Structural vulnerability estimation for tsunami loads

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Introduction

Structural vulnerability to tsunami is an important component of ongoing work at Geoscience Australia (GA) directed at assessing the risk posed by tsunami hazard to Australian communities. The models currently used are very simple, with probabilities of collapse (for residential structures) based on inundation depth and distance from coast. Damage to non-collapsed structures is calculated using stage-damage curves developed for riverine flooding. This paper describes work currently underway in the Risk Research Group at GA to develop empirically based vulnerability relationships. Also presented here is a proposed method for developing physically based damage curves using an engineering approach. This method is of particular value due to the scarcity of post-event damage data.

The paper has two main sections, a literature review and a section on the engineering approach. The literature review is the basis for the current curve development, with a review of damage reports, curves published to date, and a brief description of the database that will be used in creating empirical damage curves. The engineering approach is viewed as a long-term method for creating tsunami vulnerability curves based on physical models of fluid flow and structural behaviour. This approach also allows the opportunity to investigate mitigation options. The components of this model are discussed in Engineering Model Development.

Literature review

While major tsunami events are a relatively infrequent occurrence at any one location, there have been a number of destructive events globally over the last few decades. Since 1960 there have been three major tsunami events that have propagated across ocean basins to cause high levels of damage at far-field locations. This includes tsunami generated from earthquakes in Chile and Alaska in 1960 and 1964 respectively. These events caused damage not only in the immediate vicinity of their source but also travelled across the Pacific Ocean to cause major damage at other locations such as Japan, Hawaii, and the west coast of the United States. Likewise, the 2004 Indian Ocean tsunami caused significant damage near its source in northern Sumatra, but also propagated across the Indian Ocean to impact the coasts of Thailand, Sri Lanka, India, and several other countries.

Table 1 highlights some notable tsunami events since 1960. While this is by no means a comprehensive list, it does highlight those causing major impacts in terms of casualties and damage to onshore structures (to 2004).

Table 1 Notable tsunami events (1960-2004)

Event	Date	MW
Chile	22 May 1960	9.5
Prince William Sound, Alaska	28 Mar 1964	9.2
Moro Gulf, Philippines	16 Aug 1976	8.1
Nihonkai-Chubu, Japan	26 May 1983	7.8
Nicaragua	2 Sep 1992	7.6
Flores Island, Indonesia	12 Dec 1992	7.7
Hokkaido Nansei-Oki, Japan	12 Jul 1993	7.8
East Java, Indonesia	2 Jun 1994	7.7
Mindoro, Philippines	14 Nov 1994	7.1
Sulawesi, Indonesia	1 Jan 1996	7.8
Biak Island, Indonesia	17 Feb 1996	8.2
Chimbote, Peru	21 Feb 1996	7.5
Sissano, Papua New Guinea	17 Jul 1998	7.0
Izmit Bay, Turkey	17 Aug 1999	7.6
Vanuatu	26 Nov 1999	7.4
Camaná, Peru	23 June 2001	8.4
Sumatra, Indonesia	26 Dec 2004	9.3

Available curves

A number of tsunami damage curves are available in the literature. Examples include those by Lee et al (1978), Hatori (1984), Shuto (1993), Matsutomi et al (2001), Papadopoulos and Imamura (2001), Peiris and Pomonis (2006), Peiris (2006), and Ruangrassamee et al (2006). For various reasons the published curves are not necessarily applicable for use in risk assessments to Australian communities. Most are based on empirical data from one location and one event. The structures examined are typically dissimilar to those found in Australia. There is a lack of a population focus: undamaged structures are often not included which biases the data to damaged structures, thereby overestimating loss.

It is also difficult to make comparisons between the various curves. Firstly, there is no consistent parameter in use for the hazard, with some studies adopting run-up heights, others inundation height and some the inundation depth at structures. In cases where this parameter is the same it is difficult to standardise the various damage scales used. Several of the studies have highlighted the importance of other parameters in damage estimation including flow velocity (Hatori 1984; Matsutomi et al, 2001), although this parameter is very difficult to estimate post-event.

The most useful curves already published are those by Peiris (2006). These curves are lognormal cumulative distribution functions which provide a probability of being in a particular damage state or worse given an inundation depth. These curves were created using observed data from Sri Lanka following the 2004 Indian Ocean tsunami. The curves are based on damage to unreinforced masonry residential buildings with wall thicknesses of 250mm. The cumulative lognormal distribution is used in earthquake risk modelling at GA and is seen as a good way to describe vulnerability in a probabilistic tsunami risk assessment. There are some problems associated with applying these curves in an Australian context however, they are based on one event at one location and for a structural system not applicable to Australia. The inundation level was also measured as the water depth above ground at the centroid of the census district for each population of structures.

Database creation

Following the literature review of recent historical events a database of damage and flow characteristics was compiled. It consists of damage observations for around 330 individual structures. Figure summarises how each historical event is represented in the database. Clearly, data from the 2004 Indian Ocean tsunami comprises a large portion of the database given both its recent occurrence and the scale of its impact, which has prompted much scientific investigation. Each structure in the database was classified into one of three building classes depending on its construction material; reinforced concrete, unreinforced brick/block, and timber-frame. About half the observations comprise reinforced concrete buildings with the balance equally divided between brick/block and timber-frame type. The damage database will be used in the coming months to derive empirical damage curves for use at GA in the short/medium term. A more recent source of data may be available through the field survey undertaken jointly by GNS and NIWA (New Zealand) in Southern Java in July this year.
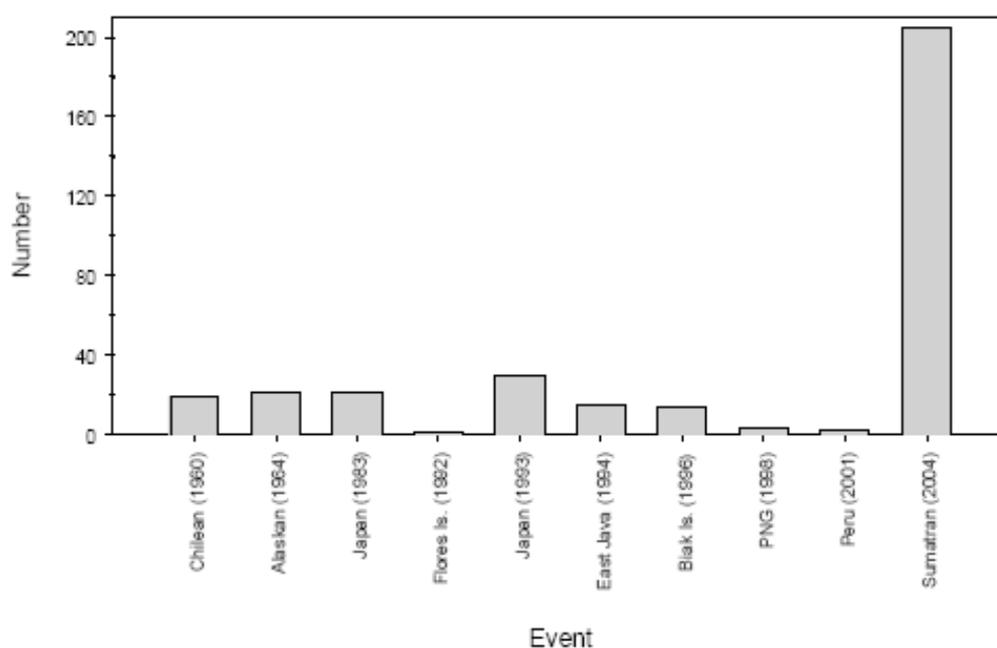

Figure 1: Observations (number of structures) in database by event

Engineering model development

The proposed longer term strategy involves developing an engineering model approach that has a similar framework as the parallel wind vulnerability work being undertaken at GA. The method requires a generalised hazard definition, an engineering model of a particular structure, and a costing module to calculate the real cost of repairs. The initial focus will be Australian residential structures. The components of the model are discussed in greater detail in the following sections.

The engineering model is based on the assumption that connection failure is the primary initiator of structural failure in residential structures (as opposed to say, a beam or wall stud failing in bending). It also assumes that component failures can be aggregated up into overall damage scenarios. The engineering model employs a Monte Carlo simulation approach that allows for the incorporation of variability (in connection strengths, building orientation, opening sizes, and key hazard parameters).

Generalised hazard definition

The generalised hazard definition is a way of generalising the complex behaviour of fluid flow around (and through) a structure and defining the resultant loads on the structure. Forces on a structure due to fluid flow include hydrostatic (horizontal and vertical), wave loads, hydrodynamic loads and debris loads.

A number of design guides exist that contain methods for designing for wave forces (including tsunami). Examples are FEMA 55 (FEMA, 2000), and USACE Technical Note III-29 (USACE, 1990). There are a number of reasons it may be problematic to use these guidelines to estimate wave loads on a structure. They tend to have a design focus and are therefore inherently conservative, while the work proposed at GA requires a mean load estimate. The equations provided in these guides are often impractical for use with a 'real' structure (i.e. wave forces on an infinitely long vertical wall).

Hazard transfer parameters will be chosen to link between hazard modelling and vulnerability. This is analogous to the 3 second gust wind speed at 10m height as used in wind engineering. Water depth and water velocity may be used to describe the hazard at a particular location. These parameters are both outputs of the inundation model used at GA to propagate tsunami waves through shallow water and over land (Nielsen et al, 2005).

Engineering model of structure

Once loads on the structure have been defined an engineering model of a structure can be used to assess damage outcomes (if any). This model requires a knowledge of connection details as well as construction practice and variability. Given this knowledge, probability distribution functions of connection failure can be used. These functions will incorporate variability in connection strengths. The effects of a breach in the building envelope also need to be considered: will the failure of a door allow a sudden inrush of water that may damage the 'back' of the structure? Likely failure modes need to be decided upon, and failure types aggregated into overall damage outcomes. For an example of this type of work, in a wind context, refer to JCU (2005).

An additional consideration for the engineering model is to develop a damage logic that can be programmed as part of the Monte Carlo simulation process. This would relieve the need for continual scenario development on a case by case basis.

The initial engineering model will be based on data collected for two storey houses in Western Sydney (JCU, 2006). The survey involved 45 brick veneer, tiled roof houses at various stages of completeness.

Automated costing module

An automated costing will take the damage outcomes from the engineering model of the structure and cost the repair. This module utilises standard repair rates, which are adjusted for the scale of damage to the component. Internal damage repair costs are also calculated by the module, as are contractor overheads. The module calculates repair costs in a neutral construction industry environment, that is, neither boom nor bust, and with no demand surge as can often follow a natural disaster. The repair costs are those required to reinstate the building to its original state.

Conclusions

This paper describes work being undertaken in the Risk Research Group at Geoscience Australia developing vulnerability curves for Australian structures exposed to tsunami hazard. Curves currently being developed are based on observed damage from a number of tsunami events that have occurred in the past five decades. Future curve development is based on an engineering approach and requires a generalised hazard definition, an engineering model of the structure of interest, and a costing module to convert damage scenarios to restoration costs. This is ongoing work and any feedback is most welcome.

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