NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING

# Risk Targeted Hazard Spectra for Seismic Design in New Zealand

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## ABSTRACT

The promotion of risk-targeted hazard spectra as the basis of seismic design internationally has increased over the past decade. Risk-targeted hazard spectra are derived through convolution of hazard curves with representative fragility functions and provide a means to target a uniform risk across a region. Using risk targets also allows performance objectives of building codes that are consistent with other life risks and enables societal input into the expected performance of structures. Current design procedures using a uniform-hazard spectra are unable to provide equal risk across the country due to variation in hazard curves in different locations and uncertainty in structural response. In this paper a framework is proposed, which can be used with the new National Seismic Hazard Model, to produce risk-targeted hazard spectra to replace the existing uniform-hazard spectra for seismic design. This study also extends the risk-targeted hazard framework through full quantification of epistemic uncertainty in seismic hazard and includes multiple risk targets for individual and societal risk at the building and city scales. The paper describes a framework which can be used to adjust current seismic design force levels in New Zealand standards to target uniform seismic risk for buildings considering both the performance of individual buildings as well as the performance of cities.

## 1 INTRODUCTION

New Zealand, like many other countries, designs buildings for ground motions with a uniform probability of occurrence, such as the 10% probability of exceedance in 50 years ground motion (Stirling et al., 2012; Gerstenberger et al., 2020). If the expected response of a structure to the design ground motion is known with certainty, then the uniform hazard approach results in uniform risk across a region (Silva et al., 2016). However, in reality, structures have uncertainty in their response due to variations in design, construction practices, strength of materials, code compliance and record-to-record variability. These variabilities result in a building response that has uncertainty around the design ground motion with non-zero probabilities of exceeding the design limit state for ground motions smaller and larger than the design ground motion. Because of the different shapes of seismic hazard curves, the probabilities of ground motions below and above the design ground motion vary spatially around a region (Luco et al., 2007). When convolved with the building response uncertainty, the result is a non-uniform risk in the mean annual frequency of the target design limit state across a region, which is an undesirable outcome of the current uniform hazard approach.

To address the issue of risk inequality from uniform hazard-based building codes, Luco et al. (2007) proposed the use of Risk-Targeted Hazard Maps to ensure buildings are designed with uniform risk across a region. This method was adopted for the International Building Code (IBC) used in United States in 2012 through the ASCE7-10 regulations (ASCE, 2010). The Luco et al. (2007) method was based on principles from earlier work using risk targets for the design of nuclear facilities (Kennedy, 2011). It has since been applied in a number of country or continent specific studies across Europe, Asia and North America (Allen et al., 2015; Douglas et al., 2013; Silva et al., 2016; Taherian and Kalantari, 2019; Tsang and Wenzel, 2016) and compared to other methods for design (Gkimprixis et al., 2019; Gkimprixis et al., 2020).

## 2 RISK-TARGETED HAZARD MAPS AND SPECTRA

The Risk Targeted Hazard Map method of Luco et al. (2007) aims to determine the design ground motion for a given intensity measure, IM (e.g. PGA, Sa(T)), that produces a uniform level of risk across a region. Risk is defined as the probability of experiencing a particular impact such as the probability of a given financial loss, downtime, injuries, fatalities, or probability of exceeding a building limit state. The risk is usually defined as mean annual frequency of a limit state, whether it be the onset of damage (DLS), the ultimate limit state (ULS), or collapse limit state (CLS), however in most applications the collapse limit state has been used (Douglas and Gkimprixis, 2018). The risk is estimated through the risk integral of Luco et al. (2007):

$$\lambda_{LS} = \int_0^\infty P(IM > im) \cdot \left|\frac{d(LS)}{dIM}\right| dIM \tag{1}$$

Where $\lambda_{LS}$ is the mean annual frequency of the specified limit state (e.g. collapse), $P(IM > im)$ is the hazard curve defined as the probability of exceeding a given intensity measure level (IM) generated from a probabilistic seismic hazard model, and $\left|\frac{d(LS)}{dIM}\right| dIM$ is the derivative of the fragility curve for the given limit state (i.e. the probability density function). Further details are provided in Luco et al. (2007).

To provide a link to other risk metrics such as fatality risk (Silva et al., 2016; Tsang and Wenzel, 2016), a consequence function is required which defines the conditional probability of a fatality given the design limit state (e.g. collapse) in which case the risk integral becomes:

$$\lambda_F = \int_0^\infty P(IM > im) \cdot \left|\frac{d(LS)}{dIM}\right| dIM \cdot P(F|LS) \tag{2}$$

Where $\lambda_F$ is now the annual individual fatality rate and $P(F|\, LS)$ is the fatality rate given the limit state (e.g. collapse). Additional limit or damage states can also be used and a similar formulation is possible for other risk metrics such as injury, downtime or financial loss.

The benefit of moving to risk-targeted hazard, in addition to better risk equality across a region, is that the design level is now explicitly defined in terms of achieving a specific risk metric (e.g. fatality risk) that can easily be understood by decision makers, building owners and the public (Saunders and Kilvington, 2016; Tanner et al., 2020). It enables the risk levels, and hence the design levels, to be determined by society as it is now explicitly related to a metric that is much more easily understood than the currently ambiguous 10% in 50 year hazard (Douglas et al., 2013). In addition, it allows earthquake risk to be compared to other potential life risks.

Three parameters are required to solve for the risk targeted design ground motion intensity measure ($IM_R^D$). In the case of collapse risk, these are the annual collapse risk target ($\lambda_C^T$), the standard deviation, beta ($\beta$), of the fragility curve which controls the steepness or uncertainty of the fragility curve, and the probability of collapse given the design ground motion P(C|IM). The P(C|IM) is the anchor point (probability) on the fragility function where the design ground motion $IM_R^D$ is then determined. Once these parameters are defined the following steps are undertaken to determine the risk targeted design ground motion, $IM_R^D$ (Figure 1):

1. For a given location obtain a hazard curve from a probabilistic seismic hazard model, $P(IM > im)$;
2. For iteration $i$, generate a fragility curve (Equation 2) with a mean, $\mu$, that corresponds to an $IM_R^i$ equal to the current uniform hazard design ground motion, $IM_U^D$ (i.e. $IM_R^i = IM_U^D$). The standard deviation, $\beta$, is assumed constant for all calculations;
3. For each intensity measure level, multiply the hazard curve by the derivative of the fragility function (Equation 1) to estimate the probability of collapse for each IM level. This is termed the risk integrand;
4. Integrate across all intensity measure levels to determine the estimated annual collapse rate ($\lambda_C^i$) for iteration $i$ (Equation 1);
5. Compare the estimated annual collapse rate ($\lambda_C^i$) with the target annual collapse rate ($\lambda_C^T$) to determine if it is within a defined tolerance. If within tolerance, go to step 6 if outside tolerance go to step 2 and use a new$\mu$;
6. Once the estimated annual collapse rate is within the defined tolerance of the target annual collapse rate, find the $IM_R^D$ that corresponds to the P(C|IM);
7. Repeat steps 1 to 6 for other locations of interest.

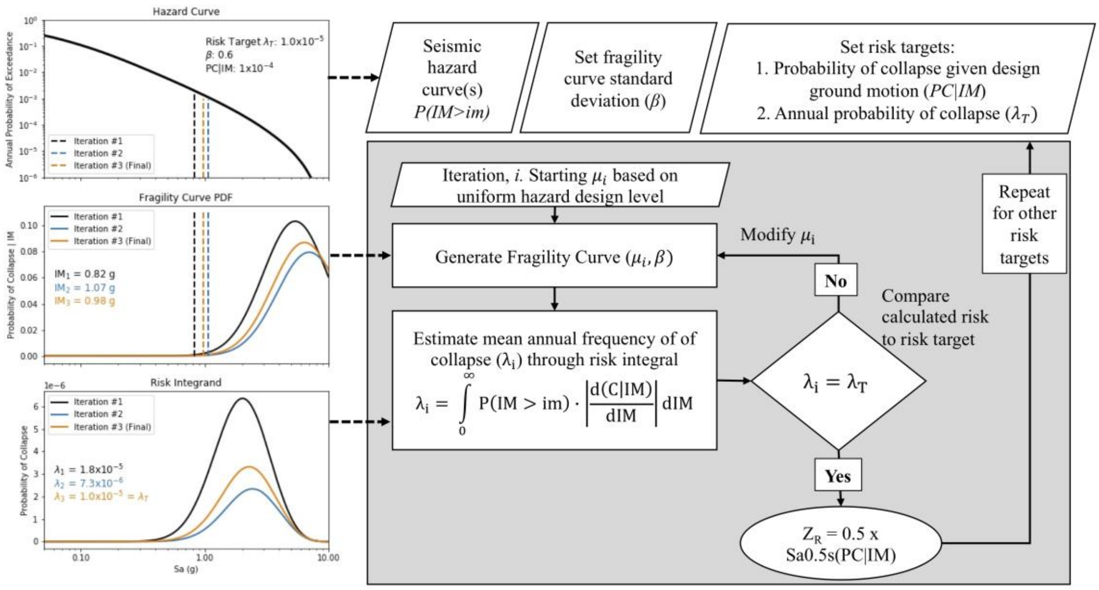


*Figure 1: Workflow for calculating risk targeted hazard spectra. The steps in the grey box are repeated until the target risk level is reached. The sloped boxes along the top are required inputs in the framework. This is similar to the ASCE 7-16 Method 2 in Chapter 21 (ASCE, 2010).*

## 3 RISK TARGETED HAZARD SPECTRA FOR NEW ZEALAND

The current uniform hazard approach to seismic design in New Zealand results in non-uniform risk across the country. This is shown in Figure 2 where a fragility curve (representing a given limit state, e.g. collapse) with a mean fixed relative to the uniform hazard design level (10% probability of exceedance in 50 years) and a constant beta (0.6), is used to estimate the risk of exceeding that limit state. Figure 2B shows that the risk varies across the country by two orders of magnitudes which is due to different shapes in the hazard curve above and below the current 10% probability of exceedance in 50 years design ground motion. It is recognised that Figure 3B does not take into consideration the exceptions (e.g. floor levels) to the 10% in 50 year ground motions used for design according to NZS 1170.5 in Northland, Auckland, and Christchurch regions. In this section we propose new design ground motions, based on risk targets which will result in uniform risk across New Zealand.

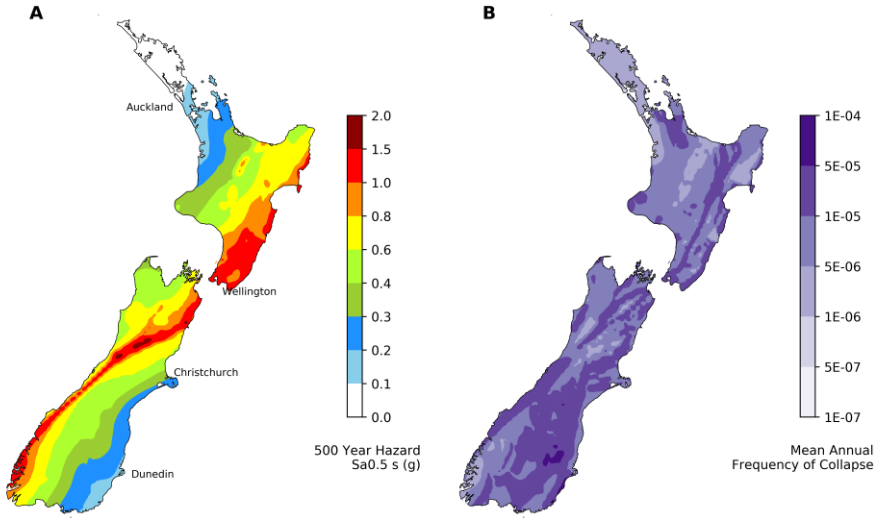


*Figure 2: A: Hazard map for 10% probability of exceedance in 50 years at Sa(0.5 s) using a mean hazard curve from the NSHM as described below. B: Estimated mean annual frequency of collapse assuming a collapse fragility curve (fixed $\beta$ = 0.6) tied to the 10% probability of exceedance in 50 years hazard. The variation in B is due to different shapes of the hazard curve not considered when using a uniform hazard (single hazard level) for design.*

## 3.1 Seismic Hazard Model

Seismic hazard curves are required for assessment of the risk-targeted hazard spectra. The 2010 New Zealand National Seismic Hazard Model (NSHM) (Stirling et al., 2012) is currently used as the basis of seismic hazard calculation for seismic design in New Zealand, however, significant updates to this model have not occurred for nearly 20 years. In order to utilize recent studies a number of modifications were made to the NSHM to include more recent ground motion models. These changes were included through the use of a logic tree that considers alternative ground motion models (GMM). The 2010 NZ NSHM does not consider epistemic uncertainty (uncertainty in knowledge, as opposed to aleatory variability in parameter estimates) as it consists of a single source model with fault and background sources representing the long-term seismicity rate, and a single ground motion model for each tectonic region type. Van Houtte (2017), compared published GMM with strong motion data from New Zealand to develop a GMM logic tree for use in seismic hazard assessment in New Zealand. The logic tree adopted for the current study has five GMM for active shallow crust earthquakes, four for subduction interface and subduction intraslab earthquakes and two for volcanic earthquakes. The logic tree has 160 terminal branches when all GMM are considered. Seismic hazard calculations were carried out using the OpenQuake engine (Pagani et al., 2014; Silva et al., 2014) with New Zealand specific configurations (Horspool et al., 2017; Van Houtte and Abbott, 2019).

## 3.2 Model Parametrisation for New Zealand Context

### 3.2.1 Risk Targets

When designing structures, the risk to people and property cannot be completely avoided due to inherent uncertainties within the design process and future hazards. The remaining risk is termed the residual risk. Recognizing residual risk, building codes are generally described in terms of accepting tolerable levels of residual risk if the design standards are adhered too. In a risk-targeted hazard method, the choice of acceptable levels of residual risk is an important parameter that influences the results.

Previous applications of risk-targeted hazard have used annual probability of collapse, or the probability of collapse over 50 years, as residual risk metrics and targets (Douglas et al., 2013; Luco et al., 2007). However, probability of collapse is still a somewhat enigmatic term for society beyond the engineering community. How collapse translates to life safety risk, economic loss or recovery from an event is not explicit and inhibits societal setting of risk targets for building codes. Further, without expressing risk targets in metrics commonly used in other fields such as annual individual fatality risk or expected annual loss, comparisons between earthquake risks and other life risks are difficult. For example, how does the 1 % in 50 years collapse risk for the IBC compare to other life safety risks in the US, and is this level of collapse risk acceptable to society? Although it is recognized that uncertainty exists between collapse and fatalities, empirical data (So, 2016) and expert elicitation methods (FEMA, 2012) can help inform appropriate selection of fatality rate models that allow collapse to be linked with expected fatalities. Silva et al. (2016) adopted a fatality rate of 0.1 given collapse (10% of occupants are assumed to die in the case of collapse of a code compliant building) for their risk targeted study of Europe which was based on expert judgement for modern code compliant US buildings (FEMA, 2012). However, empirical data, which is limited by few examples of collapse of recent buildings, suggests fatality rates are dependent on the style of collapse and could be as high as 0.8 (80% fatalities) for pancake-style collapse caused by failure of the gravity load resisting system (So, 2016).

Once risk can be expressed in terms of fatalities (or other risk metrics such as economic loss), it is then simpler to determine acceptable levels of risk for risk-targeted hazard assessments through either comparison with other acceptable life risks (Jonkman et al., 2003) or through community engagement (Saunders and Kilvington, 2015). A commonly used acceptable level of individual fatality risk for involuntary activities, such as being within a building, is $10^{-6}$ or a one in a million per year chance of dying per year (Tsang and Wenzel, 2016). This has been used as the acceptable threshold for ISO Standards 2394:1998 for the reliability of structures (ISO, 1998), dam safety in Australia (ANCOLD, 2003), the UK Health Safety Executive (HSE, 2001), and the NSH HIPAP Guidelines for land use safety planning (NSW, 2011). In New Zealand an annual individual fatality risk target of $10^{-6}$ is referred to in the New Zealand Loading standards as a performance target for new buildings (NZS, 2004) and has also been chosen following community consultation on acceptable natural hazard risk for new developments in the Bay of Plenty region in New Zealand (Saunders and Kilvington, 2015). For existing developments, a threshold of $10^{-4}$ to $10^{-5}$ has been used in New Zealand for zoning of residential properties within rock fall zones in the Port Hills of Christchurch (Massey et al., 2014) which is consistent with recommendations from the Australian Geomechanical Society (AGS, 2007). Given the explicit reference to an annual individual fatality target of $10^{-6}$ in the New Zealand loading standards, this risk target was chosen for this study.

As shown by Silva et al. (2016), a consequence function that defines the probability of death given collapse is required to provide a link between collapse and fatality risk. A value of 0.1 for the fatality rate given collapse, consistent with that used by Silva et al. (2016), was selected for this study. Further studies could explore the sensitivity of the final results to this assumption.

An annual individual fatality risk target of $10^{-6}$ would apply for the majority of structures designed at Importance Level 2 (IL2), which represents the base case for New Zealand structures. The New Zealand standards also define Importance Level 3 (IL3) structures as structures where the occupancy may be over 1000 people at any given time, and Importance Level 4 (IL4) where post-earthquake functionality is required such as hospitals. The IL2 design ground motions are scaled by 1.3 and 1.8 respectively for IL3 and IL4 buildings to achieve higher performance objectives and, as shown earlier, this results in non-uniform risk for these buildings. In a risk-targeted framework, the risk target would be lowered for different IL structures. As will be shown in section 3.4, IL3 structures with high occupancy will be included through societal risk targets. However, for IL4 structures, we propose that a risk target is set that results in a design ground motion that is on average across New Zealand towns 1.8 times larger than the design ground motion for the $10^{-6}$ risk target, consistent with existing design ground motions. This results in uniform risk for both IL2 and IL4 buildings across the country. The IL2 and IL4 risk targets are therefore set to ensure consistency with the New Zealand Building Code. However, if the Building Code or performance targets are revised, the framework is flexible enough to allow the risk targets to be modified to accommodate these changes.

### 3.2.2 Fragility-curve dispersion

The beta parameter defines the dispersion of the fragility curve used in the process described in Figure 1 to arrive at the risk-targeted hazard. The parameter is important as it should represent all uncertainty in the response of a building given an input ground motion intensity. Uncertainty can be the categorized into the aleatory uncertainty associated with variability in different design, material properties, and construction practices that meet code requirements and the variability in response of the structure to different ground motion records. As well as the epistemic uncertainty in the models used to estimate the response of the structure. For collapse of modern code-compliant buildings it is likely that design and construction flaws, in particular the combination of multiple flaws, is a significant contributor.

Few studies have investigated or determined beta for New Zealand buildings. In a non-linear time history study of a code compliant 10-story reinforced concrete moment frame building in Christchurch, Koopaee et al. (2017) found that beta for collapse state varied between 0.38 and 0.58 when considering uncertainty only from record-to-record ground motion variability. This increased to 0.6 and 0.77 when also including uncertainty in the capacity of the building. The range of beta values depended on what method was used for ground motion record selection with a final beta value of 0.68 recommended. In a similar study, Belliss et al. (2016), derived collapse fragility curves for 4- and 8-story reinforced concrete moment frame structures in each of New Zealand's three main cities; Auckland, Wellington and Christchurch. The beta for collapse ranged from 0.19 to 0.35 but only include record-to-record variability. Using empirical damage data from the 2011 Christchurch Earthquake, Lin et al. (2018) derived empirical fragility curves. Beta for heavy damage/collapse ranged from 0.55 to 0.60 for modern post-1976 buildings. Given the limited number of studies for New Zealand buildings, we adopt a beta of 0.6 following other risk targeted hazard studies (Silva et al, 2016), noting that a beta of 0.6 lies within the estimates from the limited New Zealand specific studies.

### 3.2.3 Probability of collapse | GM

The final parameter required to determine the risk-targeted hazard is the probability of collapse given the design ground motion (PC|GM). This parameter provides an anchor point on the fragility function from where the design ground motion is derived. It has practical meaning as it defines an acceptable number of collapsed buildings given a design ground motion earthquake.

It is widely considered that the current design approach in New Zealand is achieving its objective of protecting life safety, at least from a structural failure perspective (Hare, 2019). With this in mind the goal of the risk targeted hazard maps is to determine the design ground motions that result in uniform risk, through recalibration of existing Z values (i.e. hazard factor in NZS 1170.5), and not to propose absolute shifts in Z values. Following the approach of Douglas et al. (2013), who had similar objectives for mainland France, the PC|GM is a free parameter that we aim to determine. As described in more detail in the next section, this is done by finding the PC|GM that results in an average $Z_R/Z$ of 1.0 across New Zealand towns and cities. $Z_R/Z$ is the ratio of the design ground motions for risk-targeted hazard ($Z_R$) and uniform hazard (Z).

## 3.3 Designing for Individual Risk Including Epistemic Uncertainty In Seismic Hazard

The first step in the development of risk-targeted hazard maps for New Zealand is determination of risk-targeted hazard for individual fatality risk targets where a person is assumed to be within the building permanently (Crowley et al., 2017; Jonkman et al., 2003; Tsang and Wenzel, 2016). The method of Luco et al. (2007) is adopted, using parameters described in previous sections for annual individual fatality risk (AIFR) target ($10^{-6}$) a fatality rate given collapse of 0.1, beta (0.6), and how PC|GM would be determined by minimizing changes in the design level across New Zealand towns. However, instead of using the mean hazard curve as previous risk targeted hazard studies have done (Douglas and Gkimprixis, 2018; Douglas et al., 2013; Luco et al., 2007; Silva et al., 2016), the full range of epistemic uncertainty in the seismic hazard is included in the risk targeted hazard calculations.

Following the interpretation of logic trees in seismic hazard calculations of Marzocchi and Jordan (2014) and Marzocchi et al. (2015), the logic tree is assumed to represent an ensemble of possible models and not a probability tree (Musson, 2012). In this case it is appropriate to propagate epistemic uncertainty through the risk-targeted hazard framework as the true risk must be one of logic tree branches.

The following steps are followed to propagate epistemic uncertainty in the hazard through the risk-targeted hazard framework (Figure 1 and 3):

1. Select starting PC|GM,
2. For town *n*,
3. Select a hazard curve ($H_i$) from a termination of a logic tree branch *i* with weight ($W_i$),
4. Using the parameters AIFR (constant), beta (constant), PC|GM, estimate the risk-targeted design ground motion using the steps shown earlier in Figure 2, for branch *i*. Because each hazard curve is different the final fragility curve and therefore the risk targeted hazard ground motion will also be different in order to meet the risk target,
5. Repeat steps 3 – 4 for all branches of the logic tree,
6. From the resulting distribution of risk-targeted hazard IM select a risk-targeted hazard ground motion ($Z_R$) that represents the statistic of interest (e.g. $50^{th}$ percentile) using a weighted distribution considering the weight of each branch ($w_i$),
7. Determine the risk coefficient ($C_R = Z_R/Z$) for this town where Z is the uniform hazard ground motion,
8. Repeat steps 2 –7 for all towns,
9. Calculate the mean risk coefficient across all towns,
10. Modify PC|GM and repeat steps 2 – 9 until the mean risk coefficient is equal to 1.0.

The outcome of the above procedure is illustrated in Figure 4. For this procedure, an additional parameter is required in Step 6; the statistic from the distribution of risk targeted ground motions. The meaning and therefore choice of this parameter has practical and societal implications. According to Marzocchi et al. (2015) the meaning of the distribution of risk-targeted hazard is that all of the branches meet our risk target (equal risk), and the true risk-targeted hazard must lie somewhere within this distribution. The selection of a percentile to use for seismic design then has implications in the sense that if we choose the median then the risk target has a 50% probability of being exceeded. Therefore, the choice of percentile is linked to the risk aversion of the decision maker and is beyond a purely scientific- or engineering-based decision. This concept is somewhat analogous to the factor of safety used in engineering design where a number of standard deviations above the median of a distribution are used to ensure reliability and provide a margin of error. A more risk-averse decision maker would choose a higher percentile which would provide a higher level of confidence that the true risk is less than the chosen design level. A higher percentile could also be selected for structures of higher societal importance to provide a higher level of confidence in the design of these structures.  For the purposes of this study the median risk-targeted hazard was used (Figure 3).

Following the procedure defined above, the PC|GM that resulted in a mean of $C_R$ of unity across New Zealand towns was $1.0x10^{-4}$. As shown in Table 1, this PC|GM is consistent with proposals in Europe but considerably lower than that used in IBC, even when adjusted for the different return-period target.

***Table 1**. List of parameters used in this and other risk targeted hazard studies*

| Study | Location (Code) | Annual Collapse Target | PC\|GM | Equivalent RP |
|---|---|---|---|---|
| Luco et al (2007) | USA (IBC) | $2x10^{-4}$ (1 % in 50 years) | $1x10^{-1}$ | 2500 (MCE) |
| Douglas et al (2013) | France (EuroCode) | $1x10^{-5}$ (0.05 % in 50 years) | $1x10^{-5}$ | 475 |
| Silva et al (2016) | Europe (EuroCode) | $5x10^{-6}$ (0.02 % in 50 years) | $1x10^{-3}$ | 475 |
| This study | NZ (NZS1170) | $1x10^{-5}$ (0.05 % in 50 years) | $1x10^{-4}$ | 500 |

Figure 4 shows the resulting $C_R$ for New Zealand towns and cities. It can be seen in Figure 4 that for the three main cities, Auckland would decrease by 33 %, Wellington would increase by 7 %, and Christchurch would decrease by 4 %. The reason Auckland would decrease is that the existing Z is based on the floor level of 0.1, where-as the results here show that this is a conservative floor level and the design level would be lower for equal risk across the country. However, with the introduction of societal risk factors into the framework (as described in Section 3.4), as well as new seismic hazard models incorporating uncertainty in the seismicity rates for Auckland it could be argued that having a conservative floor Z value is no longer required.

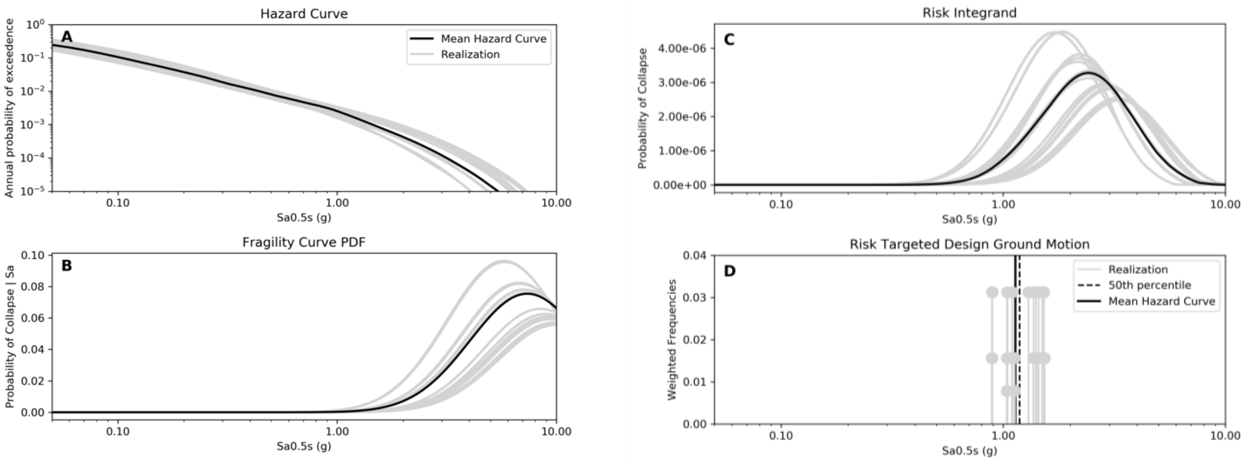


*Figure 3: A: Hazard curves (grey are realisations from the GMPE logic tree, black is the mean hazard curve). B: Fragility curves that are required to achieve the risk targets. C: Risk integrands that produce the risk target. D: Distribution of risk targeted design ground motions. The black line is if only the mean hazard curve is used, the black dashed line is the median of the distribution of realisations. The grey lollipops represent the spread of possible design ground motion realisations.*

The spatial variability of $C_R$ is not related to the existing 10% in 50 year ground motion; it is controlled by ground motions with probabilities smaller than 10 % in 50 years (i.e. larger ground motions). It can be seen in Figure 3C that the highest contribution to collapse risk is from large ground motions higher than existing 10% in 50 year ground motions. Therefore the relative difference between the 10% in 50 year (500 year return period) and 2% in 50 year (2500 year return period) ground motion influences the value of $C_R$ more than the absolute value of the 10% in 50 year motion. Sites with higher 2% in 50 year motions relative to the 10% in 50 year motion such as Dunedin (Figure 4) and Napier have high $C_R$ values. Generally, sites with higher 2%/10% in 50 year ground motions are those with fault sources that have larger average recurrence intervals such as the Hikurangi Subduction Zone (e.g. towns along the east coast of the North Island) and crustal faults with low slip rates but high characteristic magnitudes, such as the Akatore Fault near Dunedin.

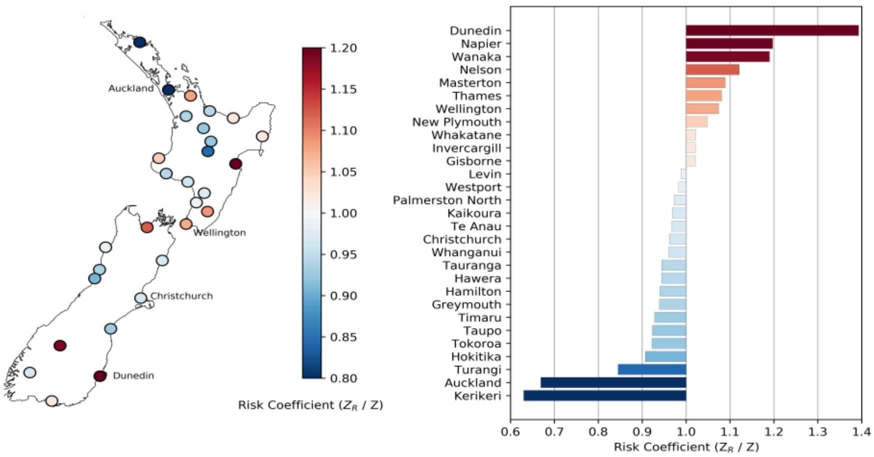


*Figure 4: Left: Map of $C_R$, the risk coefficient ($Z_R$/Z), for New Zealand cities and towns. Right: distribution of $C_R$ for each city or town.*

### 3.4 Designing for Societal Risk

The risk-targeted hazard values determined in the previous section can be considered the minimum risk-targeted design level as they consider the life safety risk to an individual permanently located in a structure. However, where the aggregation of risk occurs, such as in individual buildings with high occupancy or in towns and cities, using societal risk targets can help attain goals of achieving performance of cities by avoiding mass casualty events and, for alternative risk metrics, city wide disruption or large economic impacts.

In order to include societal risk in the risk-targeted hazard framework, societal risk targets also need to be defined. In the case of life safety, the objective of including societal risk targets is to minimize significant loss of life where there is an aggregation of risk either in a high occupancy building where collapse would result in significant loss of life or in central business districts where collapse of multiple buildings would result in a large number of fatalities.

Societal risk targets are in the form of F-N curves where acceptable annual probabilities of exceedances (F) of N fatalities are set (Figure 5D). The use of F-N curve risk limits is common in other fields such as land use planning (Saunders and Kilvington, 2015), dam safety (ANCOLD, 2003), flood protection (Jonkman et al., 2003; Vrijling, 2001), and industrial facilities (NSW, 2011). The estimated F-N curve for a given community must lie below the F-N risk limit for the risk to be acceptable. This approach allows the definition on the number of fatalities per event that is acceptable. This has more relevance for societal risk, as society is often less tolerant of rare mass fatality events (e.g earthquakes) than more frequent small fatality events (e.g. car crashes) that may result in the same expected number of fatalities per year, particularly if the exposure to the risk is involuntary as in the case of earthquakes (Tsang et al., 2020).

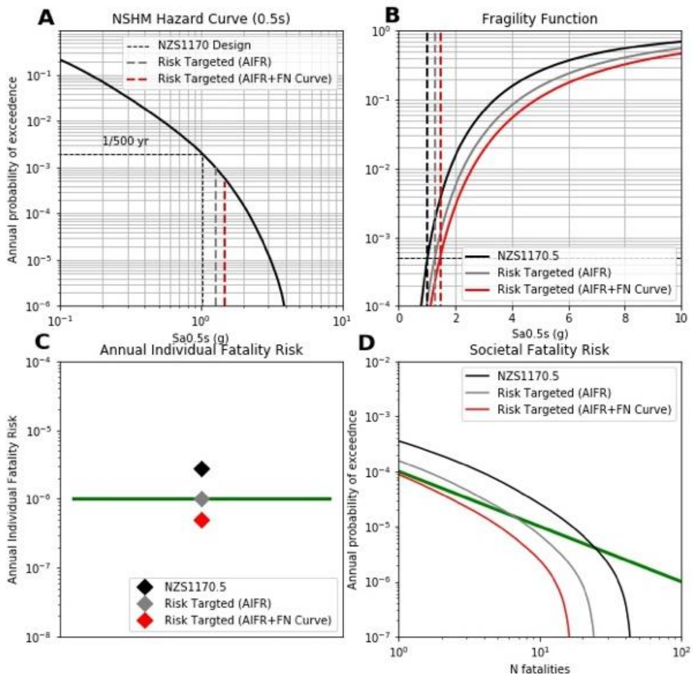


*Figure 5: Example of risk-targeted hazard considering both individual and societal risk. A: Hazard curve, B: Fragility curves, C: Individual risk levels, D: Societal risk levels. Black curves/symbols are original estimates, grey are when individual risk targets are met, and red are when societal risk targets are met.*

To estimate societal risk, an F-N curve is estimated for the building or city using the collapse fragility function and a fatality rate conditional on collapse of 0.1 from the individual risk targeted hazard calculation. Occupancy of the building is required for societal risk calculations and for this study it is assumed the building has maximum occupancy for 100 % of the time which would provide a conservative estimate of the societal risk. This is required as some buildings may have 100 % occupancy. The estimated F-N curve is then compared to the risk limit F-N curve for individual buildings and for city limits determined as part of setting risk targets. If the estimated F-N curve exceeds the risk limit F-N curve then the fragility is further adjusted, as is done for the individual building risk limit, until the estimated F-N curve is below the risk limit F-N curve . The above process is illustrated in Figure 5, where in Figure 5A shows the increase in design level (from black to grey to meet AIFR targets and grey to red line to meet societal risk targets) needed to ensure both the AIFR targets and that the F-N curve for the building falls below the risk limit F-N curve for societal risk targets (Figure 5D). In this example the F-N risk limit is arbitrarily chosen for demonstration. In practice this would be defined in the loading standards.

## 4 INCLUDING RISK TARGETED SPECTRA IN NEW ZEALAND STANDARDS

An aim of this study is to show how risk-targeted hazard spectra can be incorporated within the existing New Zealand Loading Standards framework. Three options are presented that include incorporation of the risk-targeted concept to varying levels. It is emphasised that for each of the three options below, all calculations to arrive at the risk-targeted factors would be done in advance and tabulated for application in practice; none of the detailed calculations discussed previously need to be done by the engineer and the design process remains essentially unchanged.

### 4.1 Modifying Return Period (R) Factor For Uniform Risk

The first option and the simplest, is modification of the existing R-factor in NZS 1170.5, which represents a scaling of the Z-factor for different ground motion probability of occurrences. It is the equivalent of a risk factor as its scales the ground motion according to the importance level (IL) of the structure. The majority of buildings are designed to Importance Level 2 (IL2) which has an R-factor of 1.0. For structures of high occupancy (IL3), R increases to 1.3, and for post-earthquake critical facilities (IL4), R is 1.8. For this option the risk coefficient ($C_R$) becomes the R-factor. $C_R$ is the ratio of the risk-targeted hazard design ground motion with the uniform hazard design ground motion. The R-factor would now vary regionally for the same importance level to ensure equal risk across the country. This option has the disadvantage of requiring the use of the consistent spectral shape for all locations. This will lead to consistent risk at T=0.5 sec, period at which Z is defined, but potentially varying risk at other periods.

### 4.2 Introducing $Z_R$

The second option is to use the risk-targeted design spectra, $Z_R(T, IL)$, which is conditional on spectral period (T) and importance level (IL) of the building. Structures with higher importance levels would have different risk targets and possibly a higher percentile from the epistemic uncertainty distribution of risk targeted hazard values. The $Z_R(T, IL)$ term would replace the uniform hazard factor $Z$, the return period factor $R$, and the spectral shape factor $C(h)$. The elastic site risk targeted hazard spectra $C(T)$ would be defined as:

$$C(T) = Z_R(T, IL) \cdot N(T, D) \quad (3)$$

Where $N(T,D)$ is the near fault factor, which could also be removed if near fault effects are included in ground motion models used in the probabilistic seismic hazard assessment (Shahi and Baker 2011) and is being investigated for the new NSHM. The shape of the risk-targeted hazard spectrum for Wellington is shown in Figure 6 compared to the existing design spectrum and uniform hazard spectrum (50$^{th}$ percentile). The normalised risk-targeted spectrum is lower at all periods than the design spectrum and slightly higher than the UHS at periods beyond 0.5 s. The risk-targeted hazard spectrum has truncated peaks in the 0.2 – 0.4 s period range compared to the UHS.

### 4.3 Including Societal Risk Targets

To include societal risk targets, Equation 3 would be extended to include the two societal risk factors, building occupancy factor ($O$) and the population factor ($P$), as follows:

$$C(T) = Z_R(T, IL) \cdot O \cdot P \cdot N(T,D) \quad (4)$$

The building occupancy and population factors would only be used if the building had a large enough occupancy or the building was located in a city where the CBD factor is applied (e.g. Auckland, Wellington, Christchurch). The building occupancy factor would in effect replace the need for IL3 buildings. Therefore the $Z_R(T, IL)$ term represents the base design level for the majority of new buildings with low-moderate occupancy outside of the three main city centres.

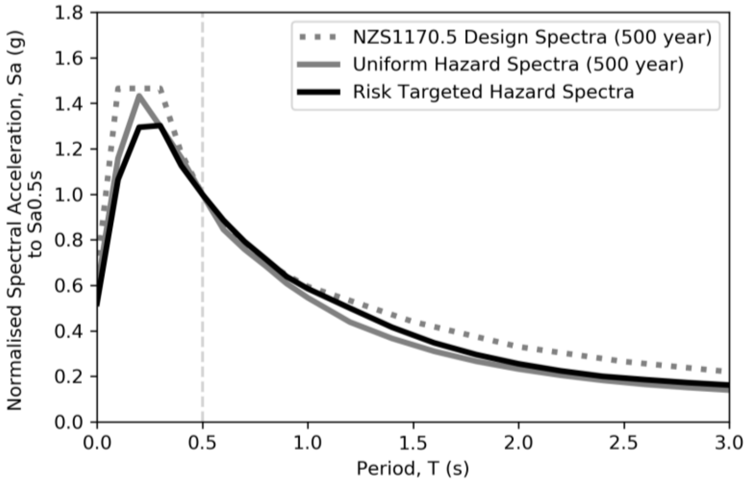


*Figure 6: Risk-targeted spectra for Wellington normalized to Sa(0.5 s) for comparison with the 500 year NZS1170.5 design spectra and the 500 year mean uniform hazard spectra.*

### 4.4 Alternative risk metrics

This study presents a framework for risk-targeted hazard spectra considering epistemic uncertainty in hazard and including individual risk and societal risk targets for fatality risk. This is consistent with the life safety objective of all building codes. However, there is growing evidence that building codes need to consider more than just life safety by including performance objectives related to economic loss and functional recovery following earthquakes (Hare, 2019). These additional risk targets can be included in the proposed framework in a similar way to how the fatality risk targets are proposed to be included in previous section, i.e. as additional factors. Once the life safety targets have been met, this provides a minimum design level to achieve life safety objectives. If the additional targets are met, then the life safety design level also meets the economic loss and functional recovery targets. However, if the additional targets are not met, then the design level would be increased until the economic loss and functional recovery targets are met. This iteration would be repeated until the risk targets are satisfied. Alternatively, the framework described in this paper could be used to target a probability of exceeding the serviceability limit state or first yield of the building.

## 5 CONCLUSION

This paper has presented using Risk-Targeted Hazard Spectra as an alternative approach for determining seismic design levels in New Zealand. Risk-Targeted Hazard design spectra achieve uniform risk across the country unlike the current uniform hazard based approach. Further, the framework proposed can include epistemic uncertainty in seismic hazard and account for individual risk at the building level as well as designing for societal risk targets at city scales. The framework is fully transparent and can be easily included within the existing standards or new standards developed in the future. The framework has been developed to be compatible with the new National Seismic Hazard Model that is currently in development.

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