bnhcrc.com.au

COST-EFFECTIVE MITIGATION STRATEGY DEVELOPMENT FOR BUILDING RELATED EARTHQUAKE RISK

Final report on economic loss modelling

Itismita Mohanty, Mark Edwards, Hyeuk Ryu and Martin Wehner
Geoscience Australia

Version	Release history	Date
1.0	Initial release of document	19/07/2017

Australian Government
Department of Industry, Innovation and Science
Business Cooperative Research Centres Programme

Disclaimer:
Geoscience Australia and the Bushfire and Natural Hazards Cooperative Research Centre advise that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, Geoscience Australia and the Bushfire and Natural Hazards CRC (including its employees and consultants) exclude all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

Publisher:
Bushfire and Natural Hazards CRC

July 2017

Citation: Mohanty, I., Edwards, M., Ryu, H. and Wehner, M. 2016. Project A9 : Cost-effective Mitigation Strategy Development for Building Related Earthquake Risk. : Preliminary Report on Economic Loss Modelling, Bushfire and Natural Hazards CRC.

Cover: Christchurch after 4 September 2010 Darfield Earthquake, Geoscience Australia

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report forms part of the output from Project A9 entitled "Cost-Effective Mitigation Strategy Development for Building Related Earthquake Risk" within the Bushfire and Natural Hazards Cooperative Research Centre.

Earthquakes have the potential to cause widespread damage to Australian communities and the economic activity that occurs within them. Recent earthquake events have illustrated this, including the Newcastle Earthquake (1989) and the Kalgoorlie Earthquake (2010). This potential is largely due to the fact that much of the Australian building stock has not been designed nor constructed with adequate consideration of earthquake hazard.

Mitigation intervention is needed to reduce this risk but an evidence base is lacking to inform investment. In particular, there is a need for economic measures of the benefits of retrofit as an offset to the sometimes large costs of upgrading structures for earthquake.

This need exists in many other countries. As part of this research a literature survey of research published internationally is underway to inform the best approach for assessing the costs of business interruption and the losses associated with injury and death. The findings of this work to date are described and are informing the research program.

This report also describes the frameworks developed for a range of Australian decision makers. Decision makers include building owners, owners of both business premises and the business within, local government, state government and national government. The scale of decision making metrics range from individual building level up to business precinct level exposures and the interdependence of building performance within them. The information and models required as inputs into the framework have been identified along with how these will be met, either with outputs from this CRC project, or from other sources.

The research on the economic loss modelling has produced a functional model. Future work will add refinements to the model such as casualty cost modules adapted from published material. In the succeeding year business interruption loss models will be developed and framework/methodology developed for assessing precinct level economic activity disruption.

ABBREVIATIONS

BI	Business Interruption
BITRE	Bureau of Infrastructure, Transport and Regional Economics
CBA	Cost Benefit Analysis
CBD	Central Business District
CGE	Computable General Equilibrium Model
COI	Cost of Illness
CM	Choice Modelling
CPI	Consumer Price Index

CV	Contingent Valuation
EOC	Emergency Operations Centre
EM-DAT	International Disaster Database, on historical earthquakes since 1900s
EQRM	Earthquake Risk Model: Geoscience Australia's current primary tool for modelling earthquake hazard and risk
GDP	Gross Domestic Product
GIS	Geographical Information System
HAZUS-MH	Hazards U.S. Multi-Hazard
NRML	Natural Hazards Risk Mark-up Language
OBPR	Office of Best Practice Regulation
OECD	Organisation for Economic Co-operation and Development
PAGER	Prompt Assessment of Global Earthquakes for Response
PESH	Potential Earth Science Hazards
PML	Probable Maximum Loss
RP	Revealed Preference Method
SP	Stated Preference Method
VSL	Value of a Statistical Life
VLY	Value of Statistical Life Year
WTP	Willingness to Pay Method
WHO	United Nations World Health Organisation

1. INTRODUCTION

The CRC Project A9 entitled "Cost-Effective Mitigation Strategy Development for Building Related Earthquake Risk" is seeking to address the need for an evidence base to inform decision making on the mitigation of the earthquake risk posed by vulnerable Australian buildings. It aims to develop information related to more vulnerable Australian building types in the following areas:-

- retrofit strategy options for high risk buildings to reduce their vulnerability;
- the current and retrofitted performance of these buildings;
- the cost of implementing the retrofit strategies; and,
- the ability to assess the benefit of avoided societal costs through the implementation of these strategies.

This report describes progress made against the last component which is directed at economic loss modelling. The work has been guided by, and is consistent with, the project team consensus achieved at a single day workshop convened at Swinburne University on the 23rd October 2015.

The economic loss modelling approach aims to encompass the information needs of a range of decision makers. These view benefits through different "lenses" and at differing scales. For this research they include:- Building owners.

- Owners of both the building and occupying business.
- Local Government for a business precinct.
- Jurisdictional and Federal Governments and their additional interest in economic loss associated with health care and lost productivity.

In this report a background is provided on the motivations for this project. The findings of a literature survey are presented, and the economic modelling frameworks proposed by the project team are described. This report corresponds with the Geoscience Australia component of the 30 September 2016 project milestone deliverable "Final Report on Economic and Damage Loss Models".

2. PROJECT BACKGROUND

Earthquake hazard has only been recognised in the design of Australian buildings since approximately 1995. This has resulted in the presence of many buildings within communities that currently are a high risk to property, life and economic activity. These buildings also contribute most of the postdisaster emergency management logistics and community recovery needs following major earthquakes. This vulnerability was in evidence in the Newcastle Earthquake of 1989, the Kalgoorlie Earthquake of 2010 and with similar building types subject to the Christchurch Earthquake of 2011. With new building construction representing 1.8% of the building stock nationally (ABCB 2014), the legacy of high risk buildings persists in all cities and predominates in most business districts of lower growth regional centres.

The two most vulnerable building types that contribute disproportionately to community risk are unreinforced masonry and low ductility reinforced concrete frames. Damage to these not only leads to direct repair costs but also to injuries and disruption to economic activity. This research project is drawing upon and extending existing research and capability within both academia and government to develop information that will inform policy, business and private individuals on their decisions concerning mitigation. It will also draw upon New Zealand initiatives that make use of local planning as an instrument for effecting mitigation. The Wellington City Council Resilience Program is an exemplar of mitigation that has progressively resulted in the retrofit of a large proportion of earthquake prone unreinforced masonry buildings in that city. Other New Zealand cities have also retrofitted vulnerable buildings. Figure 1 shows the interior of a two storey reinforced concrete frame building with unreinforced masonry infill in Napier. The city experienced a devastating earthquake in 1931 and this building was part of the extensive rebuild of the central business district (CBD) that took place in 1930's. Ductile steel moment frames have been added to strengthen the structure in the transverse direction.

Project A9 has six key elements of research that are being progressed sequentially:-

1. Australian building stock vulnerability classification (completed).
2. Review of existing retrofit options (completed).

3. Development of Australian specific retrofit options (in progress).
4. Economic loss model development (in progress).
5. Benefit versus cost analysis of retrofit options
6. National assessment of retrofit needs.

Work on the fourth element is progressing with the engagement of economist Dr Itismita Mohanty of the University of Canberra as part of the project team. Her research will draw upon international research and align with earthquake impact and risk modelling capability developed by Geoscience Australia for use in elements 5 and 6.

Figure 1: Ground floor view of retrofitted two storey retail structure of the 1930s period in Napier, New Zealand. The building is of poorly detailed reinforced concrete frame construction with unreinforced masonry infill walls. Ductile steel moment frames have been retrofitted to strengthen the structure in the transverse direction.

3. NATURE OF ECONOMIC LOSSES IN BUSINESS PRECINCTS

The severe ground shaking that accompanies an earthquake can cause physical damage to buildings. This has an attendant repair cost or, in a very severe event and/or with very vulnerable buildings, may require demolition and complete reconstruction of the damaged building.

The severity of physical damage has implications for the use of the building. Minor cracks and dislodgment of non-structural elements may permit full use of the structure post-earthquake, whereas more severe damage may limit or preclude access. Where the use of the building includes business activity, the resultant disruption to turnover and employment adds to the economic loss. This impact may extend to businesses in less damaged adjacent structures where damage cordons impact their building access.

The contents of building can also be damaged in an earthquake. In high seismic regions of developed countries restraint is often provided to contents that can topple but this is not a common practice in Australia. Floor accelerations can overturn furniture and damage fit-out. On upper floors this can be more significant as the response of the building to ground motion accentuates the floor motion. Where a building sustains partial or complete collapse, direct damage to contents will also result.

Building damage also translates into deaths and injury of occupants. It is recognised that "earthquakes don't kill people, collapsed buildings do," (https://www.unops.org/english/News/Pages/Earthquakes-dont-kill-peoplecollapsed-buildings-do.aspx#sthash.oLoV6vEu.dpuf). Earthquake triggered landslide deaths aside, the performance of poorly designed and/or built structures directly affects occupants and pedestrians close to the building. This has an insidious aspect in that it is the human contribution to our built environments that has the greatest negative influence on human safety. Medical care requirements and lost productivity caused by recovery from injury, disability or death represent a further economic cost.

Utility and supply chain issues can also affect business turnover. Loss of electricity, water, sanitation, telecommunications and gas supply can render some business premises unusable. Lack of material supply to the business or the inability to dispatch goods can also disrupt business activity and cause economic losses.

Other costs often unquantified for mitigation investment include the greater cost of emergency response, the cost to effect clean-up and Government financial assistance to a range of recipients to promote community recovery.

4. LITERATURE REVIEW ON ECONOMIC LOSS MODELLING

This research aims to identify and model different components of economic cost from building related earthquake scenario impacts in Australia. This section presents the literature review on economic loss assessment modelling of earthquakes in Australia and internationally. The scope, however, is limited to estimating the direct economic costs of business interruption and casualties. In this area a range of international studies have been reviewed (Erdik et al, 2014; Silva et al, 2014; Rose et al, 2011; Cho et al, 1999; Rose et al, 2009; Rose et al, 2007; Jain and Guin 2009 and OPUS, 2005).

Broadly there are two identified components of earthquake related economic costs: the direct and the indirect economic costs. Direct economic costs are caused by impact on property and infrastructure, and indirect economic costs are caused by supply chain interruptions, infrastructure network disruptions and other problems related to interconnectivity between economic sectors. While economic costs due to building related business interruptions can be classified into both the direct and indirect economic cost components, this study primarily focuses only on direct economic costs of business interruption along with direct economic costs of casualties.

Direct losses are those inflicted by the damage to property and infrastructure. Direct business interruption refers to the immediate reduction or cessation of economic production in a damaged property or a property cut off from at least one of its utility lifelines. It must be noted that these losses comprise the losses due to damage to buildings, their contents and the direct business interruption due to the immediate reduction or cessation of production in the damaged property or the loss of service.

Indirect losses are those due to the interruption in supply chains, infrastructure, and interconnectivity of economic sectors. Indirect losses are estimated by the ripple effects associated with the supply chain or customer chain of a directly affected business. Indirect loss calculation accounts for the impact of both property and infrastructure loss on the overall economy of the region by different sectors.

It was only in the mid-1990s that the disaster loss estimation literature emphasised more on the indirect or secondary losses such as economic, sociological, psychological, etc. away from property damage to structures (Rose et al, 2011). The most important of the indirect losses or secondary losses is the role of business interruption (BI) losses, which refer to the reduction in the flow of goods and services produced by property such as capital stock (Rose et al, 2011). However, there are both direct and indirect components of these business interruption costs.

A more clear distinction is provided by Rose et al (2011) as,

- Direct property damage relates to the effects of natural phenomena, such as fault rupture, ground shaking, ground failure, landslides, tsunami, etc. Direct BI refers to the immediate reduction or cessation of economic production in a damaged factory or in a factory cut off from at least one of its utility lifelines.
- Indirect or induced property damage is exemplified by ancillary fire caused by ruptured pipelines, frayed electrical wires, etc., and exacerbated by loss of water services. Whereas, indirect BI stems from the "ripple," or "multiplier," effects associated with the supply chain or customer chain of the directly affected business.

In a recent seminal paper Erdik et al, (2014) recognized that there is a rich body of literature available on research, tools and applications that deals with all aspects of earthquake loss estimation methodologies. They reviewed the relevant literature over the past decade for earthquake rapid response systems and highlighted the considerable advances that have been made in earthquake risk assessment methodologies. Erdik et al, (2014) established that the ground motion measurement hardware, data transmission systems and the loss assessment methodologies and software developed for Earthquake

Rapid Response Systems have been quite successfully enabling the feasible application of such systems and services throughout the world. A significant shift in the literature in this direction has been the development of earthquake loss estimation methodologies such as the HAZUS-MH (2003)[i], EQRM (Robinson et al, 2005) and the OpenQuake (Silva et al. 2014) (Risk Frontiers, 2016; Erdik et al, 2014; Rose et al, 2011; Opus 2005). They use comprehensive and rigorous loss assessment methodologies.

4.1 HAZUS-MH (2003)

Hazards U.S. Multi-Hazard (HAZUS-MH) Maintenance Release 4 is a damage and loss estimation software developed by FEMA to estimate potential losses from natural disasters. The HAZUS-MH Earthquake Model (FEMA, 2003) was developed to provide a nationally applicable methodology for the United States for estimates of damage and loss to buildings, essential facilities, transportation and utility lifelines, and casualties for scenario events or probabilistic earthquake risk assessment. HAZUS-MH uses Geographic Information Systems (GIS) technology to estimate the physical, economic and social impacts of disasters. It graphically illustrates the seismic hazard implications and identifies high-risk locations due to seismic activity. Users can then visualize the spatial relationships between populations and other more permanently fixed geographic assets or resources for the specific event being modelled, a crucial function in the pre-disaster planning process.

HAZUS-MH first discusses the inventory data including the Collection and Classification schemes of different systems, attributes required to perform damage and loss estimation, and the data supplied with the application. The software is intended for U.S. applications and includes federally collected data as default. The inventory is divided into 36 different types of buildings based on construction standards and material as well as size and building use.

The loss assessment methodology that HAZUS-MH uses consists of four interrelated components:

1. Potential Earth Science Hazards (PESH):

   This component describes the use of ground motion prediction models to calculate the level of ground shaking and deformation expected at a given site.

2. Direct physical damage:

   This component describes algorithms and data to estimate the amount of damage experienced by a structure when subjected to ground shaking and displacement. HAZUS-MH provides iterative and highly nonlinear procedures where damage becomes a function of multiple parameters, namely, the spectral acceleration at distinct periods.

   In this section HAZUS-MH describes four damage states; slight, moderate, extensive and complete. It presents methods for estimation of earthquake damage to buildings given information on the model building type and an estimate of the level of ground shaking (or degree of ground failure). Damage states are estimated for each model building type by physical descriptions of damage to building elements. HAZUS-MH further distinguishes between general building stock and essential and high potential loss facilities and uses "Special" building damage functions to determine the damage state of such buildings. The facilities that provide services to the community and those that should be functional following an earthquake are described as essential facilities. Such, facilities include hospitals, police stations, fire stations, emergency operations centres (EOC's) and schools. The methodology for damage assessment of such buildings is independently described in HAZUS-MH.

HAZUS-MH also describes methodologies for induced or indirect forms of damage. Induced Physical Damage refers to inundation from dam or levee failure, fire, hazardous material release and debris following earthquake. However, the induced or indirect forms of damage and related economic costs are outside the scope of this research.

3. Direct Economic/Social Losses:

This component deals with material losses (money spent to rebuild), casualties (fatalities and injuries), and damage to infrastructure and related consequences.

For direct economic losses the HAZUS-MH methodology describes the conversion of damage state information into estimates of monetary loss. The methodology provides estimates of the structural and non-structural repair costs caused by building damage and the associated loss of building contents and business inventory. It was identified that building damage can also cause additional losses by restricting the building's ability to function properly. To account for this HAZUS-MH estimated the direct business interruption and rental income losses separately from indirect economic losses. These losses are calculated from the building damage estimates. This expression of losses provides an estimate of the costs of building repair and replacement that is a frequently required output of a loss estimation study. The additional estimates of consequential losses give an indication of the immediate impact of such building damage on the community: the financial consequences to the community's businesses due to businesses interruption, the financial resources that will be needed to make good the damage, and an indication of job and housing losses.

In this section, HAZUS-MH also describes methodologies for the estimation of social losses such as casualties. The methodology is based on the assumption that there is a strong correlation between building damage (both structural and non-structural) and the number and severity of casualties. However, the methodology only includes casualties due to building and bridge damage and excludes casualties caused by landslides, heart attacks, car accidents, falls, power failures and casualties due to post-earthquake clean-up and construction activities and indirect events such as inundation from dam or levee failure, Tsunami, fire, hazardous material release and debris following earthquake.

4. Indirect Economic Losses:

The HAZUS-MH methodology describes indirect economic losses resulting from an earthquake event using a version of a Computable General Equilibrium (CGE) model. The model is designed to rebalance a region's interindustry trade flows based on discrepancies between sector supplies and demand (see Pan et al, 2015). The model accounts for earthquake induced supply shortages (forward linkages) and demand reductions (backward linkages).

The HAZUS-MH package provides a detailed itemised classification of the economic costs that include

1. Direct Economic Losses that include,
    a. Loss Related to Building Damage
        a) Building Repair and Replacement Costs
        b) Building Content Losses
        c) Building Inventory Losses
        d) Building Repair Time/Loss Function
        e) Relocation Expenses
        f) Loss of Income (Including Recapture Factor)
        g) Rental Income Losses
    b. Losses Related to Lifelines Infrastructure Failure
    c. Losses Related to utility Systems Failure
2. Direct Social Losses Related To Casualties
3. Direct Social Losses Related to Displaced Households' Shortterm Shelter Needs
4. Indirect Economic Losses
    a) Supply Shortage and Forward Linked Losses
    b) Demand Effects and Backward Linked Losses
    c) Regional vs National Losses

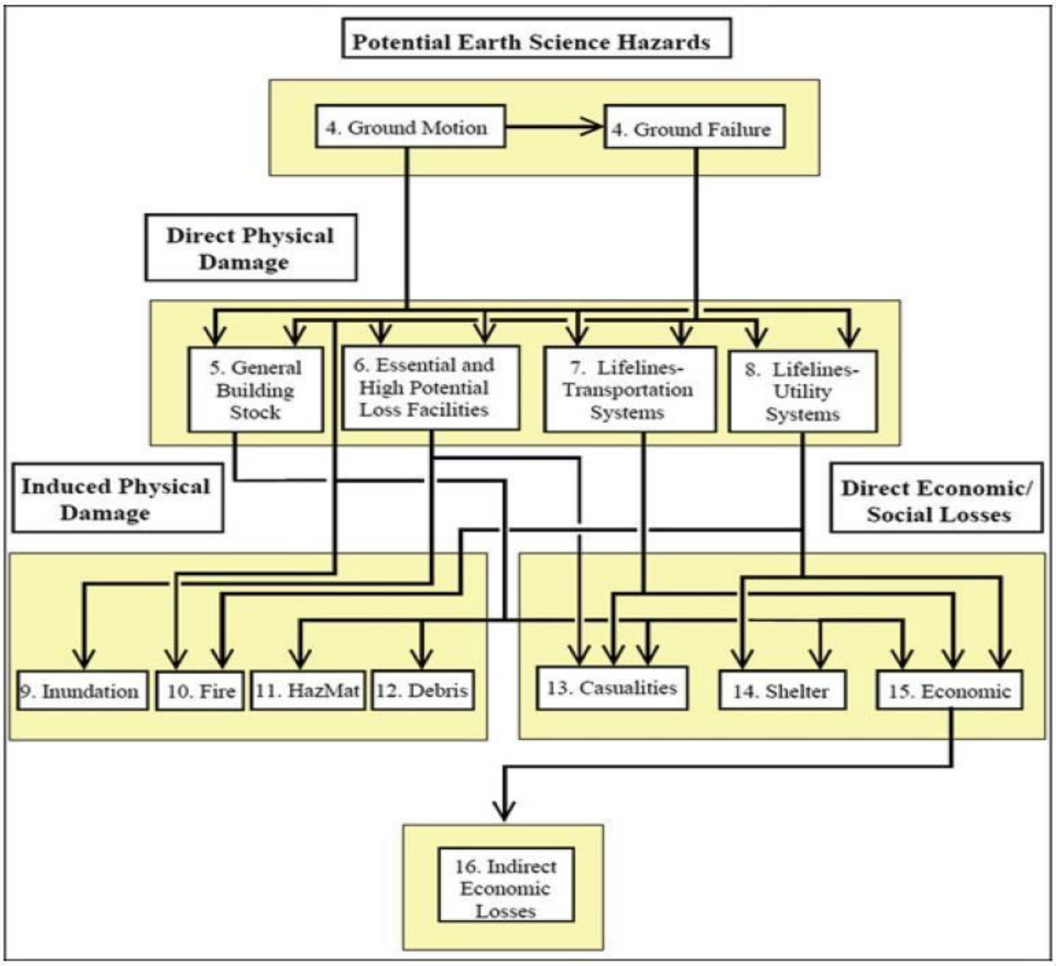

Figure 2: Flowchart from FEMA (2003)'s HAZUS loss estimation methodology (Chapter 2, page 2)

The HAZUS methodology on Direct Economic and Social Losses that includes a casualty loss model and a direct business interruption cost model are relevant to this research.

4.2 OpenQuake (Silva et al. 2014)

Another significant progress in this direction has been the development of the OpenQuake Engine (Silva et al. 2014). Silva et al. (2014) described the Global Earthquake Model that combines the main features of state-of-theart science, global collaboration and buy-in, transparency and openness in an initiative to calculate and communicate earthquake risk worldwide. One of the first steps towards this objective has been the open-source development and release of software for seismic hazard and risk assessment called the OpenQuake engine. This software aims to include a set of calculators capable of computing human or economic losses for a collection of assets, caused by a given scenario event, or by considering the probability of all possible events that might affect a region within a certain time span.

The OpenQuake methodology aims to develop five main calculators, each one contributing uniquely in the area of seismic risk assessment and mitigation. While some of these calculators may still be under development, an overview with a brief description of how they can benefit is presented in Table 1 (also see Silva et al. 2014).

Table 1 Description of the calculators of the current OpenQuake engine

Calculator	Symbol	Purpose
Scenario risk	SCN	This calculator is capable of computing losses and loss statistics due to a single, scenario earthquake, for a collection of assets, which is important, for example, for emergency management planning and for raising societal awareness of risk.
Scenario damage assessment	SDA	This calculator is capable of estimating damage distribution due to a single, scenario earthquake, for a collection of assets, which can be used for emergency management planning or to assess which assets are more seismic vulnerable.
Probabilistic Event-based Risk	PEB	This calculator computes the probability of losses and loss statistics for a collection of assets, based on the probabilistic hazard. The losses are calculated with an event-based approach, such that the simultaneous losses to a set (or portfolio) of assets can be calculated. The output of this calculator can be used to assess the aggregated expected losses for a collection of assets.
Classical PSHA-based Risk	CPB	This calculator leads to the computation of the probability of losses and loss statistics for single assets, based on a probabilistic description of the hazard. The output of this calculator is useful for comparative risk assessment between assets at different locations, which can be used, for example, for the prioritisation of risk mitigation efforts.
Benefit–cost ratio	BCR	This calculator is a decision-support tool for deciding whether the employment of retrofitting/strengthening measures to a collection of existing buildings is advantageous from an economical point of view. This output can be used to prioritize the regions in need for retrofitting/strengthening activities or to assess which seismic design is more economically adequate for a given region.

Silva et al. (2014) described that, of these five calculators: two are capable of computing loss and damage distributions due to single events, two have the purpose of estimating probabilistic seismic risk considering a probabilistic description of the events and associated ground motions that might occur in a given region within a certain time span, and one that uses loss exceedance curves to carry out retrofitting benefit–cost analysis. Of these the *Scenario Damage Assessment* and the *Scenario Risk Assessment* calculators related to single events are more relevant to the research and economic cost estimation methodology that would be adopted in this study.

The *Scenario Damage Assessment* calculator uses a rigorous methodology to estimate the damage distribution due to a single, scenario earthquake, for a spatially distributed building portfolio, which can be used for postearthquake loss assessment. Following Silva et al. (2014), the *Scenario Damage Assessment* workflow is presented in Fig. 3. The key components of the *Scenario Damage Assessment* and the *Scenario Risk Assessment* methodologies are as follows:

1. Rupture model: which determines rupture intensity.

2. Fragility model: Given a range of intensity measure levels the fragility model distributes the building stocks in the region into different damage states based on the probability of their exceeding a set of limit states.

3. Exposure Model: The exposure model contains the information on the assets of value such as buildings and infrastructure exposed to the earthquake hazard within the region of interest. A number of attributes (such as: construction type/material, height, age and value) are required to define the characteristics of each asset. Building taxonomy (classification scheme) and the geographic location allow for the association of the asset with the appropriate fragility function and the site-specific seismic hazard.

The key components of both of these earthquake loss estimation methodologies that are relevant for this research are; Ground Motion, Direct Physical Damage to General Building Stock and Direct Economic/ Social (Casualties) Losses.

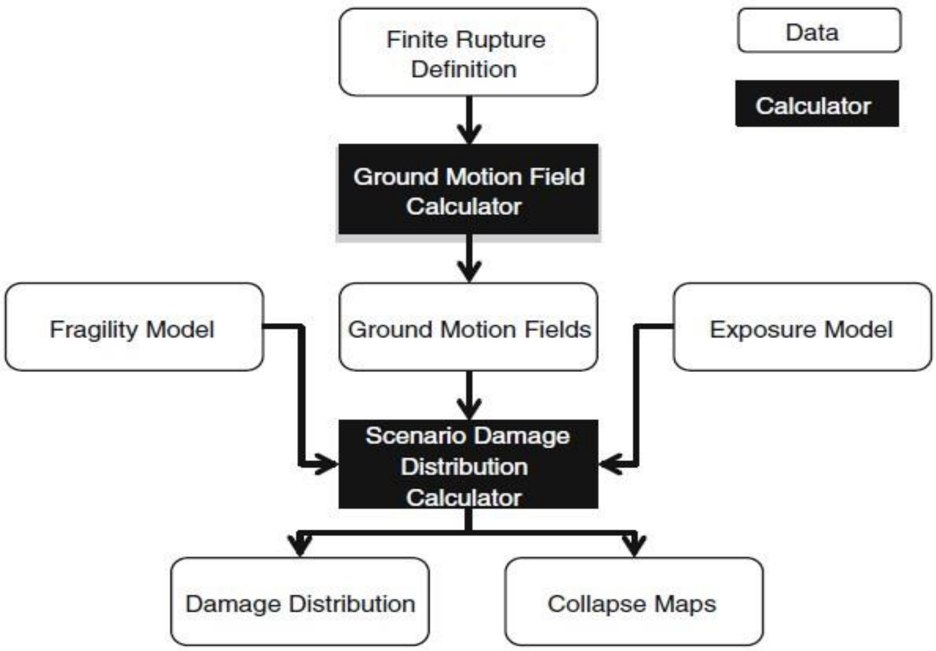

Figure 3: Workflow of the scenario damage assessment OpenQuake Engine loss estimation methodology (Silva et al, 2014: Fig. 6)

The OpenQuake engine is open-source software written in the Python programming language for calculating seismic hazard and risk at variable scales (from single sites to large regions). The scientific libraries of the

OpenQuake engine rely on input data models to represent the objects used in hazard and risk calculations and is being developed in parallel to the engine. A transparent and standard markup language- *the Natural hazards Risk Markup Language* (NRML), is used to transfer information in and out of the software. It uses input data models such as hazard source zone models, logic trees, finite ruptures, vulnerability models, fragility models, and exposure models that are represented in NRML. It also uses NRML to produce output data, which currently includes hazard curves, hazard maps, ground-motion fields, loss curves, loss maps, damage distributions and retrofitting benefitcost ratio maps.

These outputs can be used to inform seismic risk reduction including mitigation measures. They can also be used to inform post-earthquake emergency management planning or identification of the regions with higher seismic risk within a certain country where risk mitigation efforts should be prioritized. Nevertheless, Silva et al. (2014) recognised the HAZUS-MH software (FEMA 2003) as a very useful tool and a pioneering application in seismic risk assessment. HAZUS-MH methodologies have been the basis for many of the codes tested in OpenQuake modelling (also see Crowley et al. 2010).

4.3 Economic Impacts of the ShakeOut Scenario (Rose et al, 2011)

In an analysis which is more related to this research, the Earthquake ShakeOut Scenario in an eight-county Southern California region, Rose et al (2011) estimated $68 billion in direct and indirect business interruption (BI) and $11 billion in related costs in addition to the $113 billion in property damage. They emphasised that in such events the key components of shock to the economy are property damage and lifeline service outages that affect the economy's ability to produce. They identified that property damage from fire is 50 per cent greater than property damage from shaking because fire is more devastating and BI from water service disruption and fire each represent around one-third of total BI losses because of the long duration of service outage or long restoration and reconstruction periods.

Rose et al (2011) identified the following components of shocks to the economic system:

1. Direct building damage: short-period ground motion (affecting ordinary buildings)
2. Direct building damage: long-period ground motion (affecting highrise buildings)
3. Indirect building damage: fire following earthquake
4. Direct lifeline service outages

Rose et al (2011) used several formal and several ad hoc methods for their analysis. For estimation of the direct impacts they used a loss estimation model, a highway system damage model and various calculations for tall buildings. They also estimated the indirect property damage by an urban fire (following earthquake) model, and indirect business interruption impacts with an Input-Output (I-O) model. They have, however, largely used components of an

Input-Output model to estimate direct impacts of electricity, gas, and water utility outages and port on-site operation interruption, as well as disruption of import and export through the port.

They itemised (and estimated) the business interruption costs as:

1. Ordinary Building Damage
2. Ordinary Building Contents Damage
3. High-Rise Building Damage
4. High-Rise Contents Damage
5. Fire Damage
6. Fire-Related Contents Damage
7. Highway & Pipeline Damage
8. Subtotal Property (stock) Damage
9. BI from Ordinary Buildings
10. BI from High-Rise Buildings
11. BI from Fire
12. BI from Power
13. BI from Water
14. BI from Gas
15. BI from Transportation
16. BI from Ports
17. Subtotal BI (Flow) Loss
18. Relocation Costs
19. Traffic Delay Costs
20. Subtotal Additional Costs

They also discussed the important role of input data and functions necessary to carry out the estimation process. These are:

(1) inventory data on the built environment (factories, residences, infrastructure) and the natural environment,
(2) a set of damage functions that relate changes in underlying conditions to property damage and loss of function,
(3) disaster related resilience critical for evaluating economic impacts at individual building level.

Rose et al (2011) also highlighted that FEMA's HAZUS-MH System (FEMA, 2003) is a large expert system that translates physical damage and business interruption into direct dollar values of building replacement costs and business downtime costs, respectively.

4.4 The ShakeOut Scenario: A Hypothetical Mw7.8 Earthquake on the Southern San Andreas Fault (Porter et al, 2010)

Porter et al (2010) have described the occurrence and effects of a hypothetical M_w 7.8 earthquake on the southern San Andreas Fault. The scenario was hypothesised by more than 300 scientists and engineers. A customised HAZUS-MH analysis and 18 special studies were performed to characterize the effects of the earthquake on the built environment. HAZUSMH analysis was enhanced by augmenting its default inventory databases and by replacing the outputs of its built-in hazard model with externally derived maps of shaking and ground failure.

Porter et al (2010) described that the default inventory data and models within HAZUS-MH were enhanced to reflect 2008 replacement costs and incorporate a detailed database of buildings in Los Angeles County derived from tax assessor's data, and calibrated in all counties to reflect available information on unreinforced masonry buildings tabulated by the California Seismic Safety Commission. The inventory model was also enhanced by revisiting the construction type mapping schemes to reflect building density concentrations in urban core areas and construction pattern changes over time throughout the eight counties. Southern California structural engineering experts provided the local judgment to revisit these mapping schemes. With these enhancements, HAZUS-MH generated estimates of damage and economic loss figures in this study.

The scenario postulated 1,800 deaths and 53,000 injuries requiring emergency room care. The research team found it to be realistic that such an event kills 1,800 people, seriously injures 53,000, and produces losses of $191 billion (4% of the annual gross regional product), of which the largest contributor is fire following earthquake ($40 billion in building damage, $25 billion in content loss, and $22 billion in business interruption loss). Business interruption other than from fire following earthquake is the second-largest contributor to the total, amounting to $46 billion, of which $24 billion results from impaired water supply.

Porter et al (2010) identified that despite the size of these losses, they would have been much greater were it not for steadily improving buildings codes, widespread mitigation efforts for buildings, and extensive efforts by highway and roadway departments and various utilities to prepare for and reduce the impacts of future earthquakes, a process that was assisted by the scenario.

4.5 Study of Impact and the Insurance and Economic Cost of a Major Earthquake in British Columbia and Ontario/Québec (AIR Worldwide, 2013)

In a more recent study on the economic and insurance cost of a major earthquake affecting highly populated areas of British Columbia and the Ontario/Québec region in Canada, AIR Worldwide (2013) modelled both total economic loss and insured loss. In the total economic loss they included direct losses to property and infrastructure, and indirect losses due to supply chain interruptions, infrastructure network disruptions and other problems related to interconnectivity between economic sectors.

Unlike Porter et al (2010), AIR found that in the category of damage to buildings, contents, direct business interruption losses and service interruption losses, losses due to ground shaking related loss is the major component compared to any other perils following an earthquake. Further, in the ground shaking loss category, loss due to building damage is the major component to which commercial buildings contribute the most. AIR Worldwide (2013) highlighted that similar studies for different regions have shown a wide range for the contribution of losses due to infrastructure damage. They also found that the contributions of such losses to total losses are subject to large uncertainties, which depend on many factors such as the socio-economic situation of the region under study, the selected scenario and the damage estimation approach used.

4.6 Earthquake Risk Assessment Study Part 1 - Review of Risk Assessment Methodologies and Development of a Draft Risk Assessment Methodology for Christchurch (OPUS, 2005)

OPUS (2005) reviewed a range of relevant literature for developing a Risk Assessment Methodology for Christchurch. The focus of their review was to identify sources of information and techniques that would help develop a methodology for the earthquake risk assessment for Christchurch. They established that HAZUS-MH provides a general framework for the assessment of the risk from earthquakes, buildings, casualties and lifelines. In their view the HAZUS-MH framework was applicable for the earthquake risk assessment for Christchurch, with variations to suit the information available for the study. They further highlighted that fragility relationships available from HAZUS-MH along with their input data from New Zealand earthquake damage are useful tools for risk assessment of the built infrastructure and casualties.

4.7 PAGER (Jaiswal et al, 2013)

Jaiswal et al. (2013) extended the U.S. Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) empirical fatality estimation methodology (Jaiswal et al, 2010) to rapidly estimate economic losses after significant earthquakes worldwide. They used model inputs such as shaking intensity estimates made by the ShakeMap system, the spatial distribution of population available from the LandScan database, modern and historic country or sub-country population and Gross Domestic Product (GDP) data, and economic loss data from Munich Re's historical earthquakes catalogue. They developed a strategy to approximately scale GDP-based economic exposure for historical and recent earthquakes in order to estimate economic losses. The process consists of using a country specific multiplicative factor to accommodate the disparity between economic exposure and the annual per capita GDP, and it has proven successful in hindcasting past losses. Although loss, population, shaking estimates, and economic data used in the calibration process have uncertainty, approximate ranges of losses can be estimated for the primary purpose of gauging the overall scope of the disaster and coordinating response. The proposed methodology is both indirect and approximate and is thus best suited as a rapid loss estimation model for applications like the PAGER system.

Jaiswal et al. (2013) used the shaking-intensity dependent loss ratio defined as the total direct economic loss normalized by the total economic exposure in a given area at the time of the earthquake. The earthquake specific economic exposure at each intensity level is calculated for each earthquake by multiplying the total population at a given shaking intensity by per capita

GDP for the year in which the earthquake occurred and an exposure correction factor of that country. The loss ratio as a function of shaking intensity is described by a country-specific, two-parameter, lognormal cumulative distribution function. The loss ratio function when multiplied by the economic exposure associated with each shaking-intensity level provides an estimate of the total expected economic loss.

Unlike FEMA's HAZUS-MH program and the OpenQuake engine methodology based on detailed inventory-based earthquake loss estimation models, Jaiswal et al. (2013) extension of the PAGER methodology serves as a useful tool for rapid economic loss estimation. PAGER's goal is to meet the global earthquake disaster needs and produce both actionable and acceptable economic loss estimates that can help users determine appropriate levels of response in the initial hours following an earthquake disaster.

4.8 EQRM (Robinson et al, 2005)

The EQRM application is Geoscience Australia's current central tool for modelling earthquake hazard and risk. Its use formed the basis for Geoscience Australia's recent reports on Earthquake risk in the Newcastle and Lake Macquarie and Perth regions. It is a computer model for estimating earthquake hazard and earthquake risk. Modelling earthquake hazard involves assessing the probability that certain levels of ground motion will be exceeded. Modelling of earthquake risk involves estimating the probability of a building portfolio experiencing a range of earthquake induced losses. For any number of synthetic earthquakes, the EQRM application can be used to estimate:

1) the ground motion and its likelihood of occurrence (earthquake hazard),
2) the direct financial loss and its likelihood of occurrence (earthquake risk),
3) the number of casualties and injuries and their likelihood of occurrence (earthquake risk),
4) The damage and disruption to bridge assets.

Robinson et al (2005) describes the methodology behind the program and how to use it. For the purpose of this research on estimating the economic costs of an earthquake scenario the EQRM considers two types of loss:

1) direct financial loss defined as the cost involved in replacing damaged building components and/or contents; and
2) social loss defined as the number (or probability) of casualties and injuries as a result of a simulated scenario.

In the direct financial loss category EQRM models each building as comprising three main components, namely structural, non-structural drift sensitive and non-structural acceleration sensitive components. The damage experienced by each building is computed separately for each of these components and correspondingly separates the replacement cost of the building into the replacement cost for each of the three components. The proportion chosen for each building component is a function of the buildings construction and usage type.

EQRM includes a module for computing injuries and casualties associated with a scenario simulation which is still under development stage. It also has a model for assessing the likely damage state and recovery prognosis for bridge assets utilising the approach in HAZUS-MH (FEMA, 2003).

4.9 Casualty Estimation Models

In the field of rapid economic loss estimation Daniell (2014) has developed an approach to calculate fatalities and associated economic losses from earthquakes using the input of an intensity based hazard map and historical earthquakes as a proxy over multiple temporal and spatial scales. He used a concept called socio-economic fragility functions that use a direct relationship of intensity to fatalities that are calibrated by the socioeconomic status of each individual damaging earthquake over time. An extensive amount of historical provincial and sub-provincial data as well as reanalysis of historical events produced the functions that are compatible with other methodologies and existing engineering fragility functions.

Analysing EM-DAT - an international disaster database on historical earthquakes since 1900s, Guha-Sapir and Vos (2011) emphasised that there is lack of standardised definitions for human impact indicators – such as people injured or people affected – in the literature. They noted that even conventional definitions that describe the population exposed to death and injury from earthquakes have yet to be established. This significantly hinders, not only comparisons across studies, but even within studies as denominators are inadequate. Guha-Sapir and Vos (2011) also recognized that the distribution of deaths and injuries caused by earthquakes varies greatly across space and the level of economic development of the community in which it occurs. Thus, in their view statistical analysis of earthquake impact data can be useful for evaluating impact patterns over space and time. Besides, well-designed case-control studies and, more ideally, cohort studies could significantly contribute to generating evidence on risk factors for earthquake mortality and morbidity.

Ferreira et al (2010) highlighted that earthquake casualty models and simulations have shown substantial variability in estimating the numbers of victims when compared with real values, as they fail to consider a multiparameter analysis including variables such as seismic intensity, degrees of building damage, percent of occupancy at the time of the event, individual behavior (age, gender, mobility within the house during the shaking, etc.) or emergency response (effectiveness in response). In their view the fatal consequences of large earthquakes depend on proximity of earthquakes to urban populations, the vulnerability of dwellings including the construction type, the time of day, building occupancy and pedestrian population dynamics during the day.

Porter et al. (2008a, b), Jaiswal et al. (2009) and Jaiswal and Wald (2010) have concentrated on the key parameters of intensity as the hazard metric versus fatality to population ratios or the death rate in collapsed buildings, using expert opinion derived collapse ratios and historical data. They have estimated the earthquake fatality rates as total killed divided by total population exposed at specific shaking intensity levels. The total fatalities for a given earthquake are estimated by multiplying the number of people exposed at each shaking intensity level by the fatality rates for that level and then summing them at all relevant shaking intensities. The fatality rate is expressed in terms of a two-parameter lognormal cumulative distribution function of shaking intensity.

The HAZUS-MH (FEMA 2003) casualty module describes and develops its methodology for the estimation of casualties. The methodology is based on the assumption that there is a strong correlation between building damage (both structural and nonstructural) and the number and severity of casualties. This model estimates casualties directly caused by structural or nonstructural damage under four severity levels to categorize injuries, ranging from light injuries (Severity Level 1) to death (Severity Level 4). The model provides casualty rates for different structural types and damage states. Relevant issues in casualty estimation such as occupancy potential, collapse and non-collapse vulnerability of the building stock, time of the earthquake occurrence, and spatial distribution of the damage, are included in the methodology. Casualties caused by a postulated earthquake can be modelled by developing a tree of events leading to their occurrence.

4.10 Casualty Cost Estimation Models

Estimating the number and types of casualties is one important step in estimating the economic cost of casualties to the society. It is equally important to assign the monetary values of economic loss to society from casualties. It is common in present day policy making to estimate the monetary cost of mortalities and injuries for any kind of health related and/or lifesaving program evaluation or cost benefit analysis owing to the high costs involved in implementing these programs. This section reviews international (WHO/Europe, 2014; OECD, 2012) and Australian literature (BITRE, 2009; Abelson, 2008) on methodologies to estimate monetary values of mortalities and injuries in sectors other than natural disasters that involve risk to human health and life. There is little literature that estimates the monetary value of casualties due to natural disasters (Daniell et al, 2015). In Australia most work has been done in the transport sector for road accidents (BITRE, 2009) with the exception of a comprehensive study by Abelson (2008).

Cost Benefit Analysis (CBA) has been widely used as an important economic methodology for program evaluation. CBA evaluates the total expected costs of a given program against the total expected benefits. It is now widely adopted in many OECD countries, including the United States, Canada, Australia, the United Kingdom, the Nordic countries, as well as the European Commission. CBA is commonly used in the transportation, energy and environment sectors (OECD, 2012).

However, the literature on methodologies to estimate a monetary value to human life or quality of life lost varies widely. Variability from country to country depends on the purpose for which a monetary value to human life is estimated. The monetary costs that would apply to different levels of stakeholders in this study for casualties predicted for an earthquake scenario in Australia can be expressed in what is termed in the literature as "Value of a Statistical Life" (VSL) and "Value of Statistical Life Year" (VLY) (WHO/Europe, 2014; OECD, 2012; Abelson, 2008). The VSL represents the value a given population places *ex ante* on avoiding the death of an unidentified individual. VSL is based on the sum of money each individual is prepared to pay for a given reduction in the risk of premature death, in this case from an earthquake event. A related concept is the VLY, which estimates the value society places on reducing the risk of premature death, expressed in terms of saving a statistical life year (Abelson, 2008). However, there are different methods of measuring society's willingness to pay to reduce the risk of death. There are two major divisions in the literature on methodologies to estimate the VSL. They are the 'human capital approach' and the 'willingness to pay approach'.

As Abelson (2008) states, human capital or the cost of illness (COI) method is the ex-post sum of various identifiable costs, such as loss of work income and medical expenses. The human capital approach estimates the value of health as the increase in the earnings and avoidance of medical expenses of individuals as a result of improved health. The value of life is the discounted present value of output or income. However, the human capital approach has been identified as having several limitations that restrict its applicability. Since it is based on the income and the output loss estimation method, it does not have a methodology for estimating the fatalities for nonworking individuals. Also, the method does not value the pain and sufferings that people undergo. Since the present day public policies are more concerned with reducing the risk of fatalities or injuries rather than actually preventing a specific event, the human capital approach which relies on expert opinions on ex-post sum of various identifiable costs, such as loss of work income and medical expenses becomes irrelevant (Abelson, 2008). Consequently, it is inapplicable for earthquake mitigation strategy evaluation where the focus is on reducing the risk to exposure rather than preventing the earthquake itself.

The alternative approach which is more topical and is being widely accepted in the literature is the willingness to pay approach. Willingness to pay is an ex-ante measure of the amount that individuals are willing to pay for various perceived gains from reduction in risk of death and disability/injuries. The willingness to pay measure is identified as the appropriate measure for most policy purposes (WHO/Europe, 2014; OECD, 2012; Abelson, 2008). Abelson (2008) identifies that willingness to pay approach is similar to measuring the value of insurance policies. Abelson (2008) suggests that since in recent times the public policies involve only small changes in risk, it is more important to find how much *marginal* consumption (or income) individuals are willing to forego in return for this *marginal* increase in safety. Consequently, VSL is not constrained by the discounted present value of a person's earnings.

Within the willingness to pay approach there are two methodological divisions to estimate the VSL: revealed and stated preference methods. While both the methods have their limitations the stated preference method is preferred over the revealed preference method (OECD, 2012; Abelson, 2008).

Revealed Preference (RP) methods are based on an individual's revealed preference in markets where prices reflect differences in mortality risk. In case of labour market for example, where in some industries wage differentials between jobs reflect differences in level of occupational risks of mortality in the workplace (also OECD, 2012; Cropper et al, 2011; Abelson, 2008; Viscusi and Aldy, 2003). This is similar with some products in the market that reduce or eliminate mortality risks, such as buying bottled water to reduce mortality risk from contaminated tap or well water or buying motorcycle helmets to reduce mortality risks in traffic accidents (OECD, 2012; Abelson, 2008; Blomquist, 2004). However, it is noted in OECD (2012) and Abelson (2008) that the revealed preference approaches depend on a set of strict assumptions about the market and the respondents' information and behaviour which this review considers are incompatible for earthquake mortality risk assessment.

Stated Preference (SP) methods involve studies such as contingent valuation (CV) or choice modelling (CM). They construct a hypothetical market for the mortality risk change in question and ask respondents directly in surveys for their willingness-to-pay (WTP) to reduce their mortality risk. The VSL can then be derived from these surveys (OECD, 2012; Abelson, 2008). This is preferred and recognized in the literature (OECD, 2012; Abelson, 2008) as many environmental, transport and health policies for which we need to estimate VSL affect all age groups of the population while the youngest or the oldest are the worst affected. It does not only affect the workers in occupations that involve risk, for which we can estimate VSL based on wage risk studies. However, OECD (2012) finds that RP methods in terms of wage risk studies have been conducted more in the United States, while Europe, Canada and Australia rely more on Stated Preference (SP) methods, eliciting people's willingness-to-pay (WTP) for changes in mortality risks. The focus in this review is on how to estimate VSL for casualties from an earthquake scenario in Australia. Daniell et al (2015) have examined the costs from earthquakes from 1900-2014 using a simple hybrid value of a human life in each country through time that summed to $1 trillion USD of impact. Their work shows the importance of estimating the VSL and the significant impact this costing procedure has on the cost of disasters over the past century. They have established that additional 25-30% economic losses can be attributed to earthquakes when the VSL costing is taken into account.

The willingness-to-pay values vary over the population, some groups may have higher values of life than others. This implies that there is no unique VSL or VLY over the population. These values may differ over age, time, health status, type of risk and based on whether we should use the individual willingness to pay or the societal willingness to pay. However, there is insufficient evidence in the literature to support variation across age. Abelson (2008) acknowledges that, in reflecting a social judgment, it is common in cost-benefit studies to adopt an *average* WTP value for life and VSL. They are generally held constant regardless of the income of any social group either at any point in time or over time. There has been a well-accepted tradition that countries and agencies within countries commonly adopt an average VSL and VLY (WHO/Europe, 2014; OECD, 2012; Abelson, 2008).

Based upon Abelson (2008) the Office of the Best Practice Regulation (OBPR) Australia (2014) have accepted the most credible estimate for Australia is $3.5m for the value of statistical life and $151 000 for the value of statistical life year. These estimates represent an average and are based on a healthy person living for another 40 years.

Drawing on the fact that there is a lack of any comprehensive research on VSL in Australia, Abelson (2008) has recommended that Australian estimates of VSL must draw on overseas studies and values. At an international level most official VSLs are based on an average value for the death of a healthy person at an age of about 40 years. The United States Environmental Protection Agency (USEPA, 2000) recommended the general use of a VSL of US$6.1 million in 1999 dollars. The USEPA recognised that VSL peaks in middle age and declines thereafter and that VSLs may vary with health status and type of risk. It also noted that VSL is often taken to be the sum of discounted values for each life year with each life year having the same value. Consequently, there seems to be a consensus in the literature that for general use a single value is preferred along with sensitivity tests, unless more research informs about how VSL varies with individual and environmental factors.

Abelson (2008) noted that official European VSLs are considerably lower by about US$2.0 million with further variation with the UK values depending on the purpose of use. The organisation *Health Canada* uses an age adjusted VSL of Cnd$4.3 million in 1999 prices (Abelson, 2008; Krupnick et al, 2000). The WHO/Europe Health Economics Assessment Tool (HEAT) recommends a European default value of VSL €2.487 million (WHO European Region), €3.387 million (EU-27 countries) or €3.371 million (EU-27 countries plus Croatia). Abelson (2008) highlights that EU (2001) argues that VSL declines with age and the individual health status before death. However, it recommends that all EU members adopt a common value irrespective of income differences (Abelson, 2008).

In the Abelson (2008) analysis the European values of A$3.0 million to A$4.0 million appear to be a plausible VSL for a healthy prime age individual in Australia at present. Allowing 40 years of life lost and a utility discount rate of 3 per cent, a VSL of $3.5 million implies a VLY of $151,000 (both of these are measured in 2007 dollars). Using CPI data to express these estimates in 2014 dollars OBPR (2014) estimates a VSL of $4.2 million, and a VSLY of $182,000. Consistent with this approach, age-specific VSLs would equal the present value of future VLYs of $182,000 discounted by an appropriate discount rate, say 3 per cent per annum. This approach appears broadly consistent with public values, but it may represent a sharper decline in VSL than is socially preferred (OBPR, 2014; Abelson 2008).

5 PROPOSED ECONOMIC LOSS MODELLING FRAMEWORK

The literature review has identified a broad range of direct and indirect economic costs associated with severe earthquake events. Empirically it has been established that the cost of Business Interruption constitutes a major component of the total economic costs of earthquakes. The inherent lack of warning for earthquakes (compared to bushfire, riverine flood and tropical cyclones) also contributes to significant injuries and deaths. Potential losses due to health care costs and lost productivity are correspondingly higher. Consequently the scope of this research includes estimation of the following components of direct economic costs of an earthquake scenario in Australia:

- Direct building damage related loss.
- Direct building contents loss.
- Direct business activity disruption due to damaged premises
- Broader scale business activity disruption due to precinct level damage
- Cost to society from injury and loss of life

Excluded are indirect economic losses associated with interruption of supply chains or utility supply disruption, economic losses associated with other earthquake induced hazards and impacts. The exclusions include liquefaction which is less common with Australian seismicity. They also include inundation from dam or levee failure, tsunami, fire, hazardous material release and debris following earthquake along with direct economic losses related to lifelines infrastructure or other utility systems failure. In addition, the costs incurred for emergency response and clean-up are also excluded.

The aim is to provide different estimates for different levels of decision makers in Australia, for example, starting from direct business activity disruption due to damaged premises to broader scale business activity disruption due to precinct level damage. The economic loss modelling approach aims to encompass the information needs of a range of decision makers including:

- Building owners.
- Owners of both the building and business.
- Local Government for a business precinct.
- Jurisdictional and Federal Governments and their additional interest in economic loss associated with health care and lost productivity.

This research will be largely adopting the HAZUS-MH loss assessment methodology to estimate the above mentioned components of economic costs from building related earthquake scenario risk in Australia. HAZUS-MH is widely documented and endorsed as a comprehensive and rigorous loss assessment methodology that has significant contextual relevance to developed countries like Australia and New Zealand (Erdik et al, 2014; Risk Frontiers, 2015). While much of the OpenQuake engine software is based on some of the HAZUZ-MH methodologies (Crowley et al, 2010). The HAZUS-MH methodology has been developed by the US Federal Emergency Management Agency (FEMA, 2003). HAZUS-MH users have been increasing. Federal, state, regional, and local governments in US and other countries use the HAZUS-MH earthquake model for earthquake risk mitigation, preparedness, response, and recovery planning. Its scope and applicability to Australian context has widely been acknowledged in Australia (Risk Frontier, 2015; Opus, 2005; GA, 2005). The structure of the HAZUS-MH methodology is shown in Figure 2.

5.1 Direct Business Interruption Costs

Estimating Direct Economic Costs resulting from business interruptions due to damaged buildings or premises and broader scale business activity disruption due to precinct level damage has been identified as one primary component of this project.

The severe ground shaking that accompanies earthquake causes physical damage to buildings. This may involve costs related to repair, demolition and/or reconstruction of the damaged building that depend on the severity of the event.

The extent of physical damage to a building post-earthquake can result in restricting the use and access to the building. In the case of buildings used for commercial or business purposes the resultant disruption to turnover would add to the economic loss. In case of residential buildings there would also be an addition to the economic loss in terms of lost rental income or displaced households with short term shelter needs. This impact can spill over to businesses in less damaged adjacent structures, where damage cordons restrict the access to adjacent buildings, thereby adding to precinct level economic loss.

Precinct level damage implications will be modelled in this project to capture the effects similar to those encountered in the Christchurch Earthquake where cordons were in place for up to 12 months in some areas with implications for business activity (Elwood *et al*, 2015).

The building stock within business districts varies as to age, structural form and use. The timing and scale of urban growth has had a bearing on the current building stock profile within communities. For example, the Victoria gold rush of the late 1800s resulted in the construction of many large prestigious masonry buildings for public and commercial use that are present today in the cities of Bendigo, Ballarat and Melbourne. For the purposes of this research two principal structural types have been identified that are considered to contribute the most to the earthquake risk of Australian communities and the larger CBD's of Australian cities:-

1. Unreinforced masonry that is inherently brittle and poorly tied together structurally.
2. Poorly detailed and configured reinforced concrete frame and shear wall construction.

Buildings of this type have poor ductility, are often torsionally irregular and can exhibit "soft storey" behavior.

The building contents loss is also an important component of the economic cost that would be modelled in this project depending on whether a building sustains partial or complete collapse, direct damage to contents will also result.

This research proposes to model all the above mentioned components of building related direct economic costs in the estimation methodology for earthquake scenario risk in Australia.

5.2 Casualty Costs to Society from Injury and Loss of Life

Estimating building related earthquake casualty costs to society from injury and loss of life such as medical care requirements and lost productivity caused by recovery from injury, disability or death represent further economic costs that are identified as another important component of this project. The aim is to estimate monetary costs of fatalities and injuries beyond their health care costs to the exchequer that includes overall value of the life lost or quality of life lost due to disability. This will provide important information for decision makers and can result in more efficient earthquake related mitigation strategy development.

This research recognizes that along with the level of seismic intensity, causalities caused by earthquake varies significantly across space, time and the level of economic development of the community in which they occur. In a more detailed interpretation it includes extent of damage to the buildings, building occupancy at the time of occurrence, population dynamics (age, gender, mobility within the house during the shaking, etc.) or emergency response (effectiveness in response). In this context it would be appropriate for this research to adopt the HAZUS-MH (FEMA 2003) casualty module due to its specific relevance to Australia, while we propose to incorporate all the above mentioned determinants of earthquake casualty estimation methodology, the actual modelling will be subject to the limitations of inventory data availability.

The focus of this study is to estimate the monetary cost of casualities that has been identified as significant for natural disaster exposure and risk management related program implementation and for that reason earthquake related mitigation strategy development (Daniell et al, 2015).

Following the international practice and OBPR (2014), the recommendation for this research is to adopt the values of VSL and VLY estimated by Abelson (2008) for estimating the monetary cost of casualties from an earth quake scenario in Australia. Also following the OBPR (2014) recommendation this research will adjust the value of statistical life year (which could be interpreted as the value of a year of life free of injury, disease and disability) by a factor that accounts for the type of injury, disease or disability. Further, the research envisages using the Australian Institute of Health and Welfare published disability weights for diseases and injuries to adjust the VSLY (Mathers et al 1999, pp. 186-202).

5.3 Input Requirements, Resilience and Uncertainties:

In estimating the economic costs from a building related earthquake scenario the first step is to explore what determines such costs. Following Erdik et al (2014), Silva et al (2014), Rose et al (2011), Porter et al (2010) OPUS (2005) and FEMA (2003) the literature review identifies that the economic costs from a building related earthquake shakeout scenario risk are primarily a function of –

1. Hazard severity model
2. Damage Function/Fragility Functions
3. Vulnerability Function
4. Building Types
5. Inventory data
   a) Building stock: both general building stock and the essential and high loss potential building stock
   b) Demographic data
   c) Default Occupancy class square foot inventory

However, incorporating aspects of systemic resilience in the immediate aftermath of an earthquake - both static and dynamic, are important components of the business interruption cost modelling. Rose (2007) identified that *Economic resilience* is a major way to reduce losses from disasters. Its effectiveness would be further enhanced if it could be precisely defined and measured. He distinguished *static* economic resilience— efficient allocation of existing resources—from *dynamic* economic resilience—speeding recovery through repair and reconstruction of the capital stock. Rose et al (2011) only accounted for aspects of static resilience as dynamic resilience is highly variable. The two components of the static resilience they have accounted for include : first, the production recapture or rescheduling, the ability of firms to work overtime or extra shifts after they have repaired or replaced the necessary equipment and their employees and critical inputs become accessible, that is, once "loss of function" has been eliminated. HAZUS-MH includes an adjustment for this consideration, referred to as the "Building Service Interruption Time Multiplier"; second, to identify the percentage of a sector's business operations that is not dependent on a specific infrastructure type.

As Erdik et al (2014) noted, any earthquake loss estimation modelling is subject to uncertainties in seismic hazard analyses, fragility relationships, population behaviour and time space distribution of population. They arise, in part, from incomplete scientific knowledge concerning earthquakes, earthquake ground motion and their effects upon buildings, facilities and population. They also result from the approximations and simplifications that are necessary for comprehensive analyses. Incomplete or inaccurate inventories of the built environment, demographics and economic parameters add to the uncertainty. Consequently, these error components need to be factored out in any loss estimation modelling.

6. RECOMMENDATIONS ON BUSINESS INTERRUPTION AND CASUALTY COST ESTIMATION MODELLING

A range of relevant literature has been reviewed and presented in this report. The focus of this literature review has been to identify different components of earthquake related economic costs and possible sources of estimation methodology for these costs from building related earthquake scenario risk in Australia. This literature review has identified a broad range of direct and indirect economic costs associated with severe earthquake events and established that, while other costs are important, the *Business Interruption Costs* and *Casualty Costs* in the direct economic cost category constitute significant components of the total economic costs from earthquakes. The review further proposes to model and estimate these costs in this research for *estimating building related economic costs from Australian earthquake events*.

The HAZUS-MH Earthquake Model (FEMA, 2003) has been customised and adopted for both developed and developing countries. This review proposes to adopt the HAZUS-MH *Direct Business Interruption Cost Model* and *Casualty Cost Model* approaches for this research. The level of applicability and extendibility of the HAZUS-MH framework for Australia will depend on the available information and the inventory.

This research further proposes to adopt the Abelson (2008) estimated values of VSL and VSY for estimating the monetary cost of casualties from an earthquake scenario in Australia. Also, this research will adjust the value of statistical life year (which could be interpreted as the value of a year of life free of injury, disease and disability) by a factor that accounts for the type of injury, disease or disability using the Australian Institute of Health and Welfare published disability weights for diseases and injuries to adjust the VSLY (Mathers et al 1999, pp. 186-202).

7. PROPOSED BUILDING TYPE SCOPE

The building stock within business districts varies as to age, structural form and use. The timing and scale of urban growth has had a bearing on the current building stock profile within communities. For example, the Victoria gold rush of the late 1800s resulted in the construction of many large prestigious masonry buildings for public and commercial use that are present today in the cities of Bendigo, Ballarat and Melbourne. For the purposes of this research two principal structural types have been selected that are considered to contribute the most to the earthquake risk of Australian communities and the larger CBD's of Australian cities:-

- Unreinforced masonry that is inherently brittle and poorly tied together structurally.
- Poorly detailed and configured reinforced concrete frame and shearwall construction. Buildings of this type have poor ductility, are often torsionally irregular and can exhibit "soft storey" behavior.

Excluded are losses associated with interruption of supply chains or utility supply disruption. In addition, the costs incurred for emergency response and clean-up are also excluded.

8. PROPOSED COMPUTATIONAL APPROACH

This research aims to develop an economic loss modelling framework that is implementable while capturing the range of economic measures included in the scope of work. This has required a pragmatic framework and approach for which the information requirements are tractable. The proposed framework is described in detail below.

8.1 Computational Approach

The frameworks proposed for each of the range of decision makers are similar to one another, but have been adjusted to reflect the measures used by the respective decision maker. In Figure 4 the framework for decision making at an individual property level is described (for mitigated building case). As a single asset is under consideration the hazard input is the severity of ground shaking for a range of likelihoods for the building site with the effects of site soil response included. The horizontal dashed line reflects the limit of interest in avoided costs incurred for a building owner deciding on retrofit options. The added loss measures below the line are considered applicable to occupants who own both the business premises and the business. Finally, the correlations of contents damage and business disruption with building damage are captured.

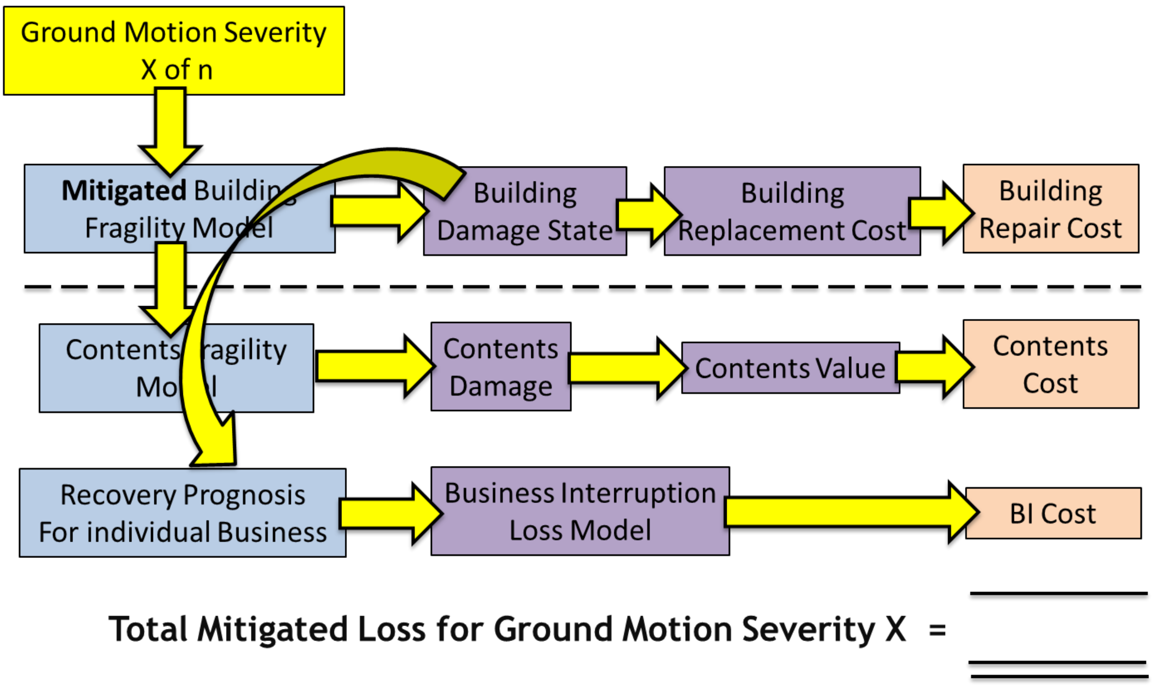

Figure 4: Economic loss modeling framework for an individual building. The mitigated case is shown and the limit of measures of interest to a building owner versus owner of both building and business is indicated by the dashed horizontal line.

For a population of buildings in a business district the spatial distribution of the ground shaking needs to be considered. The framework for this incorporates a set of earthquake scenario events that capture the range of locations and magnitude levels that need to be considered. This is illustrated in Figure 5 below. The correlation between building damage severity and injury is shown. Further, a community recovery prognosis model is incorporated that captures the relationship between severity of precinct damage, expected recovery and associated disruption to business activity while this is effected.

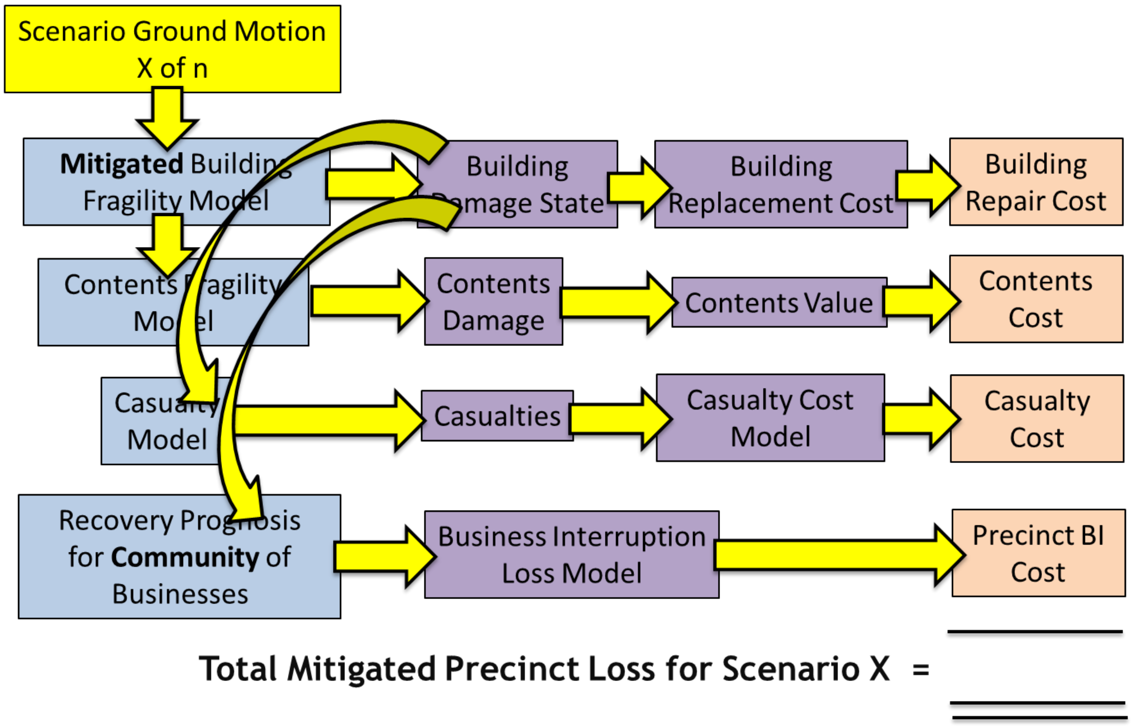

Figure 5: Economic loss modeling framework for a business precinct. The mitigated case is shown with casualties and associated costs included as of Interest to government.

8.2 Mitigation Implementation Prognosis

Mitigation measures for individual buildings can be effected in a relatively short period of time following the investment decision to do so. In contrast, the mitigation action within a population of buildings will necessarily be implemented over a period of time – even decades. Business district mitigation translates into a gradual investment and a corresponding progressive realisation of the benefits derived into the future. The research approach will consider a range of retrofit uptake rates for the building types in the scope. These rates will be influenced, and potentially incentivised, by insurance premium discounts and government initiatives to promote the action. The rates of uptake may also be influenced by local scale variations in earthquake hazard, where properties located on softer soils have higher earthquake hazard than properties underlain by stiffer soils within the same precinct, thereby realising greater returns on mitigation investment.

8.3 Loss Estimation Approach

The loss estimation approach utilises the aggregated losses for each severity of site shaking or scenario earthquake considered using the framework describes previously. The key steps in the approach are described below.

Annualised Long Term Loss for Hazard Exposure

The long term losses for earthquake hazard exposure will be evaluated for both the non-mitigated (as is) and mitigated building or precinct exposure cases. The event losses for all local hazard likelihoods or scenarios will be converted into a Probable Maximum Loss (PML) curve that will be subsequently integrated to obtain the annualised loss without mitigation and for the range of mitigation uptake scenarios considered. As the mitigation action for a precinct will not typically be a step function in any year, but a progressive implementation and loss reduction, the annualised loss will be assessed in stages that reflect the status of the retrofit in the business district at each time step.

Annual Benefit of Mitigation

The average annual economic benefit of each building mitigation strategy will be evaluated by subtracting the annualised mitigated case loss from the unmitigated value. For the precinct level assessment the annual benefit will be assessed at each of the retrofit uptake stages considered.

Benefit Versus Investment Cost of Mitigation

The future benefits of mitigation resulting from the status of retrofit will be converted to present value using standard economic discounting techniques. In this process several discount rates will be explored to assess the effect of a range of costs for capital investment. In a similar manner, for precinct level the progressive investment cost in retrofit will be discounted to present value

For individual buildings the present value of annual savings in hazard exposure cost for several bedrock hazard and site soil classes will be divided by the investment cost for each retrofit strategy considered. In a similar manner the present value of annual savings for each precinct level retrofit strategy/uptake rate/cost of capital combination will also be used to divide the present value of annual savings with the present value of the investment cost. The resultant benefit versus cost ratios (B/C) will permit comparison for optimal strategy selection in economic terms.

8.4 Information and Model Requirements

The key information and model requirements for the proposed framework and approach are:-

Hazard and Impact

National scale Australian probabilistic hazard assessment.

Seismic source zones and recurrence rates for precinct study location(s).

Surface soil (regolith) characterization for the precinct study location(s).

Seismic impact assessment software tools that integrate hazard, building exposure and vulnerability for precinct scenario modelling.

Exposure

Detailed information of building stock in study precinct(s).

Building replacement cost.

Business type.

Building contents value (range of business uses).

Human activity model that places people spatially in probabilistic terms.

Vulnerability

Building retrofit strategy options

Building retrofit option costs Building

fragility curves retrofitted Building

fragility curves non-retrofitted.

Building contents loss models.

- Building repair times for reoccupation covering the full range of damage states.
- Casualty models that define the probability of injury severity for building type and damage state.
- Business interruption models (isolated business).
- Business interruption models (precinct).
- Cost model for death and injury.

The project team has identified how all of these requirements can be met either from outputs from the CRC project, or from other external sources.

9. FUTURE WORK

Future work will include:-

- Adaptation of casualty cost models for injury associated with building damage in earthquakes.

- Development of business interruption model.

- Development of proposed framework/methodology and tools for assessing precinct level economic activity disruption. This is expected to include utilization of research undertaken in NZ on the recovery following the 2011 Christchurch Earthquake (Elwood *et al*, 2015)

10. SUMMARY

The findings of the literature review are presented in this report and have helped to shape the scope. Frameworks for quantifying and integrating a range of economic costs associated with earthquake events have been developed which will have application to a range of decision makers. The information requirements for this framework have also been identified and strategies for sourcing these developed. This research will progressively advance in parallel to the other physical testing and vulnerability assessment work enabling the project outputs to be brought together to obtain the metrics required for decision making.

This research proposes to adopt HAZUS-MH *Direct Business Interruption Cost Model* and *Casualty Cost Model* approaches for the earthquake risk assessment in Australia where we will consider the Melbourne CBD as a case study. The level of applicability and extendibility of the HAZUS-MH framework for Australia would depend on the available information and the inventory data required for realistic modelling.

This research further proposes to adopt Abelson (2008) estimated values of VSL and VLY for estimating the monetary cost of casualties from an earthquake scenario in Australia. Also, this research will adjust the value of statistical life year (which could be interpreted as the value of a year of life free of injury, disease and disability) by a factor that accounts for the type of injury, disease or disability using the Australian Institute of Health and Welfare published disability weights for diseases and injuries to adjust the VSLY (Mathers et al 1999, pp. 186-202).

REFERENCES

ABCB (2014) Resilience of Buildings to Extreme Weather Events : Final Paper, Australian Building Codes Board discussion paper, (http://www.abcb.gov.au/work-program/Natural%20 Disaster%20Mitigation.aspx).

Abelson P (2008) Establishing a Monetary Value for Lives Saved: Issues and Controversies, *Working papers in cost-benefit analysis: WP 2008-02*, Office of Best Practice Regulation, Department of Finance and Deregulation.

AIR Worldwide (2013) Study of Impact and the Insurance and Economic Cost of a Major Earthquake in British Columbia and Ontario/Québec. Commissioned by the Insurance Bureau of Canada

Bureau of Infrastructure, Transport and Regional Economics [BITRE] (2009) *Road crash costs in Australia 2006*, Report 118, Canberra, November.

Blomquist G (2004), Self-Protection and Averting Behaviour, Values of Statistical Lives, and Benefit-Cost Analysis of Environmental Policy, *Review of Economics of the Household*, Vol. 2, pp. 89-110.

Cho S, Gordon P, Moore J, Richardson HW, Shinozuka M and Chang SE (1999) Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Earthquake, Volume II of a Final Report to the National Science Foundation, Award CMS 9633386 (EHM), School of Policy, Planning, & Department of Civil & Development

Environmental Engineering; Ralph and Goldy Lewis Hall, 330, MC-0626 Kaprielian Hall, 210, MC-2531; University of Southern California.

Cropper M, Hammitt JK, and Robinson LA (2011) Valuing Mortality Risk Reductions: Progress and Challenges, *Discussion Paper RFF DP 11-10*, 1616 P St. NW Washington, DC 20036 202-328-5000 www.rff.org

Crowley H, Colombi M, Crempien J, Erduran E, Lopez M, Liu H, Mayfield M, Milanesi M (2010) GEM1 Seismic Risk Report: Part 1. GEM Technical Report 2010-5. GEM Foundation, Pavia, Italy.

Daniell JE, Schaefer AM, Wenzel F, Kunz-Plapp T (2015) The value of life in earthquakes and other natural disasters: historical costs and the benefits of investing in life safety, *Proceedings of the Tenth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Pacific*, 6-8 November, Sydney, Australia

Daniell J (2014) The development of socio-economic fragility functions for use in worldwide rapid earthquake loss estimation procedures, PhD thesis, Karlsruhe Institute of Technology, Germany

Elwood KJ, Marquis F, Kim JH (2015) Post-Earthquake Assessment and Reparability of RC Buildings : lessons from Canterbury and Emerging Challenges, Paper No. 218 In: Proceedings of 10th Pacific Conference on Earthquake Engineering, Sydney, Australia

Erdik M, S¸es¸etyan K, Demirciog˘lu MB, Zu¨lfikar C , Hancılar U, Tu¨zu¨n C and Harmandar E (2014) Rapid Earthquake Loss Assessment After Damaging Earthquakes, in A. Ansal (ed.), Perspectives on European Earthquake Engineering and Seismology, Geotechnical, Geological and Earthquake Engineering 34, DOI 10.1007/978-3-319-07118-3_2

FEMA (2003) HAZUS-MH Technical Manual. Federal Emergency Management Agency, Washington, DC

Ferreira MA, Oliveira, CS, and Mota de Sá, F (2010) Estimating Human Losses in Earthquake Models: A Discussion. In Spence R, So E and Scawthorn C (ed.) *Human Casualties in Earthquakes: Progress in Modelling and Mitigation*. Springer Dordrecht Heidelberg London New York. ISBN 978-90-481-9454-4. e-ISBN 978-90-481-9455-1. DOI 10.1007/978-90-481-9455-1 GA (2005). Robinson, D., Fulford, G. and Dhu, T. EQRM: Geoscience Australia's Earthquake Risk Model Technical Manual, Geoscience Australia.

Guha-Sapir D, Vos F (2011) Earthquakes, an Epidemiological Perspective on Patterns and Trends. In Spence R, So E and Scawthorn C (ed.) *Human Casualties in Earthquakes: Progress in Modelling and Mitigation*. Springer Dordrecht Heidelberg London New York. ISBN 978-90-481-9454-4. e-ISBN 978-90-481-9455-1. DOI 10.1007/978-90-481-9455-1

Jain VK, Guin, J (2009) ' Modeling Business Interruption Losses for Insurance Portfolios', 11th Americas Conference on Wind engineering, San Juan, Puerto Rico June 22-26.

Jaiswal KS, Wald DJ, Hearne M (2009) Estimating casualties for large earthquakes worldwide using an empirical approach: U.S. Geological Survey Open-File Report OF 2009–1136. Retrieved from http://pubs.usgs.gOv/of/2009/l136/pdf/OF09-l136.pdf

Jaiswal K, Wald D (2010) An empirical model for global earthquake fatality estimation. *Earthquake Spectra* 26(4):1017–1037

Jaiswal KS, Wald DJ (2013) Estimating economic losses from earthquakes using an empirical approach. *Earthquake Spectra* 29(1):309–324

Kircher CA, Whitman RV, Holmes WT (2006) HAZUS earthquake loss estimation methods. *Nat Hazards Rev* 7(2):45–59

Krupnick A, Alberini A, Cropper M, Simon N, O'Brien B, Goeree R, and Heintzelman M (2000) *Age, Health and Willingness of Pay for Mortality Risk Reduction: A Contingent Valuation of Ontario Residents*, Discussion Paper 0-0-37, Resources for the Future, Washington DC.

Mathers, C., Vos, T., and C. Stevenson, 1999*, The Burden of Disease and Injury in Australia, Australian Institute of Health and Welfare*, AIHW Cat. No. PHE 17, Canberra.

OECD (2012) *Mortality Risk Valuation in Environment, Health and Transport Policies*, OECD Publishing. *http://dx.doi.org/10.1787/9789264130807-en*

Office of the Best Practice Regulation (2014) *Best Practice Regulation Guidance Note Value of statistical life*, Department of Prime Minister and Cabinet, Australian Government.

Opus (2005) Earthquake Risk Assessment Study, Part 1 Review of Risk Assessment Methodologies and Development if a Draft Risk Assessment Methodology for Christchurch, Report U04/108. Opus Consulting, Wellington, New Zealand

Pan Q, Gordon, P, Richardson H & Moore J (2015) Development and Implementation of Regional Planning Model: Use Southern California Planning Model (SCPM) as an Example, CUPUM 376-Paper

Porter K, Jones L, Cox D, Goltz J, Hudnut K, Dennis M, Perry S et al (2010) The ShakeOut Scenario: A Hypothetical Mw7.8 Earthquake on the Southern San Andreas Fault. Earthquake Spectra 27(2): 239–261

Porter K, Jaiswal K, Wald D, Earle P, Hearne M (2008a) Fatality models for the U.S. Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) system. In: Proceedings of 14th world conference on earthquake engineering, Beijing, China, 8 pp

Porter KA, Jaiswal KS, Wald DJ, Green M, Comartin C (2008b) WHE-PAGER project: a new initiative in estimating global building inventory and its seismic vulnerability. In: Proceedings of 14th world conference on earthquake engineering, Beijing, China, 8 pp

Risk Frontiers – Bushfire and Natural Hazards CRC (2016) Literature Review of EQ Modelling.

Robinson D, Fulford G, Dhu T (2005) *EQRM: Geoscience Australia's Earthquake Risk Model. Technical Manual Version 3.0.* Geoscience Australia Record *2005/01*

Rose A, Wei D, and Wein, A (2011) Economic Impacts of the ShakeOut Scenario, *Earthquake Spectra* 27 (2), 539-557

Rose, A. (2009) A framework for analyzing and estimating the total economic impacts of a terrorist attack and natural disaster, *Journal of Homeland Security and Emergency Management* 6, Article 6.

Rose A (2007) Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions', *Environmental Hazards* 7, 383–398.

Silva V, Crowley H, Pagani M, Monelli D, Pinho R (2014) Development of the OpenQuake engine, the Global Earthquake Model's open-source software for seismic risk assessment. *Natural Hazards,* 72:1409–1427

United States Environmental Protection Agency [USEPA] (2000) *Guidelines for Preparing Economic Analyses*, USEPA, Washington D.C.

Viscusi WK and Aldy JE (2003) The value of a statistical life: a critical review of market estimates throughout the world, *Journal of Risk and Uncertainty, 27*, 5-76.

Whitman RV, Anagnos T, Kircher CA, Lagorio HJ, Lawson RS, Schneider P (1997) Development of a national earthquake loss estimation methodology. *Earthquake Spectra* 13(4):643–661

World Health Organization, Regional Office for Europe (2014) Health Economics Assessment Tool (HEAT). Available at http://heatwalkingcycling.org/index.php

[i] HAZUS-MH (FEMA and NIBS 2003) is developed by the United States Federal Emergency Management Agency (FEMA) for the prediction and mitigation of losses due to earthquakes (HAZUS), hurricanes and floods (Whitman et al. 1997; Kircher et al. 2006). The package is intended for U.S. applications only and includes federally collected data as default. The inventory is classed based on 36 different types of building based on construction standards and material as well as size and building use. HAZUS-MH MR2 version, released in 2006, includes the capability for rapid postevent loss assessment.