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COST-EFFECTIVE MITIGATION STRATEGY DEVELOPMENT FOR BUILDING RELATED EARTHQUAKE RISK

Melbourne case study

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Australian Government
Geoscience Australia

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Version	Release history	Date
1.0	Initial release of document	27/09/2021

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Publisher:
Bushfire and Natural Hazards CRC

September 2021

Citation: Ryu H, Wehner M, Vaculik J, Juskevics J, Edwards M, Griffith M, Mohanty I, Butt S, Corby N, Allen T & Hewison R (2021) Cost-effective mitigation strategy development for building related earthquake risk – Melbourne case study, Bushfire and Natural Hazards CRC, Melbourne.

Cover: A Melbourne streetscape showing a variety of building types.

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ACKNOWLEDGEMENTS

The contributions from Dr Abbie Rogers and Mr Curtis Rollins of the University of Western Australia is acknowledged for their provision of research outcomes from the Bushfire and Natural Hazards CRC project, *Economics of natural hazards*. In particular, the assessed household willingness to pay to preserve heritage buildings in a community was utilised to provide an added dimension of avoided community impact through earthquake mitigation implementation.

EXECUTIVE SUMMARY

Earthquake hazard was not fully recognised in Australian building design until the mid-1990's. This oversight has resulted in a legacy of vulnerable buildings that can be readily damaged in moderate to severe Australian earthquakes. In particular, older unreinforced masonry (URM) buildings built with the architectural styles, materials and construction details used in the United Kingdom are particularly vulnerable. Australian earthquakes have highlighted the vulnerability of this building type. These events include the Adelaide Earthquake of 1954, the Meckering Earthquake of 1968, the Newcastle Earthquake of 1989 and the Kalgoorlie Earthquake of 2010, all of which damaged pre WWII masonry buildings in particular. Buildings of this style are present in the older centres of our major cities, and Melbourne has a very significant number of these. As shown in this research, in number nearly half of the buildings in the Melbourne central business district are of this type of construction. The damage to these buildings can greatly add to human casualties as a result of falling masonry elements. Further, the severity of damage and losses can impede the recovery of cities like Melbourne physically, economically and socially. Finally, many of these buildings have heritage value to communities that residents may want preserved.

This document reports on the final deliverable for Project A9 *Cost-effective mitigation strategy development for building related earthquake risk* of the Bushfire and Natural Hazards Collaborative Research Centre (CRC). It builds on the masonry component research of the University of Adelaide in this project and is a milestone for Geoscience Australia. The work follows the utilisation project entitled "Earthquake Mitigation of WA Regional Towns: York Case Study", that was jointly delivered by GA and the University of Adelaide. The utilisation project developed original condition and mitigated vulnerability models for six URM building types. In this project, these outcomes have been applied to the much larger Melbourne CBD exposure.

The project had the following key components:

- Develop a building, business and demographic exposure database with the collected attributes tailored for modelling earthquake impact and the quantification of avoided consequences in economic terms.
- Attribute vulnerability models to the URM buildings in their present condition and with retrofit to a proportion after a thirty year program representing a future vulnerability condition.
- Simulate the damaging effects of a major earthquake on the present Melbourne CBD and at the end point of the retrofit program.
- Assess the change on scenario damage, casualties and economic losses as a result of the program.
- Assess the value of the program in terms of household willingness to pay to avoid losing heritage value buildings, drawing on UWA led research in the CRC.
- Assess the long term earthquake risk in the CBD precinct before and after the program of retrofit.

The work required the development of the three fundamental risk elements of earthquake hazard, community exposure and building vulnerability. It also entailed the assessment of the economic loss measures associated with human

injury, contents losses, rental income, commercial property leasing, and business activity. Additionally, it included the application of the semi-intangible value placed on human life to society. Each of these are described below.

Earthquake hazard

This study has drawn upon the latest understanding of the Melbourne region earthquake hazard by utilising the recently released National Seismic Hazard Assessment (NSHA 2018) (Allen et al, 2018a). The bedrock hazard from this assessment shows Melbourne to have a "low" earthquake hazard by global standards but significant by Australian standards. The hazard is further amplified by the presence of the sediments deposited by the Yarra River. These soil effects increase the hazard, particularly those in the study region south of the Yarra River. The effects of soil amplification can double the severity of shaking in some areas.

Community exposure

The definition of the building assets in the study region utilised several sources. The available state government building data integrated into the *National Exposure Information System* (NEXIS) was accessed and supplemented by an engineering survey database developed and maintained by GA for the Australian Reinsurance Pool Corporation. This was further refined by a desktop review of all masonry buildings utilising available street level imagery. In total there were 1,543 buildings in the study region, and 687 of these were identified as URM.

The assessment of human activity was achieved by utilising research undertaken outside of this project. This research utilised a population model developed by downscaling a destination zone based telecommunication model with pedestrian counts, the Melbourne traffic control systems movement counts, and building floor area information. Using this work it was possible to define the local human exposure at the time of the scenario event, particularly those in damaged buildings and those potentially exposed to falling masonry during a rapid onset earthquake event.

Building vulnerability

The building vulnerability assessment work for the URM building stock was a direct utilisation of the six vulnerability types identified in the earlier York WA mitigation study. This included the vulnerability in present condition, and that with mitigation measures applied to the vulnerable elements. To complete the context, the vulnerability of other building types was attributed using a suite of models developed through an adaptation of US HAZUS models, reference to heuristically developed models from a GA facilitated UN workshop (Maqsood *et al*, 2014), and through heuristic adjustments by the project team. This vulnerability of non-URM buildings remained a constant in the study as mitigation of these buildings was not considered.

Economics of cost assessment

The economic assessment considered a broad range of measures. These ranged from the direct costs to property owner, building occupiers, and businesses through to health care costs and the partially intangible value placed on the loss of a human life. The aim was to provide scalable information on benefits versus cost to a range of decision makers and investors. Importantly, the measures where not comprehensive and so represent a lower bound to the actual avoided impacts mitigation achieves. For example, the cost of emergency response, clean-up and community recovery support were not considered. Neither was a macro-economic perspective developed to capture non-impacted businesses that would benefit from a stimulus in business activity such as in the construction industry, the supply of home appliances, soft furnishings and drapery. Significantly, the value of avoided heritage building loss was considered through the utilisation of metrics developed by a UWA led CRC project.

Scenario impacts and risk

The study considered a single rare earthquake scenario having an annual likelihood of 1/5,000 of causing the targeted bedrock shaking severity beneath the Melbourne CBD, or greater. This likelihoods corresponds with a 1%, chance of this shaking severity being exceeded in the next 50 years. For the event the injuries and other losses within the scope of this study were assessed using the human exposure corresponding with 11:00am of Monday through to Thursday. The losses ranged from $737m for building damage only, through to $1.66b for the other monetary costs considered. The value of human life lost increased this to $3.97b. Where 25% of the masonry building stock was retrofitted, over 30 years, these losses reduced by approximately 16%.

The reduction in injuries if this event occurred in 30 years time was also evaluated. Serious injuries reduced by 16 and deaths by 98 persons. Urban Search and Rescue logistics would also reduce correspondingly.

In a similar manner, the long term financial risk of the Melbourne CBD study region was evaluated for building damage. It was presented as the average annualised loss for the URM building stock and for the entire study region buildings. It was also forecast 30 years into the future and the financial risk reduced by 38% for the URM building stock and by 10% across the entire study region buildings.

Discussion and outcomes

Earthquakes occur frequently in Australia with over 100 events greater than magnitude 3.0 (M_L) recorded within the Australian continent every year by Geoscience Australia. The smaller and more frequent events are typically non-damaging, whereas the less frequent larger events can be very damaging when they occur close to a community. This plays out in the economics of strengthening older structures where the benefits of avoided building damage and contents losses through retrofit for earthquake are not a full offset for the significant costs. Other avoided costs associated with business losses, lost wages, health care costs, and the value placed on human life, do increase the sum significantly but are not realised by the property owner. While not all avoided costs were considered, this project indicates that the justification for retrofit based solely on a financial investment may be difficult to demonstrate for URM buildings in Melbourne.

As was also illustrated by the earlier York study, there are other considerations for the retrofit of URM buildings in the Melbourne CBD and in other older business districts in the city. If a rare earthquake occurred locally during a period of high public exposure there would be considerable loss of life. This research has shown that if a 5,000 year Return Period (RP) event (5.5 M_w) occurring on a business day approximately 100 people would die with close parallels to the 2011 Christchurch Earthquake outcome for masonry structures (42 fatalities). This may point to cheaper levels of retrofit with the objective of tying back elements that could cause casualties, rather than having the aim of avoiding economic loss.

Further, following a rare, but credible, earthquake high value heritage buildings would be lost. The research has shown that the willingness to pay by just the residents of the City of Melbourne LGA adds a notional 10% of the total benefits of the mitigation program.

SUMMARY

The project has applied a range of retrofit measures for a suite of six URM building types developed as part of Project A9 to a very large population of URM building found in the Melbourne CBD. These measures have been demonstrated to reduce the physical vulnerability of each building. The project has also translated this vulnerability change into broader metrics that form an evidence base to inform decisions to retrofit.

The project has also demonstrated the benefit of retrofit through a virtual retrofit of a major city CBD. These benefits include reduced post event logistics for emergency management and the local government, reducing financial losses to building owners, businesses, and reducing injuries and fatalities. It has also demonstrated that retrofit reduces the long term financial cost of earthquake hazard, thereby making risk transfer through insurance uptake more affordable. Finally, it has demonstrated how valuable heritage structures can be progressively preserved for the future by protecting them from future credible earthquakes.

ABBREVIATIONS

AAL	Average Annualised Loss
ABS	Australian Bureau of Statistics
ACECQA	Australian Children's Education & Care Quality Authority
AEP	Annual Exceedance Probability
ANZSIC	Australia New Zealand Standard Industrial Classifications
AR-DRG	Australian Refined Diagnosis Related Group
ASSCM	Australian Seismic Site Conditions Map
CRC	Bushfire and Natural Hazards Collaborative Research Centre
CLUE	Census of Land Use and Employment
CBD	Central Business District
DNZ	Destination Zones
ED	Emergency Department
EM	Emergency Management
GMM	Greater Metropolitan Melbourne
HILDA	Household Income and Labour Dynamics in Australia
IHPA	Independent Hospital Pricing Authority
LGA	Local Government Area
NEP	National Efficiency Price
NHCDC	National Hospital Cost Data Collection
NSHA18	National Seismic Hazard Assessment 2018
PGA	Peak Ground Acceleration
POW	Place of Work
PSHA	Probabilistic Seismic Hazard Assessment
SAx	Statistical Area x Geography of ABS
SCATS	Sydney Coordinated Adaptive Traffic System
SCR	Stable Continental Regions
URG	Urgency Related Groups
URM	Unreinforced Masonry construction
UW	University of Western Australia
VLW	Value of Lost Welfare
VSL	Value of Statistical Life
WA	Western Australia

SYMBOLS

S_A	Spectral acceleration
M_W	Moment magnitude
R	Focal distance [km]
V_{S30}	Shear wave velocity of top 30m of surface geology [m/s]

GLOSSARY

ARI	The Average Recurrence Interval (ARI) for earthquake hazard is the expected average time between a level of ground shaking occurring or being exceeded. This is alternatively referred to as the return period of exceedance. For example, a 1,000yr ARI hazard for a location would on average be reached or exceeded once every 1,000yrs.
AEP	The Annual Exceedance Probability (AEP) for earthquake hazard is a term used to describe how likely a given local severity of shaking will occur or be exceeded in a given year. It is equal to the inverse or mathematical reciprocal of the ARI. For example, a 0.2% AEP bedrock acceleration is a level of shaking that has a 0.2% chance of occurring, or being exceeded, in any one year. It has an ARI of 500yrs.
MMI	The Modified Mercalli Intensity scale (MMI) is a scale to measure the intensity of earthquakes and was originally developed by Giuseppe Mercalli's in 1902. It is an assessment of the shaking severity experienced and is based on the local effects of the earthquake on people, property and the ground. Roman numerals are used to rate the intensity and associated damage as it is not an instrument based measure. It differs from the Richter scale which measures the size of the earthquake at its source and is instrument based.

INTRODUCTION

Earthquake hazard was only fully recognised for Australian building design in the early 1990's following the Newcastle Earthquake of 1989. This has resulted in a significant legacy of Australian buildings that are inherently more vulnerable to earthquake generated ground motion. Having accessible knowledge of the most effective measures to retrofit older masonry buildings will enable and encourage the strengthening of buildings resulting in more resilient communities.

This project entailed undertaking a mitigation implementation study in the Melbourne CBD with its concentration of older URM buildings. Many of these structures have high heritage value to the city and to Australia generally. This research activity concludes the research outcomes of the CRC Project A9 *Cost-effective mitigation strategy development for building related earthquake risk*. It directly draws on the GA led utilisation project "Earthquake Mitigation of WA Regional Towns: York Case Study", that focused on WA oldest inland settlement and for which mitigation measures were developed for six common URM building types. Utilising the outcomes of the project a range of mitigation strategies have been virtually applied to the CBD URM buildings. This has enabled an assessment of the effectiveness of these interventions on community risk and emergency management (EM) logistics in the context of rare, but credible, earthquakes.

In this report the research and its outcomes are presented and discussed. The research comprised the following key steps:-

- Earthquake hazard modelling of a major earthquake.
- Development of a database of buildings, businesses and demographic exposure.
- Assignment of vulnerability to URM buildings and to other building construction types so as to provide a complete context to scenario impacts. This work entailed some heuristic work to address the paucity of vulnerability knowledge for the latter.
- Simulation of scenario impacts with present Melbourne and after a program of URM retrofit. Impacts considered building damage, injuries, economic impacts and avoided loss of heritage value.

The overall outcomes are reported. Further, recommendations are made for future retrofit strategy implementation in Australian communities that have similar building stock.

SEISMIC HAZARD

Damaging earthquakes in Australia and other regions characterised by low seismicity are considered low probability but high consequence events. Assessing seismic hazard in stable continental regions (SCRs) brings unique challenges to hazard modellers and practitioners in terms of the characterisation of seismic sources and their ground motions (Leonard *et al.*, 2014; Allen, 2020). By their very nature, SCRs experience lower earthquake rates compared to tectonic plate margins. Consequently, the typical observation period of historical instrument based observations of seismic activity is significantly shorter than the typical seismic cycle of rare large earthquakes that may generate extreme damaging ground motions on any given fault source.

The assessment of seismic hazard requires the consideration of several component models. The two key components are the seismicity rate models and the ground-motion characterisation model (Gerstenberger *et al.*, 2020). The seismicity rate model typically considers both neotectonic geological features (Clark *et al.*, 2016) and the historical earthquake catalogue to develop the frequency of occurrence of earthquakes that may pose a hazard to any given location (Allen *et al.*, 2018b). Specific information on the geology, seismicity and seismic hazard of the Melbourne region is discussed below.

GEOLOGY AND SEISMICITY OF MELBOURNE REGION

The Greater Melbourne region straddles the northern edge of the Port Phillip Basin, which overlies the eastern margin of the Otway Basin (Holdgate *et al.*, 2002). The Selwyn and Rowsley/Lovely Banks faults bound the Port Phillip Basin, and are associated with long-term average uplift rates of approximately 35-55 m/Ma (Clark and Leonard, 2014). Within-basin the faults, such as the Beaumaris, Avalon and perhaps Bellarine faults, are associated with significantly lower uplift rates (≤10 m/Ma). These faults that are identified proximal to the greater urban region are estimated to have lower slip rates and fault density than the neighbouring Otway and Gippsland basins (Figure 1).

The city is bounded by relatively high-slip-rate, fault-dense regions: the Otway and Strzelecki Ranges (Figure 1), respectively. While further afield, these fault sources are still within 100 km of the Melbourne CBD and contribute moderately to the ground-shaking hazard, even at higher exceedance probabilities (Allen *et al.*, 2020).

The fault sources identified in Figure 1 have the potential of hosting large, surface deforming earthquakes at low exceedance probabilities. However, the regional area also possesses some of the highest rates of seismicity in the Australian historical record. The high seismicity rates are mostly associated with the topographic highs of the Strzelecki Ranges and Eastern Highlands (Figure 2), with some of Victoria's largest earthquakes also occurring offshore in Bass Strait (e.g., Gibson *et al.*, 1981; McCue, 2015). One of the most notable earthquakes in recent times was the 19 June 2012 M_W 5.1 Moe earthquake. The earthquake occurred in the Strzelecki Ranges, approximately 130 km southeast of the Melbourne CBD. Over 15,000 felt reports were received following the main shock (Hoult *et al.*, 2021), and its ground motions caused minor damage and tripped a number of coal-fired power generators in the Latrobe Valley amounting to the loss of approximately 1955 megawatts of generation capacity (Australian Energy Market Operator, 2013).

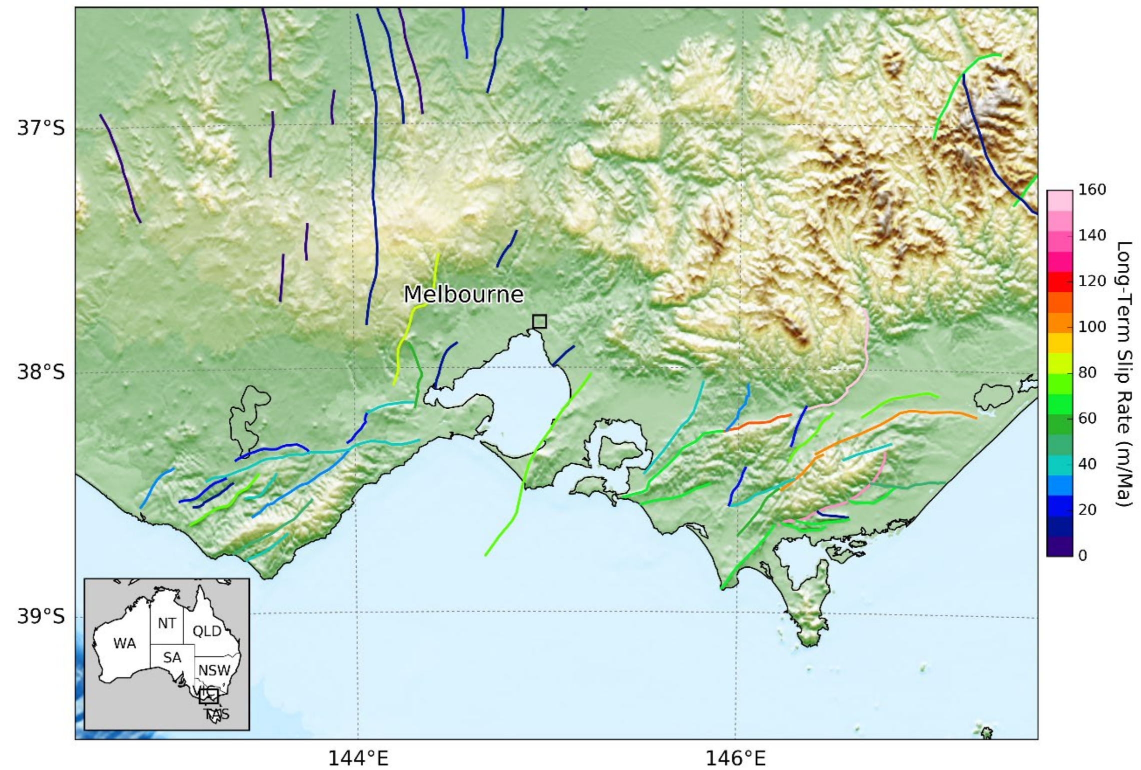

FIGURE 1: THE DISTRIBUTION OF KNOWN NEOTECTONIC FEATURES IN THE MELBOURNE REGION (CLARK *ET AL.*, 2016). KNOWN FAULTS ARE COLOUR-CODED BY THEIR ESTIMATES SLIP RATES IN METRES PER MILLION YEARS (m/Ma).

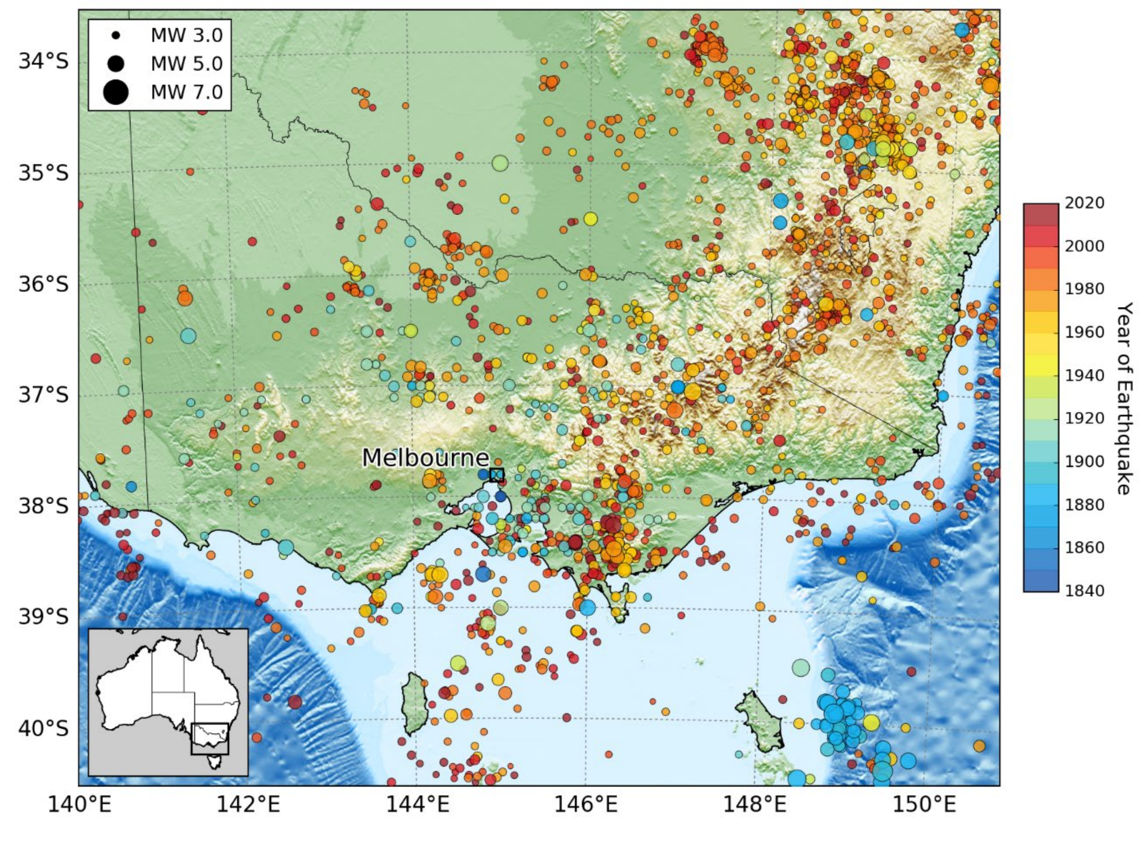

FIGURE 2: MAP OF EARTHQUAKE EPICENTERS ACROSS THE STATE OF VICTORIA IN THE 2018 NATIONAL SEISMIC HAZARD ASSESSMENT CATALOGUE (NSHA18-CAT; ALLEN *ET AL.*, 2018B). EPICENTERS ARE SIZED BY MOMENT MAGNITUDE AND COLOR-CODED BY THE YEAR OF THE EARTHQUAKE.

GROUND-MOTION CHARCTERISATION

Ground-motion models are used to estimate the shaking at a site located a given distance from an earthquake of a given magnitude on a reference site class. The intensity of the ground-shaking, in general, decreases with increasing distance from the fault rupture. The aleatory variability within, and epistemic uncertainty between ground-motion attenuation models (e.g., Toro *et al.*, 1997) is often considered to contribute some of the largest uncertainties in probabilistic seismic hazard analyses (PSHAs; Bommer and Abrahamson, 2006; Al Atik *et al.*, 2010). This is particularly true of SCRs such as Australia with few near-source data recorded from moderate-to-large earthquakes. Nevertheless, ground-motion models (GMMs) form an essential component to modern PSHAs.

The number of GMMs available for use in PSHAs continues to grow rapidly (e.g., Douglas, 2018; Goulet *et al.*, 2018) and choosing appropriate models for any given tectonic region type is a challenging task in the absence of abundant ground-motion data from moderate-to-large earthquakes (e.g., Beauval *et al.*, 2012). Ground motion models for use in the NSHA18 for the *non-cratonic* tectonic domains of Australia (including all of eastern Australia) were selected through the formal expert elicitation process (Griffin *et al.*, 2018). The weights for the final NSHA18 GMM logic tree for *non-cratonic* regions is provided in Table 1.

TABLE 1: LIST OF GMMS USED FOR NON-CRATONIC REGIONS IN THE NSHA18 TOGETHER WITH THEIR ASSIGNED WEIGHTS, MODIFIED FROM THE EXPERT ELICITATION WORKSHOP (GRIFFIN *ET AL.*, 2018).

Reference	GMM **Weight**
Allen (2012)	0.208
Atkinson and Boore (2006)	0.138
Boore *et al.* (2014)	0.166
Chiou and Youngs (2008) modified by Edwards *et al.* (2016)	0.153
Chiou and Youngs (2014)	0.130
Somerville *et al.* (2009; non-cratonic)	0.205

SEISMIC HAZARD OF THE MELBOURNE REGION

In 2018, Geoscience Australia, together with contributions from the wider Australian seismology community, released a revised National Seismic Hazard Assessment (NSHA18; Allen *et al.*, 2018a). Relative to the seismic hazard map included in the AS1170.4–2007 (R2018), the NSHA18 leverages advances in earthquake-hazard science in Australia and analogue tectonic regions over the last three decades to offer many improvements over its predecessors as summarised in Allen et al. (2020). The NSHA18 allows the calculation of hazard curves for any locality across continental Australia. A hazard curve expresses the probability of exceeding a given ground-motion intensity for some observation period *t* (e.g., 10% in 50 years). The annual exceedance probabilities can subsequently be determined following Poisson's Law. Under this assumption, the probability of no (zero) exceedances over some period of time is e^{-n}. For a probability of exceedance of 10% in 50 years, for example, the probability of zero exceedances is:

$$P(0) = 1 - 0.1 = 0.9 = e^{-n} \quad (1)$$

Taking the natural logarithm of this equation, we find the number of exceedances n in our observation period is:

$$n = -\ln P(0) = 0.1054 \quad (2)$$

The annualised exceedance rate r can then be calculated following:

$$r = n / t = 0.1054 / 50 = 0.002107 \text{ (per year)} \quad (3)$$

The average return period T_R is then calculated as the inverse of the annualised exceedance rate r:

$$T_R = 1 / r = 1 / 0.002107 = 474.6 \text{ (years)} \quad (4)$$

Based on the NSHA18 source and ground-motion characterisation, a peak ground acceleration hazard curve for the Melbourne CBD is provided in Figure 3.

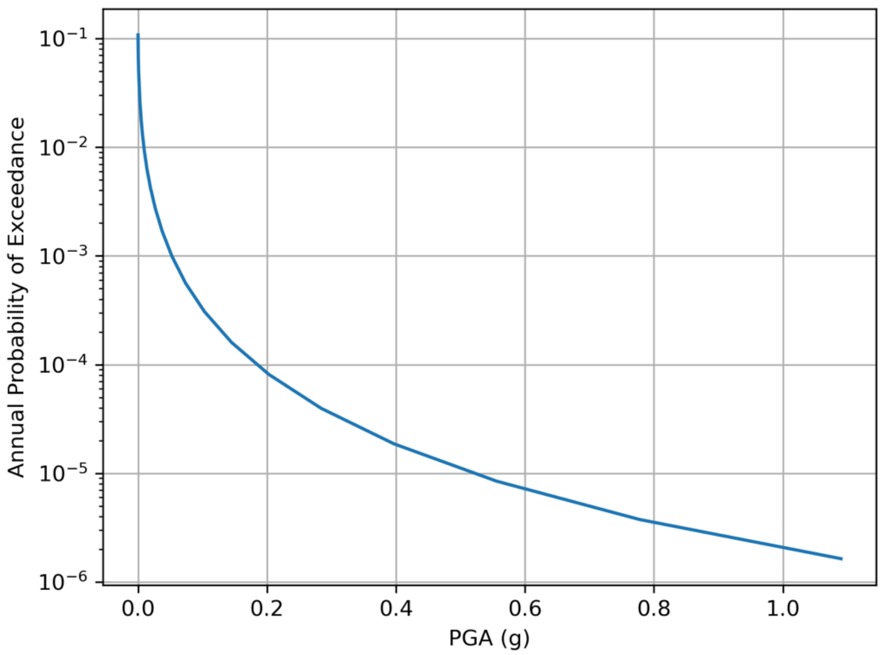

FIGURE 3: THE ANNUAL PROBABILITY OF EXCEEDING A GIVEN PGA LEVEL (IN G) FOR MELBOURNE CBD.

The deaggregation (or disaggregation) of seismic hazard identifies the percentage contribution of earthquake sources to seismic hazard at any given location (McGuire, 1995; Bazzurro and Cornell, 1999). The deaggregation procedure takes a seismic hazard model (i.e., the source rate model and ground-motion characterisation model; e.g., Gerstenberger *et al.*, 2020) and returns the predominant earthquake sources that contribute to the ground-motion hazard at any location. These deaggregations are calculated based on a user-defined ground-motion intensity measure and probability of exceedance. The outputs identify the key hazard contributors, which are provided in terms of magnitude (M_W) and distance (R) for a chosen location. The hazard can be further partitioned in to the components of the parameter, ε – the number of standard deviations that the logarithmic spectral acceleration differs from the mean (McGuire, 1995; Bazzurro and Cornell, 1999). Figure 4 shows a magnitude-distance deaggregation for a spectral acceleration, $S_A(T=0.2\text{ s})$ for a 0.5% in 50-

year exceedance probability (approximately 1/10,000 annual exceedance probability[AEP]). This figure shows, for this oscillation period and AEP, that the Melbourne hazard is dominated by near-source earthquakes of up to M_W 6.5, with smaller contributions to hazard from far-field fault sources with magnitudes exceeding M_W 7.0 (Figure 4).

Spatial deaggregations can also be returned to identify the location of earthquake sources on a 2D longitude-latitude grid (e.g., Harmsen and Frankel, 2001)(Figure 5). These deaggregations can be useful to identify the location of any earthquake source (e.g., active faults) that dominates seismic hazard for any given location. For the SA(*T*=0.2 s) for a 0.5% in 50-year exceedance probability, similar to Figure 4, it can be seen that the dominant hazard sources occur close to the Melbourne CBD, with smaller hazard contributions from fault sources in the Otway and Strzelecki Ranges (Figure 5).

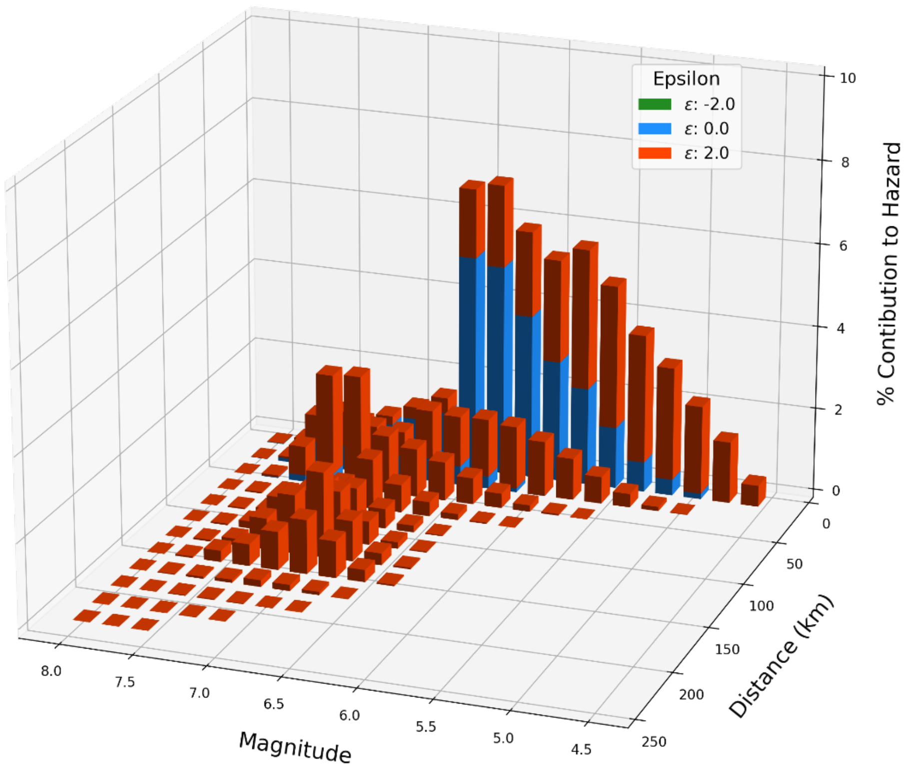

FIGURE 4: 3D MAGNITUDE-DISTANCE-EPSILON DEAGGREGATION FOR THE CITY OF MELBOURNE EXCEEDING S_A = 0.2 s AT THE 0.5% IN 50-YEAR EXCEEDANCE (APPROXIMATELY 1/10,000 ANNUAL EXCEEDANCE PROBABILITY).

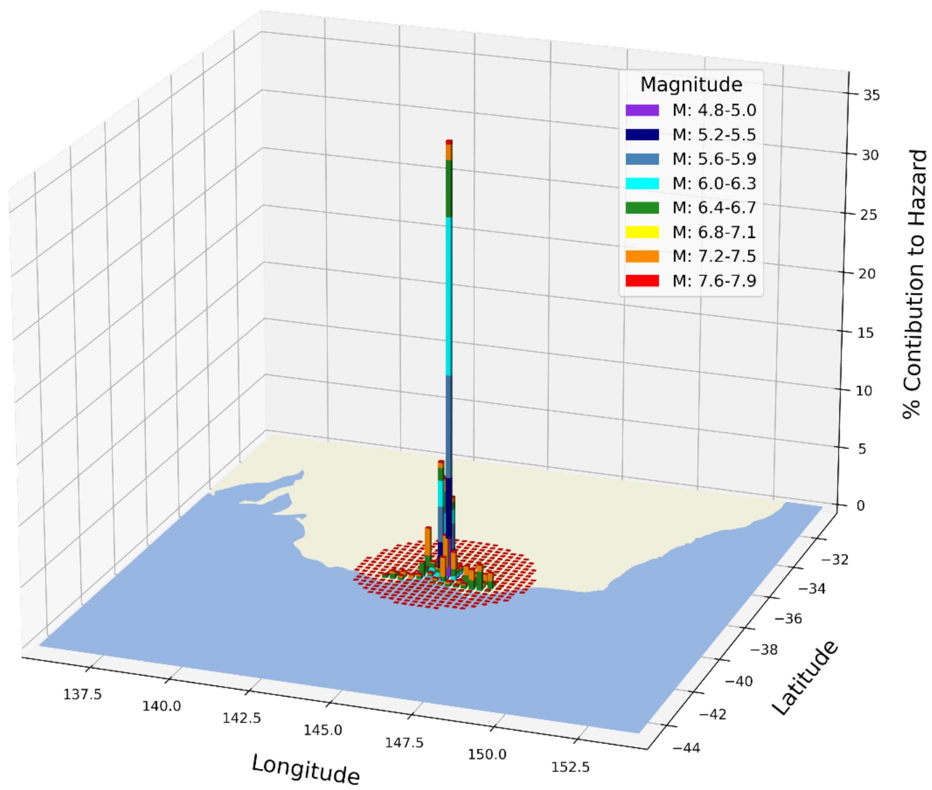

FIGURE 5: MAGNITUDE-LONGITUDE-LATITUDE DEAGGREGATION FOR THE CITY OF MELBOURNE PERFORMED FOR S_A = 0.2 s FOR 0.5% IN 50 YEAR PROBABILITY OF EXCEEDANCE.

SEISMIC SITE CONDITIONS

It is recognised that near-surface sediments (sands, silts, gravels and weathered rock) can amplify ground-shaking at the surface (e.g., Borcherdt, 1970). The Australian Seismic Site Conditions Map (ASSCM; McPherson, 2017) provides an estimate of site conditions corresponding to the modified National Earthquake Hazard Reduction Program (NEHRP) site classification (e.g., Wills *et al.*, 2000) using surficial geology together with weathering indices (Wilford, 2012). These site classes are mapped to a representative time-averaged shear-wave velocity in the upper 30 m of the foundation (V_{S30}) value, which can then be used to determine amplification factors for any ground-motion intensity measure.

The extent of the scenario earthquakes (discussed below) are extracted from the ASSCM do determine site-specific amplification factors. The weighted ground-motions assuming site-specific V_{S30} were determined using the GMMs set out in Table 1.

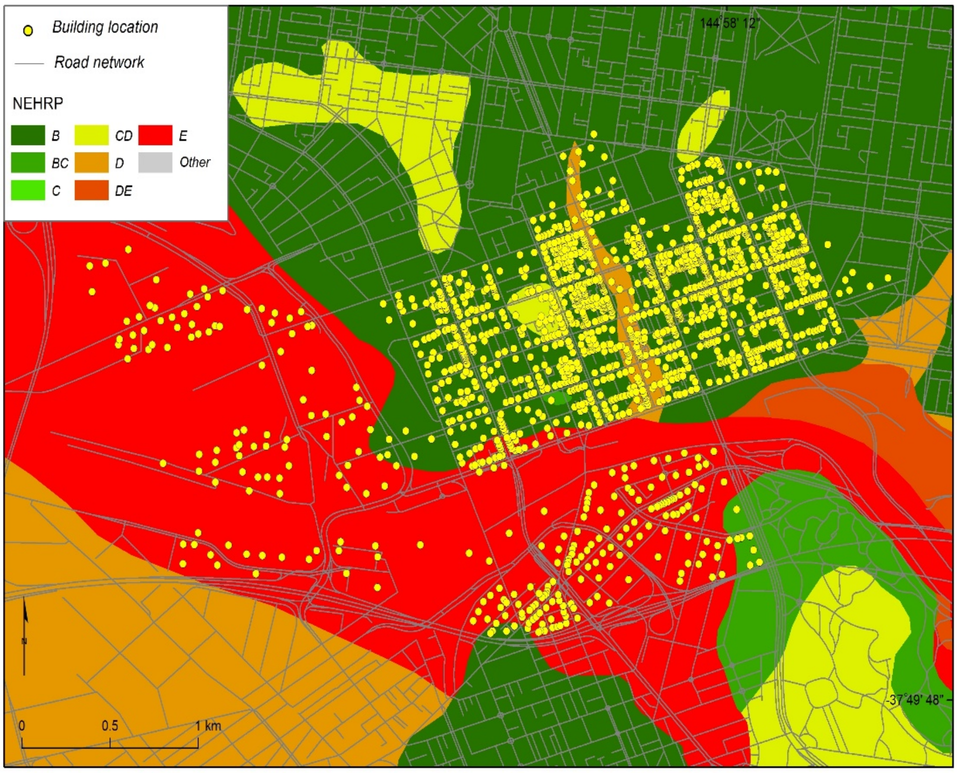

FIGURE 6: AN EXTRACT FROM THE ASSCM FOR THE STUDY REGION.

SCENARIO EARTHQUAKES

The location of scenario earthquake was chosen based on the disaggregation result. The magnitude of the scenario was determined as such the peak ground acceleration of the simulated mean ground motion at Melbourne CBD matches to the PGA value for 1% probability of exceedance in 50 years based on NSHA18. The parameter values of the scenario event are set out in Table 2.

TABLE 2 PARAMETER VALUES OF THE SCENARIO EVENT.

Magnitude (Mw)	Depth (km)	Epicentre (Long, Lat)	Distance from Melbourne CBD (km)	PGA (g)
5.5	10.0	145.011, -37.705	12.5	0.124

The ground motion fields were simulated using the *OpenQuake* software application (Version 3.10.1; Pagani et al., 2014). A single ground motion field was generated by taking a weighted average of the simulated mean ground motions through adopting the same logic tree of ground motion models used in NSHA18, as set out in Table 1.

The simulated bedrock hazard shown in Figure 7 was found to be very uniform across the study region but greater variability resulted from the incorporation of the surface soil effects is shown in Figure 8.

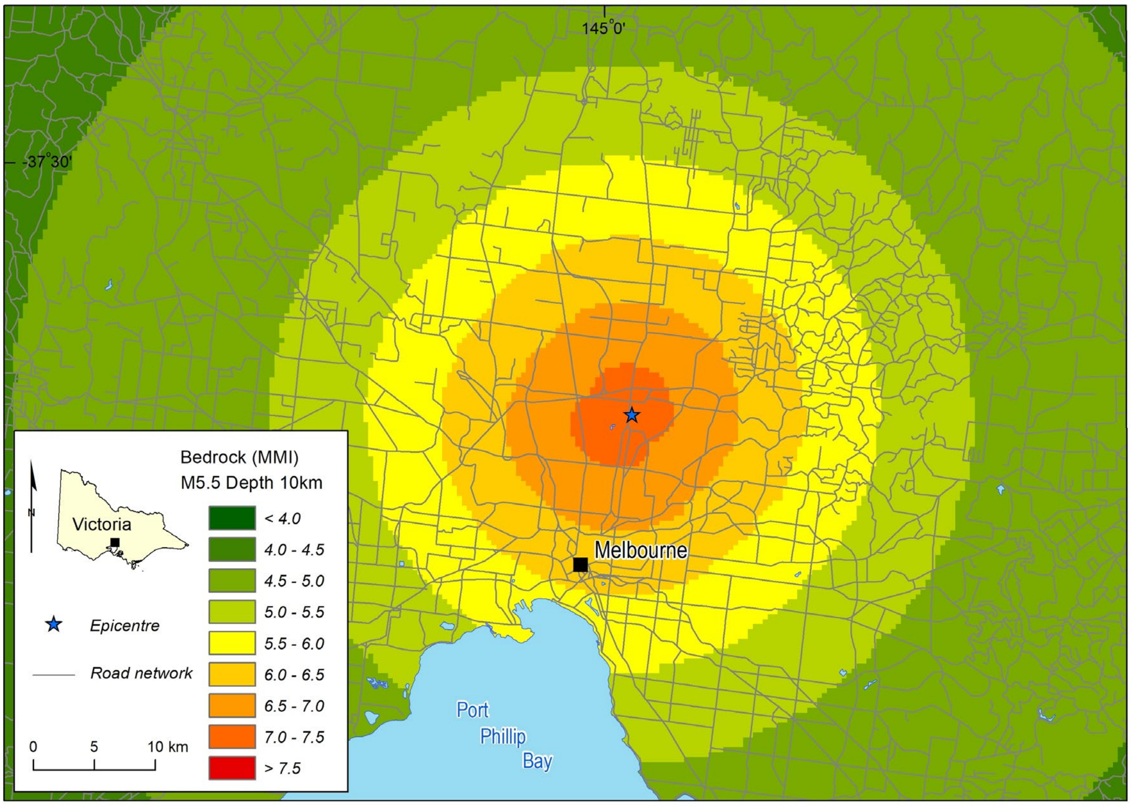

FIGURE 7 SIMULATED GROUND MOTION FIELD AT BEDROCK PRESENTED IN TERMS OF MODIFIED MERCALLI INTENSITY (MMI)

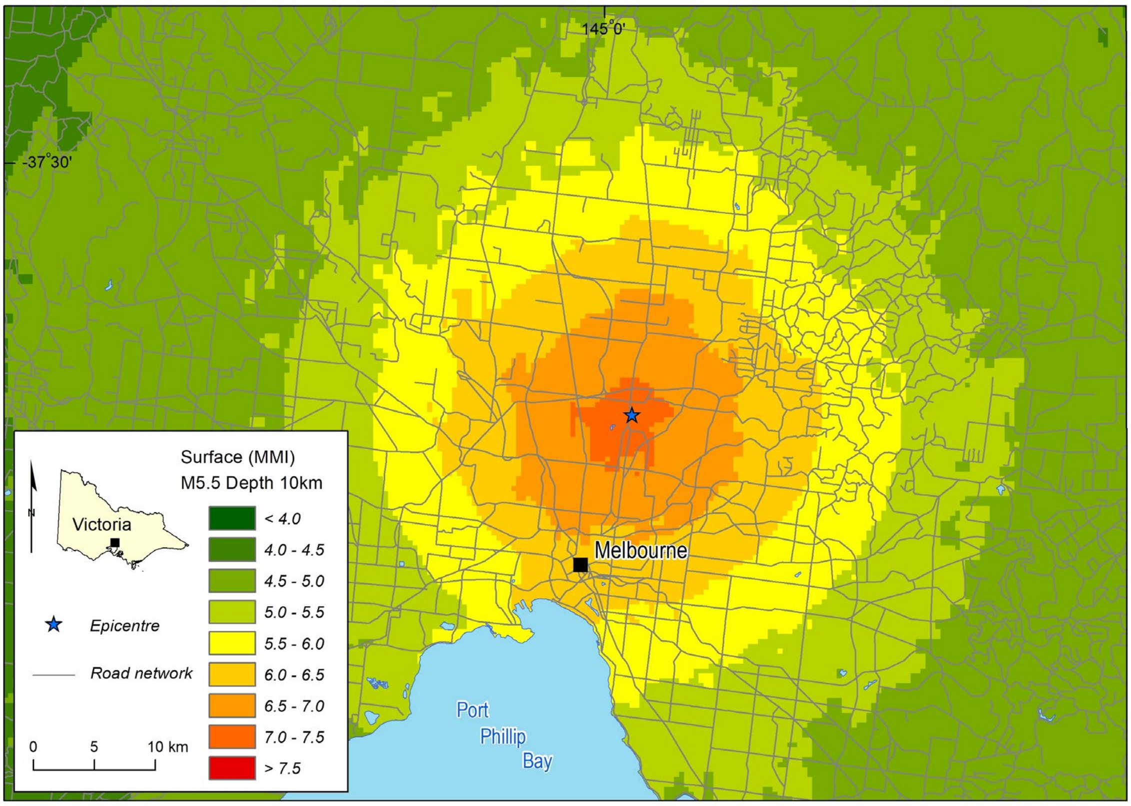

FIGURE 8 SIMULATED GROUND MOTION FIELD AT SURFACE PRESENTED IN TERMS OF MODIFIED MERCALLI INTENSITY (MMI). THE AMPLIFYING EFFECTS OF SOILS BENEATH THE MELBOURNE CBD ARE EVIDENCED.

EXPOSURE

BUILDING EXPOSURE

The assessment of impact and risk requires an exposure database in which each building is listed together with the attributes necessary to establish the building's location, structural type, value, human population (internal and external) and value of contained businesses. The development of the exposure database for the project involved establishing attributes from a range of sources for 1,543 buildings within the study area. The buildings were located within the Melbourne CBD 'rectangle', Southbank and Docklands (see Figure 9). The base information was sourced from a survey of CBD buildings undertaken by Geoscience Australia in 2009 and updated since to extend the surveyed area and capture the demolition of buildings and construction of new buildings.

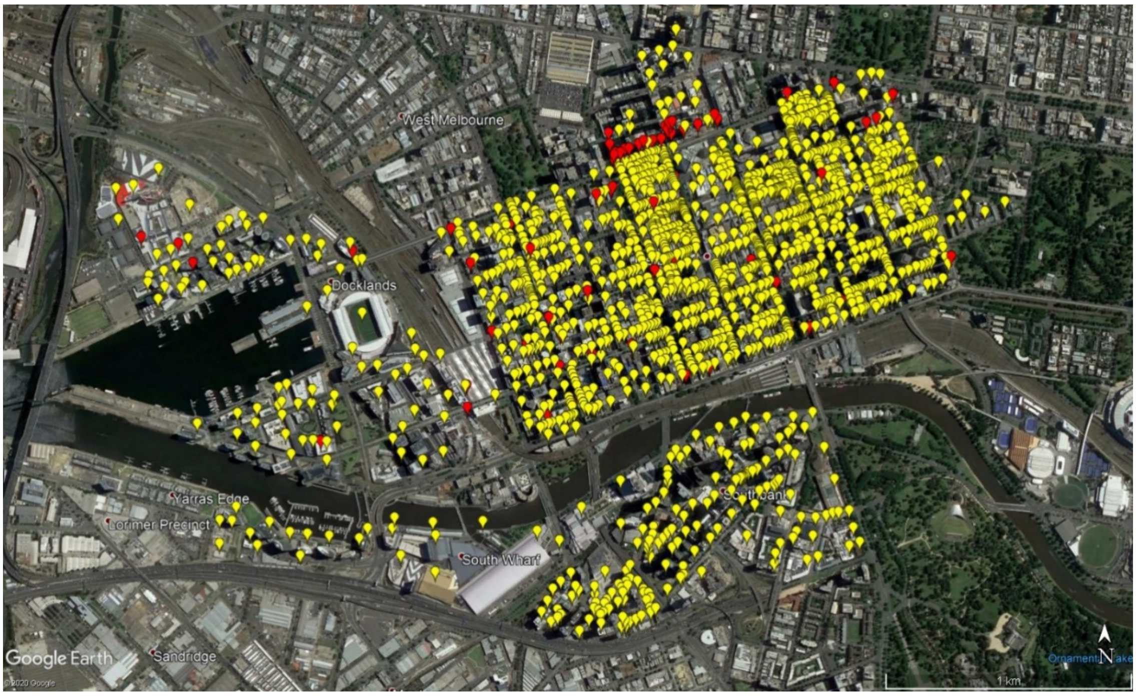

FIGURE 9 STUDY AREA BUILDINGS DENOTED BY PINS. RED DENOTES BUILDINGS ADDED DURING THE MOST RECENT SURVEY UPDATE IN 2020.

The 2009 survey captured more attributes than were required for this study. For example, the building facades were recorded in detail. The extra attributes were retained in the database although not used and not described in this report. The required attributes are listed in Table 3 together with each attribute's source. For this project, which had an emphasis on the damage caused to URM buildings, some additional attributes beyond those required to run the *OpenQuake* software were required to enable the estimation of casualties.

TABLE 3 ATTRIBUTES CAPTURED IN THE PROJECT EXPOSURE DATABASE.

Attribute	Description	Source
UFI	A unique integer identifier for each building	GA 2009 survey
Address	String with street number, street name and street type	GA 2009 survey
Latitude	Latitude of approximate building centroid in decimal degrees	GA 2009 survey
Longitude	Latitude of approximate building centroid in decimal degrees	GA 2009 survey
Storeys	Number of storeys above ground	GA 2009 survey
Vintage	Age of building classed as either "pre1996" or "post 1996" used to assign vulnerability curves	GA 2009 survey with desktop survey augmentation
No Of Buildings	An integer number noting the number of buildings at a single location	GA 2009 survey
GA Building Class	An alphanumeric descriptor of the type of building used for assigning reconstruction rates	Lookup table using surveyed building structure type, façade type, and storeys and returning the GA building class
HAZUS Building Class	An alphanumeric descriptor of the type of building used for assigning vulnerability curves	Lookup table based on GA Building Class
GA URM Class	An alphanumeric descriptor of the sub-type of URM buildings used for assigning vulnerability curves	Desktop survey of all URM buildings in the study area
Is Retrofitted	A label determining if a particular URM building is to be considered as retrofitted in the study	Randomly selected from the list of URM buildings
Site Class	A label denoting the classification of the regolith at the building location	McPherson, 2017
Floor Area	The total floor area contained in a building (m2)	Geoscience Australia's NEXIS database augmented by desktop footprinting from aerial imagery to capture missing data
Value	The building's replacement value in 2020 dollars	Computed from rates contained in GA's NEXIS database, indexed to 2020 and multiplied by Floor Area
Contents Value	The replacement value for the building's contents	Computed from Floor Area multiplied by a mean contents rate sourced from insurance data
SA1	Numerical descriptor	The ID of the Statistical Area 1 that the building falls within
SA2	Numerical descriptor	The ID of the Statistical Area 2 that the building falls within
Front_Cat_THUB	The length of building perimeter (m) fronting a footpath classified as a transport hub (URM building only)	A GIS intersection of manually captured building perimeters and footpaths classified as transport hubs
Front_Cat_VHIGH	The length of building perimeter (m) fronting a footpath classified as a very high pedestrian usage (URM building only)	A GIS intersection of manually captured building perimeters and footpaths classified as very high pedestrian usage

Attribute	Description	Source
Front_Cat_HIGH	The length of building perimeter (m) fronting a footpath classified as a high pedestrian usage (URM building only)	A GIS intersection of manually captured building perimeters and footpaths classified as high pedestrian usage
Front_Cat_MED	The length of building perimeter (m) fronting a footpath classified as a medium pedestrian usage (URM building only)	A GIS intersection of manually captured building perimeters and footpaths classified as medium pedestrian usage
Front_Cat_LOW	The length of building perimeter (m) fronting a footpath classified as a low pedestrian usage (URM building only)	A GIS intersection of manually captured building perimeters and footpaths classified as low pedestrian usage
BPS_BASE_ID	An integer building identifier used to join the exposure database to the database of economic attributes	A GIS join of latitude and longitude for each building in both databases

The project used a concise list of building types dictated by the limited number of available vulnerability curves. The classification of URM building types was subdivided because:

- The case study focussed on the effects of retrofitting URM buildings and hence a more detailed classification of URM buildings would be of use;
- URM buildings made up a surprisingly large proportion of the total building stock by number (approximately 45%);
- A range of vulnerability curves were available from the preceding utilisation project "Earthquake Mitigation of WA Regional Towns: York case Study" that applied to a more detailed classification of URM building types (Wehner *et al.*, 2020); and
- Experience from the Christchurch earthquake sequence in New Zealand showed that collapse of URM buildings into the streets can contribute significantly to the number of casualties (Moon et al, 2014).

Table 4 lists the building types used in this case study. Table 5 lists the finer classification of load bearing masonry building types used in this case study.

TABLE 4 BUILDING TYPES USED IN THIS CASE STUDY.

GA Building Class	Description	Frequency
13_LBM_T	1 to 3 storey load bearing masonry with timber internal framing	101
13_LBM_S	1 to 3 storey load bearing masonry with steel internal framing	286
13_LBM_C	1 to 3 storey load bearing masonry with concrete internal framing	131
13_C_URM	1 to 3 storey concrete frame with URM external facades	42
13_C_O	1 to 3 storey concrete frame with non URM external facades	62
13_S_URM	1 to 3 storey steel frame with URM external facades	2
13_S_O	1 to 3 storey steel frame with non-URM external facades	29
47_LBM_T	4 to 7 storey load bearing masonry with timber internal framing	9

GA Building Class	Description	Frequency
47_LBM_S	4 to 7 storey load bearing masonry with steel internal framing	110
47_LBM_C	4 to 7 storey load bearing masonry with concrete internal framing	50
47_C_URM	4 to 7 storey concrete frame with URM external facades	55
47_C_O	4 to 7 storey concrete frame with non URM external facades	127
47_S_URM	4 to 7 storey with steel frame and URM external facades	5
47_S_O	4 to 7 storey steel frame with non-URM external facades	8
835_C	8 to 35 storey with concrete shear walls and frame	402
835_S	8 to 35 storey with steel frame	37
36_C	36+ storey with concrete frame	80
36_S	36+ storey with steel frame	6
ISS_SS_S	Single steel storey portal frame shed with steel clad walls and roof	1

TABLE 5 FINER CLASSIFICATION OF LOAD BEARING MASONRY BUILDING TYPES.

GA URM Class	Description	Frequency
URM1	1 storey residential house	3
URM2	2 storey pub	3
URM3	1 storey retail	35
URM4	2 storey retail	159
URM5	2 storey post office	18
URM6	2 storey bank	94
URM7	3-5 storey commercial	309
URM8	6+ storey commercial	59
URM9	Church	7
URM10	Town hall	0

BUSINESSES

To estimate the economic loss suffered by businesses following an earthquake, data is required about the nature of businesses at the individual building level. The project utilised the Census of Land Use and Employment (CLUE)(City of Melbourne, 2018), available for the city of Melbourne. CLUE is the only data set in Australia that provides up-to-date information about land use, employment and economic activity at individual building level that can be effectively utilised in impact modelling.

CLUE data includes:

- industry structure and type (ANZSIC code and number of establishments or business locations);

- floor space type and use (office, retail, industrial, accommodation or entertainment and office vacancy rates);
- employment type (full-time, part-time, casual or contractor);
- building information (number of floors, year of construction, gross floor area and lettable area); and,
- spatial distribution (maps, CLUE small areas, blocks and customised regions).

However, CLUE does not contain information on wages/salaries of employees. Hence data on the wages/salaries of employees was sourced from elsewhere as described in the economics section.

HUMAN ACTIVITY

In addition to building exposure and business exposure, people are also "exposed" in an earthquake event to injury from building damage.

In support of the Melbourne Case Study a separate piece of research was utilised that developed the first version of a human activity model for Melbourne. The reporting includes background to the model as input to the CRC research. The role of the model is to estimate a "warm body" count of the number of people that are expected to be in, or at, a given location at a particular time on a particular day. Hence, estimates are made of populations within (potentially injured by collapsing buildings) and outside (potentially injured by parts of damaged buildings falling into the street) buildings.

Source data

The model was developed from first principles. Input data sets used included:

- ABS Census data;
- Telecommunications smart phone derived data;
- Employment data;
- School enrolments;
- Approved child care places;
- Pedestrian movements;
- Public transport passenger movements;
- SCATS;
- Student, backpacker, boarding house, hospital and clinic accommodation data;
- Hotel accommodation data; and,
- Google and Google earth images.

While some of the input data sets provided data at a point, the smallest spatial geography common to all data sets was the destination zone (DZN). The DZN is a commonly agreed statistical geography where people journey to and from a place. In most cases the DZN aligns with a SA1, or an amalgam of SA1s. In some cases the DZN is its own specific geography. In this case study the Melbourne CBD comprised 70 DZNs, Southbank 15 DZNs and Docklands 13 DZNs. Each of the three localities is a SA2.

ABS Census of Population and Housing.

Using ABS Census data it was possible to derive how many people lived and worked in a DZN, how many lived in the DZN and worked outside the DZN and how many people lived in the DZN and were not in the paid workforce. This latter cohort included children, unemployed persons, carers and retired persons. Census data was derived from the 2016 Census of Population and Housing (ABS, 2017).

Telecommunications smart phone derived data (2017)

The telecommunications derived data comprised hourly and daily counts of people designated as residents, workers and others. These people were further cross classified by age cohort (18 to 65 years and 65 years and over). The telecommunications data was adjusted further to include under 18 year old persons.

Employment data

The City of Melbourne conducts a Census of Land Use and Employment (CLUE). A 2018 count of persons working in each DZN was obtained via a consultancy with the City of Melbourne. The project had access to a unit record file for 2016 CLUE and this was used to derive a 2016 count of persons employed in each DZN.

School enrolments

School enrolment data was derived from open source data provided from the Victorian education department (Victorian Government, 2018 and Victorian Government, 2019). The data was incorporated in all relevant DZNs.

Higher education enrolments

Higher education establishments within the thee SA2s were identified by using a Google search. Where enrolment data was not available from establishment websites each establishment was contacted by phone to obtain enrolment counts.

Approved childcare places

Open source data with childcare facility locations and approved enrolments was obtained from the Australian Children's Education & Care Quality Authority (ACECQA, 2020). This data showed approved childcare places for every childcare establishment in each of the three SA2s. The data was incorporated in all relevant DZNs.

Pedestrian movements

DZN Hourly pedestrian movement data was obtained from the open source City of Melbourne Pedestrian Counting System (City of Melbourne, 2017). Data is available for any 24 hour period from 1 January 2009 to the present day. There are currently 68 pedestrian movement monitors in the SA2s of Carlton, Docklands, East Melbourne, Melbourne, Parkville and Southbank.

Public transport passenger movements

DZN public transport passenger movement data was obtained as a consultancy from Melbourne Transport. The data covered two sets of two week periods. The 1st period covered the 2019 Melbourne Grand Final weekend, the second covered a "normal" two week period. It was recognised that not all DZNs have a tram, bus or train stop.

SCATS

SCATS (Sydney Coordinated Adaptive Traffic System) is described as a "sophisticated and dynamic intelligence transport system, and is considered one of the best traffic management systems in the world." It was adopted for use in all of Victoria in 1980 and according to the available documentation, the system is being used in almost all major cities in Australia and New Zealand and in many others internationally.

The main function of SCATS is to control signal timing parameters. The system counts the number of vehicles passing in each lane. The SCATS data is open source. Vehicle counts are compiled in 15 minute intervals but there is no directional information in the data other than lane number. To translate the count to a traffic density two high resolution Google Earth images (11am AEDT 17/10/2017 and 11am AEDT 1/12/2018) were used to count vehicles and vehicle types within a defined area feeding into each traffic light intersection in the study area. Figure 10 highlights the SCATS intersections used to undertake manual Google Earth imagery counts.

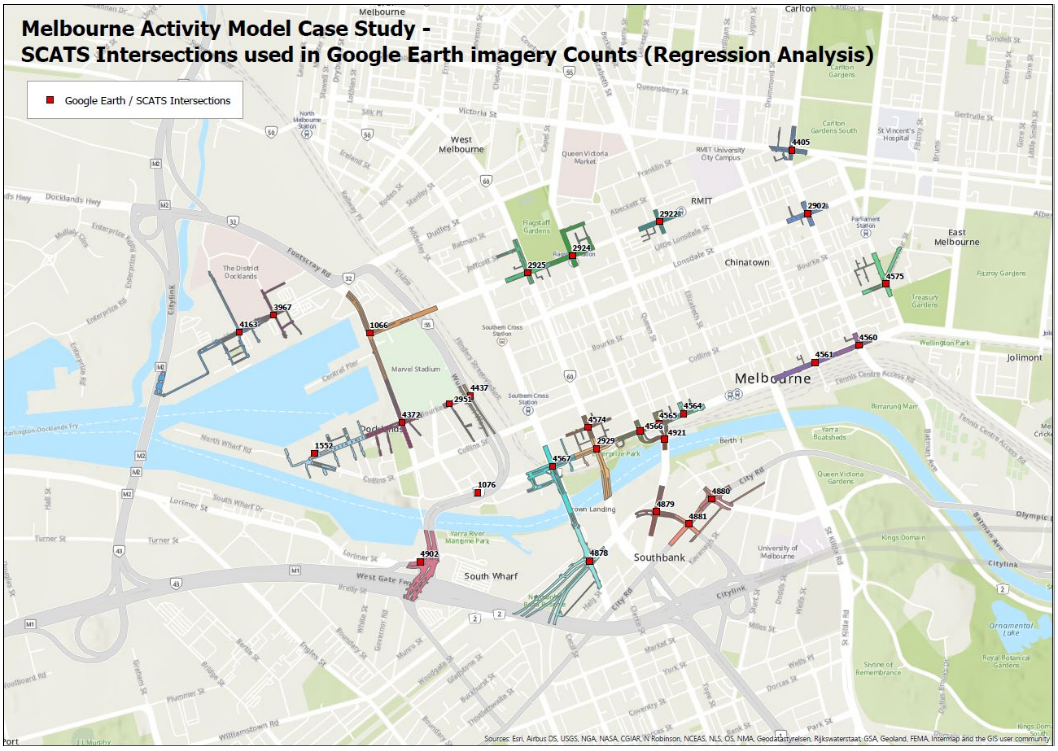

FIGURE 10 LOCATION OF SCATS INTERSECTIONS USED IN GOOGLE EARTH IMAGERY COUNTS.

Figure 11 shows SCATS intersections and road segments categorised by traffic routes.

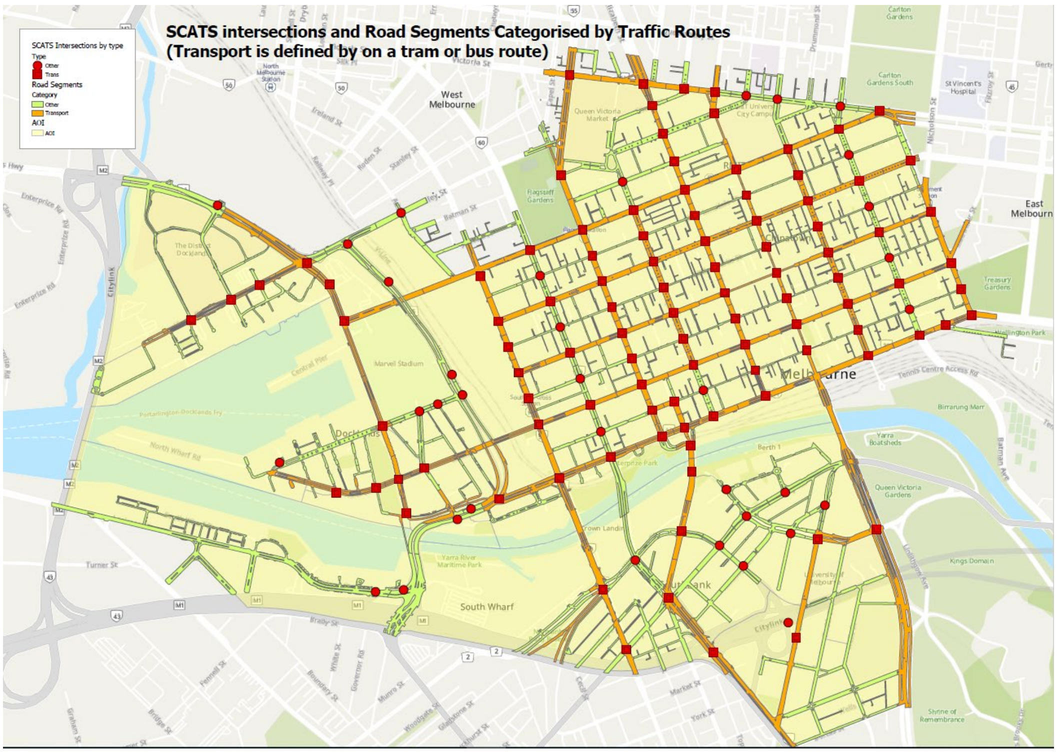

FIGURE 11 LOCATION OF SCATS INTERSECTIONS AND ORAD SEGMENTS CATEGORISED BY TRAFFIC ROUTES.

Using GIS, road segment data (carriageway; that is an actual road surface), sourced from City of Melbourne open data was dissected into the areas feeding into each SCATS intersection as per the same method (half way to the nearest known SCATS intersection), as well as an intersection with DNZ boundaries. The area of each segment was calculated in metres squared. To determine the vehicle density for each time domain / day of week a density surface was interpolated (using a Krigging technique), the input being SCATS counts (points) normalised by the area of intersection. The density recorded was a value per square metre. Figure 12 shows how the road segments were split for area calculation and SCATS ID assigned.

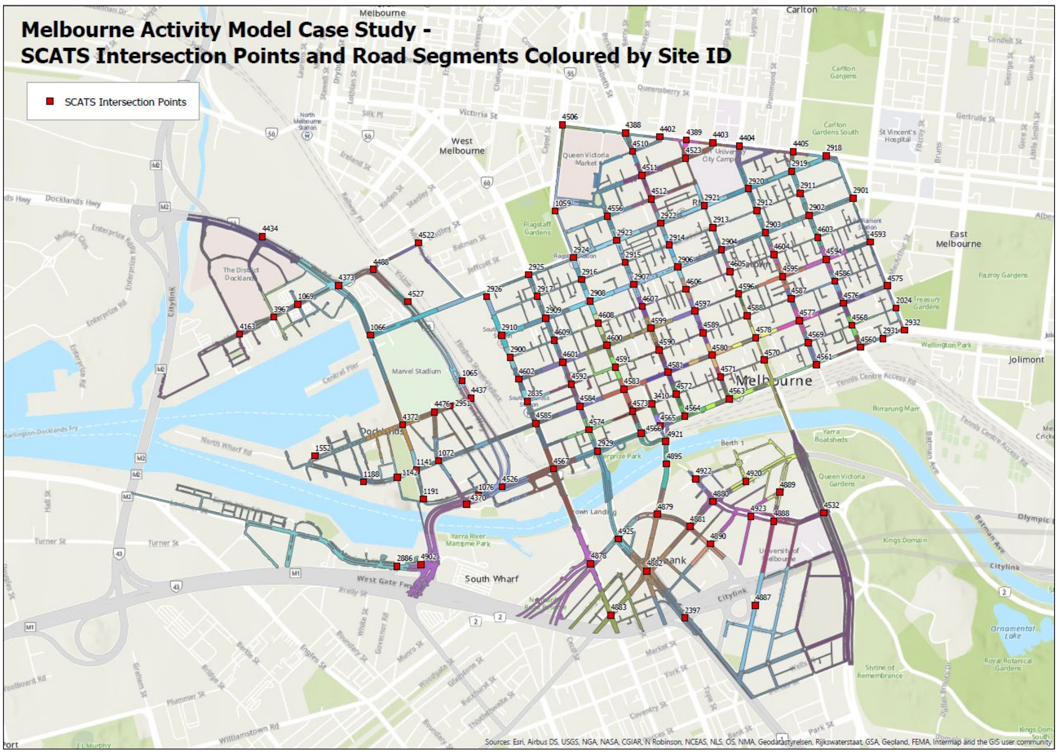

FIGURE 12 SCATS INTERSECTIONS AND ROAD SEGMENTS COULOURED BY SITE ID.

Figure 13 shows the Krigged surface of 15 min average SCATS counts for the morning time domain, Monday to Thursday period normalised by the area in square metres of the feeding intersection. SCATS Intersection ID's are also displayed.

Monday -Thursday Morning (TD) - Krigged Traffic Density Surface

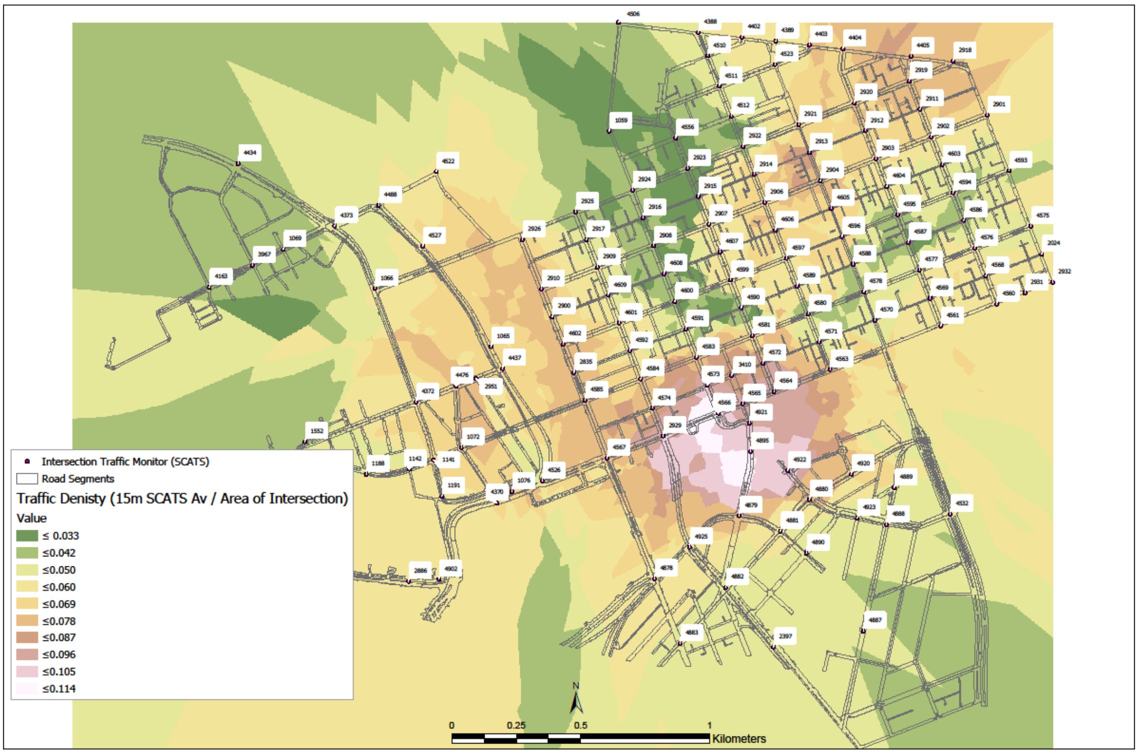

FIGURE 13 MONDAY TO THURSDAY MORNING DENSITY OF MOTOR VEHICLES.

Using the relationship established by a regression analysis of Google counts against SCATS counts the outputs of the SCATS observations by DNZ were factored to determine the number of vehicles and their type. The number of people in vehicles at a given time and day was derived using an assumed average occupant count for four different vehicle types (cars, trucks, buses and trams).

Student, backpacker, boarding house, hospital and clinic accommodation data

The location and bed counts for this data was derived from a unit record CLUE data set as well as Google searches and direct contact with relevant establishments.

Hotel accommodation data

The Melbourne branch of the Australian Hotels Association was approached to provide location and room counts for commercial establishments for each of their members. Each room was deemed to have accommodation for 2 people.

Google and Google Earth data

These two sources were used to identify additional potential locations of human activity as well as to provide confirmation of some elements of data derived from other sources.

Pedestrian density – estimating outdoor populations

Pedestrian activity across all three SA2's (Melbourne, Docklands and Southbank) was manually defined into 5 categories. The categories were based on local knowledge and pedestrian monitor readings. The five categories are; Transport hubs (Southern Cross Station, Flagstaff Station and Flinders Street Station), Very High, High, Medium and Low pedestrian densities.

Using City of Melbourne open data footpath centrelines were created, classified (into the five pedestrian activity categories) and the segment lengths calculated (Figure 14). The footpath centrelines were also intersected with the DNZ boundaries giving them a DNZ ID for later aggregation.

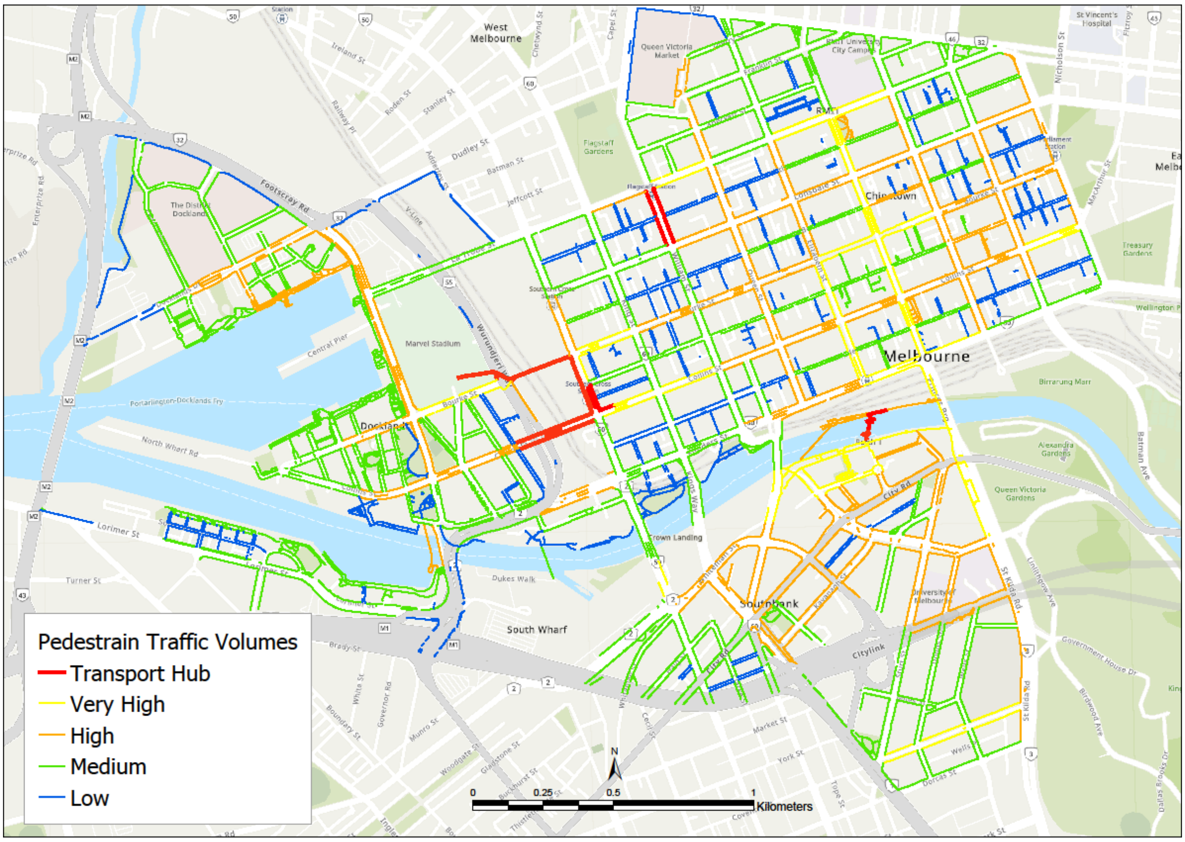

FIGURE 14 CATEGORISATION OF FOOTPATHS WITHIN THE STUDY AREA BASED ON PEDESTRIAN ACTIVITY.

Figure 15 shows categorised pedestrian monitor locations used to determine the density factors. The counts per time domain / day of week were averaged and the distance of potential travel divided by this average.

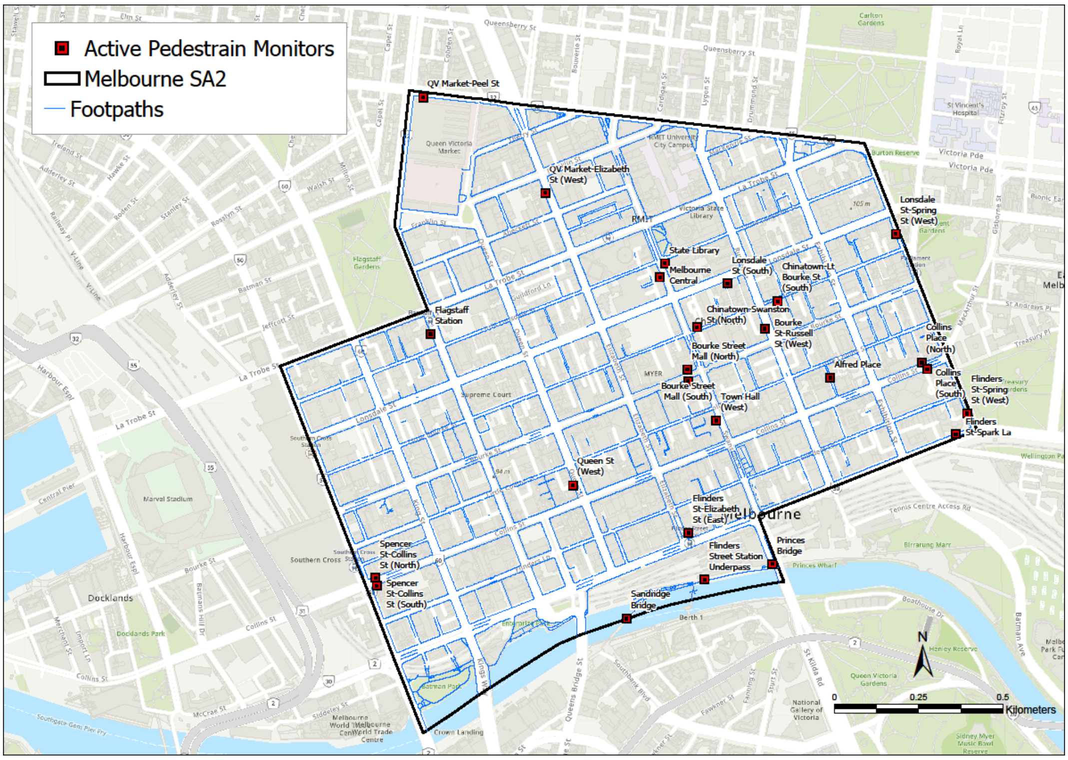

FIGURE 15 LOCATION OF PEDESTRAIN MONITORS WITHIN THE STUDY AREA FROM WHICH THE DENSITIES FOR EACH FOOTPATH CATEGORY WERE DERIVED.

Figure 16 shows the variation in pedestrian density by time domain / day of week. In this chart "low" has been excluded as the detail of the higher density categories is lost. The "low" pedestrian density ranges from around one person per 3 metres to one person per 13 metres.

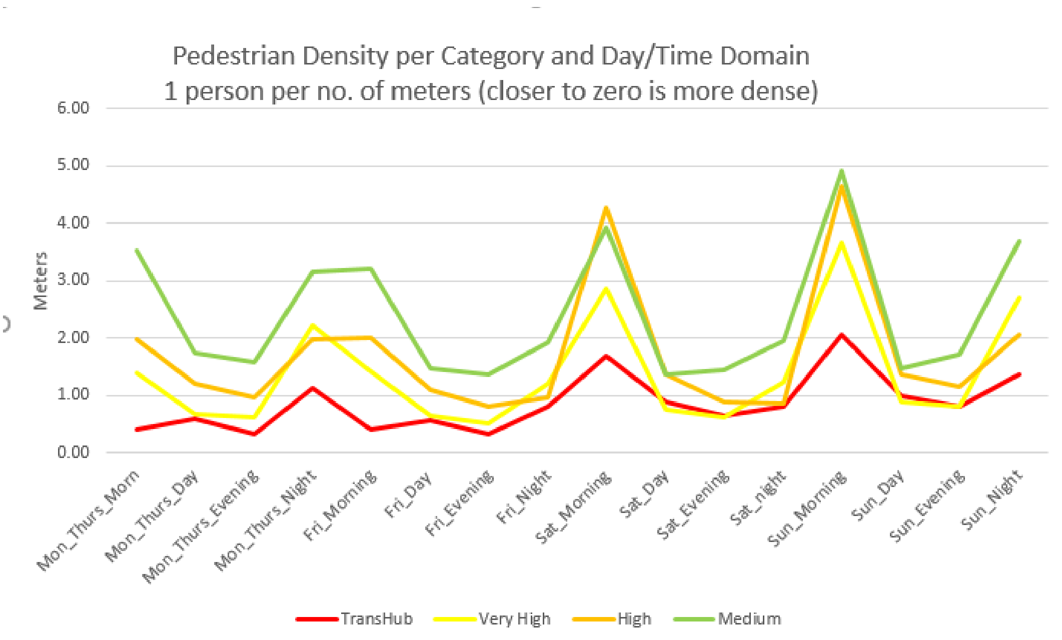

FIGURE 16 PEDSTRAIN DENSITY (METERS LENGTH OF FOOTPATH PER PERSON) BY FOOTPATH CATEGORY AND DAY AND TIME.

The street frontage for each URM building within the study area was measured and categorised into the five categories of pedestrian density. Thus an outdoor population was assigned to each URM building for the selected earthquake time and day for each scenario earthquake.

Estimating indoor day time and night time populations

The indoor population was estimated using the adjusted telecommunications data and the estimated outdoor population. As described in the following section, the indoor population was estimated over the combinations of the four day domains (Monday to Thursday, Friday, Saturday, and Sunday) and the four time domains ('Night', 'Morning ', Day' and 'Evening'). For each DZN, the indoor population was computed by subtracting both the pedestrian count and the passenger count from the adjusted telecommunications data. The resulting indoor population was distributed proportionally to the floor area within the DZN to estimate the indoor population for each building.

Developing time domains

Data sets comprising hourly cohorts were able to be restructured into distinct time dime dimensions.

Figure 17 to Figure 21 show the distribution of the adjusted telecommunications data (estimates of persons) over a 24 hour period on Monday 1 May 2017. Similar charts were produced for the other days for which the data is available. The adjusted telecommunications data has deemed "day" to be between 07:00 and 20:00 and "evening" to be the remainder of the 24 hour period. Following analysis of each of the daily data it was observed that the behaviour of the adjusted telecommunications data on Monday to Thursday was similar, the behaviour on Friday was different to the other week days in that post work activity on Friday was observably different to the other week evenings, and weekend behaviour was also different. Thus four day domains were identified: Monday to Thursday, Friday, Saturday, and Sunday.

Each line in these charts represents a different DZN. Outliers in these charts represent DZNs that have different characteristics. Examples were high movement transport hubs (Southern Cross Station) and a dining precinct (China Town).

From the analysis four time domains were defined: 20:00 to 06:59, 07:00 to 10:59, 11:00 to 14:59, and 15:00 to 19:59. These were described as 'Night', 'Morning', 'Day' and 'Evening', respectively.

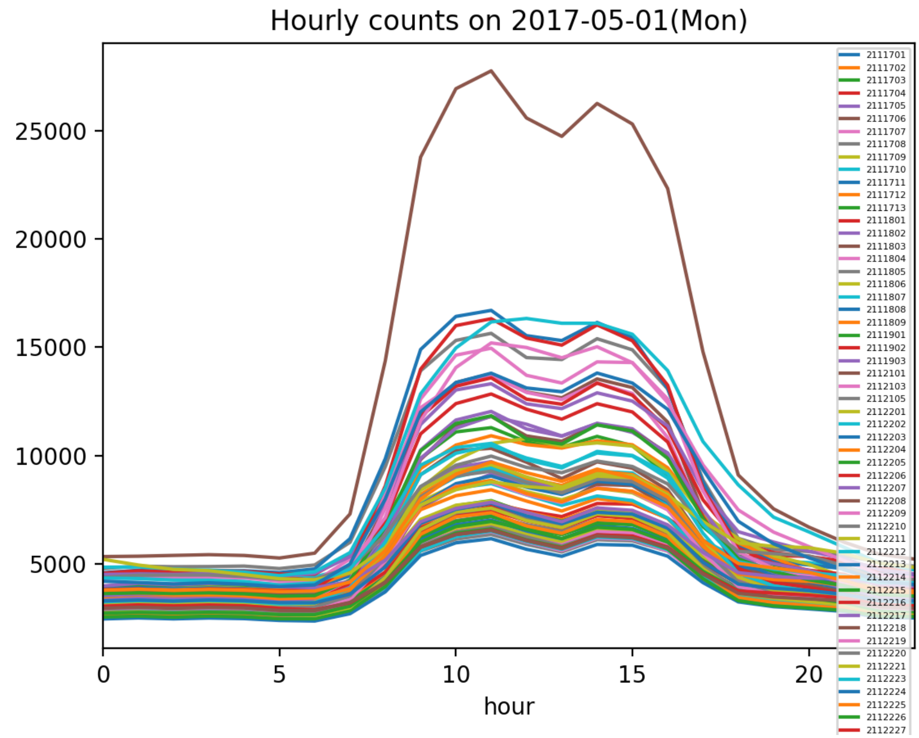

FIGURE 17 ESTIMATED HOURLY COUNTS OF PERSONS ON MONDAY 01 MAY, 2017 BY DZN.

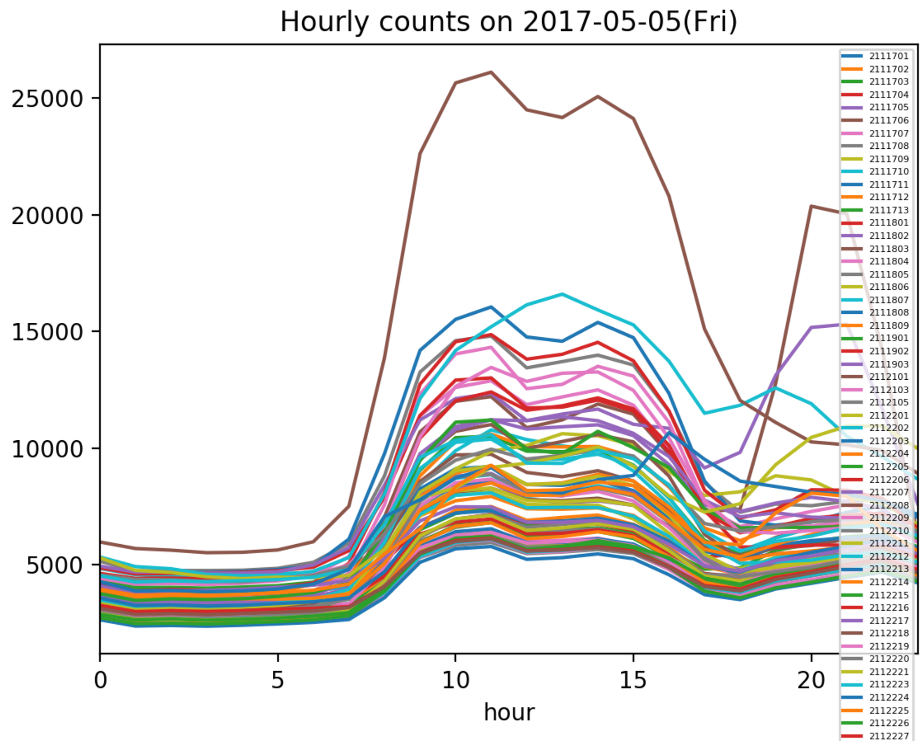

FIGURE 18 ESTIMATED HOURLY COUNTS OF PERSONS ON FRIDAY 05 MAY, 2017 BY DZN.

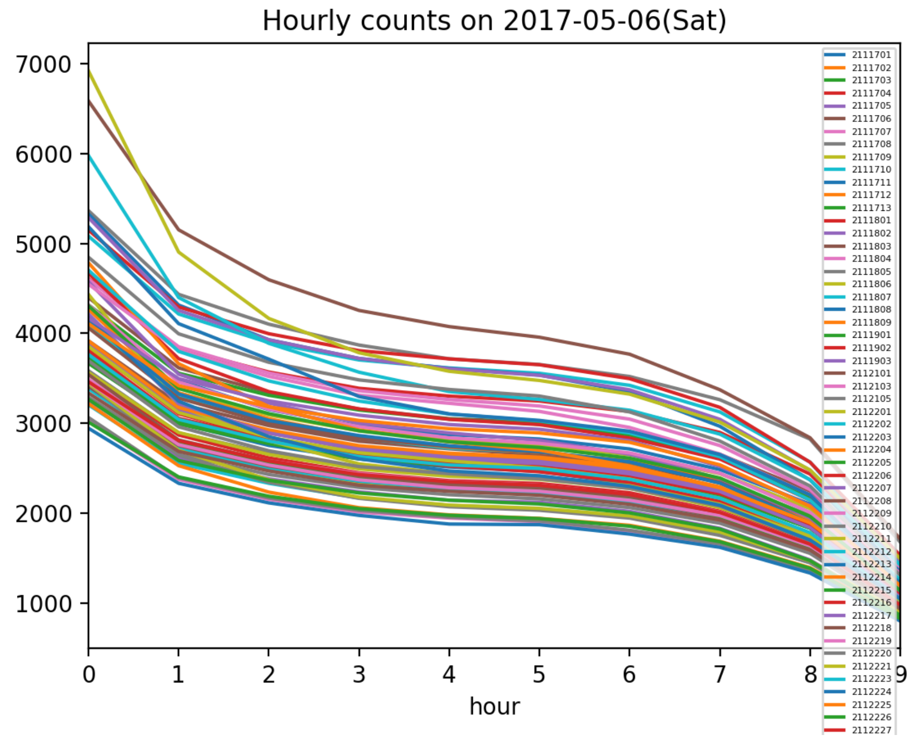

FIGURE 19 ESTIMATED HOURLY COUNTS OF PERSONS ON SATURDAY 06 MAY, 2017 BY DZN.

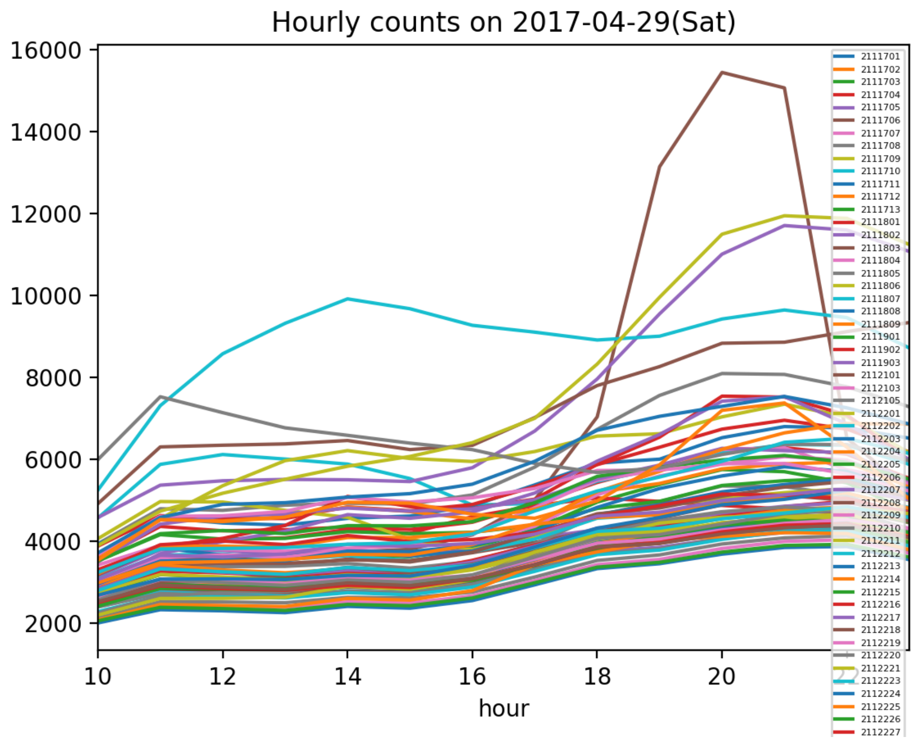

FIGURE 20 ESTIMATED HOURLY COUNTS OF PERSONS ON SATURDAY 29 APRIL, 2017 BY DZN.

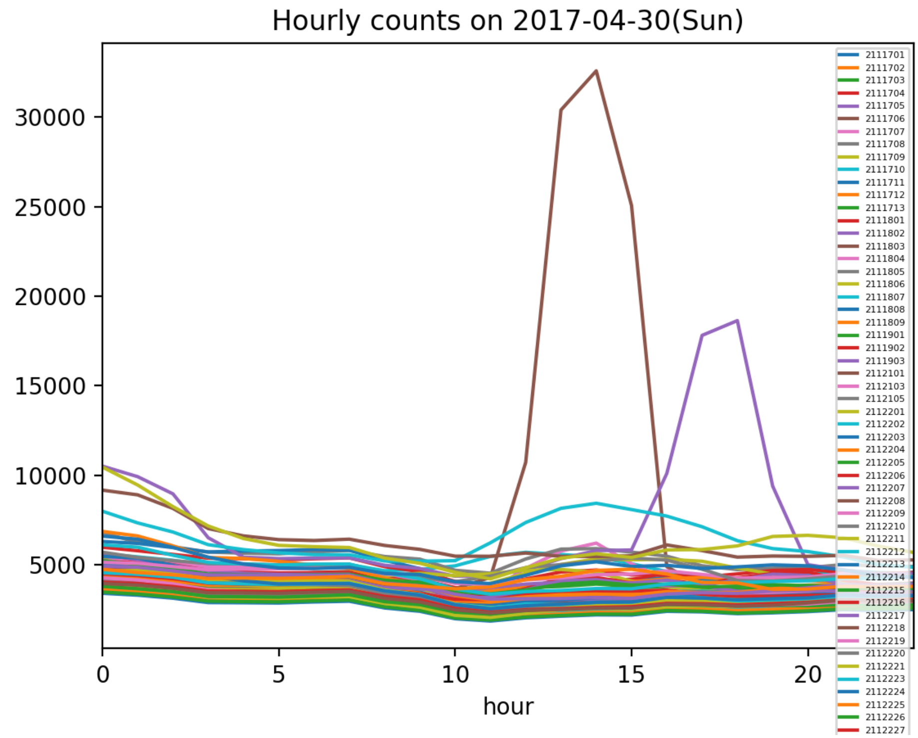

FIGURE 21 ESTIMATED HOURLY COUNTS OF PERSONS ON SUNDAY 30 APRIL, 2017 BY DZN.

BUILDING VULNERABILITY

Vulnerability models relating the mean damage index to the hazard parameter magnitude were required for each building type in Table 5 and the non-URM building types in Table 4. Vulnerability curves for URM building types URM1 to URM6 were taken directly from Wehner *et al.* (2020). Vulnerability curves for building types URM7 to URM9 were produced by heuristically adjusting the curve for URM4 (2 storey URM retail). The adjustment was informed by:

- preliminary modelling work undertaken by University of Adelaide examining the effect of building height on the fragility of roof level URM components; and,
- comparison of damage observed following the Christchurch earthquake sequence in building types URM7 to URM9 to damage observed in buildings of type URM4.

No buildings of type URM10 (Town Hall) were listed in the exposure database hence no vulnerability curve was produced for this building type.

Vulnerability curves for retrofitted URM buildings were taken directly from Wehner et al, 2020 assuming full retrofit as defined in that report, i.e. retrofit of all chimneys, parapets, gable walls and exterior walls tied to floor and roof diaphragms. Figure 22 shows vulnerability curves before and after retrofit for selected URM buildings.

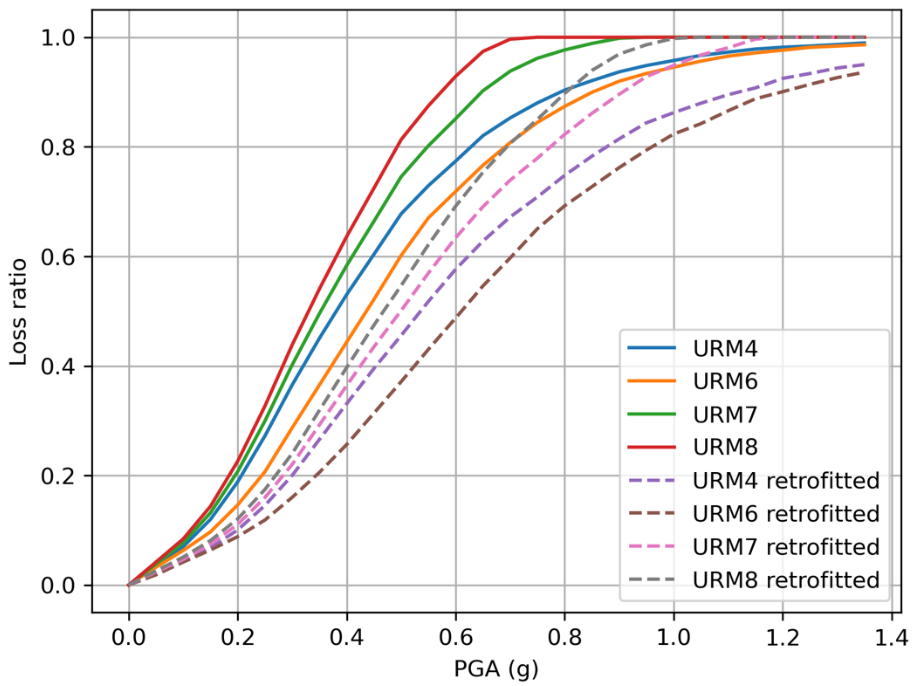

FIGURE 22 COMPARISON OF VULNERABILITY CURVES BEFORE AND AFTER RETROFIT FOR SELECTED URM BUILDINGS.

Vulnerability curves for the non-URM building types listed in Table 4 were produced by adjusting HAZUS vulnerability curves with reference to heuristically derived curves from a UN workshop (Maqsood *et al*, 2014) to produce curves that were relatively sensible when compared to the available URM curves. Two curves were produced for each building type: one representing pre-1996 vintage and one representing post-1996 vintage. This distinction is based on the introduction of modern earthquake design standards in Australia. Figure 23 shows the vulnerability curves for selected non-URM buildings types.

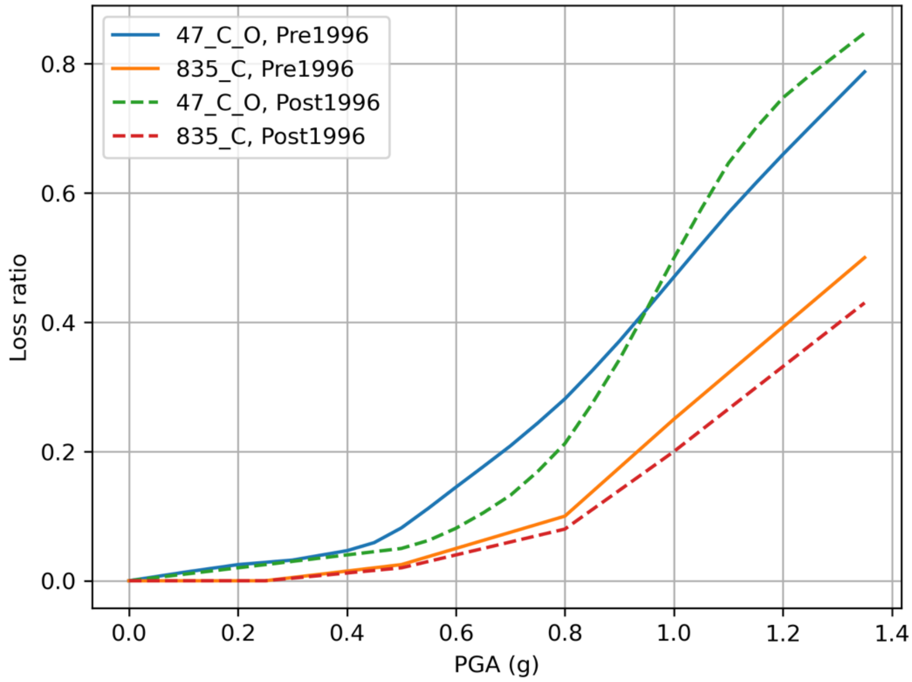

FIGURE 23 COMPARISION OF VULNERABILITY CURVES OF NON-URM BUILDING TYPES.

Fragility functions were used to determine damage states of building subjected to ground shaking. Fragility curves for URM building types URM1 to URM6 were taken directly from Wehner *et al.* (2020). Fragility curves for building types URM7 to URM9 were produced by heuristically adjusting the curve for URM4 (2 storey URM retail) similar to the adjustment to the vulnerability curves.

Fragility curves for retrofitted URM buildings were taken directly from Wehner et al, 2020 assuming full retrofit as defined in that report, i.e. retrofit of all chimneys, parapets, gable walls and exterior walls tied to floor and roof diaphragms. Figure 24 and Figure 25 show fragility curves before and after retrofit for selected URM buildings.

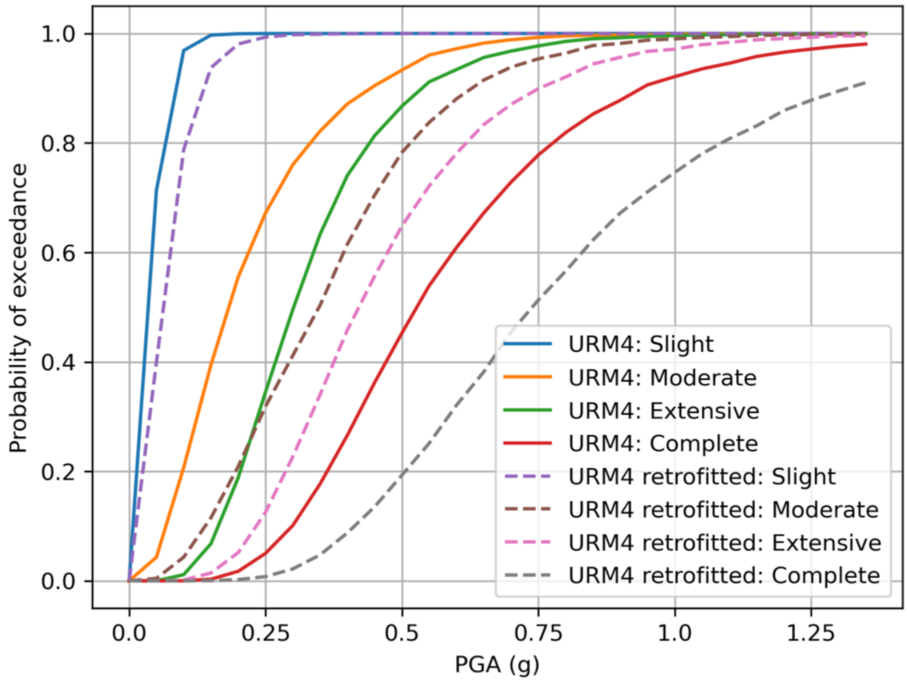

FIGURE 24 COMPARISON OF FRAGILITY CURVES OF URM4 BUILDING TYPE BEFORE AND AFTER RETROFIT.

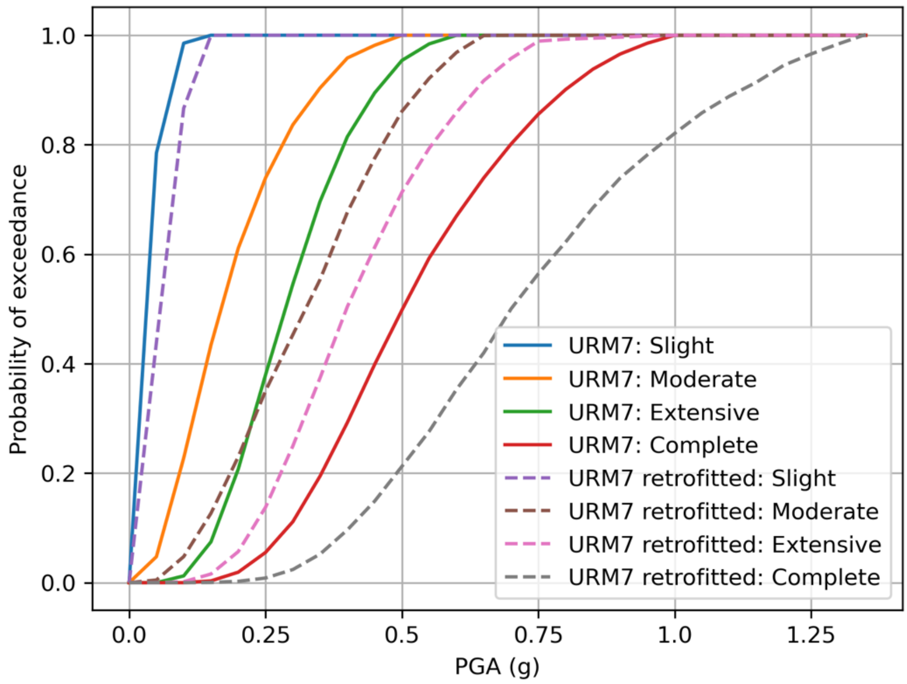

FIGURE 25 COMPARISON OF FRAGILITY CURVES OF URM7 BUILDING TYPE BEFORE AND AFTER RETROFIT.

Fragility curves for the non-URM building types listed in Table 4 were produced by applying damage state thresholds to randomly sampled values of loss ratio from the vulnerability curve. Figure 26 shows fragility curves for 835_C building type as an example.

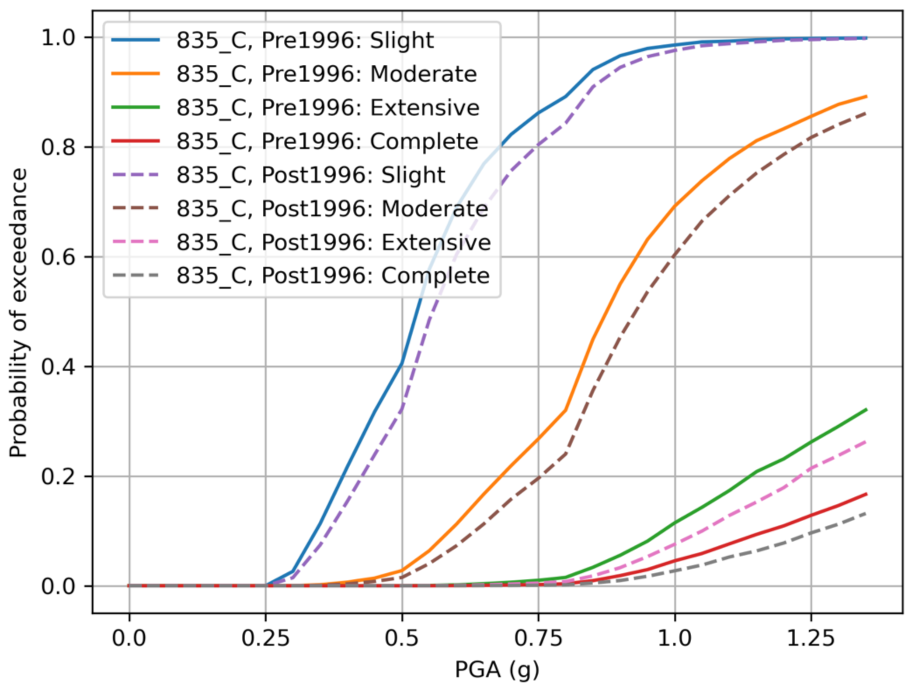

FIGURE 26 COMPARISON OF FRAGILITY CURVES OF 835_C BUILDING TYPE.

HUMAN CASUALTY AND SURVIVABILITY MODELS

COST OF CASUALTIES

Previous research in this project (Mohanty et al, 2018) presents a methodology and work plan for estimating direct health care costs in the immediate aftermath of an earthquake event in Australia. Following this methodology, earthquake induced direct health care cost of casualties were estimated for the Western Australian regional town of York (Wehner et al 2020). In this report the direct costs for the care of earthquake induced casualties for different potential scenarios in Melbourne CBD are presented. The process relied on the regular Australian patient care costs sourced from the Independent Hospital Pricing Authority (IHPA) that hosts the National Hospital Cost Data Collection in Australia (NHCDC). Whilst this data was not sourced from earthquake–specific injuries it does represent the variety of injury severities that may be expected following an earthquake. The categorisation of injury types used by the IHPA does not match with the injury categorisations used in earthquake studies which are typically more concise. Two earthquake injury categorisations are available: a five-point injury severity scale (Spence, 2007) shown in Table 6 and the four-point injury severity scale used by HAZUS shown in Table 7. Thus, a mapping was required between the categorisation used by the IHPA and one or both earthquake injury classifications. As the software used to estimate casualties following a scenario earthquake output numbers of casualties categorised by the HAZUS injury severity scale the result of the mapping process had to assign costs per casualty categorised according to Table 7. This section presents the methodology and estimates for direct health care costs for different injury severities that may be encountered following an earthquake event in Melbourne.

TABLE 6 EARTHQUAKE RELATED EXPECTED INJURY CATEGORIES. AIS DENOTES ABBREVIATED INJURY SCALES (HTTPS://WWW.ACI.HEALTH.NSW.GOV.AU/GET-INVOLVED/INSTITUTE-OF-TRAUMA-AND-INJURY-MANAGEMENT/DATA/INJURY-SCORING/ABBREVIATED_INJURY_SCALE).

Category (I)		Type of Injuries		AIS
1	Uninjured/lightly injured	Head or Face	Bruising/contusions, minor cuts	2
		Abdomen	Bruising, minor cuts	1
		Upper Extremities	Bruising, minor cuts, sprains	1
		Lower Extremities	Bruising, minor cuts, sprains	1
2	Moderately injured	Head or Face	Cuts into soft tissues	2-3
		Abdomen	Cuts into soft tissues	2-3
		Upper Extremities	Dislocation, Cuts into soft tissues	2-3
		Lower Extremities	Dislocation, Cuts into soft tissues	2-3
		Other	Dehydration/exposure; burns 1-2o; unconscious < 1hr	3
3	Seriously	Head or Face	Open head or facial wounds, fractures, brain concussion	3-4
		Abdomen	Pneumothorax and rib fractures, crushing > 3hrs, puncture organs	1-4
		Upper Extremities	Fractures – open, displaced or comminuted (pulverised)	3
		Lower Extremities	Fractures – open, displaced or comminuted (pulverised)	3
		Other	Uncontrolled bleeding; burns 2-3o (% of body?); unconscious > 1 hr	3-5
4	Critical	Head or Face	Internal head trauma, severe crushing, brain damage	5

Category (I)		Type of Injuries		AIS
		Abdomen	Spinal column injuries, internal organ failures due to crushing	5
		Upper Extremities	Traumatic amputations, arms	5
		Lower Extremities	Traumatic amputations, legs	5
		Other	Nerve injuries	5
5	Dead	Asphyxiation, burns and smoke inhalation, intracranial injuries, traumatic complications		6

TABLE 7 DESCRIPTIONS OF CASUALTY SEVERITY LEVELS USED IN HAZUS.

Injury Severity Level	Injury Description
Severity 1	Injuries requiring basic medical aid that could be administered by paraprofessionals.
Severity 2	Injuries requiring a greater degree of medical care and use of medical technology such as X-rays or surgery but are not expected to progress to a life threatening status.
Severity 3	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously.
Severity 4	Instantaneously killed or mortally injured

In Australia, direct health care costs are categorised by Australian Refined Diagnosis Related Groups (AR-DRG) and Urgency Related Groups (URG). In consultation with health care stream experts (IHPA, 2019) the AR-DRG and URG classifications were mapped to the five tier classification shown in Table 6. AR-DRG only cover admitted patients, whereas URG is used to classify and cost emergency department visits. The injury categories presented in Table 6 reveal it is unlikely that category 1 and 2 injuries need any hospital admission. These injuries are treated in the emergency department. Consequently, category 1 and 2 injuries need to be mapped to URGs. URGs are based on very broad diagnostic categories (known as Major Diagnostic Blocks) and therefore the URGs mapped to the above earthquake related categories (1 and 2) includes emergency department visits that had other injuries other than those listed in the Table 6. Also, URGs included categories for patients with any diagnosis who met the criteria of 'did not wait', 'transferred to another hospital' and 'died in ED'. They are not specific to injury diagnoses, hence they were excluded from this health care cost estimation.

The AR-DRG classification has over 800 groups, so the types of injuries listed in Table 6 may group to any number of DRGs depending on the interventions that occurred during the hospital stay, whether the patient had multiple injuries or required extended hours of mechanical ventilation, there are multiple potential DRGs for each issue. For example, a head injury that required surgical intervention are grouped to a different DRG than a head injury that was managed conservatively.

The AR-DRG classification also has a separate set of DRGs for multi trauma cases. So, if a patient has multiple types of injuries recorded, the episode was assigned to a multi trauma DRG rather than a DRG for the specific type of injury.

The Independent Hospital Pricing Authority (IHPA) provided data containing patient counts and the in scope National Efficiency Price (NEP) that are presented in Table 8 for Victoria. In Australia, National Efficient Price (NEP) in-scope cost includes a broad range of direct, indirect and overhead hospital costs.

TABLE 8 PATIENT COUNT AND ASSOCIATED COST CATEGORISED BY EARTHQUAKE RELATED INJURY TYPES (IHPA, 2019).

Category	Admitted Acute		Admitted Subacute		Emergency Department	
	Number of patients	NEP in-scope cost (AUD)	Number of patients	NEP in-scope cost (AUD)	Number of patients	NEP in-scope cost (AUD)
Category 1: Head or face	6,338	7,139,500	82	1,184,900	24,657	12,544,800
Category 1: Abdomen	3,204	6,654,700	82	1,012,000	2,614	2,010,900
Category 1: Upper extremities	2,364	4,357,600	48	755,900	35,675	12,481,000
Category 1: Lower extremities	5,370	17,894,800	312	4,195,900	43,586	16,527,700
Category 2: Head or face	6,411	11,349,600	76	1,080,300	24,434	9,187,400
Category 2: Abdomen	607	2,014,400	7	115,200	2,347	1,373,500
Category 2: Upper extremities	7,461	18,445,500	101	1,209,300	39,672	15,357,400
Category 2: Lower extremities	3,446	15,259,700	131	1,767,900	16,686	7,015,400
Category 2: Other	2,760	8,045,000	28	370,600	10,016	5,280,200
Category 3: Head or face	4,999	18,618,300	80	1,411,700	5,480	2,895,200
Category 3: Abdomen	3,694	31,910,000	286	4,052,800	4,592	5,569,700
Category 3: Upper extremities	16,579	78,144,200	971	16,520,300	46,699	22,617,800
Category 3: Lower extremities	13,104	146,546,800	4,335	72,708,700	24,906	17,395,200
Category 3: Other	413	10,981,800	26	708,800	8,130	13,986,600
Category 4: Head or face	2,418	37,983,900	575	15,134,000	8,407	6,880,700
Category 4: Abdomen	264	5,931,600	66	4,083,600	648	619,600
Category 4: Upper extremities	755	4,350,400			698	468,500
Category 4: Lower extremities	34	399,100			53	43,000
Category 4: Other	27	146,500			89	45,700
Category 5: Asphyxiation, burns and smoke inhalation, intracranial injuries, traumatic complications	155	1,074,500			558	348,600

Based on Table 8, the average estimated direct health care costs by the care types for Melbourne in 2018 are estimated and presented in Table 9.

TABLE 9 THE AVERAGE ESTIMATED HEALTH CARE COSTS BY THE CARE TYPES IN 2018.

Earthquake Injury Classifications	Patient Counts	Total NEP in Scope Cost (AUD)	Average NEP in Scope Cost (AUD)
Category 1	124,332	86,759,800	698
Category 2	114,183	97,871,400	857
Category 3	13,4294	444,067,800	3,307
Category 4	14,034	76,086,600	5,422
Category 5: Asphyxiation, burns and smoke inhalation, intracranial injuries, traumatic complications	713	1,423,000	1,996

Table 10 shows the resulting direct health care costs adopted for this study. It is derived from those costs shown in Table 9. Category 1 in Table 9 was not used as it was assumed that these injuries would be treated at home outside of the health care system) without recourse to health professionals hence society did not incur a cost. Consequently, the direct cost of health care for four injury categories are presented in Table 10 (as Severity 1-4) and they match the HAZUS (FEMA, 2006) injury categories in Table 7. Note that for the purposes of calculations the cost for Category 4 was replaced by $4.3 million (the statistical value of life) as this category represents the cost to society of deceased casualties.

TABLE 10 DIRECT HEALTH CARE COSTS.

Injury Severity Level	Direct Health Care Cost ($ per casualty)
Severity 1	857
Severity 2	3,307
Severity 3	5,400
Severity 4	1,996

The value of lost welfare from fatalities

Distinct from direct health care costs, the number of lives disabled and lost due to casualties, presented as severities 1-4 in this report also involve loss of economic welfare to the society that can be estimated using the Value of Lost Welfare (VLW) approach. These costs relate to the loss of total economic welfare (market and non-market) associated with disability and premature mortality (including the loss of utility due to lost leisure time and foregone consumption opportunities) along with less tangible losses such as those due to pain and suffering. This report only estimates the welfare loss from fatalities (Severity 4, Table 10) based on the concept of a Value of a Statistical Life (VSL) to assess the potentially avoidable economic losses. The VSL approach is a robust methodology that was developed for valuing mortality risk reductions in regulatory analysis of environmental health and transport policies in OECD countries (OECD, 2011) and Australia (OBPR, 2019). This is extended in this report to capture the economic value of avoidable earthquake related fatalities. VSL for Australia recommended by the Office of Best Practice Regulation Guidance Note is used (OBPR, 2019). The OBPR (2019) provides a credible estimate of the value of statistical life in Australia as $4.3m and the value of statistical life year is $182,000 in 2014 dollars. The note primarily intends to provide guidance on the cost-benefit analysis in Regulation Impact Statements assigning values to benefits of regulating change designed to reduce the risk of physical harm. Following the international practice and OBPR (2019), this report applied the VSL estimated by Abelson (2008) for estimating the welfare cost of fatalities.

EARTHQUAKE INDUCED INJURIES

Casualties were estimated following the methodology presented in FEMA, 2006 with adjustments for outdoor casualties as described below. Table 11 shows the casualty rates for low-rise URM (URML) buildings extracted from FEMA, 2006.

TABLE 11 CASUALTY RATES FROM FEMA, 2006 EXPRESSED AS PERECNTAGES OF EXPOSED POPULATION IN EACH CASUALTY SEVERITY LEVEL. THE FIGURES

FOR COMPLETE DAMAGE STATE ASSUME 15% OF BUILDINGS IN THAT DAMAGE STATE ARE COLLAPSED AND 85% ARE NOT.

Damage State	Indoor population				Outdoor population			
	Casualty Severity Level				Casualty Severity Level			
	1	2	3	4	1	2	3	4
None	0	0	0	0	0	0	0	0
Slight	0.05	0	0	0	0	0	0	0
Moderate	0.35	0.4	0.001	0.001	0.15	0.015	0.0003	0.0003
Severe	2	0.2	0.002	0.002	0.6	0.06	0.0006	0.0006
Complete	14.5	4.7	0.767	1.517	5	2	0.4	0.6

The outdoor casualty rates in Table 11 are extremely low. These were reviewed against photographs of damaged URM buildings in Christchurch, 2011 which showed the size and extent of fallen masonry. Hence, revised casualty rates for outdoor populations were adopted as given in The figures in

Table 12 take into account estimated values for:

- for each damage state the proportion of buildings where masonry collapses into the street; and
- the proportion of exposed people in each casualty severity level allowing for the ability of people in the street to effectively move during earthquake shaking to escape falling masonry.

TABLE 12 HEURISTIC OUTDOOR CASUALTY RATES ADOPTED FOR THE PROJECT (PERCENTAGE OF EXPOSED POPULATION IN CASUALTY SEVERITY LEVEL BY BUILDING DAMAGE STATE).

Building damage State	Proportion of buildings with masonry fallen into street (%)	Proportion of outdoor population in each casualty severity level if masonry falls into the street (%)				Proportion of outdoor population in each casualty severity level (%)			
		Casualty Severity Level				Casualty Severity Level			
		1	2	3	4	1	2	3	4
None	0	5	5	10	60	0	0	0	0
Slight	0	5	5	10	60	0	0	0	0
Moderate	25	5	5	10	60	1.25	1.25	2.5	15
Severe	75	5	5	10	60	3.75	3.75	7.5	45
Complete	90	5	5	10	60	4.5	4.5	9	54

The casualty severity levels in Table 11 and Table 12 are described in FEMA, 2006 and reproduced in Table 7.

TABLE 13 DESCRIPTION OF CASUALTY SEVERITY LEVEL.

Injury Severity Level	Injury Description
Severity 1	Injuries requiring basic medical aid that could be administered by paraprofessionals.
Severity 2	Injuries requiring a greater degree of medical care and use of medical technology such as X-rays or surgery but are not expected to progress to a life threatening status.
Severity 3	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously.
Severity 4	Instantaneously killed or mortally injured

ECONOMICS

The economic costs associated with earthquake events in Australia were estimated for the Melbourne CBD as a case study. The methodology developed by Mohanty et al (2018), an earlier publication of this CRC project, was adopted. A similar analysis was also presented earlier by this group in Wehner et al (2020) for the Western Australian regional town of York. Table 14 presents a typology of the earthquake related economic losses that have been identified for potential inclusion. In the table there are two broad categories of earthquake related economic costs: the direct and the indirect economic costs. Overall, economic costs due to building related business interruptions, can be classified into both the direct and indirect components.

TABLE 14 TYPES OF EARTHQUAKE RELATED ECONOMIC LOSSES.

Cost Category	Type of Costs	Components of Costs
Direct	Tangible	Building Repair and Replacement Cost
		Building Contents Cost
		Business Interruption Cost
		Health care Cost
		Emergency Management Cost
		Clean-up Cost
Indirect	Tangible	Business Interruption Cost
		Casualty related loss of productivity
	Intangible	Injury or disability related quality of life loss (pain and suffering, psychological distress)
		Other quality of life loss (reduced job opportunities, access to schools and public services, participation in community life, recreational activities)

Due on the data accessibility and methodological limitations the report only presents the estimation of the direct economic cost components of business interruption such as overall business income loss (employees and proprietor income loss are considered together) and rental (residential and commercial) income loss. On the other hand, the report presents both direct and indirect economic cost components of human casualties such as direct health care cost and the value of a life lost that includes loss of productivity and injury and disability related loss of quality of life.

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. The resulting economic 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. There has been a range of other secondary and intangible costs that, while identified in the literature, are not very clearly delineated or estimated. Earthquake caused human casualties and related health care cost, productivity loss and other intangible values of life loss constitute a major component of the direct, indirect and intangible costs (Mohanty et al, 2018).

Based on available data and the methodological developments so far, the cost components that are estimated in this economic assessment are presented in Figure 27. The figure illustrates how the scenario ground motion is translated through a value chain aligned to the impact framework to the economic measures shown in the yellow boxes. Specifically these are:

- Building damage loss;
- Contents loss, including plant and fit-out of businesses;
- Rental and commercial lease losses;
- Wage losses;
- Proprietor income losses;
- Health care costs; and
- Societal value of human life associated with deaths.

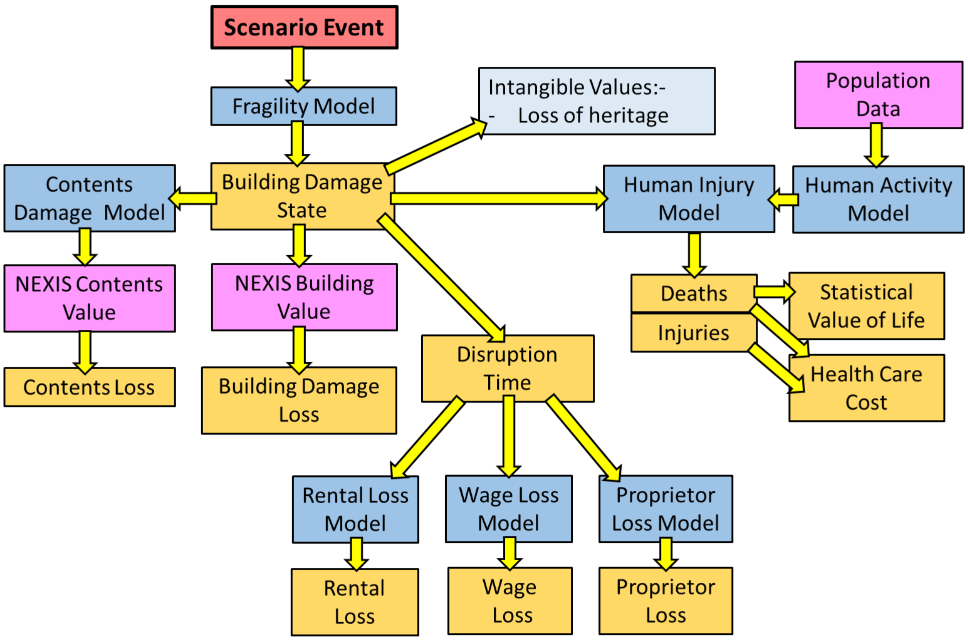

FIGURE 27 ECONOMIC MODELLING FRAMEWORK WITH THE ECONOMIC MEASURES QUANITFIED SHOWN IN YELLOW.

BUSINESS INCOME LOSS

In the business income loss category, this report presents the wage/salary income loss, which combines proprietary income loss – owner/ managers of Incorporated/Unincorporated Enterprises, and employee's income loss. These are major components of the business income loss in the Melbourne CBD for earthquake scenarios.

Income Loss

As reported in an earlier publication of this project (Mohanty et al, 2018) the wage/salary income loss can be estimated as a function of number of employees and proprietors at the building level and their average income estimated by employment type and industry classification and the building damage state and the corresponding business interruption period by the industry classification at the building level.

Methodology

The first step in estimating the wage/salary income loss in Melbourne CBD is to identify the appropriate data set that contains information on wage/salary and that can be combined with the exposure database to enable loss estimation for each building. There is no census of wage/salary information available in Australia at the building level. The Census of Land Use and Employment (CLUE 2018) (City of Melbourne, 2018) available for the city of Melbourne is the only data set in Australia that provides up-to-date information about land use, employment and economic activity at individual building level that can be effectively mapped to buildings in the exposure database.

However, CLUE does not contain information on wages/salaries of employees. The Australian Census of Population and Housing (ABS, 2017) does contain information on wages /salaries in brackets by employment type and industry classification at small geographical resolution, however it does not contain information at building level. This research combines information from 2016 Census of Population and Housing with CLUE 2018 to provide business exposure data for each building. This can be combined with the modelled damage state for each building, and hence disruption time, to compute dollar losses suffered by businesses.

A further complication is that the Australian Census of Population and Housing contains salary data by types of employment only for full time and part time, classification, whereas CLUE contains data on number of employees by their employment status categorised as – full time, part time, casual and contract. They are also categorised to the Australian and New Zealand Standard Industrial Classification (ANZSIC) at individual building level. Therefore, this report combined the CLUE data, a census of buildings and land use, with a survey data set (Household Income and Labour Dynamics in Australia Survey (HILDA), Department of Social Services, 2018) containing information by their employment categorised as – full time, part time, casual and contract. HIDA contains information on CLUE employment categories and ANZSIC industry classification. To our knowledge it is the only such survey in Australia. It also contains regional information by Greater Capital City/Rest of the State that can be applicable for Melbourne. But HILDA does not contain wage/salary information at the building level rather it contains the same at individual/household level. Consequently, this research combined the latest CLUE 2018 with the HILDA survey 2018 for the corresponding time, Wave17 Release 2018, using statistical data matching to estimate the number of employees at building level by employment types of full time and part time and industry level. This procedure mapped and allocated the contract and casual employees into full time and part time classifications and added these to the original full time and part time numbers to form overall employee numbers at building level classified by full time and part time only. Subsequently, the average wage/salary values in these categories at building level were imputed in CLUE 2018 using the matching classifications from Census 2016.

Data

2016 Census of Population Housing - Counting Employed Persons, Place of Work

In the ABS Census of Population and Housing, the Employed Persons database records a person's labour force status for the week prior to the Census Night and excludes persons under 15 years of age. It allows counting people based on where they go to work (Place of Work), where they usually live (Place of Usual Residence) and where they were counted (Place of Enumeration). Place of Work (POW) is determined from written responses to the 'Business name' and 'Workplace address' questions in the Census Form about the main place of work last week. It is coded to geographic areas known as Destination Zones (DZNs). DZNs are defined by the relevant State Transport Authority (STAs) from each state or territory, in conjunction with the ABS. Place of Work is a hierarchical field and for 2016 can be broken into State, SA2 and Destination Zone.

This project used Census data on Counting Employed Persons - Place of Work (ABS, 2016) for estimating income loss by individual employment type and industry of employment. Although DZNs do not fit neatly into Local Government Area (LGA) boundaries, a DZN to LGA correspondence was created to allow data to also be released at LGA level (ABS, 2017)

CLUE 2018

CLUE provides comprehensive information about land use, employment, and economic activity across the City of Melbourne at individual building level. This report used CLUE 2018. For CLUE 2018 the data would be collated between 2016-2018, where the actual comparison year is 2016. This makes our data matching with Census 2016 more comparable.

HILDA 2017

The Household, Income and Labour Dynamics in Australia (HILDA) Survey is a household-based panel study that collects valuable information about economic and personal well-being, labour market dynamics and family life. The survey started in 2001and follows the lives of more than 17,000 Australians each year. It collects information on many aspects of life in Australia, including household and family relationships, income and employment, and health and education. This report used HILDA 2017, Wave 16: data collected in 2016, for matching with Census and CLUE data for the corresponding period.

Data Attributes and Classification

Industry Classification

Census uses the Australian and New Zealand Standard Industrial Classification (ANZSIC) 2006 (1292.0) (Australian Bureau of Statistics, 2006) that have been jointly devised by the Australian Bureau of Statistics and Statistics NZ. This classification is a hierarchical classification with four levels, namely, Divisions (the broadest level), Subdivisions, Groups and Classes (the finest level). In total, there are 19 divisions specified under ANZSIC.

The 'Divisional' levels were used for classifying the businesses in Melbourne CBD. The datasets that are used in this report: Census of Population and Housing, HILDA and CLUE all contain information on employment by the ANZSIC. The ANZSIC industry divisions facilitated data matching between the data sets.

Employment Type

Census contains information on employees' income in different wage brackets, ANZSIC classification and employment types. The issue of different classifications of employment type between the three datasets used for the project and the method used to overcome the issue has been described above.

Income Ranges

The Census does not provide information on the absolute income of an individual/household. Instead, it records the income level of people aged 15 years and over and collects personal income in ranges of total income that the person usually receives each week. To enable estimation of income loss, mean values were assigned to each range. The total personal weekly income ranges in Census with their mean values are presented in Table 15.

TABLE 15 THE TOTAL PERSONAL WEEKLY INCOME RANGES IN CENSUS WITH THEIR MEAN VALUES. EQUIVALENT ANNUAL AMOUNTS IN BRACKETS.

Census Personal Income Ranges (ABS 2016)	Mean Incomes
Negative income	0
Nil income	0
$1-$199 ($1-$10,399)	$100
$200-$299 ($10,400-$15,599)	$249.5
$300-$399 ($15,600-$20,799)	$349.5
$400-$599 ($20,800-$31,199)	$499.5
$600-$799 ($31,200-$41,599)	$699.5
$800-$999 ($41,600-$51,999)	$899.5
$1,000-$1,249 ($52,000-$64,999)	$1124.5
$1,250-$1,499 ($65,000-$77,999)	$1374.5
$1,500-$1,999 ($78,000-$103,999)	$1749.5
$2,000 or more ($104,000 or more)	$2499.5

Note: Census reports *Not Stated* values as one category; we have pro-rata adjusted those numbers into other income categories.

Business Interruption Time

To estimate the economic loss, resulting from a building being unusable following earthquake damage, an estimate of the period from the earthquake to the building being restored to full functionality (known as the disruption time) is required. The disruption time serves as input to estimate Rental Losses, Wage Losses and Proprietor Losses.

To estimate the disruption time, claims data from the 1989 Newcastle earthquake were analysed to arrive at the relationship between time to settlement (equated to disruption time) and claim ratio (equated to damage index). In the analysis, very short settlement times with high claim ratios were discarded as these were thought to represent write-off behaviour. Similarly, very long settlement times with low claim ratios were also discarded as these were thought to represent claims with some unknown problem that caused lengthy delays in settlement.

The results of the analysis are presented in Figure 28 where the blue line represents the average time to settlement in each claim ratio interval and the dashed line is a fitted curve that was subsequently used in economic analysis.

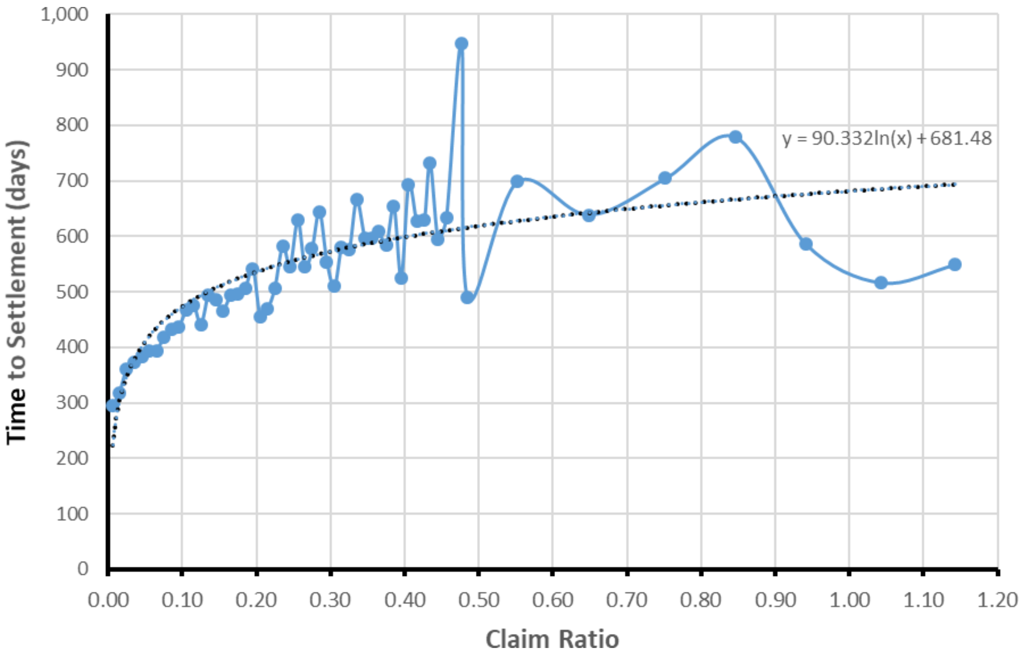

FIGURE 28 DISRUPTION TIME ESTIMATE FROM NEWCATSLE EARTHQUAKE CLAIMS DATA.

Table 16 gives the assumed disruption time by damage state based on Figure 28.

TABLE 16 DISRUPTION TIME BY DAMAGE STATE

Damage State	Slight	Moderate	Extensive	Complete
Disruption time (weeks)	2	80	93	100

Estimating Income Loss

The following section describes the step-by-step methodology for estimating the earthquake related wage/salary income loss in Melbourne CBD for different earthquake scenarios. The estimation of wage/salary/proprietary income loss for Melbourne CBD in this study simulates a base model of business income loss at individual building level. The base model is constructed using three different data sources: Census 2016, CLUE 2018 and HILDA 2017.

The total personal weekly income ranges with their mean values in Census 2016 are presented in Table 15 (also see Mohanty et al (2017)). The mean weekly income values in each income bracket by employment, labour force and industry division are multiplied with the number of employees/owners/managers and the total weekly income in each employment category was estimated. The average income in each category of employment and industry is subsequently estimated.

The following Table 17 presents the estimates of average income combining the proprietary income - owner managers of Incorporated/Unincorporated Enterprises, and wage/salary income.

TABLE 17 ESTIMATED AVERAGE WAGES/SALARIES IN MELBOURNE CBD BY INDUSTRY, EMPLOYMENT AND LABOUR FORCE STATUS, 2016 CENSUS OF POPULATION AND HOUSING.

Industry Classification (ANZSIC-Division)	Labour force Status	Number of Employed Persons	Total Income ($)	Average Income ($/week)
Accommodation and Food Services	full-time	13385	14,151,100	1,057
Accommodation and Food Services	part-time	14814	6,655,600	449
Administrative and Support Services	full-time	11204	16,876,900	1,506
Administrative and Support Services	part-time	5520	3,697,900	670
Agriculture, Forestry and Fishing	full-time	476	968,900	2,035
Agriculture, Forestry and Fishing	part-time	101	99,500	985
Arts and Recreation Services	full-time	9676	15,106,700	1,561
Arts and Recreation Services	part-time	5533	3,948,500	714
Construction	full-time	11627	21,418,000	1,842
Construction	part-time	1297	1,331,400	1,027
Education and Training	full-time	17620	31,480,500	1,787
Education and Training	part-time	9225	7,810,600	847
Electricity, Gas, Water and Waste Services	full-time	7430	15,799,800	2,126
Electricity, Gas, Water and Waste Services	part-time	842	1,187,100	1,410
Financial and Insurance Services	full-time	50333	103,756,000	2,061
Financial and Insurance Services	part-time	6810	8,960,900	1,316
Health Care and Social Assistance	full-time	19685	32,841,500	1,668
Health Care and Social Assistance	part-time	11889	11929873.76	1,003
Inadequately described	full-time	5654	9119125.79	1,613
Inadequately described	part-time	2093	1,500,700	717
Information Media and Telecommunications	full-time	20117	42,129,200	2,094
Information Media and Telecommunications	part-time	2680	3,078,300	1,149
Manufacturing	full-time	9094	17,970,200	1,976
Manufacturing	part-time	1332	1,406,500	1,056
Mining	full-time	1299	3,580,500	2,756
Mining	part-time	170	297,900	1,752
Other Services	full-time	6006	9,004,000	1,499
Other Services	part-time	2544	1,980,800	779
Professional, Scientific and Technical Services	full-time	63437	129,603,700	2,043

Industry Classification (ANZSIC-Division)	Labour force Status	Number of Employed Persons	Total Income ($)	Average Income ($/week)
Professional, Scientific and Technical Services	part-time	11555	13,746,000	1,190
Public Administration and Safety	full-time	32720	60,651,300	1,854
Public Administration and Safety	part-time	6349	7,994,600	1,259
Rental, Hiring and Real Estate Services	full-time	6,380	11,406,000	1,788

These average income values in each category are imputed into our base model from the CLUE containing employees by ANZSIC division and labour force status at individual building level and enabled estimation of the business income at individual building level.

However, an individual building in Melbourne CBD normally does not host a single business or businesses from a single industry classification (ANZSIC Division). There are multiple businesses from multiple industries housed in one building. The full time/part time employee numbers at building level are available in CLUE but are not classified by ANZSIC division. Whereas CLUE contains information on gross floor area of the building and the floor space distribution by ANZSIC division. Consequently, the total full time/part time employees at building level in CLUE were allocated into different ANZSIC divisions proportionate to the floor area (in square metre) allocated to that ANZSIC division to the gross floor area of the building. The average full time/part time salaries were then applied to the number of estimated employees in each ANZSIC division. The estimated income for each ANZSIC division were then added to estimate the total income at individual building level.

Likewise, the business interruption periods in the event of an earthquake scenario as a function of damage state were estimated using insurance claim data from the 1989 Newcastle Earthquake. In the final step, the conditional probabilities of different damage states for each building and the corresponding business interruption periods were applied to the average wage/salary income by industry, employment and labour force status and the total income loss in those categories were estimated.

RENTAL AND LEASE INCOME LOSS

This section presents the methodology, data sources and the estimated values of the rental and lease income in Melbourne CBD for residential and commercial properties.

Estimating Residential Rental Income Loss

Methodology

The estimation of residential rental income loss for Melbourne CBD in this study simulated a base model of residential rental income loss at individual building level. The base model is constructed using two data sources on Melbourne CBD: Census 2016 and CLUE 2018.

In estimating rental income loss in Melbourne CBD, the first step was to identify data sources that contain information on the properties that are rented as opposed to those that are owner occupied. Additionally, information on the actual rental payments on a weekly/fortnightly/monthly basis was required. The basic information requirements are listed below.

1. The proportions of rental and owner-occupied properties of the total residential/commercial dwellings in the region.
2. The average weekly/monthly rent paid in each category.
3. The rental interruption period for different damage states by building type.
4. The conditional probabilities of dwelling damage state by building type and earthquake scenario.

Based on input data availability, this report specifically focused on rental or lease income loss from residential and commercially occupied private dwellings only. Data contained in ABS Census 2016 is used. The Census contains tenure and rental information on residential properties only. It contains information on the weekly amount of rents that were paid by occupied private dwellings by dwelling structure, tenure type. In the base model for rental income loss, the data was customised for Melbourne CBD that included suburbs of Melbourne, Docklands and Southbank. This report uses CLUE 2018 for information at individual building level with a description of the type of space use.

Matching Census 2016 and CLUE 2018 on Dwelling Types:

The Census dwelling type categories include:

1. Separate house;
2. Semi-detached, row or terrace house, townhouse etc with one storey;
3. Semi-detached, row or terrace house, townhouse etc with two or more storeys;
4. Flat, unit or apartment in a one or two storey block;
5. Flat, unit or apartment in a three storey block;
6. Flat, unit or apartment in a four or more storey block;
7. Flat, unit or apartment attached to a house;
8. Caravan, cabin, houseboat;
9. Improvised home, tent, sleepers out;
10. House or flat attached to a shop, office, etc;
11. Not stated; and
12. Not applicable.

The residential buildings in the CLUE were not classified to such detailed categorisation as used in the Census, classifying residential accommodation in Melbourne CBD by only House/Townhouse and Residential Apartment. In order to facilitate data matching between Census and CLUE, the more detailed

Census classification was grouped into the following four broad categories. The broad categories combined one or more of the twelve Census categories.

1. Separate House
2. Semi-detached, row or terrace house, townhouse, etc
    a. One storey
    b. Two or more storeys
3. Flat or apartment
    a. In a one or two storey block
    b. In a three-storey block
    c. In a four or more-storey block
    d. Attached to a house
4. Other dwelling
    a. Caravan
    b. Cabin, houseboat
    c. Improvised home, tent, sleepers out
    d. House or flat attached to a shop, office, etc

However, for this analysis we have only included Category- 3 (above): Flat or Apartment to match Residential Apartments category in CLUE; and Category- 2 (above: Semi-detached, row or terrace house, townhouse to match House/Townhouse category in CLUE as the other categories were not present in the exposure database.

Tenure Type

The Census contains information about housing tenure - if the dwelling is

1. owned outright;
2. owned with a mortgage;
3. being purchased under a rent-buy scheme;
4. rented;
5. occupied rent free;
6. occupied under a life tenure scheme; and
7. Other.

For the purpose of residential rental income loss estimation, the information requirement is whether a rented, encumbered with a mortgage or subject to any other tenure type. Consequently, the above Census classifications were grouped into the following three broad categories.

1. Pays Rent
    a. Rented
2. Pays Mortgage
    a. owned with a mortgage

b. being purchased under a rent-buy scheme

3. Pays Neither
   a. owned outright
   b. occupied rent free
   c. occupied under a life tenure scheme

Using Census 2016, it is estimated that 66 per cent of the residential private dwellings in Melbourne CBD are paying rent.

Estimating Weekly Rent by Dwelling Type

The Census asked how much the household paid in rent or mortgage per week as a continuous variable in absolute dollar values. The rent payment details in the Census for the residential category are presented in Table 18 below. Table 18 also contains information on gross floor area by type of space use for the corresponding categories of Residential Apartment and House/Townhouse and the weekly rent per square metre was estimated.

TABLE 18 ESTIMATED WEEKLY RENT PER SQUARE METRE USING CENSUS AND CLUE.

Census Weekly Rent Total	Total Rent Value in AUD (Census 2016)	Number of Dwellings (Census 2016)	Floor Area by Space Use in Square Metre (CLUE 2018)	Estimated Weekly Rent per (AUD) Square Metre
Flat or apartment	21178691	42044	461367	45.90
Semi-detached, row or terrace house	42044	119	5140.96	13.28

This estimated weekly rent values per square metre were used to estimate total rental income values at the building level using the floor area of the building allocated to that type of space use.

Likewise, the conditional probabilities of different damage states at individual building level and the corresponding business interruption periods were applied to the total rental income values in the base model and the overall 66 per cent paying rent in Melbourne CBD were apportioned and the total rental income loss in those categories were estimated.

Estimating Commercial Rental Income Loss

The lease values per square metre in the commercial categories in the Melbourne CBD were estimated based on data contained in Colliers International, 2020. The rental values in office space use category were classified into the asset class of Premium/ A Grade/B Grade depending on the office fit outs and settings. CLUE data at individual building level does contain information on type of space use it does not contain information on the asset class of the building. Consequently, the net face rent values reported in the Collier International report in these three categories were averaged and estimated per square metre per week. The rental estimates were presented in Table 19.

TABLE 19 RENTAL ESTIMATES FOR COMMERCIAL OFFICE SPACE USE IN MELBOURNE CBD.

Building Asset Class	Vacancy Rate (%) (December 2019)	Net Face Rents ($/SQM P.A.)	Average Rent ($/SQM P.W)
Premium	3.2	784	12.38
A Grade		638	
B Grade		509	

The CLUE data categorises floor space by usage as given in Table 20. However, not all of these are considered to attract rent. Hence spaces categorised into one of the following usages were ignored in the computation of floor area in each building available for commercial rent:

- Common Area.
- Community Use.
- House/Townhouse – estimated in the residential rent category.
- Park/Reserve.
- Parking - Private Uncovered.
- Residential Apartment - estimated in the residential rent category.
- Square/Promenade.
- Unoccupied - Under Construction.
- Unoccupied - Under Demolition/Condemned.
- Unoccupied - Under Renovation.
- Unoccupied - Undeveloped Site
- Unoccupied – Unused.

TABLE 20 TYPES OF SPACE USE IN MELBOURNE CBD BASED ON CLUE DATA.

CLUE SPACE USE DESCRIPTION	Freq.
Commercial Accommodation	104
Common Area	1,121
Community Use	13
Educational/Research	121
Entertainment/Recreation - Indoor	717
Equipment Installation	209
Hospital/Clinic	90
House/Townhouse	17
Institutional Accommodation	5
Manufacturing	2
Office	613
Park/Reserve	1
Parking - Commercial Covered	79
Parking - Commercial Uncovered	3
Parking - Private Covered	284
Parking - Private Uncovered	8
Performances, Conferences, Ceremonies	53
Private Outdoor Space	4
Public Display Area	11
Residential Apartment	195
Retail - Cars	2

CLUE SPACE USE DESCRIPTION	Freq.
Retail - Shop	540
Retail - Showroom	24
Retail - Stall	26
Sports and Recreation - Outdoor	2
Square/Promenade	2
Storage	146
Student Accommodation	3
Unoccupied - Under Construction	20
Unoccupied - Under Demolition/Condemned	5
Unoccupied - Under Renovation	78
Unoccupied - Undeveloped Site	1
Unoccupied - Unused	354
Wholesale	12
Workshop/Studio	44
Total	4,909

The weekly rent total was estimated by multiplying the weekly rent per square metre with the total floor area in that usage category. Thus a weekly rent for each building could be computed which, when combined with the estimated business interruption period (related to a building's damage state), enabled the income loss to be estimated.

The Collier International Report informs a 3.2% vacancy rate in Melbourne CBD in December 2019, which was before the COVID 19 impact. That vacancy rate was applied to the overall commercial rental income loss.

SCENARIO IMPACTS

In this section the impacts of the single earthquake scenario event are presented, summarised and compared. They include direct damage loss, indirect losses and costs due to earthquake damage, semi-intangible measures of the value of life, and the intangible value placed on heritage structures.

MITIGATION TAKE-UP

Mitigation of URM buildings was modelled by randomly selecting 162 out of 687 URM buildings to be retrofitted. All the selected buildings were of types URM4, URM5 or URM7. This represented approximately 25% of the total URM population which is what was judged achievable over a 30 year campaign of mitigation.

DIRECT IMPACTS

The impacts on the study region from the scenario event were estimated for three metrics: 1) monetary loss from necessary repair of physical damage to buildings and contents; 2) number of damaged buildings; and, 3) number of casualties. For the casualty estimation, the scenario was assumed to occur at 11 AM on a weekday other than Friday.

Table 21, Table 22, Table 23 and Table 24 set out the estimated building damage loss for the scenario and how these would be moderated after 30 years of retrofit.

TABLE 21 ESTIMATED BUILDING DAMAGE LOSS FOR THE SCENARIO EVENT (M AUD).

Building Group	Unretrofitted	Retrofitted
All	736.466	663.238
URM buildings	170.423	97.195

TABLE 22 ESTIMATED CONTENTS LOSS FOR THE SCENARIO EVENT (M AUD).

Building Group	Unretrofitted	Retrofitted
All	75.224	67.757
URM buildings	17.375	9.908

TABLE 23 ESTIMATED NUMBER OF DAMAGED BUILDINGS FOR THE SCENARIO EVENT FOR ALL BUILDINGS.

Damage State	Unretrofitted	Retrofitted
Slight	502	532
Moderate	172	139
Extensive	40	32
Complete	3	2

TABLE 24 ESTIMATED NUMBER OF DAMAGED BUILDINGS FOR THE SCENARIO EVENT FOR URM BUILDINGS.

Damage State	Unretrofitted	Retrofitted
Slight	99	129
Moderate	47	14
Extensive	10	2
Complete	1	0

Table 25 and Table 26 set out the modelled casualties for the scenario event.

TABLE 25 ESTIMATED INDOOR CASUALTIES FOR THE SCENARIO EVENT.

Injury Severity Level	Unretrofitted	Retrofitted
1	113	95
2	53	42
3	1	1
4	2	1

TABLE 26 ESTIMATED OUTDOOR CASUALTIES FOR THE SCENARIO EVENT.

Injury Severity Level	Unretrofitted	Retrofitted
1	45	37
2	44	35
3	89	73
4	535	438

The projected reduction in loss is larger for URM buildings than for the overall population of community buildings due to the larger proportion of buildings retrofitted and the typically greater vulnerability of these older URM buildings.

INDIRECT IMPACTS

Estimated indirect losses to businesses caused by physical damage to buildings preventing businesses housed in those buildings from functioning are presented below. Table 27 presents the combined proprietary (owner/managers) and wage/salary income losses in Melbourne CBD for the scenario event and the modelled reduction in these losses with retrofit strategy into the future.

TABLE 27 ESTIMATED COMBINED WAGE LOSS INCOME LOSS FOR THE SCENARIO EVENT (M AUD).

Building Group	Unretrofitted	Retrofitted
All	628.7	520.1
URM buildings	162.7	54.0

Table 28 below presents the residential rental income loss in Melbourne CBD for the scenario event and the modelled reduction in these losses with retrofit strategy taken 30 years into the future.

TABLE 28 ESTIMATED RESIDENTIAL RENTAL INCOME LOSS FOR THE SCENARIO EVENT (M AUD).

Building Group	Unretrofitted	Retrofitted
All	24.9	22.9
URM buildings	3.1	1.0

The estimated commercial rental income loss values for the earthquake scenario for Melbourne CBD are presented in Table 29.

TABLE 29 ESTIMATED COMMERCIAL RENTAL AND LEASE INCOME LOSS FOR THE SCENARIO EVENT (M AUD).

Building Group	Unretrofitted	Retrofitted
All	198.4	154.4
URM buildings	66.1	22.1

The estimated cost of the scenario earthquake injury related medical care and the value of lost life for the current case study area and after the retrofit of 25% of the URM buildings has been assessed. The results for indoor casualties are summarised in Table 30 and for exterior casualties (by far the largest) in Table 31.

TABLE 30 ESTIMATED HEALTH COST (AUD) DUE TO INDOOR CASUALTIES FOR THE SCENARIO EVENT (M AUD).

Injury Severity Level	Unretrofitted	Retrofitted
1	0.097	0.081
2	0.174	0.138
3	0.0047	0.0037
4	6.8	5.3

TABLE 31 ESTIMATED HEALTH COST (AUD) DUE TO OUTDOOR CASUALTIES FOR THE SCENARIO EVENT (M AUD).

Injury Severity Level	Unretrofitted	Retrofitted
1	0.038	0.031
2	0.144	0.118
3	0.483	0.396
4	2,299.6	1,884.4

The direct and indirect losses, both financial and in terms of the value of lost life, are summarised in Table 32. The relativity between the costs is apparent with building damage losses and wage losses the largest components of the financial losses. The semi-intangible value of lost life is a very significant additional metric and dominates the total assessed loss. With reference to Table 32, if can be seen that 64% of the reduced losses to society as a whole were associated with avoided fatalities. From a comparison of the financial losses in isolation between the present condition and after retrofit, they reduce by 14%, and with all losses combined they reduce by 16%.

TABLE 32 SUMMARY OF ESTIMATED LOSSES ACROSS ALL METRICS FOR THE CURRENT STUDY REGION AND AFTER RETROFIT (M AUD).

Building Condition	Building Damage [$m]	Contents Loss [$]	Wages Loss [$]	Rental Loss [$]	Lease Loss [$]	Heath Care Cost [$]	Value of Lost Life [$]	Total [$]
Present	736.5m	75.2m	628.7m	24.9m	198.4m	0.9m	2,306.5m	3,968m
After Retrofit	663.2m	67.9m	520.0m	22.9m	154.4m	0.8m	1,889.1m	3,319m
Reduction	73.3m	7.3	108.7	2.0m	44.0m	0.1m	417.4m	649m

INTANGIBLE VALUE ASSESSED FOR HERITAGE BUILDING PRESERVATION

This research has considered a further measure of lost value, drawing upon the intangible value research undertaken by the UWA as part of the CRC (Rogers *et al*, 2021). Part of this research was supported by the outcomes of the York, WA, mitigation study and assessed the value placed by households in a community on the heritage buildings they have. The outcomes of this research have been applied with the aim of capturing more fully the community benefits of the retrofit program explored.

In the Melbourne CBD 687 URM buildings were identified. With reference the City of Melbourne's heritage register (https://www.melbourne.vic.gov.au/building-and-development/heritage-planning/Pages/i-heritage-database.aspx) 470 of the URM buildings in the study region were found to be heritage listed (68%). The retrofit program is predicted to reduce the number of URM buildings that sustain extensive or complete damage from 11 to 2. If retrofit was evenly applied to URM buildings (heritage and non-heritage listed) in the retrofit program, it could be concluded that 68% of the voided severe damage outcomes related to heritage buildings (6 say).

In the UWA research it was assessed that 64% of residential households are willing to pay to avoid the loss of a heritage buildings in both large and medium earthquake events. The average household value assessed in the research was $195 per heritage listed buildings. As a lower bound figure, if the 89,200 households in the City of Melbourne LGA area (2019 census) is only considered, the intangible benefit of the avoided loss would be:-

$$\text{Avoid Heritage Value Loss} = 89{,}200 \times 0.64 \times \$195 \times 6 = \$67\text{m}$$

This value would be an indicative 10.3% increase in benefit of the 30 year retrofit program in the event of the rare earthquake considered. The actual value would be much greater if the value placed on the heritage buildings by households outside of the City of Melbourne LGA were added. There are nearly 2 million households in the greater Melbourne metropolitan area.

MELBOURNE CBD EARTHQUAKE RISK

AVERAGE ANNUALISED LOSS ASSESSMENT

Average Annualised Loss (AAL) is the common measure of long term financial risk associated with long term exposure to a hazard environment. It is the measure used by the insurance industry to price the component of an insurance premium related to earthquake hazard. In this project AAL was calculated for building damage as a measure of the current earthquake risk in the study area. It was also calculated into the future using the vulnerability models for retrofitted buildings to assess the reduction in risk achieved. The results are presented in Table 33 for all building stock and for the URM subset alone.

The AAL for all the unretrofitted buildings in the Melbourne CBD was estimated to be 0.0028% which is less than the value of 0.0098% recently assessed for the Perth metropolitan area based on NSHA18 (Edwards et al., 2019) bedrock hazard, surface soils and Perth building stock. The bedrock hazards for the Perth and Melbourne CBD's are almost identical at a 5,000year ARI, but the building stock of Perth is predominantly unreinforced masonry and located on overall softer soils that leads to the greater AAL for Perth. As with the scenario impact results, risk reduction by retrofit is clearly observable with approximately 38% reduction in AAL for the URM buildings. For the all buildings the long term loss associated with earthquake hazard was modelled to be reduced by 7%.

TABLE 33 AAL (%) FOR ALL AND URM BUILDINGS.

Building Group	Unretrofitted	Retrofitted
All	0.0028	0.0026
URM buildings	0.0315	0.0194

SCENARIO LOSS LIKELIHOODS

The loss exceedance curves were developed through an event-based probabilistic calculation using the NSHA18 input seismic source and ground motion models to assess the likelihood of the scenario losses. These curves enable the assessment of the likelihood of experiencing a loss as distinct from experiencing a severity of bedrock shaking. The scenario was selected to match a likelihood of ground shaking intensity in the centre of the study area at the bedrock surface level (Soil Class Be). The loss experienced in the scenario is the result of the surface shaking as modified by the overlying soils and the distribution of the building stock across the area. The likelihood of loss as a measure of impact does not necessarily correspond with the likelihood of ground shaking.

The scenario losses have been plotted on the loss exceedance curve for the present day in Figure 29. Scenario loss has a return period of 5,000 year. It can be seen that the rarity of scenario loss is indicated to be almost the same as that of the ground motion.

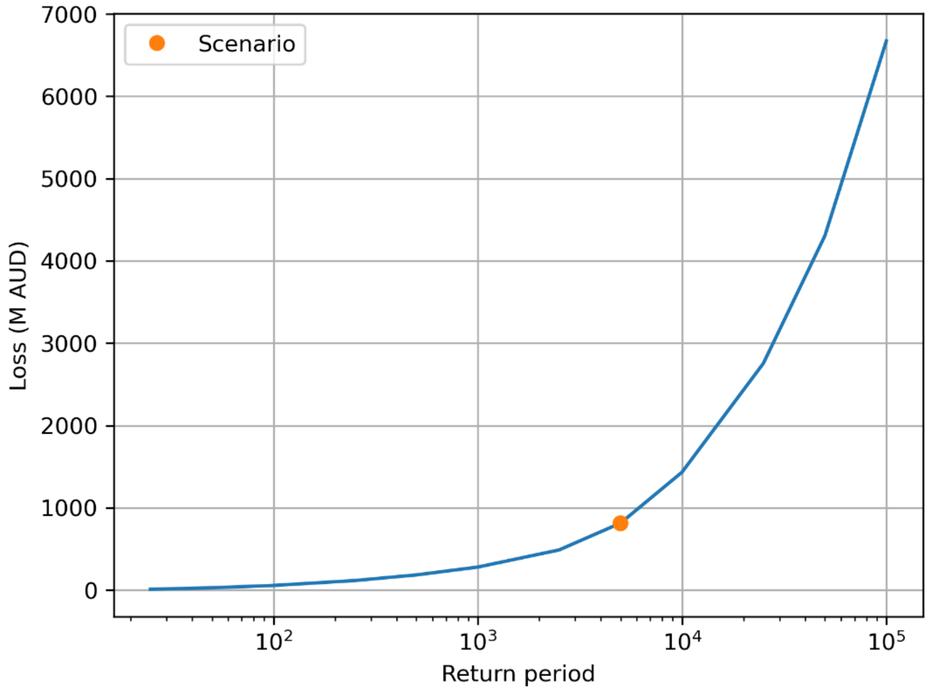

FIGURE 29 LOSS EXCEEDANCE CURVE FOR THE PRESENT DAY WITH AGGREGATE LOSS FROM THE SCENARIO EVENT PLOTTED.

The effect of retrofit on the entire building stock can be seen in the loss exceedance curves in Figure 30. The horizontal shift of the curves indicates a reduced likelihood of loss achieved through retrofit. The horizontal shift is more evident for the URM buildings and plotted in Figure 31.

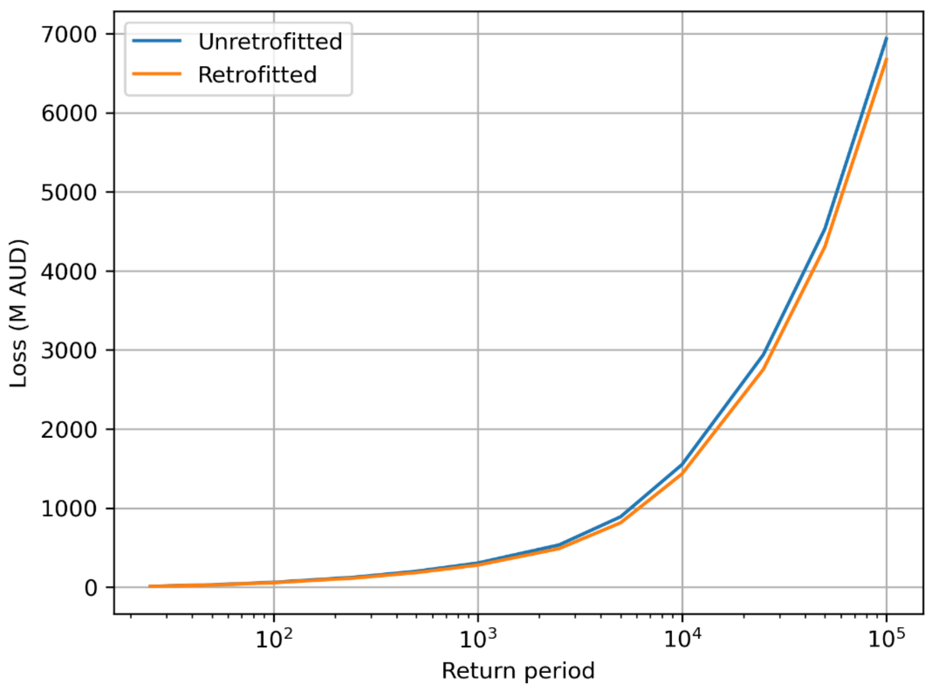

FIGURE 30 LOSS EXCEEDANCE CURVES FOR THE RETROFIT COMPARED WITH THE CURRENT STATE FOR ALL BUILDINGS.

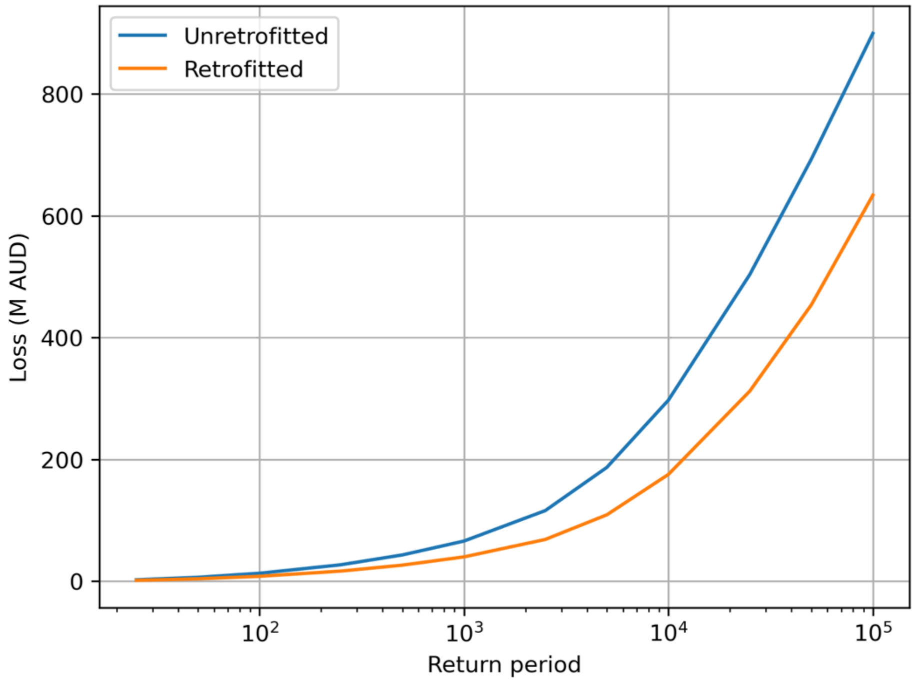

FIGURE 31 LOSS EXCEEDANCE CURVES FOR THE RETROFIT COMPARED WITH THE CURRENT STATE FOR URM BUILDINGS.

DISCUSSION

The building stock of central Melbourne has a concentration of older masonry structures. For the study region selected for this project, some 45% of the buildings present are of this vulnerable type of construction. Mitigating these legacy structures in Melbourne and in other Australian communities would necessarily be a progressive task that would realistically take decades to fully implement. In this research a realistic uptake rate was adopted that would address 25% of the 687 masonry buildings of the study region. This has enabled the effectiveness of this program to be explored virtually in the context of a rare but credible earthquake occurring beneath central Melbourne (1% chance of being exceeded in the next 50 years).

It was found that direct damage to buildings and contents for all building types was reduced by 10%. The reduction for the URM subset was 43%. Indirect losses associated with wages, rental income, commercial leases and health care cost reduced by 18%. With the consideration of the value of lives lost to society, the reduction was 16% overall through the targeted retrofit of 162 of the 1543 buildings in the case study area. Importantly, the measures where not comprehensive and so represent a lower bound to the actual avoided impacts mitigation achieves. For example, the cost of emergency response, clean-up and community recovery support were not considered.

While a single scenario event is informative, risk is the combination of all potential earthquake events ranging from smaller more frequent ones to larger and rarer events. Financial risk considers the full spectrum and in this study it was found that the risk posed by the URM building stock at the end of the 30 year program was reduced by 32%, which could translate into reduced property insurance. This is not expected to be enough alone to incentivise property owners.

The benefits in terms of avoided injury were also clearly illustrated. Deaths due to falling masonry immediately outside of building frontages dropped from 535 to 438 or 18%, with a similar percentage reduction for severe injury. The retrofit of the most vulnerable 10% of the building stock was shown to result in a more significant reduction in casualties. This finding is informative in that, while economic benefits may not offset the mitigation investment, the avoidance of loss of life may be a priority. Cheaper levels of retrofit with the objective of protecting life rather than property may be indicated.

Significantly, the study utilised other recently delivered CRC research to consider the value placed on many of these vulnerable buildings by the community itself. Some 68% of the URM buildings in the study region are heritage listed and it was found that, if residents within the City of Melbourne LGA only is considered, the indicative benefits from avoided loss of heritage value structure was approximately 10% of (and on top of) all others measures considered. The project has illustrated how visibility can be given to less tangible values to enable a broader consideration of the benefits in mitigation decision making.

SUMMARY OF RESULTS

This case study project has demonstrated the utility of the mitigation research and economic framework developed under the overarching Bushfire and Natural Hazards CRC Project A9, *Cost-effective mitigation strategy development for building related earthquake risk*. With the focus on URM buildings, it has also been a further and direct application of the utilisation project entitled "Earthquake Mitigation of WA Regional Towns: York Case Study".

The research has provided a quantitative assessment of the effectiveness of a virtual retrofit of central Melbourne's most vulnerable buildings. URM buildings disproportionately contribute to the community risk and also yield the greatest benefits when retrofitted.

One key area of benefit highlighted was the avoided loss of life and associated value. This may point to the need to address vulnerable masonry building elements in high exposure pedestrian precincts where the potential loss of life is considerably greater.

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