6.0 TSUNAMI PROPAGATION

In this Section we first give an overview of what has been learnt from numerical modelling of tsunami. We then briefly discuss the amplitude-distance relationships used to estimate wave heights from distant and local tsunami sources. These estimates of wave heights at the coast were then used as input into inundation models (Section 7).

6.1 Insights from numerical modelling

Numerical modelling of tsunami serves a double purpose: it allows us to estimate the effects of events which have yet to happen, and it enables us to evaluate our understanding of past tsunami.

The process of numerical tsunami modelling can considered as three stages:
- Source modelling, in which the generation of the tsunami, either by earthquake, landslide, volcano or bolide impact, is simulated.
- Propagation modelling, in which the dispersal of the tsunami waves around the ocean, sea, or lake, is simulated.
- Inundation modelling, in which the water flow over dry land is simulated.

The modelling process is usually performed using specially designed computer programs. The latest 3-dimensional tsunami models simulate both propagation and inundation, overcoming the difficulty of changing boundary conditions at the shore, which is the most dynamic and complex phase of a tsunami.

Tsunami source models are well developed for earthquakes, where the surface deformation is estimated by assuming that the earthquake represents a finite dislocation within an elastic body. These techniques have been tested against data from numerous real events and generally demonstrate a reasonable agreement, although the 26 December 2004 earthquake has highlighted some areas for improvement (Lay et al, 2005). Both landslides and volcanoes tend to have great variability in the mechanisms by which they initiate tsunami, and the physics of those mechanisms is in some cases only partly understood. Consequently, while modelling of past events can be undertaken, and specific scenarios for future events can be investigated, it is harder to develop general insights.

Propagation modelling, in which the processes by which tsunami waves spread out from the source are simulated, is well understood in terms of the underlying physics, though uncertainty in some parameters remain. This area of modelling is now at a stage where many useful insights can be gained (see Figures 6.1 and 6.2 by way of illustration).

Inundation modelling is an area in which numerical modelling is at a preliminary stage because of limitations of resources and data availability. There are many different processes taking place during inundation, each of which may be well understood in isolation, but effective modelling of the combined processes remains challenging. Developing high-resolution models can capture these processes but are time-consuming and require high capacity computing. Useful insights for inundation modelling can be gained from studying the impacts of real tsunami.

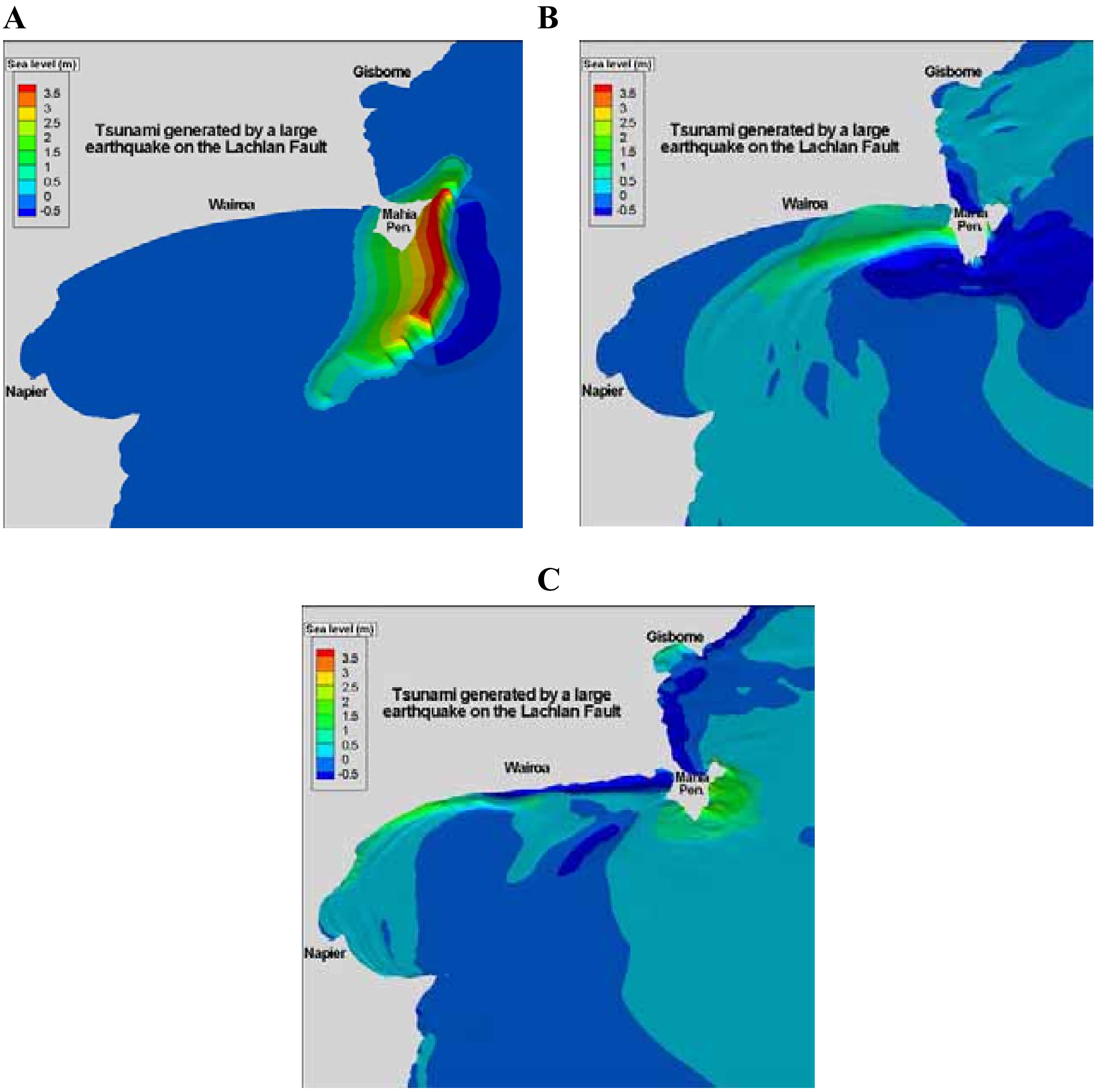
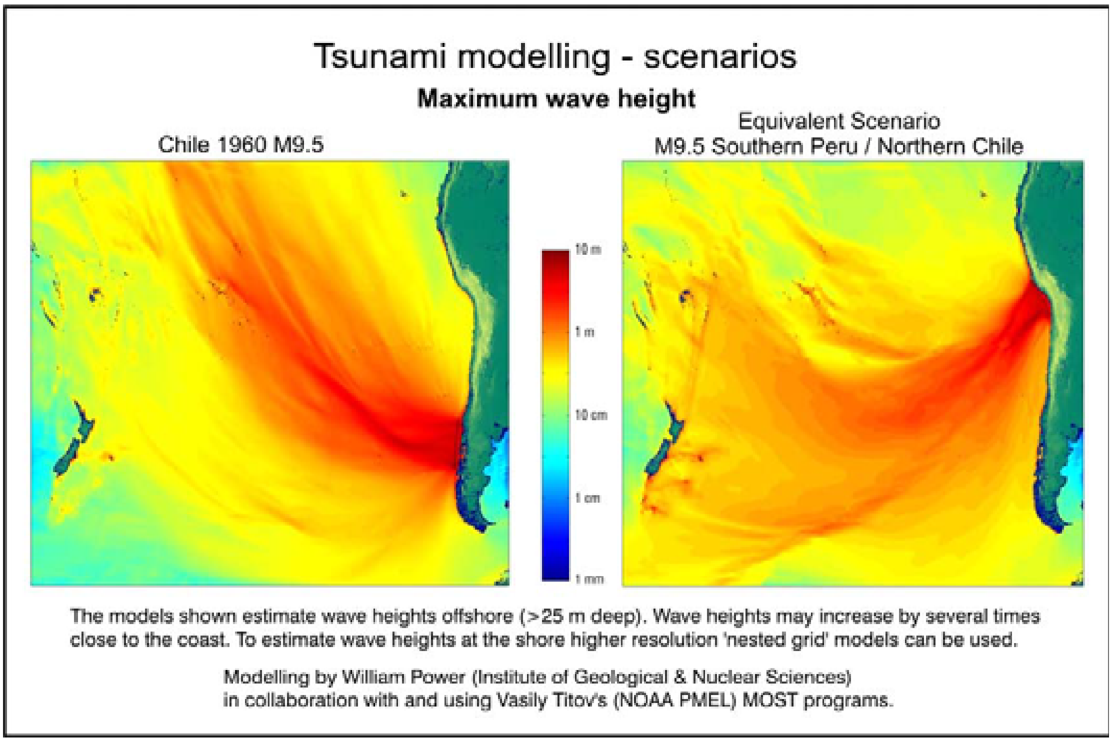


Figure 6.1 A series of images illustrating the propagation of a tsunami generated by an earthquake on the Lachlan fault. Modelling by Roy Walters (NIWA) for the Hawke's Bay Aquarium.



Tsunami modelling - scenarios

Maximum wave height

The models shown estimate wave heights offshore (>25 m deep). Wave heights may increase by several times close to the coast. To estimate wave heights at the shore higher resolution 'nested grid' models can be used.

Modelling by William Power (Institute of Geological & Nuclear Sciences) in collaboration with and using Vasily Titov's (NOAA PMEL) MOST programs.

Figure 6.2 A comparison of two scenarios for South American tsunami affecting New Zealand, illustrating the effect that directivity of the source can have on distant locations.

Some general insights from numerical modelling:

- Earthquake-generated tsunami typically propagate in such a way that most of the wave energy is directed perpendicular to the fault on which the earthquake occurred, and the initial wave is separated into two components travelling in opposite directions.
- Landslide sources can be highly directional, sending a fairly concentrated tsunami 'beam' perpendicular to the slope which has given way and in the direction of the landslide movement (Ward, 2001; Walters et al, submitted). Many volcano sources can also be highly directional, but more typically radiate in a circular pattern.
- Where the dimensions of the tsunami source are small, less than a few 10's of km in the case of ocean sources, the resulting waves are subject to dispersion, in which the different frequencies present in the tsunami wave propagate at different speeds. This leads to a stretching-out of the tsunami wave train, and generally lower amplitudes. This is one reason why landslides and volcanoes tend not to be a tsunami risk at large distances.
- Tsunami waves tend to become concentrated above undersea ridges because of refraction. In this situation the ridge acts as a 'waveguide', which can lead to enhanced tsunami wave heights at locations where these ridges lead to the shore (Koshimura 2001). In New Zealand a good example is given by the Chatham Rise, an area of shallow bathymetry which lies between Banks Peninsula and the Chatham Islands. The presence of this ridge leads to larger wave heights reaching Banks Peninsula than would otherwise be the case.
- Bays and inlets around the coast have specific natural frequencies, determined by the time it takes for water to slosh into and out of the bay (e.g. Walters & Goff, 2003). If the natural frequency of a bay matches that of the tsunami waves then amplification will occur. This can often explain variations in tsunami height, which may at first appear

random, along a given section of coastline. Identifying the natural frequencies of coastal bays and comparing them with characteristic frequencies for tsunami is a useful first step towards identifying those areas most at risk.

Specific insights regarding New Zealand:

- Of the South American tsunami sources, it is those lying between the Peru-Chile border (19°S) and the 8°S line of latitude, which are most effective at directing tsunami towards New Zealand. The tsunami of 1868, which was the worst distant source tsunami of historical times in this country, originated from the southern half of this region (about 17.7°S). The last large tsunami from the northern half of this region (about 12.5°S) was in 1746, too early to appear in written records in NZ, but modelling suggests that such tsunami are likely to also have a strong impact here. Locations on the east coast of New Zealand tend to be the most vulnerable to South American tsunami, but the ability of tsunami to bend around corners in the coastline, means that they can still pose a hazard to locations which are out of the line-of-sight.
- Distant tsunami originating from locations in the Northern hemisphere, such as Cascadia, and the Aleutians, and also from areas of the southwest Pacific north of New Zealand, tend to have their greatest impact on Northland, the Coromandel, and the Bay of Plenty.
- Local tsunami generated by submarine landslides and thrust faults can have a large local impact on the east coast of New Zealand from Kaikoura northwards to Northland.

Numerical modelling of relevance to New Zealand is tabulated in Appendix 4.

Problems and limitations of tsunami modelling:

- In many areas of the world, including New Zealand, there are very limited data on, for example, wave period, number of waves in the tsunami, and variability along a coast during historic tsunami which can be used to validate models.
- A critical input to propagation models is the bathymetry of the seafloor. This is because the speed, and ultimately the direction, of the tsunami are controlled by the depth of water. Consequently the model results are only as good as the bathymetry data allow. Much good bathymetry data exists, but the processes of combining different sources of bathymetry and processing it into the required form is one of the most labour-intensive aspects of tsunami modelling. The proprietary nature of many bathymetry databases is also an obstacle to the preparation and use of bathymetry grids for tsunami modelling.
- Most propagation models assume that coastlines behave as perfect reflectors of tsunami waves, but this omits the natural dissipation of tsunami energy which occurs when they run up against the shore (Dunbar 1989), leading to a gradual reduction of the accuracy of the model. This is a particular problem for modelling the effect of tsunami from distant sources, as incoming waves may arrive over the course of several hours and interact with earlier waves, especially in locations where tsunami waves may become ‘trapped’ within bays and inlets.
- Inundation modelling requires detailed data on the topography of the areas being considered, ideally with a vertical resolution of less than 0.25 m. Currently there are very few areas of New Zealand which have topography mapped to this resolution. High-resolution inundation modelling also benefits from data on the size and shape of buildings and on the nature of different land surfaces, e.g. whether forested, cultivated, urban, etc. Ideally the nearshore bathymetry and on-land topography and cultural roughness can be

obtained as a seamless digital elevation dataset to enable simulations using the full power of high resolution hydraulic modelling software.
- Source characterisation represents a problem for tsunami modelling. Where models are used for real-time forecasting it is usually only possible to determine very basic information on the characteristics of the source in the time available. This problem also applies to modelling of past tsunami because there may be little source information available. This is particularly true for local-source tsunami because the waves are often strongly influenced by the details of the source, for example the distribution of fault-slip in an earthquake. Deep-water wave buoys maybe useful in forecasting the potential effects of distant tsunami, as they "record" the source characterization in that particular event.

6.2 Estimating wave heights from distant-source tsunami

Based on a compilation of historic, largely Pacific Ocean, data, Abe (1979) proposed the following equation for estimating the wave height, H, of a tsunami at a distant shore due to an earthquake of magnitude M_w

$$H = 10^{(M_w - B)} \qquad 6.1$$

where B is a parameter that varies for each site and earthquake source. B can be determined using either historical data, or numerical modelling, or a combination of both. The data that Abe (1979) based this equation on has considerable scatter, so the relationship has significant uncertainty. This has been incorporated into the calculations in this study, and are discussed in more detail in Appendix 5.

Five distant source regions were identified in this study:
- Region 1: South America between 45°-19°S and 8°-0°S
- Region 2: South America between 19°S and 8°S
- Region 3: Cascadia (NW USA and Vancouver Island, Canada)
- Region 4: West Aleutians / Rat Island
- Region 5: Southern New Hebrides

Region 5 is strictly speaking a regional source, as the travel time to New Zealand is just under 3 hours, however it was convenient to describe this source here.

The historical evidence suggests that the South American sources are the most important of these regions. Historical data for Region 1 come from the tsunami of 1877 and 1960, and data for Region 2 come from the tsunami of 1868 and 2001. Some sites have no historical data for these events, in these cases numerical model results were substituted. The model used for this substitution was chosen on the basis of giving the 'best-fit' to the data at sites where observations were recorded.

The historical data, and models of historical events, were not themselves sufficient to accurately quantify B for all sites and sources, so additional synthetic (non-historical) scenarios were used. Two scenarios each were modelled for Regions 1 and 2, and one scenario each for the other Regions. Within Regions 1 and 2 the locations for the synthetic earthquakes were chosen to represent the geographical spread of possible event within the regions.

This combination of tsunami-height information from historical observations, reconstructions of historical events, and synthetic models, was then used to estimate B for each site and source region. More details of this analysis, including the uncertainty treatment, are given in Appendix 5.

6.3 Estimating wave heights from local source tsunami

For local source tsunami, the equivalent Abe relationship to that used for distant sources is given by

$$H = 10^{M_w - \log R + 5.55 + C} \qquad 6.2$$

where H is the wave height at a local coast, R is the source-to-site distance and C is a parameter that varies for each site and earthquake source. The best available values of C are derived from Japanese data and have possible values of 0.0 and 0.2, depending upon location. For our analysis we have used both values with equal weight. This equation estimates the tsunami height based only on earthquake magnitude and distance, and takes no account of the effects of bathymetry or source orientation, consequently it is important to take into account the uncertainty in its estimates. More details of this analysis, including the uncertainty treatment, are given in Appendix 5.