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Earthquake Design for Uncertainty

Advisory

Jointly prepared by NZSEE, SESOC and NZGS
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Seismic design of building structures

DISCLAIMER

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Foreword

SUMMARY OF THE PROBLEM

Managing uncertainty in earthquake engineering has always been a key challenge for New Zealand structural and geotechnical engineers. Severe earthquakes are relatively rare, but without consideration in design the impacts can be devastating and lasting. Understanding how earthquakes affect buildings and how much shaking they could produce is a significant challenge.

The early pioneers of modern seismic design recognised these challenges, devising philosophical approaches and methods of design which befit such an uncertain environment. These principles are as relevant as ever today. They are what enables us to deliver safe designs for New Zealanders despite the tremendous difficulty in describing earthquake ground motions.

The uncertainty of earthquake demands has recently been given increased prominence due to the anticipated release of a new National Seismic Hazard Model (NSHM) for New Zealand, in late September 2022. This advisory considers what this could mean for new building design. Primarily, it uses the opportunity to reinforce the importance of design practices which recognise and allow for the significant challenges in defining earthquake hazards.

Hazard models are one of the tools used by engineers and regulators to determine what earthquake actions buildings should be designed for. Currently, these design actions are stipulated in the New Zealand Standard for earthquake actions [1], NZS 1170.5:2004. The hazard models used during development of that standard are now more than 20 years old, with many advances in understanding made since.

MBIE have initiated a Seismic Risk Working Programme (SRWP) to review the Building Code compliance documents used for structural design, and how well they meet our Building Code objectives and society's expectations of seismic performance. New research and lessons from recent earthquakes on the design and performance of buildings will inform this work, as well as the new NSHM information.

After an assessment of risk settings in the context of this new information, changes may be recommended to building design practices, and the way design actions are established from hazard models. Building Code Verification Method updates related to this work are planned in two stages, the first in late 2023 and the second in late 2025.

KEY MESSAGE

Ground shaking intensity at a site is unavoidably uncertain. New hazard model outputs are just one visible example of uncertainty. However, uncertainty in building performance *can* be controlled through good design—and the impacts of hazard uncertainty greatly reduced.

This is best achieved by scheming structures so that they behave in a controlled, predictable manner during earthquakes—even when subjected to shaking that is more intense than anticipated. This is fundamentally good earthquake engineering design. It results in more reliable and less fragile buildings. It recognises that our understanding of earthquake hazards is a continual learning process. Crucially, it lessens the importance of knowing exactly what shaking a building may need to tolerate. It means we can reduce our focus on design loads and still minimise risk.

The engineering recommendations in this advisory describe how, with careful design, the impacts of changing hazard levels (now and into the future) can be mitigated at little cost, but with large impacts on risk reduction. Following the principles in this guidance will lead to improved seismic performance of buildings, even whilst continuing to use the seismic design loadings specified in NZS 1170.5. This advisory encourages Engineers and Clients to discuss the incorporation of these principles as a primary focus in responding to hazard uncertainty.

Extended Engineering Background

PURPOSE OF THIS GUIDANCE

The purpose of this guidance is to reiterate the importance of designing buildings so that they behave in a predictable, desirable manner when subject to earthquake shaking, which mitigates the risks of uncertain demands. The principles outlined in the advisory describe *fundamentally good structural engineering practice* that is *effective at reducing risk* irrespective of whether codified seismic hazard is considered stable or not. Some of these principles respond to learnings from the performance of modern buildings in recent earthquakes—whilst others (such as ductility and capacity design) are decades old. This guidance explains why these principles remain as important as ever in modern seismic design.

This guidance is presented in the context of the recently initiated Seismic Risk Work Programme—and the Building Code Verification Method updates that are planned in relation to this work. This context is useful, because it provides designers with a clear tangible example of uncertainty in seismic design. A summary of this work programme and planned timeframes are provided.

Following the principles in this guidance will lead to improved seismic performance of buildings, even whilst continuing to use the seismic design loadings specified in NZS 1170.5. This guidance applies to new building design, and the new components of alterations and seismic retrofit work. It is not intended to apply to the assessment of existing buildings. The recommendations within this advisory generally extend beyond the minimum requirements of the current Building Code compliance documents and are therefore non-mandatory.

GENERAL APPROACH: A FOCUS ON REDUCING RISK

Whilst uncertainty in the ground shaking hazard is out of an engineer's control, uncertainty in building performance *can* be controlled (although not eliminated) through design.

Past earthquakes have shown that significant failures generally do not arise simply because the shaking intensity was greater than expected. Instead, failures typically eventuate in poorly configured structures featuring issues such as poor or missing load paths, vulnerable details, and irregular configurations. Consequently, dependable structural performance is better achieved by avoiding such issues than by simply seeking to increase the strength of a structure in response to hazard uncertainty

Better certainty of performance is achieved by scheming structures so that they behave in a controlled, reliable manner during earthquakes—even when subjected to shaking that is more intense than anticipated. This approach manages the *actual risk* holistically, rather than just the hazard (loads) specifically.

Key focusses in achieving these outcomes include:

- Regularity, clear load paths
- Ensuring redundancy of load paths
- Capacity design (and controlled inelastic behaviour)
- Robust detailing that ensures ductile response, avoids strength loss, and suppresses brittle failure
- Providing tying between elements and deformation compatibility in all parts of the system, especially vertical load carrying elements
- Considering soil/structure interaction, managing, or avoiding the consequences of the ground changing during and after shaking
- Avoiding excessive flexibility and softening with displacement
- Avoiding limited displacement capacity in a system or detail, before a significant and rapid change to undesirable behaviour occurs

New Zealand's performance-based Building Code framework enables adoption of a virtually unlimited range of structural forms. However, while all buildings must achieve a specified minimum level of performance, the robustness and reserve capacity of different structural forms varies greatly. Some structures deliver significantly higher reliability than others, and in turn will deliver significantly lower risks of collapse, injury or death or expected losses when subjected to stronger than expected shaking. This mostly comes about from an ability to retain strength under inelastic deformation—whether that be lateral strength, or sustained ability of an element or construction detail to carry gravity loads.

Promoting the use of such systems is more likely to result in better risk and performance outcomes than simply increasing design actions. It is also more likely to result in a building being assessed more favourably in the future against a different hazard setting—as the overarching purpose of existing building assessment is after-all to assess *risk*.

WHY IS UNCERTAINTY SO FUNDAMENTAL TO EARTHQUAKE ENGINEERING DESIGN?

Earthquake engineers have always been faced with the challenge of "designing for uncertainty." This arises from the considerable uncertainty in the possible ground shaking, compounded by uncertainty in the performance of the buildings and their foundations when subjected to ground shaking.

Uncertainties are sometimes categorised as being either epistemic or aleatory [2] and it can be helpful to understand the distinction. Epistemic uncertainties arise from imperfect knowledge of real underlying phenomena, and the challenges in defining an exact model with our current scientific knowledge. On the other hand, aleatory variability refers to inherent randomness affecting the phenomena.

Simplistically, aleatory variability (the randomness in earthquake occurrences) can be captured using probabilistic hazard curves, in the form that we currently know (and which have been used for a few decades). Epistemic uncertainty represents the range of scientifically credible estimates of these hazard curves—this has not been considered in previous NZ NSHMs. The upcoming NSHM revision will include quantification of epistemic uncertainty for the first time in New Zealand, as shown in Figure 1. This is achieved by considering numerous fault source models and numerous ground motion models [3], with more weight placed on those models that are more likely to realistically represent the phenomena.

The result is a range of scientifically credible estimates, and multiple potential hazard curves. The figures below have been produced by the NSHM team as an explanatory example. They apply to an individual site and show an example of the range in hazard estimates that can be produced by using different models and different assumptions.

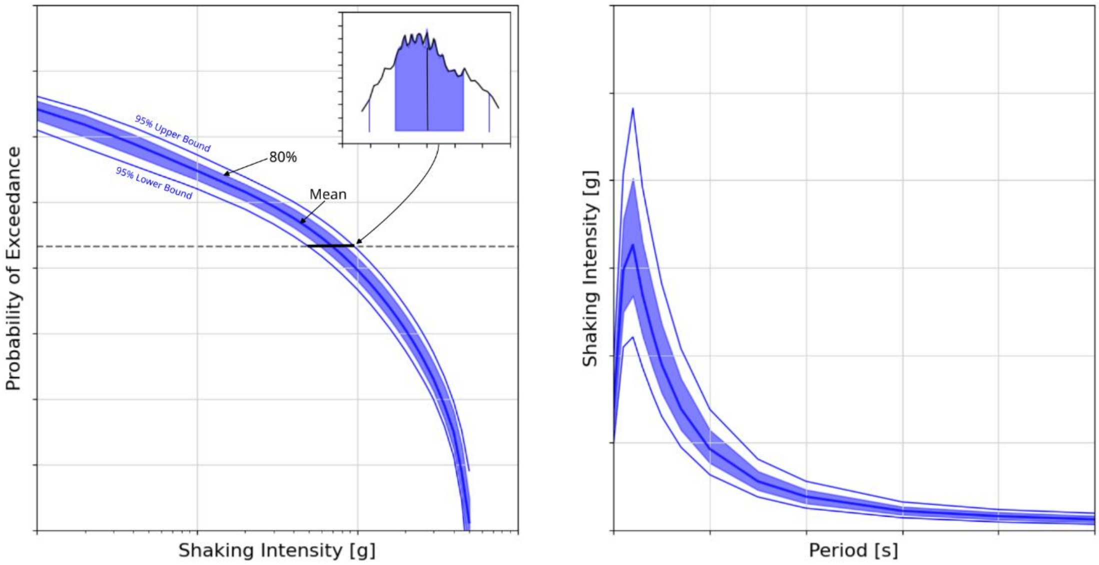

Figure 1: Sample hazard curve with log scale to horizontal axis (left) and uniform hazard spectrum (right) at an example site, with uncertainty bands illustrating epistemic uncertainty. The inset is a cross section of the hazard curve at the probability of exceedance indicated by the dashed line. It is a probability density function indicating the uncertainty in the mean (and the bands within which the true mean most likely falls). Supplied by GNS on behalf of NSHM team.

In practical terms, the science of seismic hazard analysis can helpfully provide us with a range of plausible shaking intensities along with an indication of likelihood. But we will never know the earthquake that a given design will ultimately need to face. Over time, learning and research continue to find ways to select and constrain models to better fit the underlying phenomena. Learning can also lead to a better understanding of what we *don't* know. *The way we design buildings should recognise this learning process and the uncertainty that we live with*.

Clear design processes and stipulated design loadings can obscure the uncertainty that underlies seismic design. It is important to remember that whilst the potential for changes in the "design earthquake" represents an uncertain time for practicing engineers, it simply highlights the uncertainty that naturally exists in seismic design and risk assessment—which requires an appropriate design response.

UPDATING OUR BUILDING CODE COMPLIANCE DOCUMENTS: PROCESS AND ANTICIPATED TIMEFRAMES

In collaboration with Engineering New Zealand, MBIE has initiated the Seismic Risk Work Programme. This programme will provide an assessment of earthquake risk settings and propose appropriate changes to compliance documents for Building Code Clause B1: Structure [4], i.e. Verification Method B1/VM1. The Seismic Risk Working Group (SRWG) report of November 2020 [5] made a number of recommendations on these topics.

It is expected that that Building Code compliance document updates will be made in two stages: a first stage expected for the 2023 Building Code update, with a more substantial update expected for the 2025 cycle. Drafts of each would be released for public consultation in mid-2023 and mid-2025, and transition periods would apply following the established process for Building Code updates. These updates would modify or replace the New Zealand Standard for earthquake actions [1], NZS 1170.5:2004. This programme and associated timeframes are subject to change.

A major project to update New Zealand's National Seismic Hazard Model (NSHM) is nearing completion, and this will provide important inputs to the Seismic Risk Work Programme. The NSHM is expected to be released by late September 2022. This is a major collaborative project led by GNS, that consolidates and supplements available research, builds consensus, and delivers a holistic picture of the current state of knowledge. The NSHM predicts the likelihood of different ground shaking intensities (seismic hazard) across the country. The new NSHM will also provide an assessment of epistemic uncertainty in the hazard.

The NSHM only provides an assessment of the hazard. It does not consider the likely performance of a building and hence cannot fully capture the risk to the building and its occupants. An assessment of risk settings and design practices in the context of this new information is needed prior to being able to identify the appropriate design intensities for buildings. This is the function of the Seismic Risk Work Programme.

The current minimum code requirements are expressed in B1/VM1 and remain the minima for design until changed. The Geotechnical Practice Modules [6,7] can be applied as Section 175 Guidance to demonstrate compliance for geotechnical aspects. This guidance document recommends approaches an engineer can take to help ensure reliable performance from a building—regardless of the minimum design actions adopted.

Engineering Recommendations for Structural and Geotechnical Design

This section provides guiding principles for designers to consider, including some more specific and detailed recommendations which can be implemented to better manage seismic hazard uncertainty.

Designers are referred to the following documents for more comprehensive design guidance.

- Earthquake Geotechnical Engineering Practice Modules [7]
- SESOC Interim Design Guidance [8]

The Geotechnical Practice Modules are classified as *Section 175 Guidance* under the Building Act and can be used to demonstrate compliance with the Building Code. The SESOC Interim Design Guidance document includes clarifications on current Verification Method requirements as well as specific recommendations for improved practice. An update to the SESOC Interim Design Guidance document is in preparation during 2022. Designers should find its recommendations are complimentary to achieving the principles outlined in this advisory.

1 Peer review

Design errors and poor judgement are a common cause of unsatisfactory building performance during earthquakes. Consequently, comprehensive peer review should be considered as another tool for reducing risk—and is strongly recommended. When appropriately scoped, independent peer review reduces the risk of design errors impacting performance. It can also allow for constructive challenge on the judgement required in applying good design principles (such as those contained in this guidance). This can be achieved through reference in peer review briefing to Engineering New Zealand’s *Practice Note 2: Peer Review*, and specifically by *Regulatory Peer* review against the applicable compliance documents, and by *Specific Peer Review* against the principles set out in this advisory.

2 Structural regularity and redundancy

Past earthquakes have shown that structures with significant irregularities are prone to unanticipated behaviour and disproportionately poor performance. Attempts to mitigate irregularity through design have variable effectiveness. Although it is acknowledged that some project and design outcomes drive a level of compromise, irregular structural forms are strongly discouraged and are less likely to achieve the principles in this guidance.

This need not excessively restrict architectural expression and flair. However, it is imperative that engineers scheme the building so that it has a regular primary structure. For example, where a building has an unusual floor plan, this may require that some columns are detailed so that they do not contribute significantly to resistance of lateral loads. Instead, inertia forces from outlying floor areas can be transmitted to other locations by robust diaphragms.

It is recommended that the combined primary structural gravity and lateral systems are proportioned with enough regularity that it is possible to identify a clear plastic mechanism for the structure as a whole (and so that it is possible to capacity design such a system). The configuration should also avoid the application of provisions in NZS 1170.5:2004 Amendment 1 [9] related to unbalanced strength and ratcheting, and inelastic unrestrained torsion. The structural form should not be dependent on the performance of only a few elements.

NZS 1170.5, ASCE 7 and their respective commentaries provide helpful definitions of irregularities. For more reliable performance, designers should seek to review and minimise these, rather than simply assessing regularity against the limited normative provisions of NZS 1170.5.

3 Ductile behaviour and capacity protected hierarchy

Should a structure’s strength be exceeded, ensure that it is able to absorb energy by deforming with an identifiable and reliable plastic mechanism which distributes plasticity proportionately. Inelastic deformation should be limited to clearly identified and appropriately detailed regions. Do this by applying capacity design and avoiding use of upper limit actions from nominally ductile or elastic analysis that are otherwise permitted in some material standards. These limits can undermine ductile hierarchy, are sensitive to hazard uncertainty and design load fluctuation, and so could lead to unexpected outcomes.

This includes the application of axial load limits appropriate for the various detailing categories as required by the material standards. This is important to ensure stable plastic behaviour. These limits should be applied to the capacity derived axial actions, and the limits should not be waived by use of elastic force checks (which artificially limit forces).

Ductility Demand

Selecting an assumed design ductility that is less than the maximum permitted by material standards while simultaneously adopting detailing suitable for higher ductility demands provides design redundancy which is desirable.

To maintain dependable behaviour, it is essential that adoption of lower design ductility assumptions do not come at the expense of capacity design hierarchy and ductile detailing—hence the recommendation to apply complete capacity design processes.

4 Deformation compatibility and tying

As required by the verification methods, designers should recognise and accommodate the deformations arising from the response of a building to earthquake shaking. This needs to include deformations that are explicit outputs of typical analysis, such as lateral drift. It must also include second order effects, such as geometric rotations and elastic or plastic elongations, which are not considered in typical analysis. Detailing should be provided for primary structural, secondary structural, and non-structural elements which is demonstrably compatible with such deformations. This requirement has not been consistently applied in engineering practice, as evidenced by failures in recent earthquakes.

For primary structure (floors and structure providing vertical and lateral support to floors), heavy secondary structures and heavy facades, it is recommended that designers avoid seating or support details which rely on deformations remaining within tolerable limits of fragile details or those with a hard stop. Irrespective of the application of “stronger shaking” factors or adjustments (for example “maximum considered earthquake” factors), it is better to apply configurations which avoid this.

For example, double structure may be provided instead of ledges. Alternatively, ledge and clearance details should be configured so that they can clearly accommodate significantly more displacement than could ever reasonably be experienced.

Anti-seismic devices such as isolators, dampers, friction devices or BRBs with a limited range before a significant change in behaviour occurs should have their range sized conservatively. Limited range in novel/anti-seismic devices can present significant safety and collapse risks. Engineers should treat supplier literature and design guidance for such devices cautiously.

Capacity should be provided to tie all elements together under the plausible structural and foundation deformations, for compatibility between elements, for restraint of axial load, and under the deformations of the non-structural components.

5 Robustness, continuity, and proportionality of load paths

Buildings require detailing to withstand demands greater than the Ultimate Limit State actions, and higher than expected movements from foundation compliance.

Capacity design processes ensure that desirable global post-yield behaviours occur and provide important axial load limitation and protection to critical vertical load resisting elements. This is preferable. However, if this is impractical for the building configuration or scale, *robustness*, *redundancy*, and *deformation compatibility* principles become critically important to desensitise response—and must be applied to primary load paths providing gravity support and lateral stability.

Robustness is also necessary in all designs to validate simplifying assumptions often applied in a design office context—where many complex strains, rotations and deformations at structural intersections are not directly accounted for. This requires elements to be detailed and proportioned to supress brittle failure and allow for higher forces or strains.

Strategies to effectively deliver robustness can vary by material and construction type. Some general explanatory examples include:

- Careful attention to full stress development and reinforcing anchorage in reinforced concrete intersections (for example floor slab to wall/beam intersections, and wall intersections), sometimes requiring supplementary confinement.
- Appropriate confinement levels to general reinforced concrete elements.
- Connections that develop the capacity of lateral bracing system members through complete connection load paths (applicable to structural steel).
- Connections that provide inelastic reserve deformation capacity which is significant in the context of overall building deformations (for connections in structural timber, and some types of structural steel connections).

More comprehensive guidance and commentary on good practice detailing is found in SESOC Interim Design Guidelines [8] which is expected to be updated later in 2022.

6 Limiting drift and displacement sensitivity

Limiting Ultimate Limit State design inter-storey drift below the code prescribed limits of 2.5% can allow some design redundancy—and this in conjunction with ductility capacity (from capacity design) is one of the most effective ways to desensitise designs against design load uncertainty or fluctuation. There are also benefits in reducing the likelihood of drift-induced damage to primary and secondary structural elements. Reduced drift should therefore be considered as part of an appropriate design response to the hazard uncertainty.

Limiting drift may be less practical for some structure types, but designers should recognise that high drifts in combination with low natural stability (P-Delta) are particularly risky. These structures can be disproportionately affected by shaking that is more intense than anticipated – with much higher risk overall of drift related damage and strength loss to both primary and secondary structures.

To reduce this sensitivity, it is recommended that designers consider either:

- Limit the stability coefficient as defined by NZS 1170.5:2004 Amendment 1 to 0.2 instead of 0.3 (based on the seismic actions currently defined by NZS 1170.5:2004), OR
- Design buildings with sufficient dependable post-yield stiffness to offset P-Delta effects or take specific and quantified measures to improve a buildings' recentring characteristics.

7 Soil structure interactions and reducing vulnerability to changes in soil behaviour

Earthquake shaking can result in deformation and/or degradation of strength and stiffness of ground including:

- Slope instability
- Degradation of shaft capacity of piles, micropiles and anchors
- Liquefaction and associated consequences including lateral spread.

Designers should consider these effects through the full range of earthquake shaking intensity, including beyond Ultimate Limit State (ULS) design shaking. This will require effective collaboration between geotechnical and structural engineers, and at critical decision points, with the client and architect. This collaborative work is particularly important at the concept design stage when the form of the building, structure and foundations are selected.

The design objectives include a low probability of collapse with ULS shaking, and collapse is not expected with intensities greater than ULS shaking (beyond ULS). It is not the intent to meet ULS design requirements beyond ULS intensity of shaking, but rather to check the soil, foundation and structure system for potential instability or collapse mechanisms beyond ULS shaking. If collapse potential is identified, then the design should be modified to mitigate this. If undesirable ground behaviour could develop beyond ULS shaking, it may only be a critical concern where it could also lead to dramatic changes in structural behaviour—with critical consequences such as loss of support or gross instability.

Module 4 of the Geotechnical Practice Modules [10] provides guidance which can be followed for Ultimate Limit State design. Module 4 also proposes that robustness and stability of the structure be provided at levels of shaking beyond ULS. Here further general guidance is provided for beyond ULS.

Where susceptibility for ground deformation and/or degradation of strength and stiffness (including liquefaction) is identified, a design should be developed that *avoids* or *mitigates* these effects—rather than relying on triggering analysis and accepting the risk of these effects occurring beyond the trigger without review. Avoidance or mitigation could include the following:

- Select an alternative site or location within the site.
- Apply ground improvement to mitigate liquefaction, lateral spread, or slope instability.
- Select a form of foundation which can protect the structure from these effects, for example deep foundations to competent and reliable bearing strata, or raft foundation.
- Develop the structural design to tolerate the adverse effects of liquefaction, lateral spread, or slope instability. For example, apply robust tying of the substructure, and select a structural form which can tolerate possible reduced support under foundations, and/or tolerate *significant* deformations—without presenting a risk of loss of vertical support or gross lateral instability.

In low seismic hazard zones where the likelihood of liquefaction triggering beyond ULS has been assessed to be very low and the cost of avoidance or mitigation is prohibitive, consideration could be given by the project team and client, to accept the liquefaction risk.

8 Use of site-specific hazard studies (incorporating interim hazard information)

Practitioners and clients may choose to have a site-specific hazard investigation carried out to inform areas of their design. However, they should recognize that even modern hazard studies are based on data and models which are the subject of ongoing research and there is always potential for material fluctuation in outputs.

Even peer reviewed hazard assessments by reputable consultants are likely to have variances to what will be presented as the basis for design after the current revision of the NSHM. No PSHA can allow for the extent that hazard model change is incorporated into future Building Code updates, nor the extent to which building *design* and *detailing* requirements may feature in these updates.

Seismic risk is a function of both hazard *and* structural response. Therefore, it is recommended that client recommendations prepared by practitioners on interim design measures include, and prioritise, the important design-related principles outlined in this guidance (whether or not a decision is made to consider interim PSHA outputs to elevate design loads).

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