A Methodology for Consistent Modelling of Natural Hazards

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EXTENDED ABSTRACT

The need for a new approach to understand and manage the risk posed by natural hazards in Australia has been acknowledged and emphasised by Australian Commonwealth and State governments. To this effect the Council of Australian Governments (COAG) commissioned a review of natural disaster relief arrangements in June 2001. The results of the review were published in the report *Natural Disasters in Australia: Reforming Mitigation, Relief and Recovery* released by the Department of Transport and Regional Services (DOTARS) in early February 2004.

The report proposes a fundamental shift in focus beyond relief and recovery towards cost-effective, evidence-based disaster mitigation. Consequently, while disaster response and reaction plans remain important, the move is now towards anticipation and mitigation against natural hazards.

The report includes twelve reform commitments. Many of these commitments are being implemented through the Disaster Mitigation Australia Package (DMAP), being administered by DOTARS. DOTARS has invited Geoscience Australia (GA) to be a technical advisor and to assist in the implementation of DMAP over the next five years.

DOTARS and GA are working together to implement two of the most important reform commitments specified under recommendation 4 of the report. These two reform commitments are:

- Develop and implement a five year national program of systematic and rigorous disaster risk assessments.
- Establish a nationally consistent system of data collection, research and analysis to ensure a sound knowledge-base on natural disasters and disaster mitigation.

In this context GA is developing risk models and innovative approaches to assess the potential losses to Australian communities from a range of sudden impact natural hazards. These models aim to assess the economic and social impacts of natural hazards in a consistent way to allow the direct comparison of risks from different hazards. Currently, GA is developing risk assessment models for earthquakes, inundations, tsunami, cyclones, and synoptic winds.

A consistent approach to incorporating uncertainties into risk models for each of these hazards is essential so that risks from different hazards may be compared. This is a particularly difficult task due to the numerical models for various hazards being developed in isolation, e.g. the methodology used in an earthquake risk model can be totally different from the methodology used in a cyclone risk model (one model can be deterministic whilst the other can be probabilistic, for instance) making comparison of results from both models very difficult.

This paper aims to highlight and address this issue by identifying the main sources of uncertainty in earthquake and cyclonic inundation models and presenting a generalised approach for modelling natural hazards.

1. INTRODUCTION

The need to develop a new approach to understand and manage the risk posed by natural hazards in Australia has been acknowledged and emphasised by Australian Commonwealth and State governments. To this effect the Council of Australian Governments (COAG) commissioned a review of natural disaster relief arrangements in June 2001. A report with the results of the review was published by the Department of Transport and Regional Services (DOTARS) in early 2004 (DOTARS, 2004).

The report proposes a fundamental shift in focus beyond relief and recovery towards cost-effective, evidence-based disaster mitigation. Consequently, while disaster response and reaction plans remain important, the move is now towards anticipation and mitigation of natural hazards.

In this context Geoscience Australia (GA) is developing risk models and innovative approaches to assess the potential losses to Australian communities from a range of sudden impact natural hazards. These models aim to assess the economic and social impacts of natural hazards in a consistent way to allow the direct comparison of risks from different hazards. Currently, GA is developing risk assessment models for earthquakes, inundations, tsunami, cyclones, and synoptic winds.

It is essential that the risk models for each of these natural hazards incorporate uncertainties in a consistent way so that results from the models are comparable. This paper aims to highlight and address this issue by identifying the main sources of uncertainty in earthquake and cyclonic inundation models and presenting a generalised approach for modelling natural hazards.

2. RISK ANALYSIS

Risk, as a product of natural hazards, depends on two factors: the probability of a certain event occurring and the consequences of that event. The consequences depend on the hazard's characteristics and on the exposure and vulnerability of people and the built environment.

The consequences of natural hazards can generally be classified as building and infrastructure damage, direct and indirect economic losses; and societal losses (injuries, fatalities, social dislocation). For the calculation of these consequences a large number of scenarios must to be considered and hence computer simulation needs to be used.

3. MODELLING NATURAL HAZARDS

The first step in the simulation of natural hazard events is the development of a mathematical model to represent the physics of the phenomenon. Broadly speaking, two kinds of mathematical representations can be developed: deterministic and probabilistic.

Deterministic models provide results for a specific scenario, usually the worst case scenario, but they do not provide information about the effect of uncertainties on the results. Probabilistic models, on the other hand, can account for uncertainties by using random variables. In Monte Carlo simulation of these kinds of models a large number of events is considered by taking samples from the random distribution. The consequences of each of these events and their probability of occurrence can then be determined.

To ensure that the simulation includes a plausible population of events likely to affect the region of interest, values for the random variables used to model the hazard can be obtained from historical records. By working with a range of possibilities and modelling uncertainty in a rigorous manner, probabilistic models provide a more complete picture of the risk. For this reason probabilistic models are becoming the preferred methodology for risk analysis (Woo, 2002).

The most difficult part of probabilistic model development is the identification and inclusion of uncertainty in the model. In particular it is important to distinguish and represent two kinds of uncertainty: aleatory and epistemic.

Aleatory uncertainty includes natural variability and the inherent randomness of complex physical phenomena. This kind of uncertainty can be estimated but it cannot be reduced. Examples of variables containing aleatory uncertainty are the location, time and intensity of the next cyclone to affect Australia.

Epistemic uncertainty is the result of inadequate data and incomplete model development due to limitations in knowledge of the phenomenon's physics. This kind of uncertainty can be reduced with better data collection, advances in knowledge of the physics of a phenomenon and refinement in models to represent it. In a cyclone model epistemic uncertainty exists in the model itself and the values of model parameters such as central pressure, radius to maximum winds, translation speed, and location and characteristics of buildings affected by the phenomenon.

In general, aleatory uncertainty can be included in a model by using probabilistic functions to capture the system random variation whilst epistemic uncertainty can be included by using multiple models. For a complex problem a user can have a number of models to represent, for example, the hazard's source zone, magnitude, attenuation, and damage. To keep the problem tractable, a logic tree is frequently used. Branches can represent different models or values, each with assigned likelihood based on judgement/experience. The final result will be given by the combination of all branches weighted by their corresponding likelihood (Wen et al., 2003).

4. COMPUTER SIMULATION

A second point to consider in the development of a consistent methodology for risk studies is the type of simulation performed. There are two basic methodologies to simulate natural phenomena: event-based and hazard-based. In the case of earthquakes, an event-based simulation calculates the damage that each simulated earthquake would produce at each building.

The hazard-based method calculates risk from a hazard map rather than by simulation of every event. This method overestimates risk as discussed in Patchett et al. (2004).

The event-based methodology is preferred for our models. Its main advantage is that it assesses the consequences of each simulated event and hence the results are more realistic. This also allows a more detailed presentation of results. In the case of earthquakes, results can be disaggregated by event distance and magnitude. Damage can be disaggregated based on building construction type, suburb, etc. The disadvantage is that it requires more computer storage to keep a record of each event simulated.

5. METHODOLOGY FOR CONSISTENT MODELLING OF NATURAL HAZARDS

To develop a consistent model for natural hazard events the problem is divided according to the movement of energy through the system. The basic division should consider source, pathway and receptor (Dawson, 2003). These components can then be broken into six parts:

- the source zone which is the region were the event originates;
- the origin of the event within the source zone;
- the magnitude of the event;
- the transmission of energy from the origin to the region of interest;
- the site effect which is the way the region of interest reacts to the event, and;
- the consequences. (To simplify the discussion, the only consequences considered here is building damage.)

Fig. 1 shows the main components of a natural hazard model. Fig. 1a refers to an earthquake model, Fig. 1b refers to a cyclonic inundation model. The energy delivered by an earthquake, EQ_{En}, is a function of magnitude, distance and soil characteristics. The energy delivered by a cyclone, Cy_{En}, creates a storm surge (SS) which causes the inundation (In). The inundation is a function of the tidal level, wave amplitude and the site's topography.

This paper focuses on the GA-developed Earthquake Risk Model (EQRM) and Inundation Model (InM). Reference will be made to externally developed cyclone models which are used to provide boundary conditions for InM.

The rest of the paper is organised into subsections to deal with each of the components listed above. Following the subheading a brief discussion of the way the earthquake model deals with the issue is presented (paragraph marked EQRM). A discussion of the way the inundation model addresses the same problem then follows (paragraph marked InM). By comparing and contrasting the way these models deal with the same problem, a generalised methodology for consistent modelling of natural hazards can be developed.

EQRM is a probabilistic model developed to assess the risk posed by earthquakes. Dhu and Jones (2002) and Jones et al. (2005) describe its successful application in some regions of Australia. Still under development, InM is a deterministic model that simulates water flowing into a region of interest and the associated damage caused to buildings. The model can be driven by a cyclonic storm surge or by a tsunami (Nielsen et al., 2005). Only storm surges will be considered in this paper.

5.1. Modelling source zone and origin

EQRM: It is assumed that the earthquake's origin lies within a source zone. A number of source zone models have been developed for Australia by researchers such as Leonard (2005), Brown and Gibson (2004) and Gaull et al. (1990). As stated previously, the existence of different models for the same problem is the result of epistemic uncertainty (Beven, 2001; Merz and Thieken, 2004; Nilsen and Aven, 2003). To accommodate this source of uncertainty EQRM allows the user to select more than one source zone model, each with an assigned likelihood based on the user's judgement/experience.

The next stage is to define the earthquake's origin. To capture the aleatory uncertainty inherent in this parameter, random variables are used. In EQRM, the rupture within a known source is modelled as a linear source defined by a starting point, azimuth and length. Values for these parameters are generated using uniform distributions.

InM: In cyclonic inundations the area where the phenomenon can occur and its characteristics are defined by the cyclone landfall. Cyclonic winds are the driving forces that produce the storm surge on a given coastline. A number of models are available to calculate cyclonic wind fields, see Holland (1980) and Shapiro (1983). As with earthquakes the availability of multiple models represents epistemic uncertainty that can be incorporated into risk estimates by using a weighted combination of the available models.

The origin in InM is a given segment of the coastline where it is assumed that the cyclone landfall, and hence the storm surge, occurs. Most simulations use uniform distributions calculated from historical records for the generation of storm surges in the segment of interest (McInnes et al., 2003; Daneshvaran et al., 1997).

5.2. Modelling magnitude

EQRM: Aleatory uncertainty of magnitude in earthquakes is modelled using a random variable with a probability density function given by the bounded Gutenberg-Richter law, as presented in Kramer (1996). This distribution is typically calculated from an analysis of historical data.

InM: Given that a cyclone has landed in the specified coastline segment, storm surge wave amplitude depends mostly on the cyclone's direction of approach (**ø**) and wind speed (w_s). In turn, wind speed depends mainly on cyclone forward speed (Vt), central pressure difference (Δp) and cyclone size. Cyclone size is defined as the radius from the cyclone centre to the region of maximum winds and is represented by R_{MAX} .

Probabilistic functions to model all of these cyclone parameters have to be developed to capture their aleatory uncertainty. As with earthquakes these are typically derived from historical data. For example, McInnes et al. (2003) analysed Bureau of Meteorology (BoM) data for Cairns (55 cyclones) and found that Vt and **ø** could be modelled by normal distributions. Central pressure was modelled using a Gumbel distribution. Data to model R_{MAX} were unavailable so a constant value was allocated to this parameter. Similarly, Daneshvaran et al. (1997) used records of cyclone landings on the Florida peninsula from the US hurricane database (126 samples) and fitted lognormal distributions for Vt and R_{MAX}, a normal distribution for **ø** and a Weibull distribution for Δp. They also found a strong correlation between Δp and R_{MAX} and modelled this correlation by fitting an empirical equation to the mean of $\ln(R_{MAX})$ versus Δp.

5.3. Energy Transmission

EQRM: The transmission of earthquake energy requires the propagation of seismic waves from the source through the rock to the ground at the site of interest. These waves are attenuated by friction from the rock. Aleatory uncertainty in the process is modelled by using conditional probabilistic distributions of intensity measures such as spectral acceleration. These distributions are conditioned on the occurrence of an earthquake with a particular magnitude (M) at a given distance (d) and are referred to as attenuation models (Fig. 1a).

There is a great deal of uncertainty associated with modelling this energy transmission in Australia due to a lack of recorded data. Currently, this process is modelled by using a combination of models from other parts of the world thought to be similar to Australia (Robinson and Fulford, 2005):

As before, epistemic uncertainty in attenuation is taken into account by using multiple weighted attenuation models. Aleatory uncertainty is included by modelling magnitude and distance using random variables.

InM: In inundation models the transmission of the phenomenon's energy to the built environment is due to the flow of water over the region of interest driven by the storm surge, as shown in Fig. 1b. Similar to the attenuation model in earthquakes, the depth and shape of the ocean floor (bathymetry) influence the storm surge height. However, unlike earthquakes, inundation models typically model bathymetry in a deterministic fashion. For this reason it is necessary to use fine resolution grids to accurately represent the bathymetry of the region of interest. Two techniques for doing this are presented in Hubbert and McInnes (1999) and Zerger (1998).

For consistency with the earthquake attenuation model, the main variables of a cyclone model (Vt, Δp, R_{MAX} and direction of approach) should also be modelled using random variables. Similarly, epistemic uncertainty in the cyclonic inundation model can be taken into account by using different weighted windfield models.

5.4. Site effect

EQRM: The transference of the earthquake energy from the bedrock to the surface is affected by the presence of regolith (soil, geological sediments and weathered rock that overlie the un-weathered bedrock; Robinson and Fulford, 2005). Regolith can change the level of ground shaking experienced during an earthquake; this is modelled using a site response model. In this kind of model a study region is usually classified into a series of site classes which define regions of similar regolith. Aleatory uncertainty in ground shaking factors has been incorporated through the development of probability density functions for these factors in each class (Dhu and Jones, 2002).

InM: The site effect in inundation modelling depends on the topography. For this reason it is important to develop very accurate Digital Elevation Models (DEM) for the region of interest. There are two sources of error in these models: one is the resolution of the DEM used to represent the region. The second is the aliasing effect produced when trying to represent continuous surfaces using discontinuous points. Comparison of DEM elevation points with GPS information shows that the error can be significant.

A methodology to calculate the error is discussed in Zerger (1998), however its implementation is possible only for given regions. For national risk studies in which DEMs of some regions are not available it is necessary to develop a general technique for topographic representation. Given the scale of these studies, there may be merit in attempting to create generalised "topography classes" and associated probability distributions in an analogous manner to earthquake site classes.

Another problem found in inundation, which is not found in earthquake studies, is the shielding effect of the built environment such as houses, tanks and roads. Detailed structural footprints are required to model this effect deterministically. However, it is not always possible to have this detailed information, especially in national risk analysis. One plausible alternative for modelling this effect is to treat a group of structures as a momentum sink. This could again be defined by a probability distribution analogous to regolith site classes. Similar to an earthquake's site effect which changes ground shaking, a momentum sink reduces the impact of water flow on the buildings of the study region.

5.5. Building damage

EQRM: The damage produced by an earthquake is calculated using fragility curves. The detail of this approach is described in FEMA (2003a), however the key point here is that this approach incorporates aleatory variability in structural response. Consequently, two buildings subjected to the same ground shaking can suffer different amounts of damage.

InM: Building damage due to inundation depends on over-floor water depth, velocity, duration and building characteristics. In most models over-floor water depth is considered the major source of damage (Blong, 2001). More recent studies show that the impact of velocity is also an important factor in building damage and have produced damage curves which take in to account this factor in inundation models (Dale et al., 2004).

The damage analysis in inundation models is substantially simpler than the corresponding analysis for earthquakes. One of the reasons for this is that it is assumed that inundation does not affect the building structure. Only in cases of high velocity flows or when the structure is hit by inundation-borne debris is structural damage considered (for example, in tsunami) (FEMA, 2003b).

Building damage by inundation is based on stage-damage curves. These curves are produced from records of damage to buildings by inundation. Unlike the earthquake damage analysis, neither of the inundation damage models referred to above (Blong, 2001; Dale et al., 2004; FEMA, 2003b) addresses the problem of uncertainty analysis in either damage calculation or the production of the stage-damage curves. This limitation not only restricts the range of scenarios considered in the inundation model but introduces inconsistencies between the earthquake and the inundation model results.

6. CONCLUSIONS

The modelling literature shows that there are currently numerous differences in modelling methodologies for natural hazards, especially in the treatment of uncertainties. This problem makes it difficult to compare risks posed by different natural hazards.

In this paper we have presented a schematic methodology for consistent modelling of natural hazards. In this methodology natural hazards have been broken up into six basic components following the flow of energy. Each component has been examined independently and models to represent it have been briefly discussed.

Following this methodology it is possible to develop consistent models to study the risk posed by natural hazards. To illustrate the main points of the methodology two risk models, earthquake and inundation, currently under development in Geoscience Australia, were discussed. The aim of the work reported in this paper is to develop consistent and comparable risk models for natural hazards.

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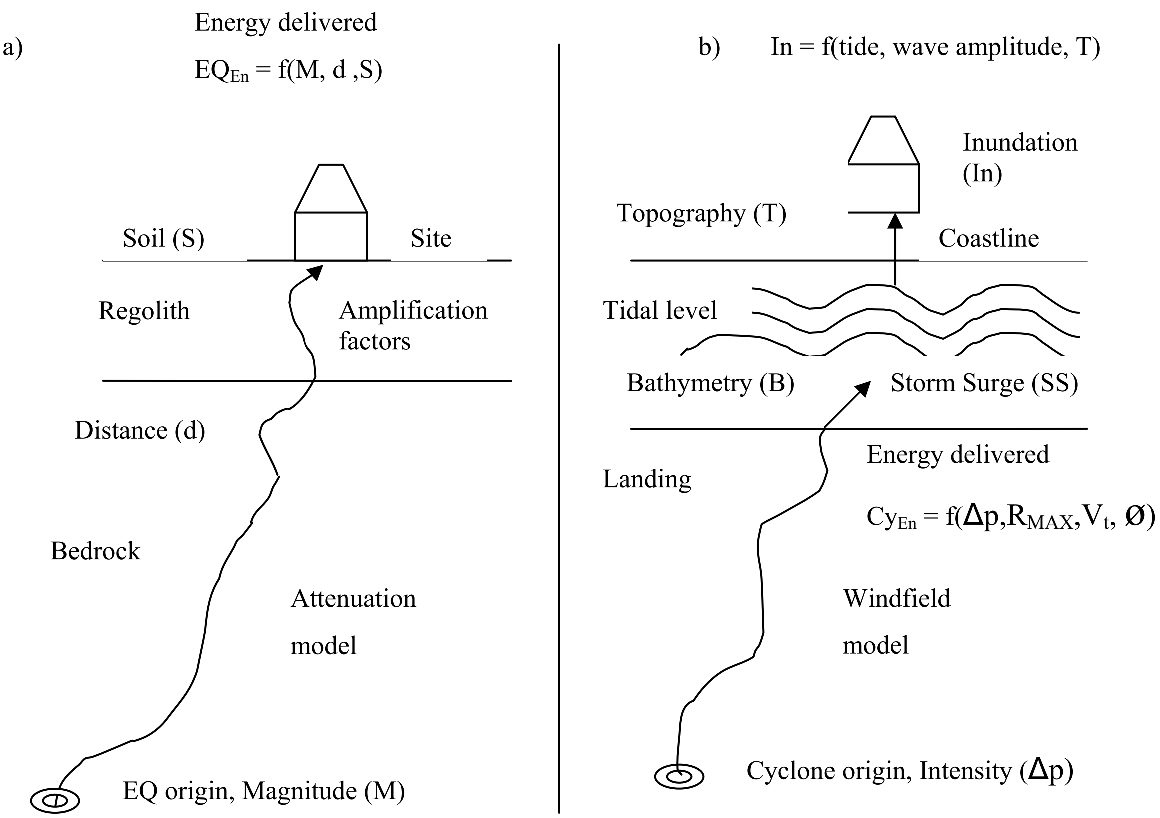

Fig. 1. Main elements affecting energy delivered to region of interest (not to scale).
a) Earthquake. b) Inundation. EQ_{En} = Earthquake energy.
Cy_{EN} = Cyclonic energy. SS = f(Windspeed, Δp, B).