Quake Centre
Delivering Industry Solutions

A Risk-Informed Framework for Earthquake Ground Motion Hazard Assessment in New Zealand

Prepared for the University of Canterbury Quake Centre by James Dismuke and Jeff Fraser

www.quakecentre.co.nz

With contributions from:

- Brendon Bradley, University of Canterbury
- Tony Fairclough, New Zealand Geotechnical Society
- Clark Fenton, University of Canterbury
- Matt Gerstenberger, GNS Science
- Russell Green, Virginia Tech University, Virginia, USA
- John Hooper, Magnusson Klemencic Associates, Seattle, Washington, USA
- Alan Hull, Golder Associates, Portland, Oregon, USA
- Rob Jury, New Zealand Society for Earthquake Engineering
- Campbell Keepa, New Zealand Society for Earthquake Engineering
- Didier Pettinga, Holmes Consulting
- Greg Preston, University of Canterbury Quake Centre
- Nathan Schumacher, Ministry for Business, Innovation and Employment
- John Scott, Earthquake Commission
- Jenni Tipler, Ministry for Business, Innovation and Employment
- Liam Wotherspoon, University of Auckland

Quake Centre
Delivering Industry Solutions

A Risk-Informed Framework for Earthquake Ground Motion Hazard Assessment in New Zealand

Prepared for the University of Canterbury Quake Centre

James Dismuke and Jeff Fraser
June 2020

Table of contents

Table of figures

1 Introduction

Earthquakes cause hazards that affect humankind, either directly (e.g. ground shaking) or indirectly (e.g. liquefaction caused by ground shaking). Understanding earthquake ground shaking, or the earthquake ground motion (GM) hazard, is critical to understanding the earthquake risk for planning, design and development in New Zealand. There are several techniques for determining GMs for input into the planning and design of built infrastructure. Each has its pros and cons, and some techniques are more suited to some projects than others. This report discusses some of these techniques and when they could be applied to projects to improve the understanding of earthquake GM hazards for planning and design.

When designing infrastructure or planning for land use, it is important to understand the design GM as well as the uncertainty inherent in its determination. The GM hazard analyses discussed here can be used to determine the level, or intensity, of earthquake shaking for design of a project. These analyses are best performed early in the project lifecycle, to inform preliminary and feasibility-level studies as suggested on Figure 1, so that all phases and technical aspects of the project (i.e. geotechnical and structural) are completed with a consistent definition of earthquake GMs. This is especially important for projects where earthquake design is a significant project component, as it is for most of New Zealand.

Performing specific GM hazard analyses during or after detailed design is not ideal because this practice can lead to an unconservative design in cases where the preliminary GM assumption is too low, or a conservative design in cases where the preliminary GM assumption is too high. In either instance, this could result in costly redesign, or, in extreme cases, a change in design GM level could make the project unfeasible late in the project lifecycle.

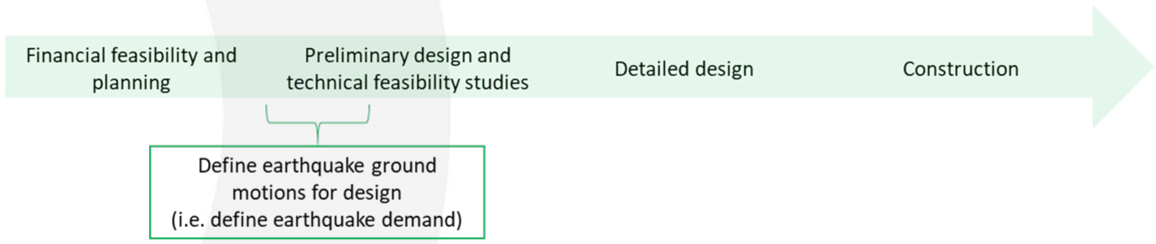


Figure 1. Earthquake ground motion hazard analysis in the project lifecycle.

This report provides a framework for decision makers, policy makers, developers, owners, engineers and others to select the level of effort (i.e. appropriate GM hazard analysis techniques) for assessing GM hazard to suit the risk-profile of their specific projects. Detailed technical guidance about how to perform hazard analyses are not in the scope of this report.

2 Background

In New Zealand, the earthquake ground motion (GM) that is considered in building design is specified in a generalised manner in New Zealand Standard 1170.5:2004, *Structural Design Actions – Part 5: Earthquake Actions – New Zealand*. However, other techniques can be used to estimate the design level GMs. Clause 3.1 of NZS 1170.5:2004 has an allowance for "Special Studies" that can be used to provide more accurate ground motions that supersede the simplified parameters provided in that standard. Herein, discussion of NZS 1170.5:2004 refers to the general approach documented in the standard, unless special studies are referred to specifically.

Special studies can be implemented on a site-specific basis, which is an improvement over the generalised way NZS 1170.5:2004 addresses GM hazard in New Zealand. Some of the techniques for site-specific hazard analysis are discussed in this report, as well as when these techniques could be applied to projects to improve the understanding of earthquake GMs for planning and design. For clarification, all references to NZS 1170.5:2004 made within this report pertain specifically to determination of design elastic response spectra and are not directed at any other aspect of the standard.

Many projects would benefit from using a site-specific analysis instead of NZS 1170.5:2004 because site-specific analyses reduce uncertainty that is inherent in a general procedure. To justify the use of a site-specific analysis requires understanding of several criteria, for example:

- The cost of the site-specific study
- The construction cost implications resulting from an optimised design
- The operating cost implications resulting from an optimised design
- Impacts to insurance requirements from a detailed definition of GM risk
- The effect on economics and earthquake resilience at local, regional and national scales resulting from an optimised design.

This implies that some projects will greatly benefit from a site-specific analysis; however, for other projects it may not be justified. For example, there is a generally insignificant cost saving in the design and construction of a 1- or 2-storey residential timber-framed building using a site-specific GM hazard analysis instead of NZS 1170.5:2004, so the cost and effort required for the site-specific analysis is not justified. In contrast, consider design and construction of a regional hospital facility with a requirement for post-disaster functionality. There is no question of the benefit, or requirement, for such a structure to use the most rigorous design approaches, due to the importance of the facility. A site-specific GM hazard analysis would be the keystone for understanding the earthquake risk of this hospital facility.

Most significant projects in New Zealand will fall in between the two extreme examples given above, and, as such, may benefit from site-specific analyses to various degrees. There is an opportunity in New Zealand to gain a better understanding of earthquake GMs using contemporary GM hazard analysis techniques where they benefit a project. This may lead to increased resilience, reduced construction costs, and reduced operating costs in New Zealand over the long term.

3 Scope of report

This report provides a framework for decision makers, policy makers, developers, owners, engineers and others to select the level of effort (i.e. appropriate GM hazard analysis techniques) for assessing GM hazard to suit the risk-profile of their specific projects. Detailed technical guidance about how to perform the hazard analyses is not in the scope of this report. This report comprises:

- Definition of terms and concepts used in the report
- Summary of current New Zealand guidance
- Methods and techniques for determining earthquake ground motions for design
- Risk-informed framework for determining earthquake ground motions
- Answers to frequently asked questions.

4 Definition of terms and key concepts

4.1 Hazard, consequence and risk

There are numerous definitions of risks across a wide range of applications, but generally risk is the probability of loss. The risk of a natural hazard affecting a location is typically the product of hazard and consequence, where:

Hazard

A hazard is the intensity and likelihood of a natural phenomenon.

For example, a peak ground acceleration (PGA) of 0.3 times the acceleration of gravity, g, is defined with an annual probability of exceedance (APE) of 1/500. In this example the intensity is the PGA of 0.3 g and the likelihood is 1/500 APE. Thus, the PGA hazard is 0.3 g and there is a 1/500 average chance (or 0.2 % average probability) that a PGA of 0.3 g is exceeded each year. Note that this example is not intended to correspond with any specific location in New Zealand.

Consequence

A consequence is the product of exposure and vulnerability, where exposure is the total exposed value present at the location or area, and vulnerability is the degree of resistance to damaging forces.

Exposure could be the probable number of people occupying an asset at the time of an earthquake or the probable cost to repair or rebuild an asset after experiencing earthquake damage. Vulnerability is often assessed by engineers as part of the design process, that is, by computing the factor of safety or probability of failure.

Risk

Risk is the product of hazard and consequence, i.e. risk = hazard x consequence.

Risk is given in terms of minimum annual probable cost, which comes from the definition of hazard and consequence:

Risk (minimum annual probable cost) = hazard (annual probability of exceedance) x consequence (cost x probability of loss).

4.2 Uncertainty in hazard and consequence

The notion of best- or typical-engineering practice combined with adoption of standard building codes and specifications generally achieves very low probabilities of failure, so low that in the authors' experience, we often forget that uncertainty exists. However, we live in a world with uncertainty, which is reflected in the ISO31000, (2009) definition of risk as simply, "the effect of uncertainty on objectives."

Earthquakes are uncertain and random events, and being natural phenomena, ground motions that arise from earthquakes are difficult to measure and predict with confidence. On top of this, earthquake ground motions can have tremendous consequences for humans and our societies. This combination of high uncertainty and significant consequence drives the need to understand earthquake risk and its uncertainty in all aspects: the analysis of GM hazards, analysis of earthquake performance, and analysis of cost and exposure. It is fundamentally important to understand, and in many cases account for, these uncertainties when making risk-informed decisions (e.g. ISO31000, 2009). In the context of an earthquake, this can be conceptualised by the questions posed in Figure 2.

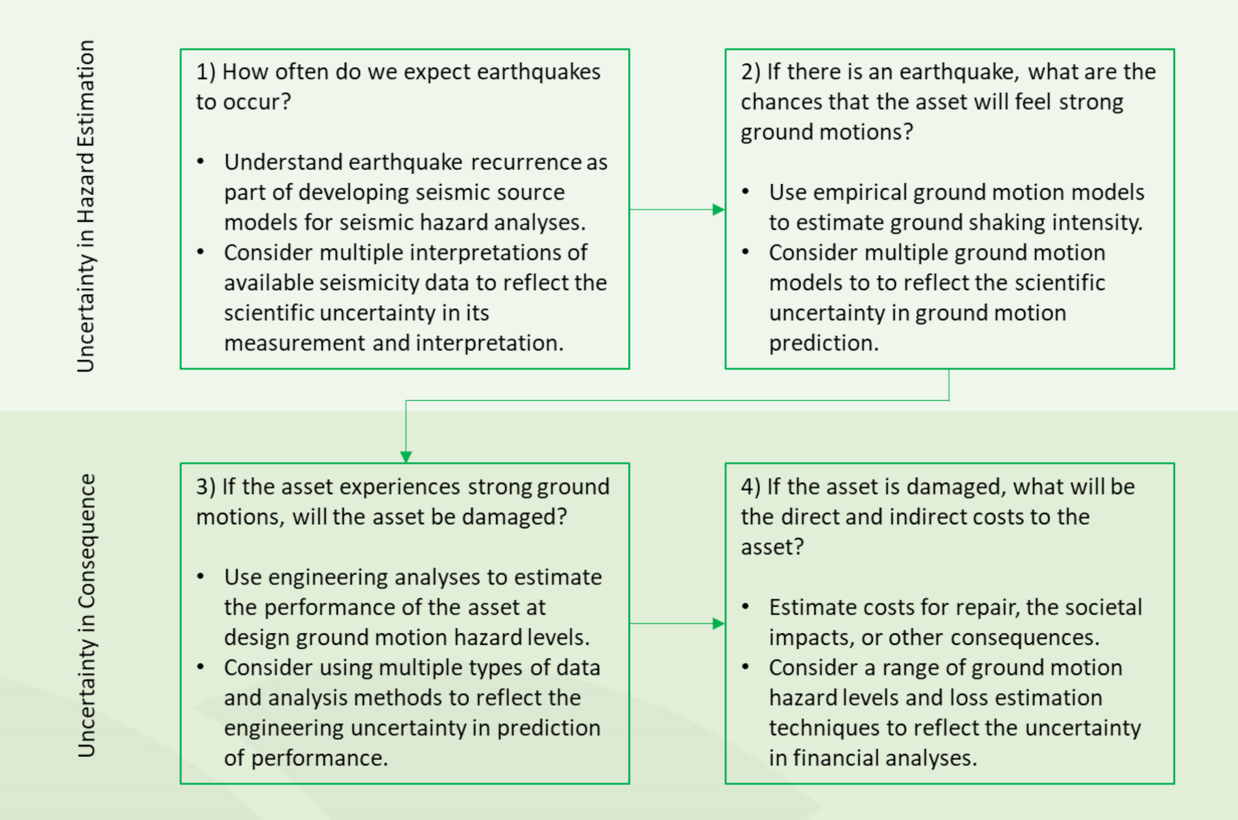


Figure 2. Uncertainty in hazard and consequence.

Methods for answering Questions 1 and 2 are the focus of this report, but earthquake risk cannot be assessed without also answering Questions 3 and 4. In common practice, there is a demarcation between the professionals that evaluate GM hazard and GM consequence. This is sensible because the technical expertise required to analyse faults and probabilities of ground shaking is different from the expertise required to analyse structural or geotechnical performance, both of which are different from the expertise required to assess the financial impacts of earthquakes.

4.3 Uniform risk, design criteria and GM parameters

The likelihood and consequences of an earthquake vary across New Zealand depending on the proximity to potential earthquake sources, physical and human geography, and the resilience of the built environment. Through standards and guidelines, the engineering profession, amongst others, seeks to create a built environment in which the risk of earthquakes is the same throughout New Zealand. This is a **uniform risk** approach, and it is based on the concept that, although the earthquake hazard varies throughout New Zealand, the earthquake risk should be the same everywhere if we meet earthquake standards and guidance.

It is critical to emphasise the distinction between 'design criteria' and 'design parameters' when discussing the uniform risk approach:

- NZS 1170.0:2002*, Structural Design Actions – Part 0: General Principles*, defines earthquake **design criteria** in terms of annual probability of exceedance (APE), which is commensurate with the importance level of the project. Importance level is a simplified measure of potential consequences to ground shaking. That is, the importance level of a project increases if the consequence of failure of the project affects many lives or has wide geographical impact. In turn, the specified APE decreases to offset the increasing importance (e.g. 1/500 APE for low importance, 1/2500 for high importance). This is conceptually like balancing the right side of the risk equation, such that an increase in consequence must be designed for a lower hazard probability to maintain uniform risk.
- Engineers require a ground acceleration (i.e. GM **design parameter**) that coincides with the APE design criteria. While the design criteria are established in NZS 1170 for all projects based on importance level, the potential earthquake ground accelerations vary across the diverse geological and seismological landscape of New Zealand. The procedures set out in NZS1170.5:2004 provide a method to estimate the acceleration response spectrum (i.e. the design parameters for the project design criteria or APE). Alternatively, to account for the variation in the GM hazard at different locations around New Zealand, a GM hazard analysis (e.g. a probabilistic seismic hazard analysis) can be used to determine the acceleration response spectrum for the design criteria.

4.4 GM hazard over time

The evolution of earthquake loading standards in New Zealand exhibits a general increase in GM design parameters over time. This is primarily due to:

1. An increasing understanding of the frequency and distribution of earthquakes in New Zealand
2. Improved understanding of faults in New Zealand, for example, our growing awareness of the Hikurangi Subduction Zone beneath the North Island
3. Our evolving ability to predict earthquake ground motions
4. Improved understanding of local effects of sedimentary basins, nonlinear soil behaviour and topography, all of which cause significant local variability in earthquake ground motions
5. More rigorous methods for addressing uncertainty in probabilistic seismic hazard analyses in seismic hazard practice, largely driven by the availability of ever-increasing computing power.

4.5 Limit states and the 'cliff edge'

New Zealand, like many countries, uses **a limit state approac**h whereby a design must achieve target performance or ensure specific consequences at various hazard levels (e.g. various APE). For example, a hypothetical serviceability limit state (SLS) target performance might be to have negligible building damage in the event of a 1/25 APE ground motion and a hypothetical ultimate limit state (ULS) target performance of no loss of life in the event of a 1/500 APE ground motion.

The limit state approach does not consider **the 'cliff edge' wher**e the consequences are more severe rapidly or instantaneously beyond the design hazard level. That is, a design can satisfy the limit state without any consideration of what lies beyond. For example, a cliff edge exists if the structure achieves the life-safety performance (i.e. the ULS target in the preceding example) at the specified design ground motion, but will potentially collapse if the building is struck by a ground motion that is just slightly greater than the design hazard level, potentially putting dozens or hundreds of lives at jeopardy. While this design technically achieves the life safety performance, decision makers may find the fact that there is little margin against building collapse to be uncomfortable and an unacceptable risk to the project.

It is impossible to understand if the target performance is achieved or how near or how far a design comes to its cliff edge without understanding the accuracy and precision of the GM hazard analysis that defines the design ground motion, the completeness of the data used as a basis for design, the capabilities and limitations of the design analyses, and the skill of the contractor that builds the project.

Text Box 1: Accuracy, precision, and consistent crudeness

Accuracy and precision are well-known concepts for describing uncertainty:

- Accuracy is defined as how close a prediction comes to the correct answer. How close a bullet comes to hitting the bullseye in Figure 3. is an example of accuracy.
- Precision describes the variability of predictions, or the scatter in the results. For example, the closely grouped cluster of bullet holes in the upper left target shown on Figure 3. have a greater precision than the widely spaced cluster of bullet holes shown on the lower left target.

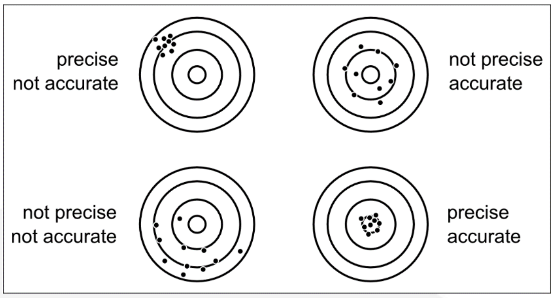


Figure 3. Accuracy and precision.

The principle of consistent crudeness ties accuracy and precision together in the context of engineering design:

…to some extent the choice of level of detail in any part of an engineering procedure must to some extent be governed by the crudest part of the procedure. (Elms 1992 p.72)

That is, the accuracy and precision of a complex engineering analysis is limited by the accuracy and precision of the input parameters and analysis equations. Detailed engineering design calculations should make use of equally detailed input parameters to preserve the level of consistent crudeness. The accuracy and precision of a complex engineering analysis are unknown if the accuracy and precision of the input is unknown.

5 New Zealand guidance

There are several New Zealand documents that identify the need to consider earthquake hazards, the GM design criteria, and simplified methods for estimating the GM hazard.

5.1 Earthquake design parameters provided by NZS 1170.5:2004

Most projects in New Zealand are designed using earthquake GM parameters estimated with NZS 1170.5:2004. NZS 1170.5:2004 provides a method of estimating a design earthquake response spectrum for any location in New Zealand and for range of APE. This method is based on a simplification of the then current, National Seismic Hazard Model developed by GNS. The engineering and seismological concepts addressed in NZS 1170.5:2004 are necessary simplifications of these concepts in order to generalise the method for ease of use and applicability across the diverse landscape of New Zealand. In fact, all global standard- and code-based methods of determining earthquake design spectra are simplified for use in practice for similar reasons.

Earthquake science and our understanding of GM hazards have advanced considerably in the recent past, such that the GM parameters provided in NZS 1170.5:2004 are outdated. Some of the implications of this are alluded to above. In addition, Bradley (2015), in a paper entitled *Benefits of site-specific hazard analyses for seismic design in New Zealand*, presents a useful background for the technical reader on the weaknesses of the current earthquake loading parameters in NZS1170.5:2004, along with the benefits of site-specific hazard analyses. **Furthermore, in some areas of New Zealand, site-specific probabilistic seismic hazard analyses (PSHA) using contemporary knowledge and hazard analysis techniques result in significantly greater GM parameters than NZS 1170.5:2004. That is, in these cases, NZS 1170.5:2004 was found to be unconservative.**

NZS 1170.5:2004 is more than 16 years old, and scientific understanding of the GM hazard in New Zealand has changed dramatically since its last update for the reasons stated above. Clause 3.1 of NZS 1170.5:2004, in recognition of its limitations, has an allowance for “Special Studies” as mentioned above.

It should be noted that a plan has been put in place for an update of the New Zealand Seismic Hazard Model. This will be ongoing.

5.2 Other existing risk-informed criteria for selecting GM design parameters

Documents that include risk-informed criteria for selecting GM design parameters are the New Zealand Dam Safety Guidelines and the NZTA Bridge Manual:

- The New Zealand Dam Safety Guidelines (NZSOLD, 2015) incorporates a risk-informed approach to developing earthquake loading by means of a consequence assessment focused on life safety. The guideline is used to determine the potential impact classification (PIC) for an existing or proposed dam. Based on the PIC, the guidance recommends seismic performance criteria and suitable methodology to determine the parameters.
- The NZTA Bridge Manual includes a risk-informed approach for deciding when a site-specific GM hazard study is required. This approach requires a site-specific GM hazard study when the value of earthworks is greater than $7M and recommends a site-specific GM hazard study when the value is between $4M and $7M.

5.3 Relevant legislation and other guidance

For reference, various legislation and guidance pertaining to earthquake design in New Zealand are listed below.

Relevant legislation (in various circumstances):

- Design of buildings: Building Act 2004
- Assessment of geologic seismic hazards: Resource Management Act 1991
- Design of buildings: Building (Earthquake-prone Buildings) Amendment Act 2016
- Design of port facilities: Port Companies Act 1988
- Design of lifelines and regional studies: Civil Defence Emergency Management Act 2002
- General: Local Government Act 2002
- Residential structures: Earthquake Commission Act 1993

Relevant guidance for design criteria (e.g. APE):

- For most structures: NZS1170.0
- For major roading projects: NZTA Bridge Manual

- For dams (water and tailings): NZSOLD
- Relevant guidance for design parameters (e.g. acceleration response spectra):
- For most structures: NZS1170.5:2004
- Geotechnical: MBIE/NZGS Module 1
- For major roading projects: NZTA Bridge Manual
- For base isolated structures: Draft Base Isolation Guidelines
- Existing buildings assessment: 2017 Seismic Assessment of Existing Buildings

6 Determining earthquake ground motions

Earthquake ground motions for engineering design in New Zealand, and in many seismically active countries around the world, are defined using probabilistic seismic hazard analysis (PSHA). PSHA is a well-known calculation method that estimates the ground motions generated by earthquakes in the region around a site. The calculation considers all seismic sources (i.e. known faults and background seismicity), both large and small, to provide a complete understanding of potential ground motions. Additional information about PSHA can be found in Cornell (1968), McGuire (2004), Kramer (1996), and Baker, Bradley, and Stafford (2019, in press) among other publications.

It is necessary to understand the following in order to perform PSHA:

- The fault and background seismic sources in the region of the site
- How earthquake ground motions travel from the source through the Earth's crust to the site
- How the geological conditions of the site affect the ground motions
- The purpose of the PSHA and the analyses it will be used to undertake.

The use of the PSHA will determine the required outputs and drive the scope of work. These items are shown schematically in Figure 3. Before the methodologies for characterising GM hazards are described, it is worth considering the cause of earthquake ground motions and how earthquake ground motions are characterised. Refer to Text Box 2 for more information.

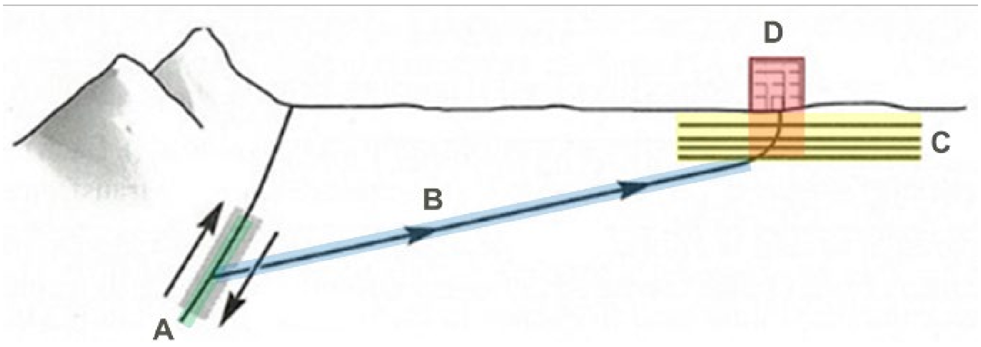


Figure 3. Components for estimating earthquake ground motions: A) seismic source model; B) ground motion model; C) site effects model; and D) structural design (background image source: Kramer 1996).

GM hazard is often assessed using prescribed procedures and parameters set out in documents such as NZS 1170.5:2004, NZGS Module 1, or the NZTA Bridge Manual. These documents are based in part on PSHA that incorporates the components shown on Figure 3. As discussed, prescribed methods are simplified to be applied by a range of users and to a range of site and geographical conditions. In situations where it is desired to understand the GM hazard in greater detail, such as if complex engineering analyses or a detailed risk analysis of the project will be performed, the methodology used for site-specific PSHA can be customised. The differing levels of complexity for each of these studies are described in Appendix A.

Text Box 2: Earthquakes and ground motions

Earthquakes are caused by the rupture of faults and give rise to several primary hazards (e.g. ground shaking and surface fault rupture) and secondary hazards (e.g. landslides, liquefaction and tsunamis). Fault rupture is the release of stored elastic energy by sudden brittle dislocation of the fault. This release of energy travels through the earth as seismic waves. It is these seismic waves that cause the ground to shake during an earthquake.

The seismic wave energy of an earthquake spreads out from the fault rupture like waves on a pond from the impact of a pebble. The energy dissipates as the seismic waves travel away from the fault rupture, such that the ground shaking caused by a large magnitude earthquake a long distance away might be similar intensity to ground shaking caused by a small magnitude earthquake at a close distance.

The media commonly reports earthquake magnitude to describe the strength of an earthquake. Magnitude is indeed a direct measure of earthquake energy, but the way earthquake ground shaking feels to an observer depends on several factors, such as the distance of the earthquake from the observer and the conditions of the ground directly below the observer. The distinction between earthquake magnitude and earthquake ground shaking is important, and engineers need to understand both.

Earthquakes are commonly depicted in the media as acceleration time series:

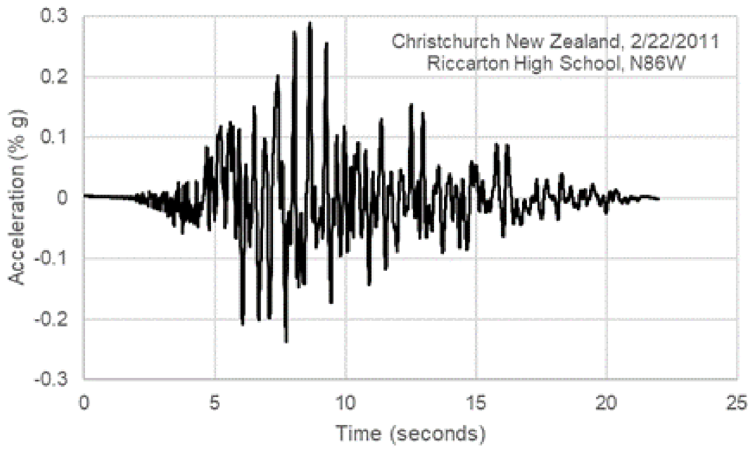


Figure 4. Example earthquake acceleration time series.

It is difficult for engineers to easily use an acceleration time series for design because they are complex and no two earthquakes cause the exact same pattern of ground shaking. Engineers simplify the acceleration time series using an acceleration response spectrum:

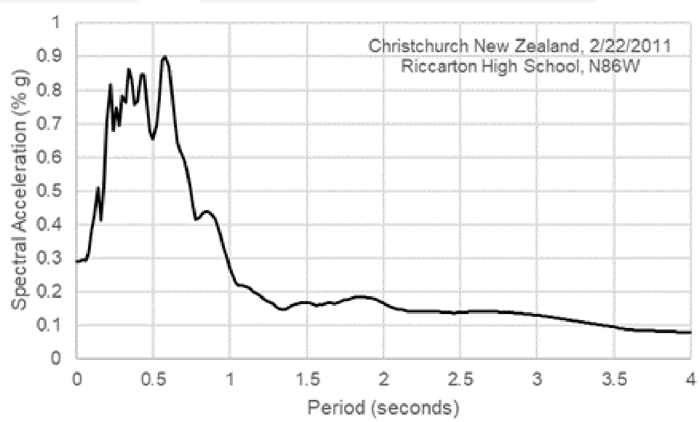


Figure 5. Earthquake acceleration response spectrum.

The acceleration response spectrum simply indicates how a range of different structures respond to an acceleration time series. The vertical axis of the response spectrum (Spectral Acceleration) represents the intensity of shaking. The horizontal axis (Period - aka, natural period, natural frequency or spectral period) represents different structures. For example, a tall building might have a period of 2 seconds, a short building might have a period of 0.5 seconds, and a bridge might have a period of several seconds. A response spectrum is a convenient representation of ground motion for engineers, however they also need to understand several other qualities of the earthquake shaking, such as duration.

7 The case for performing site-specific PSHA in New Zealand

The case for performing site-specific PSHA for projects in New Zealand in 2019 is strong primarily because of the age of NZS 1170.5:2004 and the advances in seismic hazard science since its adoption. As stated, in some areas of New Zealand, site-specific PSHA using contemporary knowledge and hazard analysis techniques results in significantly greater GM parameters than NZS 1170.5:2004, that is, in these cases NZS 1170.5:2004 was found to be unconservative. In these cases, projects planned or designed based on NZS 1170.5:2004 have considered GM parameters that are too low, and as such, have greater earthquake risk than desired. In most of these cases, the parties involved may not be aware of this fact unless they have specialist expertise in seismic hazard analysis.

There are several sources of uncertainty in NZS 1170.5:2004 that are not directly quantified, but these can be identified based on review of Section C3 of NZS 1170.5 Supp 1:2004, for example:

1. **Spectral shape factor:** This factor considers the effect of the ground conditions on the GM hazard and design acceleration response spectrum. NZS 1170.5:2004 broadly considers five site classes (i.e. ground conditions) for all New Zealand, whereas the ground conditions are different at every site.
2. **Return period factor**: This factor scales the acceleration response spectrum for 1/500 APE to other APEs (e.g. 1/500 APE to 1/1000 APE). The same factors are given for all New Zealand, despite the differing tectonic settings across the country.
3. **Near fault factor**: This factor adjusts the acceleration response spectrum for the fact that earthquake GMs are considerably more intense near the fault, which is due to several reasons not discussed herein. The same factors are applied to all faults and at all APEs. The list of locations where these factors apply is not exhaustive, and other faults where a near fault factor could be considered have been identified subsequent to NZS 1170.5:2004.
4. **Lack of other site effects**: No consideration is provided in NZS 1170.5:2004 to account for basin or topographic effects.

In addition, the PSHA that derived the parameters in NZS 1170.5:2004 is outdated and some of its key weaknesses are:

1. Not all the sources (i.e. faults) that we currently know of are included in the seismic source model, which means that some areas of New Zealand are modelled using an incomplete seismic source model.
2. There have been about 20 more years of earthquake ground motions recorded on an increasingly robust seismic monitoring network of sensors than what is accounted for in the PSHA's seismic source model.

3. Epistemic uncertainty regarding fault sources and earthquake magnitudes was not incorporated, meaning that the seismic source model is unjustifiably precise.
4. Ground motion models used in the study have now been superseded by two generations of new ground motion models. This affects all faults in New Zealand but has a particularly significant effect on the ground motions estimated for faults associated with the Hikurangi Subduction Zone.

Of secondary importance, the documentation of the seismic hazard in NZS 1170.5:2004 does not provide a complete description of the hazard analysis and its outputs. In particular, magnitude-distance deaggregations (aka disaggregation) are not provided. Magnitude-distance deaggregations are the means for an engineer to identify reasonable design scenarios and understand important aspects of the GM other than the acceleration response spectrum. For example, a hazard deaggregation would be used to understand the expected duration of the earthquake for design calculations as earthquakes with larger magnitudes shake for a longer duration, subjecting sites to more cycles of deformation.

Additionally, a magnitude-distance deaggregation provides essential information for the selection of suitable recorded ground motions, which are required for any time-history analysis method. Time-history analyses performed without knowledge of the magnitude-distance deaggregation have presumably assumed the required information or relied on the limited available information (e.g. the NZTA Bridge Manual). It is therefore not possible to know if these analyses are conservative or unconservative, yet the analyses are used in detailed, and often state-of-the-art, designs that are promoted to have a high degree of accuracy and precision. The principal of consistent crudeness is violated in such cases and it is misleading to advertise a high level of certainty without knowledge of the limitations of the input parameters.

In the authors' opinion, there are clear and convincing reasons to perform site-specific PSHA for any project, and furthermore, site-specific PSHA should be mandatory in areas where NZS 1170.5:2004 is known to be unconservative. The cost of a high-standard-site-specific PSHA can be prohibitive; however, there are various degrees of PSHA and techniques that can be adopted to suit the specific cost, importance and technical challenges of a project, as discussed below.

8 Risk-informed framework for determining earthquake ground motions

The technical advantages of using site-specific PSHA over standard- or code-based methods are compelling, and it stands to reason that any project would benefit from site-specific analysis. However, site-specific PSHA takes time and can incur a significant cost for some projects. The various tasks of a GM hazard analysis can be selected on a somewhat modular basis and at various cost points to suit a specific project, and the methodology presented below provides a general framework for selecting these procedures taking into consideration the benefit of using site-specific analyses, the cost implications, and the importance of the project.

The risk-informed framework requires an assessment of the risks that are relevant and unique to a project. It is somewhat circular to suggest a 'risk' based approach to selecting the methodology to estimate the hazard, which is itself part of the risk, but the intention of this framework is to highlight that more effort should be used to understand the hazard in situations where the consequences of not knowing (i.e. the uncertainty) have a significant effect. For example, the risk for high importance or high consequence projects is magnified when the probability of the hazard has large uncertainty. That is, we really want to be sure of ourselves when it matters most. In these cases, an improved understanding of the hazard (i.e. with smaller uncertainty) is required to offset the high consequence in order to preserve the uniform risk approach.

The level of effort expended on selecting the methodology should be commensurate with the value and importance of the project in broad terms. This is shown schematically in Figure 6.

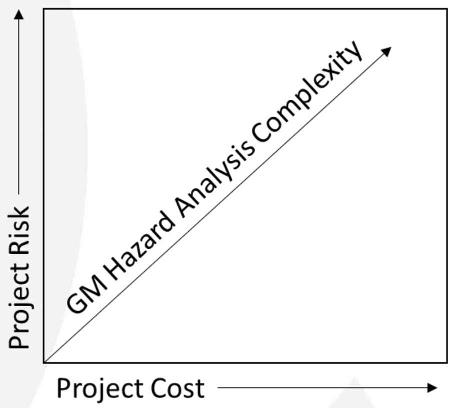


Figure 6. Schematic representation of risk-informed framework for determining EQ ground motions.

The risk-informed framework for selecting the method to determine EQ ground motions comprises four steps:

1. Estimate the capital cost to design and build the project.
2. Assess the risk factors for the project using Table 1. Table 1 is a prompt to select a risk level for the project taking into account a range of considerations (e.g. life safety and economic impact).
3. Select a GM hazard analysis approach using Table 2. Table 2 is a tool to help select the appropriate level of rigour to be applied in the GM hazard analysis considering the project costs and risk level.

Review the assessment from technical- and project-risk perspectives.

Several worked examples of the application of the proposed method are included as Appendix B.

Most projects can use the tables and flow charts presented below to select an appropriate GM hazard analysis, but higher value and higher importance projects may consider some form of cost-benefit analysis whereby the costs of a site-specific analysis should be compared to the cost of potentially taking a conservative or unconservative approach to the selection of GM parameters.

Step 1. Estimate capital cost

Capital cost is used as a key factor because it is typically known or set early in the project life, the time when the EQ hazard analyses should be performed. The exposure of a project to significant consequences increases with the capital cost, so, generally, projects benefit from more rigorous EQ hazard analyses as capital cost increases.

Step 2. Assess the risk level

Projects are exposed to a range of different consequences in addition to the capital cost. Table 1 provides a prompt to consider the consequences, impact or resilience of a project to set the risk level for this framework. The risk level descriptions are a guide only, and it is expected that the user will apply their judgement to select each risk level.

NZS 1170.0 and clause A3 of the New Zealand Building Regulations 1992 identify the key considerations for making decisions about the importance of buildings (used to select risk criteria) based on the consequence of failure on the following factors:

- Human life safety, occupants and those off the project site
- Environment
- Economic cost to repair or replace the structure
- Community and society
- Post-disaster recovery.

We typically focus on the negative consequences when assessing the risk level of a project, but it is often worthwhile to focus instead on the positive consequences of the project. In this respect the risk level could be defined as aspirational.

In addition, the user could think about other more indirect considerations when assessing the earthquake risk of a project, some of which are:

- **Equity consequences** may also be considered by decision makers, for example where an individual benefits from a project but in the case of failure the costs are borne by others. This skews the perspectives on decisions, whereby an applicant may consider this a feasible exercise and a consenting authority or stakeholder may take a different perspective.
- **Multiple hazards** may need to be considered concurrently where their occurrence is interdependent. For example, a building in a low-lying coastal site may be able to be evacuated following a major earthquake, but if the streets are expected to be full of debris preventing egress from aftershock or tsunami, the project should look to incorporate a solution.
- **Changes in prescribed parameters** may occur during the life of the project and this may impact on the project economics. For example, the prescribed loading in New Zealand standards has changed over time, and earthquake prone building legislation and guidance have affected the economics of numerous projects, and new standards and guidance are in development, such as the Base Isolation Guidelines. More rigorous GM hazard analysis can somewhat offset the risk of future code changes.
- **Insurance providers** sometimes require site-specific GM hazard analysis, and in other cases having a site-specific GM hazard analysis may result in lower insurance premiums.

Step 3. Select a GM hazard analysis method

There are several alternative approaches to assessing GM hazards. The risk-informed GM hazard analysis decision matrix is given as Table 2. This matrix gives an indicative analysis method based on the project capital costs and the assessed risk level. The complexity of the GM hazard analysis increases with increasing project cost and risk level. Table 3 and Appendix A describe the methods proposed in Table 2. Table 2 suggests a minimum approach, and a more rigorous GM hazard analysis can be performed for any project.

Step 4. Review

The assessed risk level and selected GM hazard analysis method should be reviewed from a technical standpoint and from a project standpoint. From a technical-risk standpoint the project professionals need to assess whether the selected method is applicable and feasible. For example, the understanding of New Zealand seismicity is increasing over time, and some ground motion models (GMMs) used in the National Seismic Hazard Model (NSHM) to predict ground motions from the Hikurangi Subduction Zone have been recently superseded. Direct application of the NSHM may not be ideal if the hazard for a site is significantly dominated by subduction zone earthquakes. That is, if the example project results in Approach B from Table 2, which suggests that the NSHM approach is suitable for the project, the technical review may highlight that the source model approach be upgraded to Approach C because of the significance of the Hikurangi Subduction Zone on the seismic hazard of the site. A specifically trained earthquake geologist is best placed to perform this technical review, but other professionals with adequate expertise in seismic hazard modelling may also be capable.

The project-risk review provides a high-level check on the sensibility of the selected GM hazard analysis selection. For example, some of the questions that could be asked as part of this review are:

- Can the cost of the selected GM hazard analysis be recovered through increased design and construction efficiency compared with the use of a notionally conservative design based on NZS 1170.5:2004?
- Is the potential loss of income due to extended earthquake damage repairs significant?
- Are there insurance benefits for using site-specific GM hazard analysis methods over NZS 1170.5:2004?
- Will the increase in GM design parameters when NZS 1107.5:2004 is updated and revised cause the project to then be under designed for the GM hazard?
- Are there significant project financial risks due to uncertainty in NZS 1170.5:2004 that can be eased by performing a site-specific GM hazard analysis?

The answers to these questions or other questions could provide justification to scale the GM hazard analysis up or down to suit the project.

9 Multi-hazard considerations

NZS 1170.0:2004 provides performance criteria for **earthquakes**. New Zealand engineering practice has predominantly interpreted this specifically as earthquake GMs. However, it is widely understood that earthquakes cause a range of hazards that can occur concurrently, for example, ground shaking and liquefaction followed by tsunami. GMs are just one earthquake hazard, and it is often overlooked that the criteria (i.e. APE) is set for all earthquake hazards. Insurance companies are aware of this and it is one of the reasons why the uniform risk approach does not result in a uniform risk from earthquakes across the country. For example, some structures that have been strengthened to meet a high standard of resilience to earthquake GMs, may have a high vulnerability to liquefaction or tsunami that provides an unacceptable life safety threat.

Other jurisdictions (e.g. USA) and high consequence industries (e.g. nuclear and the petroleum) have shown an evolution in hazard assessment that has increasingly considered the effect of multiple earthquake hazards in a risk-targeted framework. This may be reasonably expected to occur in New Zealand over the coming decades and, as such, there may be merit in considering a multi-hazard, risk-targeted approach to setting acceptable design criteria. This may extend beyond earthquake hazards to include other hazards such as fire and other sources of ground deformation and inundation.

10 Commonly asked questions

What does a site-specific PSHA provide that NZS 1170.5:2004 does not?

A site-specific PSHA directly quantifies the uncertainty, or confidence, in each step of the hazard analysis, and the scientific and engineering judgments used in site-specific PSHA are documented in detail so that the reader can understand the uncertainty of input parameters and output parameters. In comparison, NZS 1170.5:2004 does not document uncertainty in the earthquake loading parameters.

As discussed above, the magnitude-distance deaggregation is important information for the reader to understand the hazard analysis and to inform engineering design. Presentations of magnitude-distance deaggregation are integral to a site-specific PSHA report, but this same information is not communicated in documentation about NZS 1170.5:2004.

Site-specific PSHA can be expensive and there are few experts in New Zealand able to undertake and review these studies to an acceptable standard. Do all projects need a site-specific PSHA?

In theory, a simplified procedure like NZS 1170.5:2004 provides conservative GM design parameters so that the procedure can be used confidently for most projects, accepting that the derived acceleration response spectrum is conservative. In this case, a site-specific PSHA is an appropriate option when either a) project design optimisation using the PSHA offsets the cost to perform the PSHA, b) the project is of very high importance or significance, or c) if there are other circumstances that require or benefit from a PSHA.

It is commonly believed that NZS 1170.5:2004 is conservative, but this is a misconception for some areas of New Zealand for the reasons discussed in this report. Without robust documentation, it is not possible to ascertain if NZS 1170.5:2004 is conservative or unconservative. Therefore, the case for site-specific PSHA varies from location to location and should also consider the implications of designing for GM parameters that may render the project earthquake prone the next time the prescribed methods are revised.

At what stage in a project should a site-specific PSHA be undertaken?

It is useful to undertake a site-specific PSHA relatively early in a project so that the benefits can be considered through all design stages. For larger projects, the uncertainty of the seismic hazard should be considered as an important part of cost-benefit analysis. When selecting the foundation and structural form, the seismic hazard and its uncertainty should be considered as it can have a significant impact on cost. If the building form is developed before understanding the seismic hazard it can require expensive solutions or redesign work.

Assessment of earthquake loading should not be incorporated as a tender item as it promotes selecting the lowest justifiable seismic hazard (to keep tender costs and tender price low), which is often using a prescribed method. The implications of the selected seismic hazard for a project should be considered in terms of both the capital cost of the project but also of the risk to the operation of the project throughout the project's design life. Ideally, if a site-specific PSHA is required, it should be completed and incorporated within the tender documents.

11 Limitations

The intention of this document is to help decision makers select the appropriate methodology to estimate earthquake ground motion (GM) hazard. This is not a prescriptive methodology and it is not intended to provide a sanctioned best practice document. Use of the advice provided herein is at the reader's own legal risk.

12 Tables

Table 1. Indicative risk factors

Consideration	Risk level			
	I	II	III	IV
Life safety	Failure of structure impacts none or few lives.	Assess with judgement.	Assess with judgement.	Failure of structure impacts many lives.
Economic impact	Rebuild affects project only.	Rebuild affects area of local or city-wide significance.	Rebuild affects area of regional significance.	Rebuild affects area of national significance.
Civil defence and lifelines	Disruption of lifelines has limited significance.	Disruption of lifelines has local or city-wide significance.	Disruption of lifelines has regional significance.	Disruption of lifelines has national significance.
Engineering analysis	Simple, closed form solutions.	Analyses that require understanding of ground motion parameter other than spectral response (i.e. duration or magnitude).	Time history analysis of limited scope.	Detailed, nonlinear analyses, possibly incorporating seismic-soil-structure interaction.
Other	Project is highly resilient to the ‘other’ consideration.	Assess with judgement.	Assess with judgement.	Project has low resilience to the ‘other’ consideration.

Table 2. Risk-informed GM hazard analysis matrix

Risk level	Project value			
	Low (up to $10M)	Moderate ($10M to $50M)	High ($50M to $100M)	Very high (more than $100M)
I	A	A	B	C
II	A	B	C	C
III	B	C	C	D
IV	C	D	D	D

Table 3. GM hazard analysis methods

Approach	Seismic source model	Ground motion model	Site effects and seismic ground response
A: NZS 1170.5	NZS 1170.5	NZS 1170.5	NZS 1170.5
B: NSHM	NSHM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects
C: Site-specific NSHM	NSHM with update	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects
D: Site-specific PSHA	Project-specific SSM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects

References

Note: References are not provided for standards and guidelines which have hyperlinks in the electronic version.

Baker, J., Bradley, B., and Stafford, P. (in press). Seismic Hazard and Risk Analysis.

Bradley, B.A. (2013). A New Zealand-specific pseudospectral acceleration ground-motion prediction equation for active shallow crustal earthquakes based on foreign models. *Bulletin of the Seismological Society of America* 103(3): 1801-1822.

Bradley, B. A. (2015). Systematic ground motion observations in the Canterbury earthquakes and region-specific non-ergodic empirical ground motion modeling. *Earthquake Spectra* 31(3): 1735-1761.

Cornell, C.A. (1968). Engineering seismic risk analysis. *Bulletin of the Seismological Society of America* 58(5): 1583-1606.

Elms, D.G. (1992). Consistent crudeness in system construction. In: *Optimisation and artificial intelligence in civil and structural engineering*, Ed. Topping B.H.V. Kluwer Academic Publishers, vol. 1 71-85.

Kramer, S. L. (1996). *Geotechnical Earthquake Engineering*. Prentice Hall Civil Engineering and Mechanics Engineering Series. Upper Saddle River, N.J., U.S.A.

McGuire, R. K. (2004). *Seismic hazard and risk analysis*, Earthquake Engineering Research Institute. Oakland, CA, U.S.A.

Appendix A: Components for estimating earthquake ground motions

National Seismic Hazard Model (NSHM) of New Zealand

The current National Seismic Hazard Model (NSHM) of New Zealand (https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards-and-Risks/Earthquakes/Earthquake-Forecast-and-Hazard-Modelling/2010-National-Seismic-Hazard-Model) is not suitable for use in site-specific seismic hazard analyses without project-specific review by a qualified earthquake geologist, seismologist or other person with specific expertise in seismic sources and ground motion models. Furthermore, a revised, well communicated and publicly available New Zealand national seismic hazard model would provide a basis to revise NZS 1170.5:2004 and would facilitate cost-effective, site-specific studies. The 2018 National Seismic Hazard Assessment of Australia (http://www.ga.gov.au/about/projects/safety/nsha) and the United States Geological Survey Earthquake Hazards Program (https://www.usgs.gov/natural-hazards/earthquake-hazards) are examples of national-scale hazard studies.

Seismic source model

The seismic source model (SSM) includes information about the location and geometry of faults, the potential earthquake magnitudes that could occur on the faults, and the frequency or rate of earthquakes. Typically, the SSM also includes a background seismicity model to account for earthquakes on unknown faults. The SSM is item A in Figure 3.

SSMs developed broadly for national seismic hazard models, such as the National Seismic Hazard Model (NSHM) of New Zealand, or the national seismic hazard model developed by the USGS for the United States, provide the underlying basis for building code seismic design parameters, such as those provided in NZS 1170.5:2004. These general SSMs are sometimes freely available or pre-loaded into commercial PSHA software packages. National SSMs are suitable for PSHA performed for a wide range of projects, but they typically lack fine-tuning for local seismologic conditions, or the latest research in which case it may be necessary for the model to be adapted for a project by including site- and region-specific information. Completely new models must be defined for areas where an existing model does not exist. The SSM is most commonly developed by seismologists and earthquake geologists with specific experience in seismology and fault characterisation and parameterisation for seismic hazard analysis.

Faults extend several kilometres below the ground surface, but only large faults create earthquakes that rupture the ground surface. Ground surface rupture is key evidence of a fault's existence. These 'known' faults are studied worldwide, and the published research is essential when creating an SSM.

Not all faults create earthquakes large enough to rupture the ground surface, but we know about these 'unknown' faults by studying the historical record of earthquakes and by inference from other proxies such a deformation of Earth's surface identified by GPS surveys. In fact, most earthquakes globally occur on unknown faults. Earthquakes have occurred since the creation of Earth more than a billion years ago; however, humans have only been in existence for thousands of years, and written records of earthquake activity date back merely hundreds of years. These records, along with other geological data, must be interpreted and extrapolated to understand how often earthquakes occur in order to create an SSM.

Developing an SSM requires significant judgement given the imperfect information available about faults and earthquake activity, which is why involvement of specialist earthquake geologist is required. This report proposes four methods for selecting or developing a SSM, which are, in order of increasing technical rigour:

- **Use NZS 1170.5:2004**:

  NZS 1170.5:2004 is suitable for projects in New Zealand where the cost or importance of the project does not justify site-specific PSHA studies.

- **Use the freely available NSHM**

  The NSHM is available online at https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards-and-Risks/Earthquakes/Earthquake-Forecast-and-Hazard-Modelling. The NSHM can be used to perform a PSHA calculation for any specific location in New Zealand, as opposed to NZS 1170.5:2004, which provides ground motion parameters on a broad, regional or city-wide scale. This NSHM SSM can be implemented in PSHA calculations without needing expert knowledge in earthquake geology, but an earthquake geologist should be consulted to verify that the NSHM is appropriate for the specific site and tectonic setting.

- **Adapt the freely available NSHM to site-specific conditions**

  The SSM in the NSHM can be reviewed and updated based on newly available research or site-specific data. This approach can include a wide range in scope depending on the specific project, tectonic setting and complexity of SSM. Involvement of a specialist earthquake geologist is required.

- **Create a new SSM**

  A new SSM created from raw data and first principles is a significant undertaking, but it provides the greatest flexibility and clarity of uncertainties in the SSM. The scope of an SSM will vary depending on the project and seismologic setting. In general, a greatly simplified model should incorporate a wide range of epistemic uncertainty, such that any further refinement of the model will increase confidence in the hazard analysis. Creation of a new SSM is difficult in the complex tectonic setting of New Zealand, and, as such, a specialist earthquake geologist working with an expert peer reviewer or peer review panel should be involved. This team will also ensure that a reasonable degree of epistemic uncertainty is considered.

Ground motion models

Ground motion models (GMMs) describe the intensity of ground shaking at the site caused by an earthquake. GMMs are empirical models that have also been known as attenuation equations or ground motion prediction equations. They relate earthquake magnitude and distance from source to site, among other parameters, to the ground acceleration expected at the site. GMMs are item B in Figure 3.

GMMs are available for a wide range of tectonic settings, ground conditions, and areas of the world. The most commonly used GMMs were developed through the Pacific Earthquake Engineering Research Center (PEER) as part of the next generation attenuation projects (NGA). In some cases, general GMMs have been adapted to specific regions, such as the GMM for New Zealand developed in Bradley (2013).

In practice, GMMs that are suitable for specific tectonic settings and fault mechanisms are selected on a project-by-project basis. No two GMMs provide identical ground motion predictions, so typical practice is to select an ensemble of GMMs appropriate for the site to capture the uncertainty between models. It may be necessary to select multiple ensembles of GMMs if there are multiple types of seismic sources that affect a site (e.g. shallow crustal and subduction GMMs).

This report proposes two approaches for selecting GMMs:

- **Use NZS 1170.5:2004**: NZS 1170.5:2004 is suitable for projects in New Zealand where the cost or importance of the project does not justify site-specific PSHA studies.
- **Use published GMMs**: Several published GMMs are available and may be used in PSHA. Ensembles of GMMs must be selected appropriately for the specific considered fault mechanism and tectonic setting. This is the standard practice globally, and it is suitable for all PSHA studies.

Site-specific GMMs could be developed for a site if appropriate empirical or experimental data are available. This level of analysis is not likely to be required for New Zealand practice, and existing, published GMMs will be suitable for nearly all projects; however, modifications or corrections to existing GMMs based on site observations, if available, should be implemented, as discussed below.

Site effects and seismic ground response

Regional geologic structures, the ground conditions at a site, and topography significantly affect earthquake ground motions. These site effects are represented as item C in Figure 3.

Site effects are accounted for in NZS 1170.5:2004 using a general site classification scheme, and GMMs account for site effects using various simple parameters. These simplified methods are appropriate for a range of situations, but in some cases, it is required or desirable to explicitly account for site effects in greater detail.

This report proposes four methods for considering site effects, in order of increasing technical rigour:

- **Use NZS 1170.5:2004**: NZS 1170.5:2004 is suitable for projects in New Zealand where the cost or importance of the project does not justify site-specific PSHA studies.
- **Use published GMMs**: Published GMMs quantify the effects of soil conditions using the average shear wave velocity in the upper 30 m below ground surface, V_{s30}, and the effects of a site being situated over a broad geologic basin using the depth to V_s of 1 km/s and 2.5 km/s, Z_1 and $Z_{2.5}$, respectively. These models are limited to sites with V_{s30} above about 180 m/s to 200 m/s, which covers most conditions in New Zealand. Direct modelling of site effects using seismic ground response analyses should be considered for sites with very soft ground conditions (i.e. V_{s30} below about 180 m/s to 200 m/s).

- **Use non-ergodic GMMs or correction factors**: Modifications or corrections to GMMs based on site observation data enable non-ergodic ground motion predictions that account for a range of phenomena, such as the effect of the near surface soil and regional geologic structure. Bradley (2015) is an example of such refinement for the Christchurch region. Observations of ground motions and correction factors in Wellington are in development at the time of writing this report. These factors should be implemented in all cases where they exist for the specific site or region.
- **Seismic ground response analyses**: The behaviour of the soils underlying a site can be directly modelled with a seismic ground response analysis (SGRA). This approach is not used for sites underlain by rock. SGRA is a useful tool for understanding the response of any site, but it is typically required when the site comprises very soft or sensitive ground conditions that are likely to exhibit highly nonlinear behaviour during an earthquake. These types of soils are not accurately represented in simplified site effects models (e.g. those embedded in GMMs). SGRA can be performed in 1D, 2D or 3D using a variety of constitutive models and analysis methods to suit the technical needs of a project.
- **Topographic effects**: Topographic features such as cliffs slopes and ridges can influence the design earthquake spectra. Annex A of Eurocode 8: Design of structures for earthquake resistance: Part 5 Foundations, retaining structures and geotechnical aspects provides some factors and considerations for topographic amplification.

Appendix B: Worked examples

Timber-Framed Residential Structure

Comments:

- Generally negligible economic and life safety consequences.
- Simple and well-established analysis methods, no significant geologic hazards. Project budget under $1M

Assessment:

- Risk Level I
- GM Approach A

Review Notes:

Technical approach is typical for residential projects

Table 4: Indicative risk factors

Consequence	Risk Level			
	I	II	III	IV
Life Safety	Failure of structure impacts none or few lives.	Assess with judgement.	Assess with judgement.	Failure of structure impacts many lives.
Economic Impact	Rebuild affects project only.	Rebuild affects area of local or city-wide significance.	Rebuild affects area of regional significance.	Rebuild affects area of national significance.
Civil Defence and Lifelines	Disruption of lifelines has limited significance.	Disruption of lifelines has local or city-wide significance.	Disruption of lifelines has regional significance.	Disruption of lifelines has national significance.
Engineering Analysis	Simple, closed form solutions.	Analyses that require understanding of ground motion parameter other than spectral response (i.e. duration or magnitude).	Time history analysis of limited scope.	Detailed, nonlinear analyses, possibly incorporating seismic-soil-structure interaction.
Other	Project is highly resilient to this consideration.	Assess with judgement.	Assess with judgement.	Project has low resilience to this consideration.

Table 5: Risk-Informed GM Hazard Analysis Matrix

Risk Level	Project Value			
	Low (up to $10M)	**Moderate ($10M to $50M)**	**High ($50M to $100M)**	**Very High (more than $100M)**
I	A	A	B	C
II	A	B	C	C
III	B	C	C	D
IV	C	D	D	D

Table 6: GM Hazard Analysis Methods

Approach	Seismic Source Model	Ground Motion Model	Site Effects and Seismic Ground Response
A: NZS 1170.5	NZS 1170.5	NZS 1170.5	NZS 1170.5
B: NSHM	NSHM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
C: Site-Specific NSHM	NSHM with update	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
D: Site-Specific PSHA	Project-specific SSM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.

Aged care facility in urban Christchurch

Comments:

- The facility will be busy and will affect many lives in an earthquake.
- Relatively small economic impact as hospital is not critical for local economy.
- Hospital portion of facility is a critical city-wide lifeline but is just one of several hospitals regionally.
- A simple structural form is proposed, so a simple design approach is anticipated. No significant geologic hazards.
- Project budget $30M.

Assessment:

- Risk Level III
- GM Approach C

Review Notes:

GM approach is suitable, no comments.

Table 7: Indicative risk factors

Consequence	Risk Level			
	I	II	III	IV
Life Safety	Failure of structure impacts none or few lives.	Assess with judgement.	Assess with judgement.	Failure of structure impacts many lives.
Economic Impact	Rebuild affects project only.	Rebuild affects area of local or city-wide significance.	Rebuild affects area of regional significance.	Rebuild affects area of national significance.
Civil Defence and Lifelines	Disruption of lifelines has limited significance.	Disruption of lifelines has local or city-wide significance.	Disruption of lifelines has regional significance.	Disruption of lifelines has national significance.
Engineering Analysis	Simple, closed form solutions.	Analyses that require understanding of ground motion parameter other than spectral response (i.e. duration or magnitude).	Time history analysis of limited scope.	Detailed, nonlinear analyses, possibly incorporating seismic-soil-structure interaction.
Other	Project is highly resilient to this consideration.	Assess with judgement.	Assess with judgement.	Project has low resilience to this consideration.

Table 8: Risk-Informed GM Hazard Analysis Matrix

Risk Level	Project Value			
	Low (up to $10M)	Moderate ($10M to $50M)	High ($50M to $100M)	Very High (more than $100M)
I	A	A	B	C
II	A	B	C	C
III	B	C	C	D
IV	C	D	D	D

Table 9: GM Hazard Analysis Methods

Approach	Seismic Source Model	Ground Motion Model	Site Effects and Seismic Ground Response
A: NZS 1170.5	NZS 1170.5	NZS 1170.5	NZS 1170.5
B: NSHM	NSHM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
C: Site-Specific NSHM	NSHM with update	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
D: Site-Specific PSHA	Project-specific SSM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.

IL4 fire station in rural North Island

Comments:

- Fire station is primarily a garage for the fire vehicles and is not staffed full-time.
- Relatively small economic impact as station is not critical for local economy.
- Station is a critical lifeline for the region.
- A simple structural form is proposed, so a simple design approach is anticipated. There is a liquefaction hazard.
- Project budget $5M.

Assessment:

- Risk Level III
- GM Approach B, upgraded to C

Review Notes:

The current NSHM is not suitable without review. The approach should be upgraded from B to C until the NSHM is updated

Table 10: Indicative risk factors

Consequence	Risk Level			
	I	II	III	IV
Life Safety	Failure of structure impacts none or few lives.	Assess with judgement.	Assess with judgement.	Failure of structure impacts many lives.
Economic Impact	Rebuild affects project only.	Rebuild affects area of local or city-wide significance.	Rebuild affects area of regional significance.	Rebuild affects area of national significance.
Civil Defence and Lifelines	Disruption of lifelines has limited significance.	Disruption of lifelines has local or city-wide significance.	Disruption of lifelines has regional significance.	Disruption of lifelines has national significance.
Engineering Analysis	Simple, closed form solutions.	Analyses that require understanding of ground motion parameter other than spectral response (i.e. duration or magnitude).	Time history analysis of limited scope.	Detailed, nonlinear analyses, possibly incorporating seismic-soil-structure interaction.
Other	Project is highly resilient to this consideration.	Assess with judgement.	Assess with judgement.	Project has low resilience to this consideration n.

Table 11: Risk-Informed GM Hazard Analysis Matrix

Risk Level	Project Value			
	Low (up to $10M)	Moderate ($10M to $50M)	High ($50M to $100M)	Very High (more than $100M)
I	A	A	B	C
II	A	B	C	C
III	B	C	C	D
IV	C	D	D	D

Table 12: GM Hazard Analysis Methods

Approach	Seismic Source Model	Ground Motion Model	Site Effects and Seismic Ground Response
A: NZS 1170.5	NZS 1170.5	NZS 1170.5	NZS 1170.5
B: NSHM	NSHM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
C: Site-Specific NSHM	NSHM with update	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
D: Site-Specific PSHA	Project-specific SSM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.

Tall building in Wellington

Comments:

- Busy commercial building in the CBD.
- Moderate economic impact due to location and function of building and importance of surrounding infrastructure in the CBD.
- Not a critical lifeline and adjacent roads have alternative routes.
- Building will be designed to have base isolation usign complex nonlinear response analyses.

Project budget $80M.

Assessment:

- Risk Level IV
- GM Approach D

Review Notes:

- GM approach is appropriate because this will be a significant building in a challenging setting.
- The design relies on response history analyses.
- Principal of consistent crudeness requires detailed seismic hazard studies to select appropriate ground motions for design.

Table 13: Indicative risk factors

Consequence	Risk Level			
	I	II	III	IV
Life Safety	Failure of structure impacts none or few lives.	Assess with judgement.	Assess with judgement.	Failure of structure impacts many lives.
Economic Impact	Rebuild affects project only.	Rebuild affects area of local or city-wide significance.	Rebuild affects area of regional significance.	Rebuild affects area of national significance.
Civil Defence and Lifelines	Disruption of lifelines has limited significance.	Disruption of lifelines has local or city-wide significance.	Disruption of lifelines has regional significance.	Disruption of lifelines has national significance.
Engineering Analysis	Simple, closed form solutions.	Analyses that require understanding of ground motion parameter other than spectral response (i.e. duration or magnitude).	Time history analysis of limited scope.	Detailed, nonlinear analyses, possibly incorporating seismic-soil-structure interaction.
Other	Project is highly resilient to this consideration.	Assess with judgement.	Assess with judgement.	Project has low resilience to this consideration.

Table 14: Risk-Informed GM Hazard Analysis Matrix

Risk Level	Project Value			
	Low (up to $10M)	Moderate ($10M to $50M)	High ($50M to $100M)	Very High (more than $100M)
I	A	A	B	C
II	A	B	C	C
III	B	C	C	D
IV	C	D	D	D

Table 15: GM Hazard Analysis Methods

Approach	Seismic Source Model	Ground Motion Model	Site Effects and Seismic Ground Response
A: NZS 1170.5	NZS 1170.5	NZS 1170.5	NZS 1170.5
B: NSHM	NSHM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
C: Site-Specific NSHM	NSHM with update	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
D: Site-Specific PSHA	Project-specific SSM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.

Wharf in Timaru

Comments:

- Not staffed full-time, not used for cruise ships.
- Wharf is to be resilient and serve as a lifeline to aid economic recovery in the case of an earthquake.
- Challenging and variable ground conditions involving existing reclamation requiring seismic-soil-structure interaction analyses.
- Project budget $20M.

Assessment:

- Risk Level IV
- GM Approach D

Review Notes:

The current NSHM is not suitable without review. The approach should be upgraded from B to C until the NSHM is updated.

Table 16: Indicative risk factors

Consequence	Risk Level			
	I	II	III	IV
Life Safety	Failure of structure impacts none or few lives.	Assess with judgement.	Assess with judgement.	Failure of structure impacts many lives.
Economic Impact	Rebuild affects project only.	Rebuild affects area of local or city-wide significance.	Rebuild affects area of regional significance.	Rebuild affects area of national significance.
Civil Defence and Lifelines	Disruption of lifelines has limited significance.	Disruption of lifelines has local or city-wide significance.	Disruption of lifelines has regional significance.	Disruption of lifelines has national significance.
Engineering Analysis	Simple, closed form solutions.	Analyses that require understanding of ground motion parameter other than spectral response (i.e. duration or magnitude).	Time history analysis of limited scope.	Detailed, nonlinear analyses, possibly incorporating seismic-soil-structure interaction.
Other	Project is highly resilient to this consideration.	Assess with judgement.	Assess with judgement.	Project has low resilience to this consideration.

Table 17: Risk-Informed GM Hazard Analysis Matrix

Risk Level	Project Value			
	Low (up to $10M)	**Moderate ($10M to $50M)**	**High ($50M to $100M)**	**Very High (more than $100M)**
I	A	A	B	C
II	A	B	C	C
III	B	C	C	D
IV	C	D	D	D

Table 18: GM Hazard Analysis Methods

Approach	**Seismic Source Model**	**Ground Motion Model**	**Site Effects and Seismic Ground Response**
A: NZS 1170.5	NZS 1170.5	NZS 1170.5	NZS 1170.5
B: NSHM	NSHM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
C: Site-Specific NSHM	NSHM with update	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
D: Site-Specific PSHA	Project-specific SSM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.

10-storey building in Christchurch CBD

Comments:

- Busy commercial building in the CBD.
- Moderate economic impact due to location and function of building and importance of surrounding infrastructure in the CBD.
- Not a critical lifeline and adjacent roads have alternative routes.
- A simple structural form is proposed, so a simple design approach is anticipated. Liquefaction hazard.
- Project budget $35M.

Assessment:

- Risk Level III
- GM Approach C, downgraded to B

Review Notes:

- The current NSHM is not suitable without review; however, an earthquake geologist has assessed the NSHM for application to this project and we are
- comfortable with the source model. Ok to use Approach B for this project.

Table 19: Indicative risk factors

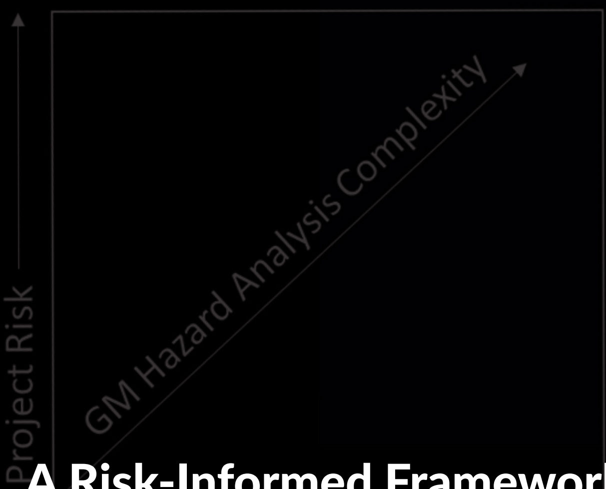
Consequence	Risk Level			
	I	II	III	IV
Life Safety	Failure of structure impacts none or few lives.	Assess with judgement.	Assess with judgement.	Failure of structure impacts many lives.
Economic Impact	Rebuild affects project only.	Rebuild affects area of local or city-wide significance.	Rebuild affects area of regional significance.	Rebuild affects area of national significance.
Civil Defence and Lifelines	Disruption of lifelines has limited significance.	Disruption of lifelines has local or city-wide significance.	Disruption of lifelines has regional significance.	Disruption of lifelines has national significance.
Engineering Analysis	Simple, closed form solutions.	Analyses that require understanding of ground motion parameter other than spectral response (i.e. duration or magnitude).	Time history analysis of limited scope.	Detailed, nonlinear analyses, possibly incorporating seismic-soil-structure interaction.
Other	Project is highly resilient to this consideration.	Assess with judgement.	Assess with judgement.	Project has low resilience to this consideration.

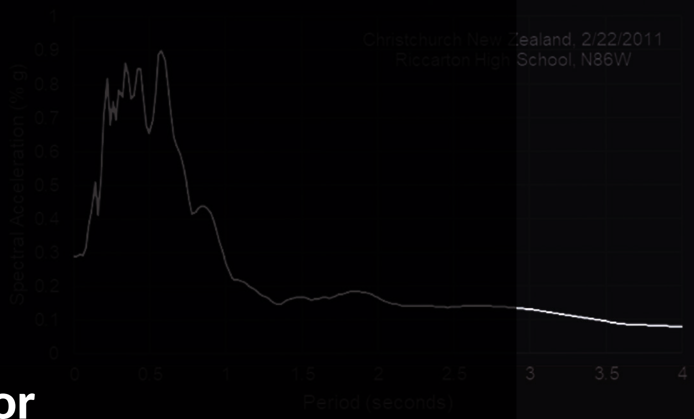
Table 20: Risk-Informed GM Hazard Analysis Matrix

Risk Level	Project Value			
	Low (up to $10M)	Moderate ($10M to $50M)	High ($50M to $100M)	Very High (more than $100M)
I	A	A	B	C
II	A	B	C	C
III	B	C	C	D
IV	C	D	D	D

Table 21: GM Hazard Analysis Methods

Approach	Seismic Source Model	Ground Motion Model	Site Effects and Seismic Ground Response
A: NZS 1170.5	NZS 1170.5	NZS 1170.5	NZS 1170.5
B: NSHM	NSHM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
C: Site-Specific NSHM	NSHM with update	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.
D: Site-Specific PSHA	Project-specific SSM	Published GMMs	Published GMMs, non-ergodic correction factors (if applicable), seismic ground response analysis (if applicable), topographic effects.





A Risk-Informed Framework for Earthquake Ground Motion Hazard Assessment in New Zealand

Primary Contact Greg Preston
Engineering Core Block
Ground Floor, Rm 138
M +64 27 262 2629
E greg.preston@canterbury.ac.nz

www.quakecentre.co.nz