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EARTHQUAKE SAFETY REQUIREMENTS BASED ON INDIVIDUAL AND SOCIETAL FATALITY RISK

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ABSTRACT

It is acknowledged that residual risk exists in our buildings even if they were designed in conformance with modern codes of practice. Various approaches have been implemented or proposed in recent years for setting risk-targeted performance requirements for seismic design. The annual collapse risk limit of 2×10^{-4} stipulated in the International Building Code (IBC) since 2012 was recently examined by the authors and a more stringent requirement of 10^{-4} has been recommended for controlling individual fatality risk to a tolerable level. On the other hand, the collapse probability of 1% or 0.5% in 50 years for a single building may be considered very low by some; however, the aggregated risk for the whole society could become significant, especially for a metropolitan city like Melbourne, Australia, with a total population of over four million people. This paper introduces a methodology for evaluating the adequacy of existing code requirements for collapse prevention and life safety by comparing societal risk functions based on regional earthquake loss modelling with a proposed regulatory requirement that aims to limit the mortality rate to "as low as reasonably practicable (ALARP)".

Keywords: building structure; societal risk; F-N function; earthquake fatality; collapse

1. INTRODUCTION

Even if building structures were designed in conformance with the best standard and practice in the world, 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. It should be logical and appropriate that the performance requirements in seismic codes of practice and earthquake safety policy are defined along with the consideration of the residual risk of structural collapse and casualty (Wiggins 1972, Liel and Deierlein 2012, Porter 2014, Dolšek 2015).

"Residual risk" is defined by the United Nations International Strategy for Disaster Reduction (UNISDR 2009) as "the risk that remains in unmanaged form, even when effective disaster risk reduction measures are in place, and for which emergency response and recovery capacities must be maintained". In the context of seismic design, standards and codes of practice are considered as effective disaster risk reduction measures, whilst stronger earthquake ground motions and substandard performance of structures can be considered as "unmanaged", as they are not intended to be "considered" in the codes.

1.1 Risk-based Design Objectives

Recently, there have been attempts to incorporate risk measures of individual building in seismic structural design. The 2012 edition of the International Building Code (IBC) (adopted principally in the United States) and the 2010 edition of the structural design standard ASCE/SEI 7 have firstly set out risk-targeted performance requirements for seismic design. However, the implications of the requirements for life safety have not been explicitly considered. The first objective of this paper is to discuss whether the stipulated requirements in IBC-2012 and ASCE/SEI 7-10 are adequate for mortality control or not.

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In the European context, Dolšek (2015) has contemplated a set of risk-based performance objectives for seismic design of buildings and Dolšek et al. (2017) have proposed a decision model that contains important parameters for risk-based seismic design of buildings, 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. An iterative risk-based structural design procedure has also been put forward (Sinković et al. 2016). Meanwhile, a risk-targeted map has been developed for mainland France (Douglas et al. 2013) and preliminary study has been conducted towards developing such a map for the whole Europe (Silva et al. 2014).

On the other hand, acceptable level of failure probability of individual building has been recommended by Tanner and Hingorani (2015) and Tsang and Wenzel (2016) 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 (Tanner and Hingorani 2015) and hypothetical scenario-based *F-N* diagram for a group of identical (non-ductile concrete frame) buildings subjected to a uniform strong shaking (Liel and Deierlein 2012). The *F-N* curve / diagram is a plot of the annual rate, *F*, of exceeding *N* fatalities in one earthquake.

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, there is no indication or direct link to the impact on the whole society.

1.2 Societal Risk

Societal risk was defined by Jones (1992) as "the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards." As a damaging earthquake can lead to widespread destruction and casualties, societal risk should be quantified for a region in the scale of a city or a province. Furthermore, it is desirable if the societal risk is evaluated in a probabilistic manner, from which the outcome would be a recurrence relationship for an event-based loss quantity, economic loss or casualty, i.e. *F-N* curve if fatality is the loss quantify being evaluated.

For the development of risk-based structural safety requirement and design methodology, the practising engineering community and policy makers typically require information that are unambiguous and can be communicated with various groups of stakeholders. Hence, the second objective of this paper is to present a transparent procedure for developing societal risk function based on loss modelling of earthquake scenarios that are consistent with a wide range of the probabilistic hazard using the Greater Melbourne Region as a case study.

1.3 Evaluation of Code Levels

Once the societal risk function is available, it provides an indication about the level of risk or the amount of loss in a somewhat probabilistic manner. An important missing link would then be a guiding principle or a regulatory framework that sets forth safety requirements in a society, such that the actual risk function can be benchmarked against. This paper attempts to put forward a practical scheme for determining regulatory *F-N* function with the consideration of a tolerable level of earthquake fatality risk and the total population of the region, which can be suitable for adoption in a public safety regulation or guideline.

2. INDIVIDUAL FATALITY RISK

2.1 Target Collapse Risk Limit in International Building Code (2012)

It is stipulated in IBC-2012 and ASCE/SEI 7-10 that the collapse risk (probability), P(C), of ordinary building shall be limited to lower than 1% in 50 years (i.e. the notional lifetime of a building) (or an annual probability of exceedance of 2×10^{-4}), when a building is designed in accordance to the risk-targeted maximum considered earthquake (MCE_R) ground motion (as described in FEMA P-750 report, prepared by BSSC 2009), in contrast to the previous editions that were based entirely on the return period of design ground motion without considering the seismic risk of structures. Meanwhile, the probability of collapse should be limited to 10% under the MCE_R action.

In the next section, the annual individual fatality risk, P(D), in buildings designed in conformance to IBC-2012 and ASCE/SEI 7-10 will be estimated using Equation (1), based on the conditional probability of dying given collapse of structure, P(D|C), through an analysis of casualty data in Hazus Technical Manual (FEMA 2012). The estimates will then be benchmarked against the tolerable level of individual annual fatality risk of 10^{-6} as recommended by various organizations: ISO 2394:1998 (ISO 1998), Eurocode EN1990:2002 (CEN 2002), The Ministry of Housing, Spatial Planning and the Environment (VROM) of the Netherlands (Ale and Piers 2000), U.S. National Academy of Engineering as proposed for The Long Beach City Council, California (Wiggins 1972). This risk limit has been well supported by historical mortality data caused by natural hazards (Starr 1969, 1972). A brief review of the relevant documents has been given in Tsang and Wenzel (2016).

$$P(D) = P(C) \times P(D|C) \tag{1}$$

Using the CATDAT Damaging Earthquakes Database and event deaths vs. population per year, and distributing the average annual mortality rate in the unit of micromorts (i.e. annual mortality rate of 10^{-6}), it can be seen that such a limit was indeed exceeded in many countries historically (Tsang et al. 2017). The historical implications of this limit are discussed in Daniell et al. (2017, 2018).

2.2 Fatality Risk Based on Hazus Data

For estimating the conditional probability of dying given collapse of structure, P(D|C), Hazus (https://www.fema.gov/hazus/) has provided an authoritative and comprehensive set of background data for estimating earthquake-related casualties. The estimates provided by Hazus have been made based on extensive databases of casualties induced by past earthquakes. Both instantaneous deaths and immediate life threatening injuries are combined in the fatality estimates in this paper.

Estimates of fatalities due to various levels of damages of different types of structures in past earthquakes have been summarized in Hazus Technical Manual (FEMA 2012). Undoubtedly, there is a high level of variability in the estimated losses between individual buildings in the same category. Each estimate is considered as the average for a group of buildings with similar characteristics (e.g. structural form, construction material, number of storeys), which can fulfil the need for planning and policy-making, i.e. the purpose of this study.

Detailed calculation of the overall conditional probability of dying, P(D|C), for different categories of buildings have been presented in Tsang and Wenzel (2016). Given the "collapse" of structure, the fatality risk ranges from 0.23% for steel light frame to 1.95% for low-rise concrete structure with unreinforced masonry (URM) infill walls. It is noted that the definition of "collapse" in IBC and ASCE/SEI is in fact more consistent with "Complete Structural Damage (*CSD*)" state as defined in Hazus (FEMA 2012), or "Collapse Prevention" level as defined in FEMA Publication 273 (ATC 1997), or "Near Collapse" level in Vision 2000 performance-based seismic design framework (SEAOC 1995) and Eurocode 8 – Part 3, where the structural system is on the verge of experiencing partial or total collapse.

Next, assuming that all the buildings are designed in conformance to IBC-2012 and ASCE/SEI 7-10, with a (uniform) collapse risk, P(C), of 1% in 50 years or an annual probability of exceedance of 2×10^{-4}, the annual individual fatality risk, P(D), in buildings can be calculated using Equation (1). The results are presented in Figure 1, in which the tolerable level of individual annual fatality risk of 10^{-6} has been included as a benchmark. It can be observed that lighter structures, including timber and steel light frame, generally lead to fatality risk lower (i.e. safer) than the benchmark risk level, while heavy concrete structures can lead to more fatalities. The individual annual fatality risk in steel buildings is estimated to be around 1×10^{-6} to 2×10^{-6}, whereas the risk in concrete buildings is around 1.5×10^{-6} to 4×10^{-6}, which is higher than the benchmark level.

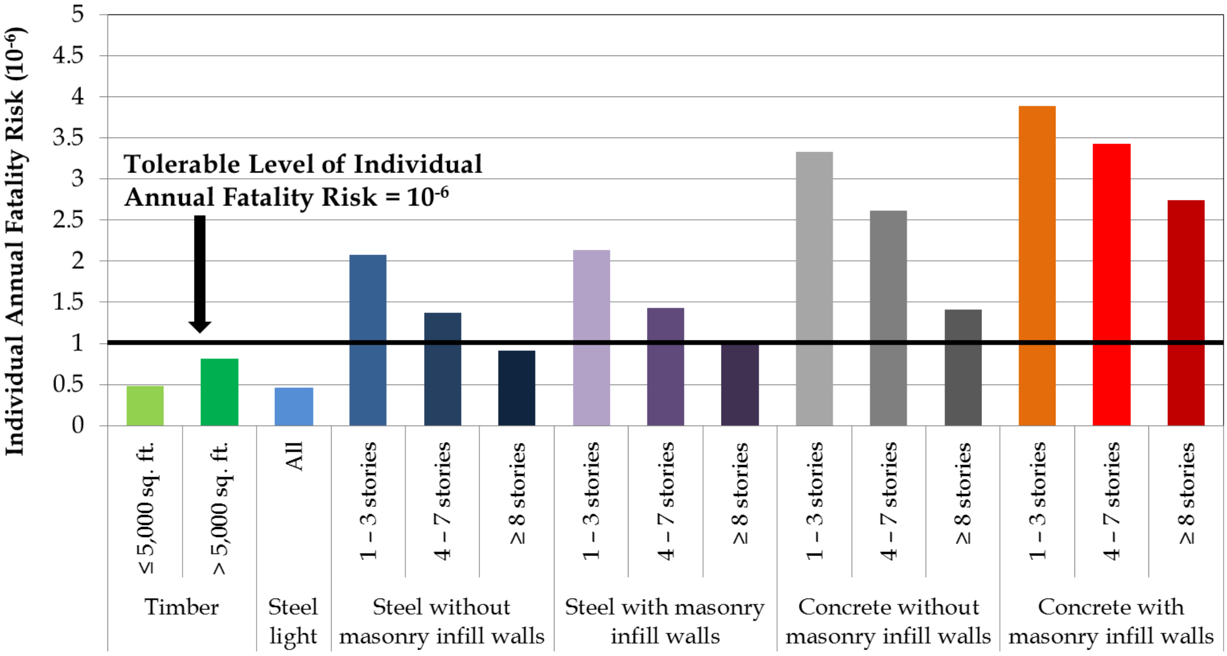

Figure 1. The estimated annual individual fatality risk in different Hazus categories of buildings that are designed in conformance with the collapse risk requirement in IBC-2012 and ASCE/SEI 7-10

2.3 Proposed Target Collapse Risk Limits

In order to control the fatality risk in all categories of buildings to the same tolerable level (i.e. 10^{-6}), a set of target collapse risk limit, $P_L(C)$, for the structural design of (ordinary) buildings has been put forward in Tsang and Wenzel (2016). The proposed annual collapse risk limit ranges from 0.5×10^{-4} to 4.5×10^{-4}. The required risk limit for structural design could be more lenient for timber and steel light frame construction, as the collapse of these light-weight structures poses a lower risk of killing the occupants. However, more stringent requirement should be specified for heavier buildings, in particular concrete structures. These limits can serve as a guide for setting the minimum requirements in the structural design of different categories of ordinary buildings.

Ideally, different risk limit requirements could be stipulated for different categories of buildings in the design standard, in order to achieve a uniform level of fatality risk. However, it may be viewed as overly meticulous given the generally high level of uncertainties involved in structural design and construction practice. Nevertheless, it is clear from the results (see Figure 1) that the requirement in the current design standard is insufficient in terms of mortality control. If a uniform target has to be recommended, an annual collapse risk of not higher than 1×10^{-4} can be proposed.

3. SOCIETAL FATALITY RISK FUNCTION

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. It is usually done for selected scenario earthquakes, each of which may be associated with a return period, such that the outcomes carry some meanings of the probability of exceedance. A fully probabilistic or stochastic approach that requires simulations of thousands of earthquake scenarios through rigorous loss estimation can provide a full picture of the characteristics of a societal loss recurrence function; however, more input parameters actually require more justification and do not necessary lead to more accurate results or reduce the amount of uncertainties, whilst it usually loses transparency that might hinder repeatability of the outputs. Hence, a semi-probabilistic procedure has been proposed by Tsang et al. (2018) for obtaining *F-N* function as illustrated through a case study as follows.

3.1 Definition and Characterisation of the Greater Melbourne Region

Melbourne (Coordinates: 37°48'49" S, 144°57'47" E) is the most populous city in the state of Victoria in Australia, which has a total population of 4205584 (as of 2011) according to the Australian Bureau of Statistics. In this case study, the whole region is divided into 9658 geo-units, as defined by the Australian Statistical Geography Standard (ASGS) 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 (in the unit of the number of people per square metre times 10^{-5}) of each geo-unit are shown in Figure 2. It is shown that the population is mainly concentrated within the Central Business District (CBD) area and inner suburbs of Melbourne, with up to 9847×10^{-5} people per square meter, whilst it is no more than 123×10^{-5} people per square meter on the outskirt of Melbourne. The ground condition of each geo-unit has been broadly categorised according to NEHRP soil classification scheme. Building exposure data was collected from NEXIS that follows Hazus classification scheme.

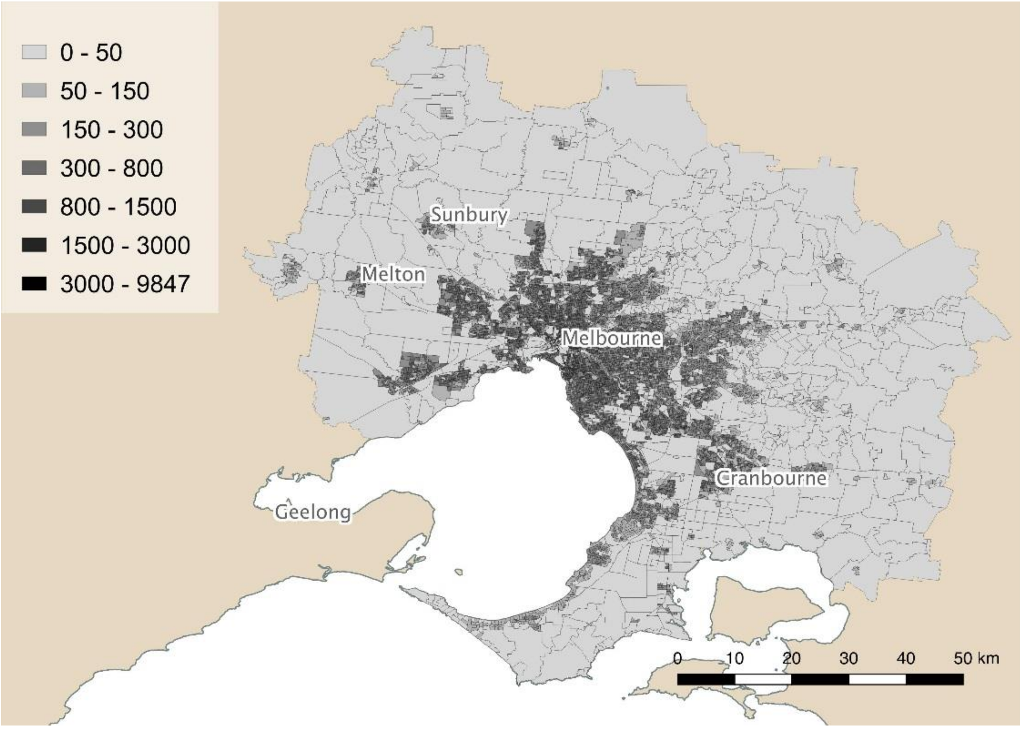

Figure 2. Population density in each of the 9658 geo-units in the Greater Melbourne Region (in the unit of the number of people per square metre times 10^{-5}) (Tsang et al. 2018)

3.2 Selection of Hazard-Consistent Probabilistic Scenarios

The selection of scenario earthquakes should be based on the predicted demand on the (uniform hazard) spectrum at the predominant natural period (T) of the potentially more vulnerable groups of buildings in the Greater Melbourne Region, which are low-rise unreinforced masonry (URML) and low-rise concrete moment frame (C1L). As the predominant period of these two types of 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. The uniform hazard spectra (UHS) for a wide range of return periods, T_{RP}, presented in Somerville et al. (2013) were adopted.

Correction was made to remove the consideration of ground motion uncertainties from the uniform hazard spectra. The probabilistic hazard rates were multiplied by a correction factor of 0.313 (more details can be found in Werner 2016 and Tsang et al. 2018), such that the reduced rates would be corresponding to the median spectral response values, which were then used for identifying scenario earthquake events. The two major ground motion prediction equations (GMPEs) employed in the probabilistic seismic hazard assessment (PSHA) study by Somerville et al. (2013), i.e. Somerville et al. (2009) and Allen (2012), were used for back-calculating the magnitudes of the scenarios for each fault along with its distance from the population centroid. Information about the locations and geometry of faults are available from the website of Geoscience Australia (2017). 68 scenario earthquakes have been identified, and their epicentres are shown in Figure 3.

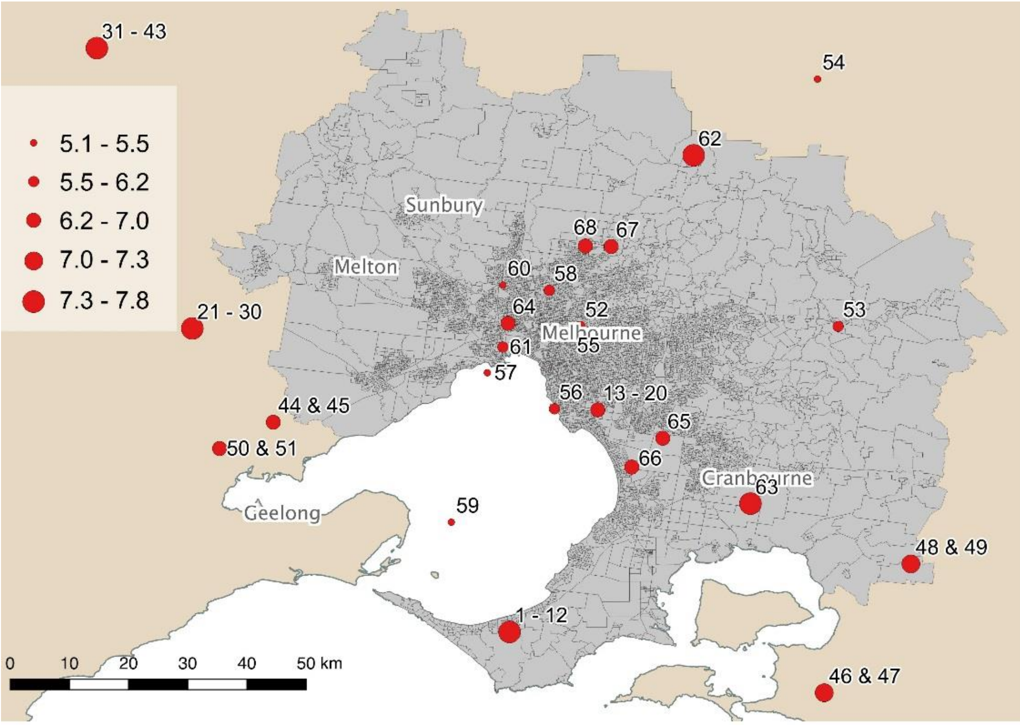

Figure 3. Distribution of the epicentres of 68 probabilistic scenario earthquakes identified for fatality estimation in the Greater Melbourne Region (size of circle indicates the relative magnitude of earthquake) (Tsang et al. 2018)

3.3 Scenario-based Fatality Estimation

The computer software SELENA (Molina et al. 2010) has been adopted for earthquake loss modelling in this case study. Only fatalities directly due to structural damage are considered, which include both indoor and outdoor fatalities. 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 amount of fatalities was estimated based on the methodology given in Coburn and Spence (2002).

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. In this study, Australian buildings were conservatively classified at pre-code level by this definition.

Sample result (instantaneous deaths only) for the scenario earthquake with magnitude 7.8 occurring on the Muckleford fault is shown in Figure 4 (with the location of epicentre annotated).

3.4 Parametric F-N Function

A societal risk recurrence function, in terms of number of fatalities (i.e. an *F-N* curve), can be 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 as obtained in Section 3.3, versus the corrected return periods, T_{RP} (or rates of exceedance, F) of the hazard as calculated in Section 3.2. Equation (2) 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 210000, which is approximately 5% of the total population of the region. This *F*-*N* function is plotted as “Pre-Code” in Figure 5. More details can be found in Tsang et al. (2018).

$$\frac{1}{F} = T_{RP} = 2475\left(\frac{2700^{-1} - 210000^{-1}}{N^{-1} - 210000^{-1}}\right) \tag{2}$$

The corresponding Average Annual Loss (*AAL*) of life, or Potential Loss of Life (*PLL*), 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 triples the tolerable individual risk limit of 1 micromort (ISO 1998; Tsang and Wenzel 2016).

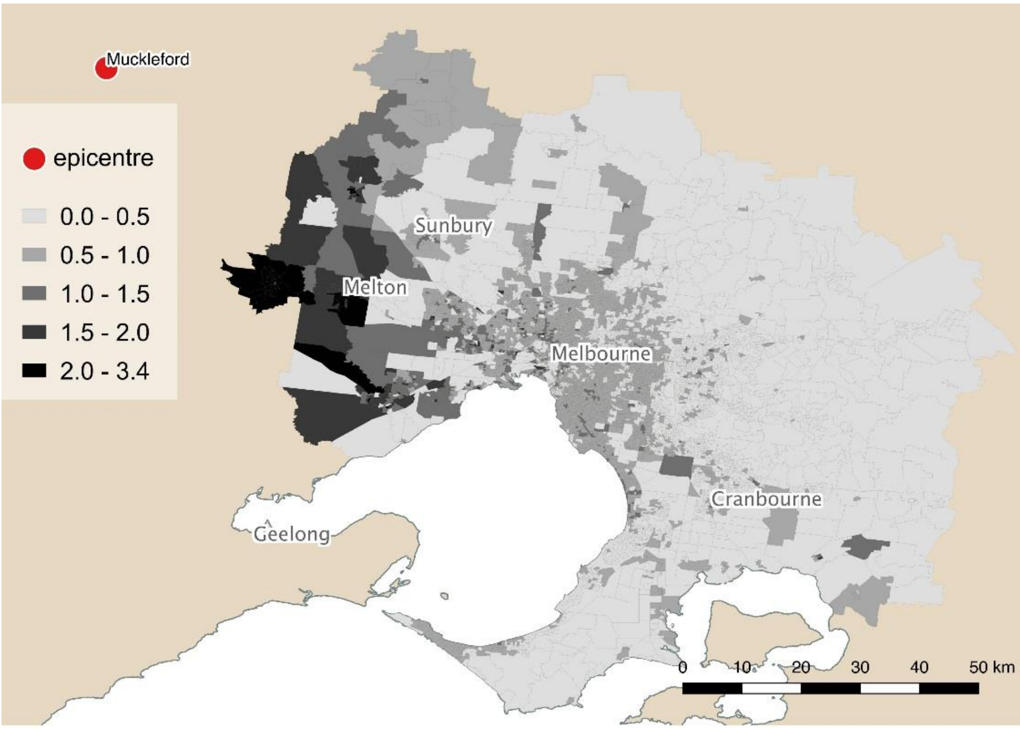

Figure 4. Number of fatalities (instantaneous deaths only) as a percentage of the population in each geo-unit in the Greater Melbourne Region due to a magnitude 7.8 earthquake occurring on the Muckleford fault (Tsang et al. 2018)

4. EVALUATION OF CODE LEVELS USING *F-N* FUNCTION

Recent studies have focused on setting target collapse risk limit for seismic design of individual buildings. Such a low level of collapse risk for a single building is probably considered acceptable, as the potential consequence and impact to the society might be limited. However, as there are numerous buildings in the affected region of a major earthquake event, the aggregated risk to the whole society has to be taken into account in the evaluation of the safety level of our engineered structures. In this section, a methodology is proposed for evaluating the safety level of existing building stocks in a region, and for justification of a required change of design code level. Section 4.1 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 4.2 and followed by an illustration in Section 4.3 with the actual societal risk functions (as presented in Section 3) for the Greater Melbourne Region.

4.1 Benchmark ALARP F-N Functions

In the field of safety engineering, industrial risk is being quantified at a system level. For example, the potential losses in the surrounding area are taken into account in the safety evaluation of a petrol station. 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, 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 and lower bounds of ALARP region can respectively be generalized in a parametric form as:

$$\log(F_{BU}) = a - b \times \log(N) \tag{3a}$$

$$\log(F_{BL}) = (a-2) - b \times \log(N) \tag{3b}$$

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.

The annual average PLL implied by the benchmark upper bound ALARP function, PLL_{BU}, can be calculated by:

$$PLL_{BU} = \sum_{1}^{N_{B,max}} F_{BU}(N) \tag{4}$$

For example, the values for the parameters of the ALARP *F-N* functions recommended by the Hong Kong Planning Department (1994) (reported in Christian 2004) for safety evaluation of a single asset are: $a = -3$; $b = 1$; $N_{B,max} = 1000$. This is shown as the dashed grey line in Figure 5. The calculated PLL_{BU} implied by the upper bound ALARP function is 0.0076. If the tolerable fatality risk for an individual is 10^{-6}, the implicit number of affected population would be 7600. This is consistent with the number of occupants at a particular time in a single asset likes an exhibition center, that can be in the order of thousands to ten thousands. $N_{B,max}$ of 1000 would be around 13% of the affected population.

4.2 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 a power plant. 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 4.1 cannot be directly used for evaluating the earthquake safety level of a society. An appropriate way of setting the ALARP *F-N* function is needed in the first place.

It is proposed herein 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}. With a total population of 4.2 million in the Greater Melbourne Region, 4.2 fatalities each year or 42 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:

$$\theta_P = \frac{\mathcal{P} \times \lambda_{D,tolerable}}{PLL_{BU}} \tag{5}$$

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:

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

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

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

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

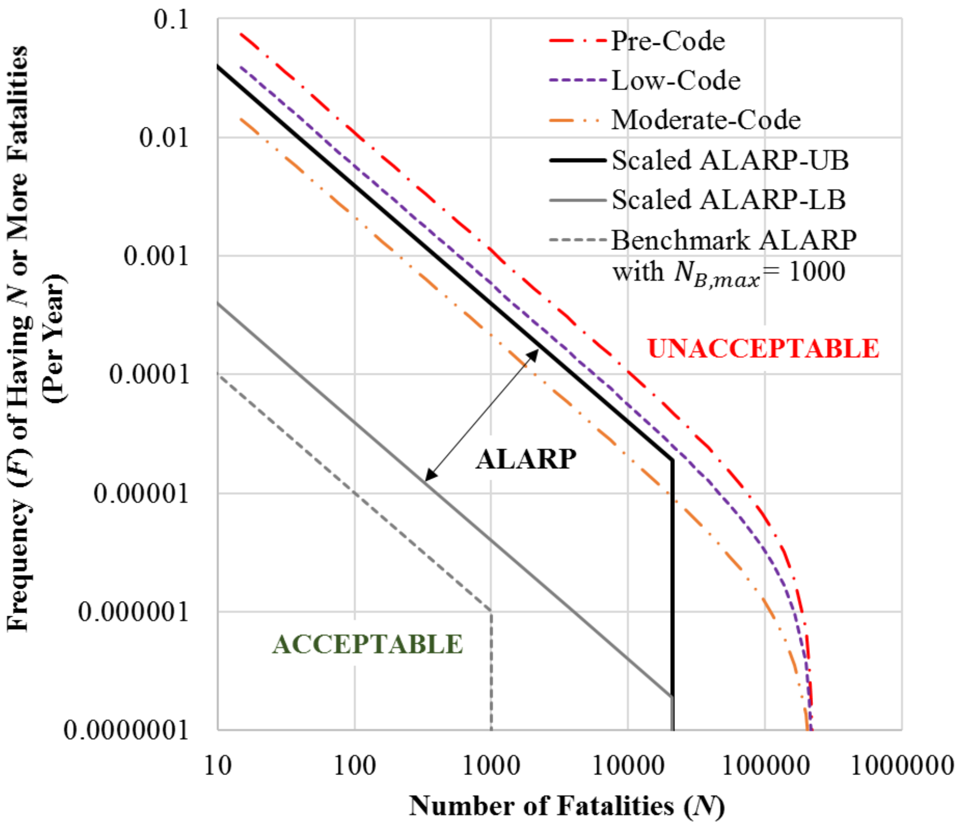

Figure 5. The societal earthquake fatality risk function, *F-N* curve, for the building stocks and the population in the Greater Melbourne Region, based on Hazus characterization for various code levels, in comparison with the population-scaled regulatory ALARP *F-N* functions as proposed in this study.

4.3 Illustration

An existing benchmark curve (i.e. the dashed grey line in Figure 5), after being scaled by the population-scaled factor, θ_P, can then be used for assessing societal earthquake risk. The total population, $\mathcal{P}$, of the Greater Melbourne Region is 4205584. 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 (4) and (5). The *F-N* functions for the upper and lower bounds of the ALARP region can be obtained using Equations (6a) and (6b), which are plotted in Figure 5.

The societal risk functions based on pre-code building stocks, low-code building stocks and moderate-code building stocks are shown on the *F-N* plot of Figure 5. The capacity curves and fragility functions in Hazus 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 building structures in Melbourne to satisfy Hazus low-code requirements is inadequate from the societal risk perspective, parts of the building stocks need to be retrofitted in order to bring the residual risk level in the society down to an ALARP level.

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 for $N_{B,max} = 1000$ to 264 for the largest value of $N_{B,max} = \mathcal{P}$. Although the factor seems to vary significantly, the observed trend and the conclusion drawn in the previous paragraph are still valid for any value of $N_{B,max} \geq 1000$. 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.

In fact, the tolerable level of risk has been found to decrease with an increasing number of exposed persons (Starr 1969). 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 (2009) 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. $\lambda_{D,tolerable} < 10^{-6}$, should be adopted for such metropolitan areas.

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.

An ideal building code should indicate the target levels of collapse and fatality risk since it is a legal document that sets forth structural design requirements for protecting life and property. It was found that the target risk limit of 2×10^{-4} that is stipulated in the 2012 edition of the International Building Code (IBC) is insufficient for controlling individual annual fatality risk (due to structural failure in earthquakes) to the tolerable limit of 10^{-6}. A value of 10^{-4} or lower is recommended as the target annual collapse risk for ordinary buildings.

This paper has also presented a transparent procedure for obtaining a societal risk function for fatalities, in the form of *F-N* curve, based on regional loss modelling of probabilistic hazard-consistent earthquake scenarios. This can then be compared with the population-scaled regulatory *F-N* functions, as proposed in this paper, that define the upper and lower bounds of the "as low as reasonably practicable (ALARP)" region on the *F-N* plot. This evaluation exercise has been illustrated using the Greater Melbourne Region as a hypothetical case study based on the characterizations for the various code levels defined in Hazus.

There is a common belief that it is uneconomical to design structures to resist stronger earthquakes. However, the public usually does not have a role in setting the seismic performance goals, and it is actually not known how much the owners are willing to pay for better earthquake protection (Porter 2014). In fact, a higher safety standard can alternatively be achieved by better understanding of the weakest links of structures, encouraging the use of best practices, as well as more stringent monitoring and quality control during construction. These measures will undoubtedly enhance structural robustness, and reduce gross errors and the chance of premature or unexpected failure, which can fundamentally reduce the uncertainties and risk levels.

As the consequences of structural failure concern life safety and economic losses, the responsibility of decision making should be shared amongst relevant government authorities, property developers, code writers, insurance companies, engineers and builders, as well as the general public, in order to minimise the residual risk to a tolerable level.

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7. REFERENCES

Ale BJM, Piers M (2000). The assessment and management of third party risk around a major airport. *Journal of Hazardous Materials*, 71(1-3): 1-16.

Allen TI (2012). *Stochastic ground motion prediction equations for southeastern Australian earthquakes using updated source and attenuation parameters*. Record 2012/69, GeoCat 74133, Geoscience Australia, Canberra, 66 p.

ASCE/SEI 7-10 (2010). *Minimum Design Loads for Buildings and Other Structures*. Structural Engineering Institute (SEI), the American Society of Civil Engineers (ASCE), Reston, Virginia, U.S., 2010.

ATC (1997). *NEHRP Guidelines for the Seismic Rehabilitation of Buildings* (FEMA Publication 273). Prepared by Applied Technology Council (ATC) for the Building Seismic Safety Council (BSSC), Washington, D.C., U.S.

CEN (2002). EN 1990: *Eurocode: Basis of Structural Design*, European Committee for Standardisation (CEN), Brussels, Belgium.

CEN (2005). EN 1998-3: *Eurocode 8: Design of Structures for Earthquake Resistance – Part 3: Assessment and Retrofitting of Buildings*. European Committee for Standardisation (CEN), Brussels, Belgium.

Christian JT (2004). Geotechnical engineering reliability: How well do we know what we are doing?. *Journal of Geotechnical and Geoenvironmental Engineering*, 130: 985–1003.

Coburn A, Spence R (2002). *Earthquake Protection*. 2nd Edition, Wiley, Chichester, 436 pp.

Daniell JE, Schaefer AM, Wenzel F, Tsang HH (2017). The global role of earthquake fatalities in decision-making: earthquakes versus other causes of fatalities. Paper No. 170, *Proceedings of the 16th World Conference on Earthquake Engineering*, Santiago, Chile, January 9-13, 2017.

Daniell JE, Pomonis A, Tsang HH, Wenzel F, Gunasekera R, Schaefer A (2018). The top 100 fatal earthquakes: examining fatality risk reduction globally with respect to seismic code implementation, *Proceedings of the 16th European Conference on Earthquake Engineering*, Thessaloniki, Greece, June 18-21, 2018.

Dolšek M (2015). *EAEE Working Group 1: Future directions for Eurocode 8 - Chapter 4: Performance objectives*. University of Ljubljana, Slovenia.

Dolšek M, Sinković NL, Žižmond J (2017). IM-based and EDP-based decision models for the verification of the seismic collapse safety of buildings. *Earthquake Engineering and Structural Dynamics*, 46(15): 2665-2682.

Douglas J, Ulrich T, Negulescu C (2013). Risk-targeted seismic design maps for mainland France. *Natural Hazards*, 65(3): 1999-2013.

FEMA (2012). Hazus®-MH 2.1, *Multi-hazard Loss Estimation Methodology – Earthquake Model*, Technical Manual. Federal Emergency Management Agency (FEMA), Washington, D.C., U.S.

Geoscience Australia (2017). Neotectonic Features. Earthquakes@GA. http://www.ga.gov.au/earthquakes/

Hong Kong Government Planning Department (1994). Potentially hazardous installations. *Hong Kong Planning Standards and Guidelines*, Chap. 11, Hong Kong.

International Building Code (IBC) 2012. International Code Council (ICC), Country Club Hill, Illinois, U.S.

ISO (1998). ISO 2394:1998. *General Principles on Reliability for Structures*. International Organization for Standardization (ISO), Geneva.

Jones DA (1992). *Nomenclature for hazard and risk assessment in the process industries*. Institution of Chemical Engineers (IChemE).

Liel AB, Deierlein GG (2012). Using collapse risk assessments to inform seismic safety policy for older concrete buildings. *Earthquake Spectra*, 28(4): 1495-1521.

Molina S, Lang DH, Lindholm CD (2010). SELENA – An open-source tool for seismic risk and loss assessment using a logic tree computation procedure. *Computers and Geosciences*, 36(3): 257–269.

NEHRP Recommended Seismic Provisions for New Buildings and Other Structures (FEMA P-750). 2009 Edition, prepared by Building Seismic Safety Council (BSSC) for the Federal Emergency Management Agency (FEMA) National Earthquake Hazards Reduction Program (NEHRP), Washington, D.C., U.S.

Porter KA (2014). Safe enough? How building codes protect our lives but not our cities, *Proceedings of the 10th U.S. National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, Alaska, U.S., July 21-25, 2014.

SEAOC (1995). *Vision 2000: Performance Based Seismic Engineering of Buildings*. Vision 2000 Committee, Structural Engineers Association of California (SEAOC), Sacramento, California, U.S.

Silva V, Crowley H, Bazzurro P (2014). Risk-targeted hazard maps for Europe, *Proceedings of the 2nd European Conference on Earthquake Engineering and Seismology*, Istanbul, Turkey, August 25-29, 2014.

Sinković NL, Brozovič M, Dolšek M (2016). Risk-based seismic design for collapse safety. *Earthquake Engineering and Structural Dynamics*, 45: 1451-1471.

Somerville P, Graves R, Collins N, Song SG, Ni S, Cummins P (2009). Source and ground motion models for Australian earthquakes, *Proceedings of the 2009 Australian Earthquake Engineering Conference*, Newcastle, Australia, December 11-13, 2009.

Somerville P, Bayless J, Skarlatoudis A, Thio HK (2013). Assessment of seismic design motions at low probabilities: comparing Australia and New Zealand, *Proceedings of the 2013 Australian Earthquake Engineering Conference*, Hobart, Tasmania, Australia, November 15-17, 2013.

Starr C (1969). Social benefit versus technological risk. *Science* 165(3899):1232-1238.

Starr C (1972). Benefit-cost studies in sociotechnical systems. In: *Perspectives on Benefit-Risk Decision Making*. Report of a Colloquium conducted by the Committee on Public Engineering Policy, National Academy of Engineering, April 26-27, 1971, Washington, D.C. U.S. 17-42 pp.

Tanner P, Hingorani R (2015). Acceptable risks to persons associated with building structures. *Structural Concrete*, 16(3): 314-322.

Tsang HH, Wenzel F (2016). Setting Structural Safety Requirement for Controlling Earthquake Mortality Risk. *Safety Science*, 86: 174-183.

Tsang HH, Wenzel F, Daniell JE (2017). Residual Fatality Risk Estimates for Setting Earthquake Safety Requirement, *Proceedings of the Sixteenth World Conference on Earthquake Engineering*, Santiago, Chile, January 9-13, 2017.

Tsang HH, Daniell JE, Wenzel F, Werner AC (2018). A Semi-Probabilistic Procedure for Developing Societal Risk Function. *Natural Hazards*, DOI: 10.1007/s11069-018-3233-z.

UNISDR (2009). *2009 UNISDR Terminology on Disaster Risk Reduction*. United Nations International Strategy for Disaster Reduction, Geneva, Switzerland, May 2009. 30 pp.

Werner AC (2016). Estimating FN-curves for earthquake risk assessment – the Melbourne case, Master Thesis. Geophysical Institute, Karlsruhe Institute of Technology

Wiggins JH Jr. (1972). Earthquake safety in the City of Long Beach based on the concept of balanced risk. In: *Perspectives on Benefit-Risk Decision Making*, Report of a Colloquium conducted by the Committee on Public Engineering Policy, National Academy of Engineering, April 26-27, 1971, Washington, D.C. U.S. 87-95 pp.