VALIDATION OF TSUNAMI MODELLING ALONG THE NSW COAST

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Abstract

Investigations of potential tsunami inundation are being undertaken as part of Stage 2 of the New South Wales (NSW) tsunami risk assessment, established by the Office of Environment and Heritage (OEH) and the NSW State Emergency Service (SES).

Inundation modelling at five NSW coastal sites is being undertaken to provide for an improved understanding of the tsunami risk along the NSW coastline. This will enable future consideration of tsunami impacts in coastal zone management and planning, as well as assisting in the development of tsunami emergency planning, response and community education.

The study involves the modelling of tsunami resulting from earthquakes of a range of magnitudes, and from a variety of global source locations. Tsunamigenic databases developed by the Bureau of Meteorology and GeoScience Australia were utilised and scenarios from these were used as boundary conditions for shelf scale Delft3D inundation models.

The current paper outlines the exposure of the NSW coast to tsunami events, the general methodology being used to address site specific risk from tsunami and presents the results of validation testing of the modelling approach to international benchmark standards, as well as to local historical records.

Introduction

The NSW Office of Environment and Heritage (OEH) and the NSW State Emergency Service (SES) have commissioned a study to undertake investigations of potential tsunami inundation as part of Stage 2 of the New South Wales (NSW) tsunami risk assessment. Inundation modelling at five NSW coastal sites was undertaken to allow for an improved understanding of the tsunami risk along the NSW coastline and to assist in the development of tsunami emergency planning, response and community education.

The preliminary risk scoping undertaken as part of Stage 1 of the tsunami risk assessment indicated that the coast of NSW has a moderate tsunami hazard level. The offshore hazard is relatively uniform along the NSW coast, with near shore wave amplitude values for a return period of 500 years ranging from about 0.5 metres to 1.1 metres, and a value of about 0.8 metres off Sydney. The main contributors to the hazard at this return period come from earthquakes on the Vanuatu, Kermadec, and Puysegur trenches. The corresponding hazard level is about two metres in Western Australia and about one quarter of a metre along the southern coast of Australia. Some parts of Asia have a hazard level as high as ten metres at a 500 year return period. (Somerville et.al., 2009).

The current paper outlines the methodology being used in the study and the results of validation testing against international benchmark tests and recent locally measured tsunami events.

Study area

Five coastal locations were specifically investigated as part of the assessment. These five study areas, shown in **Figure 1**, were identified in Stage 1 of the Tsunami Risk Assessment as being potentially more vulnerable than other locations in NSW to tsunami inundation and were therefore selected for detailed tsunami inundation modelling. The five coastal locations include:-

- Swansea/Lake Macquarie ;
- Manly;
- Botany Bay/Kurnell;
- Wollongong/Port Kembla; and
- Merimbula.

The extent of each study area was defined by local geomorphic features, such as headlands and

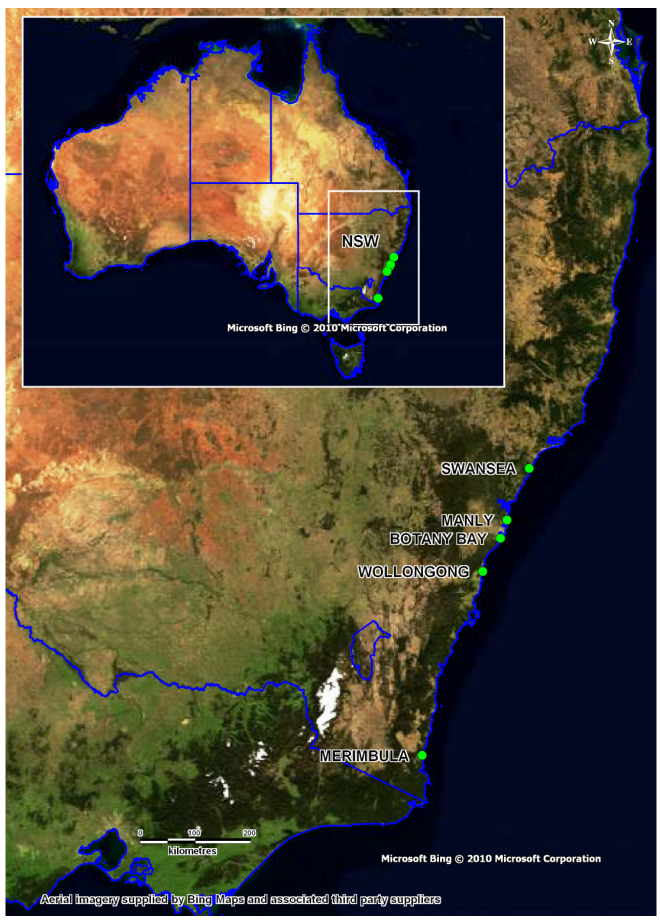

Figure 1 – Study Area

embayment's, and as far landward so as to define the full extent of expected tsunami inundation. This was nominally defined as the area up to the 15mAHD contour.

Understanding Tsunami

Tsunami is a Japanese word; "tsu" meaning harbour and "nami" meaning wave. A tsunami generally consists of a series of propagating long waves (called a tsunami wave train) that can travel trans-oceanic distances. Due to the immense volumes of water and energy involved, tsunami can devastate coastal regions, as exemplified by the 2004 Boxing Day tsunami, where, according to the U.S. Geological Survey over 230,000 people from 14 different countries perished and millions more were displaced.

Causes of Tsunami

Tsunami are caused by the sudden displacement of a large volume of water. While this displacement may be caused by landslides, volcanic eruptions and even meteorite impacts, approximately 75% of all tsunami are generated by earthquakes. Furthermore, because the vertical displacements and rupture lengths of earthquakes can be estimated by scientists, it is possible to generate approximate surface wave time-series for these tsunami. Therefore, this assessment only covers tsunami generated by earthquakes along subduction zones.

Tsunami Propagation

Tsunami waves in the deep ocean usually possess a wavelength of approximately 10 to 500 km. Because of these large wave lengths, their speed of propagation generally follows shallow water wave theory, where wave speeds are given by the formula:-

$$c = \sqrt{gd}$$

where:

c = the wave speed
g = acceleration due to gravity ($9.81 m/s^2$)
d = water depth (m)

As deep ocean water depths are typically 4000 to 5000m, such waves can travel at speeds up to 800km/hour; hence they can cover trans-oceanic distances in a matter of hours. However, due to these enormous wavelengths tsunami waves generally possess periods in the vicinity of 10 to 30 minutes and amplitudes, in deep water, typically smaller than 1m. This makes tsunami difficult to detect in deep water and it is common for ships out to sea to not notice their passage.

Nearshore Behaviour of Tsunami

The danger of tsunami lies not in deep water, but rather when they come ashore. As a tsunami leaves the deep water of the open ocean and arrives at shallow waters near the coast, it undergoes a transformation called wave shoaling. That is, tsunami propagation speed is related with depth, and so as a tsunami wave propagates into shallow water, it will slow down. As the period of the wave remains the same, more water is forced between the wave crests causing the heights of the wave to increase and the wavelengths to decrease. Because of this shoaling effect, a tsunami that was imperceptible in deep water may grow to have wave heights of several metres or more near the coast, but travels more slowly.

When the crest of the wave propagates onto land the resulting temporary rise in sea level is called ‘run-up’ (usually expressed in metres above a reference datum). The momentum and energy in this moving wall of water (potentially up to several metres high) damages or destroys most things in its path, before minutes later rushing back out to sea. A large tsunami will have multiple waves arriving over a period of hours, with significant time between the wave crests, usually 10 to 30 minutes (Kamphuis, 2010). The first wave to reach the shoreline may not have the highest run up.

As the wave approaches the coast it is also affected by differences in near shore bathymetry and the shape of the coastline. Apart from the shoaling process, the wave is also subject to refraction, diffraction and reflection resulting in very large variations in the runup height. Resolving these effects is necessary to estimate runup heights at any particular location.

Tsunami Scenario Selection

NSW is exposed to tsunami originating from a range of possible sources, mostly from within a highly active seismic zone known as the ‘Pacific Ring of Fire’ which spans 40,000km, borders four continents and is made up of volcanoes, earthquakes, deep sea trenches and major fault zones. However, it is considered that the most significant tsunami threat to the NSW coast would be from those originating along the various tectonic subduction zones on the edge of the Indo-Australian Plate, in the South West Pacific. These include the New Hebrides Trench, the Solomon Trenches, the Tonga-Kermadec Trench and the Puysegur Trench. Distant tsunami sources including Mid and South America, Cascadia, the Aleutian Islands and Japan also pose a tsunami risk to the NSW coast. In fact, since European settlement it is the Peru-Chile Trench that has generated the majority of the largest tsunami measured along the NSW coast (Beccari and Davies, 2009). **Figure 2** presents the major source zones that have been considered within this assessment.

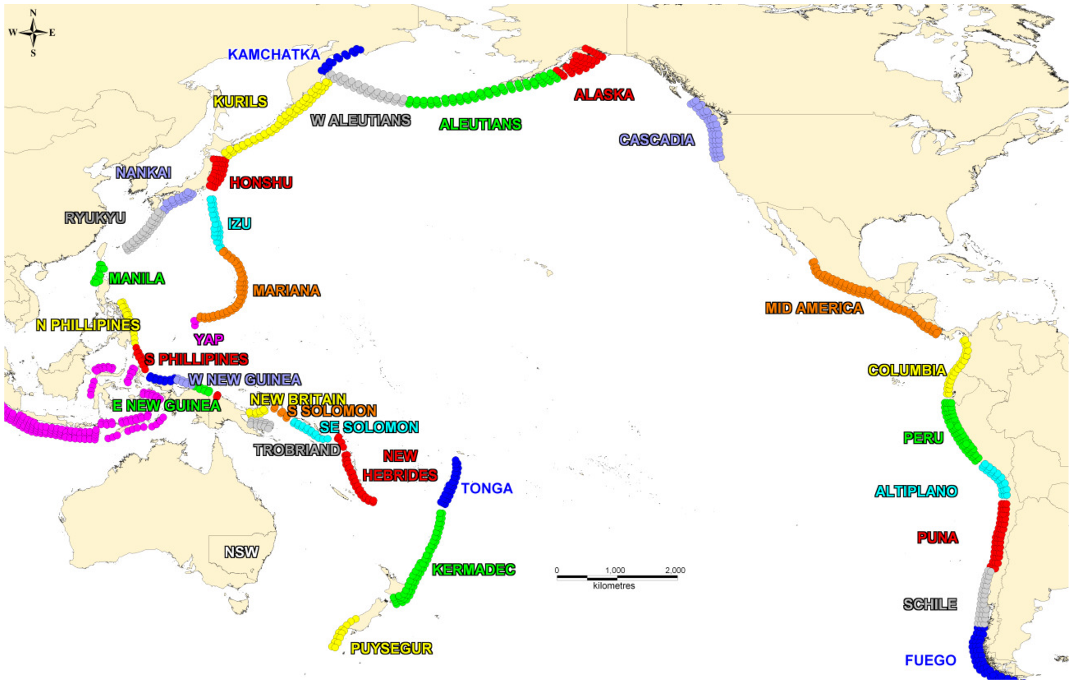

Figure 2 –Tsunami Source Zones for NSW

Emergency response planning is required to consider the full range of possible tsunami magnitudes. That is, from lower magnitude tsunami impacting the marine and immediate foreshore environment, through the range of tsunami events of increasing magnitudes resulting in land inundation threat and including the worst case or 'highest credible threat' event. As is done for catchment flooding and coastal storms, event modelling for this study was based around return period events of magnitudes up to the 10,000 year ARI event, this being of a similar order to concepts such as the Probable Maximum Flood (PMF) in flooding/coastal engineering terminology.

However, the calculation of return period estimates of tsunami magnitudes required an event database of adequate length. With available measured records along the NSW coast being scarce, two synthetic tsunami databases were accessed to provide data for this assessment. The two databases were drawn upon to allow for both an initial identification of the tsunami risk and to consider individual events as well as draw upon tsunami time-series data for use as boundary conditions for the inundation modelling. The two databases are:-

- the Tsunami Data Access Tool (Tsu-DAT)
- the Enhanced Tsunami Scenario Database: T2 (T2 Database).

Tsu-DAT (GeoScience Australia)

Tsu-DAT provides a tool to access GeoScience Australia's database of numerical modelling results of thousands of individual synthetic tsunami events and provides a summary, in terms of both probability and average recurrence interval (ARI), of the likelihood of a given tsunami height occurring at a given offshore location (at the 100m depth contour). Data within the Tsu-DAT tool was derived from the Probabilistic

Tsunami Hazard Assessment (PTHA) of Australia (Burbidge et al, 2008). This assessment modelled thousands (76,000+ in total) of synthetic tsunami to estimate the likelihood of a tsunami wave of a given amplitude occurring at an offshore location, defined at the 100m depth contour (GeoScience Australia, 2010b). Each event is based on a realistic subduction zone rupture derived from geological assessments of tectonic dynamics.

T2 Database (Bureau of Meteorology)

The BoM's T2 database includes output from the numerical modelling of thousands of hypothetical tsunami events, in terms of water level and depth-averaged velocity signals. The T2 database has been developed to inform the Australian Tsunami Warning System with the aim of providing numerical predictions of tsunami events based on observed earthquake magnitudes, seismic moments and location. It is intended to be used as a predictive tool within real time emergency management systems.

The T2 database contains tsunami wave signals that are the results from a prescribed set of modelled events which are generated by earthquakes of magnitudes (Mw) of 7.5, 8.0, 8.5, and 9.0 from all subduction zones within the Indian and Pacific Oceans (see **Figure 2**). This series of pre-computed scenarios form the basis of the BoM's real-time tsunami warning system. Output from the T2 database includes full time series information at any grid point in the global T2 propagation model domain.

Database Utilisation

For tsunami event selection and the subsequent inundation modelling, a collaborative approach was implemented, which made use of information from both databases. Tsu-DAT is a useful tool for identifying from where tsunami events, which pose a risk to a given site, may originate and how often these may occur in a probability risk based approach. Thus, the initial identification of the tsunami risk and individual events was made using GA's Tsunami Data Access Tool (Tsu-DAT).

From there, subsequent tsunami time-series for use as boundary conditions for the inundation modelling would be taken from the BoM's Enhanced Tsunami Scenario Database: T2 (T2 database).

The T2 database provides tsunami time-series at any location/contour depth within the BoM's model domain. This allows for the extraction of tsunami time-series data at the inundation model boundaries. This allowed the Delft3D inundation models to extend seaward of the continental shelf edge before significant shoaling has occurred.

This is preferable for inundation modelling in order to ensure that the correct hydrodynamics of the shallow water tsunami wave are being generated within the Delft3D inundation model. It also allows for a verification of the Delft3D inundation model using time-series data from locations inshore from the adopted inundation model boundaries, also extracted from the BoM T2 Database, for both water levels and currents.

Inundation Models

Inundation models covering each of the study sites (**Figure 1**) were established using the Delft3D software package. The Delft3D numerical scheme has been adopted in many tsunami studies worldwide and has been compared to world standard benchmark verifications with good agreement.

For tsunami propagation and transformation Delft3D solves the non-linear shallow water equations which are thought to provide a reasonable description of tsunami behaviour.

Model Extents/Resolution

The extent and size of the individual study area grids varied depending on site specific features such as landforms (headlands and embayment's) and the topographic lie of the land.

Regional models were constructed for each site and utilised the 'domain decomposition' structured grid system in Delft3D. Model systems at each site typically consisted of three to five grids and extended approximately 50km north and south of each specific study area and out beyond the 3000m depth contour (between 50 and 100km offshore). This practice ensured that issues associated with high frequency boundary reflections were avoided at the offshore boundary. On land the grids extend up to the 15mAHD contour which is considered to cover the maximum possible extent of coastal inundation at these sites.

The grid resolution for the overland sections of the model is in the order of 10m. This grid resolution is considered to adequately describe the overland terrain for the purposes of inundation modelling and hazard extent definition. The offshore resolution is 500m with increasing grid resolution for each nested grid.

Model Verification and Validation

The observed record of tsunami events along the NSW coast is limited. Generally, observations are obtained from tidal measurements and there exists only a handful of anecdotal reports of small run-up occurrences. Site specific data of a tsunami of sufficient magnitude to cause inundation along the New South Wales coastline was not available for this study. Mega-tsunamis have been hypothesised based on paeleotsunami records with severe inundation up to 100mAHD (Dominey-Howes, 2007) however, the exact cause and pre-conditions (such as mean sea level) for such run-up events is unknown. As such, the Delft3D model setups at the five NSW sites could not be directly verified.

Indirect verification of the model scheme and approach was therefore required which included:-

- Tidal Calibration
- Verification against International Benchmark Cases
- Overland Roughness Investigations
- Site Specific

Tidal Calibration

Each regional oceanographic model domain was calibrated to either predicted or measured (where available) tidal signals. This exercise was carried out to ensure that the model systems correctly describe the propagation of long period shallow water waves from deep to shallow water.

Benchmark Verification

To overcome the lack of site-specific field data, the National Oceanic and Atmospheric Administration (NOAA) in the USA have recommended a series of 'benchmark' events to be replicated in order to validate models (NOAA, 2007). This is referred to as 'benchmark verification' and this process provides confidence in the model system utilised where site specific data do not exist.

Data from the 1993 Okushiri Island (northern Japan) tsunami event was used as the 'benchmark verification' case for the Delft3D model used for this assessment.

On 12 July 1993, a magnitude Mw7.8 earthquake occurred with the epicentre located at 42.76^{O}N and 139.32^{O}E, off the south western coast of Hokkaido, Japan near Okushiri Island. The coastline of both Okushiri Island and the Oshima Peninsula of Hokkaido were affected by the event. Field data (e.g. run-up height and water levels at gauges) were available for the model validation for the event at locations including at Monai and Aonae (Okushiri Island) and Iwanai and Esashi (on the Oshima Peninsula of Hokkaido).

Field surveys by a number of authorities and institutions following the event were undertaken that provided a spatial description of tsunami run-up around Okushiri Island (Takahashi, 1994). Unusual features of the observed tsunami, included:-

- An extreme run-up height of 31.7mMSL measured near the village of Monai. This tsunami run-up mark was discovered at the head of a very narrow gulley within a small cove (CRIEPI, 2004). It is considered that the large run-up height was a result of unique and complex bathymetric and topographic features.
- The arrival of the first wave at a location known as Aonae, five minutes after the earthquake and a second wave, 10 minutes after the first. The first wave came from the west, while the second wave came from the east.

In addition to the field surveys, a 1:400 scale laboratory experiment of the Monai Valley for the tsunami event was established, using a physical model tank at the Central Research Institute for Electric Power Industry (CRIEPI) in Abiko, Japan. The primary objective for the physical model was to replicate the water level signal at three output locations (referred to as Channel 5, 7 and 9) as well as the maximum run-up level. This data provides a point of reference for numerical simulations.

To conduct the benchmark verification, a Delft3D model system was created for the Okushiri Island area using the same model parameters as that adopted for the five NSW Tsunami Inundation Models. The Disaster Control Research Centre (DCRC), Japan, digitised the bathymetric and topographic data from several sources and this publicly available data (Matsuyama and Tanaka, 2001) was used in the development of the Delft3D model grid.

DCRC also constructed an initial wave profile from a 1.1m subsidence (depression) and two separate water level uplifts along the subduction zone of 4.9m and 2.2m, respectively, and this was used for the model initial conditions.

Overall, results of the Delft3D modelling showed very close comparisons in terms of modelled versus observed run-up and modelled versus observed physical model water level information. The extreme wave run-up near Monai village is replicated by the Delft3D model, with a level of 32mMSL being reproduced. Furthermore, a comparison of the time-series water level data at the three physical model wave gauge locations show that the Delft3D model reproduces both the tsunami signal peaks and phasing extremely well. See **Figure 3** below.

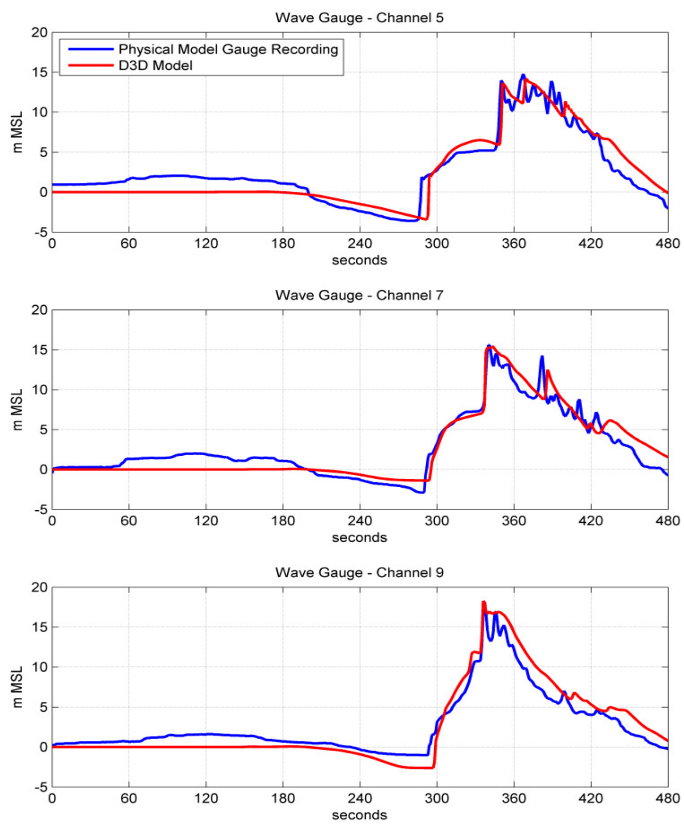

Figure 3 – Modelled and measured sea level for 3 wave gauge locations

Some discrepancy between the signals may result from the initial condition in the physical model, which is different from the numerical model description at time zero in the simulation. The cause of this initial difference is unknown although has been observed during other model validation tasks (Nielson et. al., 2005).

Model output also showed that the initial wave comes from the west and arrives five minutes after the earthquake event, and this is followed approximately 10 minutes later by a second wave coming from the east as per the observed conditions.

Figure 4 shows that the run-up levels around Okushiri Island closely resemble those of the measured/observed data. The spatial variability of run-up levels around the island are reproduced very well, with all major variations described. Furthermore, the run-up in the small valley to the north of Monai reaches 32.0m, a close match to the 31.7m measured after the event.

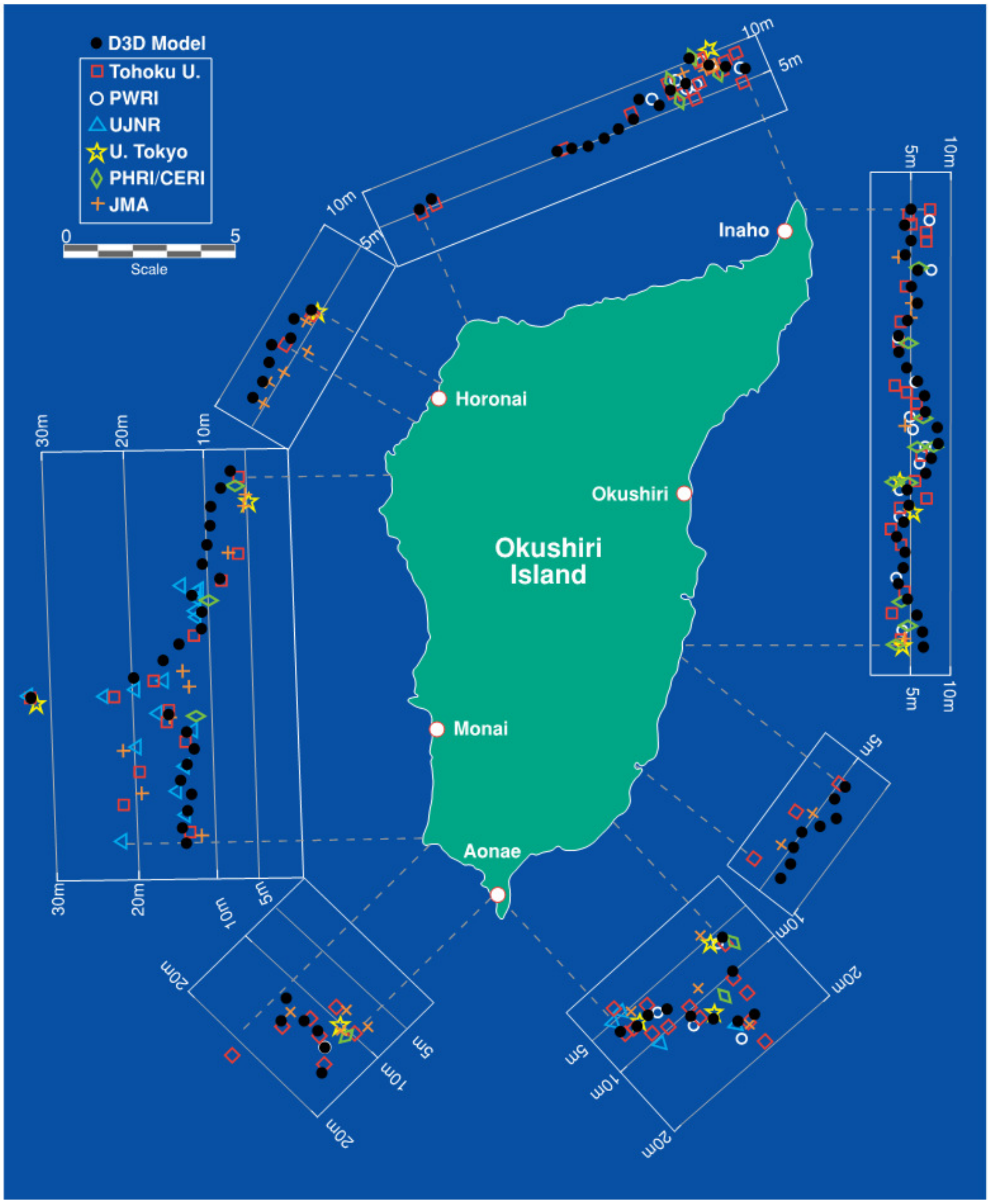

Figure 4 – Modelled and measured Tsunami Run-up around Okushiri Island

The close agreement between the Delft3D model results and the Okushiri benchmark data suggests that the Delft3D modelling scheme is an appropriate modelling tool for use in the NSW Tsunami Inundation study.

Overland Roughness

As the propagation of tsunami over the shoreline and coastal land areas would be heavily influenced by the model roughness parameter that is adopted for the foreshore area, it was necessary to use a spatially variable roughness grid, so that a range of land characteristics (such as roads, residential properties and parklands) were accounted for during inundation modelling.

Investigations were conducted into the sensitivity of the mannings roughness value to be used for the various kinds of land usage. Unlike nearshore swell wave run-up and overtopping, tsunami may propagate kilometres inland, thereby increasing the influence of roughness on the propagation of the waves. This effect is compounded by the retained water from preceding waves that provide deeper water for on-land propagation.

In order to investigate the effect and sensitivity of these roughness parameters, a 'numerical flume' model that described a smaller sample area was developed over a section of the Lake Macquarie study area. The flume consisted of a 200m wide grid domain that extended from the offshore boundary of the overall model up to the +15mAHD contour. Initially a fine 2m grid resolution over the foreshore areas was established that described impermeable physical structures such as buildings (based on cadastral and aerial image information) as raised structures and then determining the extent of the flow through that area during a tsunami.

Utilising a spatially variable roughness option within Delft3D the flume model was run again with the physical structures removed, and instead replaced by a spatially variable roughness grid which contained a range of roughness values to describe different types of land, see **Figure 5**.

From these results it was possible to determine which combination of roughness values provided a flow extent that most closely resembled the flow extent obtained when physical structures were present. In this way the authors were able to derive a suitable roughness parameter for each land type (see **Table 1**).

Table 1 – Adopted Overland Roughness Values

Land Usage	Manning Roughness Value (n)
Road	0.02
Residential/Commercial	0.10
Parkland/Forrest	0.07
Open Grassland	0.03

Figure 5 – Example of a Spatial Roughness Grid

Historical Tsunami Validation

In order to confirm reasonable propagation of the T2 tsunami signals to inshore locations, it was important to validate the Delft3D model output to measured tsunami signals (from appropriate tide gauges along the NSW coast) for historical tsunami events.

The first stage in this task was to identify appropriate (actual) events to compare with the adopted modelling approach. The subduction zone earthquake events listed in **Table 2** resulted in observable tsunami signals, albeit of small magnitude, at sites along the NSW coast. The BoM subsequently provided scenarios from the T2 database to match these events as closely as possible, having compared each to deep water tsunameter observations of the actual events. Those comparisons were not provided to the authors and hence are not reported herein.

Table 2 – Identified Seismic Events Causing Tsunami along the NSW Coast

Subduction Zone	Locality	Date	Earthquake Magnitude (Mw)	BoM Recommended T2 Scenario
Japan Trench	Honshu, Japan	11/03/2011	9.0	311c scaled up to 9.0
Peru-Chile Trench	Chile, South America	27/02/2010	8.8	408d scaled down to 8.8
Puysegur Trench	New Zealand South Coast	15/07/2009	7.9	218b scaled down to 7.9
Tonga Trench	Gizo, Solomon Islands	02/04/2007	8.1	172b scaled up to 8.1
Peru-Chile Trench	South Central Chile	22/05/1960	9.5	401d scaled up to 9.2

Appropriate tide gauge data on these dates were obtained at 4 of the 5 study sites for comparison to the modelled outcomes.

Consistent methods of analysis were applied to the measured and modelled signals to enable a meaningful comparison between the two to be made. As the T2 scenarios used in the modelling were not exact replicas of the recorded events, but rather were a best representation, achieving an exact match with historical records in terms of the tsunami wave train was not feasible.

Validation was therefore conducted by comparing a historical record with its representative T2 scenario in terms of statistical wave characteristics for a period of 20 hours after the tsunami was first detected inshore.

The following steps were applied in the validation:-

- The tsunami signal was isolated by calculating the residual (subtracting the predicted tidal signal) and applying a high pass filter (50% cut-off at 3 hours period) to remove any other influences on the signal (such as atmospheric) not associated with tsunami events.
- Model output was extracted at a 1 minute time-step and the simulation start date shifted to the time of the subduction zone earthquake.
- The time of tsunami arrival (for both measured and modelled, separately) was visually estimated using the aid of a low-pass filter with a cut-off frequency (50%) of 15minutes.
- The maximum wave height (or peak current speed) was found by identifying the peak of the signal. The mean wave height was estimated by averaging the peaks over a 20 hour (or length of model output) period following the arrival of the tsunami.
- An integrated spectral density time-series was calculated for both the measured and modelled signals. Spectral analysis (using Fourier Transforms) was completed on sequential overlapping windows of the signals to provide a time varying description of the spectral energy, otherwise known as a spectrogram.

- Average 2D energy spectra were calculated over the first 20 hours of the event (or length of model output) to identify the peak period. Spectral moments of the average 2D spectra were then calculated to derive the mean wave period values.

The comparisons between modelled and measured signals of historical events provided reasonable matches in terms of tsunami arrival time, wave height, currents and spectral energy (see **Figures 6** and **7**, for example). This indicates that the adopted modelling approach using the Delft3D numerical model with T2 scenarios for water level boundary conditions is capable of replicating what is physically realistic and lends assurance that the results of the inundation modelling can be used with a degree of confidence.

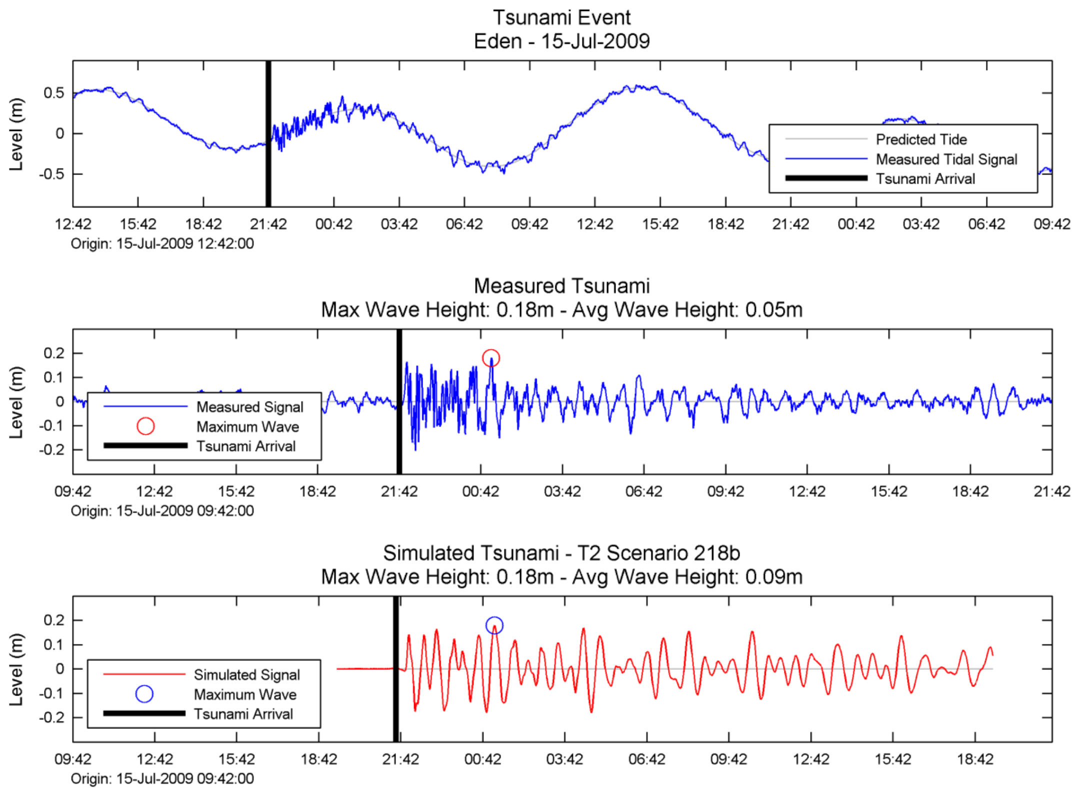

Figure 6 – Tsunami Validation. Eden Harbour 15 July 2009

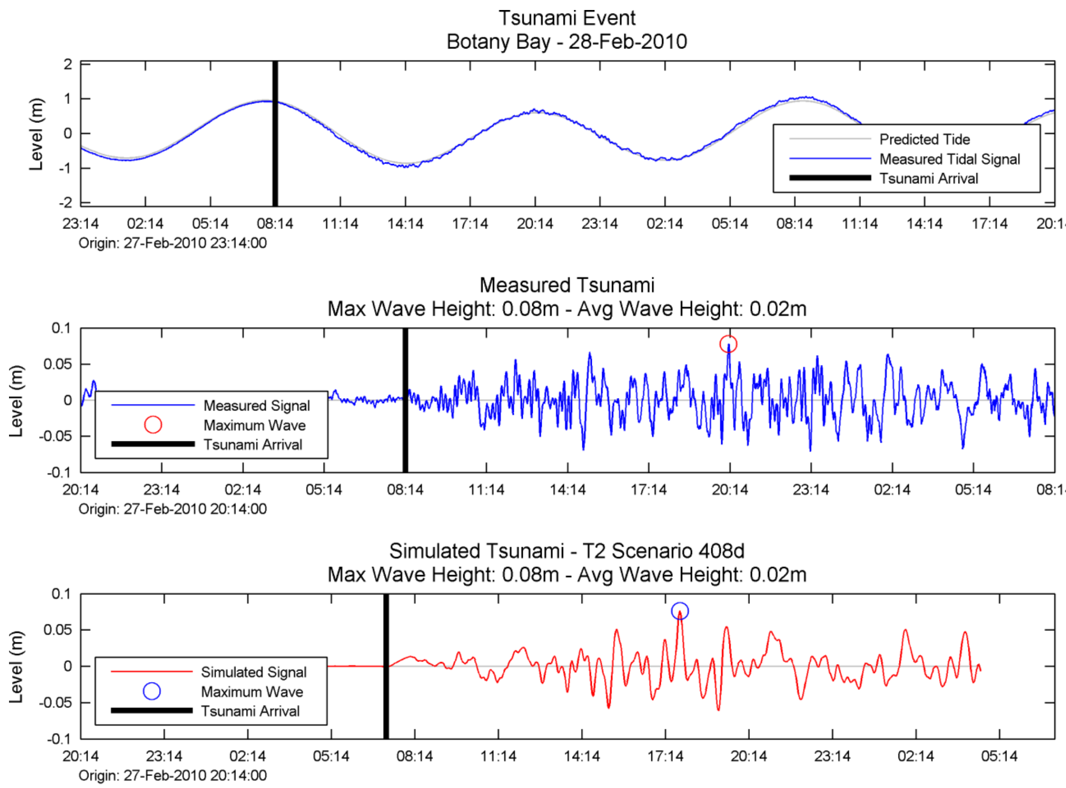

Figure 7 – Tsunami Validation. Botany Bay 28 February 2010

Additionally, as part of the historical tsunami validation, historical records were analysed in order to identify the site specific wave characteristics of each historical tsunami event. Upon initial inspection of the results, a number of characteristics were observed.

Figure 8 plots tsunami wave properties at the tide gauge locations for the five historical events (measured data in the top panel). These plots suggest that tsunami wave properties are site specific with each site displaying differing responses to the same events. This is likely a result of local factors, such as shoreline shape, bathymetry, size of the embayment and exposure/coastal orientation.

For example, **Figure 8** shows that the recorded wave height is always larger in the Port Kembla Inner Harbour (most likely due to local resonance) than the Port Kembla Outer Harbour, despite them being connected waterways, and that Fort Denison and Botany Bay have consistently smaller wave heights than the other sites. This may be the result of the Parramatta and Georges Rivers allowing tsunami wave energy to pass through these sites; as opposed to the other sites which are located in enclosed bays/ports. Furthermore, although not presented herein, Port Kembla Inner and Outer Harbours show the smallest variance in average period (being potentially governed by resonance), and tended to show shorter wave periods than Botany Bay or Sydney Harbour. Eden Harbour showed consistently longer wave periods than the other sites, perhaps a result of being less enclosed than the other locations.

Consistent outcomes such as these, observed over a number of differing events (in terms of offshore magnitude/wave period etc.), suggest that local site specific characteristics are as important as the offshore characteristics (such as tsunamigenic source and magnitude) in producing the observed tsunami signal at a given site.

The results of the modelling showed good agreement with the measured results in terms of both the numerical results and the overall site and event specific trends. The lower wave heights at Fort Denison and Botany Bay were replicated well, as were the higher wave heights at Port Kembla inner and Outer Harbours. Furthermore, measured results showing that the Japanese Tsunami of 2011 tended to produce the largest wave heights (except at Fort Denison), was simulated very well.

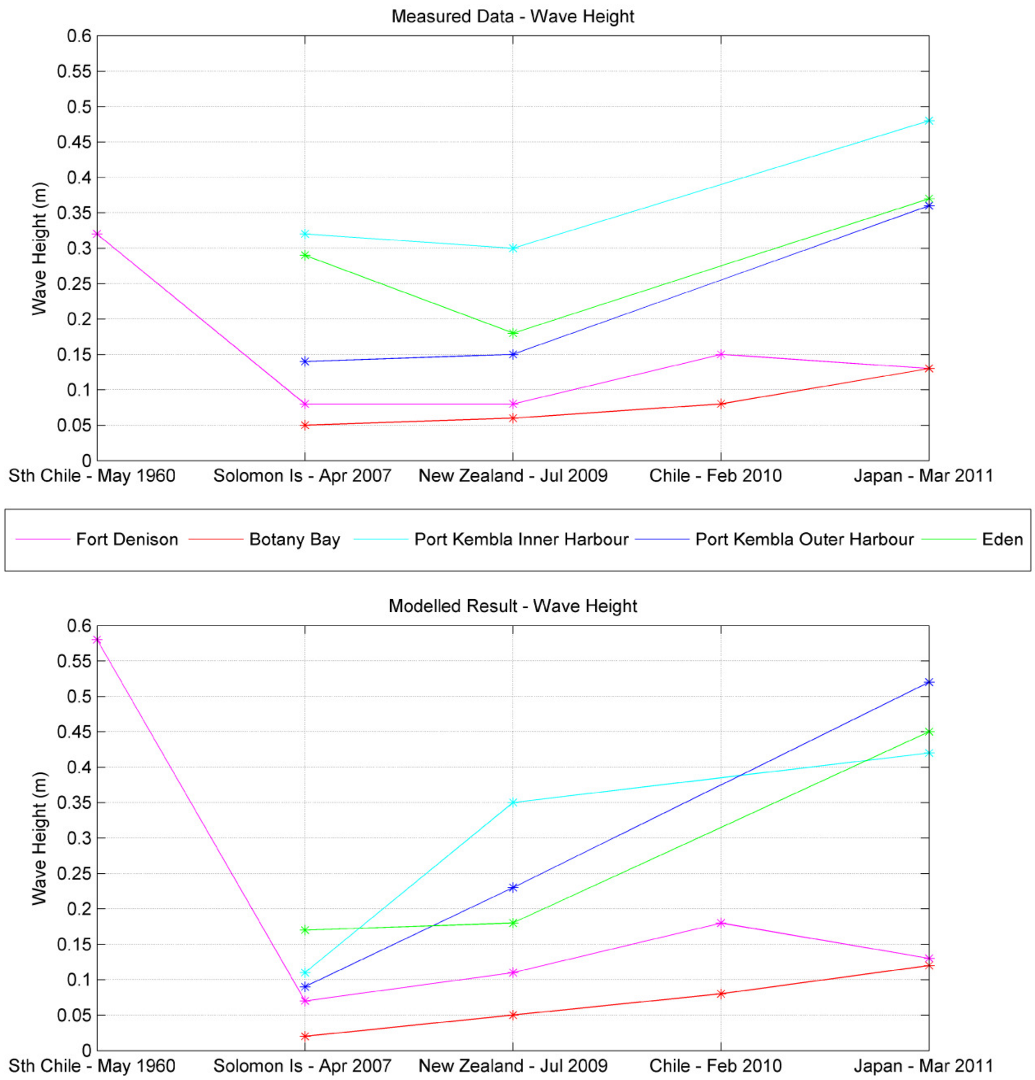

Figure 8 – Wave Heights of Measured and Modelled Historical Events

Concluding Remarks

Inundation modelling is being undertaken as part of an assessment of tsunami risk along the NSW coast. The methodology adopted involves inundation modelling utilising Delft3D. The modelling is being undertaken utilising a probabilistic approach drawing upon the Geoscience Australia Tsunami Data Access Tool (Tsu-DAT) and the Bureau of Meteorology Enhanced Tsunami Scenario Database: T2 (T2 Database). The two databases are being used both as an initial identification of the tsunami hazard and to consider individual events as well as draw upon tsunami time-series data for use as boundary conditions for the inundation modelling.

Results of model tests utilising Delft3D both against the international benchmark test case and several recent measured tsunami events are presented. These showed good agreement with the measured results in terms of both the numerical results and the overall site and event specific trends.

Future work will examine probabilistic scenarios and complete numerical modelling at the five study sites; and provide:-

- Water Level
- Inundation Depth (D)
- Extent of Inundation
- Duration of Inundation
- Velocity (V); and
- Hydraulic Hazard (V x D).

These will help to inform and support the NSW Tsunami Risk Assessment and emergency response planning.

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