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Seismic Risk and Building Regulation in New Zealand

Findings of the Seismic Risk Working Group

3 November 2020

MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

New Zealand Government

Introduction

Regulatory stewardship is at the heart of how MBIE performs its role overseeing the Building Act and associated regulations including the Building Code. In recent years, MBIE has reviewed how it administers the Building Code and what best practice delivery looks like. MBIE is committed to embracing continuous improvement, ensuring we regularly review and improve both the technical content of the Building Code and how we develop and deliver that content.

In 2019 MBIE partnered with GNS Science and the Earthquake Commission (EQC) to commission GNS Science to carry out a comprehensive update of New Zealand's National Seismic Hazard Model (NSHM). This is a significant project that is expected to be completed in 2022.

The National Seismic Hazard Model is the foundation of many of the safety critical building performance settings in the Building Code – in particular, the NSHM underpins seismic performance requirements by calculating the likelihood and expected strength of earthquake shaking in different parts of New Zealand.

To support the introduction of this revision, in late 2019, MBIE commissioned a group of experts to provide advice on how the updated NSHM could be applied within the Building Code. This advice gives direction to MBIE on preparing the Building Code to incorporate the outputs of the NSHM and will enable MBIE to incorporate the updated NSHM quickly and efficiently once the NSHM revision project is complete.

The group of experts commissioned by MBIE delivered their report earlier this year. The following document shares the advice provided by this group and outlines MBIE's proposed plan for preparing to update the Building Code.

MBIE would like to take this opportunity to thank Engineering New Zealand (EngNZ) and the experts who contributed to the Seismic Risk Working Group (SRWG) for their input into the report *Rethinking Seismic Risk in the Building Control System*. MBIE appreciates the valuable insight this report has given us into the current approach to seismic risk and its implications for the design of new buildings in New Zealand.

Dave Robson

Manager Building Performance and Engineering

The Seismic Risk Working Group

One of the functions of MBIE is to manage New Zealand's building system and implement building legislation and regulations to meet New Zealand's current and future needs.

The National Seismic Hazard Model (NSHM) is currently being updated by GNS Science, Te Pū Ao, for the first time in a number of years. The NSHM is the scientific data that underpins many of the regulatory system decisions that MBIE makes on how to deal with Earthquake risk in New Zealand. The updated NSHM will incorporate advances in earthquake science and experience gained from earthquakes that have occurred over the last decade.

MBIE saw an opportunity for early engagement with the update of the NSHM to ensure we can prepare to implement the outcomes quickly and efficiently within the building regulatory system and mitigate any impacts.

The SRWG were asked to focus on how NSHM results should be used within the Building Code to support the design and construction of future buildings. Additionally the SRWG report highlighted a number of matters that related to wider building industry issues that were reported on for the purpose of providing context for the SRWG recommendations.

The SRWG Report

The SRWG made a number of recommendations across a broad range of topics covering seismic performance objectives and expectations, current design practices, gaps in the existing system and seismic hazard considerations.

MBIE sought feedback specifically on seismic design and the use of hazard information from the National Seismic Hazard Model. The SRWG identified 5 principals for translating hazard information into design provisions and provided options for MBIE to consider regarding the appropriate incorporation of uncertainty and regional earthquake scenarios into these provisions.

The group agree that seismic design provisions should:

1. be as simple as possible,
2. deliver consistent and acceptable performance,
3. consider and reflect the uncertain nature of earthquakes and buildings,
4. be set at the appropriate level in the building control system e.g. Act, Code or Verification Method,
5. be stable but adaptable to maintain consistency in design but allow flexibility for future advances in hazard or building performance.

Additionally, the group provided a number of recommendations on wider issues. Some of the key themes include;

- **Clarity of performance objectives:** The provisions in the Building Act and Building Code are generally appropriate but are not stated with sufficient clarity or transparency to inform the development of Verification Methods or Alternative Solutions.

- **Policy/risk settings**: Policy/risk settings should sit above (in terms of the legal hierarchy) the technical means to achieve them. These settings should reflect both Government intent and societal expectations. In the past, Standards' committees have at times made policy decisions based on industry consensus that may or may not reflect the intent of Government policy.
- **Certain design provisions result in inconsistent building performance**: Inconsistent performance may be exacerbated due to;
  - Design provisions allowing for trade-offs between strength and ductility
  - The treatment of irregular structures
  - Liquefaction that is triggered at shaking levels between SLS and ULS
- **Geotechnical considerations:** Geotechnical provisions for seismic design should be substantially overhauled so as to appropriately incorporate ground conditions, foundation performance and soil-structure interaction in the design process.

Priorities for Action by MBIE

The SRWG report provides confidence to MBIE that a number of current initiatives such as the Construction Sector Accord, the Geotechnical work programme and Low Damage Design project are working on the right issues.

MBIE's primary focus is to ensure that the outputs of the updated NSHM are appropriately implemented within the Building Code system and, as such, our proposed work programme prioritises these issues. In response to the SRWG report, MBIE will focus on ensuring that;

- policy/risk settings are clear and transparent,
- seismic design provisions contribute to consistent building performance,
- seismic loading provisions are appropriate, considering the uncertain nature of earthquakes

The proposed seismic work programme will not address some of the other recommendations of the SRWG report, such as assurance processes for construction monitoring, treatment of damaged buildings and the process for revising technical Standards, because these are related to wider system issues. However, as noted above, these recommendations are still useful and will be used to inform future work.

MBIE's Proposed Seismic Risk Work Programme

MBIE has incorporated the findings of the SRWG with issues relating to seismic risk that MBIE had already identified to develop a proposed seismic risk work programme.

As part of this programme of work, MBIE will consult with the building industry, building owners and the NZ public on how the current B1 Building Code Clause should be interpreted as quantitative building performance requirements to ensure stable, consistent and appropriate seismic performance of future buildings.

Seismic Loading

Incorporate the NSHM outputs: Work alongside GNS to consider how the NSHM uncertainties and region-specific design loads can appropriately be incorporated within the B1 Verification Methods to provide a stable basis for building and foundation design into the future.

Seismic Analysis and Design

Update design and analysis approaches in B1: Update the design and analysis approaches in B1 verification methods (currently within NZS1170.5) and consider whether these deliver consistent acceptable performance. Ensure the seismic design process is easy for professionals to follow, delivers consistent seismic performance and provides a stable basis for seismic design of buildings.

Geotechnical requirements

Integrate the geotechnical work programme: MBIE's existing geotechnical work programme will be co-ordinated with the seismic loading and seismic analysis and design work streams and will ensure the performance of geotechnical designs will be consistent across materials and systems. This will include updates to the Geotechnical Modules and Verification Methods for foundation design, retaining walls and slope stability.

Next Steps

The Seismic Risk Work Programme is being progressed in tandem with work on the NSHM project with the intention of enabling the Building Code to incorporate the NSHM update quickly and efficiently. MBIE have already begun work on all parts of the Seismic Risk Work Programme.

MBIE will consult with the building industry and the New Zealand public in the near future to give everyone a chance to provide feedback on the appropriate settings for building performance requirements. Outside of formal consultation on the performance requirements, MBIE is also committed to communicating with the building industry on the Seismic Risk Work Programme as it progresses. We look forward to working with the building industry to develop solutions that support the delivery of safe buildings.

Links to more information

Check out the links below to learn more about seismic risk in New Zealand, the National Seismic Hazard model, the Building Code and the team at MBIE that supports the Building Code.

- GNS Science, Te Pū Ao: https://www.gns.cri.nz/
- The National Seismic Hazard Model: https://www.gns.cri.nz/Home/Our-Science/Natural-Hazards-and-Risks/Earthquakes/National-Seismic-Hazard-Model-Programme
- Building Performance at MBIE: https://www.building.govt.nz/
- The Building Code: http://www.legislation.govt.nz/regulation/public/1992/0150/latest/DLM162576.html
- Using the Building Code: https://learning.building.govt.nz/course/index.php?categoryid=15

Appendix A: Rethinking Seismic Risk in the Building Control System – Options for Change

RETHINKING SEISMIC RISK IN THE BUILDING CONTROL SYSTEM

OPTIONS FOR CHANGE

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engineering new zealand
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1.INTRODUCTION

In 2020, MBIE commissioned Engineering New Zealand in 2020 to help prepare for the release of an updated National Seismic Hazard Model (the Seismic Model). Our brief was to bring together an expert group to discuss the current building regulatory system and identify possible improvements ahead of the Seismic Model's release.

MBIE selected the Seismic Risk Working Group (the Group) members from both engineering practice and academia, including people with seismological, structural and geotechnical expertise. The Group saw its work as complementing ongoing efforts to improve design performance after the earthquakes of the past decade. It considered the treatment of seismic risk and implications for design, with a particular focus on new buildings.

The Group analysed the existing building control system as the basis for identifying potential improvements. Working alongside the regulator, members shared experience and insights. They developed options to strengthen practices and clarify regulation to better manage seismic risk, so that New Zealand's buildings better serve us both during and after earthquakes.

This report outlines observations, principles, key focus areas and recommendations for change that emerged directly from the Group's discussions and associated assignments. Recommendations range from reconsidering performance objectives to resolving current gaps in the system. The Group agreed that a wider range of information relevant to seismic risk could be better incorporated and reflected in design, and this process could be more transparent and robust, while supporting the setting of levels for new hazard data.

Some recommendations anticipate the outputs of the Seismic Model, so are predicated on further development and evaluation. Close collaboration between key relevant disciplines of seismology, geotechnical and structural earthquake engineering will be a critical part of updating of the Seismic Model, now and in future years. Other recommendations highlight the need for wider engagement to ensure that both performance objectives and how they are achieved keep pace with societal expectations and insights.

The Group completed the process by endorsing its recommendations, which they believe can inform wider consultation and analysis, facilitate practice improvement, and catalyse a range of programmes and initiatives to improve seismic design and performance in New Zealand.

2. RECOMMENDATIONS

The recommendations have been thematically categorised, with those in **bold** the most important, but are not listed in priority order. They are not mutually exclusive, nor is this an exhaustive list: it will evolve with further discussion, analysis and collaboration between the sector and with the regulator.

PERFORMANCE OBJECTIVES

1. **Review current Building Code clauses (including consideration of seismic risk settings) to ensure they articulate societal expectations and are reflected in the Building Act.**
2. **Review whether NZS 1170.5 and supporting Standards provide sufficient means and criteria, including limit states, to enable design that is fully consistent with the performance objectives outlined in the Building Act and the Building Code.**
3. **Develop a better understanding of 'amenity' as it applies in the Building Code and ensure consistent clarity in supporting documentation.**
4. **Assess the required performance of fire-resisting/protection systems following earthquake and how this may be achieved in design.**
5. Reassess whether the secondary effects of earthquake such as fire-following, tsunami and slope instability are adequately reflected in performance objectives and/or should be addressed in seismic design provisions.

STRUCTURE OF THE BUILDING CONTROL SYSTEM

6. **Aspects of NZS 1170.5 – specifically regarding Importance Levels (ILs) for buildings - need to sit above the technical means by which those are achieved.**
7. **Ensure the Building Code (i.e. clause B1), relevant compliance documents and supporting documents provide clear commentary with sufficient quantitative clarity around intent for seismic performance.**
8. Ensure the means by which Alternative Solutions can be demonstrated to meet the performance objectives, are clearly stated.

ASSESSING AND IMPROVING PERFORMANCE

9. **Review current practice that allows additional strength to be offset by reductions in ductility. Consider whether the requirements for elastic strength and stiffness are sufficient to deliver desired objectives under moderate levels of shaking, as well as performance in aftershocks or future events that may follow large earthquakes (e.g. ULS levels of shaking) during the life of a building.**
10. Require irregular structural forms or potential stiffness incompatibilities to be considered in the selection of overall building performance requirements, not just control the analysis method that must be used to design them.
11. **Review the entire approach to the incorporation of geotechnical information for seismic design to ensure a consistent and robust approach that will enable designers to achieve target performance objectives. This includes challenging the basis for retaining B1/VM4, which does not provide appropriate guidance for foundation design of engineered structures.**
12. Consider incorporating the assessment of performance of the structure / ground / foundation system at shaking levels between SLS and ULS.
13. Facilitate a challenge relating to the current provision of education and training for seismic design.

14. Review assurance processes for construction monitoring to ensure seismic design is being executed and realised as intended.

ADDRESSING GAPS IN THE SYSTEM

15. Develop provisions for the treatment of damaged buildings in the Building Act, noting the absence of guidance following recent earthquakes was problematic for regulators and building owners alike.
16. **Incorporate considerations of ground conditions, foundation performance and soil-structure interaction effects in the design process. Such provisions could include reference to ground failure (e.g. liquefaction), non-liquefaction-related foundation settlement and consideration of 'off-site' geotechnical hazards.**
17. Relevant key Standards should be clearly aligned, accessible and able to be efficiently applied by practitioners across the industry.
18. **Develop a process that assures the quality and continuity of revision for selected technical Standards (e.g. by establishing standing committees for timely review of design and material standards).**

SETTING THE LEVELS (CONSIDERING THE NATIONAL SEISMIC HAZARD MODEL)

19. **Consider appropriate and alternative ways (e.g. different engineering parameters) for using the seismic hazard output in design. This recommendation recognises the need to use different engineering parameters in structural and geotechnical design of buildings and infrastructure.**
20. **Provide guidance enabling the Seismic Model team to provide the required parameters in a manner that adequately reflects inherent uncertainties and design needs. This will need to commence early but will require an iterative process as the results are received and evaluated.**
21. **Consider incorporating region-specific hazard characteristics for selected regions (or urban centres), where justified by benefits and data availability.**
22. **Address how to practically achieve risk-based design through the Building Code. In parallel to the Seismic Model, develop a decision-support framework, explicitly based on appropriate risk targets, that uses the National Seismic Hazard Model to support the selection of design factors, such as zonation Z, importance factors, and consideration of collective risk in cities.**

3. PURPOSE

GNS Science is managing a programme to update the New Zealand National Seismic Hazard Model (the Seismic Model), which informs policy settings within the NZ Building Code system. The update programme will incorporate New Zealand's recent experience of earthquakes, together with global advances in earthquake science, characterisation of hazard and uncertainty and their applications to engineering design (e.g. Abrahamson et.al., 2017). This first substantial update since the 1990s (with a minor update in 2010) provides a timely opportunity to re-examine current design practice.

The Group was convened to discuss and consider high level principles, in anticipation of the updated Seismic Model, including how they may be used in engineering design methods, and to recommend options for improved seismic performance and treatment of seismic risk.

Risk in this report aligns with the New Zealand Disaster Resilience Strategy (2019) definition, being: ***the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined as a function of hazard, exposure, vulnerability and capacity.***

The topic of risk is discussed further in Section 7.4 of the report.

4. SCOPE

The Group brought together expert knowledge on approaches to seismic design. Members did not advocate or formulate policy but worked to ensure that their best knowledge and experience could inform the development of that policy. MBIE enabled the Group's free and frank discussions on the basis that this was early, preliminary work, which will need further assessment and evidence-gathering by MBIE and others before proceeding to policy analysis, prior to any implementation decisions or processes.

4.1 IN SCOPE

The Group was asked to consider how updated Seismic Model results should be framed within the Building Code and its supporting documents to inform the design and construction of *future buildings*. This included considering the following questions: what are the implications of changes for practice – and short- plus long-term benefits; how will direct application of the changes in the hazard affect current methods for defining standards, and what further changes to Standards and associated documents would be needed?

This work describes options to create a better framework for translating seismic hazard into design for different types of structures.

4.2 OUT OF SCOPE

The Group excluded existing buildings and a variety of infrastructure and services such as roading, rail, bridges, and dams. Policy settings related to the determination of tolerable risks or impacts and the specification of resilience metrics were not in scope; nor were material- or system-specific considerations of detailing. Where these topics were contextually relevant and were discussed in Group meetings, key points are compiled such as in the Appendices.

5. PRINCIPLES AND APPROACH

The Group agreed on principles to inform clear, practical, easy to interpret and transparent approaches to incorporating seismic hazard and risk into the design process. Recommendations are intended to reflect the minimum needed (least cost, not restricting innovation) to enhance and uphold the general competence of the industry.

Principles adopted by the Group were:

1. Clear/simple. The approach to updating seismic provisions should be appropriate for engineering design. This is as simple as possible but no simpler.
2. Achieve purpose. Seismic provisions should deliver consistency of acceptable performance.
3. Consider uncertainty. Provisions should reflect the uncertain nature of earthquakes and building behaviour.
4. Decisions at the right levels. Provisions should be assigned to the appropriate level of the building control system: that is, Act, Code or Standard.
5. Stable but adaptable. Seismic provisions should anticipate the need to maintain as much consistency in design over time as possible. But at the same time, they should remain open to material advances in knowledge of hazard or building performance that inform future design and construction.

The Group deliberated between February and June 2020, including collective and individual and sub-group contributions of discussions, notes, assignments, reference materials and conversations with other experts familiar with the field in New Zealand and internationally. Topics canvassed and debated included the following:

- Are the existing New Zealand Building Code provisions sufficient to deliver the expectations currently set out in the Building Act?
- How best to incorporate risk and risk to the community in particular? Are current methods transparent enough?
- Are the current design points (represented by the design limit states) sufficient to deliver the required objectives?
- Should there be more focus on SLS1[1] and SLS2 in addition to checks on ULS[2] and beyond?
- Should the Importance Levels (ILs) be at the Verification Method (VM) level or higher up in the hierarchy of the Building Code Control system and what would this look like?
- How to incorporate consideration of geotechnical issues?

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[1] The Serviceability Limit State (SLS) considers the condition beyond which specified service criteria are no longer met.

[2] The Ultimate Limit State (ULS) represents the condition beyond which the design capacity is exceeded but collapse is not expected.

- How to quantify the building code performance requirements and where is it appropriate to define these?
- What part does insurance play in the setting of performance requirements?
- Are there factors other than minimum strength and stiffness that should receive greater attention e.g. configuration? Do current methods adequately account for these or sufficiently penalise when not present?
- What might an alternative design approach look like and what are the options?
- What are the uncertainties in the whole design process (demand and capacity) and how best to represent these?
- What is the balance to be achieved between design sophistication and performance outcomes? How can innovative approaches be evaluated rigorously for acceptable performance?
- Are the current verification methods easily extendable to provide solutions beyond minimum requirements? If so, can or should the different performance achieved be quantifiable?

6.EVALUATING THE CURRENT SYSTEM

6.1 MAPPING THE CURRENT SYSTEM

The current performance framework of the building control system (Figure 1) was discussed by the Group, and issues mapped in relation to seismic hazard and design considerations for earthquakes. In summary:

- The Building Code is performance-based, with performance requirements for the outcome of building work aspects set at a mandatory regulatory level. They include structure, durability, fire safety, access, moisture, safety of users, services and facilities, and energy efficiency.
- The Building Code does not prescribe how the performance is to be achieved. Any systems, materials and methods can be used provided the designer can demonstrate that the performance criteria are met. This provides for innovation and design flexibility.
- For many buildings and building work, traditional or empirical methods are all that are required. To reduce compliance costs and time for both designer and consenting authority, MBIE publishes deemed-to-comply Acceptable Solutions (AS) and Verification Methods (VMs) for the various Building Code clauses.
- These prescriptive documents are collectively often referred to as “Code supporting documents” and characterised as tertiary regulation. If they are followed, the consenting authority is required to issue a building consent for the work.
- For seismic design, within the scope of this project the loadings Standard NZS 1170.5 is the most relevant document, alongside ‘guidance’, which is equally important to achieve the desired performance particularly when assessing Alternative Solutions.

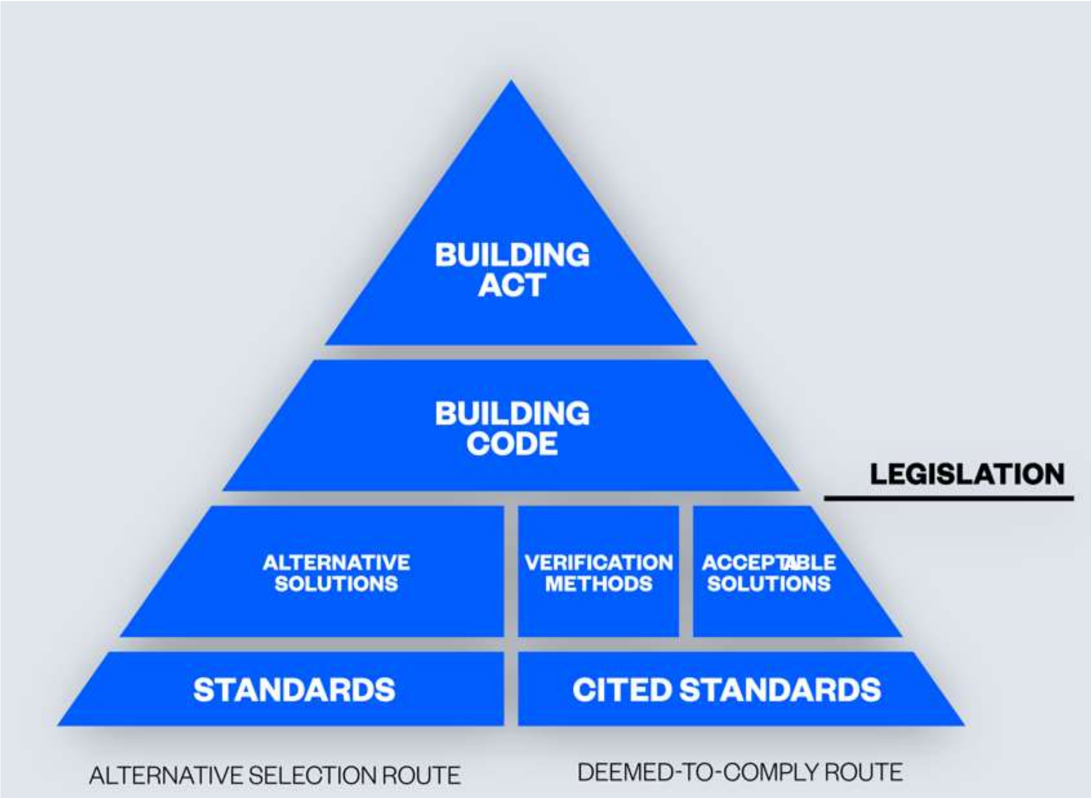

Figure 1. New Zealand Building Control System (schematic)

6.2 THE BUILDING ACT HAS CONSIDERABLE FLEXIBILITY

In the Group's view, the Building Act's high-level objectives are flexible enough to accommodate a change to how seismic risk is addressed. The Building Code must consider the design and compliance of one building at a time, whereas the Act should address this within the context of a group of buildings. Therefore, is it important that the performance objectives set in the Act are modified suitably when mapped into the Building Code.

The Group noted that the Act's objectives are reasonably well articulated, but that more specific definition of high-level objectives might preclude changes required in future.

Potential solutions

- Explicit consideration of resilience[3] is needed if the system is to mandate the ability to recover
- Explicit consideration of building performance as it relates to aggregated risk (communities and cities) is needed
- There is nothing in the Building Act that contemplates post-earthquake repair, so some local authorities have required that the disaster and repair be treated as an alteration.

6.3 RELATIONSHIP BETWEEN BUILDING CODE CLAUSE B1 AND THE ACT'S OBJECTIVES

Structures must perform satisfactorily in earthquake shaking beyond the return periods defined for the ULS to meet the objectives of clause B1. The definition of ULS relates to strength, strain, ductility, deformation limits specified for ULS in NZS 1170.5 and a reserve capacity (undefined) to avoid structural collapse, even though the structure may have sustained significant structural damage. However, as seen in the 2016 Kaikōura earthquake, variability in the performance of code-complying structural elements (including floors) can lead to unintended outcomes. This is a natural part of code development and requires that we write in anticipation of outcomes, using current research and industry experience, and need to monitor and adjust as understanding evolves.

The seismic hazard is often presented with respect to the likelihood of occurrence over a 50-year building life. The Group noted there is a difference between "any 50-year period" and the "next 50 years", so the setting of performance objectives requires greater specificity. "Low probability" of collapse/instability – or causing loss of amenity – has different likelihoods during construction, alteration and throughout the life of a building. In the context of design-compliance, the 50-year (or greater) time-window has been used in engineering design as a proxy for unlimited life. This highlights the importance of considering an appropriate window for the particular hazard and risk assessment.

Recognition that there is an expectation of satisfactory performance at levels of shaking beyond ULS specified hazard is required as part of the risk-based code framework. For new systems that fall outside the scope of existing Verification Methods (VMs) and Alternative Solutions (AS), compliance must be demonstrated as an Alternative Solution, but there is little guidance to provide benchmarking for Alternative Solutions and their fulfilment of acceptable performance. The Group recognised that

[3] Resilience: The ability to anticipate and resist the effects of a disruptive event, minimise adverse impacts, respond effectively post-event, maintain or recover functionality, and adapt in a way that allows for learning and thriving (National Disaster Resilience Strategy, 2019).

uncertainties increase significantly as shaking increases, but expectations of performance need to be more clearly articulated.

The Group observed that incremental evolution of VMs through Standards processes has not ensured strategic consideration of risk. Current methods do not incentivise designers to think about the long-term spectrum of performance. Without more guidance on mitigating life-safety risk (for both designers and those responsible for verifying the compliance of a design), innovative solutions may be produced that have a probability of collapse greater than traditional systems.

In conclusion, the Group considered that the B1 provisions of the Code – its objectives, functional and performance requirements – do not sufficiently encapsulate the principles and purposes of the Act. In particular, the objective regarding sustainability and the principle to consider whole-of-life costs. They noted that B1 is decades old, and older than some of the Act amendments. Stability in B1 has a specific structural connotation relating to safeguards against injury caused by structural failure, whereas "loss of amenity" is described in terms of structural behaviour, which is ambiguous and needs to be clarified. The Group would like to see greater clarity and consistency of performance statements between the Code and supporting documentation, together with wider (societal) engagement and direction on risk tolerance.

Potential solutions

- The interpretation of Clause B1 could be made clearer, in terms of the definition of "amenity", "low probability" and "likelihood".
- Geotechnical considerations are not adequately addressed. In its current form, B1/VM4 is not applicable at many sites in major New Zealand population centres and, crucially, does not consider deformation of the soil and foundation, hence is not applicable to engineered structures.
- The closely spaced contours in the current Seismic Model leads to variation of design loads in calculations when making even the smallest changes to the Model.
- Greater clarity and quantification of performance requirements is needed to inform the development of Alternative Solutions and Standards (like NZS1170.5)
- The code does not differentiate between risk and hazard ("consequence" could be considered instead of risk/hazard). Few lay people understand how hazard is framed technically, in terms of probability of shaking level > X, whereas consequences are more generally understandable
- The Code does not contemplate potential compounding hazards – e.g. the impairment of fire control systems following earthquakes and aftershocks. Temporarily reduced levels of fire safety compliance (e.g. temporary outage of signage for egress) might be useful to consider, to facilitate 'shelter-in-place' arrangements in the immediate post-earthquake recovery period. Currently under S 112 of the Act, a building must be reinstated to facilitate access and escape from fire, as near as practicably possible to the pre-disaster state.
- Buildings with high consequences for loss of human life or high economic, social, or environmental consequences have been assigned higher Importance Levels, meaning that more robust design is required. For structural design these have been defined in the Standard NZS 1170, referenced in B1/VM1, but this is a public policy issue and should not be left solely to a Standards committee to decide.

The process for reviewing hazard levels and adapting design provisions in the Building System needs to be regular and rigorous. There is not necessarily a direct relationship between hazard and design loads, and the framework for assimilating new knowledge of seismic hazard must enable balanced consideration of both demand and capacity.

7. KEY TOPICS THE GROUP DISCUSSED

The Group discussed key aspects of seismic design and performance, and the supporting regulation and technical guidance that are currently available to support the design process. Key focus areas have identified options to strengthen, clarify and adapt regulation to improve the management of seismic risk. Potential improvements range from resolving current gaps in the system, through to better defining performance objectives, and considering how geotechnical features can be better reflected in design as well as initiatives to support the setting of levels for new hazard data.

Knowledge has changed significantly

Since the New Zealand Loading Standard NZS 1170.5 was published in 2004, much more has been learned about the seismic hazard. The 2010-11 Canterbury earthquake sequence, the 2013 Cook Strait-Marlborough earthquakes and the 2016 Kaikōura earthquake, as well as the 2011 Tōhoku Japan earthquake and tsunami and related geological studies, have revealed variability in earthquake shaking, including the effects of complex rupture, local amplification and basin-edge effects, and the potential impact and likelihood of subduction earthquakes from the Hikurangi subduction zone.

There have also been lessons for design, including the torsional stability of ductile buildings, strength asymmetries and potential 'ratcheting' behaviour, actions in diaphragms, and the vulnerability of parts and components (Jury et. al. 2018). These topics are challenging for both practitioners and regulators in all jurisdictions. New Zealand has an opportunity to share its unique experience of urban earthquakes of the past decade, and to adopt (or avoid) selected features of established or emerging international practice. Relevant examples include, the Canadian Commission on Building and Fire Codes (2015); Adams et.al. (2019); ACI 318 (2014), and the changes from ASCE 7-10 to ASCE 7-16.

7.1 DAMAGE THRESHOLDS, LIMIT STATES AND POST-EARTHQUAKE PERFORMANCE

Current practice limitations

The design process intends to provide a structure with sufficient strength and stiffness to meet the performance requirements prescribed in clause B1 and informed by NZS 1170.5 and other key standards, with allowances to be made for the consequences of failure. However, we do not have evidence that the design process always results in a building that meets the performance requirements of B1.

Strength varies according to the ductility selected in design. This means that while the SLS1 outcomes should be similar for all buildings, and the full "design shaking" (or more) should produce similar outcomes for all buildings, the states in between may be quite different in terms of damage and repairability. Assessment of stiffness varies based on assessment of the impact of inelastic action (cracking and yield more broadly).

Identifying the connection between design displacements and expected displacements for design earthquakes is needed to clarify the physical meaning of the calculated values and to establish that they adequately serve this purpose. The displacements currently calculated in NZS 1170.5 for the ULS are levels of displacement that provide only the basis for compliance checks to be carried out.

The design process can lead an engineer to believe strength is the most critical parameter in seismic design whereas **configuration is believed to play a much greater role than strength alone**. Currently irregularities in configuration only require the engineer to use a more refined analysis procedure (e.g. dynamic analysis) to improve the estimation of demands resulting from irregularities. While this may result in an increase in the design strength of some elements it is not clear the response of irregular structures will meet the performance requirements of B1 in a similar manner to regular structures, which in recent events have tended to out-perform structures of irregular design.

Limiting the focus of seismic design to the consequences of a single earthquake on a single building may underestimate – perhaps grossly – the **potential impact on surrounding buildings or neighbourhoods**. Where the hazard is lower than elsewhere, but the risk concentration is high - for example in Auckland - the historical practice of introducing minimum seismic demand thresholds (Z values) to indirectly address aggregated risk, is neither transparent nor properly tested in terms of societal expectation of performance outcomes.

On the topic of Limit States, the Group noted that the latest version of NZS 1170 (Amendment 1), which introduced a Serviceability Limit State 2 (SLS2), remains uncited in the Building Code. There are inter-storey deflection limits for ULS and a requirement at SLS1 and SLS2 to avoid unintended engagement of non-structural items to protect these, and under ULS if engagement could affect the ULS behaviour of the structure. **Whether or not these limits are indeed providing the means to consistently achieve the performance objectives of the Building Code is unclear**, so the Group considers that review is warranted.

In the cited NZS 1170.5, SLS2 only applies to IL4 buildings (e.g. hospitals and other facilities deemed to have crucial disaster response/recovery functions)[4]. By targeting SLS drift, there is an inherent focus on stiffness and on limiting deformations to minimise structural damage. However, while all elements need to satisfy SLS1, only those elements considered to be critical to functional performance or continued occupation (NZS 1170.5 Amendment 1) need to satisfy the additional strength requirements for SLS2, allowing for some non-linear behaviour.

The Group discussed performance for shaking at levels beyond and less than ULS, with reference to recent earthquakes in New Zealand and Japan (2010-2016), **including the binary nature of liquefaction-triggering**, witnessed just above SLS 1 shaking levels in vulnerable regions. Section 7.2 discusses the potential need to consider performance of the ground/foundation system at shaking levels between SLS and ULS. This is because in the case of liquefaction hazard, ULS loading on structure foundations may often occur at levels of shaking that are not much greater than SLS. This is also true, but less so, for slope stability hazard.

The Group identified that, in terms of recent earthquakes in New Zealand and Japan, perceptions of safety and feasibility of repair or re-occupancy have involved **damage at shaking levels well above the return periods used for SLS in New Zealand**. The Group believes this warrants review, because New Zealand's approach currently only considers re-occupancy for SLS and for ULS only a single event is considered with no provisions for the treatment of damaged buildings in the Building Act. In New Zealand, the former has highlighted geotechnical performance, mostly in respect of settlement and its impact on structures. However, residual capacity or repair objectives at ULS or beyond remain fundamentally important for post-

[4] SLS2 was extended to all non-structural and secondary structural items (parts and components in 1170.5) in the uncited Amendment 1 to provide for continued occupancy as well as essential service functionality, but there may not be adequate provisions in Building Act to make this a compliance requirement.

earthquake recovery. There is nothing in the Act that requires any particular standard to be achieved for either state.

Design currently only considers a single ULS earthquake event. **No explicit post-earthquake performance objectives exist, including for repaired buildings.** Neither aftershocks in the short term nor future design level earthquakes during subsequent occupation are covered. A distinction must be made between 're-occupation', and 'post-earthquake shelter in place', because the former implies post-repair, for which there is no current standard set, whereas the latter implies residual capacity checks. It is difficult to see how that could be achieved except through rapid visual inspection, which is covered outside the Building Code in practice guidelines.

The elevated seismicity rate in Canterbury following the 2010-2011 earthquakes was judged to require an increase from Z=0.22 to Z=0.3. This effectively meant an undamaged, contemporary building was now only designed to 72% of the post-earthquake design load level. If buildings are expected to perform throughout an earthquake sequence, **then they should presumably be designed to a load level that reflects post-earthquake seismicity**. This is a separate issue from immediate or near-term post-earthquake performance.

A relevant comparative review of New Zealand, United States and Japanese design practices (Pettinga et.al., 2019) indicated that **more explicit evaluation of yield deformation (displacement-based design) produces lower values of design ductility demand than have been assumed in New Zealand design** to-date. Pettinga also noted an alternative design approach is to design elastically to SLS and confirm acceptable performance checks for life-safety (and beyond). This would be a simple modification to our design approaches which may be easier to implement (Appendix A1).

Building owners may expect buildings to be repairable following defined levels of shaking. Recent experiences have revealed limited understanding in the engineering profession of the impact of prior earthquake damage (or "softening") on a building's performance in future earthquakes, including the potential for greater non-structural damage at SLS levels of shaking. Large-scale demolition of earthquake-damaged buildings, influenced in part by insurance at levels that may not be sustainable, has had negative impacts on recovery time and the environment, including lost embodied carbon in buildings and waste production. Decisions about repair or reoccupation can be fraught with uncertainty.

As a result of the Canterbury earthquake sequence, a significant number of Christchurch commercial buildings and several thousand homes were **judged uneconomic to repair, despite having met performance objectives for life safety**. The situation was complex, involving in some cases damage to foundations and superstructure, in others uncertainty in establishing the residual capacity of buildings to withstand future earthquakes. We understand there were also many cases where insurance policy wordings reduced incentives to repair, or conversely entailed high costs of investigation and/or a conservative approach to repair. Incorporating these lessons into the Building Act and the Code would help alleviate similar future impacts and aid recovery and sustainability objectives.

Potential solutions

The engineering profession has struggled to articulate in simple terms the metrics and trade-offs that are central to the decision-making described above. Better understanding and explanation of these topics is a prerequisite to improved understanding and management of seismic risk in New Zealand[5]. Some solutions that the Group identified include the following:

- Some judgement calls on potential performance benefits (or costs) are fundamental and **should be facilitated at a higher level of governance** than, for example, standards committees, and within a decision framework that engages building owners and other interested parties.
- Building Importance Levels (ILs) currently sit within the VMs but **should sit <u>above</u> the technical means** (e.g. limit states) by which they are achieved.
- Clearer guidance is needed for designers and asset owners **to understand levels of strength and post-yield behaviour** so that buildings achieve both minimum code requirements as well as any desired performance beyond that minimum. It is important to realise that strength and post-yield behaviour are critical elements in the design, but they are insufficient to address all performance-based design requirements on their own.
- **Ductility demand assumed in design should be reduced** while maintaining current ductile detailing requirements to ensure the building is sufficiently robust in its nonlinear behaviour to account for uncertainty in future ground motions.
- When designing an irregular structure, the designer should be **required to demonstrate how non-linear behaviour will be accommodated**, even in shaking well beyond ULS levels, so that the life safety requirements of B1 are met.

Limit states and damage states

The current process defines minimum levels of strength; from the SLS or the ULS, whichever is more critical. **There is a case for raising the minimum level of strength**, such that new buildings would then be designed to withstand a wider range of earthquake excitations and therefore achieve a higher level of resilience (in addition to the life-safety objective).

A key decision is **whether the SLS1 loading is increased relative to ULS, or whether ULS ductility and drift limits are lowered**. At the moment, the potential effects of ground deformation and foundation settlement should implicitly be included. However, in practice these may be considered solely against criteria for SLS1, which should now be recognised as inadequate.

Multiple earthquakes are likely to impact a building during its life span and need to be factored into its expected performance. These objectives could be phrased in terms of amenity and life safety, but both terms require greater specificity than currently exists. The Group noted that yield levels will need to be set higher than current levels to achieve this.

Facilitating inspection and repair is a resilience measure but for it to become widespread **it needs to be sought after by investors** not merely codified. This is potentially a provision of Limit States to be considered further.

[5] Tanner et.al. (2020) describe an approach to wider engagement with communities around expectations of seismic performance. Such work is beyond the scope of this report but may inform a process to align evolving societal expectations with design objectives.

A combination of the approaches described above would enable better approximation of damage states, ranging from immediately occupiable to repairable within a certain period or accepting demolition (replacement)[6].

Revising technical standards

Some technical standards should also be **simplified to achieve more consistent application** across the industry. Examples of unwarranted complexity include certain provisions of NZS 1170 (ratcheting) and those of the concrete standard (NZ3101 – e.g. joint design).

Soil site class or more appropriate definitions of the conditions beneath a foundation – which directly influence seismic loading on structures – are also in urgent need of revision. Arguably, the revisions would simplify the identification of ground conditions and improve consistency.

Overall, a process needs to be developed that **assures regular revision of relevant technical standards**, within a system-level framework, utilising relevant local and international research and experience.

Guidance for detailed post-earthquake assessment of buildings developed to support the Canterbury earthquake recovery (MBIE 2014) **could be adapted for national usage** and supplemented to address the complex forensic requirements for longer-term, post-earthquake capacity assessment (c.f. Elwood et. al. 2016; Siddiqui et.al., 2019b). The guidance for detailed damage evaluation would need updating and to be made non-regionally specific. Regulatory benchmarks would therefore be needed for the maintenance of buildings, and the monitoring of alterations post-construction, to mitigate poor performance following earthquakes.

A combination of the approaches described above would enable better approximation of damage states, ranging from immediately occupiable to repairable within a certain period or accepting demolition (replacement)[7].

7.2 GROUND AND FOUNDATION PERFORMANCE

Current practice limitations

The seismic performance of a building is fundamentally linked to the performance of both its foundations and the underlying soils (the ground). However, the **Loadings Standard does not explicitly incorporate geotechnical criteria into structural performance objectives**; nor does it provide guidance on important issues that need to be considered in relation to ground and foundations.

The only explicit geotechnical considerations are found in Verification Method B1/VM4, which has several **fundamental caveats/limitations** including:

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[6] A relevant example of recent guidance aimed at enhancing design practice is Ministry of Education (2016) Designing Schools in New Zealand - Structural and Geotechnical Guidelines, version 2.0 http://www.education.govt.nz/assets/Documents/Primary-Secondary/Property/Design/Design-guidance/Designing-schools-in-New-Zealand-Structural-and-Geotechnical-Guidelines-05042016.pdf

[7] A relevant example of recent guidance aimed at enhancing design practice is Ministry of Education (2016) Designing Schools in New Zealand - Structural and Geotechnical Guidelines, version 2.0 http://www.education.govt.nz/assets/Documents/Primary-Secondary/Property/Design/Design-guidance/Designing-schools-in-New-Zealand-Structural-and-Geotechnical-Guidelines-05042016.pdf

- It "assumes general ground or slope stability and provides methods only for ensuring against local failure of the foundation." It is inapplicable to the design and verification of performance of entire structures when the ground conditions may have significant consequences for design. In most cases, the assumption of ground stability cannot be confirmed without geotechnical investigation and analysis, and the methods in B1/VM4 do not "ensure" that foundation failure will not occur.
- B1/VM4 is not to be used to design foundations on "loose sands, saturated dense sands or on cohesive soils having a sensitivity greater than 4". This effectively excludes its use in most low-lying, sedimentary (i.e. not bedrock) areas of New Zealand's major urban and regional centres[8].

B1/VM4 is, on the one hand, detailed (offering basic, textbook-type calculations). But on the other hand, it covers only a small portion of what should be addressed when considering foundation performance in design. Anecdotal experience indicates the points raised above are not well understood by designers and consenting authorities. A critical consideration in the seismic assessment of foundations is **how the earthquake shaking might affect the strength and stiffness of foundations soils, and how this in turn could affect bearing capacity and settlement of foundations**. The Ministry of Education guidelines referenced on page 15[6] do not limit settlement. Rather, in areas that are vulnerable to differential settlement, they require designers to consider the effects of the settlement and ways to mitigate it.

In foundation design, assessment at ULS is related to bearing capacity (i.e. the strength of soils), whereas SLS assessment is related to settlement calculations (i.e. the stiffness of soils). **Foundations should be designed so that both bearing capacity and settlement requirements are satisfied**, and in most cases settlement requirements govern the design. This can sometimes be ignored where the impacts of moderate levels of settlement will be negligible. However, different forms of structure may be more vulnerable, and the impact of differential settlement might need specific review. In many such cases, the best mitigation may be redundancy to improve resilience. Establishing the appropriate mechanism for the design of foundations (static or seismic) is not covered adequately in B1/VM4.

Potential solutions

In the context of seismic performance and also general structure performance these include:

- For both structural and geotechnical aspects of design, consider **incorporating the assessment of performance of the structure/ground/foundation system at shaking levels between SLS and ULS**. This could be a specific "intermediate limit state", but this may not uniformly represent the critical level of ground shaking.
- **The shape of the curve between elastic behaviour (generally up to SLS1) and fully developed ULS displacements needs to be considered, with and without settlement**. Liquefaction sometimes occurs between SLS1 and intermediate ("SLS2") levels, then settlements can suddenly become large. Criteria that satisfy the existing SLS2 should be reviewed for fitness-of-purpose for geotechnical assessment in the design process reference.
- Review the entire approach to the **incorporation of geotechnical information for seismic design** to ensure a consistent and robust approach that will provide confidence that target performance

[8] Sensitivity of soil is a measure of the loss of strength with remoulding. High sensitivity equates with high loss of strength when disturbed.

objectives have been achieved. This includes challenging the basis for retaining B1/VM4, which does not provide appropriate guidance for foundation design of engineered structures.

- Incorporate considerations of **ground conditions, foundation behaviour and soil-structure interaction effects in the design process**. Such provisions would include reference to ground failure (e.g. liquefaction), non-liquefaction-related foundation settlement and consideration of 'off-site' geotechnical hazards.
- **Failure of the soils beneath the foundations** should not be the limiting determinant of the building's structural performance. Geotechnical information provides crucial insight into options for structural design, noting that 'rocking' foundation systems have saved many buildings in earthquakes of the past decade, by premature rocking of foundations where a less desirable structural failure might otherwise have eventuated.
- Provide guidance on **performance objectives for various ground conditions and foundation types** – these could cite NZGS modules (among others) as technical references but will need to be framed for compliance as exists for structure.
- Provide guidance on **possible soil-structure interaction effects** while considering the two critical interaction mechanisms described in the appendix – provide broad criteria to guide holistic design for different classes of structures. This would also aid work required to introduce a consensus to assess and codify SSI.
- Stipulate more clearly **how to evaluate founding conditions**. B1/VM4 in current form does not provide appropriate guidance in many New Zealand urban settings, nor is it likely that all geotechnical factors that can influence foundation design can be adequately addressed in a single VM. The recently developed MBIE/NZ Geotechnical Society modules provide a more robust basis for technical reference.

Zoning of land for all development (including commercial) urgently needs to address related issues that require hazard assessment. This topic, which includes exposure to other natural hazards and is addressed already in some regional plans, is beyond the scope of the current report but is integral to more sustainable risk management practices.

7.3 INCORPORATING UNCERTAINTY AND REGIONAL SCENARIOS INTO SEISMIC PROVISIONS

Current practice limitations

In past New Zealand seismic hazard models, **only one type of uncertainty was included in the hazard estimates**. That uncertainty was the scatter of recorded ground motion data around a given median ground motion model (GMM) prediction, incorporating numerous factors that contribute to hazard between the earthquake source and sites of interest. In hazard model calculations, the distribution of the scattered data, from all possible sources, was integrated to estimate the mean ground shaking level.

There are **now many modern GMMs in the literature**, derived from empirical or simulation-based approaches. There are no definitive ways to predict ground motion, but the work underway to update the Seismic Model will incorporate a suite of plausible, well-supported GMMs in the hazard calculations.

There needs to be **consistent design actions for structures and the ground**. This should be anticipated as part of the detailed work required to implement the updated Seismic Model along with a framework to evaluate loadings guidance as new knowledge is gained.

The omission of epistemic uncertainty has contributed to periodic step-changes in estimates of seismic loading (the Z factor) as new understanding of seismic hazard has emerged. Where this effect has been quantified elsewhere, calculations have shown that, from GMM uncertainty alone, the 5% and 95% quantiles of hazard curves can span a factor of eight in areas where seismicity rates are low; **so a better representation of uncertainty should contribute to greater stability in the Seismic Model.** By including epistemic uncertainty, we will tend to buffer movements of future mean estimates, as more knowledge of hazard is acquired.

In the New Zealand context, this could include much of the North Island, north of Wellington. Other parts of the country will be affected to a greater or lesser extent. **Including uncertainty in earthquake rate modelling will initially increase the span of the total uncertainty**, and engineering judgement is required to provide the design actions which is where the Group has identified the need for close liaison between engineers and the Seismic Model team.

The challenge the Group has considered is how to incorporate what is known about the hazard in ways that facilitate equivalent improvements in outcome (“consistent crudeness”) across the design process. Current provisions for seismic hazard in building design are simplified and “averaged” across the country – NZS 1170.5:2004 uses a single shape of the design spectrum and a single amplification factor, for a given site soil class, across New Zealand. **Such averaging of the hazard can result in significant differences from site-specific analyses of seismic hazards at a given location**. The anticipated Seismic Model update will clarify contributing hazard factors and indicate those which may warrant explicit consideration. Some factors may dominate the hazard and its uncertainty in certain regions; an issue of uneven treatment of risk therefore needs to be anticipated and addressed.

Forecasts of earthquake occurrence rates are distinct from shaking levels and address the magnitude frequency distribution of earthquakes. For example, in a forecast for the next 50 years for all New Zealand, the relative uncertainty in that distribution would be lower than for, say, thousands of 5 km x 5 km grid cells representing the same area (a rough proxy for the current spatial detail in Z-factor). However, a whole-of-country approach would be less useful for many applications, so the level of accuracy should be tailored accordingly.

Potential solutions

The best approach will maximise rigour while also considering the implications of abrupt changes and the subjectivity associated with spatial definitions. The Group favours an approach that will optimise the balance between:

- informing decision making on the appropriate spatial precision
- informing decision making based on tolerable levels of uncertainty
- being appropriate for design

There is an inherent trade-off between the first two. The question is: how to measure the right levels of both spatial precision and uncertainty?

One option is to consider how uncertainty increases with geographic precision, which means using risk metrics that reveal the threshold at which the estimates of risk become "too" uncertain for loadings guidance. At the lower end of accuracy, this approach would also indicate when, by aggregating information, the outcome may become unduly conservative.

The following considerations require further work and testing. If adopted, they would represent a material advance in collaborative practice between seismology, geotechnical and structural engineering:

- There are significant **variations in spectral shape** across New Zealand that are currently not considered. Regionalised spectral shapes should inform and enhance risk mitigation options as the spectral shape will influence the performance of the buildings.
- **Region-specific hazard assessment**[9] should be evaluated for implementation in several ways depending on the trade-offs between the desired simplicity and enhanced accuracy in the hazard definition.
- If accepted, this approach could be **implemented gradually into the codified hazard**, with amplification factors and spectral shapes adopted where adequate models and data are available. Complex or controversial issues could be omitted for future considerations/updates or alternative site-specific evaluation.
- Region-specific assessment would allow:
  - i. Identification of the **most likely scenario earthquakes** (magnitudes, rupture distances, and epsilon[10] value) that will produce the ground motion intensity for a given return period[11]. Note that no additional calculations would be needed because the hazard includes the scenario earthquake details.
  - ii. Determination of **amplification factors and spectral shapes** consistent with ground motion intensity (i.e. level of expected soil non-linearity, if any) and ground characteristics in that region (e.g. stratigraphic site amplification, depth of sedimentary basin, basin-edge effects).
  - iii. Development of a **region-specific hazard curve**.

Items (ii) and (iii) would address signature features of the hazard and focus on quantification of key contributing factors at that location. This approach would permit seismic assessment using time history analyses if unique risk exposures necessitated this kind of specialised approach.

Region-specific values would be obtained for each calculation point in the hazard assessment for Items (i) and (iii) described above. Detailed analyses could be included or omitted from the codified hazard definitions, depending on the level of simplification or detail adopted in the presentation of the hazard assessment.[12]

As mentioned above, the trade-off between geographic precision and uncertainty of the hazard must be reconciled with loadings requirements for design, which could be:

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[9] For this discussion, 'region-specific hazard' contemplates seismic *hazard at a scale that reconciles current understanding of hazard with exposure – generalized from peak exposure (cities) in a region* as opposed to a site-specific analysis which could evaluate the hazard unique to a specific site

[10] A measure how far above or below the median ground motion is the specific scenario, at the site of interest

[11] For example, for a 500 year return period ground motion in Wellington, there is a 45% chance that the ground motion will be generated by a Hikurangi subduction zone earthquake with M = 8.2 to 8.6 and R = 8 – 17 km, and 16% chance that it will be generated by a Wellington Fault with M = 7.5 and R = 2 km. Similarly, for a 500-year return period ground motion in Auckland, there is over 90% chance that the ground motion will be generated by unknown source covered by *"distributed seismicity"* hazard with M = 5-7.2 and R = (approximately) 0-50 km.

[12] In relation to localized site effects (Item (ii)) is unwarranted and currently not feasible at a national level.

Hazard zonation

- Pros: easily done, easily understood.
- Cons: potentially subjective, but not necessarily arbitrary – perhaps could be considered in conjunction with changes to the shape of spectral curves to reflect regional characteristics. Step changes at zone boundaries need to be considered and mitigated, and number of zones and shaking level for each zone

Optimised geographic precision

- Pros: potentially easily done, transparent, can be combined with risk (i.e. combined with method 2)
- Cons: requires decision about what optimisation metrics are used, potentially complicated and difficult to explain.

Quantile based, e.g. hazard curves or spectra that are greater than the mean

- Pros: easily done, transparent.
- Cons: requires subjective threshold selection, which does not necessarily contemplate risk tolerance or value-at-risk and may not be sensitive to the entire range of hazard estimates.

Based on risk metrics

- Pros: considers the full range of hazard, from the entire distribution of possible earthquakes within a considered uncertainty range; might be tailored to a range of stakeholder needs; would address uncertainty in risk as well as hazard; could be reconciled with the performance-based design framework
- Cons: not yet standard practice

Compared to current practice and subject to the additional analysis recommended the Group would like to see:

- Region-specific hazard curves and spectral shapes for significantly differing hazard levels and the major cities (e.g. Auckland, Wellington, Christchurch)[13.]
- Specific hazard curves and spectral shapes for all locations where data is available, and there is a need for more specific hazard definition.
- Additional consideration of complex local effects (e.g. basin-edge effects in Wellington, liquefaction effects in Christchurch).

Developing a consistent way of measuring hazard and risk – Section 7.4 - even if the risk threshold(s) are yet to be agreed or codified, would provide consistency across the system and the following advantages. Consistent crudeness is required for all inputs, and the final provisions need to be able to be applied reliably by all engineers. This would mean:

- Better understanding of hazard characteristics for critical locations in New Zealand (both by professionals and the public).

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[13] The selection of regions could involve several criteria, for example: (i) high exposure of people and assets (from a national risk perspective), (ii) high hazard and high exposure, and (iii) data availability for location-specific enhancement of hazard definition. This requires further work to ensure the criteria are consistent, clear, and durable.

- Identification of, and focus on, key factors contributing to the hazard.
- Identification of the most-likely earthquake scenarios.
- Detailed hazard information critical to geotechnical assessment and structural design would stimulate consideration of the dynamic response of building and foundation systems, and the evolution of design procedures.
- Consistent consideration of complex effects will result in their inclusion or exclusion in adopted hazard definitions.
- Safer building designs and improved seismic performance would be achieved more consistently in areas with high shaking potential (i.e. risk reduction in areas most likely to be affected in future events)
- Advanced earthquake-scenario-based dynamic analyses will be more reliably performed to reduce risk for important buildings. This approach would also provide a useful pathway for Alternative Solutions in the Building Code

7.4 RISK DISCUSSION

Current practice limitations

The Group noted that earthquakes and recovery efforts during the past 10 years have revealed weakness in **communication and public understanding of seismic risk**. The seismic hazard, presented in forms such as the annual exceedance probability (AEP), the return period of the design level of shaking or the likelihood of exceedance over a 50-year design life, is frequently used as a proxy for seismic risk. However, these forms do not consider other factors influencing the actual risk, including density of buildings, their fragility and occupant exposure.

There are many ways of measuring or communicating earthquake risk. For example, the continuum of risk measures as presented in the risk spectrum below.

Figure 2: Risk measures

The damage state can be considered as a condition that the building may reach at some given level of shaking. The serviceability (SLS) and ultimate (ULS) limit states provide reference points directly from the design process; and hence notionally equate to a known level of shaking. However, as mentioned in Section 7.1, the design process needs to deliver a building that is likely to meet the performance requirements that have been set, and that can show compliance with the design standards that have been established. There should be no expectation that design delivers a particular performance at the level of shaking set for a design limit state. Limit states are relevant at a compliance level, not at the performance level. There is uncertainty in the building performance which is not captured here.

This means **the likelihoods of the shaking level being exceeded and the limit state being achieved are not the same**. The collapse limit state (CLS) is less certain, because building collapse is not a condition easily designed for nor predicted. The potential for confusion is compounded if the ULS condition is observed before the design level of shaking is reached, perhaps implying the design requirements have not been met. In reality there is a continuum of damage conditions, as illustrated in Figure 3, with reference to the limit states. Figure 3 illustrates how ULS can be anywhere from the onset of yield to irreparable damage. While collapse is difficult to model, collapse may a better-defined damage state (thresholds aside) than "ultimate" – which is not really a defined damage state.

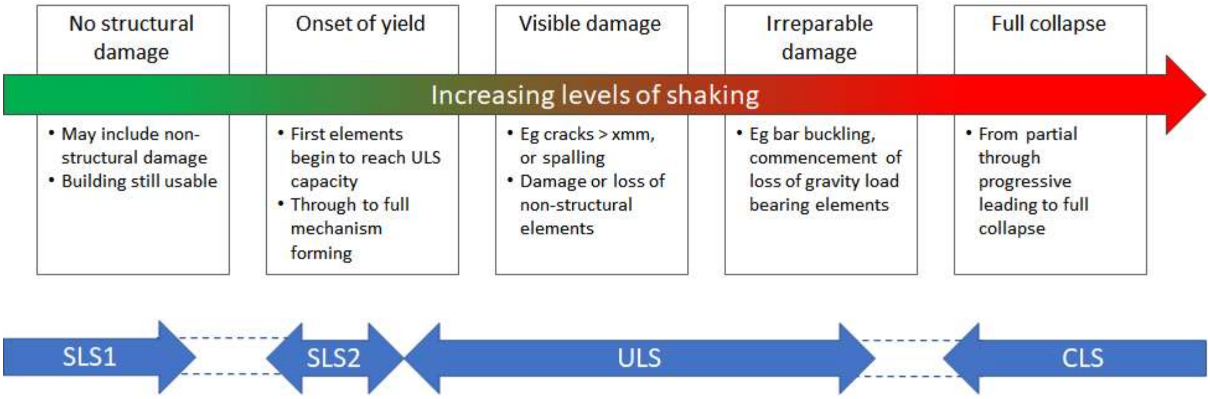

Figure 3: Mapping of limit states to building condition14

One accepted measure of risk in international standards (and flowing from there through to building codes) is the **annual fatality rate** (AFR). As stated in the commentary to NZS 1170.5, an accepted basis for building codes is an AFR of 1 x 10^{-6} but a range of values is available. Injury and fatality risk are the first measures that assess human impact directly, in terms of what many stakeholders are trying to avoid. This is also at the core of New Zealand's Building Act and Regulations, which include the objective "to safeguard people from injury caused by structural failure". However, other potentially severe impacts (for example, economic and social) are not as directly addressed under the current Building Code.

Assessing the risk of injury requires consideration of severity and sources of injury, many of which are not controlled by building designers. Fatality risk requires assessment of full or partial collapse which, as noted above, is not easily predicted, although damage states may be selected as a proxy for collapse (e.g. large inter-storey drifts). The Group notes that modern buildings should be able to sustain at least 1.5-2 times the ULS displacement before collapse is imminent (e.g. Stirrat and Jury, 2017).

The Code is only one component of the wider Building Controls system, which also includes **risk-based consenting and review processes**. A compelling argument can be made for the Code to include adequate allowance for failure to comply, meaning that potential failure of non-compliant modern buildings should be included in the AFR.

Risk aggregation occurs as **towns and cities grow and develop**. The risks also depend on the number of building occupants, which is not directly accounted for in all cases through IL3 and warrants review. For example, there are inconsistencies between large residential buildings which are considered IL3 when they accommodate more than 5000 people and an area greater than 10,000m2, versus day-care facilities that accommodate more than 150 children. When buildings and infrastructure are concentrated, the total loss (whether economic or injury/death) associated with a single event or series of events is compounded. This

[14] Note that the separations between limit states are not generally clear-cut, nor are they consistent across differing building structures and materials. The bars mapping the limit state to the condition are purely illustrative, and the term CLS should not be construed as a suggestion to introduce it. Rather it simply gives it a name.

poses a considerable risk to New Zealand, where the ability to diversify geographically is modest and GDP exposure to single-event loss is disproportionately high. This may be partly offset by insurance for direct financial losses, but large-scale events also tend to be more complex and recovery can be slow where insurance claims remain to be assessed and settled. The ongoing availability of insurance and it being reasonably priced indefinitely should not be assumed and does not mitigate liabilities associated with cascading economic and social costs, which typically are borne by governments.

At present in low seismicity areas New Zealand takes a deterministic approach to the **disproportionate impact that infrequent events might cause by the aggregation of multiple risks**. This is seen in Auckland, for example, where lateral loads have been adjusted in 1170.5 to reflect a judgement that the uniform hazard approach does not deliver an appropriate level of strength in that region's buildings.

This is potentially **exacerbated in regions of lower seismicity**, where the ambient seismic hazard that informs Building Code considerations may not reflect more severe shaking with long recurrence intervals. By contrast, Building Code requirements in more active seismic regions tend to reflect greater contribution from severe earthquakes, because of their shorter recurrence intervals in relation to assessed building life. The approach in current standards is to design for one return period, without necessarily recognising the variation in the shape of the hazard curve. As a result, hazard at longer return periods than 475 years which may be more material in terms of its contribution to the risk we are trying to address, may not be counted to the degree that it probably should.

Potential solutions

The Group recognised that systematic engagement with affected stakeholders would be required to resolve some of the issues raised above. Longer term this needs to be addressed and maintained through education and training with regard to seismic design, which involves consideration of priorities for postgraduate education and post-experience professional development.

More transparent and objective criteria for evaluating risk are needed now to support those conversations. Before the updated Seismic Model is deployed, these ideas could be usefully developed:

- Individual building performance and aggregated risk for all buildings **involve different considerations**, and require different approaches for risk assessment, and for targets potentially represented within the code, including:
  - Use of injury and / or loss as risk targets as well as death / or collapse (within current settings)[15].
  - Use of a broader view of risk, including additional performance objectives, e.g. collapse, recovery timeframes, and re-occupancy.

  Economic outcomes are the relevant aggregated risk parameters to move toward, but do not need to be achieved immediately. Using a risk-based framework to set design levels in the Code will enable risk metrics to be introduced to our design approaches at a later date when models become more robust.
- The Building Code needs to anticipate the **long-term certainty** that earthquakes could eventually affect any New Zealand city even though individual buildings have a limited life. The building code system

[15] Injuries related to falling (or falling objects) which are related to accelerations can be identified. This might mean we should control accelerations in buildings.

should evolve to support the design of towns and cities as they change and grow, so that risk aggregation is addressed slowly but surely.

A practical way to consider this would be to extend the current approach to an appropriate means of **including hazard in our assessment/design through a risk-based framework**. The advantage of this approach is that we could disaggregate the risk to identify that 'scenarios of least regret' are captured and considered.

A limitation currently is that, although higher Importance Levels may be assigned to certain classes of building, this is limited to individual buildings with certain functional characteristics including post-disaster functions [16]. A risk-based design framework could provide a more appropriate means to select IL factors, importantly considering the uncertainties in ground motion and building performance.

An assessment framework and decision-support tool are needed to develop agreed criteria for the treatment of risk. A proof of concept could be developed on a comparable timeline to the updated Seismic Model. Risk-targeted design approaches (or spectra) have been developed along this line in other countries (e.g. Luco et.al. 2007), and although an incomplete picture of the risk relevant for design exists, the framework would be a step toward the objectives outlined above. The Group noted that risk targets are already used in New Zealand in risk-based land use planning, in the Port Hills of Christchurch and in the Bay of Plenty region.

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[16] The latter category highlights the difficulty of addressing this issue; for example, when considering the design of an IL4 building on an existing hospital site, where proximity to other buildings and infrastructure may compromise the post-disaster functionality, either through adjacent collapse hazards, accessibility or availability of essential infrastructure through the site.

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9. APPENDICES

A1 LIMIT STATES AND DESIGN PERFORMANCE OUTCOMES

The current process requires the designer to decide what ductility is appropriate given the detailing proposed, which then implies a minimum level of strength to achieve the ULS. This strength is then checked against the strength required to meet SLS1 and SLS2. The focus is therefore on ULS with some adjustment, if required, for serviceability.

An option that has been used in the past is to recognize the primacy of strength in design. The verification method defines this elastic strength at a level consistent with the onset of damage. This could be onset of significant damage – for example, the development of the plastic mechanism or all plastic hinges. This strength is then factored up, if required, to cover the ULS objectives, based on the assumed ductility and is thus assumed to comply. An advantage with this approach is its focus on the behaviour of the structure at the actual demand level designers are contemplating and for serviceability levels which are expected to occur much more frequently than the ULS events. Disadvantages are that not all parts of the current design procedures, such as capacity design, can necessarily be dealt with using this simple approach.

The means to achieve the life-safety objective assuredly have been debated and not yet resolved, but the performance objectives of the current Code requires structures to have a realistic chance of surviving earthquake shaking much greater than 1.5 times ULS shaking – and up to three times ULS shaking has been suggested in one recent review (Stirrat and Jury, 2017).

ULS has stayed pretty much the same except for ductility factors, and Serviceability Limit State 1 (25-year return period shaking) has remained since 1992. ULS is defined only for a single-event, not multiple closely spaced events, and the hazard is currently magnitude-weighted relative to M 7.5 reflecting its origins in a focus on crustal faulting in Wellington. The philosophy of SLS 1 is that it should define the onset of damage and SLS2 was introduced to raise load levels such that buildings might remain functional after an earthquake. For occupancy, SLS2 is about sheltering people in place, not providing business continuity.

Although SLS2 is higher than SLS1, it currently pertains only to non-structural elements – but has been intended by the Standards committee to encompass the whole building.

A2 LAND PERFORMANCE AND SOIL-STRUCTURE INTERACTION

A 2.1 Ground Movement and Foundations

NZS 1170.0:2002 does not require explicit consideration of the performance of foundations beyond the SLS and ULS levels of shaking. This implies an assumption of linear performance between the two limit states which is rarely fulfilled with respect to liquefaction hazard. Using the simple example of level ground liquefaction (i.e. no consideration of lateral spreading or slope stability hazards), there can be a ‘step change’ in soil behaviour and therefore foundation performance between the two “codified” limit states. For example, in the cities of Hastings and Napier in Hawke’s Bay, it is not uncommon to predict (using typical simplified triggering procedures) no liquefaction under SLS ground shaking (pga = 0.14g, Mw = 6.2), but full triggering under ULS ground shaking (pga – 0.42g, Mw = 6.5). However, full triggering is also predicted at the 100-year level of shaking (pga = 0.25g, Mw = 6.3). The 2010-2011 Canterbury earthquakes have shown with unprecedented effect, that consideration of two limit states is not adequate to predict the desired or expected performance.

To what reasonable limit should foundations perform? While not necessarily compromising life-safety objectives, the failure of foundations may well preclude repair of an otherwise repairable structure.

Ground/foundation performance should ideally be viewed by the designer in the context of overall building system performance. In principle, the performance of the ground/foundation system should not be the key limiting determinant of building performance and building code provisions should accordingly provide guidance to ensure adequate performance.

If this principle is accepted then any form of local or global ground failure as a result of soil liquefaction, slope instability, or loss of bearing capacity should be avoided or mitigated, as such failures may result in uncontrolled performance of the building system. Foundation failure or "rupture" should not occur, or at least not occur prior to the onset of a high level of damage in the building itself. Even in the latter case, the foundation failure should not result in an uncontrolled performance of the building system.

A 2.2 Soil-Structure Interaction

Seismic soil-structure interaction[17] (SSI) is another important consideration in the efforts to achieve adequate building performance during earthquakes. There are two important effects of SSI on the building performance. First, flexibility of the foundations (both soil and the foundation itself) modifies the dynamic response of the building system, the most important effects being the increase in the fundamental period of the system and increase of damping in the system. Second, foundation deformation results in both transient (during shaking) and permanent displacements at the foundation level of the building. These include uniform settlement, tilt and differential settlement and potential damage to the foundation itself, with a potential corresponding loss of structural integrity.

Traditionally, effects of SSI have been considered to be beneficial to the building response (i.e. considerations of SSI would reduce the structural response), but this belief arises in part from an incorrect assumption that the shape of codified spectra represents the spectra of all relevant future earthquakes, at a given site. Indeed, SSI can increase the dynamic response of the building and a useful lesson from the failures along the waterfront in Wellington during the 2016 Kaikōura earthquake (e.g. Siddiqui 2019a) is that effects of flexible (soft) soils should be carefully evaluated for flexible structural systems.

Transient and permanent displacements at the foundation level, and the consequent effects on the building performance, are even more important to account for in design because these will be the dominant interaction effect in case of relatively poor ground conditions and excessive deformability of foundations. Such effects were widespread across the building stock in the CBD of Christchurch where excessive tilts and differential settlements of multi-storey buildings were observed.

A3 NEW ZEALAND SEISMIC HAZARD AND ANALYSIS FOR ENGINEERING DESIGN

The level of seismic hazard varies significantly across New Zealand. Highest levels are observed within the Australia/Pacific plate boundary zone where high rates of tectonic displacement occur, diminishing with distance from this zone and being substantially lower towards Auckland and Northland, and southeast Otago in particular. The intensity of ground motion expected for a specific return period in major urban centres in New Zealand may vary by a factor of 10 to 20, for some intensity measures.

A 3.1 Probabilistic Seismic Hazard Analysis (PSHA)

Over the past several decades, science-based hazard information has been used in seismic provisions for buildings in New Zealand and internationally. The cornerstone methodology for providing such hazard

[17] SSI or more recently SFSI (soil-foundation-structure interaction)

information is known as the probabilistic seismic hazard analysis (PSHA), which allows to estimate probabilities of earthquake shaking intensities at a given location (area) while considering key contributing factors to the hazard and uncertainties. PSHA involves three principal steps in the hazard evaluation:

- *Source characterisation* (identification of location of earthquake sources, magnitude, and recurrence interval (probability of occurrence over time) of earthquakes);
- *Estimation of ground shaking intensity at a site* (using GMPE[18]) which accounts for source characteristics (magnitude, fault type, rupture distance), effects of seismic wave propagation through the Earth's crust, and effects of local site conditions (bedrock depth and geometry, and site characteristics, i.e. effects of near-surface soils).
- *Seismic Hazard Curve determination for a site* by aggregating the effects of Steps 1 and 2 over all relevant earthquake sources and for all relevant combinations of factors. The seismic hazard curve eventually provides a measure for each intensity of ground shaking in terms of how likely that motion is to occur over a specified time interval. For example, it allows determination of ground motion intensity for a mean recurrence interval in years (e.g. ground motion intensity with 475-year return period (on average), or 10% probability of occurrence in 50 years).

There are significant complexities and uncertainties associated with the processes and their modelling in each of the principal steps; these are typically described by a mean and standard deviation in the relationships. Use of logic tree methods is also common, for example to account for different interpretations of an earthquake source or to allow for use of several GMPEs with different weighting. The variation between the 'hazard curves' produced by this modelling approach represents what is known as "epistemic uncertainty" – the uncertainly regarding which model may be "right".

A3.2 Seismic Hazard and Treatment of Uncertainty for Engineering Design

Both *demand* and *capacity* uncertainties need to be considered and the aggregate of the two will influence the performance outcomes of the building. Currently there are factors of safety used in design, often two standard deviations for material properties, and allowances for construction tolerances, that are used in capacity calculations.

However, on the hazard or demand side, seismic actions are currently derived from the 'mean hazard'. A better understanding of the overall system uncertainty is needed before making final decisions about how to incorporate any changes from the review of the national seismic hazard model. Code clause B1.3.4 refers to accounting for uncertainty, refer to subclauses (c) effects of uncertainty resulting from construction activities and sequencing, (d) variations in properties of materials and characteristics of the site, and (e) accuracy limitations on methods to predict stability of buildings.

Are there design safety factors or other performance adjustment factors (e.g. S_p) in current use that blur the lines between capacity and demand, and which could be refined – or removed - if the hazard understanding is improved? The balance of this section focuses on hazard uncertainty.

In the loadings Standard NZS 1170.5 the seismic hazard is parameterized such that the only discriminating factor between different regions is the hazard 'Z'-factor. In other words, across all New Zealand a single

[18] GMPE – Ground Motion Prediction Equation; GMPEs include independent variables for earthquake magnitude, fault type, rupture distance, sedimentary basin depth, and site characteristics. GMPEs are formulated to capture the essential physics of seismic wave propagation, with specific ('calibration') coefficients set based on regression analysis of ground motion records from past earthquakes and, in some cases, computer simulations of earthquakes.

shape of the spectrum is adopted for a given site class, a single amplification factor for all earthquake intensities for a given site class, and a single shape of the hazard curve. This delivers a constant ratio between SLS and ULS hazards, but the simplifications (or averaging of PSHA output) inevitably result in some level of deviation (from small to large) of the codified hazard definition from the computed PSHA hazard at any given location.

Another source of deviation between the codified hazard and possible PSHA computations arises from efforts to 'unify' the hazard definition using principles of uniform hazard (i.e. ground motion with equal probability of exceedance) or uniform risk for ground motion that is presumed to produce an equal probability of collapse in 50 years for structures. Where levels of seismicity vary significantly, uniform hazard and uniform risk criteria can result in design motion parameters that are deemed either unreasonable or economically unjustifiable at the extremes of the range (i.e. the highest and lowest seismicity regions in the entire hazard range). Hence, some adjustments are commonly adopted typified by the minimum 'Z'-factor in New Zealand, or deterministic limits and collapse-probability adjustments in USA.

The adjustments of the codified hazard – in terms of a single amplification factor and a single spectral shape - may be particularly large for uniform treatment of a given site soil-class, when applied across a wide range of earthquake magnitudes, or low to high shaking intensities. This approach can mask different levels of non-linearity in the response of local soils under vastly different local site conditions. In this process, the effects of the above factors are "averaged", and the adopted factors can be substantially different from the output of a bespoke analysis for a given location.

The principal objectives of the current New Zealand Standard are that "(1) buildings achieve a level of performance so that frequently occurring earthquake shaking can be resisted with a low probability of damage, and (2) the fatality risk is at an acceptable level". It is implicitly assumed that these objectives should be achieved while considering trade-offs between enhanced performance and increased construction cost. The objectives should be achieved in a uniform fashion throughout New Zealand, and PSHA outputs are used to these goals.

In the current Standard, PSHA outputs are summarized in the form of:

- Elastic site hazard spectra (in a normalized form, i.e. response spectra shapes), for five site classes (A, B, C, D, E) – (Section 3, NZS 1170.5:2004)
- Hazard factor Z (tabulated and also as contour maps); the hazard factor corresponds to a PGA for site classes A and B, for 500-year return period (Section 3.1.4, NZS 1170.5:2004; Supplement to Section 3.1.4, NZS 1170.5:2004)
- A unique shape of the seismic hazard curve is essentially adopted through the Return Period Factor (Table 3.5, Section 3.1.5, NZS 1170.5:2004)

Combining the above three parameters, elastic spectra can be defined for different soil classes and different return periods throughout New Zealand. These ground motion parameters define "uniform hazard" across all locations, for a given return period (i.e. ground motion parameters with equal probability of exceedance across all locations in New Zealand). However, the hazard is only nominally "uniform hazard", as discussed in the body of the report.

A4. RISK MEASURES AND METRICS

A 4.1 Risk measures

Risk is classically defined as the product of hazard and consequence. Seismic risk may be defined as the potential for (economic, social, health, and environmental) consequences due to seismic events occurring in a specified period, for example 50 years. While most people have a general understanding of risk and probability, the everyday contexts in which it is usually encountered often do not assist understanding of the earthquake context.

There are many factors including the complexity of the risk formulations and the long timeframes over which risk must be assessed. The Group acknowledges that awareness of risk from infrequent natural disasters is not a constant, in the way that more frequently occurring events remain in closer consideration.

Economic impact can include the impact of injury and death and lends itself to assessment of cost-benefit ratios, a valuable tool for planning. It can include assessment of both direct and indirect costs, but it should be noted that assessment of both repair costs and downtime are highly contextual. For example, the cost to repair a single damaged building will be considerably different to the cost of repair for one building among many in a heavily damaged city. Therefore, these measures should be regarded as relative indices rather than absolute measures.

Resilience is the new objective but remains difficult to measure. Resilience (currently at least) is unitless and has no unique definition. The general form of resilience may be represented by a curve representing a drop in performance with a recovery over time, as shown below in Figure A4.1.

Resilience may be considered as a combination of factors and requires consideration of a much broader context. This includes factors outside a building, such as service connections, and the wider infrastructure and assessment of adjacent buildings, the status of which may impact on the usability of the building being designed or assessed. It is also very dependent on the users' context, as resilience in a post-disaster context may be considered acceptance of what you can do without, and for how long, which may vary subjectively. Any implication that buildings can be designed to be 'earthquake-proof' should be avoided as a solution for resilience. Instead, resilience should reflect a broader set of controls and acceptance, under given circumstances, of effects that can be managed over a limited timeframe.

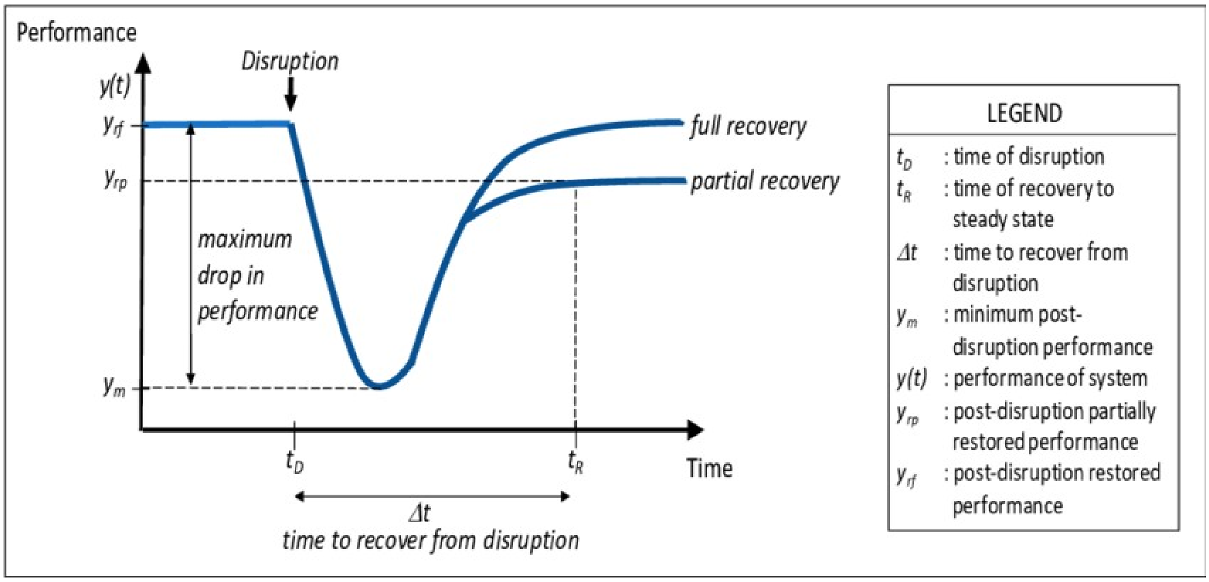


Figure A4.1: General form of Resilience curve (Madni[19])

A 4.2 Life Risk Metrics

One accepted measure of risk in international standards (and flowing from there through to building codes) is the annual fatality rate (AFR). As stated in the commentary to NZS 1170.5, an 'accepted' basis for building codes is an AFR of 1×10^{-6} (but a range of values is available). The AFR in this case is derived from a combination of factors, including:

- The underlying hazard – the probability of shaking of a given level.
- The probability of collapse under the given level of shaking, for a specific building design
- The probability of people being injured or killed in the collapse
- The probability of people being in the building at the time of shaking

Each of these factors includes significant uncertainty and the determination of the AFR across the entire country is impractical. Design standards are informed by a combination of research and observation of actual performance. The latter is dependent on where earthquakes strike, noting that New Zealand generally has several earthquakes a year of a magnitude sufficient to cause damage. However, the spatial distribution of earthquakes relative to our towns and cities means that opportunities to observe measure significant building response are rare.

Looking back at records of New Zealand earthquakes over the last 100 years, there have only been eight earthquakes causing fatality, commencing with Murchison in 1929. Integrating the numbers of fatalities with the population growth over that period, the actual AFR has been 2.3×10^{-6}, a little higher than the accepted rate, but within the same order of magnitude. There are several important points to note in this:

1. Because this record extends back over 100 years, it includes deaths in buildings that were neither compliant with the current building code nor retrofitted to modern standards.
2. This record includes deaths that cannot be attributed to building failure (for example from earthquake induced landslides).

[19] Madni, Asad M, Erwin D and Sievers M, Constructing Models for Systems Resilience: Challenges, Concepts and Formal Methods, Systems Journal (2020), 8, 3

3. Arguably, there have been no deaths in buildings designed since the advent of modern design standards (post-1976), where the building met the code of the day. However, it should be noted that the 45-year service history of the oldest of 'modern' buildings is too short to accurately assess this.

For these reasons, the Group noted that the observed AFR could be regarded as being higher than representative of modern buildings, so it might be inferred that modern buildings satisfy the AFR $< 1 \times 10^{-6}$ objective. A drawback of the AFR as a risk measure is that it does not capture the effects of aggregated risk or of the economic loss from earthquake damage or capture the wider impact of injury.

A 4.3 Current Usage

The most common expressions used for seismic risk in the industry at present tend to be representations of the hazard, expressed as either the return period or the Poisson probability of likelihood within a period, typically the nominal 50-year building life. So, for a typical IL2 building, a 500-year return period shaking (with a 1/500 annual probability) or 10% probability of exceedance in 50 years is adopted. These measures are relatively simple although comprehension can get more difficult, the more they are explained – there is no such thing as a 500 year earthquake (level of shaking), it is a composite of all the shaking (subject to some magnitude weighting), and it does not relate to X earthquake/shaking level on Y fault/earthquake source(which most people comprehend).

Regarding building performance, the use of hazard is really a proxy for life safety, or sometimes damage. In this sense it should be considered a relative measure, as matters such as the inherent reliability factors that are used to ensure adequate performance of structures are not addressed in this usage. The impact of ductility (and 'softening') is particularly important if considering damage and post-earthquake serviceability. Life safety is generally an outcome of *collapse* (which is not an explicit consideration in the design or assessment process) and *occupancy* which is only considered in the sense of peak numbers, not hours of use.

There are no probability functions commonly in use for buildings in New Zealand, although representative fragility curves do exist for many buildings or building element types which might allow this to be developed. However, where such approaches have been introduced, they have reportedly been technically difficult to use[20].

A5. 2010-2016 NEW ZEALAND EARTHQUAKE SERIES - PERFORMANCE OVERVIEW

A 5.1 The Major Earthquakes – Canterbury Sequence 2010-2011 and Kaikōura 2016

A5.1.1 Canterbury Sequence

The 2010-2011 Canterbury earthquake sequence comprised four major events with a series of aftershocks. The most critical of the Christchurch earthquakes were the Mw 7.1 Darfield earthquake of 4 September 2010 and the Mw 6.2 Christchurch earthquake of 22 February 2011. A range of acceleration and displacement spectra are shown below for these earthquakes.

The levels of shaking recorded in or near Christchurch varied but the series is generally accepted as having been at or in excess of the 500-year shaking from NZS1170.5 as it stood at the time the sequence started

[20] FEMA P58 (2020) is an example of probabilistic methods applied in USA.

(Z=0.22). The contrasts between the records are striking in that the accelerations in the short period ranges from the Darfield event were relatively low, but there was amplification in the 2-3 second range, exceeding NZS1170.5 demand; and there were large displacements at two of the four sites; whereas the Christchurch event had very high accelerations across the range and large displacements at all four reference sites. Both sets of records suggest higher amplifications in a narrow shorter period range – 2-3 seconds for Darfield and 3-4 seconds for Christchurch.

Figure A5.1: Response Spectra from the 4 September 2010 Darfield Earthquake

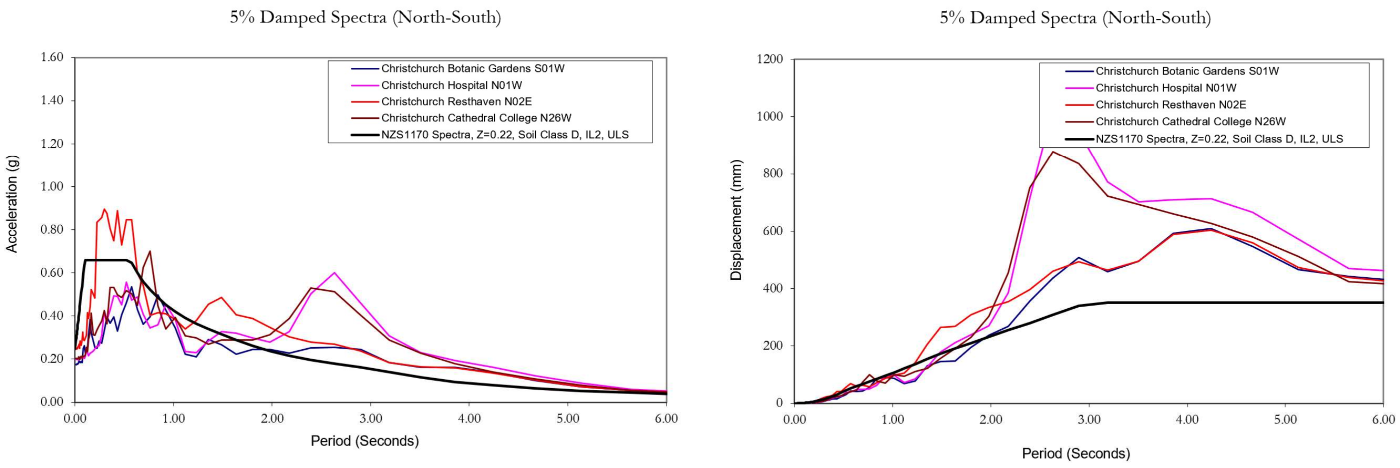
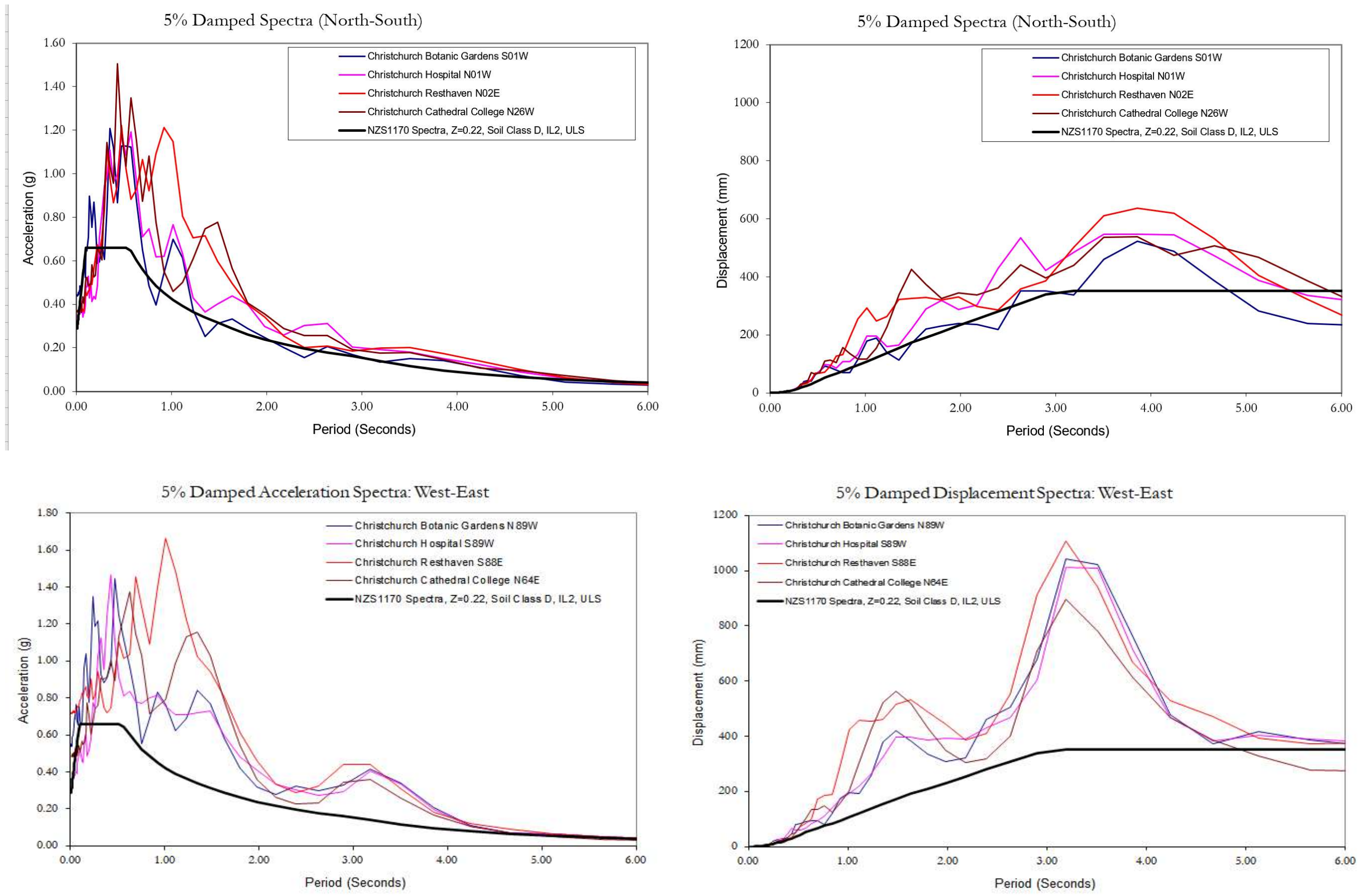


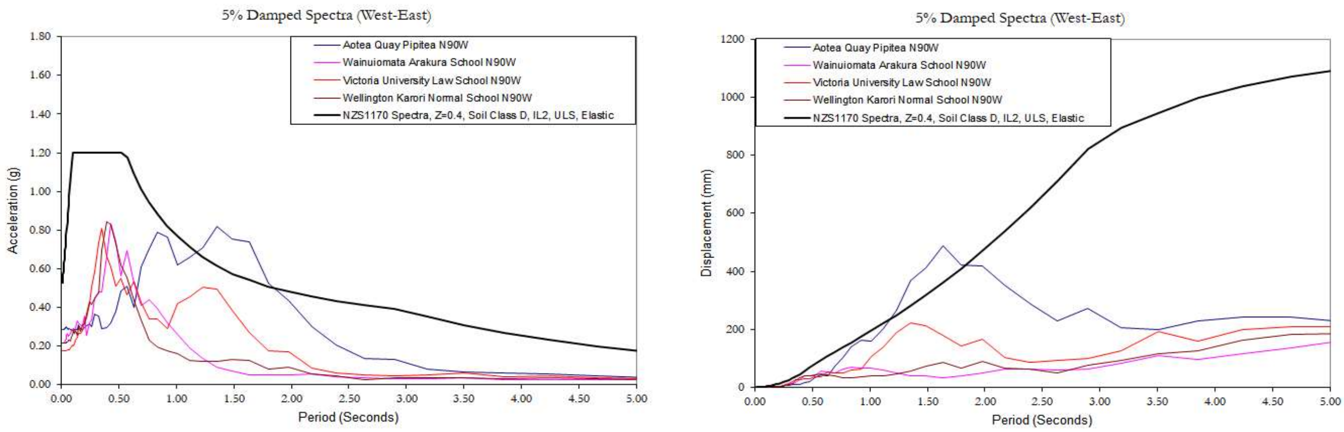
Figure A5.2: Response Spectra from the 22 February 2011 Christchurch Earthquake



A5.1.2 Kaikōura Earthquake

The Mw 7.8 Kaikōura earthquake (14 November 2016) originated near Waiau on the Humps fault and in a complex series of ruptures, ended on the Needles fault of Cape Campbell, focusing much of its energy on Wellington (which will be used here for comparison purposes). Shaking in Wellington was highly variable according to location, with shaking measured across the period range. Unlike the Christchurch series, only a select range of buildings was tested, with shaking of up to the 500-year shaking (for Z=0.4) for buildings in the approximate period range of 1-2 sec, in the areas subject to basin and edge effects. The shaking was otherwise closer to the SLS level. Note that the peak accelerations in the 1-2 sec range in the affected areas are in the same range as recorded for the Darfield earthquake but due to seismic zoning in NZS 1170, the capacity of modern buildings (1976 to present) should be in the range of 50% to 80% higher.

Figure A5.3: Response Spectra from the 14 November 2016 Kaikōura Earthquake



A 5.1 Performance Observations – Darfield Earthquake

The Darfield earthquake caused widespread light to moderate damage to pre-modern era buildings (primarily URM, but some concrete), with relatively little damage to modern (post-'76) buildings.

Focusing on the buildings that were more or less code-compliant:

Multi-storey: There was generally light damage to a number of modern era buildings, notably some of the taller (~20 storey) buildings. – which is in part explained by Fig A5.1 above, with the greatest seismic actions recorded in the 2-3 second period range. This was evident in plastic hinge formation in ductile concrete frames (e.g. Price Waterhouse tower) and in damage to flooring systems (e.g. Clarendon towers – significant movement of units and fracture of mesh). Damage was generally assessed as repairable.

Low-rise: For the most part, buildings were undamaged or lightly damaged. Some issues were noted in tilt-panels buildings with connections and cracking/hinging of thin panels

Residential: Timber-framed houses performed well, unless on liquefiable sites or those affected by lateral spreading adjacent to waterways. Damage on liquefiable sites ranged from light to severe, with a range of damage associated with differential settlement to homes and in-ground services. Several buildings nearly collapsed in areas of severe lateral spreading.

Conclusions (for generally code-compliant buildings only):

1. The life safety objective was met in all cases. This would have been expected given the level of shaking, although note that there were quite high displacements.

2. Amenity was harder to assess. No modern buildings were slated for demolition after this event due to shaking damage, but it could be argued in hindsight that a number were more seriously damaged than was realised at the time and so should possibly have been closed for repairs with more urgency.
3. Liquefaction was a special case, where the range of damage for the most severely affected sites was well beyond what would be considered acceptable for the amenity objective, at least in the lay-person's view.

A 5.2 Performance Observations - Christchurch Earthquake

If the public and profession had been generally satisfied with building performance in the Darfield earthquake, that changed with the Christchurch earthquake. Much shorter in duration, the close proximity led to very high ground accelerations in the centres of Lyttleton and Christchurch. There were a number of full or partial building collapses and widespread damage. More critically, 185 people lost their lives and many more were injured (3,129 during the earthquake and 1,293 in the aftermath, according to The Press, 2014). In consideration of modern era (post-76) buildings:

Mid- and High-rise concrete structures: There was one notable collapse (CTV) and several buildings that were crippled to varying degrees, by a range of issues, including:

- Loss of stair support (Forsyth Barr and others to a lesser degree)
- Severe plastic hinge degradation (Clarendon Towers, PWC tower and others)
- Ratcheting and subsequent failure of a story (Grand Chancellor)
- Significant diaphragm damage in precast flooring systems

Many of the damaged structures were subsequently demolished, with relatively few repaired. The Forsyth Barr tower is notable as the only repaired high-rise concrete structure restored to use, along with a handful of medium-rise structures in the CBD.

With respect to the performance objectives:

- No generally code-compliant building failed to meet the life safety objective. Arguably, a greater duration of shaking may have tested this further. There remains much over whether the damaged buildings (that had exceeded ULS capacity) were in fact repairable, much of it related to assessment of the remaining life of steel that had been strain-hardened and/or strain-aged. Subsequent academic research has shown that a much greater proportion of buildings may have been repairable, but it is important to acknowledge the significant role of insurance in determining the outcome (Marquis et.al. 2015). However, there were significant issues with non-structural elements (with one death due to a falling concrete panel).
- Because the earthquake was clearly well beyond the SLS shaking level, amenity is difficult to assess objectively. The number of buildings demolished and the length of time that the city was shut down would suggest that this was not met, but the level of insurance cover has had a significant part to play in this. Had there been less insurance available, many more buildings may have been repaired and/or occupied in the interim.

➢ *Low rise concrete structures*: Generally performed well, although suffering from similar issues to the taller buildings, particularly where on poorer ground with significant liquefaction. A greater proportion have been subsequently repaired. Review of performance objectives is otherwise as Mid- and High-rise concrete structures.

- *Multi-storey steel structures*: There were relatively few large steel-framed buildings. The (high-rise) Renaissance hotel was restored to use after extensive repairs to active links in braced frames and a mid-rise (originally Transport House) was demolished. Both. suffered effects of high flexibility
- *Industrial and tilt-up structures:* These structures generally responded well, in absence of liquefaction, although there were some issues with behaviour of panels (where thin panels hinged under face loading) and panel connections (some poorly detailed, exacerbated by the impacts of shrinkage over multiple bays of rigid connections). Some unusual design approaches were 'found out', e.g., cantilevering columns without roof bracing or panels supporting rafters only (no portals). Where there was liquefaction, more significant issues were encountered with heaving of slabs and shallow foundation failure.

With respect to the performance objectives:

- No generally code-compliant building failed to meet the life safety objective although there were significant potential life safety issues with non-structural elements and more particularly, contents, such as racking.
- Again, amenity is harder to assess. The determining factor was generally liquefaction. Businesses with little or no settlement were able to return to work quickly, those with significant movement were often not. Insurance had a significant role, with owners in some cases delaying reoccupation of usable buildings (common across all building types, but possibly more prevalent in industrial facilities with lower amenity needs).

- *Residential:* Most (>90%) residential buildings are timber framed, and generally continued to perform well. There were, however, some new loading actions, with extreme ground accelerations affecting the Port Hills leading to ridge effects, rock-roll and cliff edge failures. An interesting impact of this was that the architecturally designed homes that more typically populate the hillside suburbs were exposed. These homes often performed less well than the more typical homes due to glazed open fronts, varying foundation conditions from slopes, and use of heavy or brittle cladding.

Liquefaction was even more widespread and intense around the city, particularly in proximity to existing or former waterways, leading to the creation of the Residential Red Zone, affecting over 8,000 properties.

- All generally code-compliant building met the life safety objective in consideration of shaking damage to structures.
  This objective was not satisfied in residential buildings from the perspective of rockfall damage and in some cases, with the performance of heavy residential roofing and cladding systems which fell in ways that could have resulted in death.
- Timber-framed homes on flat non-liquefiable ground generally performed well given the level of shaking. Arguably, the Darfield earthquake had already demonstrated the failings of homes on liquefiable ground.

A 5.3 Performance Observations - Kaikōura Earthquake

Note: this discussion is focused on modern (post-'76) Wellington buildings only.

This damage that resulted from this earthquake surprised many people, although the reasons are quite clear, once the geological context is understood. Given the highly selective nature of the amplifications in the 1-2 second period range from the basin and edge effects the most critically affected buildings were almost entirely within the Thorndon and Te Aro basins, including the waterfront occupied mainly by Centre

Port. There were some outliers, notably the building at 61 Molesworth street that was demolished under emergency provisions. Most affected buildings were typically concrete moment frame structures in the range from 6 to 15 storeys, with a few shear wall structures also suffering significant damage.

There was one clearly critical life safety failure (Statistics House) and a number of other instances that could be judged as near to failure. Failure modes of precast flooring systems were a principal concern, with a Targeted Assessment Programme initiated by Wellington City Council to identify buildings most likely to have suffered hidden damage. Through this process 64 buildings were evaluated (not including a further eight, badly damaged buildings that had been separately identified and were being dealt with through other avenues). Of those, approximately 50% had evidence of a critical damage state to varying degrees[21].

Precast flooring assessment and repair is an ongoing issue for the profession, with considerable debate still continuing as to the extent of the problem, the level of risk and the means of remediation. Due to the relationship between building drift and shaking level, it is generally considered that most buildings with precast floors are probably not "earthquake prone", but there is little or no margin above 33%NBS for many concrete moment frame structures, particularly in regions of higher seismicity.

Conversely, buildings not in the affected areas, or those with natural periods well outside the affected range, were generally undamaged and met both life safety and amenity provisions. This included unreinforced masonry buildings, to the surprise of many. Notwithstanding, an interim retrofitting requirement for URMs was mandated by the council, addressing parapets and upper storey walls, with the aim of reducing risk for pedestrians.

Conclusions (for generally code-compliant buildings only):

- The life safety objective was met in all but one case, although several more were close to failure. This was slightly unexpected, given the general level of shaking, until the high levels of amplification in the basin areas became apparent.
- Amenity was generally met in areas not subject to basin effects. There was some loss of amenity in otherwise undamaged buildings in the affected areas, related to non-structural elements and contents damage.
- The basin and edge effects skew the outcome considerably and are not currently allowed for within the distribution of shaking considered in NZS 1170. These effects produced shaking approaching or even exceeding the code ULS shaking level in an earthquake that otherwise would have met the definition of the Moderate Earthquake in the Building Regulations.

A 5.4 Other Matters for consideration

Following are a few issues that emerged during the earthquake recovery and were discussed by the Group, even though they are not strictly related to the Building Code.

The Role of Insurance

This is still not a complete picture, but a few discussion points include:

- There have been marked differences in behaviour observed between insured and non-insured building owners. There were examples of the former seeking replacement when on purely technical criteria this was not necessarily warranted. Similarly, the latter were often desperate to get back

[21] Wellington City Council Targeted Assessment Programme Summary Report, Kestrel Group, 7 May 2017

into their buildings even where on technical grounds this was inadvisable or impractical (unsafe and/or not repairable). Contrasting imperatives had a considerable impact on whether buildings were demolished or repaired, regardless of actual repairability.

- In many cases (perhaps more commonly observed in the industrial sector) business operations were held up or severely compromised by owners waiting for insurance resolution, which was not necessarily forthcoming. Externally, this sometimes appeared to give worse outcomes for businesses than if they had simply worked around the damage and not waited for insurers. However, the behaviour was reinforced by the fear of losing potential claim value if it could be shown that the property remained usable.
- A common assumption prior to 2010 was that "insurance will make us whole again, so no point in spending money on our buildings to avoid earthquake damage". Subsequently the underlying assumption changed but there remains heavy reliance on the availability of insurance on much the same terms. However, neither availability nor affordability can be relied upon and in particular, regional pricing could make insurance at the previous levels unaffordable.
- There has been a marked reluctance among building owners (including corporate and institutional owners, and Government, for example Ministry of Education) to consider other means of seismic risk mitigation than transfer through insurance. However, for owners of widespread property portfolios, full or partial self-insurance (via larger deductibles) may be a cost-effective option, particularly if considered in conjunction with a practical risk reduction program including both retrofit of existing building stock and use of low damage techniques for new construction.
- There are still active claims from 2010 in progress. The likelihood of amicable settlement appears generally to decrease with time, often due to entrenched expectations that are sometimes fuelled by 'experts'. While this observation could be inferred to imply that responsibility for the retrenched attitudes sits with the advisers, there are other contributors, in no special order:
    1. Expectations of rapid recovery in the immediate aftermath of the earthquakes (particularly in Christchurch) resulted in heightened pressure on a system that had yet to be developed.
    2. Variations in the wording of insurance contracts created confusion among policyholders and their advisers and highlighted over time the disconnect between underwriting and claims management.
    3. The lack of guidance in legislation or regulation relating to repairs or assessment of damaged buildings has left a vacuum that has allowed or encouraged some to insist on impractical standards of repair, based on loose expressions of 'as when new', a phrase that implies far more precise meaning than is actually the case. More is written about this below.
    4. Related to the lack of guidance, the role of building consent authorities in determining the suitability or otherwise of repair methods was unclear.

Land Use

The Christchurch earthquake series highlighted the significance of land use planning decisions in determining earthquake outcomes. There were several significant widespread damage outcomes that were related to land use decisions but not directly addressed under the Building Code:

- Liquefaction. A number of more recent subdivisions, including most notably Bexley, were on land subject to liquefaction and lateral spreading even at relatively low levels – in some cases in levels of shaking at or even below the SLS level. Liquefaction was well understood before these subdivisions were permitted. Liquefaction and lateral spread affect both buildings and infrastructure. This issue is most easily mitigated before infrastructure or housing is built, at the initiation of the subdivision.

- Rockfall and slope stability. These issues are readily easily identifiable but are not fully included in the conventional design and consenting process with respect to seismic actions. Damage to housing in close proximity to both the top and the bottom of the cliffs and steep slopes of the Port Hills (during the Lyttelton earthquake) due to rock roll and rock fall showed considerable life safety risk compared to otherwise equivalent structures away from those areas. In this case, the uniform seismic hazard model does not result in a uniform risk when other secondary hazards exist.
- Tsunami could be considered as another secondary hazard in much the same way as rockfall.

Building Adjacencies

- In all three earthquakes, there were numerous instances of undamaged or lightly damaged buildings being closed or inaccessible due to the adjacent damaged/dangerous building. In the current system, the extent to which adjacent buildings are considered is in the requirement for building separation in NZS 1170.5, which requires an estimation of the adjacent building drift to ensure adequate clearance is required (Although more commonly, this is not done and instead designers assume the adjacent building drift will be constrained to the site boundary – not always a safe assumption).
- If functional recovery were to be considered as a performance objective, this would need to be addressed in some way, noting that until a full cycle of building upgrade/replacement is managed within a city, this will tend to be compromised. However, where buildings serve a critical post-disaster function, it should be a consideration.

Risk Aggregation

- The Christchurch earthquakes provided a clear illustration of the consequences of risk aggregation and what can happen with a 'direct hit', where the most intense shaking from a moderate magnitude earthquake is largely concentrated in urban areas. The cost of the rebuild has been assessed as about $40b[22], with approximately $30b of the costs being covered by insurance. Notably, repairs to residential buildings nearly exhausted the Natural Disaster Fund of $5.6b[23], leaving the country vulnerable in the short term to further large disasters.
- The fact that there was so much insurance cover available insulated the country from the worst of the impacts. If insurance costs were to increase significantly or availability reduced, the impact of future similar events would be even more profound. The impact of increasing rates could reduce the private sector uptake of insurance. This can be illustrated clearly in a comparison of New Zealand's extraordinarily high levels of insurance at the time of the Christchurch earthquakes (approximately 85% of all property had earthquake insurance) compared to other similarly seismically active regions:

California	17%
Japan	12-17%

[22] Wood A, Noy I, Parker M, Reserve Bank of New Zealand Bulletin, Vol 79, No 3, February 2016

[23] *ibid*

Chile	27%
Turkey	4%
New Zealand	80%

- There are relatively few large population centres in New Zealand, so the financial and economic impact of a major earthquake will always be higher compared to larger, geographically diversified territories. New Zealand's risk exposure and its current reliance on high insurance penetration could be mitigated to a degree by providing greater levels of protection for both horizontal and vertical infrastructure in larger centres, in order to reduce the potential cost of such an event.

Relatively few centres may be affected: if the metropolitan areas are combined, the 7th largest city, Palmerston North has a population of less than 100,000 people, which may represent an affordable risk. Although there is considerable concern that increasing seismic performance of buildings will impose significant cost on owners, this is not necessarily the case. The difference in construction costs between centres with differing seismic design load levels is probably more heavily influenced by local demand and supply factors and the style of building, where designers adapt to load levels[24].

The Direct Hit

- The significance of the 'direct hit' merits consideration. NZS 1170 sets the minimum seismic actions based on the shaking from a Magnitude 6.5 earthquake at 20km radius. In the Christchurch earthquake, there was damage beyond 20km from the epicentre, but the level of shaking within the 20km radius significantly exceeded the minimum shaking levels. The corollary is that if there is a direct hit in a city with design shaking level less than Christchurch, the levels of damage are likely to be even greater.
- There may be a false sense of security implicit in the so-called 'equal risk' approach of setting the shaking level to the 500-year return period throughout the country (with or without the minimum actions). In moderate to low seismic zones, potentially damaging earthquakes have little influence on the seismic loading as the assumed recurrence intervals are too long to contribute to the 500-year shaking. But where faults are deemed 'active' it should be assumed they will eventually rupture. No city is designed for a finite life and every city in New Zealand will at some point experience strong shaking even if the recurrence period of the causative earthquake source is in the 1000's of years.

Building Act Considerations

The Building Act has a focus on the design, consenting and construction of buildings in order to achieve performance standards including aspects relating to amenity and safety of occupants. It also has sections devoted to achieving better life safety performance from the worst of existing buildings. It does not address what must happen when buildings are damaged. There are several aspects to this:

- Firstly, the need for assessment of the safety of buildings following a damaging event, whether man-made or natural. This means that the default standard for assessment tends to be either use

[24] For example, in 2019, the typical new commercial office building cost was approximately $4,000/m2 in Auckland, compared to $3,700/m2 in Wellington, with approximately three times the seismic loading.

of the Building Code (not to be confused with %NBS) or assessment against the original design, irrespective of the condition of the building at the time of the disaster. The former is problematic for buildings which have never been in compliance and the latter may not be known for many older buildings. Moreover, neither reflect the principle (assumed) that buildings should be able to be repaired to a reasonable standard, which may not be as good as prior to the damage but may be adequate for the remaining life of the building. This was achieved through the rapid development and deployment of specific guidance following both the Christchurch and Kaikōura earthquakes but would clearly benefit from both better defined legislative/regulatory settings and the development of formalised comprehensive guidance with the benefit of research and observations since the earthquakes.

- Secondly, the standard of repair to be attained if it is deemed that repair is needed. As noted in Section 6.2 there is nothing in the Building Act currently, so some local authorities have required that the disaster and repair be treated as an alteration. Under S 112, this means that the building must be reinstated to comply with the Building Code, to at least as great an extent as before the disaster, with the exception of escape from fire and accessibility, which should comply as nearly as is practicably possible. An example of a code that addresses this is the California Existing Building Code, which nominates a repair standard. Interestingly, this code also addresses disproportionate earthquake damage, requiring additional evaluation and potentially retrofit as well as repair for buildings found to have sustained greater levels of damage than expected. This process would help to identify and mitigate risk from buildings that do not meet performance expectations in even moderate events.
- Thirdly, the question of whether minimum standards for occupancy should be set that could reflect reduced expectations of performance in the period following a disaster. This would facilitate shelter-in-place and the potential use of partially damaged buildings that may otherwise be rendered unusable due to non-compliance, when either the risk tolerance could be lifted temporarily, or other short-term measures put in place that would provide acceptable safety. An example of this is the closure of buildings due to cracking in the firewalls, where either a higher level of risk could be accepted for a limited period, or the risk could be managed to a suitable level by frequent inspections or surveillance.

These measures could potentially assist the insurance claims process by providing a clearer path to resolution of both extent of damage and required repairs.