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SEISMIC PERFORMANCE OBJECTIVES: ADEQUATE FOR COMMUNITY RESILIENCE?

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Abstract

Structural engineers design buildings and infrastructure according to the earthquake action to a certain level of return period specified in the code of practice, whilst the rationale behind such requirement is commonly untold. In fact, even if a structure is designed strictly in conformance with a modern code of practice, there is still a small chance of failure or collapse in an extreme earthquake event, due to the uncertainties in material properties and actual ground motion characteristics. This residual risk should be taken as a governing parameter for determining or evaluating the performance goals of seismic design. Various approaches have been implemented or proposed in the last decade for setting risk-based performance requirements for seismic design. But then, how safe is safe enough? Are they adequate for ensuring community resilience after an earthquake? This is a missing piece of knowledge in seismic design.

This paper attempts to provide this missing piece by evaluating whether the stipulated performance objectives are adequate for community resilience or not. The earthquake fatality risk for society is estimated based on regional earthquake loss modelling for Melbourne, Australia, which is a region of lower seismicity. This is then benchmarked against a regulatory requirement based on an approach proposed by the authors for evaluating the adequacy of existing code level for life safety and community resilience. The results show that the earthquake fatality risk for society appears to be unacceptable.

There is a common belief amongst engineering professionals that it is uneconomical to design structures to resist stronger earthquakes. However, the public has never/rarely been asked about their preferences actually. Recent research has shown that building owners are indeed willing to pay for better earthquake protection and resilience (i.e. habitable or functional after a major earthquake event).

As the consequences of structural failure concern life safety, an ideal building code should indicate the expected level of fatality risk since it is a legal document that sets forth requirements for protecting life and ensuring community resilience. The research outcomes presented are important resources for guiding the development of future editions of seismic codes globally.

Keywords: Residual risk; Performance goal/objective; Life safety; Fatality; Societal; Community resilience; Building

1. Introduction

1.1 Current seismic performance objectives

The current seismic performance objectives have firstly been established in the 1968 edition of the document titled "Recommended Lateral Force Requirements and Commentary", published by the Structural Engineers Association of California (SEAOC) (commonly known as the SEAOC Blue Book) [1]. This set of performance objectives has been passed onto later editions and the recent editions state that "structures designed in conformance should, in general, be able to:

Level 1: resist a minor level of earthquake ground motion without damage;

Level 2: resist a moderate level of earthquake ground motion without severe structural damage, but possibly experience some non-structural damage;

Level 3: resist a major level of earthquake ground motion having an intensity equal to the strongest either experienced or forecast for the building site, without collapse, but possibly with some structural as well as non-structural damage".

Similar set of design objectives has also been adopted in other codes and standards all around the world, including the Australian Standard AS1170.4, the National Building Code of Canada (NBCC), the New Zealand Standard NZS1170.5 and the Chinese Code for Seismic Design of Buildings GB50011 [2, 3]. These performance requirements at various levels of seismic actions have further been expanded and developed into the performance-based earthquake engineering framework since the 1990's [4–7].

For collapse prevention level (i.e. Level 3), as it is difficult to reliably forecast the intensity level of the strongest earthquake ground motion, an intensity level associated with a reference probability of exceedance (PE) in a notional design life of 50 years, or the corresponding reference return period (RP) is typically adopted. Such intensity level is regarded as maximum considered earthquake (MCE) ground motion. It recognises that no design code or standard can provide 100% confidence of life safety: "The protection of life is reasonably provided, but not with complete assurance", as stated in the SEAOC Blue Book. In other words, there exists certain level of residual risk in our structures. Hence, it should be logical and appropriate that the PE for Level 3 is defined along with the consideration of the residual risk of structural collapse and casualty [8–11].

1.2 Risk-based performance objectives

Recently, there have been attempts to incorporate risk measures in seismic design of buildings. The 2010 edition of the structural design standard ASCE/SEI 7 has firstly set out risk-targeted performance requirements for seismic design, as proposed by Luco et al. [12], which was then adopted by reference in the 2012 edition of the International Building Code (IBC) (adopted principally in the United States) [13]. Essentially, the requirements of collapse prevention (i.e. Level 3) were re-defined in terms of "*risk-targeted*" maximum considered earthquake (MCE_R) ground motion (as described in FEMA P-750 report [14]), which requires ordinary buildings to be designed to have equal (uniform) collapse risk of 1% in 50 years (i.e. annual PE of 2×10^{-4}). Meanwhile, the probability of collapse should be limited to 10% under the MCE_R action.

The rationale behind such requirements is actually not clear, and there has been inadequate formal discussion over such an important issue [10, 15]. In fact, the newly-defined MCE_R ground motion levels and the previous MCE ground motion levels at various locations in the U.S. are broadly consistent (within plus or minus 15%, except very few locations such as around the New Madrid Seismic Zone). Also, the collapse risk of 1% in 50 years is about what had been achieved in the western U.S. with the previous requirements. In other words, the overall seismic performance of building stock designed (or upgraded) according to the new requirements has not been enhanced at the national level.

In the European context, Dolšek [16] has contemplated a set of risk-based performance objectives for seismic design and Dolšek et al. [17] have proposed a decision model that contains parameters for risk-based seismic design, which are used for guiding the future revision of Eurocode 8. Apart from the target collapse risk, the target expected economic losses for a given period of time can be used for controlling the amount of damages due to earthquakes. Meanwhile, a risk-targeted map has been developed for mainland France [18] and preliminary study has been conducted towards developing such a map for the whole Europe [19]. A comprehensive review can be seen in Douglas and Gkimprixis [20].

On the other hand, acceptable level of failure probability of individual building has been recommended [11, 21] that can be used as a performance objective in seismic design for controlling fatality risk. There are also attempts to evaluate structural design requirement or safety policy by employing building-based fatality risk using *F-N* curve [21] and hypothetical scenario-based *F-N* diagram for a group of identical (non-ductile concrete frame) buildings subjected to a uniform strong shaking [9]. The *F-N* curve / diagram is a plot of the annual rate, *F*, of exceeding *N* fatalities in one earthquake.

1.3 Societal fatality risk as a community resilience measure

The aforementioned risk-targeted or risk-based design requirements are mainly based on collapse risk or probable losses (economic or fatality) in individual (or a group of identical) buildings. These are certainly excellent attempts to provide a more scientific and rational basis for the safety level of a structure and an individual. However, as there are numerous buildings in the affected region of a major earthquake event, the potential consequence and impact to society has to be taken into account in the evaluation of the safety level of our engineered structures as well as the resilience of the community.

Once the societal risk function is obtained, which provides an indication about the level of risk or the amount of loss in a probabilistic manner, an important missing link would be a regulatory framework that sets forth community resilience objective, such that the actual risk function can be benchmarked against. This paper attempts to put forward a practical scheme (initially proposed in [22, 23]) for determining regulatory *F-N* function with the consideration of a tolerable level of individual fatality risk and the total population of the region, which can be suitable for adoption in a public safety regulation or guideline. The proposed approach is illustrated in a case study for the Greater Melbourne Region based on regional earthquake loss modelling.

2. Regulatory Community Resilience Objective

The primary focus of seismic design objective is upon life safety. This should still be valid nowadays even when other objectives, such as economic loss control and functionality, have attracted the attention these days. In this section, a methodology is proposed for evaluating community resilience based on life safety, and for justification of a required change of design code level. Section 2.1 introduces the benchmark format of *F-N* function in existing regulations for examining industrial risk. A proposed method for scaling the benchmark *F-N* function based on population will be introduced in Section 2.2 and followed by an illustration in Section 3 & 4 with the actual societal risk functions for the Greater Melbourne Region (as originally presented in [24]).

2.1 Benchmark ALARP F-N functions

In the field of safety engineering, industrial risk is being quantified at a system level. The risk is the combination of the frequency of recurrence and the consequence of an event. This is typically presented by an *F-N* plot, as shown in Fig. 1, on which the unacceptable and acceptable regions are usually defined, whilst a region called ALARP is usually specified in between the two. ALARP stands for “as low as reasonably practicable”, which is also known as SFAIRP, i.e. “so far as is reasonably practicable”. This is typically used in the regulation and management of systems that involve significant amount of risk. The residual risk is considered tolerable if the actual *F-N* function falls into the ALARP region. Further risk reduction can be justified by a cost-benefit analysis.

The benchmark *F-N* functions for the upper (*BU*) and lower (*BL*) bounds of ALARP region can respectively be generalised in a parametric form as:

$$\log(F_{BU}) = a - b \times \log(N) \tag{1}$$

$$\log(F_{BL}) = (a - 2) - b \times \log(N) \tag{2}$$

The benchmark *F-N* functions for ALARP are typically truncated by a maximum value, $N_{B,max}$, that limits the number of fatalities in an event. Depending on the rescue and emergency services capability of the region of interest, the limiting fatality number, $N_{B,max}$, can be predefined by relevant government authority. For example, it may be set as a percentage of the total population in the affected area.

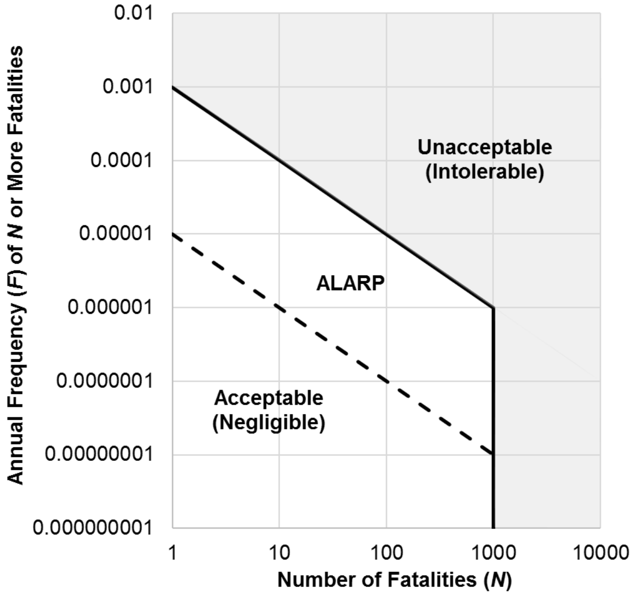

Fig. 1 – Example of *F-N* diagram typically used in safety regulations and guidelines [23]

The annual average Potential Loss of Life (*PLL*) implied by the benchmark upper bound ALARP function, PLL_{BU}, can be calculated by:

$$PLL_{BU} = \sum_{1}^{N_{B,max}} F_{BU}(N) \tag{3}$$

2.2 Population-scaled ALARP F-N functions

The ALARP *F-N* function for safety evaluation is typically used for a single asset, e.g. a building that houses a large number of occupants or a critical infrastructure likes an airport. Hence, the extent of the affected area is fairly limited, say, in the order of a hundred metre radius, except that the effects can be diffused like radioactive substances from a damaged nuclear power plant. However, the affected region of a damaging earthquake that could lead to structural failure and loss of life is much larger, in the order of tens of kilometre radius. Hence, the benchmark ALARP *F-N* function in existing regulations as described in Section 2.1 cannot be directly used for evaluating the earthquake resilience of a society. An appropriate way of setting the ALARP *F-N* function is needed in the first place.

It is proposed that a tolerable amount of the average annual *PLL* due to structural failures in the affected region can be computed based on the tolerable annual fatality rate, $\lambda_{D,tolerable}$, of 10^{-6} [22, 23], which has been commonly adopted by various governments, organisations and documents, as reviewed in [11]. With a total population of five million people in the Greater Melbourne Region, five fatalities each year or fifty every decade might be considered tolerable. This forms the basis of the upper bound ALARP *F-N* function, which has to be scaled by the total population of the affected region, $\mathcal{P}$. For this purpose, a population-scaled factor, θ_P, is introduced for adjusting the ALARP *F-N* functions for a specific region:

$$\theta_P = \frac{\mathcal{P} \times \lambda_{D,tolerable}}{PLL_{BU}} \tag{4}$$

The rate of exceedance of the *F-N* functions for the upper and lower bounds of ALARP region can then be scaled by the population-scaled factor:

$$\log(F_{PU}) = a - b \times \log(N) + \log(\theta_P) \tag{5}$$

$$\log(F_{PL}) = (a-2) - b \times \log(N) + \log(\theta_P) \tag{6}$$

such that the annual average PLL implied by the scaled upper bound ALARP function, PLL_{PU}, becomes,

$$PLL_{PU} = PLL_{BU} \times \theta_P = \mathcal{P} \times \lambda_{D,tolerable} \tag{7}$$

3. Earthquake Fatality Estimates for Melbourne

Regional earthquake loss modelling is occasionally conducted by government agencies, re-insurance sector or asset managers of spatially distributed infrastructure for assessing the resiliency of a city, evaluating probable financial impact, or deriving disaster management plan. A semi-probabilistic procedure has been proposed for obtaining *F-N* function based on a suite of selected scenario earthquakes, each of which is associated with a return period (or probability of exceedance) [24], as briefly described in this Section.

3.1 Characterisation of the Greater Melbourne Region

Melbourne has a total population of 4,205,584 (as of the 2011 census) according to the Australian Bureau of Statistics. In this case study, the whole region is divided into 9,658 geo-units, as defined by the Australian Statistical Geography Standard (ASGS 2016) based on the census data of 2011, and can be found in the National Exposure Information System (NEXIS) developed by Geoscience Australia. The population density of each geo-unit are shown in Fig. 2.

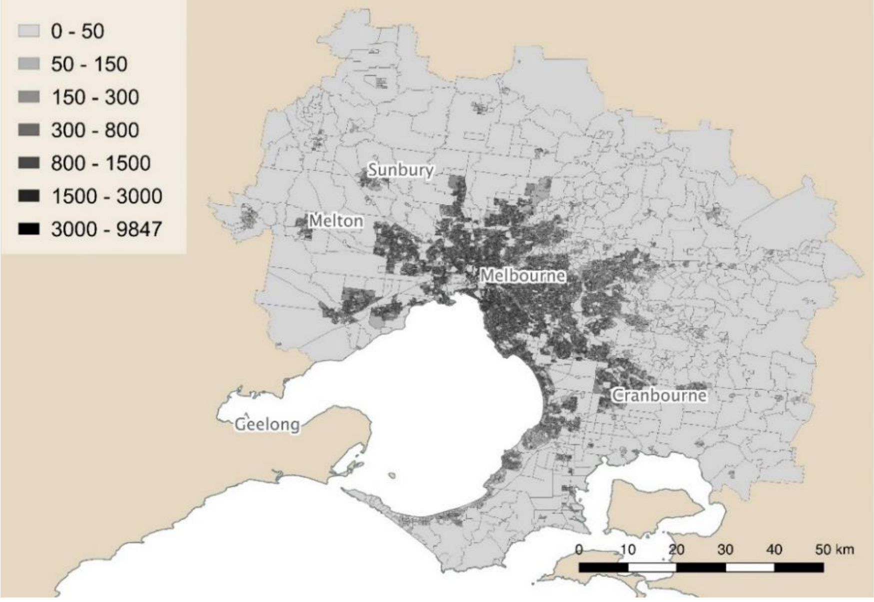

Fig. 2 – Population density in each of the 9,658 geo-units in the Greater Melbourne Region (in the unit of the number of people per square metre times 10^{-5}) [24]

The ground condition of each geo-unit has been broadly categorised according to NEHRP soil classification scheme, based on the average shear wave velocity over the upper 30 m of sediments inferred from the topographical condition. Building exposure data was collected from NEXIS and based on the classification scheme recommended in Hazus Technical Manual [25]. The distributions of the ratio (in percent) of floor area of low-rise unreinforced masonry (URML) to the land area of each of the 9,658 geo-units in the Greater Melbourne Region are shown in Fig. 3. The distribution of population (in percent) at different time of a day is based on the recommendation in the User and Technical Manual of SELENA [26].

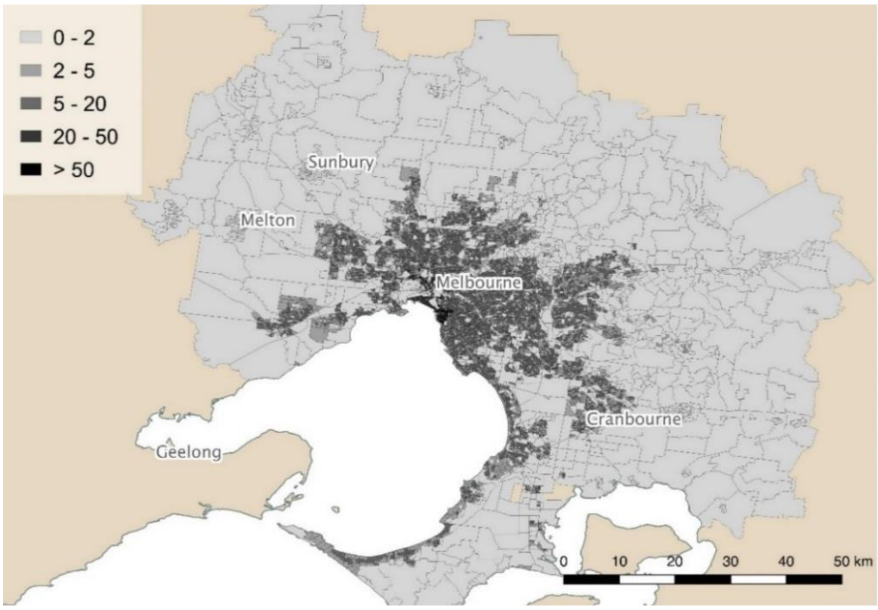

Fig. 3 – Distribution of the ratio (in percent) of floor area of low-rise unreinforced masonry (URML) to the land area of each of the 9,658 geo-units in the Greater Melbourne Region [24]

3.2 Selection of probabilistic earthquake scenarios

It is reasonably expected that the more vulnerable building types across the whole Australia generally is low-rise unreinforced masonry (URML) and low-rise concrete moment frame (C1L), whilst the seismic demand on high-rise buildings is low, which is typical in regions of low-to-moderate seismicity. As the predominant period of these two types of potentially vulnerable constructions is in the order of 0.3 sec, the spectral acceleration response at this single natural period (i.e. $SA_{0.3}$) was adopted for selecting hazard-consistent scenario earthquakes.

PSHA studies were conducted for the study region by various groups [27–29]. As seismic hazard predictions for annual frequency of exceedance as low as 10^{-5} are required for capturing the low-probability but high-loss events, the only set of hazard results that provides estimates for annual frequencies down to 2×10^{-5} (i.e. return period of 50,000 years) for Melbourne, Australia, can be found in [30], and was therefore adopted in this study.

Information about the locations and geometry of faults are available from the website of Geoscience Australia. The common faulting mechanism in Australia is reverse faulting due to the compressive behaviour of the continent [31]. The major known faults in and surrounding the Greater Melbourne Region are shown in Fig. 4. It is noteworthy that no major fault has been identified in the CBD area and inner suburbs of Melbourne. The maximum magnitude considered were estimated based on the correlation in Wells and Coppersmith [32]. 68 scenario earthquakes specifically matched for spectral acceleration response at T = 0.3 sec have been identified and the distribution of the epicentres is shown in Fig. 5.

3.3 Scenario-based fatality estimation

In this study, only fatalities directly due to structural damage are considered, which include both indoor and outdoor fatalities. The latter could be caused by the failure of parapet walls or the fall of non-structural wall panels. However, the estimates exclude those caused by co-existing events like fires, tsunami and landslides, or indirect causes including heart attacks, power failure and the release of hazardous materials.

The computer software SELENA was adopted for earthquake loss modelling. The key feature of SELENA compared to other loss estimation software is that a logic tree computational algorithm is implemented, such that epistemic uncertainties of any input (e.g. GMPEs) can be taken into account. Each input data is assigned with a factor that defines the relative weighting of the respective branch of the logic tree.

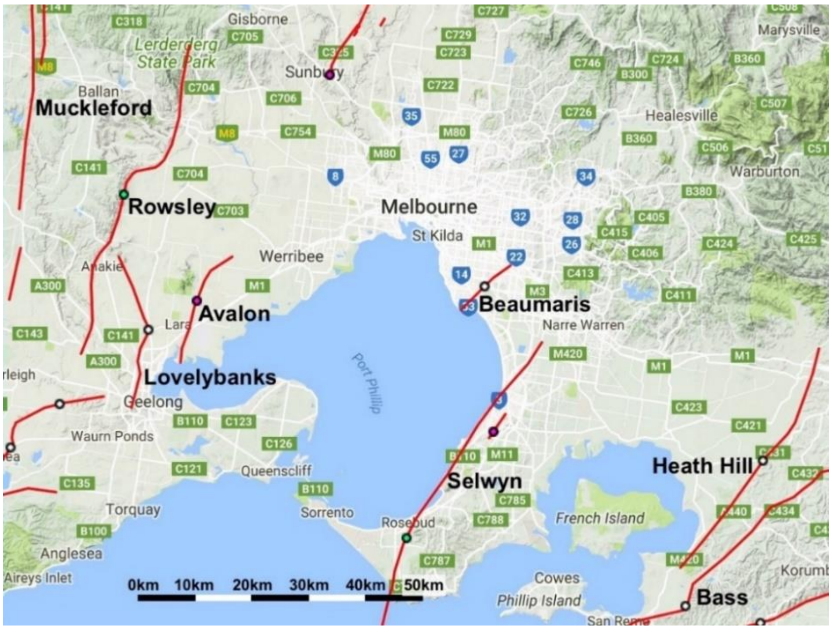

Fig. 4 – Major known faults in and surrounding the Greater Melbourne Region (reproduced from Geoscience Australia based on Google Maps) [24]

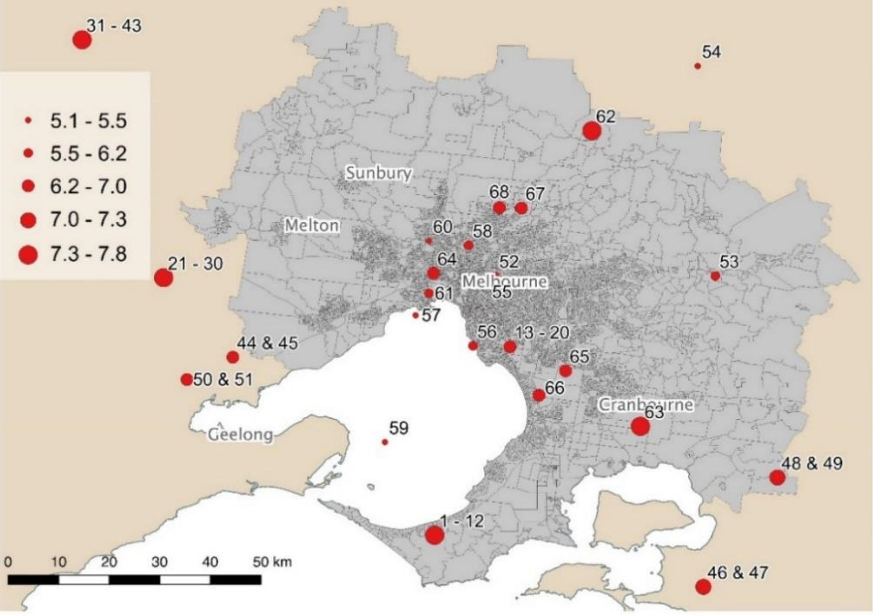

Fig. 5 – Distribution of the epicentres of 68 response-specific probabilistic scenario earthquakes identified for fatality estimation in the Greater Melbourne Region. The size of each circle indicates the relative size (magnitude) of earthquake [24]

On the other hand, a finite rupture model with a rupture surface geometry has to be defined for each earthquake scenario, along with the selected GMPE(s). A deterministic set of ground motion field can be computed for the study region, whilst spatial correlation of the ground motions can be incorporated as an add-on for a more accurate representation of the variabilities of the ground motions. A geo-unit is the basic unit in the loss modelling. In other words, the ground motion intensity and the associated response spectral parameters are uniform across the whole geo-unit.

As the structural response behaviours of Australian buildings are not completely known, the recommendations of capacity curves and fragility functions in Hazus Technical Manual were adopted in this illustration. In Hazus, the vulnerability of buildings has to be classified based on design code levels, namely, high, moderate and low, according to the Design Seismic Zones specified in the Uniform Building Code (UBC) (preceding the IBC). Meanwhile, a fourth level, pre-code, is recommended for buildings which were not designed and built according to a modern seismic code.

The first seismic structural design code in Australia was introduced in 1979, whilst earthquake-resistant design was basically not exercised until the 1989 Newcastle Earthquake. A brand-new Australian Standard for earthquake action was then published in 1993, and enforced in 1995. However it was not mandated and required for all commercial buildings until around 2008, following the 2007 release of the revised Australian Standard on earthquake actions, AS 1170.4. Considering the replacement rate around 2% per year nationally, the majority of the building stock in Australia was not specifically designed for earthquake resistance. Hence, Australian buildings were conservatively classified at pre-code level by this definition. Also, the number of fatalities was estimated based on the methodology given in [33]. The fatality rate and its distribution due to a magnitude 7.8 event occurring at the Muckleford fault (i.e. Number 43 in Fig. 5) is shown in Fig. 6 (with the epicentre annotated).

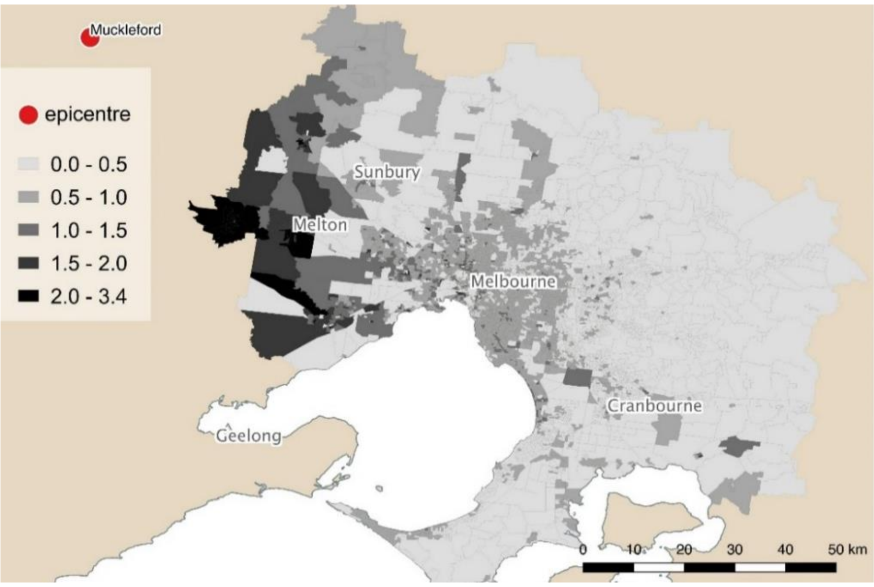

Fig. 6 – Fatality rate as a percentage of the population in each of the 9,658 geo-units in the Greater Melbourne Region due to a magnitude 7.8 earthquake occurring at the Muckleford fault [24]

4. Adequate for Community Resilience?

4.1 Societal fatality risk function

A societal risk recurrence function, in terms of number of fatalities (i.e. an *F-N* curve), has been constructed based on a dataset of the simulated amounts of fatalities in the Greater Melbourne Region due to the suite of 68 selected earthquake scenarios versus the corrected return periods, T_{RP} (or rates of exceedance, *F*) of the hazard [24]. Eq. (8) is the idealised *F-N* function in the form of an upper-truncated Pareto distribution function for the Greater Melbourne Region. The reference point of the function, i.e. N_{ref} and $T_{RP,ref}$, is anchored at 2475 years with 2700 fatalities. Based on the trend of the dataset at the long return period end, the estimated largest (i.e. truncated) number of fatalities, N_{max}, is in the order of 210,000, which is approximately 5% of the total population of the region. This *F-N* function is plotted as "Pre-Code" in Fig. 7. More details can be found in Tsang et al. [23].

$$\frac{1}{F} = T_{RP} = 2475\left(\frac{2700^{-1} - 210000^{-1}}{N^{-1} - 210000^{-1}}\right) \tag{8}$$

The corresponding *PLL*, or Average Annual Loss (*AAL*) of life, is around 13 per year on average. With respect to the population of the study area, this is translated to an average annual mortality rate of 3 in the unit of micromorts (i.e. 3×10^{-6}), which is three times of the tolerable individual risk limit of 1 micromort [11, 34].

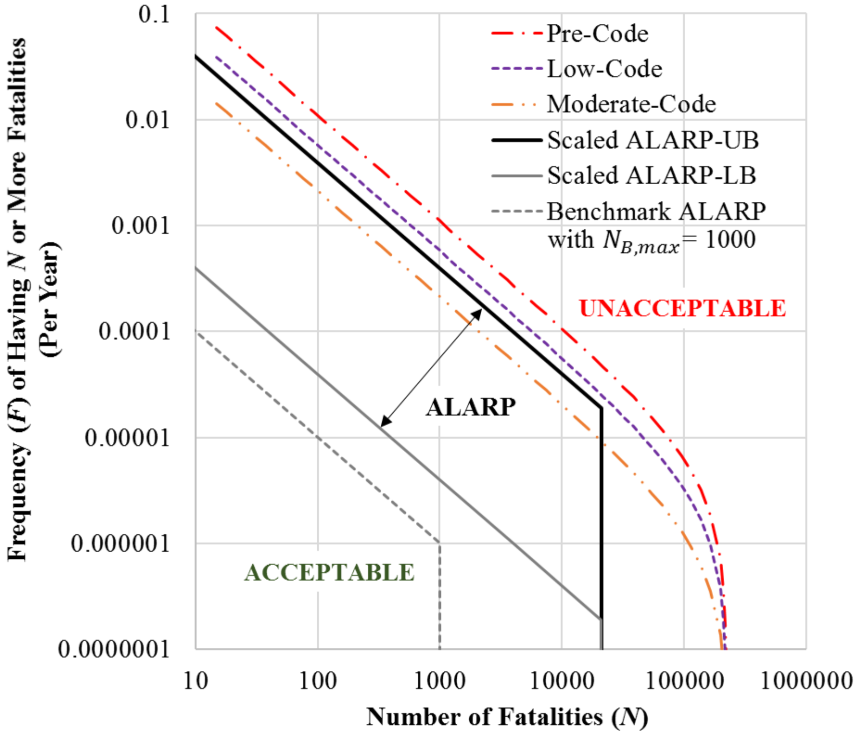

Fig. 7 – The societal earthquake fatality risk functions, *F-N* curves, for the building stocks and the population in the Greater Melbourne Region, based on Hazus characterization for various code levels, in comparison with the population-scaled regulatory ALARP *F-N* functions as proposed in Tsang et al. [22, 23]

4.2 Evaluation of code levels

An existing benchmark curve (i.e. the dashed grey line in Fig. 7), after being scaled by the population-scaled factor, θ_P, can then be used for assessing community resilience. The total population, $\mathcal{P}$, of the Greater Melbourne Region is 4,205,584 (as of the 2011 census). Given the tolerable annual fatality rate, $\lambda_{D,tolerable}$, of 10^{-6}, the tolerable amount of the average annual *PLL* due to structural failures is then equal to 4.2. If the limiting fatality number, $N_{B,max}$, is assumed as 0.5 percent of the total population, i.e. 21028, then $PLL_{BU} = 0.01065$ and $\theta_P = 395$ based on Equations (3) and (4). The *F-N* functions for the upper and lower bounds of the ALARP region can be obtained using Equations (5) and (6), which are plotted in Fig. 7.

Detailed analysis has revealed that the highest fatality rates occur in two model building types, namely, low-rise unreinforced masonry (URML) and low-rise concrete moment frame (C1L) [24]. In order to bring down the *F-N* curve to ALARP, it would be more effective if new constructions of these two building types are built to a higher safety standard or certain proportion of existing buildings of these two types are retrofitted to a higher level of earthquake resistance. Hence, low-code and moderate-code designs of these two building types were adopted in a hypothetical study for an evaluation of the potential risk mitigation effects of designing structures to higher code levels, as shown on the *F-N* plot of Fig. 7.

The capacity curves and fragility functions in Hazus [25] have been adopted for all three code levels, as a complete set of information is not available for the study region. It is shown that the entire *F-N* curves for pre-code and low-code fall into the “unacceptable” region, whilst the *F-N* curve for moderate-code, except the low-frequency tail, falls into the ALARP region. This shows that designing the two vulnerable types of building structures in Melbourne to satisfy Hazus low-code requirements is still inadequate from the community resilience perspective.

The procedure presented above is rather robust except that the value of $N_{B,max}$ is an unknown. Hence, a sensitivity study was conducted to check if different values of $N_{B,max}$ would lead to very different outcomes. It is found that the population-scaled factor, θ_P, would vary from 553 (when $N_{B,max} = 1000$) to 264 (when $N_{B,max} = \mathcal{P}$, i.e. the whole population). The general conclusion drawn in the previous paragraph is still valid for the whole range of $N_{B,max}$. In reality, relevant government authority should be able to predefine a reasonable value (or range) of $N_{B,max}$ based on the rescue and emergency services capability, as well as the risk tolerability in the society.

5. Conclusions and Closing Remarks

Risk-informed decision making is becoming a standard for an advanced society, partly because relevant knowledge and tools are currently available. Meanwhile, a more transparent and accountable governance is expected by the general public. A more rational and scientific approach is always preferred when a variety of opinion and interest groups is involved in the decision making process. The public should also have a role in setting the seismic performance goals as it concerns their life safety and community resilience.

This paper has presented a rational and transparent procedure for setting regulatory *F*-*N* functions, scaled by the population of the study region, which define the upper and lower bounds of the "as low as reasonably practicable (ALARP)" region on the *F*-*N* plot [23]. An evaluation exercise has been illustrated using the Greater Melbourne Region as a case study based on the characterizations of building stocks for the various design code levels as defined in Hazus. The results show that the earthquake fatality risk for society appears to be unacceptable.

There is a common belief amongst engineering professionals that it is uneconomical to design structures to resist stronger earthquakes [10]. However, the public has never/rarely been asked about their preferences actually. Recent research has shown that building owners are indeed willing to pay for better earthquake protection and resilience (i.e. habitable or functional after a major earthquake event) [15].

In fact, a higher safety standard can alternatively be achieved by better understanding the weakest links of structures, encouraging the use of best practices, as well as more stringent monitoring and quality control during construction. These will undoubtedly enhance structural robustness, and reduce gross errors and the chance of unexpected failure, which can fundamentally reduce the uncertainties and risk levels [11].

It is noteworthy that the evaluation in this study has been based on a tolerable level of individual fatality risk of 10^{-6}. Is this level really tolerable? In fact, the tolerable level of risk has been found to decrease with an increasing number of exposed persons [35]. In other words, the tolerable level should be lower in a densely populated region, as the number of people being affected at the same time is enormous, and there might be a lack of emergency response capacity in the society for coping with the potential disaster. UNISDR [36] defines it as an "intensive risk", as it is "associated with the exposure of large concentrations of people and economic activities to intense hazard events, which can lead to potentially catastrophic disaster impacts involving high mortality and asset loss". In principle, a lower tolerable level of risk, i.e. $\lambda_{D,tolerable} < 10^{-6}$, might be adopted for such metropolitan areas.

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