How Safe is Safe Enough? Melbourne Case Study

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Abstract

Residual risk exists in our buildings even if they were designed in conformance with modern codes of practice. The risk of being killed by earthquakes in Melbourne was discussed in the AEES 2018 Conference (Tsang et al. 2018a). This follow-up paper attempts to address a fundamental question in seismic design: "*How Safe is Safe Enough?*" Various approaches have been implemented or proposed in the last decade for setting risk-targeted performance requirements for seismic design. A target collapse risk limit for a single building may be considered very low by some; however, the aggregated risk for society could become significant, especially for a metropolitan city like Melbourne. This paper introduces an approach proposed by the authors (refer Tsang et al. 2019 for full details and discussion) for evaluating the adequacy of existing code level 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 earthquake mortality rate to "as low as reasonably practicable (ALARP)". The proposed approach is then applied to Melbourne in a case study. The results show that the earthquake fatality risk for society appears to be unacceptable.

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

1 Introduction

"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 ground motions (Tsang 2008, 2011) and substandard performance of structures can be considered as "unmanaged", as they are not intended to be "considered". 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 2016a, Tsang and Wenzel 2016).

Recently, there have been attempts to incorporate risk measures in seismic design of individual building. 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. (2007), which was then adopted by reference in the 2012 edition of the International Building Code (IBC) (adopted principally in the United States).

In the European context, Dolšek (2015) has contemplated a set of risk-based performance objectives for seismic design and Dolšek et al. (2017) 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. 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). A comprehensive review can be seen in Douglas and Gkimprixis (2018).

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.

Once the societal risk function is obtained based on regional earthquake loss modelling, which provides an indication about the level of risk or the amount of loss in a somewhat probabilistic manner, an important missing link would be 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 (Tsang et al. 2018c, 2019) 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. The proposed approach is illustrated in a case study for the Greater Melbourne Region.

2 Regulatory *F-N* Functions

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 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 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 with the actual societal risk functions (as presented in Tsang et al. 2018a,b) for the Greater Melbourne Region.

2.1 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, as shown in Figure 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.

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

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

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 1. 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.

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 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 2.1 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 in Tsang et al. (2019) 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}, which has been commonly adopted by various governments, organisations and documents, as reviewed in Tsang and Wenzel (2016). 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 Melbourne Case Study

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 by Tsang et al. (2018a,b) 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).

3.1 Societal Risk Function for Melbourne

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, as described in Tsang et al. (2018b). Equation (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 210000, which is approximately 5% of the total population of the region. This *F-N* function is plotted as "Pre-Code" in Figure 1. More details can be found in Tsang et al. (2019).

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

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 triples the tolerable individual risk limit of 1 micromort (ISO 1998; Tsang and Wenzel 2016, Tsang et al. 2017, Daniell et al. 2017, 2018).

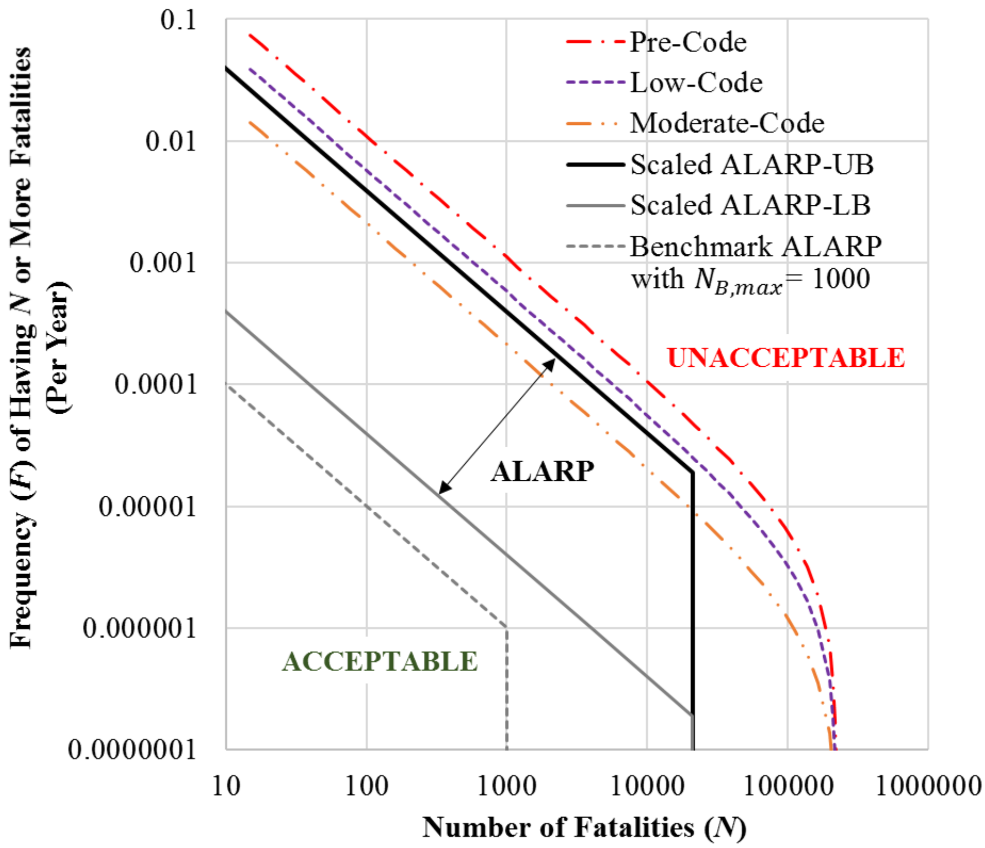

Figure 1. The societal earthquake fatality risk functions, *F-N* curves, for the building stocks and the population in the Greater Melbourne Region, based on Hazus characterization for various code levels, in comparison with the population-scaled regulatory ALARP *F-N* functions as proposed in Tsang et al. (2018c, 2019).

3.2 How Safe is Safe Enough?

An existing benchmark curve (i.e. the dashed grey line in Figure 1), 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 (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 Figure 1.

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) (Tsang et al. 2018a,b). 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 Figure 1.

The capacity curves and fragility functions in Hazus (FEMA 2012) 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 societal risk 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 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 as shown in Figure 2 and the general 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.

4 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.

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. An evaluation exercise has been illustrated using the Greater Melbourne Region as a hypothetical 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 (Porter 2016a). 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) (Porter 2016b).

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 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.

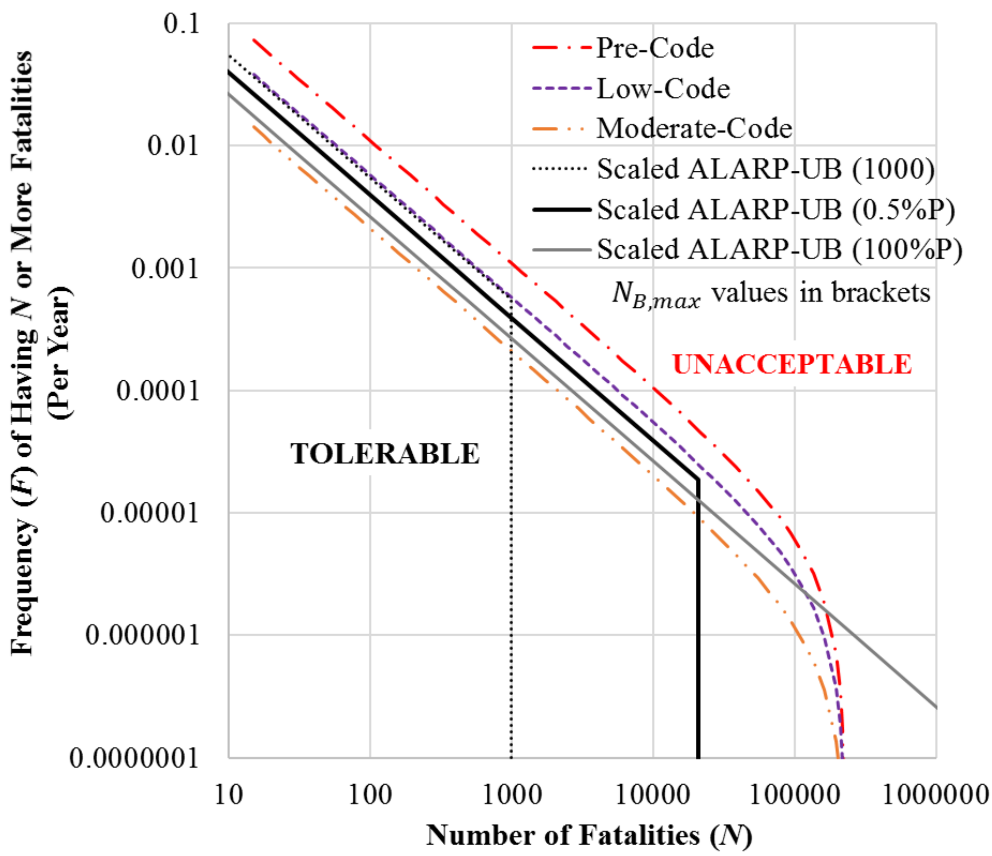

Figure 2. The societal earthquake fatality risk functions, *F-N* curves, for the Greater Melbourne Region, as shown in Figure 1, in comparison with the population-scaled upper bound regulatory ALARP *F-N* functions based on different values of the limiting fatality number, $N_{B,max} = 1000, 0.5\%\mathcal{P}$ or $100\%\mathcal{P}$.

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