2.0 TSUNAMI IMPACTS

2.1 INTRODUCTION

Compared to other perils tsunami are rare events, but they can be extremely destructive. Coastlines have always been a favoured location for human settlements, and coastal communities have continued to develop in recent times. Consequently, more people and facilities are now at risk from tsunami. Tsunami risk is a function of three factors: 1) the nature and extent of the tsunami hazard; 2) the characteristics of the coastline; and 3) the degree of exposure and vulnerability of people and the built environment (United States National Tsunami Hazard Mitigation Program, 2001).

Unlike earthquakes, where damage is normally confined to a smaller area, tsunami impact long stretches of coastlines, often entire ocean basins. They usually extend inland for a few hundred metres, possibly up to several kilometres in low-lying areas. Onshore behaviour and characteristics of tsunami are also quite distinct from other coastal hazards (Yeh, 2009). Inundation depth, run-up and consequently the level of damage vary significantly over short distances due to a number of factors, including the topography and geomorphology of the coast—near-shore bathymetry, beach slope, coastal orientation and configuration, and direction of the arriving waves (Ghobarah et al., 2006; Reese et al., 2007; Rossetto et al., 2007). In addition, the complex interactions between tsunami and the land surface cause unique wave patterns, with large-scale reflection and refraction (Salinas et al., 2005). Bays, sounds, inlets, rivers, streams, offshore canyons, islands, or artificial channels can amplify the wave height and exacerbate local damage.

2.2 TSUNAMI RISK

The simplest definition of risk is

$R = F \times D$

where F is the frequency or likelihood of an event occurring and D is the damage or consequences (Standards Australia and Standards New Zealand, 2004; Hollenstein, 2005). Hollenstein (2005) recommends extending the definition for natural hazard applications by defining the hazard as probability P (or its reciprocal, the return period) and an intensity I. He also splits the consequences into two factors—exposure E (describing the spatial and temporal distribution of the assets) and vulnerability V. The vulnerability provides a means to estimate impacts; it is the relative fragility to damage or harm of the exposed assets or people, to the hazard at that magnitude. For example, for a given hazard exposure, some assets may remain undamaged due to their strength or the hazard protection measures in place, whereas other weaker or more vulnerable structures may suffer a degree of damage.

That results in the following risk definition:

$R = P \times I \times E \times V$

Sometimes vulnerability is further broken down into vulnerability and resilience and / or adaptive capacity (Malone, 2009). Despite these slight variations (see Thywissen, 2006 for comparisons), hazard, exposure (magnitude of the hazard that is manifest at the location of assets) and vulnerability are the three common key components of a risk analysis (Figure 2.1).

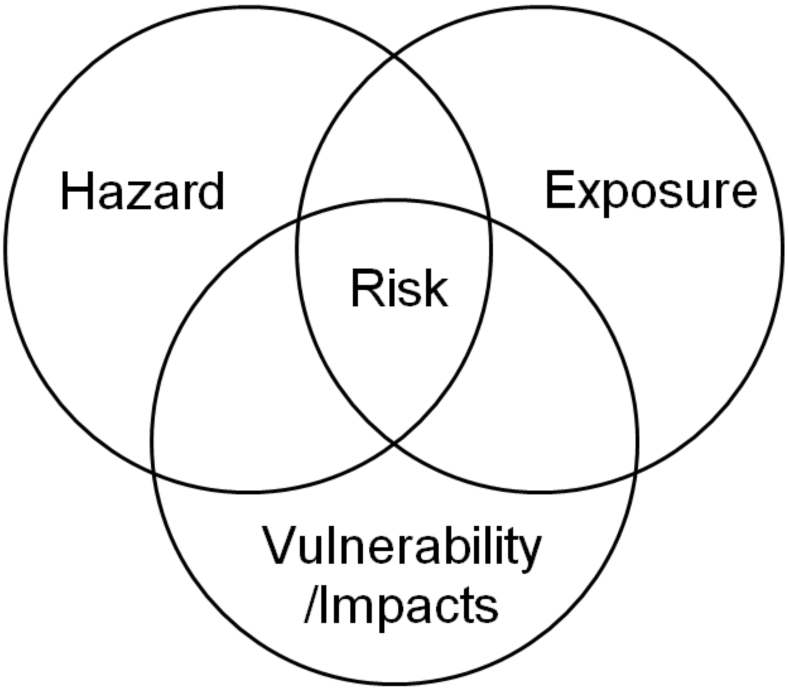

Figure 2.1 The intersection of hazard, exposure, and vulnerability yields the risk (Reese and Schmidt, 2008).

Risk analyses have become almost a standard procedure in dealing with natural hazards. They provide a powerful aid in decision making and offer a structured, systematic and consistent method in order to understand, characterize and quantify risk so it can be managed.

All three components, the hazard assessment as well as the exposure and vulnerability analysis include data collection, modelling, and monitoring of vulnerability factors. From these three assessments, the specific risk can be derived.

2.3 TSUNAMI IMPACT TYPES

In the breakdown of risk given in the previous section, vulnerability refers to the possible impacts of the tsunami. These impacts can be further subdivided into different types. There are many different ways that tsunami impacts have been subdivided, depending on what aspects are being focussed on.

Generally, the effects of any disaster can be categorised into tangible and intangible effects, and into direct and indirect effects (Bureau of Transport Economics, 2001; ECLAC, 2003; UNDP, 2004; Smith and Petley, 2009). Direct effects are the first order and most visible consequences due to the immediate impact, such as structural damage, or if intangible, damage to archaeological sites for instance. Indirect effects emerge later as a consequence of the event, but not due to the direct impact; examples are the disruption of economic and social activities (Bureau of Transport Economics, 2001; Smith and Petley, 2009). Tangible effects can be quantified monetarily, whereas intangible effects cannot. Instead of direct and indirect effects, the terms damages and losses are sometimes used (ECLAC, 2003): Direct damages are the costs of “totally or partially destroyed physical assets and indirect losses are losses in the flows within the economy that arise from the temporary absence of the damaged assets” (ECLAC, 2003). ECLAC (2003) also uses a third category, macroeconomic effects. However, macroeconomic effects are normally covered by assessing direct and indirect impacts. Hence, it is just a complementary way to assess these impacts from a different perspective. They should not be added to direct and indirect impact estimates, as this results in double counting (McKenzie et al., 2005). UNDP (2004) on the other hand classifies “short- and long-term impacts of a disaster on the overall economy and socio-economic conditions (fiscal and monetary performance, effects of relocated workforce, etc.)” as secondary effects. Table 2.1 shows a summary of possible types of direct tsunami damage, depending on the nature of the impact. Table 2.2 summarises the main indirect and intangible impacts of tsunami.

Another categorisation of the direct effects of the tsunami focuses on what aspect of the tsunami caused the damage. Sometimes, most of the damage is caused by the advancing wave front or surge. In other situations, the greatest damage is caused by debris impact, the outflow of water back to the sea, or erosion that can undermine the foundations of structures built along coastlines. Yalciner et al. (2011) classify these factors into i) primary and ii) secondary tsunami impacts:

“Primary impacts of tsunamis are based on (drag, lift and inertia) forces which are caused by hydrostatic and hydrodynamic impacts due to the motion of the water. The forces causing primary impact depend on the shape and characteristics of the structure, flow depth and flow characteristics.

Secondary impacts of tsunamis are caused in general by dragging of objects, debris flow and driftwood, contaminants together with flowing water. Scour around structure foundations can also cause damage. The resonant oscillations of basins can continue the agitations and cause additional damage inside the basins. The contact with water results in damage of certain building components, e.g., insulation, internal lining, floors, electrical system components such as switches, fuse boxes, control panels, air conditioning, hot water cylinders, etc. In some cases fire can also be observed as a secondary impact of tsunami.”

Table 2.1 Potential direct impacts of tsunami.

	People and animals	Built environment	Natural environment
Inundation	Drowning	Damage by inundation/water contact	Disturbance of marine habitats (coral reefs, seagrass beds, lagoons, mangroves, intertidal flats)
		Failure of mechanical equipment, electrical and communication systems and equipment	Loss of protected areas
		Structural damage due to hydrostatic forces (e.g. pressure on outside walls)	Disturbance of terrestrial habitats (forests, wetlands, riverine areas, beaches, dunes, surface and groundwater, soils)
		Damage due to buoyancy (flotation or uplift forces)	Damage to farmland and yield
		Saturation causing slope instability (e.g. stopbanks)	
Currents	Washed off feet	Structures washed away due to hydrodynamic forces (pushing forces and drag)	Loss of coastline/beach, dunes, seagrass beds, etc. due to erosion
	Impact with structures	Walls, fences, road surfaces, railways, ports/harbours, power, telecom poles, gas, oil or water pipelines damaged or destroyed	Breaking and overturning of trees
		Scouring of building or bridge foundations, power poles, coastal or river defences, railways and road embankments	Fish and shellfish thrown ashore, with consequent contamination
		Scattering and subsidence of concrete blocks	Destruction and loss of rafts, fishes and shells in aquaculture
		Ship, boat and wharf damage	Harbour change in water depth (erosion and accumulation)
		Damage to farms buried by sands	Disturbance, soil erosion and siltation
Debris	Injured or killed by debris	Structural damage by debris impact	Hazardous waste
		Rails and roads buried by sediment and debris	Build-up of marine debris
Contamination /Fire	Injury/illness due to contact with contaminated water	Oil spills from vehicles, ships, heaters, storage tanks	Salinisation
		Contamination due to sewage	Contamination of near-shore environment
		Fire from gas or electricity leaks	Eutrophication
		Damage from sediment deposition	
		Fire from waterborne flammable materials	

Table 2.2 Summary of main indirect and intangible impacts of tsunami.

Indirect			
Social	**Infrastructure**	**Economic**	**Intangible**
Increased costs for medical treatment and care	Disruption of networks (roads, lifelines, etc.)	Disruption to flows of goods and services	Inconvenience of disruption of services
Disruption of households (e.g. extra travel costs, temporary accommodation, etc.)	Loss or reduction of earnings and income	Costs of relocation	Health effects
		Additional costs in public sector (e.g. extra staff, training, etc.)	
Increased debts	Loss of production and services		Loss of memorabilia
Increased poverty	Clean-up costs	Disruption of businesses	Loss of confidence
Costs of relocation	Increased operating and distribution costs	Loss or reduction of earnings and income	Loss of contracts
Additional heating costs	Costs of demolition and debris removal	Loss of production and services	Stress, trauma, depression
Loss of jobs / livelihood	Increase in water and sanitation operating costs	Costs of emergency response and relief	Loss of environmental assets
Loss or reduction of earnings and income	Increase communications service during recovery phase	Clean-up costs	Loss of heritage/cultural assets
Increased prices for food, energy, and other products		Decrease in tourism	Loss of tourist attractions
Decreased land-prices		Losses in yields (crop and livestock)	Decrease in air and water quality
Disruption of provision of basic public services (education, health, cultural, etc.)		Revenue losses to federal, regional and local governments (from reduced tax base)	Degradation of landscape quality, loss of biodiversity and soil erosion
Increased operating costs		Costs of higher unemployment	Reduced quality of life, and inequities in the distribution of impacts and disaster relief
		Fewer businesses (due to bankruptcies, etc.)	Lack of food and drinking water
		Costs of responding to new situation (e.g. tourism campaign)	Reduced investor confidence
		Costs of demolition and debris removal	Social conflicts
		Downstream effects of relocation and restructuring on economy and workforce (decline of GDP, decrease in exports, inflation)	

2.4 ASSESSING THE COSTS OF TSUNAMI IMPACTS

Natural disasters are a significant and rising cost to communities and will be exacerbated in most cases by climate change. A rising sea level acts as a kind of a multiplier: as the base sea level is higher, so too will be the elevation of the tsunami as measured relative to the landscape (n.b. measures to mitigate other hazards exacerbated by sea level rise, such as storm surge, may also reduce tsunami risk). Having good information on the costs of natural disasters serves various purposes. According to the Bureau of Transport Economics (2001) “every dollar spent on mitigation is worth two dollars of response and recovery”. Damage or risk assessments / analysis can help assess the effectiveness of different mitigation measures, since they focus on potential damage rather than on individual hazards (Hollenstein, 2005). Emergency managers and planners are also demanding increasingly more quantitative information on possible consequences and the risks associated with different hazards, including tsunami, to be in a position to compare the impacts across the different hazards before making investment decisions on risk reduction for their region (Blong, 2003; Durham, 2003; Reese and Smart, 2008).The economic viability of communities also depends upon the continued operation of infrastructure and essential services. Hence, it is critical to know the risks from natural hazards in order to minimize them.

The cost of tsunami impacts is usually assessed using damage or impact analyses. These are normally part of a comprehensive risk assessment process, which in return should be embedded in an overall risk management framework. The terms “risk analysis”, “risk assessment”, and “risk evaluation” are not consistently used in natural hazard literature. The determination of consequences and likelihood, and hence the level of risk, is normally described as risk analysis (Standards Australia and Standards New Zealand, 2004; ISDR, 2004). However, other authors use the term risk assessment (Dilley, 2005; Hollenstein, 2005). According to the Australian and New Zealand Risk Management Standard (Standards Australia and Standards New Zealand, 2004) risk assessment also includes the process to “determine risk management priorities by evaluating and comparing the level of risk against predetermined standards, target risk levels or other criteria” (see also ISDR, 2004). For the rest of this chapter we will use the terms risk analysis and damage assessment as part of a risk analysis process, because the focus of this chapter lies on the impacts of tsunami.

Damage assessments can be categorised as either ex ante (i.e., occurring before a disaster has occurred and so using either scenarios or probabilistic representations of the hazard) or ex post, occurring after a specific disaster has occurred as a form of post-disaster survey. Ex ante and ex post assessments are essentially the prediction / verification cycle that characterises scientific endeavour. As such, ex post assessments serve to verify how well past ex ante assessments predicted the consequences of a specific disaster and also to provide information for the next round of ex ante assessments in anticipation of future disasters.

If conducted ex-post, these assessments are essential to prioritise relief and rehabilitation needs (McKenzie et al., 2005). They are also necessary for validating scientific models and understanding the limitations and uncertainties of the models and the outputs they produce. This can only be achieved if sufficient validation data is available. Natural disasters provide an invaluable opportunity to capture such data for hazard exposure and risk modelling. However, detailed and comprehensive tsunami impact data is still limited (Douglas, 2007). Apart from validation, post-event assessments also improve our understanding of vulnerability to natural hazards. Observed damage provides useful insights into the factors contributing to building and infrastructure vulnerability and consequential community risk.

Tsunami damage assessments, both ex-ante and ex-post, were very sparse prior to the 2004 Indian Ocean tsunami (Hatori, 1984; Shuto, 1993; Izuka and Matsutomi, 2000; Matsutomi et al., 2001; Papadopoulos and Imamura, 2001). Since the 2004 tsunami, the number of studies has increased significantly. All components of risk, including exposure and vulnerability, can be analysed quantitatively, semi-quantitatively or qualitatively. For each category, examples can be found in the literature:

Qualitative damage analysis (Dalrymple and Kriebel, 2005; EERI, 2005; Stansfield, 2005; Ghobarah et al., 2006;Saatcioglu, 2007; Rosetto et al., 2007; Kaplan et al., 2009);

Semi-quantitative/ index-based approach (Dominey-Howes and Papathoma, 2007; Dall'Osso et al., 2009; Omira et al., 2010; Strunz et al., 2011).

Quantitative using fragility or vulnerability functions (Kimura et al., 2006; Peiris, 2006; Ruangrassamee et al., 2006; Reese et al., 2007; Dias et al., 2009; Koshimura et al., 2009; Koshimura et al., 2009a; Leone et al., 2010; Matsutomi et al., 2010; Murao and Nakazato, 2010;Reese et al., 2011; Suppasri et al., 2011, Valencia et al., 2011[18]) or experimental studies / loadings-based assessments (Okada et al., 2005; Yeh et al., 2005; Palermo and Nistor, 2008; Thusyanthan and Gopal, 2008;Pimanmas et al., 2010; Nistor et al., 2011)

2.4.1 Qualitative damage assessments

All approaches have their advantages and disadvantages. A **qualitative tsunami damage assessment** is descriptive rather than numerical and can rely on relatively coarse data and judgments in order to describe damage or categorise it into order-of-magnitude bands. This approach is resource efficient but fairly subjective. This can be an adequate approach if quantitative precision is not needed, initial screening is required, or numerical, detailed data is not available (Ale, 2002; Standards Australia and New Zealand, 2004). However, the results cannot be compared with other events or hazards, and they are also not suited as baseline data for cost-benefit analysis or to evaluate risk reduction measures. All the above examples are ex-post assessments and summarise impacts and findings from historic events.

For ex-ante analysis, risk matrices (Figure 2.2) are the most common tools. They provide a systematic method for assigning a hazard level to a failure event, based on the severity and frequency of the event. This allows the establishment of risk categories for given combinations of frequency, magnitude and estimated consequences. This approach makes it possible to link the risk analysis results back to risk management actions and decision making. The Australian/New Zealand Risk Management Standard (2004) gives comprehensive instructions on how to use risk matrices.

[18] see Grezio and Tonini (2011) for a comparison of existing tsunami fragility functions.

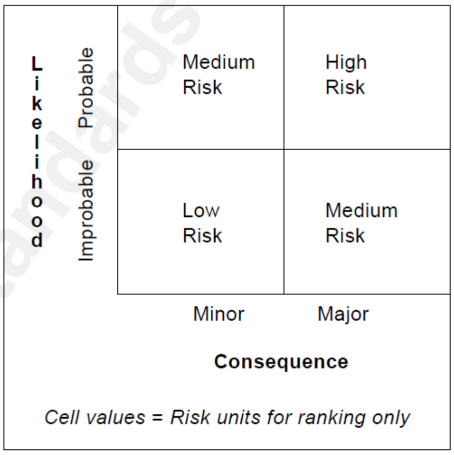

Figure 2.2 Example of a qualitative risk analysis matrix (source: Standards Australia/Standards New Zealand, 2004).

2.4.2 Semi-quantitative damage assessments

Semi-quantitative tsunami assessments provide an intermediate level between the descriptive evaluation of qualitative damage / risk assessment and the numerical evaluation of quantitative risk assessment, by evaluating risks with a score and producing rankings. It is more sophisticated than a qualitative assessment, as it is more consistent and rigorous in assessing and comparing risks and risk management strategies. It requires more data and mathematical skills than a qualitative approach, and avoids some of the greater ambiguities that a qualitative risk assessment may produce (FAO/WHO, 2009). On the other hand, these rankings are not always realistic, nor do the rankings always reflect an accurate relationship to the actual magnitude or consequence of the tsunami (Standards Australia and Standards New Zealand, 2004).

2.4.3 Quantitative damage assessments

"Quantitative assessment can be either deterministic (i.e., single values such as means or percentiles are used to describe model variables) or probabilistic (i.e., probability distributions are used to describe model variables)" (FAO/WHO, 2009). They use numerical values for both consequences and likelihood, using data from experimental studies, and synthetic or historic data (Standards Australia and Standards New Zealand, 2004). They provide more in-depth information and allow cost-benefit analysis to be based on the results. It is important to understand that the results are only as good as the input data, which means the best approach always depends on the circumstances, data and resources available.

2.4.4 Tsunami damage assessments – ex ante

Ex ante tsunami damage assessments are built up using the components of risk described in Section 2.2 above. Depending on how qualitative the assessment is, these components may be broken down into smaller parts and assigned individual values. Qualitative assessments tend to use more broad-brush approaches that may lump several components together. Below we briefly touch on the hazard and the exposure components, but focus mainly on the vulnerability component of the risk.

2.4.4.1 Tsunami hazard

Every disaster starts with a hazard, in this case a tsunami. Much of the rest of this report is dedicated to understanding and quantifying the tsunami hazard. A detailed understanding of what events have occurred in the past (including prehistoric events) and their effects provides the basis for understanding what could or will happen in the future (see Chapter 3). In order to quantify tsunami risk, each magnitude is tied to a specific return period or its inverse, frequency. “The latter ensemble is the magnitude-frequency relationship of a tsunami and it is always an inherent characteristic of a specific locality or region” (Thywissen, 2006). Numerical modelling can simulate events, and compute the wave propagation and its effects on structures that have to be protected.

2.4.4.2 Tsunami exposure

Tsunami exposure is another pre-requisite to quantify the risk of tsunami. In the context of natural disasters, exposure is understood as the number of people and/or other elements at risk that can be affected by a tsunami event (Thywissen, 2006). In an uninhabited area the human exposure is zero, although other elements such as agricultural assets, cultural or natural environments may be at risk. It is the exposure that drives the damage, not the vulnerability. However, vulnerability determines the severity of the impact.

Assessing an area’s tsunami exposure requires a good understanding of the elements at risk within the study area. Elements at risk or assets are spatial-temporal phenomena, valued by human society, and under threat of being damaged by hazards, e.g. buildings, lifelines, business disruption, economic impacts, etc. (Schmidt et al., 2011). The knowledge of the distribution of people, the location and function of critical infrastructure, and the spatial extent, distribution and types of buildings, are the key to determining their exposure to tsunami (Strunz et al., 2011). Also relevant are attributes that characterise the assets and describe their vulnerability pertinent to the specific hazard, e.g. floor height, which determines when the water enters a building.

A consistent national database of the building stock and infrastructure is not currently available in New Zealand. Such a database is essential to conduct damage assessments or risk analysis. The database must be sufficiently detailed to allow robust estimates of loss to be made. Even though most of the required information does exist somewhere, there are currently no joint or governmental efforts to establish such a database. RiskScape, an initiative by GNS Science and the National Institute of Water and Atmospheric Research Ltd. (NIWA) is in the process of developing a national building database as part of the programme. The database will be a key element of the multi-hazard loss modelling tool that is RiskScape. An important part of this database is the building inventory, which will be derived from a national property dataset maintained by Quotable Value Limited (QV), a New Zealand state-owned enterprise for property valuation and information. The inventory is available as point datasets of property centroids with a range of attributes attached to it such as building age, number of storeys, building material, etc. Additional attributes that QV does not hold, such as floor heights or roof pitch, have to be added, based on survey information and proxies. RiskScape will allow users to update the database when additional or more detailed local information is available, so that, with time, the QV data gets replaced with local and more detailed information. The compilation of infrastructure data is significantly more challenging, as most of the data is held by private companies, in different formats with inconsistent information. In some cases there might also be commercial security concerns, so that access has to be restricted.

2.4.4.3 Tsunami vulnerability

Vulnerability refers to the potential for casualties, destruction, disruption or other form of damage or loss with respect to a particular element/asset. Vulnerability is in some ways a predictive parameter and describes the susceptibility of the element at risk. It identifies what may happen to the element under conditions of a particular hazard (Canon et al., 2005). “Vulnerability is a permanent and dynamic feature that is revealed during an event to an extent that depends on the magnitude of the harmful event. This means that vulnerability can often only be measured indirectly and retrospectively, and the dimension normally used for this indirect measure is damage or more general harm. What is normally seen in the aftermath of a disaster is not the vulnerability per se, but the harm done.” (Thywissen, 2006). Risk combines vulnerability with the probable frequency of impact to be expected from a known magnitude of a tsunami or other hazard. Vulnerability should not be confused with exposure; they are two separate, but complementary components of risk (Alexander, 2000).

The vulnerability of an element at risk can be characterised by the relationship between the magnitude of the hazard and the damage it causes. The most common quantitative method to describe vulnerability and estimate potential damage is the fragility and damage function. They are also referred to by a variety of other names, including depth-damage functions or stage-damage curves. According to Douglas (2007) and Schultz et al. (2010), fragility functions are key components in a risk analysis framework because they permit rational decision making for both immediate evacuation due to an incoming tsunami as well as for long-term hazard planning and mitigation. As such, they are the backbone of rigorous risk and damage estimation. Fragility functions were first introduced for conducting seismic risk assessments at nuclear power plants (Kennedy et al., 1980; Kaplan et al., 1983).

Reese et al. (2011) state that, “**fragility functions** describe a (probabilistic) relationship between demand and damage”. Therefore, in the case of structures subjected to tsunami, the demand on structures needs to be quantified as a function of one or more predictor variables such as water depth, velocity, and entrained debris. The observed building and infrastructure damage needs to be catalogued in sufficient detail to enable the post-tsunami damage state (e.g., minor, major, complete damage) of the structure to be obtained, as well as details regarding the building/infrastructure itself, to examine the dependence of fragility on structure type”.

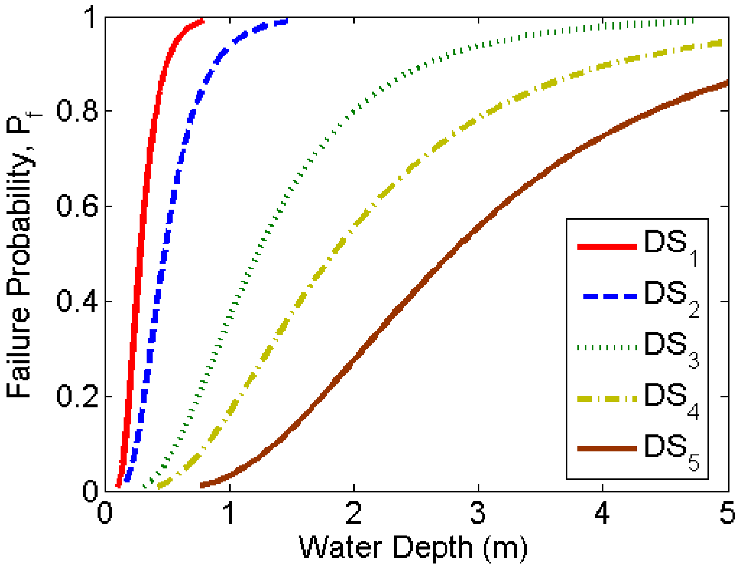

Figure 2.3 Example of tsunami fragility functions (source: Reese et al., 2011); in this case for five different damage states.

For each damage state DSi, the failure probability gives the probability that the building is damaged to at least that state when inundated to a given water depth.

Damage curves or functions, on the other hand, relate tsunami characteristics such as inundation depth, velocity or duration to the percentage damage (relative to replacement cost) for a variety of elements such as buildings, cars, and household goods (Reese and Ramsay, 2010).

Fragility or damage functions are typically based on either:

- Empirical curves developed from historical tsunami and damage survey data, or
- Synthetic functions (hypothetical curves) based on expert opinion developed independently from specific tsunami and damage survey data.

Both methods have their advantages and disadvantages (see Middelmann-Fernandes, 2010). RiskScape for instance uses a combination of both, as it has been found that synthetic damage curves calibrated against observed damage gave the most accurate results (McBean et al., 1986). However, unlike earthquakes, our knowledge about and experience with tsunami vulnerability is limited, and consequently the majority of existing fragility functions are simple empirical ones.

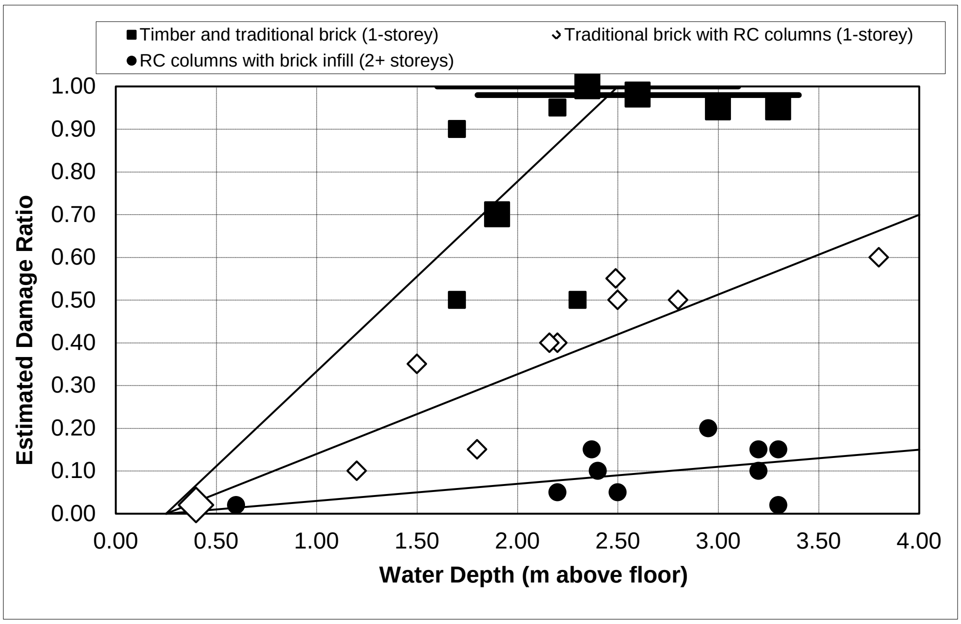

Figure 2.4 Example of tsunami damage functions (source: Reese et al., 2007).

2.4.4.4 Building damage

Table 2.3 gives an overview of existing tsunami studies that quantify building vulnerability and tsunami building damage. Most of the sixteen studies use fragility functions as the preferred method, four use damage functions, and two use judgement criteria (defined tsunami demand parameter thresholds such as critical flow depth or velocity that causes damage or collapse). The majority of the studies use data from the 2004 Indian Ocean tsunami, either collected in field surveys or derived from image interpretation. A few studies have also used numerical modelling to corroborate field data and calculate the hydrological parameters such as flow velocities. This is because usually only inundation depth is recorded in the field. All of the studies use inundation depth as a tsunami demand parameter; only a few have addressed vulnerability due to other predictors such as velocity, debris, etc.

Which of the damage or fragility functions are best suited for the New Zealand building stock? The answer is unfortunately not simple. Why do Murao and Nakazato’s (2010) damage curves, for instance, estimate 45% damage at 4 m inundation, whereas Peiris’ (2006) shows 80% and Kimura et al.’s (2006) 100% at the same depth? Even though the study areas are more or less the same (certain districts in Sri Lanka) the authors used different sources both for their building data (e.g., field surveys, questionnaires and third party) and inundation data (field surveys, modelling and third party). Given the dependence of the final result on these derived functions, it is important to evaluate the accuracy and reliability of the data. Nonetheless, there is always an uncertainty associated with empirical functions, because they are extremely site-dependent and not applicable to other areas without an expert’s adjustment to account for regional and structural differences. There may also be bias due to the specific circumstances of the event the data is based on. If the fragility functions rely on just one demand parameter, for instance inundation depth, and velocity is neglected, the effect is buried in the fragility functions and contributes to the uncertainty (Reese et al., 2011). For these reasons, synthetic fragility functions are often used instead of empirical functions (Middelmann-Fernandez, 2010).

“Empirical fragility functions also often do not take into account mechanical properties of the structure. Because of the time constraints of field surveys, comprehensive structural inspections of buildings are often not feasible. If these differences in the structural capacity are ignored, and the functions are applied to individual structures or smaller clusters of buildings, not all buildings of the same type will suffer the same level of damage for a given event intensity and damage might be under or overestimated. Some of the fragility functions are also based on a relatively small number of field observations and are hence subject to greater uncertainty" (Reese et al., 2011). All these aspects must be taken into account before applying empirical fragility functions to other areas.

Apart from damage and fragility functions and judgement criteria or thresholds, calculating the tsunami load that impacts on a building is another approach to quantify tsunami building damage. Either field survey data is used or physical model laboratory tests are conducted to calculate the load of a tsunami wave. The information is also used for improving the design of coastal structures (Thusyanthan and Gopal, 2008). According to Palermo and Nistor (2008), three parameters are relevant for tsunami-induced forces: (1) Inundation depth, (2) flow velocity, and (3) flow direction. There are static and dynamic loads, the (1) hydrostatic force, (2) hydrodynamic drag force, (3) surge force, (4) buoyancy force and (5) debris impact (Okada et al., 2005; Palermo and Nistor, 2008). Okada et al. (2005) give an overview of previous studies on tsunami wave pressure and forces. Grundy (2008) also notes that it is equally important to address vulnerability to scour, sediment deposit and impact from debris.

Tsunami-induced lateral forces can meet or exceed seismic forces (Palermo and Nistor, 2008), in particular for low-rise buildings (Okada et al., 2005). According to Chan (1994), a water depth of 1.3 m and a velocity of 1.7 m/s results in a maximum wall pressure of 29 kPa, while a 70 cm depth and a velocity of 2 m/s give a peak pressure of 5 kPa (Hattori et al., 1994). That equals the horizontal bracing demand stipulated for an average one-storey house in New Zealand (Berryman, 2005). However, Thurston and King (2003) have shown that if a house is constructed to the New Zealand building code, it may be up to twice as strong as the bracing demand required for a high wind zone. The actual horizontal strength could be in the range 10-40 kPa/m (Berryman, 2005). This is still well below the impact that a tsunami can cause. Thusyanthan and Gopal (2008) have calculated a peak load of 127.5 kPa at a wave velocity of 5 m/s from a wave tank experiment.

The problem with applying this approach is that building strength varies. Matsutomi et al. (2010) states that wooden buildings in Japan and Samoa will be completely destroyed at a drag force of between 9.7 and 17.6 kPa/m, which corresponds with an inundation depth of 2 m or a velocity of 2.9 m/s. For stone/brick buildings, the thresholds lies at 118-215 kPa/m or 7 m inundation depth and 5.5 m/s velocity respectively. There are not only these obvious differences between countries, but also within New Zealand. In order to apply this loadings approach, one would have to define a typical house for each category. However, due to variations in construction methods and techniques, quality of workmanship, ignorance of building codes and standards, deterioration, etc., most buildings, even of the same type and material, will have different strengths. Ideally this approach should quantify the range of strengths that similar sorts of buildings could withstand. This would explain part of the uncertainty encompassed in the fragility functions.

In the absence of robust, well-constructed and validated fragility models, semi-quantitative approaches are a good alternative. The Papathoma Tsunami Vulnerability Assessment (PTVA) Model for instance is such a semi-quantitative approach (see Papathoma et al., 2003; Dominey-Howes and Papathoma, 2007; Dall'Osso et al., 2009). It provides a Relative Vulnerability Index (RVI) for every single building, which can help planners and emergency managers in their decision-making process. The model takes into account all the main factors that influence building vulnerability (Dominey-Howes and Papathoma, 2007;

Middelmann-Fernandez, 2010; Reese et al., 2011) such as number of stories, building material, ground floor openings, shielding and foundations, as well as the shape and orientation of the building. These authors also introduced a multi-criteria approach for weighting the various attributes in order to limit concerns about subjective ranking of attributes (Dall'Osso et al., 2009). This makes the PTVA model a useful tool for the assessment of building vulnerability. Limitations are the high data demands, with detailed information about each building required, as well as not accounting for secondary tsunami impacts such as debris.

2.4.4.5 Casualties

Quantifying disaster-related casualties helps emergency response coordinators and other public health officials respond to the needs of disaster victims (e.g., allocating resources) and develop policies for reducing the injuries and mortality due to future disasters. Understanding disaster impact and casualty factors can aid in anticipating the consequences of future disasters and in developing risk reduction strategies (Doocy et al., 2007).

The causes of injuries and deaths from tsunami are manifold. The most frequent reasons are drowning, people being swept away by fast moving water and impact from debris causing injuries to the head, spinal, thoracic and abdominal regions. Survivable injuries often include near-drowning, aspiration pneumonia, or orthopaedic injuries such as fractures, sprains and strains (Hogan and Burstein, 2007). Warning and evacuation can significantly decrease the number of casualties. A large percentage of tsunami victims are women, the elderly and children, who are often too weak to swim against the bore or not able to escape as fast as other people (Nishikiori et al., 2006; McAdoo et al., 2008; Reese et al., 2011). Nishikiori et al. (2006) identified being indoors at the time of the tsunami and the house destruction level as other risk factors.

Table 2.3 Summary of existing damage and fragility functions (extended from Grezio and Tonini, 2011).

Reference	Tsunami event	Methodology	Demand parameter	Data	Building categories
Hatori (1984) [in Koshimura et al. 2009]	Meiji Sanriku 1896; Showa Sanriku 1933, Chile 1960	Fragility functions	Inundation depth	Field survey	Unknown
Shuto (1993)	Meiji Sanriku 1896	Fragility functions	Inundation depth	Field survey	Unknown
Iizuka and Matsutomi (200) [in Shuto & Arish 2006]	Unknown	Thresholds	Inundation depth (m) Flow velocity (m/s) Hydrodynamic force (KN/m2)	Unknown	Wood Concrete block Reinforced concrete
Kimura et al (2006) [in Murao & Nakazato 2010]	Indian Ocean Tsunami 2004	Damage functions	Inundation depth (m)	Questionnaires	Unknown
Namegaya and Tsuji (2006) [in Koshimura et al. 2009]	Indian Ocean Tsunami 2004	Fragility functions	Inundation depth (m)	Image Interpretation	Unknown
Peiris (2006)	Indian Ocean Tsunami 2004	Fragility functions	Inundation depth (m)	Field survey	Masonry residential
Ruangrassamee et al. (2006)	Indian Ocean Tsunami 2004		Inundation depth Distance from shore	Field survey	Reinforced concrete
Reese et al. (2007)	Java 2006	Damage functions	Inundation depth (m)	Field survey	Timber/Bamboo Brick traditional Brick traditional with reinforced columns Reinforced concrete frame with brick infill walls
Dias et al (2009)	Indian Ocean Tsunami 2004	Fragility functions	Inundation depth (m)	Field survey, Stats	Masonry residential (temporary and permanent materials)
Koshimura et al. (2009)	Indian Ocean Tsunami 2004	Fragility functions	Inundation depth (m) Flow velocity (m/s) Hydrodynamic force (KN/m2)	Field survey, image interpretation and numerical modelling	Low rise wooden houses Timber constructions Non-engineered reinforced constructions
Matsutomi et al. (2010)	Samoa 2009	Thresholds	Inundation depth (m) Flow velocity (m/s)	Field survey and flow experiments	Wood Stone, bricks, concrete-block

Reference	Tsunami event	Methodology	Demand parameter	Data	Building categories
			Hydrodynamic force (KN/m2)		Reinforced concrete
Murao & Nakazato (2010)	Indian Ocean Tsunami 2004	Damage functions	Inundation depth	Field survey	Non-solid (timber frame and masonry) Solid (reinforced concrete, steel)
Leone et al. (2011)	Indian Ocean Tsunami 2004	Fragility functions	Inundation depth (m)	Field survey and photo interpretation	Wood Brick Brick with reinforced columns Reinforced concrete collective structures (weak) Reinforced concrete collective structures (strong)
Reese et al. (2011)	Samoa 2009	Fragility functions	Inundation depth (m) Debris Shielding	Field survey	Generic Timber residential Masonry residential Reinforced concrete residential Shielded/unshielded – masonry residential Debris/non debris – masonry residential
Suppasri et al. (2011)	Indian Ocean Tsunami 2004	Fragility functions	Inundation depth (m) Flow velocity (m/s) Hydrodynamic force (KN/m2)	Image interpretation and numerical modelling	Mixed type Reinforced concrete Wood
Valencia et al. 2011	Indian Ocean Tsunami 2004	Damage functions	Inundation depth	Field survey and photo interpretation	Light constructions Brick/masonry Brick with reinforced columns and masonry infill Non-engineered reinforced concrete

Table 2.4 Summary of existing studies of methods for predicting casualties.

Reference	Tsunami event	People vulnerability
Miyano & Ro (1992) [in Shuto & Arish 2006]	Tonankai 1944	Percentage of deaths and injuries as function of percentage of destroyed buildings
Shuto (1993)	Meiji Sanriku 1896	Deaths as a percentage of destroyed buildings
Kawata (2001)	Meiji Sanriku 1897, Sanriku 1933, Tou-Nankai 1944, Nankai 1946, Hokkaido Nansai-Oki 1993	Death rate as function of tsunami height
EEFIT (2005)	Indian Ocean Tsunami 2004	Total casualties (sum of deaths, missing and injuries) as a function of number of total damage to houses
Doocy et al. (2007)	Indian Ocean Tsunami 2004	District level mortality rates as a function of environmental indicators
Oya et al. (2006) [in Shuto & Arish 2006]	Indian Ocean Tsunami 2004	Percentage deaths as function of tsunami height
Koshimura et al. (2006)	Synthetic model	Tsunami casualty index
Reese et al. (2007)	Java 2006	Percentage casualties (death and injuries) as function of inundation depth Number of death as function of number of collapsed houses
Koshimura et al. (2009, 2009a)	Indian Ocean Tsunami 2004	Death ratio (death and missing) as function of inundation depth
Leone et al. (2010)	Indian Ocean Tsunami 2004	Percentage of dead and missing people as function of percentage of total destruction

In a similar treatment to flooding, most studies use a correlation between the casualty rate and the inundation depth. More recently there has been a tendency to relate casualties to levels of damage. Table 2.4 gives a summary of existing casualty studies.

Comparing the three studies that have correlated the inundation depth with fatality rates gives significantly different results. While Reese et al. (2007) and Koshimura et al. (2009, 2009a) both estimate a fatality rate of 6% for an inundation depth of 2 m, Oya et al. (2001; in Shuto and Arish, 2006) gives a range of 0.01–0.3%. For a depth of 4 m, the differences are even bigger, with Reese et al. (2007) estimating 14%, Koshimura et al. (2009) 52% and Oya et al. (2001; in Shuto and Arish, 2006) between 0.01 and 20%.

Relating the casualties with the number of destroyed buildings shows a similar variance. For instance, for 500 destroyed buildings, Miyano and Ro (1992; in Shuto and Arish, 2006) estimate 39 casualties, Reese et al. (2007) 154, Leone et al. (2011) 574, EEFIT (2005) 287 and Shuto (1993) 3500. It should be noted though, that some of the studies include injuries and/or missing people, while others only give estimates for the fatalities. However, it highlights that casualty estimation is even more subject to tsunami characteristics and site specific factors. The tsunami casualty rate, even if the tsunami height is the same, has significant variation within each event and depends on the location within each community. How many people have (self-)evacuated, was there any warning prior to the arrival of the tsunami, were the people in buildings or outdoors, etc.? Consequently, every casualty function represents specific circumstances, both in terms of the hydrological characteristics and the specifics of the location. Hence, Koshimura et al. (2006) recommend combining various factors.

The most significant factor is likely to be whether the residents in a community take part in the evacuation or not (including self-evacuation). Koshimura et al. (2006) use a tsunami casualty index indicating the casualty potential at a location. The index is based on the local hydrodynamic characteristics of the tsunami inundation flow and a human body model (physical characteristics of evacuees such as weight and height). This approach does still not include all relevant factors, as suggested in some flood casualty studies (see McClelland and Bowles, 2002; Priest et al., 2007; Tapsell et al., 2009; Reese and Ramsay, 2010) but is certainly a step towards more accurate casualty estimation.

2.4.4.6 Other tsunami damage

The 2004 Indian Ocean Tsunami and the more recent 2011 tsunami in Japan have shown that damage to infrastructure and lifelines can be immense. A community's resilience to a disaster is greatly affected by the continued operation of infrastructure and some essential services. Some of these are essential for emergency operations, some are linked to the provision of basic needs—food, water, shelter, and others are important for public health. The economic viability of communities depends upon the continued operation of these utilities. Hence, it is critical to be able to quantify the risk to lifelines and the economy from tsunami in order to minimize them. However, hardly any quantification methods exist yet, other than for buildings and people. Shuto and Arish (2006) are one of the few who have developed additional (damage) functions, such as for fishing boats, destruction of road- and railway embankments and oil-related fires.

2.4.5 Tsunami damage assessment – ex post

(source: Yalciner and Reese, 2011)

The assessment of damage to the built environment after a tsunami has occurred is crucial for better understanding of planning and design specifications. The most common method of ex-post damage assessments is structural surveys, which investigate the performance of the built environment. These surveys examine the relevant factors associated with damage and failure of buildings and other structures due to the tsunami. They provide valuable information about the tsunami resistance of structures and the adequacy of current building standards and practices. In addition, they also help to improve emergency response and identify specific opportunities to mitigate the impacts of future tsunami.

The built environment includes all human-made structures, ranging from residential, commercial or industrial buildings to lifelines.

A list of the key structures is given in the following.

- Residential buildings
- Commercial buildings and centres
- Industrial buildings and complexes
- Educational buildings
- Health services
- Social, cultural and public assembly areas
- Emergency services
- Communication centres
- Infrastructure (roads, fresh and waste water networks, electricity, oil, gas and communications networks)
- Tourism, tourist facilities
- Marine and land transportation terminals (piers, quays, warehouses, lifelines etc.)
- Historical or cultural buildings and monuments
- Military areas
- Storage facilities (including tanks)
- Solid waste storages

Impacts to buildings are manifold, ranging from damage to windows, doors, interior and exterior walls, structural walls/frames, and foundation damage/scouring, or even total collapse. Infrastructure damage includes damage to telecommunication, electricity, roads, rail and other networks; flood structures and networks and other public utilities.

Collecting comprehensive and detailed data about structural damage will improve model-based estimates of structural and non-structural damage, casualties, and economic losses. A field investigator looking at structural damage is expected to assess the type and level of damage to buildings and infrastructure. It is important that damage is documented for a sufficient number of similar buildings or infrastructure elements in the same area—damaged and undamaged—so that both an average level of damage and the variety of the damage can be determined. It is important to note what did not fail, as well as what did.

The following information should be collected in order to determine the damage level of the building (Yalciner and Reese, 2011):

- Building use
- Type of structure
- Building material
- Address and/or GPS coordinates
- Distance from the shore
- Number of storeys
- Size
- Wall cladding material
- Roof cladding material
- Age
- Floor height above ground
- Foundation type
- Foundation height
- Sheltered / exposed
- Orientation to the tsunami waves
- Nearby ground characteristics
- Possible debris, sediment impacts
- A photo of each surveyed building should be taken

If infrastructure and other structures are inspected (e.g. roads, piers, etc.), all the relevant information from the above list should also be collected.

According to Yalciner and Reese (2011) "the observed building and infrastructure damage needs to be catalogued in sufficient detail to enable the post-tsunami damage state (e.g., minor, major, complete damage) of the structure. It is therefore common to classify the damage into the following categories": (Table 2.5)

Table 2.5 Damage state classification (Reese et al., 2011).

Damage State (DS)		**DS description**
DS_0	None	None
DS_1	Light	Non-structural damage only
DS_2	Minor	Significant non-structural damage, minor structural damage
DS_3	Moderate	Significant structural and non-structural damage
DS_4	Severe	Irreparable structural damage, will require demolition
DS_5	Collapse	Complete structural collapse

This allows the assignment of a repair cost, or repair cost ratio (denoted as loss functions) to each damage state if needed.

How structures perform is dependent on the building material and construction type, but it is also a function of the tsunami characteristics such as inundation depth, flow and impact velocity, duration of the inundation and any entrained sediment or debris. Thus, it is necessary to collect not only the details and attributes of the surveyed building or infrastructure element, but also hydraulic information for each surveyed structure. The following information should also be collected if possible:

- Inundation depth (flow depth)
- Maximum water elevation in inundation zone
- Flow velocity
- Direction of incoming tsunami waves
- Inundation duration
- Flow directions in inundation zone
- Evidence of debris

Yalciner and Reese (2011) also state that “in addition to identifying damage to individual structures, field investigators should consider performing an overall building survey on a representative sample basis. Geo-coded spatial data sufficient to make a map of what types of buildings and infrastructure are/were available in each area and the type and extent of damage at each sample building and element should also be collected. Any survey should produce a damage map for each area that includes measurements of the hazard intensity (e.g., inundation depth) and the level of damage.

To ensure a consistent survey and damage assessment, a standardized survey template and damage scale templates should be used throughout”.

2.5 REFERENCES

Ale, B.J.M. (2002). Risk Assessment practices in the Netherlands. *Safety Science* 40, 105-126.

Alexander, D. (2000). Confronting Catastrophe - New Perspectives on Natural Disasters. Oxford University Press, Oxford, p. 282.

Berryman, K. (Compiler; 2005). Review of tsunami hazard and risk in New Zealand [online]. Institute of Geological & Nuclear Sciences client report 2005/104, 139pp. Available at: www.civildefence.govt.nz [Accessed 20 May 2011].

Blong, R. (2003). A new damage index. *Natural Hazards*, 30 (1): 1–23.

Bureau of Transport Economics (2001). Economic costs of natural disasters in Australia. Report 103, Bureau of Transport Economics, Commonwealth of Australia, Canberra.

Cannon, T.; Twigg, J.; Rowell, J. (2005). Social Vulnerability, Sustainable Livelihoods and Disasters [online]. Report to DFID Conflict and Humanitarian Assistance Department (CHAD) and Sustainable Livelihoods Support Office. London. Available at: http://www.proventionconsortium.org/themes/default/pdfs/CRA/DFIDSocialvulnerability_meth.pdf [Accessed 17 May 2011]

Chan, E.S. (1994). Mechanics of deep water plunging-wave impacts on vertical structures. *Coastal engineering*, 22(1-2):115-133.

Dall'Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G., Dominey-Howes, D. (2009). A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage. *Nat. Hazards Earth Syst. Sci*., 9: 1557-1565.

Dalrymple, R.A., Kriebel, D.L. (2005). Lessons in Engineering from The Tsunami in Thailand. *The Bridge*, 35: 4-13.

Dias, W.P.S., Yapa, H.D., Peiris, L.M.N. (2009). Tsunami vulnerability functions from field surveys and Monte Carlo simulation. *Civil Engineering and Environmental Systems*, 26 (2):181-194, doi: 10.1080/10286600802435918.

Dilley, M. (2005). Natural Disaster Hotspots: A Global Risk Analysis [online]. Synthesis Report, International Bank for Reconstruction and Development/The World Bank and Columbia University. Available at: http://www.ldeo.columbia.edu/chrr/research/hotspots/ [Accessed 19 May 2011]

Dominey-Howes, D., Papathoma, M. (2007). Validating a Tsunami Vulnerability Assessment Model (the PTVA Model) Using Field Data from the 2004 Indian Ocean Tsunami. *Natural Hazards*, 40: 113-136

Doocy, S., Gorokhovich, Y., Burnham, G., Balk, D. Robinson, C. (2007). Tsunami Mortality Estimates and Vulnerability Mapping in Aceh, Indonesia. *American Journal of Public Health*, Supplement 1, Vol 97 (S1):146-151.

Douglas, J. (2007). Physical vulnerability modelling in natural hazard risk assessment. *Nat. Hazards Earth Syst. Sci.*, 7: 283–288.

Durham, K. (2003). Treating the Risks in Cairns. *Natural Hazards*, 30 (2): 251–261.

Economic Commission for Latin America and the Caribbean (ECLAC) (2003). Handbook for Estimating the Socio-economic and Environmental Effects of Disasters.

EERI (Earthquake Engineering Research Institute) (2005). The Great Sumatra Earthquake and Indian Ocean Tsunami of December 26, 2004. Report #6.

EEFIT (2005). The Indian Ocean Tsunami 26 December 2004: Mission findings in Sri Lanka & Thailand. London.

FAO/WHO (2009). Risk Characterization of Microbiological Hazards in Food: Guidelines. *Microbiological Risk Assessment Series* No. 17. Rome. 116pp.

Ghobarah, A., Saatcioglu, M. Nistor, I. (2006). The impact of the 26 December 2004 earthquake and tsunami on structures and infrastructure. *Engineering Structures*, 28: 312–326.

Grezio, A., Tonini, R. (2011). Tsunami fragility curves and tsunami vulnerability:state of the art [online]. Draft. Available at: http://bymur.bo.ingv.it/frames/uploads/tsunami_vulnerability_report_v1.pdf [Accessed 24 May 2011].

Grundy, P. (2008). Strategies for Disaster Risk Reduction on Coasts.Paper at the third IFED Forum, Shoal Bay, Australia, 12-15 December 2007. Available at: http://www.ifed.ethz.ch/events/Forum07/Paper/Grundy_paper.pdf [Accessed 09 May 2011].

Hatori, T. (1984). On the damage to houses due to tsunamis. *Bulletin of the Earthquake Research Institute* 59(3): 433-439 (in Japanese).

Hattori, M., Arami, A., Yui, T. (1994). Wave impact pressures on vertical walls under breaking waves of various types. *Coastal Engineering*, 22(1-2):79-114.

Hogan, D.E., Burstein, J.L. (2007). Disaster medicine. Kluwer, Philadelphia.

Hollenstein, K. (2005). Reconsidering the risk assessment concept: Standardizing the impact description as a building block for vulnerability assessment. *Natural Hazards and Earth System Sciences*, 5, 301–307.

International Strategy for Disaster Reduction, ISDR (2004). Living with risk. Geneva.

Izuka, H., Matsutomi, H. (2000). Damage estimation due to tsunami inundation flow. *Proceedings of Coastal Engineering, JSCE*, Vol.47, 381-385 (in Japanese).

Kaplan, M., Renaud, F.G., Lüchters, G. (2009).Vulnerability assessment and protective effects of coastal vegetation during the 2004 Tsunami in Sri Lanka. *Nat. Hazards Earth Syst. Sci*., 9: 1479–1494.

Kaplan, S., Perla, H.G., Bley, D.C. (1983).A methodology for seismic analysis at nuclear power plants. *Risk Analysis,* 3(3):169–180.

Kawata, Y. (2001). Disaster mitigation due to next Nankai earthquake tsunamis occurring in around 2035. ITS Proceedings, Session 1, Number 1-8:315-329.

Kennedy, R.P., Cornell, C.A., Campbell, R.D., Kaplan, S., Perla, H.F. (1980).Probabilistic seismic safety study of an existing nuclear power plant. *Nuclear Engineering and Design*, 59(1980):315–338.

Kimura, K., Ishimi, K., Sato, S., Fukuda, T., Mikami, T., Kikuchi, S. (2006). Verification of tsunami wave source model and formulation of a vulnerability function for buildings based on the investigation of actual damage due to the Sumatran earthquake and tsunami: subject area being the damage at Matara city, Sri Lanka. *Coastal Engineering Committee*, Vol.53: 301-305 (in Japanese).

Koshimura, S., Katada, T., Mofjeld, H.O., Kawata, Y. (2006). A method for estimating casualties due to the tsunami inundation flow. *Nat. Hazards*, 39(2): 265–274.

Koshimura, S., Namegaya, Y., Yanagisawa, H., (2009). Tsunami Fragility - A New Measure to Identify Tsunami Damage. *Journal of Disaster Research*, 4 (6): 479-488.

Koshimura, S., Oie, T., Yanagisawa, H., Imamura, F. (2009a). Developing Fragility Functions for Tsunami Damage Estimation Using Numerical Model and Post-Tsunami Data from Banda Aceh, Indonesia. *Coastal Engineering Journal*, Vol. 51, No. 3 (2009) 243–273.

Leone, F., Lavigne, F., Paris, R., Denain, J-C., Vinet, F. (2010). A spatial analysis of the December 26th, 2004 tsunami-induced damages: Lessons learned for a better risk assessment integrating buildings vulnerability. *Applied Geography*, doi:10.1016/j.apgeog.2010.07.009.

Malone, E. (2009). Vulnerability and Resilience in the Face of Climate Change: Current Research and Needs for Population Information [online]. Report for Population Action International, Washington. Available at: http://www.populationaction.org/Publications/Working_Papers/Vulnerability_and_Resilience/Malone_resilience.pdf [Accessed 14 May 2011].

Matsutomi, H., Okamoto, K., Harada, K. (2010). Inundation Flow Velocity of Tsunami on Land and its Practical Use [online]. No 32 (2010): Proceedings of 32nd Conference on Coastal Engineering, Shanghai, China, 2010. Available at: http://journals.tdl.org/ICCE/article/viewFile/1141/pdf_215. [Accessed 22 May 2011].

Matsutomi, H., Shuto, N., Imamura, F., Takahashi, T. (2001). Field Survey of the 1996 Irian Jaya Earthquake Tsunami in Biak Island. *Natural Hazards,* 24: 199–212.

McAdoo, B.G., Moore, A., Baumwoll, J. (2008). Indigenous knowledge and the near field population response during the 2007 Solomon Islands tsunami. *Nat Hazards*. DOI 10.1007/s11069-008-9249-z.

McBean, E., Fortin, M., Gorrie, J. (1986). A critical analysis of residential flood damage estimation curves. *Can. J. Civ. Eng*., 13: 86–94.

McClelland, D.M., Bowles, D.S. (2002). Estimating Life Loss for Dam Safety Risk Assessment - a Review and New Approach. Institute for Water Resources, U.S. Army Corps of Engineers, Alexandria, VA.

McKenzie, E., Prasad, B., Kaloumaira, A. (2005). Economic Impact of Natural Disasters on Development in the Pacific [online]. Volume 2: Economic Assessment Tools. Available at: http://www.ausaid.gov.au/publications/pdf/impact_pacific_tools.pdf [Accessed 15 May 2011].

Middelmann-Fernandes, M.H. (2010). Flood damage estimation beyond stage-damage functions: an Australian example. *Journal of Flood Risk Management*, 3: 88-96.

Murao, O., Nakazato, H. (2010). Vulnerability Functions for Buildings Based on Damage Survey Data in Sri Lanka after the 2004 Indian Ocean Tsunami. Proceedings of the International Conference on Sustainable Built Environment (ICSBE-2010), Kandy, 13-14 December 2010, p.371-378.

Namegaya, Y., Tsuji, Y. (2006). Distributions of the Swept Away Houses in Banda Aceh City, Indonesia, due to the 2004 Indian Ocean Tsunami Estimated by Satellite Images. *Annual Journalof Coastal Engineering*, JSCE, Vol.53: 286-290 (in Japanese).

Nishikiori, N., Abe, T., Costa, D.G.M., Dharmaratne, S.D., Kunii,O., Moji, K. (2006). Who died as a result of the tsunami? – Risk factors of mortality among internally displaced persons in Sri Lanka: a retrospective cohort analysis. *BMC Public Health, (*6): 73.doi: 10.1186/1471-2458-6-73.

Nistor, I, Palermo, D., Al-Faesly, T., Cornett, A. (2011). Investigations and Experimental Modelling of the Tsunami-Induced Extreme Hydrodynamic Forces on Structures [online]. Proceedings of 34th International Association of Hydraulic Engineering (IAHR) Congress, Brisbane, Australia, July, 2011.

Okada, T., Sugano, T., Ishikawa, T., Takai, S., Tateno, T. (2005). Tsunami Loads and Structural Design of Tsunami Refuge Buildings. The Building Centre of Japan.Tokyo.

Omira, R., Baptista, M.A., Miranda, J.M., Toto, E., Catita, C., Catalaõ, J. (2010). Tsunami vulnerability assessment of Casablanca-Morocco using numerical modelling and GIS tools. *Nat Hazards*, 54:75–95

Palermo, D., Nistor, I. (2008). Tsunami – induced loading on Structures. *Structure*. (3), 10-13.

Papadopoulos, G.A., Imamura, F. (2001).A proposal for a new tsunami intensity scale. Proceedings of International Tsunami Symposium 2001, IUGG, 569-577.

Papathoma, M., Dominey-Howes, D., Zong, Y., Smith, D. (2003).Assessing tsunami vulnerability, an example from Herakleio, Crete. *Nat.Hazards Earth Syst. Sci.,* 3, 377–389.

Peiris, N. (2006). Vulnerability functions for tsunami loss estimation. First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, 3-8 September 2006. Paper No. 1121.

Pimanmas, A., Joyklad, P., Warnitchai, P. (2010). Structural Design guideline for tsunami evacuation shelter. *Journal of Earthquake and Tsunami*. (4), 269-284.

Priest, S., Wilson, T., Tapsell, S., Penning-Rowsell, E., Viavattene, C., Fernandez-Bilbao, A. (2007). Building a model to estimate Risk to Life for European flood events. Floodsite Final Report, T10-07-10.

Reese, S., Cousins, W.J., Power, W.L., Palmer, N.G., Tejakusuma, I.G., Nugrahadi, S. (2007). Tsunami vulnerability of buildings and people in South Java.Field observations after the July 2006 Java tsunami.*Nat. Hazards Earth Syst. Sci*., 7 (5): 573-589.

Reese, S., Schmidt, J. (2008).Tsunami and flood hazard exposure of city council infrastructure in Christchurch City. NIWA client report: WLG-2008-67.Unpublished.

Reese, S., Smart, G. (2008). High resolution inundation modelling as part of a multi-hazard loss modelling tool. In: Samuels, P., Huntington, S. Allsop, W. and J. Harrop (eds): Flood Risk Management. Research and Practice. Proceedings of the European Conference on Flood Risk Management Research into Practice (FloodRisk 2008), Oxford, Uk, 30.09-02.10.2008, pp. 1663-1668.

Reese, S., Ramsay, D. (2010). Riskscape: Flood fragility methodology. NIWA technical report, WLG-2010-45.

Reese, S. Bradley, B.A., Bind, J., Smart G.M., Power, WJ.,Sturman, J.D. (2011). Empirical building fragilities from observed damage in the 2009 South Pacific tsunami.*Earth Science Reviews*, Special issue.doi:10.1016/j.earscirev.2011.01.009

Rossetto, T., Peiris, N., Pomonis, A., Wilkinson, S.M., Del Re, D., Koo, R., Gallocher, S. (2007). The Indian Ocean tsunami of December 26, 2004: observations in Sri Lanka and Thailand. *Nat Hazards*, 42:105–124.

Ruangrassamee, H., Yanagisawa, P. Foytong, P. Lukkunaprasit, Koshimura, S., Imamura, F. (2006). Investigation of tsunami-induced damage and fragility of buildings in Thailand after the December 2004 Indian Ocean tsunami. *Earthquake Spectra*, 22 (S3):S377–S401.

Saatcioglu, M., Ghobarah, A., Nistor, I.(2007).Performance of Structures Affected by the 2004 Sumatra Tsunami in Thailand and Indonesia. In: T. S. Murty, U. Aswathanarayana and N. Nirupama (Editors), The Indian Ocena Tsunami. Francis & Taylor, London, pp. 297-321.

Salinas, S.V., Low, K.K., Liew, S.C. (2005). Quick Analysis of Wave Patterns Generated by Tsunami Waves and Captured by SPOT Imagery. Geoscience and Remote Sensing Symposium, 2005.IGARSS '05.Proceedings. 2005 IEEE International,(5), p.3634-3636.

Schmidt, J., Matcham, J., Reese, S., King, A., Bell, R., Smart, G., Cousins, J. Smith, W., Heron, D. (2011). Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling. *Nat Hazards*. DOI: 10.1007/s11069-011-9721-z

Schultz, M.T., Gouldby, B.P., Simm, J.D., Wibowo, J.L. (2010). Beyond the Factor of Safety: Developing Fragility Curves to Characterize System Reliability. USACE Water Resources Infrastructure Program, Final report ERDC SR-10-1.

Shuto, N. (1993). Tsunami intensity and disasters. In: Tinti, S. (ed.). Tsunamis in the World. Kluwer Academic Publisher, Dortrecht, 197-216.

Shuto, N., Arish, N. (2006). Tsunamis, Disasters and Countermeasures.Paper at the International Workshop on Fundamentals of Coastal Effects of Tsunamis [online], December 26-28, 2006, Hilo Hawaii. Available at: http://tsunami.orst.edu/workshop/2006/doc/premeeting/Shuto.pdf [Accessed 17 May 2011].

Smith, K., Petley, D.N. (2009). Environmental Hazards.Assessing risk and reducing disaster.5th Edition. Routledge. New York.

Standards Australia/Standards New Zealand (2004). Risk Management Guidelines. Companion AS/NZS 4360:2004. Sydney & Wellington.

Stansfield, K. (2005). Effects of the Asian tsunami on structures.*The Structural Engineer*, 83(11): 20-21.

Strunz, G., Post, J., Zosseder, K., Wegscheider, S., Mück, M., Riedlinger, T., Mehl, H., Dech, S., Birkmann, J., Gebert, N., Harjono, H., Anwar, H.Z., Sumaryono, Khomarudin, R.M., Muhari, A. (2011). Tsunami risk assessment in Indonesia. *Nat. Hazards Earth Syst. Sci*., 11, 67–82.

Suppasri,A., Koshimura, S., Imamura, F. (2011). Developing tsunami fragility curves based on the satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand. *Nat. Hazards Earth Syst. Sci*., 11, 173–189.

Tapsell, S.M, Priest, S.J., Wilson, T., Viavattene, C., Penning-Rowsell, E.C. (2009). A new model to estimate risk to life for European flood events. In: In: Samuels, P., Huntington, S. Allsop, W. & J. Harrop (eds): Flood Risk Management. Research and Practice. Proceedings of the European Conference on Flood Risk Management Research into Practice (FloodRisk 2008), Oxford, Uk, 30.09-02.10.2008, pp. 933-943.

Thurston, S.J., King, A.B. (2003). Full sized house cyclic racking test. Proceedings 2003 Pacific Conference on Earthquake Engineering, 13-15 February 2003, Christchurch.New Zealand Society for Earthquake Engineering. Paper No. 029

Thusyanthan, N.I., Gopal, S.P. (2008). Tsunami wave loading on coastal houses: a model approach. Proceedings of ICE, *Civil Engineer* 161, paper 07-00037, 77-86. Doi:10.1680/cien.2008.161.277

Thywissen, K. (2006). Components of Risk.A Comparative Glossary. 'Studies of the University: Research, Counsel, Education'. Publication Series of UNU-EHS, No. 2/2006.

United Nations Development Programme (UNDP) (2004). Reducing Disaster Risk: A Challenge for Development [online]. New York: United Nation Development Programme, Bureau for Crisis Prevention and Recovery. Available at: http://www.undp.org/cpr/whats_new/rdr_english.pdf [Accessed 14 May 2011].

United States National Tsunami Hazard Mitigation Program (2001). Designing for Tsunamis. Seven Principles for Planning and Designing for Tsunami Hazards. Available at: http://nthmp-history.pmel.noaa.gov/Designing_for_Tsunamis.pdf [Accessed 16 May 2011].

Valencia, N., Gardi, A., Gauraz, A. L., Leone, F., and Guillande, R. (2011). New tsunami damage functions developed in the framework of SCHEMA project: application to Euro-Mediterranean coasts. *Natural Hazards and Earth System Science*.in review.

Yalciner, A., Reese, S., Koshimura, F.I. (2011). Tsunami coastal impact, damage information, and engineering aspects. In: UNESCO-IOC .Post-tsunami survey field guide.Second Edition.IOC Manuals and Guides No.XY. Paris, UNESCO.

Yalciner, A., Reese, S. (in press). Structural damage surveys. In: UNESCO-IOC .Post-tsunami survey field guide.Second Edition.IOC Manuals and Guides No.XY. Paris, UNESCO, 2011.

Yeh, H., Robertson, I., Preuss, J. (2005). Development of Design Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites. Report No 2005-4, Washington Dept. of Natural Resources.

Yeh, H. (2009). Tsunami impacts on coastlines. In: Bernard, E.N. & Robinson, A.R, (eds): The sea. Tsunamis.Harvard University Press, Cambridge, p.333-370.

This page is intentionally left blank.