikes, non-structural collapse of building, washout	Low	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Edwards, 2006; Horspool & Fraser, 2015; Kazama & Noda, 2012; Scawthorn et al., 2006; Tang & Edwards, 2012)

Lifeline Component	**Flow Depth < 0.5m**		**Flow Depth 0.5m – 2m**		**Flow Depth >2m**		**Information Quality**	**Sources**
	Probability of Damage	**Damage Type**	**Probability of Damage**	**Damage Type**	**Probability of Damage**	**Damage Type**		
Power Stations	Negligible	Negligible	Medium - High	Salt Water contamination to electrical components and structures, debris and sediment cover, non-structural collapse of building, washout of some outdoor components	High	Salt water contamination to electrical components and structures, debris and sediment cover, non-structural collapse, washout, shut down of cooling systems	Low	(American Society of Civil Engineers, 2005; AON Benfield, 2011; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Scawthorn et al., 2006)
Petroleum								
Tanks	Negligible	Negligible	Negligible - Low	Debris strikes, buckling of tank base, lifting of empty or small tanks, scour of foundations	Medium-High	Sliding, overturning , debris strikes, scour & liquefaction of foundations floating, impact damage, crushing, loss of fuel, fires	Low	(AON Benfield, 2011; Cruz et al., 2009; Francis, 2006; Ghobarah et al., 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Kim et al., 2014; McClelland, 2011; Saatcioglu, 2007; Scawthorn et al., 2006; Tang & Edwards, 2012; Tomita et al., 2011)
Pipes	Negligible	Negligible	Low-Medium	Scour and exposure of buried pipes, utility bridges severed, pipes attached to mobilised tanks severed, debris strikes	Medium	Scour and exposure of buried pipes, utility bridges severed, pipes attached to mobilised tanks severed, debris strikes decoupling, fire	Low	(AON Benfield, 2011; Cruz et al., 2009; Francis, 2006; Ghobarah et al., 2006; Horspool & Fraser, 2015)
Refinery Facilities	Low	Light debris and silt coverage shorting of low lying electrical components & plant machinery	High	Debris coverage, debris strikes, shorting of electrical components and plant machinery, oil spillage, non-structural collapse of buildings, washout of light structures, washout of outdoor components, fire, explosions	High	Debris coverage, debris strikes, shorting of electrical components and plant machinery, oil spillage, non-structural collapse of buildings, fire, explosions, washout	Medium	(Cruz et al., 2009; Graf et al., 2014; Reese et al., 2011; Tang & Edwards, 2012)
Gas								
Storage	Low	Scour of foundations	Low-Medium	Lifting of empty and small tanks, debris strikes, scour to foundations	High	Scour of foundations, displacement of tanks, debris strikes, fires	Medium	(Auckland Engineering Lifelines, 2014; Eguchi et al., 2013; Francis, 2006; Horspool & Fraser, 2015; Kazama & Noda, 2012; Nojima, 2012; Scawthorn et al., 2006; Tang & Edwards, 2012)
Pipes	Low	Scour of backfill	Low	Scour of weak backfill, exposure, pipes crossing waterways and above ground meters and valves damaged by debris impacts,	Low-Medium	Bending and breakage, decoupling at entry point to buildings & floated tanks, scouring & exposure, fracturing, siltation, blockage, fire, wastage, above ground meters and valves damaged by debris impacts	Low	(Francis, 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Nojima, 2012; Tang & Edwards, 2012)
Water								
Waste Water & Sewerage								
Pipes	Low	Silt infiltration	Low	Siltation, scour of weak backfill, exposure, bending, debris strikes, damage to water meters, utility bridges severed by debris strikes	Medium	Scour, bending and breakage, decoupling & exposure, fracturing, siltation, blockage, utility bridges severed	Medium	(American Society of Civil Engineers, 2005; Auckland Engineering Lifelines, 2014; Edwards, 2006; Eguchi et al., 2013; Francis, 2006; Ghobarah et al., 2006; Horspool & Fraser, 2015; Kim et al., 2014; Lekkas, 2011; Matsuhashi, Fukatani, Yokota, Ozaki, & Horie, 2012; Sagara & Ishiwatari, 2012; Tang & Edwards, 2012; Villholth & Neupane, 2011)
Pumping Stations	Negligible – Low	Inundation of some electrical components	High	Contamination & failure of electrical & pumping equipment, sediment & debris cover, debris strikes, damage to filters	High	Contamination & failure of electrical & pumping equipment, sediment & debris cover, debris strikes, structural collapse, equipment washout, often only inground equipment remaining	Medium	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Edwards, 2006; Eguchi et al., 2013; Horspool & Fraser, 2015; Horspool et al., 2016; Scawthorn et al., 2006)
Septic Tanks	Low	Salt water contamination	Low	Floating of exposed low volume polyurethane tanks, sedimentation, scour of weak backfill	Medium	Sediment infill, scour, floating of low volume tanks	Low	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Edwards, 2006; Francis, 2006; Horspool & Fraser, 2015; Villholth & Neupane, 2011)
Treatment Facilities	Medium–High	Salt water contamination	High	Siltation, erosion of embankments, inundation of machinery, water damage of structure interiors, salt water contamination of filters pumps & ponds	High	Siltation, erosion of embankments, inundation of machinery, water damage of structure interiors, salt water contamination of filters pumps & ponds, washout	Medium	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Edwards, 2006; Eguchi et al., 2013; Horspool & Fraser, 2015; Kazama & Noda, 2012; Matsuhashi et al., 2012; Sagara & Ishiwatari, 2012; Scawthorn et al., 2006; Villholth & Neupane, 2011)
Drinking Water								
Pipes	Low	Minor siltation	Low	Scouring, exposure and floatation, debris strikes, damage at bridges	Medium	Scouring, exposure and floatation, debris strikes, damage at bridges	Medium	(American Society of Civil Engineers, 2005; Auckland Engineering Lifelines, 2014; Edwards, 2006; Eguchi et al., 2013; Francis, 2006; Ghobarah et al., 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Lekkas, 2011; Miyajima, 2014; Scawthorn et al., 2006; Tang & Edwards, 2012; Villholth & Neupane, 2011)

Lifeline Component	Flow Depth < 0.5m		Flow Depth 0.5m – 2m		Flow Depth >2m		Information Quality	Sources
	Probability of Damage	Damage Type	Probability of Damage	Damage Type	Probability of Damage	Damage Type		
Wells	Medium	Salt water contamination of shallow wells	High	Salt water & sewage contamination, groundwater contamination, debris strikes to components	High	Salt water & sewage contamination, ground water & aquifer contamination, scour, debris strikes, components exposed & washed away	Low	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Chandrasekar & Ramesh, 2007; Edwards, 2006; Horspool & Fraser, 2015; Kim et al., 2014; Villholth & Neupane, 2011)
Storage	Low	Salt water contamination	Low-Medium	Salt water and sewage contamination, siltation, debris strikes to tanks & reservoir embankments, low volume polyurethane tanks floated, scour of foundations, tilting of water towers	High	Salt water and sewage contamination, siltation, debris strikes to tanks & reservoir embankments, low volume polyurethane tanks floated, scour of foundations, tilting of water towers, floating of low volume concrete reservoirs, washout	Low	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Edwards, 2006; Francis, 2006; Horspool & Fraser, 2015; Villholth & Neupane, 2011)
Treatment & Pump Facilities	Low	Water damage to electrical & mechanical equipment	Medium-High	Water damage to structure interiors, salt & sewage contamination, equipment & machinery washed away, damage to electrical equipment	High	Water damage to interiors, salt & sewage contamination, collapse of structures, equipment & machinery washed away, damage to electrical equipment	Medium	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Edwards, 2006; Eguchi et al., 2013; Horspool et al., 2016; Scawthorn et al., 2006; Villholth & Neupane, 2011)
Storm Water								
Outflows	High	Sediment infiltration, scour	High	Scour, debris & sediment blockage of pipes, scour around pipe or outtake	High	Scour, debris & sediment blockage at outflow, siltation of pipes, collapse of outflows, washout or scour around pipe	Medium	(Auckland Engineering Lifelines, 2014, Horspool et al., 2016)
Open drains and channels	Medium	Debris blockage	High	Scour of embankments, debris blockage, siltation, blocked culverts, removal of vegetation	High	Scour of embankments, debris blockage, siltation, blocked culverts, removal of vegetation, widening of unreinforced channels, covers lifted	Medium	(Auckland Engineering Lifelines, 2014; Edwards, 2006; Francis, 2006; Ghobarah et al., 2006; Goff et al., 2006; Horspool et al., 2016; Kazama & Noda, 2012; Villholth & Neupane, 2011)
Irrigation								
Canals	Medium	Debris blockage, siltation, salt contamination	High	Scour of embankments, debris blockage, siltation, removal of vegetation, salt contamination	High	Scour of embankments, debris blockage, siltation, removal of vegetation, salt contamination	Low	(American Society of Civil Engineers, 2005; Kurian et al., 2007)
Storage	Low	Salt contamination	Low-Medium	Salt contamination, scour of foundations, floating of low volume polyurethane tanks	High	Salt contamination, scour of foundations, floating of tanks, floating of low volume concrete reservoirs	Low	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Edwards, 2006; Francis, 2006; Horspool & Fraser, 2015; Villholth & Neupane, 2011)
Machinery	Negligible - Low	Debris strikes	Medium	Debris strikes, water damage to electrical components, washout of outdoor equipment	High	Debris strikes, water damage to electrical components , washout	Low	(American Society of Civil Engineers, 2005; Auckland Engineering Lifelines, 2014; Robert; Bell et al., 2005; Graf, Lee, & Eguchi, 2014; Horspool & Fraser, 2015; Kazama & Noda, 2012)
Pipes	Low	Minor siltation	Low	Scouring of weak backfill, exposure, debris strikes, utility bridges cracked or severed, decoupling	Medium	Scouring and exposure, debris strikes, fracturing, siltation, blockages, severed, decoupling	Low	(American Society of Civil Engineers, 2005; Auckland Engineering Lifelines, 2014; Edwards, 2006; Eguchi et al., 2013; Francis, 2006; Ghobarah et al., 2006; Horspool & Fraser, 2015; Kazama & Noda, 2012; Lekkas, 2011; Miyajima, 2014; Scawthorn et al., 2006; Tang & Edwards, 2012; Villholth & Neupane, 2011)
Pumping Stations	Negligible – Low	Inundation of some electrical components	High	Contamination & failure of electrical and pumping equipment, sediment & debris cover, debris strikes	High	Contamination & failure of electrical and pumping equipment, sediment & debris cover, debris strikes, structural collapse, equipment washout	Medium	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Edwards, 2006; Eguchi et al., 2013; Horspool & Fraser, 2015; Scawthorn et al., 2006)
Flood control								
Stop banks	Negligible	Negligible	Low	Removal of vegetation, scour particularly at base	Medium	Scour at base, piping, removal of vegetation, blowouts, washout	Low	(Robert; Bell et al., 2005; Chandrasekar & Ramesh, 2007; Francis, 2006; Hart & Knight, 2009; Horspool et al., 2016)
Walls	Negligible	Negligible	Low	Scour of foundations, tilting of concrete blocks	Medium-High	Liquefaction and scour of foundations, tilting of concrete blocks, removal of materials - especially on backside & wall breaks	Low	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Cruz et al., 2009; Edwards, 2006; Francis, 2006; Kazama & Noda, 2012; Kurian et al., 2007; Lekkas, 2011; Saatcioglu, 2007; Suppasri et al., 2013; Yeh et al., 2013)
Coastal Management								
Sea walls	Negligible	Negligible	Medium	Scour of base and foundations, washout or movement of concrete or boulders	High	Liquefaction and scour of foundations, tilting of concrete blocks or boulders, removal of materials - especially on backside & wall breaks	Medium	(American Society of Civil Engineers, 2005; Robert; Bell et al., 2005; Cruz et al., 2009; Edwards, 2006; Horspool et al., 2016; Kazama & Noda, 2012; Kurian et al., 2007; Lekkas, 2011; Saatcioglu, 2007; Suppasri et al., 2013; Yeh et al., 2013)
Breakwaters	Negligible	Negligible	Medium	Scour of base and foundations, some partial washout	High	Liquefaction and scour of base and foundations, washout	Medium	(American Society of Civil Engineers, 2005; Francis, 2006; Horspool et al., 2016; Kazama & Noda, 2012; Lekkas, 2011; Suppasri et al., 2013; Tomita et al., 2011)

Lifeline Component	Flow Depth < 0.5m		Flow Depth 0.5m – 2m		Flow Depth >2m		Information Quality	Sources
	Probability of Damage	Damage Type	Probability of Damage	Damage Type	Probability of Damage	Damage Type		
Dunes and Embankments	Negligible	Negligible	Low	Removal of vegetation, scour, debris coverage	Low – Medium	Loss of vegetation, scour, debris coverage, migration, washout	Low	(Robert; Bell et al., 2005; Chandrasekar & Ramesh, 2007; Hart & Knight, 2009)
Telecommunications								
Wireless								
Cellular Towers	Low	Erosion of base, tilting of supports	High	Erosion of base, titling, debris strikes that may cause leaning or washout, water damage of electrical components, buckling of monopole structures, washout of base station	High	Erosion of base, titling, debris strikes, water damage of electrical components, collapse of tower, collapse of low rise supporting buildings, twisting of lattice type towers, washout of base stations, washout	Medium	(Edwards, 2006; Ghobarah et al., 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Kwasinski & Tang, 2012; Kwasinski, 2013; Lekkas, 2011; Nagayama, 2011; Tang & Edwards, 2012)
Exchange centres	High	Minor water damage to interiors & low lying generators	High	Scour of cables entering building, water damage to interior, shorting of electrical components & generators	High	Scour, damage to interiors, shorting of electrical components and generators, equipment washed away, collapse, washout	Medium	(Edwards, 2006; Francis, 2006; Horspool & Fraser, 2015; Kazama & Noda, 2012; Kwasinski, 2013; Nagayama, 2011; Scawthorn et al., 2006; Tang & Edwards, 2012)
Radio transmitters	Low	Erosion of tower base, tilting of supports	High	Erosion of tower base, titling, debris strikes, collapse of support towers	High	Erosion of base, titling, debris strikes, collapse of tower, collapse of low rise supporting buildings, washout	Low	(Ghobarah et al., 2006; Horspool & Fraser, 2015; Kwasinski, 2013; Scawthorn et al., 2006)
Internet								
Overhead Cables	Low	Scour of support base	High	Debris impacts to support, tilting or washout of utility pole if struck by debris, cables severed, water damage to low lying components	High	Debris impacts to support, tilting of support pole, collapse of support, cables severed or washed away, water damage to components, collapse of support	Medium	(Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; McClelland, 2011; Nagayama, 2011)
Buried cables	Low	Scour of weak backfill material, shorting of home switch boxes	Medium	Scoured and exposed – especially at entrance to buildings, ducting & cables across waterways severed, debris impacts, corrosion	Medium	Scoured and exposed – especially at entrance to buildings, ducting & cables across waterways severed, debris impacts, corrosion	Low	(Francis, 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Kwasinski & Tang, 2012; Kwasinski, 2013; Nagayama, 2011)
Switch boxes	Medium	Water damage to internal components	High	Debris impacts, water damage to internal components, washout	High	Debris impacts, water damage to internal components, washout	Low	(Horspool & Fraser, 2015; Kazama & Noda, 2012)
Landline								
Overhead cables	Low	Scour of foundation of poles, partciularly if set in soil	High	Debris impacts to support, tilting or washout of support pole, cables severed, water damage to components	High	Debris impacts to poles causing tilting or washout of pole and lines, some shearing of pole base, cables severed if reached by water, water damage to components	Medium	(Horspool & Fraser, 2015; Horspool et al., 2016; Kazama & Noda, 2012; Kwasinski & Tang, 2012; Kwasinski, 2013; McClelland, 2011; Nagayama, 2011; Scawthorn et al., 2006)
Buried cables	Low	Scour of backfill material	Medium	Scoured and exposed – especially at entrance to buildings, ducting & cables across waterways damaged or severed, corrosion if cable housing compromised	Medium - High	Scoured and exposed – especially at entrance to buildings, ducting & cables across waterways severed, debris impacts, corrosion if cable housing compromised	Low	(Francis, 2006; Horspool & Fraser, 2015; Horspool et al., 2016; Kwasinski & Tang, 2012; Kwasinski, 2013; Nagayama, 2011)
Exchange centres	Medium	Minor water damage to interiors	High	Scour of foundations, water damage to interiors, short circuiting of electrical components, washout of light structures	High	Scour of foundations, water damage to interiors, short circuiting of electrical components, collapse, washout	Medium	(Francis, 2006; Horspool & Fraser, 2015; Kazama & Noda, 2012; Kwasinski & Tang, 2012; Kwasinski, 2013; McClelland, 2011; Nagayama, 2011; Scawthorn et al., 2006; Tang & Edwards, 2012)
Switch boxes	Medium	Water damage to internal components	High	Debris impacts, water damage to internal components, washout	High	Debris impacts, water damage to internal components, washout	Low	(Horspool & Fraser, 2015; Kazama & Noda, 2012)

Information Quality Rating:

Low: Observations from one tsunami event with little or no quantitative damage information available

Medium: Observations from more than one tsunami event with little quantitative damage information available

High: Observations from more than one tsunami event with comprehensive quantitative damage information available

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