Scoping study for evaluating the tsunami vulnerability of New Zealand buildings for use as evacuation structures

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CONTENTS

APPENDIX

ABSTRACT

This report scopes out needs and issues for guidance on evaluating the tsunami vulnerability of tsunami evacuation buildings in New Zealand- those specifically designed or designated as places to evacuate to in the event of a tsunami warning. It includes the results of a workshop attended by staff from GNS Science, Hawkes Bay Civil Defence Emergency Management Group, Opus (engineer), Department of Building and Housing, Ministry of Civil Defence and Emergency Management and Napier City Council (building inspector).

The outcomes are intended to fit within the context of nationally-consistent tsunami warning, evacuation mapping, planning and signage. Warning and evacuation should be considered in conjunction with other risk mitigation options, especially land use planning. Buildings selected or built for vertical evacuation must also be resistant to any initial earthquake.

We briefly review the characteristics of tsunami, overseas tsunami building design and impact examples, tsunami impacts on infrastructure including typical load and force, categories and components of loading, and existing data on these loads. Example of tsunami resilient buildings are given for reinforced concrete, steel framed and timber framed constructions in a variety of countries that have experienced large tsunami.

Applications and limitations of tsunami evacuation buildings in New Zealand are discussed in the context of land use planning, emergency management, community issues, building consent, risk reduction, and liability. The specific scope of the Building Act, Building Code and compliance documents to cover different sizes of tsunami for different building types is explored. The application of these documents to both new and existing buildings is considered with possible future options suggested. A range of recommendations for detailed future work are given. These are mostly focussed on development of a New Zealand-specific Standard or technical information and the many aspects that need to be considered.

KEYWORDS

Tsunami, evacuation building, building code, building act, scoping study, land use planning, effective warning systems, review, issues and options

1.0 INTRODUCTION

This report scopes out needs and issues for guidance on evaluating the tsunami vulnerability of New Zealand buildings for use in tsunami evacuation (see preliminary definition of 'tsunami evacuation building' in Section 1.2). This project is funded by a Foundation for Research Science and Technology (now part of the Ministry of Science and Innovation) Envirolink medium advice grant for Hawke's Bay Regional Council, with benefit to all regional (and other) councils. The research was conducted by GNS Science and Opus with input from other agencies as mentioned.

We specifically focus on the required performance under tsunami loading of new and existing buildings designated as 'tsunami evacuation buildings'. The wider required performance of all buildings in tsunami is also relevant context and is discussed in Section 5.2.

The structure of this scoping report is largely the outcome of an informal project workshop that the authors held on 17 May, 2011 at GNS Science, Avalon with the following attendees: Graham Leonard (GNS Science, hazard mapping), Wendy Saunders (GNS Science, landuse planning), Lisa Pearse (Hawkes Bay Civil Defence Emergency Management (CDEM) Group), Gegar Prasetya (GNS Science, tsunami modelling), Noel Evans (Opus, engineer), Dennis Monastra (Department of Building and Housing), Richard Smith (Ministry of Civil Defence and Emergency Management (MCDEM)), Gary Marshall (Napier City Council, building inspector), Andrew Hickey (MCDEM). Apologies were given from Peter Wood (MCDEM), Andrew King (GNS Science), David Johnston (Joint Centre for Disaster Research (JCDR)) and Stuart Fraser (JCDR).

The timing of this project is fortuitous in two respects. The 2011 Tōhoku earthquake and tsunami in Japan has impacted a similar building stock to New Zealand from a subduction zone earthquake of a magnitude that we cannot rule out in New Zealand. In addition, a GNS Science-JCDR Ph.D. student Stuart Fraser has recently started a thesis looking at the design of tsunami resistant evacuation buildings in New Zealand. We can expect that Stuart's work will draw upon the recent data from Japan and that he will potentially conduct a substantial proportion of the work recommended here as needed to underpin future guidance document(s) for New Zealand. Stuart was unable to attend the workshop for this project because he was on an engineering reconnaissance mission to Japan.

1.1 Tsunami risk reduction context

Tsunami risk reduction should include a variety of approaches. Guidance for New Zealand is now in place for evacuation mapping (MCDEM, 2009), signage (MCDEM, 2008) and land use planning (Saunders et al., 2011). These documents refer to the potential for vertical evacuation, and we recognised a need for New Zealand-specific guidance on the selection or construction of buildings as vertical evacuation structures. Evacuation inland or to higher ground should be the primary consideration, with vertical evacuation structures being considered only for reducing the residual risk due to the limitations and uncertainty around the effectiveness of these structures (see Section 4.2). Evacuation may be in response to any natural, informal or official warnings (see detailed discussion in MCDEM, 2009). See Section 4.2 for discussion of situations where evacuation structures are likely to be considered.

1.2 Tsunami evacuation buildings and performance

This report focuses on issues and options for the design of 'tsunami evacuation buildings'. These are buildings that are specifically designed or designated as places to evacuate to in the event of a tsunami warning. The definition for tsunami evacuation buildings will need to be re-visited when detailed guidance is developed.

Different categories or levels of performance for such buildings should also be considered at that detailed guidance development stage. For example, the top performing tsunami evacuation building may be one that not only withstands the tsunami but also remains 'fully functional' for some time after the event including maintaining operational stairways so that people can escape from the building after the event has passed. A building with a lesser performance, but nevertheless still acceptable as a tsunami evacuation building, may be one which assures people's safety throughout the event (once they have attained a certain minimum height) but from which people have to be rescued. There may also be different levels of performance for existing buildings. These matters are discussed in general in Sections 5.2 and 5.3. However, further detailed investigation is needed - building designs for new buildings and assessments and upgrades for existing buildings will need to account for the required functionality of the building once the event has passed.

1.3 Earthquake resistance

Buildings selected or built for vertical evacuation must also be resistant to any initial earthquake, including the ground acceleration that can be expected from a magnitude 9+ subduction zone earthquake offshore of the eastern North Island.

2.0 TSUNAMI AND THEIR IMPACTS

Section 2.1 is reproduced from Saunders et al. (2011), adapted from MCDEM (2010).

2.1 What is a 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 flood coastlines, causing devastating property damage, injuries, and loss of life. The principal sources of tsunami are:

- large submarine or coastal earthquakes, in which there is significant displacement of the seafloor;
- underwater landslides (which may be triggered by an earthquake or volcanic activity);
- large coastal cliff or lakeside landslides; and
- underwater volcanic eruptions.

Tsunami waves differ from ordinary coastal waves (see Figure 1) in that the entire column of water, from the ocean floor to the surface, is affected. Tsunami waves contain considerable energy. This means tsunami waves travel much further, both in coastal surges and retreats, than ordinary coastal waves. Tsunami also create phenomena not characteristic of ordinary waves such as strong currents.

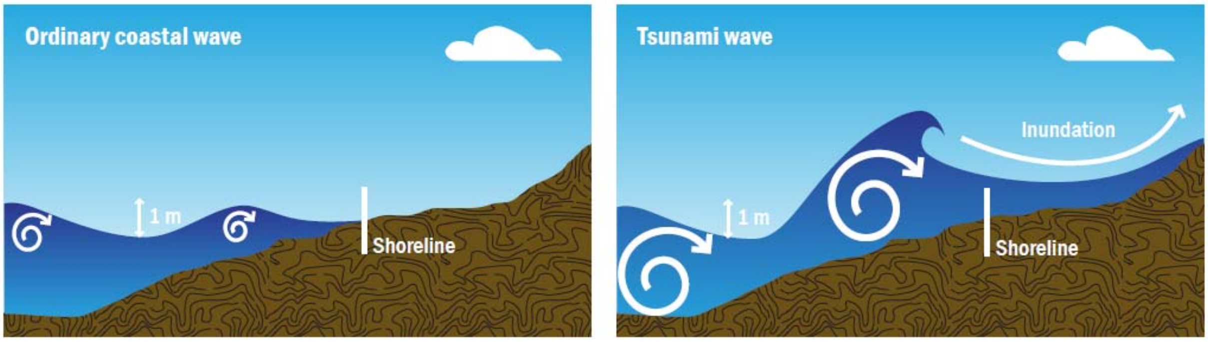

Figure 1 Wave energy in ordinary coastal waves is limited to the surface of the ocean. This energy rapidly dissipates as the wave breaks on the shoreline (left). Energy in tsunami waves, however, affects the entire column of water from the ocean floor to the surface (right). This energy does not readily dissipate. Instead, water is pushed upwards over a large area giving it a long wavelength, and once it reaches a coastline it can travel much further inland than an ordinary coastal wave. A one metre tsunami cannot be likened to a one metre ordinary wave. One metre of wave height, the height between peak and trough, is shown; note how the amplitude (further defined in Figure 2) increases to greater than one metre as the wave reaches the shoreline.

A tsunami can occur at any season of the year and at any time, day or night. On the open ocean tsunami waves are small and barely noticeable but when the waves enter shallow water they rise in height. Some tsunami can be very large and can rapidly and violently inundate coastlines, causing loss of life and property damage. Others can be small but still dangerous to those near or in the coastal water. It is important to remember that not all earthquakes will generate a tsunami, and that earthquakes are not the only sign of an impending tsunami so it is critical to know what to do as a precaution if you are in a vulnerable area.

Tsunami waves are described by their length, period, height, amplitude, and their run-up (see Figure 2). *Wave length* is the distance between consecutive peaks. *Wave period* is the time between two consecutive peaks passing a point. *Tsunami wave height* is a measure of the vertical trough-to crest height of a tsunami wave. Tsunami wave height is not constant – it increases substantially as the waves approach the shore and is dependent on the near shore sea bottom configuration. Conversely, *tsunami wave length* decreases as the wave approaches the shore. Once the wave reaches the shore the *amplitude* is the height of the wave peak above the sea level at the time; and as the wave travels inland *flow depth* is then used to describe the depth of water flowing over a specific point.

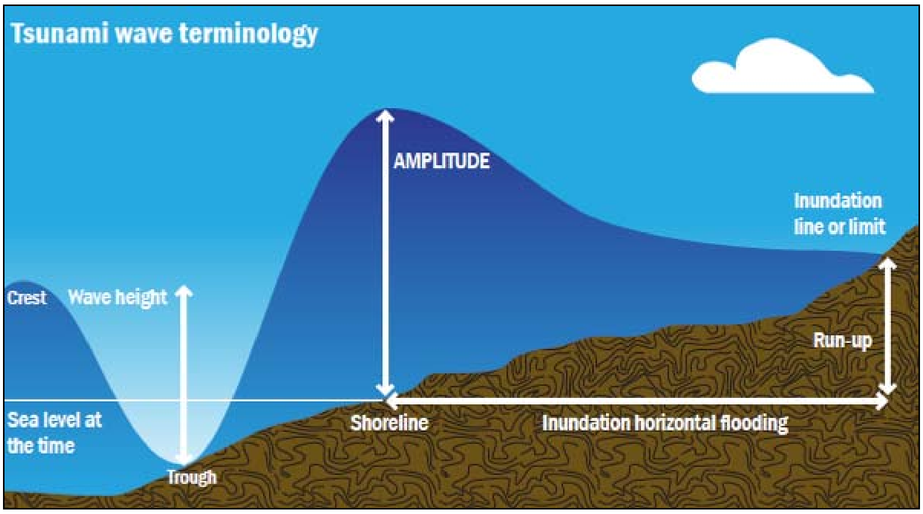

Figure 2 Tsunami terminology (MCDEM, 2010, p22).

Tsunami run-up is the maximum vertical elevation (above either mean sea level or the sea level at the time of the tsunami) that the tsunami reaches at the inland limit of inundation. Run-up is dependent on the type and size of the tsunami, as well as coastal topography and land use. Tsunami run-up is a more useful measure than tsunami wave height as it relates more closely to the onshore effects of a tsunami.

Run-up is not the only way to describe tsunami impact. Flow depth and speed, collectively referred to as 'flux', are the most important factors for engineering purposes such as for coastal protection or building design and construction (Figure 3). The inundation distance and flux may be more important than the run-up. For example, for gently sloping topography, the run-up may be minimal even though the tsunami impacts can be large; for steep slopes, the run-up will be greater but the impact is often less as less infrastructure is built on steep slopes.

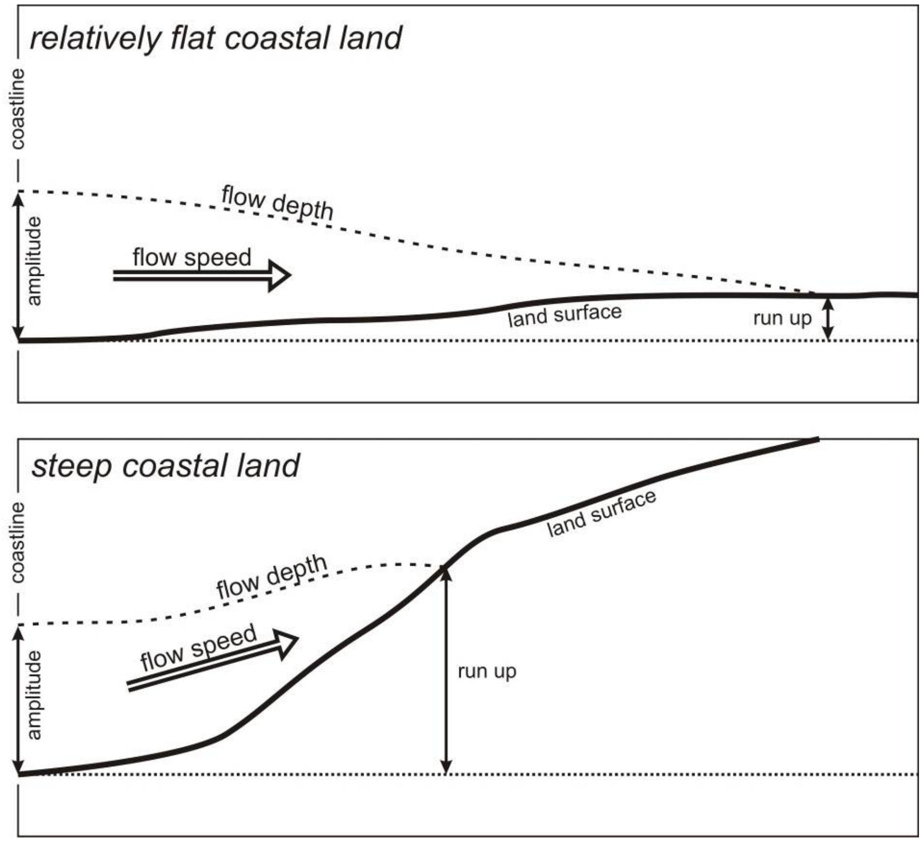

Figure 3 The same flow depth and speed (referred to together as 'flux') can give markedly different inundation distances and run-ups over flat compared to steep land.

2.2 Impacts of tsunami on infrastructure

A series of tsunami events since the Indian Ocean tsunami on December 26, 2004 had raised awareness of the tremendous forces and impact of tsunami on coastal infrastructure, communities and economies. Resilience of coastal infrastructure to tsunami forces has become a major concern for those who live in tsunami-prone areas, especially for those who live on flat ground or in low-lying areas where horizontal evacuations to higher ground are difficult or impossible. Post-tsunami survey results show different types of damage to coastal infrastructure. This is due to a combination of: the variety of impact forces of tsunami, the buildings' design and construction materials, and the ground conditions.

Since 2004, 11 significantly damaging tsunami have occurred (including the recent event in Japan on March 11, 2011), all showing very site-specific impacts to the coast. These tsunami were generated by earthquakes of different source mechanisms and magnitudes, resulting in different types of initial wave conditions. This has complicated the making of any general rule as to how tsunami impact the coast and infrastructure.

When a tsunami approaches the coast, different types of wave shape are formed, resulting in different types of forces acting on coastal infrastructure. Shuto (1991) relates the tsunami wave shape, height, possible impact to coastal infrastructures and scale of disaster into one table based on tsunami record at Shizuoka Prefecture in Japan. In Table 1 wooden houses are very susceptible to the tsunami wave forces when compared to stone or reinforced concrete houses. Shuto and Fujima (2009) further classified damage to coastal structures by tsunami-induced currents based on past event in Japan into four categories:

1. If the tsunami height is lower than the embankment crest and the tsunami is stopped along the embankment then the water concentrates in the openings such as underpasses or bridges with increasing velocity, damaging the neighbourhood of such openings
2. Tsunami-induced currents damage narrow waterways in harbour or bays as the tsunami scours the sea bottom at the toe of structures, often destroying them
3. If tsunami are higher than defence structures their overflow hits the back slope and toe that are usually unprotected, compared to the protection provided against forces from the ocean side
4. When a tsunami is receding during return flow, landed water can drop from quay tops like a water-fall, hitting the nearly exposed sea bottom. This scouring leads to the destruction of many quay walls

Table 1 Relationships of Tsunami wave shape, height and damage to infrastructure based on Shuto (1990).

<table>
<tr><td>Tsunami Height (m)</td><td>1</td><td>2</td><td>4</td><td colspan="2"></td><td>8</td><td>16</td></tr>
<tr><td>Tsunami wave shape</td><td>Tide</td><td>Swell-up</td><td colspan="3">Break after 2nd wave</td><td colspan="2">Break at 1st wave</td></tr>
<tr><td>Wooden Houses</td><td colspan="2">Partially Destroyed</td><td colspan="5">Completely Destroyed</td></tr>
<tr><td>Stone Houses</td><td colspan="3">Endurable</td><td colspan="4">Completely Destroyed</td></tr>
<tr><td>Reinforced Concrete Houses</td><td colspan="4">Endurable</td><td colspan="2"></td><td>Completely Destroyed</td></tr>
<tr><td>Fishing Vessels</td><td colspan="2"></td><td>Damage Occurs</td><td colspan="2">50% Damaged</td><td colspan="2">100% Damaged</td></tr>
<tr><td>Tide Water Control Forests</td><td colspan="3">-Slightly Damaged
-Block Drifts
-Slight Tsunami</td><td colspan="2">-Partially Damaged
-Block Drifts</td><td colspan="2">Completely Damage</td></tr>
<tr><td>Fish-Culture Rafts</td><td colspan="7">Damage occurs</td></tr>
<tr><td>Villages along the Coasts</td><td></td><td>Damage Occurs</td><td colspan="3">50 % Damage</td><td colspan="2">100 % Damaged</td></tr>
</table>

Prasetya et al. (2008) analysed the structural damage due to the December 26, 2004 tsunami event (Mw 9.2) in Banda Aceh. This showed that the effects from both the earthquake ground shaking and the tsunami were obvious. Very strong ground shaking had been felt by most of people in Banda Aceh. This ground shaking weakened the structural integrity of most of the houses in Banda Aceh before the tsunami arrived. When the tsunami arrived it also carried a variety of floating debris including boats, ships, cars, floating barges, and rubble from the buildings that had already collapsed or been partially damaged by the earthquake. Responses of different building types to the tsunami flow depth are illustrated in Figure 4. Reinforced concrete structures (2 and 3 storeys) that withstood the quake were damaged by tsunami waves with flow depths that reached 10m and greater. The typical damage experienced by these buildings included the loss of walls, but, leaving roofs intact (mostly tile). The columns of these buildings were often left standing, however, there was often scouring at their base (photos 3, 5 and 6).

The damaged experienced by a dwelling was also observed (photo 1). The dwelling withstood the quake but there was damage to the walls from the tsunami flow depth of 1.8m. However, when the flow depth was greater than 4m, this type of house was completely destroyed as illustrated in photo 4.

Photo 2 shows the typical damage to a house due to earthquake shaking. This house was located near the house in photo 1 and experienced a similar flow depth.

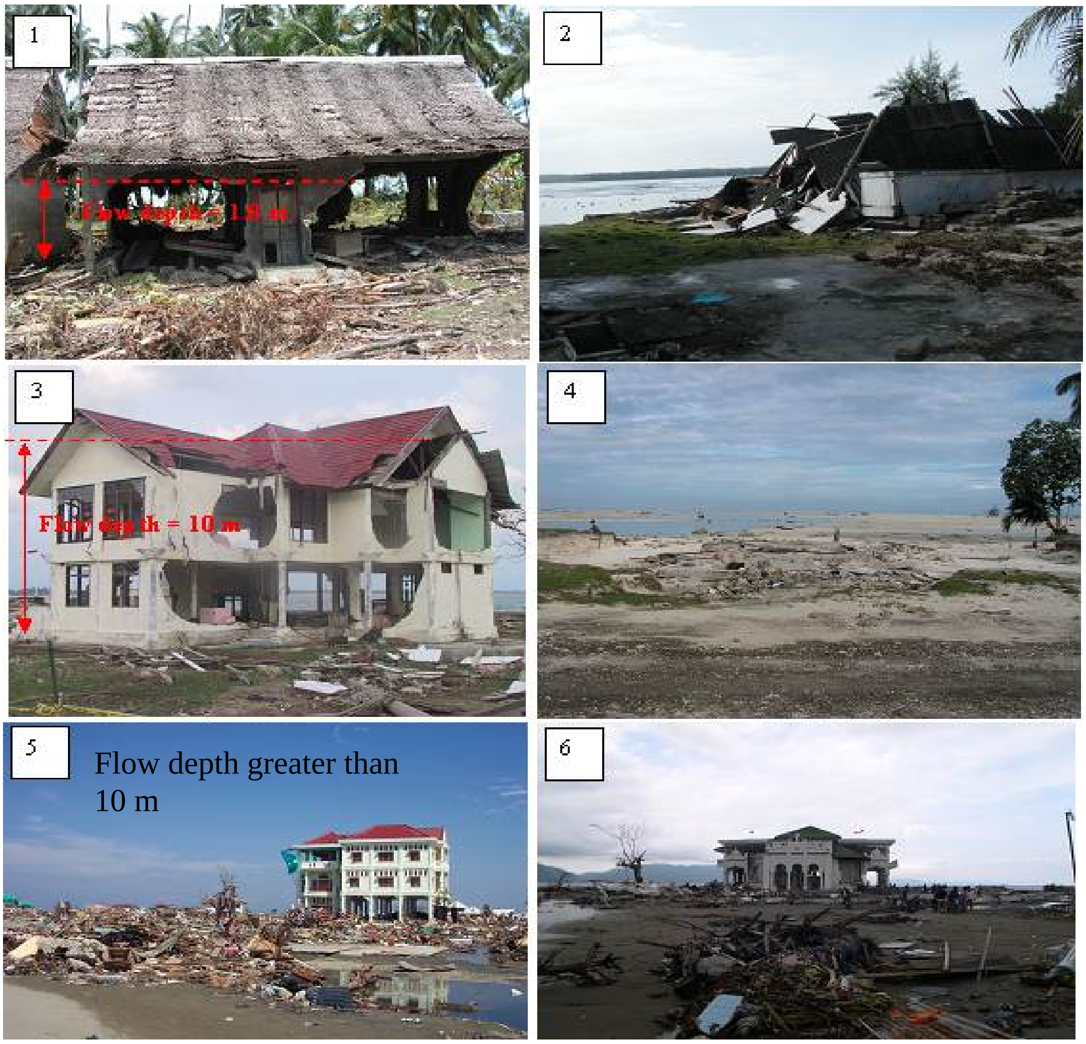

Figure 4 Typical damage to different types of houses due to tsunami with different flow depths in Banda Aceh and Nias Island after the 26 December 2004 event. Most of the 3 storey reinforced concrete structures survived the tsunami with flow depths greater than 10m (photo 5 and 6) whereas other buildings which surrounded these were completely wiped out. With this flow depth, no sheltering effects from the buildings or trees reduced the tsunami impact. A simple house with a palm tree roof was resistant to the earthquake shaking (photo 1) when compared to the neighbouring concrete house (photo 2). However, this house suffered damage from the tsunami with a flow depth of 1.8 m or half of the height of the house (Modified from: Prasetya et al. 2008).

In Thailand the majority of reinforced concrete buildings, except those very close to the shoreline, survived the 2004 tsunami with minor structural damage even though they were not designed for tsunami or earthquakes (Lukkunaprasit et al., 2009). This was possibly due to the earthquake shaking not having been as strong as in Banda Aceh, and therefore not weakening the structural integrity of the building much or at all before the tsunami arrived. Other factors such as the protective functions of trees and other vegetation also play a major role in slowing down the tsunami flow speed further inland. Buildings provided a sheltering effect on buildings or other structures behind them as illustrated in Figure 5 in Thailand during the December 26, 2004 event (Mw 9.2) and in Samoa during the September 29, 2009 event (Mw 8.0) (Figure 6).

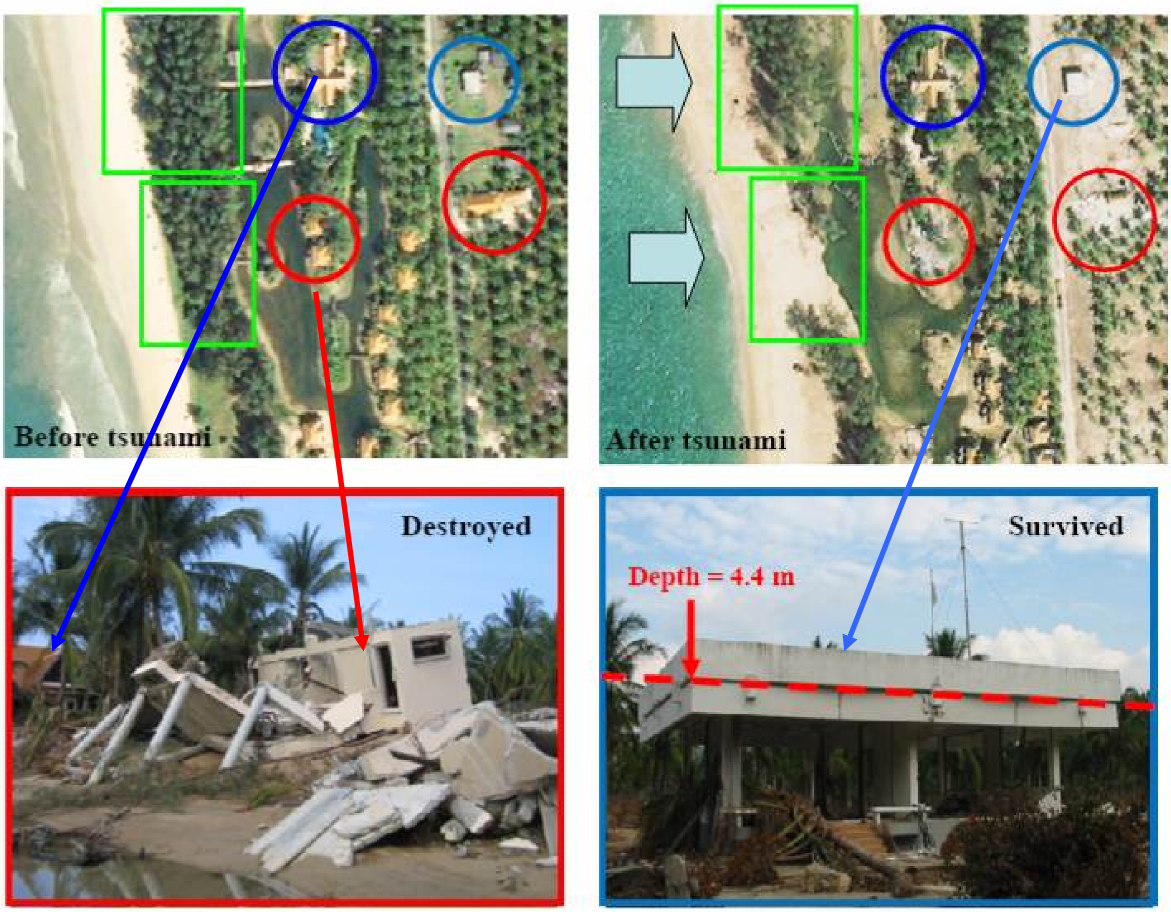

Figure 5 The protective function of trees and buildings to infrastructure situated behind them in Thailand. For the blue circles, the first building located behind a reasonably thick green belt survived while other buildings located at the same distance from the coast but with a thinner green belt were destroyed (red circles) - the green belt in the latter case were completely wipe out by the tsunami. The destruction extended further inland (red circles). For the blue circle situation, as a consequence of the first building surviving the building further inland also survived due to double protection; first by the relatively thick green belt and secondly by the ocean-ward house (also having been protected by the green belt). Even though the flow depth reach up to 4.4 m, apparently the flow speed was reduced significantly when it passed through the second blue circled building. Another factor that contributed to the survival of this building its ground floor configuration of walls which allowed the tsunami to flow through the building. This type of building is effective for vertical evacuations (photos courtesy: Suppasri et al. 2010).

Figure 6 Well-built buildings such as churches, which were located close to the shore, provided a protective function to buildings behind them during the 2009 South Pacific tsunami in Samoa. The flow depth measured at the front of the building is approximately 4.5 m, and the simple houses located behind it were well protected while others were completely wiped out by the tsunami. The red arrows show the direction of the incoming tsunami (Photos courtesy: NZ Air Force).

After the 26 December 2004 event, Hwang (2005) provided guidance to mitigate the risk from a tsunami. They state that building design must properly consider the following:

- Duration of impact: the impact from waves, overland flows and debris on ground-supported and elevated structures
- Localized scour: occurs around the foundation elements and is critical in most building collapses because of the loss of either bearing capacity or anchoring resistance around the posts, piles, piers, columns, footings, or walls
- Tsunami loads: if the tsunami acts as a rapidly rising tide most damage is due to buoyant and hydrostatic forces. A bore-like wave will create a strong current and its effect can be devastating, as can plunging breaking waves

Some structural components, such as grade beams and diagonal braces are used to enhance the performance of piers and columns to prevent the collapse of structures. Grade beams can be wooden or concrete and provide support in the horizontal plane parallel to the floors to help keep structures from collapsing. Diagonal braces can add considerable support to piers and columns and are normally attached to the pile near the top and are secured to the adjacent pile either near or on the ground surface.

Scouring at the front corner of buildings was commonly observed during the post tsunami event field survey as illustrated in Figure 7. The scouring that occurred at the only surviving structured at Lampuuk Beach – Lhok Nga (top photo) with flow depth approximately 15.0m (tsunami flow overtopped the mosque) was similar to scouring that occurred at buildings near the coast during the Samoa 2009 event (lower photo) with flow depth approximately 4.0m.

Figure 7 The scouring that typically occurred at the front corner of the building during the December 26, 2004 (Mw = 9.2) at Lampuuk – Lhok Nga Banda Aceh (above) and at Mutiatele - Upolu Island Samoa (below) during the Samoa event (Mw = 8.0). (Photos courtesy: H K Suheimi)

Many new theories, best practises, methodologies and mitigation efforts for survival and resilience to tsunami were put in place in tsunami prone areas after the December 26, 2004 event. However, the last two events that took place in Mentawai on October 25, 2010 (Mw 7.7) and Japan on March 11, 2011 (Mw 9.0) illustrate continued significant shortcomings.

The Mentawai event, even though it had a lower earthquake magnitude of Mw 7.7 with tsunami height of 3 - 7 m, killed more than 400 people. This island is located within the most sophisticated early warning system in the Indian Ocean and public awareness campaigns had been run on how to survive a tsunami (Sieh, 2006).

In Japan, towns that had been designed to be ready anticipating tsunami were completely devastated. Thousands of inhabitants perished due to tsunami with flow depths of up to 20m. During this event, the early warning system generally worked properly; some public buildings functioned well for vertical evacuation structures and saved people's lives, and most of the vertical evacuation buildings still stood even though they experienced strong shaking. However, at some places the incoming tsunami overtopped the vertical evacuation buildings and the tsunami dike/wall. After these two recent events, a lot of questions still need to be answered ranging from source determination and generation mechanism, through to early warning system (versus natural warnings) and education, to mitigation efforts and land use planning.

2.3 Typical tsunami load and forces

Understanding tsunami inundation processes is a key factor in all mitigation efforts as the overland tsunami flows can generate forces that significantly affect any coastal infrastructure located along its path. The last two decades of events have shown just how variable tsunami height can be along a few kilometres of the coastline.

Since tsunami wave length (in order of a few kilometres) is very long compared to wind waves, and the continental shelf and the near-shore bathymetry are very important factors in controlling the tsunami wave behaviour. Some tsunami waves will arrive like a tide with rising and falling of sea level, others will break offshore and propagate as a bore. Some will break inshore through an extreme plunging breaking mechanism that produces an extreme 'punch' force followed by the transient force with a duration corresponding to the tsunami wave length, as illustrated in Figure 8. The 'punch' forces can effectively destroy building walls, while the transient forces will wash away the rest of the building and also cause scouring to the foundations of the structure, contributing to collapse of the building. The parameters that are essential for defining the magnitude and application of these forces are inundation depth, flow velocity, and direction. These parameters according to Nistor et al. (2010) mainly depend on tsunami wave height and period, coastal topography and the roughness of inland topography.

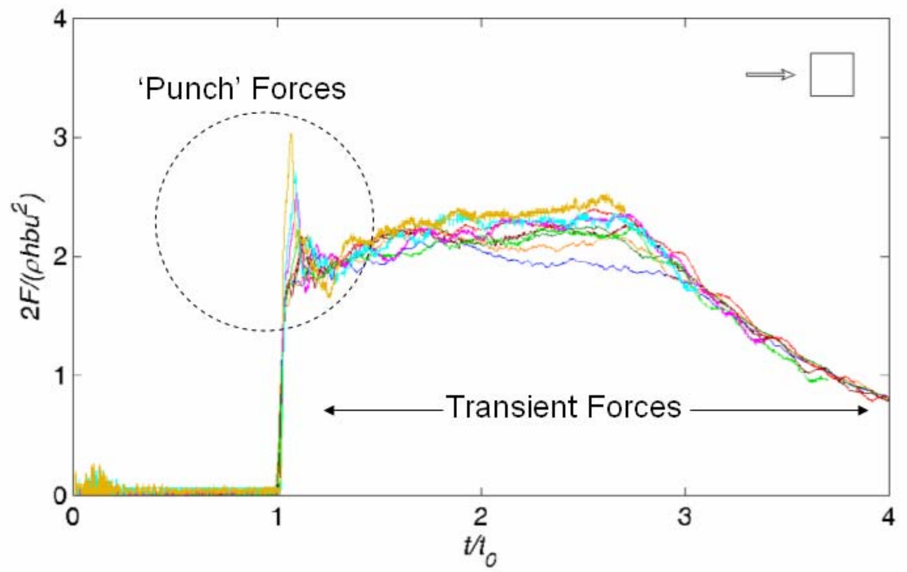

Figure 8 Laboratory data that show the hydrodynamic force on a square column (Arnason, 2005). The first part is the 'punch' force follow by the transient forces. The arrows on the top corner show the wave direction and the box is the model structures.

Thusyanthan and Madabhusi (2008) provide a literature review on tsunami wave loading based on Okada et al. (2004), U.S. ARMY CERC (1990), FEMA (2003), and Dias and Mallikarachi (2006). They conclude that the overall loading per unit width for a vertical wall can be as high as 18 times the hydrostatic force. Okada et al. (2004), U.S. ARMY CERC (1990) and FEMA (2003) consider the tsunami wave loading as combination of the hydrodynamic and hydrostatic forces. While Dias and Mallikarachi (2006) used three components: hydrostatic, hydrodynamic and impact loading.

For the purpose of vertical evacuation, FEMA (2008) published the FEMA P646 Guidelines for Design of Structures for Vertical Evacuation from Tsunamis. This guideline suggests eight different force components that should be included in tsunami load estimation to provide design requirements for tsunami evacuation buildings which could withstand tsunami events. For vertical evacuation constructions on land, and at some distance from the shoreline, according to FEMA P646 as well as Yeh et al. (2005) and Heintz and Robertson (2008), the eight components of tsunami forces are as follows:

- Hydrostatic forces: provide a local effect on elements when the non-loaded side is dry in consideration of the strength of each structural wall panel or building. Not used for the evaluation of a building as whole.
- Buoyant forces: related to the inundation depth and the rate of water-level increase. This provides the effect of reducing the total dead weight of structures that may impact the overturning resistance.
- Hydrodynamic forces: drag forces controlled by the maximum value of the product of the inundation depth, the square of flow velocity, and the shape of the structural element.
- Impulsive forces: short duration loads related to the flow velocity of the leading edge of the run-up. This impulse force is a hydrodynamic force known as a ‘punch force’ that provides a powerful force for a short duration. This force is followed by transient forces or sustained hydrodynamic forces.
- Debris impact forces: a short duration load which is related to maximum flow velocity and depth, debris mass, and debris stiffness.
- Debris damming forces: related to the damming effects caused by accumulation of waterborne debris and controlled by the breadth of the debris dam, flow depth and velocity.
- Uplift forces: the vertical (upward) force on the underside of floor structures is caused by rapidly rising flood waters and occurs in combination with buoyant forces.
- Gravity loads from retained water: controlled by weights of water retained in the structures.

These tsunami forces will not necessarily occur simultaneously or affect a particular structure at the same time. There will be a combination of one or more forces that lead to loading combination considerations. This loading combination needs to be incorporated into evacuation building design. Examples of calculations of each force including the load combinations are provided in the FEMA P646 guidelines.

Loading calculations must take into account that tsunami are a mixture of water, sediment and debris. Sediment grain size distribution is also important and as a starting point debris may include vehicles, containers, logs, parts of buildings (especially sheet steel) and whole timber-framed buildings. Erosion and sedimentation during the tsunami will also affect loading and should ideally also be accounted for dynamically in combined loading calculations.

3.0 EXAMPLES OF TSUNAMI RESILIENT BUILDINGS

3.1 Japan

Vertical evacuation buildings are used extensively in Japan (often within high population areas) and include both existing buildings assessed to be tsunami resilient and newly designed shelters where there is no existing building that can be used for vertical evacuation. Examples of specifically designed structures are included in FEMA (2008) and EEFIT (2011). During a post-event survey in May 2011, EEFIT made observations of 23 structures that were used for vertical evacuation in the March 11, 2011 Tōhoku, Japan earthquake and tsunami. These structures were overwhelmingly of reinforced concrete construction and were most commonly office or apartment blocks, schools, hospitals or car parks. Generally, they were three storeys or higher; examples of two storey structures were observed but these were overtopped in this event. Signage was found to be very inconsistent, with most of the observed structures lacking official signage on the building exterior (EEFIT, 2011).

The evacuation structures observed were sited with a range of orientations to the coastline: some parallel to the coast in their longitudinal direction, others perpendicular. This did not significantly influence structural damage to steel or reinforced concrete structures. No timber framed evacuation structures were observed. An important factor governing the extent of structural and non-structural damage appears to be the sheltering effect of other large reinforced concrete structures. Designated vertical evacuation structures performed well structurally (observed damage was generally limited to scour, debris strike, glazing and contents damage), but the number of evacuation sites overtopped by tsunami waves shows that some designated sites were not appropriate for the flow depths experienced. There appear to be inconsistencies in the designation and signage of evacuation structures between municipalities, and an underestimation of tsunami hazard that has led to inappropriate designation of certain structures.

Observations of tsunami damage to reinforced concrete, steel frame and timber framed buildings in Japan, are presented below, with more examples available in EEFIT (2011).

3.1.1 Reinforced concrete

Observations from the March 11, 2011 Tōhoku earthquake and tsunami have shown that many reinforced concrete structures (with and without shear wall) are capable of withstanding tsunami loads in 20m of flow depth, despite experiencing impact from small debris or scour of 2-3m depth around deep foundations. It was commonly observed that reinforced concrete infill panels failed under lateral loading. There are instances of reinforced concrete structures (piled and non-piled) which were subject to a 17m flow depth and were toppled; in one instance a structure was moved inland 30m from its original site. The exact mechanism which caused this appears to be a combination of debris impact, lateral forces shearing piles where present, and uplift forces.

Some reinforced concrete structures suffered collapse due to suspected debris strike, and this was also seen to have caused damage to external access / egress at several evacuation sites. It is not feasible at this stage to determine a probability of debris strike or of the size of debris due to the transient nature of damaging debris. Where small debris was observed at or in a reinforced concrete structure, it had caused non-structural damage, but no structural failure. Difficulties arise in constraining the impact of debris in post-event reconnaissance, due to its reworking in subsequent waves or return flow.

3.1.1.1 Existing buildings

Several buildings that had been assessed for their integrity related to seismic shaking and possible tsunami forces within the high risk zone were designated as vertical evacuation buildings, as illustrated in Figure 9. The locations of the buildings were marked on evacuation or hazard maps and tsunami evacuation signage was placed on the buildings. Observations made in Tōhoku during May 2011 indicate that vertical evacuation signage is not currently present on all designated evacuation buildings in Japan (EEFIT, 2011). Further examples of vertical evacuation buildings and discussion of their performance in the March 11, 2011 tsunami are available in EEFIT (2011).

Figure 9 An existing building designated as suitable for vertical evacuation within the high-risk zone and high-density population. The tsunami evacuation signboard is put on the building (Source: Shuto and Fujima, 2009).

Aonae Elementary School

After tsunami struck Okushiri Island in 1993 a new elementary school building was constructed as a tsunami resistant structure with a breakaway wall to reduce tsunami forces (Figure 10). The upper floor of the buildings can be used as a tsunami refuge.

Figure 10 Aonae Elementary School, Okushiri Island.

3.1.1.2 Tsunami Shelter, Sange District, Town of Kaiyo

The Sange District has experienced tsunami in the past resulting from the Nankai earthquake. Most people evacuated to nearby high ground during the tsunami event. However, to solve the problem of overcrowding on evacuation routes, a new refuge building was constructed (Figure 11). The design was, based on previous tsunami, for a 5m tsunami elevation with 1m of co-seismic land subsidence. There is a stone/rock memorial near the vertical evacuation site; this rock (5.5 m (wide) and 3.0 m high) was displaced by tsunami after the Keicho-Nankai earthquake on December 16, 1605.

Figure 11 Refuges Shelter – Sange District – Town of Kaiyo with the historical stone.

3.1.1.3 Nishiki Tower

This multi-purpose reinforced concrete structure was built at a small fishery town of Nishiki, Mie Prefecture in central Japan. This structure was designed within a five-minute walk from each neighbourhood (Figure 12 and 13) and symbolises the town's long history of experiencing disaster. The town has been severely damaged by tsunami approximately once every 100-150 years (Nakaseko et al. 2008). The tower has five levels and is tube-shaped to resist powerful waves. At the first floor is a store-room of fire fighting equipment and toilets; a meeting room is on the second floor; a small museum on the third floor, and a shelter for tsunami on the fourth floor with evacuation space on the fifth level.

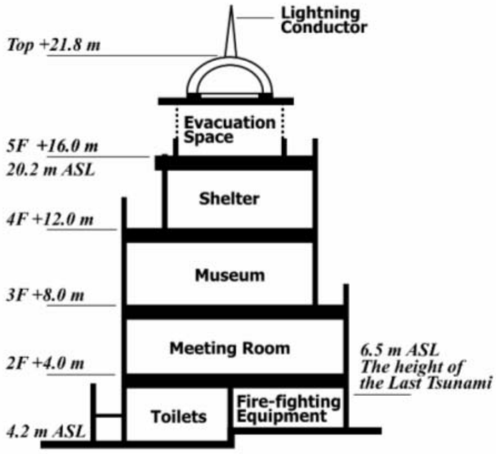

Figure 12 Vertical evacuation at Nishiki, Mie Prefecture – the Nishiki Tower consists of 5 levels and a circular plan shape to reduce lateral tsunami forces.

Figure 13 The location of Nishiki tower at Nishiki Town, Japan.

3.1.1.4 Shirahama Beach Resort vertical evacuations

This reinforced concrete elevated shelter (Figure 14) was built at a beach resort, and can hold up to 700 people in an area of 7.535 square feet. This structure is built to withstand earthquake forces and has piles driven about 66 feet deep into bedrock to avoid potential soil liquefaction. The elevation of this structure is 11.5 m above sea level; the design elevation is based on numerical simulations and a historic earthquake that produced a tsunami of 7.5 m high at this location in 1854.

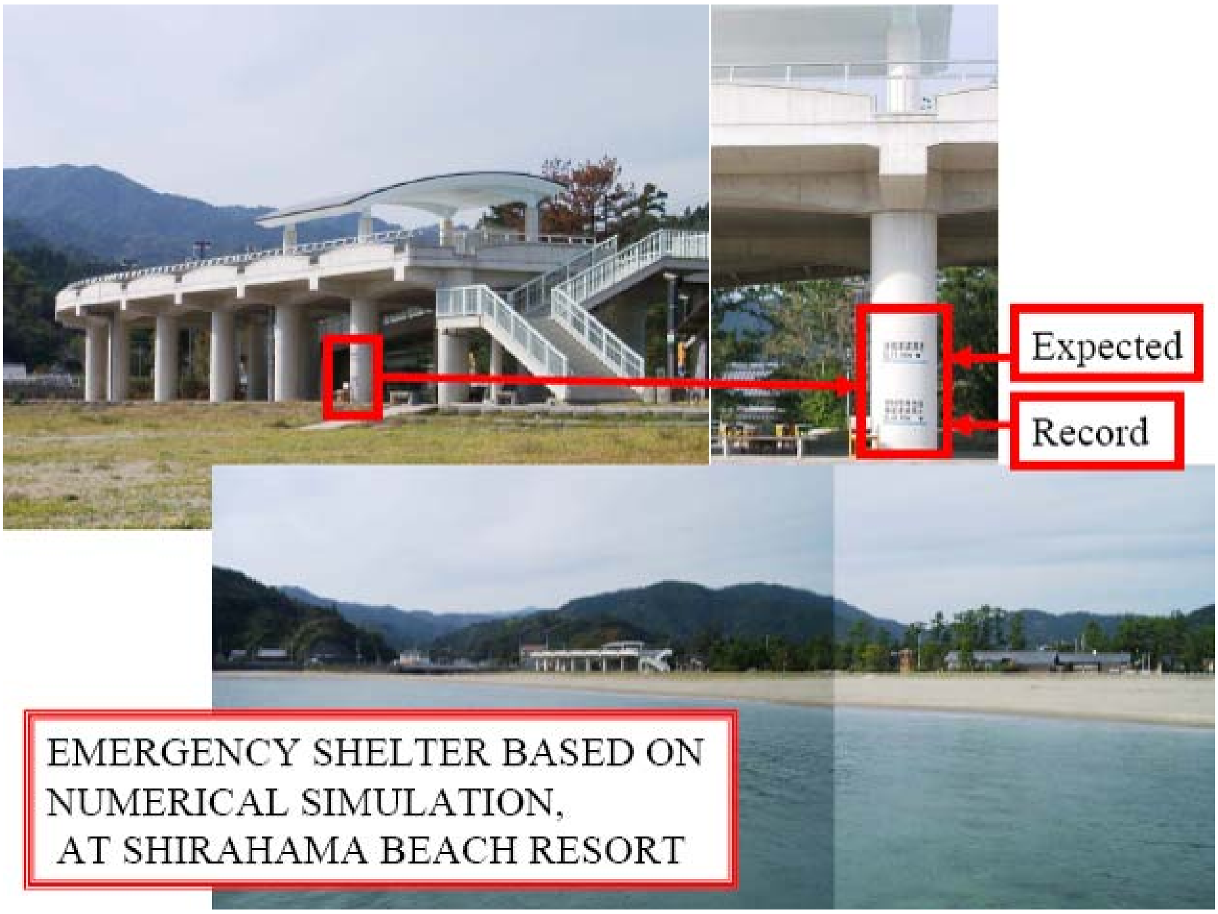

Figure 14 An emergency shelter based on numerical simulation assessment at Shirahama Beach resort, Japan. On the pile of the structure is written the tsunami inundation height expected based on numerical simulation and from the historical record (Source: Shuto and Fujima, 2009).

3.1.2 Steel frame

Steel frame structures of up to four storeys were observed in Japan during the EEFIT survey. Steel structures generally remained standing but suffered extensive damage to panel walls below the maximum height of tsunami flow due to lateral loads or small debris strike. Once panel walls are compromised, the open structural frame allows for through-flow, thus reducing lateral loads on the structure. Scour of steel frame structures was not observed during field investigations, which implies their resistance to additional scour effects. However, this does not rule out the possibility that scour did occur around some steel frame structures that were not inspected. Absence of scour would most likely be related to reduced turbulence around thin steel members once cladding has been damaged and removed in the tsunami. The only observed cases of structural frame failure were when large debris impact occurred (exterior or interior impact). While steel frame structures have the potential to remain structurally sound and allow for short-term vertical evacuation provided they are of sufficient height, extensive non-structural damage may endanger temporary occupants and render the structure unsuitable for use as a refuge for any length of time.

3.1.3 Timber frame

Japanese residential construction is most commonly one or two storey timber frame. The vast majority of these structures had suffered partial or complete collapse due to failure at the foundation tie points or wall studs. This provides further evidence to support previous observations that timber frame buildings are unsuitable for use as designated vertical evacuation structures. In addition, most one and two storey timber buildings will not be sufficiently high to be evacuation structures compared to tsunami flow depth and splash-up potential.

3.2 Indonesia, Thailand, Malaysia, Sri Lanka

Geohazards International launched a project in August 2010 to design a prototype 5 to 10 metre-high area of raised ground (a "Tsunami Evacuation Raised Earth Park") in Padang (Geohazards International, 2010) as an alternative to using buildings for evacuation. There are several Japanese-built reinforced concrete multi-storey evacuation buildings in Banda Aceh (Figure 15) including the offices of TDMRC (Tsunami Disaster and Mitigation Research Center) at Syiah Kuala University.

Figure 15 Left: Three Japanese-built tsunami evacuation buildings in Banda Aceh in 2008. Right: A close-up of one being used in an evacuation drill that year.

3.3 United States

The United States currently has no official tsunami vertical evacuation facilities, although several projects are underway to implement this capability.

As already discussed, FEMA produced guideline reports P646 (Guidelines for Design of Structures for Vertical Evacuation) and P646A (Vertical Evacuation from Tsunamis: A Guide for Community Officials) which look at the design of vertical evacuation facilities and strategies. These reports present various evacuation options, considerations of tsunami loads and design criteria, and a suggested decision making process including operational and siting considerations for an effective community evacuation strategy (FEMA, 2008 and FEMA, 2009).

Project Safe Haven, run by Washington State Emergency Management (Project Safe Haven 2011a,b), emphasises community engagement in Washington State, U.S. The project has drafted strategies for siting earth berms and structures for the Washington coast through community-led planning and design workshops, which emphasise the needs and local knowledge of the community in selecting locations and designing evacuation buildings and / or berms.

In Cannon Beach, Oregon, proposals have been made to rebuild city hall as a vertical evacuation building. The project is currently being delayed by lack of funding, and there is currently discussion about whether this is the most suitable option in Cannon Beach. It is believed that a key road bridge on the edge of town is susceptible to collapse in an earthquake and tsunami, and there are calls for it to be repaired instead of the city hall being reconstructed.

Although there are no specially designed vertical evacuation buildings in the State of Hawaii, in the event of tsunami residents and tourists are advised to use the upper storeys of hotels as a means of vertical evacuation.

4.0 APPLICATIONS AND LIMITATIONS IN NEW ZEALAND

This project focuses on buildings for use as tsunami evacuation buildings. Residential buildings and buildings for other uses are outside of the scope, as is the consideration of hard defences such as sea walls. Sea walls as used in Japan were discussed briefly at the this project's workshop and it should be noted that walls are unlikely to be able to be built high enough at any remotely affordable cost in New Zealand. Furthermore, there are other factors such as the New Zealand Coastal Policy Statement which discourages the use of structures to mitigate the effects from natural hazards, coastal access, usability of the coast, visual pollution, and sediment budget impacts that should be carefully considered when discussing hard defences.

NZ hazard management policy is guided by the CDEM Act, Building Act and the Resource Management Act. The primary statute for risk reduction is the RMA (refer Saunders et al. 2007), with land use planning providing the key opportunity for reducing consequences from tsunami.

4.1 Land use planning

The Resource Management Act 1991 (RMA, New Zealand Government, 1991) is the primary land use legislation in New Zealand, and has the following purpose:

To promote the sustainable management of natural and physical resources. <u>Sustainable management</u> means managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their <u>social,</u> <u>economic</u>, and <u>cultural wellbeing</u> and for their <u>health and safety</u>.

Sustainable management includes provisions for people's health and safety, which is often incorrectly considered purely the domain of the Building Act 2004. Tsunami evacuation planning – which provides for peoples health and safety – is therefore also considered an issue to be addressed via the RMA through district plan provisions.
A district plan is prepared under Part 5 of the RMA to control the use of land within the district of a territorial or unitary authority. Through the district plan, it is common for certain criteria to be placed on buildings. While district plans are land use orientated, they can and do include requirements and constraints for buildings. For example, minimum floor levels for buildings within a flood hazard area can be stipulated (see Information Box 1); as can building materials and visual appearance (see Information Box 2) (Saunders, 2010).

Information Box 1: Thames- Coromandel District Plan (Thames-Coromandel District Council, 2007), Natural Hazard provisions for flooding.

Section 4.53 Natural Hazards - Standards
Floor levels of all houses and all habitable rooms shall meet the following standards:
1. In areas covered by flood management plans:
   (a) Primary overland flow areas: Not less than one metre above natural ground level;
   (b) Secondary overland flow areas: Not less than 0.5 metres above natural ground level;
   (c) Ponding areas: Not less than 0.5m above the flood datum level stated on the planning map;
   (d) Overland flow and ponding areas: Not less than one metre above natural ground level.

Section 457 Non-complying activity assessment criteria and protocols
1. Buildings in floodways protocols:
   (b) The following are not permitted under existing use rights on any such site:
      (i) Any increase in the ground coverage of any building;
      (ii) Any raising of the natural ground level;
      (iii) The erection of any fences or walls on or abutting any such site;
      (iv) Lowering the floor level of any existing habitable room in any existing building;
      (v) Converting any existing non-habitable room in any existing building;
      (vi) Converting any existing non-habitable room into a habitable room;
      (vii) Any new building;
      (viii) Any garden amenity which is above natural ground level;
      (ix) On any such site, any works or development or activity which would further impede flood flows or increase the susceptibility of the site or any other site to flooding or flood damage.
   (c) Activities other than houses and their accessory buildings which are non-complying activities in the zone are subject to the same existing use right constraints as houses (as set out above).

Information Box 2: Queenstown Lakes District Plan (Partially Operative, Queenstown Lakes District Council, 2009)

Objective 3 - Residential Amenity (Chapter 7, p4-5)
Pleasant living environments within which adverse effects are minimised while still providing the opportunity for individual and community needs.

Policies:
3.3 To ensure the external appearance of buildings reflects the significant landscape values and enhance a coherent urban character and form as it relates to the landscape.

Implementation Methods
Objective 3 and associated policies will be implemented through a number of methods including:
(i) District Plan: (a) Rules relating to building height, sunlight and outlook for neighbours, street scene, separation from neighbours and outdoor living space.

Assessment Matters – Arrowtown (Chapter 7, p48)
(d) Exterior Materials and Finishes
The extent to which the exterior materials and finishes reflects the following:
Building materials and their finishes generally shall be:

- schist with lime mortar with or without a low percentage of cement for walls and chimneys, with a natural finish or finished with a lime, sand plaster and/or a natural limewash;
- painted timber rusticated or shiplap weatherboards for walls;
- painted corrugated steel or uncoated timber shingles for roofs;
- painted timber for roof and wall coverboards, baseboards, and cornerboards;
- painted timber windows, glazing bars, sills, and frames;
- painted timber door panels, stiles, mullions, rails, glazing bars, sills, and frames;
- natural or limewashed bricks for chimneys;
- painted timber architraves to doors and windows for timber clad houses;
- lime-sand rendered architraves may be applied to schist buildings;
- painted corrugated steel for walls;
- painted timber framing to verandahs.

As such, district plans can regulate both building requirements and design criteria to meet outcomes agreed to by the community. A discussion of the specific role of the Building Act 2004 (New Zealand Government, 2004) and Building Code (Section 3, New Zealand Government, 1992) in hazard management can be found in the research report published for Ministry for the Environment in 2006 (Tonkin & Taylor, 2006).

The consideration of vertical evacuation structures could be used as a named tool or requirement as part of tsunami risk reduction in land use planning. Emergency management requirements are already being applied in some cases in New Zealand for flooding (e.g. in the Kaihikatea Estate Environment Court ruling in the Coromandel, an emergency management plan was required, including warnings systems and evacuation planning; Saunders, 2011). This can most easily be applied in situations where a resource consent is required. Resource consents are triggered by rules in the district plan, which are supported by corresponding objectives and policies. Any objectives, policies or rules in the district plan pertaining to natural hazard mitigation need to be consistent with those in the CDEM (Civil Defence Emergency Management) Group Plan as prescribed by the Civil Defence Emergency Management Act (New Zealand Government, 2002).

4.2 Emergency Management & Community Issues

The purpose of selecting or designing evacuation structures is to be able to effectively respond to warnings. Locally sourced tsunami within the New Zealand context will have a travel time of less than 1 hour from time of generation until it reaches the shore.. Tide gauge records from Japan indicate that the time between ground shaking and arrival of the 1^{st} tsunami wave was a minimum of around 25 minutes. The available time for evacuation may be longer than this as the subsequent tsunami waves can be larger than the first wave. A similar natural warning (such as ground shaking) is also likely to be felt for a locally generated tsunami. Other natural and informal warnings may also occur for tsunami (such as the sea receding or rapidly rising) and these could also trigger the use of vertical evacuation structures. For regional and distant source tsunami, there is more time for evacuation and official warnings (for example sirens) are possible. Given the potentially larger amount of time for evacuation for regional and distant source tsunami, evacuation to high ground or inland should be the primary objective.

Evacuation structures are therefore more likely to be considered for:

- places where the distance to travel to a safe locations is too great in the available warning lead-up time;
- where the route to safety may be difficult, severely damaged or is likely to be congested; or
- vulnerable populations (e.g. elderly, disabled) who cannot travel the distance to safety that other more-able people can.

Evacuation mapping is desirable before considering any vertical evacuation structures. This will ensure that the locations of the structures are appropriate and easily assessable. Within the workshop run for this project it was noted that final inundation area maps can mask the patterns of inundation throughout an event. In some areas inundation may take some time to occur and this can be useful when creating evacuation plans. Care however has to be taken to ensure that complex time-varying evacuation plans are not developed as they are difficult to implement and to communicate to the public.
A potential priority order when planning evacuation routes could be as follows:

- The primary evacuation should be to high ground or to areas which are inland from a tsunami.
- Secondly, existing buildings could be evaluated to determine their appropriateness for vertical evacuation. This evaluation would consider the height of the building, its structural integrity, its potential capacity and is location relative to the population which would require the use of this building.
- Thirdly, new buildings could be designed and constructed to manage the residual risk after the first two steps have been fully explored.

The other issues that need to be considered for evacuation structures are:

a. Agreement with building owners
   Ensuring security while providing access will need to be well planned. Liability and insurance will also need to be negotiated with the necessary legal requirements outlined in a formal agreement
b. Preparedness of the tourism sector; population swelling day-to-day, seasonally.
   Important to educate tourist hosts on community response plans and the capabilities/capacities of evacuation structures.

c. Multi-hazard priorities – avoiding hazards.
   The need to identify evacuation structures that avoid other risks, such as hazardous sites, those that could release fumes and gases following a tsunami, or buildings that could collapse onto the evacuation structure.
d. Bystanders and contra-flow back towards the ocean (e.g. to schools)
   The need to ensure communities see evacuation structures as a last resort, not as potential viewing structures. Evacuation schemes will need to take into account that there may be contra-flow into evacuation zones, despite education and signage.
e. Signage
   All signage should be consistent with the Technical Standard for the Civil Defence Emergency Management (CDEM) Sector (TS 01/08), which includes in-place vertical tsunami evacuation route signs and safe-locations for in place evacuation.
f. Education / participation / exercises
   Evacuation planning is a fundamental component of emergency planning for tsunami, and this should include education and regular community exercises. Evacuation structures should be included in these exercises when appropriate.
g. Building capacities versus populations evacuating
   It is recognised that any evacuation structure will have limited capacities as to the number of evacuees it can safely hold, etc., and that evacuation plans should carefully consider these matters and educate communities on risks involved and on options available.
h. Hot spots where some sections of the community may particularly want to consider vertical evacuation structures include Napier, Gisborne, Mount Maunganui, Lower Hutt, Wellington, Christchurch.
i. Surveys of existing building stock for potential evacuation structures are required and this issue should be considered in any future work on evacuation buildings. In 2006 Councils were required to develop policies on ‘Dangerous, Earthquake Prone, and Insanitary Buildings under the Building Act 2004. These evaluations can contribute to this survey work. Councils will need to know what building resources they have and, using the (future) guideline(s), what is the likely physical response to tsunami?

4.3 Building consenting

The tsunami resistance of evacuation structures would be checked at the building consent stage (see Section 5.0) The Building Act would not (or could not) require that a building be a tsunami evacuation building, but once so designated the Building Act provisions would ensure it performed structurally as required. Further, whether a building is designated as a tsunami evacuation building or not it must nevertheless be Building Code compliant. If tsunami is a likely load to be encountered during a building’s life then tsunami loading must be considered and appropriately designed for.

4.4 Risk reduction, existing buildings and liability

Where new buildings are proposed to be designated as tsunami evacuation buildings they need to be specifically designed for such purposes as described below.

New and existing buildings not specifically designed as tsunami evacuation buildings may, nevertheless, be suitable for such purposes. The buildings would need to have been previously inspected and verified as suitable for such purposes. There may be some buildings that comply by default, but from initial discussion based on FEMA (2008) this appears unlikely. Others will fall short to varying degrees. Buildings in the latter category may however be the best option available when other means of evacuation have been exhausted or are not otherwise available. In these circumstances, such buildings (even with increased risk) could be included as part of a wider strategy for tsunami risk reduction.

Classifying an existing building as ‘suitable’ for tsunami evacuation in an emergency when in fact it is not, will be accompanied by the potential for exposure to liability. The building might not be high enough or strong enough for the actual event, but in some places and situations may be the best (or only) option available.

The use of non purpose designed buildings for vertical evacuation should probably be advised along with the inherent additional risk, so that public perception that it is the best available risk reduction option in the circumstances is fostered as opposed to an expectation that the building is categorically ‘safe’. This probably requires further discussion and consultation with specific communities early in the discussion as to whether such a building should be used.

5.0 BUILDING ACT, BUILDING CODE AND COMPLIANCE OPTIONS

Whether a building, new or existing, is designated a tsunami evacuation building is not a matter for the Building Act to determine. The assigning of such a classification would presumably come from other legislation such as the Civil Defence Emergency Management Act. Once the requirement exists, however, that the building be designated a tsunami evacuation building then the provisions of the Building Act come into play to ensure that the building can perform its life refuge and post-disaster function as required.

The Building Act (New Zealand Government, 2004) requires that all new building work comply with the Building Code. The Building Code, itself contained in legislation (First Schedule of the Building Regulations 1992), is a performance based Building Code that spells out in 35 technical clauses, under the seven general headings of Stability, Fire Safety, Access, Moisture, Safety of Users, Services and Facilities and Energy Efficiency, how completed building work must perform. The Building Code doesn't tell you how to build but instead spells out what completed building work must achieve. The Building Code's structural provisions require that account shall be taken of all physical conditions likely to affect the stability of buildings so that if buildings are likely to be subjected to tsunami then the Building Code requires that they be accounted for. This report focuses on the design of buildings designated for evacuation where tsunami is clearly a likely load. The situation for other buildings is discussed briefly in Section 5.2.

In practice, compliance with the Building Code is achieved by referral to acceptable design Standards that specify loadings and material resistance properties. Loadings are usually derived on the basis of return periods of hazard events which vary according to location, the hazard, building importance, the design working life of the building. Currently, there is no New Zealand Standard for the design of buildings for tsunami loadings.

The United States Federal Emergency Management Agency (FEMA) has published *"Guidelines for Design of Structures for Vertical Evacuation from Tsunamis"* FEMA P646 / June 2008. Since there is no current New Zealand Standard, the FEMA Guidelines are suggested as a starting point for developing a means of compliance for the design of buildings for use for vertical evacuation. This could also be used as a starting point for the design of all buildings for which tsunami is a likely load.

In the above-mentioned guidelines, the Tsunami Performance Objective in deriving the design loadings includes the potential for significant damage while maintaining a reliable and stable refuge when subject to the Maximum Considered Tsunami. Most tsunami evacuation structures would be expected to be repairable, although the economic viability of repair will be uncertain. This approach is consistent with how we design essential facilities, such as hospitals, police and fire stations, and emergency operations centres, for seismic and wind events.

In the Guidelines, wave-breaking forces are not considered on the basis that vertical evacuation centres should be located some distance inland from the shoreline and out of the wave-breaking zone.

The Guidelines Tsunami Structural Load Effects include:

1. hydrostatic forces
2. buoyant forces
3. hydrodynamic forces
4. impulsive forces
5. debris impact forces
6. debris damming forces
7. uplift forces
8. additional gravity loads from retained water on elevated floors

The height for hydrostatic load forces is based on a maximum height taken as 1.3 times the predicted maximum run-up elevation. The dynamic load forces are dependent on calculating the maximum flux per unit mass which is the maximum value of a function of velocity and flow depth at the structure, which can be obtained by running a detailed numerical simulation model or acquiring simulation data. Thus detailed information from a model of the design tsunami at the actual site is necessary in order to calculate the design loadings.

The Guidelines also summarise the structural design concepts relevant to the design of vertical evacuation structures. They note that tsunami resistant structures have:

1. Strong systems with reserve capacity to resist extreme forces
2. Open systems that allow water to flow through with minimal resistance
3. Ductile systems that resist extreme forces without failure
4. Redundant systems that can experience partial failure without progressive collapse.

Other structural considerations include Foundation/Scour Design and Breakaway Wall Concepts.

These concepts and a number of other considerations noted could well form the basis for also evaluating buildings that are not specifically designed for vertical evacuation from tsunami. Also noted are a number of concepts for adapting and modifying existing structures, as well as a number of planning considerations. The main considerations are likely to be lateral load, uplift and scour.

A review of tsunami impacts to different combinations of foundation types, substrates and foundation-building connections would help to determine the best resistance to all three of these at the substrate-foundation and foundation-building interfaces.

5.1 Frequency and size of tsunami

As noted above, buildings designed for vertical evacuation from tsunami should be considered to be in the same Importance Level as other structures with special post–disaster functions i.e. Importance Level 4 as defined in AS/NZS 1170.0:2002. With the normal design working life for buildings being 50 years it is recommended that such buildings be designed for an ultimate tsunami event limit state with the same probability as an Importance Level 4 building for earthquake i.e. 1 in 2,500 years.

The likely load used for design should correlate to a specific tsunami frequency, which will in turn have an expected size (e.g. wave height, flux etc), or to a specific size, which will have a calculable frequency. The maximum size could be anywhere up to 'maximum credible' such as that from the local subduction zone. See Appendix 1 for discussion of frequency and size related to all buildings.

Different frequency/ capability criteria might be considered for the classification of existing structures compared to new specifically designed construction. This could be similar to the example of retrofitting earthquake prone buildings when compared to the construction requirements for new buildings. Three possible options exist for comparison with the recommended tsunami design. Either for a lesser event (say 1 in 1000 or 1 in 500 year events which correspond with lesser Importance Levels), a percentage of new purpose designed building requirements, or 'as nearly as reasonably practicable' to a purpose designed building, may be applied to give some level of understanding.

5.2 Application to new buildings in general

The design of buildings not intended for evacuation from tsunami is beyond the scope of this project, but in terms of application of the Building Code all buildings must consider likely loads including tsunami. This section, therefore, discusses application of the Building Act, Building Code and Standards to all buildings.

The Building Act and Building Code apply to all buildings, so tsunami loading needs to be considered in their design. If tsunami is a likely load then the Building Code requires a 'low probability' of failure. The Building Code is a minimum Code providing for acceptable levels of safety and health having regard to a number of things including national cost. The Building Code provides for the protection of 'other property' (defined term in Building Code) but there is no requirement in the Building Code to protect one's own property. This means for buildings other than tsunami evacuation buildings, if evacuation procedures are 100% efficient (so there is certainty that people will not be in buildings when the tsunami strikes), then there is no need to even consider structural strength in withstanding tsunami. In reality though, this can rarely be assured - especially given that there may be little or no warning of the tsunami or warnings, even if given, for a variety of reasons may not be heeded by all.

Future design documents for new buildings need to consider not only how to design a tsunami evacuation building (the focus of this report) but how to design all new buildings, across all of AS/NZS 1170's Importance Levels, so Building Code compliance is achieved. Structural design needs to account for both sides of the structural equation; namely, firstly determining the demand on buildings (loadings) and secondly the building's capacity (resistance). The information on demand needs to account for not only the 2500 year event appropriate to tsunami evacuation buildings but also the lesser events that other buildings need to be checked for (see Appendix 1).

5.3 Application to existing buildings in general

The Building Act's requirements in respect of existing buildings are limited. Apart from requirements where an owner elects to alter or change the use of a building, Councils have powers where buildings are deemed to be 'earthquake-prone', or 'dangerous and insanitary'. It is doubtful however whether a building which would be unsafe in a tsunami, at least an earthquake generated tsunami, can be classified as either earthquake-prone or dangerous.

If this is the case then there appears no mechanism in the Building Act to require a minimum tsunami resistance in existing buildings let alone to require the tsunami resistance to be checked and improved.

The Building Act's earthquake-prone provisions relate to a building's ability to withstand an earthquake generated at the site (refer to s122 of Building Act and the definition of 'moderate earthquake' in the Building (Specified System, Change the Use, and Earthquake-prone Buildings) Regulations 2005) and therefore don't appear to be able to include considerations of a building at risk because of a tsunami generated at some remote location. The dangerous and insanitary provisions of the Building Act likewise don't appear to be able to be applied because earthquake, having been considered elsewhere in the Building Act, cannot be considered again when assessing if a building is dangerous (see s121 of the Building Act).

If comparisons are drawn with the Building Act's earthquake prone provisions, it is conceivable that similar requirements would apply for buildings in general and for those designated as tsunami evacuation buildings. If such an approach was to be followed, then existing buildings, across the board, would be considered acceptable if their performance was one-third as good as a new building designed for the purpose. From work done by the NZNSEE in relation to earthquake resistance of buildings, this equates to, in the order of, 10 - 15 times the risk. This level of risk should be assessed in terms of its acceptability for existing buildings in general or in particular for tsunami evacuation buildings which are required to have a post disaster function.

Issues to be discussed in relation to the Building Act and existing buildings that are likely to need to withstand tsunami loads include:

- Availability, signage, access
- Liability (see section 4.4)
- Level of performance required compared to new building design?
- Should there be a different approach between buildings in general and buildings designated as tsunami evacuation buildings given the latter are life safety refuges with possible post disaster functions?
- In what situations if any should there be any watering down of the requirements as they apply to new buildings?
- What buildings, if any, should be checked, rated, and be required to be upgraded? Presumably it is impractical and serves no purpose to check the tsunami resistance of low rise housing but what of apartment and other buildings?
- Once the required level of performance of an existing building is determined how are they to be assessed, rated and strengthened?
- How is this information to be used by building owners and the authorities?
- How is it to be conveyed to the public or should it be?
- Should information about a building's vulnerability be made available when it may be the best option or indeed the only option available?
- What purpose is served by making information about a building's inadequacies known?
- The potential for provisions in the Building Act to ensure buildings are checked and, as required, upgraded over time
- The potential for requirements to check certain other buildings which because of factors such as their location, construction, age, size and height people could believe to be adequate in a tsunami and elect to stay

- Possible amendment to enable 'tsunami-prone' buildings to be identified and brought up to some minimum level
- Does finding that a building is not earthquake-prone (following appropriate assessment) provide, by default, sufficient strength to withstand tsunami given it is above the required height?

5.4 Limitations of timber framed residential buildings

The design of residential buildings for evacuation from tsunami is beyond the scope of this project and is discussed only briefly here. The typical New Zealand timber framed construction, apart from normally being a maximum of two storeys, has the potential to tear or float off its foundation or partially collapse during a tsunami. The following should be considered in regard to residential buildings. Effective warning and self-initiated evacuation systems can significantly reduce the risk to people in residential buildings. However, there may be times (e.g. night) or circumstances (e.g.: not noticing the warning because the earthquake shaking was not considered significant enough to self-evacuate; warning system disrupted (EQ power failure)) that evacuation may not occur from residential buildings, and a system to ensure evacuation of occupants is necessary. See Appendix 1 for a discussion on design requirements.

6.0 RECOMMENDATIONS

A site for vertical evacuation should be considered within places at significant risk of tsunami where there is a high population and distance or access to high ground is prohibitive. A combination of scientific input on inundation behaviour and local resident participation are highly important in deciding on a vertical evacuation site. Existing buildings can be considered, and if unsuitable or inadequate, then new buildings may need to be designed for vertical evacuation. Evacuation buildings must have sufficient structural integrity to resist expected tsunami and earthquake forces. The authors make the following recommendations:

- While the recommendations below are being acted upon, the Guidelines for Design of Structures for Vertical Evacuation from Tsunami (FEMA, 2008) is suggested as a starting point for developing a New Zealand solution.
- Development of a New Zealand-specific Standard or technical information that can be cited by the DBH in its B1 Compliance Document as a means of compliance for the design of new purpose-built tsunami evacuation buildings. Consider also any necessary application to all new and existing buildings.
- Development of a protocol for the assessment of existing buildings in relation to the above document for new buildings. This may be, for example, a separate guideline or a section of the above guideline.
- Amendments to the Building Act to enable buildings to be assessed and strengthened as required to resist tsunami.
- Consideration of what frequency and size of tsunami constitutes the likely load that tsunami evacuation buildings and buildings in general should be built to resist in New Zealand. This may vary around the country.
- Ensuring that loading forces from tsunami and the overall flow-depth (including ‘splash-up’) are both considered. A building that stands up but is over-topped in the likely load event is no use, and a building tall enough but which is significantly damaged and does not maintain life safety is similarly of no use.
- Consideration of the damage state of the structure after a tsunami-generating earthquake but before the tsunami.
- Consideration of loading due to entrained debris and water.
- Consideration of tsunami impacts to different combinations of foundation types, substrates and foundation-building connections
- Consider that tsunami forces will not necessarily occur simultaneously or affect a particular structure at the same time. There will be a combination of one or more forces that lead to loading combination considerations.
- Explore and scope further the role of land use planning policies and documents for incorporating tsunami evacuation buildings into land use planning and CDEM Group plans.
- Incorporate clear guidance for the application of the above document(s) for both emergency management and land use planning within those document(s).
- Consideration of secondary hazards to the evacuation structures once occupied – fire hazard from floating debris / volatile materials.
- Consider the potential for evacuee isolation – vertical evacuation structures must have appropriate resources to act as refuge for up to 3 days following an event.

- Development of guidelines for the warning infrastructure to be placed on buildings – experience from Japan showed that signage was inconsistently applied to designated structures. Consideration should be made for the siting of warning sirens on evacuation buildings.
- Issues and options for building ‘bypass’ by evacuees should be explored, where people evacuating from near a designated building might better head to high ground leaving the building for people travelling from places even further away from the high ground.
- Consideration of mobile population distributions such as day vs night, seasonal changes and event-related population swelling when doing building location and capacity calculations
- As a forward path we recommend:
    - That the Ministry of Civil Defence & Emergency Management considers the development of NZ-specific guidance for vertical evacuation planning, as part of the national tsunami risk management programme.
    - That the Ministry of Civil Defence & Emergency Management advocate for these recommendations within central & local government agencies and appropriate national associations, including Department of Building and Housing (to be known as Ministry of Business, Innovation and Employment from 1 July 2012).
    - That this report be provided to Ministry of Civil Defence & Emergency Management, Department of Building & Housing, Standards New Zealand, the Building Industry Authority, Building Officials Institute of New Zealand, New Zealand Institute of Architects, Building Research Association New Zealand, Institute of Professional Engineers New Zealand, Association of Consulting Engineers New Zealand Inc, New Zealand Universities and New Zealand CDEM Groups.

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APPENDIX

APPENDIX 1 FREQUENCY AND SIZE DISCUSSION FOR OTHER BUILDINGS

All other new buildings need to be designed for tsunami as appropriate. Continuing the AS/NZS 1170 approach (and just discussing houses); houses come within Importance Level 2 and accordingly need to be designed for the 500 year event (10% chance of exceedance in 50 years) or possibly even a lesser event as considered appropriate. Whereas it is clear that houses will not be able to withstand events of the order of the 2500 year event (and nor should they) they may well be able to be designed to withstand the 500 year or whatever lesser event is considered appropriate. Further, the Building Code doesn't require that failure can never occur but requires that buildings have a 'low probability' of failure in withstanding likely loads. What constitutes a 'low probability' for a house will be judged against different criteria than the low probability of failure for a tsunami evacuation building. A tsunami evacuation building needs a low probability of failure indeed as it is an essential life safety refuge possibly with a post disaster function. Therefore, what is low here needs to be very low. A house also needs a low probability of failure but given a number of factors including the number of occupants, the likelihood of people being in the house (given education and warnings), and the national cost of making houses tsunami resistant, the low probability threshold is likely to be much higher. All this needs further consideration, but accounting for the lesser design event and a higher low probability of failure it may well mean that practical house designs are achievable. As noted above, an appropriate design is one that provides for an appropriate level of safety for building users, not one that limits property damage.

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