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OPINION PAPER

A DIFFERENT WAY OF THINKING ABOUT SEISMIC RISK: A CALL FOR DEBATE

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ABSTRACT

Seismic risk has traditionally been approached using probabilistic analysis. This dilutes the potential impact of low probability, extreme events that may lead to severe consequences including excessive land damage, building damage, injuries and death. The communication of risk in probabilistic terms is also not clearly understood by most audiences. Further, it is evident that few building developers, owners and users have a good understanding the implications of this and the capacity design of buildings, which may not be repairable after a severe event.

There is also an adverse impact on planning and land use, where decisions that may affect many people are based on a limited view of adverse outcomes such as liquefaction, lateral spread and slope stability in severe earthquakes.

A different way of thinking about seismic risk is proposed. An approach of using scenarios derived from a combination of deterministic as well as probabilistic thinking would prompt consideration of impacts over a range of events. This would allow full consideration of which outcomes are clearly not acceptable and which are. This may facilitate planning for both private and public sector, with a common understanding that is relatively easily communicated to both experts and lay people.

This risk evaluation framework would also facilitate consideration of mitigation, by bringing focus on unacceptable outcomes of severe events that are currently obscured by pure probabilistic analysis. This was missing in Christchurch, which experienced the sort of event we can readily anticipate and should actively plan for in other parts of New Zealand.

This would help us avoid future red zones and excessive damage and demolition. It will inform development of building codes and standards and will help us evaluate risk and provide resilience and redundancy across the range of interconnected infrastructure networks.

Informed debate is needed with key decision makers to discuss the underlying objectives of our regulation and how these may be better met by such an approach, without engineers allowing themselves to be trapped in past thinking and assumptions.

INTRODUCTION

Engineers in New Zealand have designed and analysed buildings for decades using seismic actions generated from probabilistic seismic hazard analysis (PSHA). This paper questions whether the approach currently used is delivering the outcomes that society is now expecting; and proposes a different way of approaching this challenge. It is presented in the expectation of starting debate—a debate which engineers should be leading, based on observation and lessons learned over the last 9 years of post-earthquake experience.

Background

For most buildings, seismic actions which equate to the shaking level that has a return period of 500 years are used for ULS design. Statistically, this has a likelihood of exceedance of 10% in a 50 year period. It may be coincidental, but 50 years is commonly referenced as the nominal design life of a new building.

This is ostensibly a pragmatic way of achieving the required performance objectives of the Building Regulations [1], noting that use of PSHA and the 500 year shaking probably preceded the performance objectives. The relevant legal performance objectives are outlined in clause B1 as follows:

> *B1.1 The objective of this provision is to:*
>
> *(a) safeguard people from injury caused by structural failure,*
>
> *(b) safeguard people from loss of amenity caused by structural behaviour, and*
>
> *(c) protect other property from physical damage caused by structural failure.*

The performance objectives are not numerically based but the Structural Design Actions Standard [3,4] is a deemed to comply approach to achieve the objectives. If followed, together with the relevant material design Standards, it is expected that a compliant outcome will usually be achieved.

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There are some anomalies in this approach that are not necessarily contradictory, but which may appear counter-intuitive, particularly for non-engineers:

1. In some areas, the 500 year return period design shaking may be less intense than shaking generated on 'controlling faults' that may have a similar recurrence interval. This comes about due to the diluting effect of other sources of shaking, notwithstanding that we use magnitude weighting to partially mitigate this effect.
2. It implies that earthquakes are random events that occur with predictable distributions (regarding both return period and intensity of shaking). In fact, the probability of rupture for an existing fault is essentially 100%. The unknowns are when the rupture may occur and how intense the resulting shaking will be. The latter can be influenced heavily by the potential for consequential rupture of adjacent faults, triggered by the first rupture. The Kaikōura earthquake was a significant recent example of this.
3. The 50 year design life artificially limits the consideration of earthquake although its main purpose is really to set some parameters for durability considerations. However, many buildings are considerably older than 50 years and obviously, the longer a building lasts, the more likely it is to experience a significant earthquake. As far as the author is aware, no-one has yet put a design lifespan to a city.
4. As observed following the Canterbury earthquakes, the period following a major earthquake may experience increased seismicity levels. This resulted in a significant increase in the seismic hazard factor for Christchurch and parts of Canterbury (from Z=0.22 to Z=0.3), meaning that a building that had been code compliant prior to the earthquake could have been at 70% capacity after, regardless of its actual performance. If we expect buildings to be good for more than one significant earthquake or earthquake series, our consideration of seismicity should logically include consideration of the ongoing seismicity after the earthquake.
5. Engineers assess life safety of existing buildings against a relatively arbitrary legal measure of 33%NBS. However, the potential for collapse of some types of non-earthquake prone buildings in a severe earthquake potentially represents a greater risk of loss of life. Note that the building responsible for the most lives lost in Christchurch (CTV) was not considered earthquake prone. That outcome has been widely deemed unacceptable, although that may have been at least in part because it was the most extreme outlier in the otherwise generally satisfactory performance of modern buildings (from a life safety perspective).

THE PUBLIC VIEW OF RISK

A question that follows is whether the risks are fully understood by building owners and the public, especially those responsible for determining policy.

Communication of seismic risk has been an emergent issue over the period since the Canterbury and Kaikōura earthquakes, fuelled by public concern and the media. The Canterbury earthquakes highlighted that severe earthquakes may occur anywhere in the country, although some may still consider the north and the southeast of the country are 'non-seismic' or at least as having such low seismicity that it can be ignored. The message that a significant earthquake may occur in areas not hitherto understood to have such a risk may have been lost, but overall public consciousness has been raised, particularly in the immediately impacted areas, from direct experience. This may reduce as memories recede, but it is notable that the popular media report much more seismic activity than prior to the events.

Over many years (commencing at the time of the Napier Earthquake of 1931), there has been an element of qualitative risk evaluation in the field of building safety, generally focused on unreinforced masonry buildings (URMs), which are widely understood to present a significant hazard. In some cases, this may have been overstated, noting that many URMs survived the Canterbury earthquakes well, even though subsequent seismic ratings condemned them.

There has more recently been significant focus on quantitative risk management, reflected in assessment of the ultimate (seismic) capacity, expressed as a percentage of the new building standard (%NBS). Society craves numerical analysis. It is easy to compare two numbers, notwithstanding such comparisons are often spurious due to the lack of other context and the missing knowledge that the true comparison is with an equivalent new building.

%NBS has now slipped into the vernacular and is regularly used by non-engineers, particularly with reference to commercial real estate (both leasing and sales). Naturally, a higher value is seen as 'better' than a lower value. However, the understanding of underlying building performance is minimal, perhaps not helped by lack of transparency in engineers' reviews.

There is possibly little in the general public awareness to distinguish between 'the big one' and a moderate local earthquake that may nevertheless result in severe localised shaking and damage. This is exacerbated by a general lack of understanding of the difference between magnitude and intensity, the former measured at source and the latter at the site of interest. It is notable since the Canterbury earthquakes that the media seem much more likely to report earthquakes of M_w 6 or less than before, possibly in response to public awareness that this magnitude of earthquake may cause significant damage. But it is rare to see discussion of intensity.

Acceptance of Risk

There is much discussion if not dissension as to what an acceptable seismic capacity (and hence risk) is. The legislation; i.e. the Building Act, 2004 [4], sets the Moderate Earthquake as the life safety threshold. The regulations define a Moderate Earthquake is one which generates a level of shaking "that is the same duration as, but one third as strong as the earthquake shaking" that would be used to design an equivalent new building at the site, equating to 33%NBS. If a building has capacity of 33%NBS or lower, it is considered earthquake prone.

Some misconstrue this as a statement that the building is dangerous and should be abandoned, but it is simply the level of capacity which is legally required to be upgraded to achieve a more acceptable level of safety over a reasonable timeframe. This effectively represents society's lower threshold for risk, but it is notable that even government departments (where the 33%NBS threshold emanated from) generally are insisting on much higher seismic ratings for new tenancies, with most 'sophisticated' users in larger centres targeting 67-80%NBS or more.

Even the intuitively simple concept of 100%NBS is confusing. Firstly, it is not consistent across all buildings, as it varies with building use (as reflected in the Return Period factor, R; in turn a function of the building Importance Level, IL). Secondly, although 100%NBS represents the absolute minimum standard of a new building that 'just' complies with the NZBC, most new buildings should have significantly greater capacity. Further, as noted above, that the shaking from the controlling fault may not be adequately reflected by the design spectra for a site. May engineers have cringed as their clients refer to a new 'earthquake proof' building that just complies with the Building Code [5].

From all of this we could conclude that there is no popular view of what is acceptable, in part because the behaviour of buildings in 'real' events is not well communicated. Although the ultimate (seismic) capacity is intended to describe the performance over a range of earthquake shaking, the single score masks that for most people.

Understanding the Seismic Rating System

It is debateable whether there is widespread awareness of the limitations of the seismic rating system of the NZSEE Guidelines [6], the most significant of which may be that it does not provide a measure of the potential for repair and reuse after the damaging earthquake. This is not a new issue—the implications of ductility and capacity design have been well understood by engineers and barely understood or acknowledged by developers, building owners and users since their implementation in the 70's. Engineers are far from innocent in this, having failed to adequately communicate the significant structural damage that would result from a large earthquake and the potential lack of repairability.

If the implications of this had been better understood, different approaches to design and assessment may have been adopted in the Building Code or at least more frequently requested by some owners.

SO WHAT?

The question may be asked—does it matter that much if the public does not really understand seismic risk very well? In general, probably not. But the lack of understanding of society as a whole, reflected in our high-level Building Code development, emergency planning, insurance planning, resource allocation etc may be to the detriment of our long-term development and wellbeing, particularly if insurance conditions change significantly.

In general, it can be shown that the benefit/cost ratio of seismic protection is low; the argument could be made statistically that we need not bother with any specific seismic design provisions. However, this neglects an important point about earthquakes—that they are not truly random and any known fault will eventually produce an earthquake. Hence the better question may be to ask 'what when?', not 'what if?

WHAT WHEN?

The problem with the approach of designing or assessing to a 500 year return period level of shaking is that the understanding of the range of events and their outcomes is lost. The benchmark level of safety acceptance set by the Moderate Earthquake is also potentially giving a false sense of security. Under certain scenarios, the overall outcomes for buildings with greater capacity (i.e. buildings with ultimate (seismic) capacity greater than 33%NBS) may be less acceptable for society. It is worthwhile to consider some examples:

Example 1: Wellington

Some brief context:

- Wellington is considered a high seismic zone (Z=0.4). It is over or close to major faults that are capable of large magnitude earthquakes, as well as being affected by the Hikurangi subduction zone. It is potentially vulnerable to long duration severe earthquakes as well as moderate earthquakes from a variety of sources.
- Building types are variable with the CBD having a range of building types from concentrations of URMs in Te Aro; to medium and high-rise reinforced concrete buildings prevalent in the CBD.
- The Kaikoura earthquake sparked the upgrading initiative focused on URMs. The parapets and brick facades were (rightly) perceived as high risk elements in the event of a moderate earthquake, despite not having been significantly damaged in the Kaikoura earthquake. Most if not all of the affected buildings would have capacities less than 33%NBS, that is, would be Earthquake prone and legally required to upgrade over time. The mandated work did not necessarily remove this requirement fully and hence many may still be earthquake prone despite this work, but less hazardous for pedestrians.
- The same event also highlighted significant concerns with the performance of precast floors, but there is still no consensus as to how this should be treated. It is generally agreed that these buildings are unlikely to have capacities less than 33%NBS, although many would not exceed 50%NBS. So accepted by society (under current legislation) as sufficiently safe to use without upgrade, indefinitely.

Now consider earthquake scenarios and speculative outcomes:

Scenario 1: A moderate earthquake closer to Wellington would likely produce different characteristic shaking than the distant fault effects of the Kaikoura earthquake, resulting in greater intensity shaking in the short period range. The resulting response spectra for buildings would vary across soil types and may be expected to be approximately reflective of the standardised spectra and likely in the range of 33-67% of the shaking in the loadings standard. Strong shaking may last only 10-15 seconds, not long enough to excite tall buildings. This would cause significantly greater damage to URMs but is unlikely to affect the taller buildings around the CBD to the extent that the Kaikoura earthquake did. A reasonable set of damage assumptions may be:

- URMs that had not been upgraded would suffer typical damage—a few collapses and much loss of facades, parapets and appendages, probably resulting in injuries with some deaths, generally in the street and within adjacent lower buildings. As illustrated in Christchurch, the concentration would be low as these buildings typically have relatively low population density (noting that the Christchurch occupant density was artificially low due to the September 4th 2010 earthquake).
- There could be full or partial collapse of particularly poor multi-storey buildings, but these would be 'outliers' and most reinforced concrete and steel buildings should suffer only minor to moderate damage, not significantly affecting safety.
- There could be some areas of liquefaction damage in vulnerable areas such as the Petone foreshore.
- From this, we may conclude that the current risk indicator of %NBS is working as it should.

Scenario 2: Now consider the alternative of a severe earthquake on one of the local controlling faults. This may result in a large magnitude (MW 7+) earthquake, with strong motions lasting in excess of a minute, likely to significantly exceed the design level shaking across most building categories. Possible damage outcomes include:

- For URM, as the moderate earthquake, only more so. The long duration is likely to lead to the full or partial collapse of most unstrengthened buildings and significant damage even to strengthened URMs.
- Reinforced concrete buildings will be severely damaged. Many pre-1976 buildings may suffer full or partial collapse in the primary structural systems. Post-76 ductile buildings will suffer significant damage but should not collapse.

- Precast flooring systems will suffer extensive damage. Many floors in ductile moment frame buildings without secondary supports are likely to lose support, with the ensuing likelihood of pancaking collapse of multiple floors.
- The most significant loss of life is likely to be from pancaking floors in multi-storey buildings, where we risk the prospect of seeing complete frames standing in buildings with no floors.
- Liquefaction will be widespread in many low-lying areas, with accompanying lateral spread.
- This throws the current risk measure of %NBS into doubt. From an engineering perspective, it has probably worked, but the public perception is unlikely to be as generous.

In conclusion, the current approach to determining acceptable risk may be accurate in terms of engineering outcome, but the outcomes will likely be deemed unacceptable to the public in general, particularly if there is widespread loss of life from precast flooring in buildings which leave lateral systems still standing.

Example 2: Auckland

Now consider Auckland, a city that seldom figures highly in seismic risk considerations. However, as a city in New Zealand, a country pushed up out of the ocean at the confluence of the Australian and Pacific plates, earthquake remains a possibility, no matter how low. A quick comparison with Japan, for example, shows a similar geography, and yet with a very different national consciousness of seismic hazard. In context:

- Auckland is considered a low seismicity zone (Z=0.13), generally governed by the minimum criteria (noting that Amendment 1 lowered the Northland area to Z=0.1 only in 2016).
- The mix of buildings is similar to Wellington, although there are probably lower concentrations of URMS and a greater distribution of high-rise buildings. There are several interesting points to consider:
  - As URMs predated seismic design considerations, they are essentially the same format of building anywhere across the country. That implies that a URM in Auckland is generally lower risk than in Wellington, for example, because of the lower assessed seismic hazard with similar inherent lateral load capacity.
  - Conversely, modern buildings have been designed to lower earthquake loads since the first introduction of a graduated seismic design loading distribution in 1992 [7,8]. This was a refinement of the uniform hazard philosophy adopted in New Zealand and elsewhere.

There is little information regarding significant earthquakes in the Auckland region, although there is at least one report of a possible ML 6.5 earthquake 20km north of Pukekohe in 1835 and a Mw 6.2 centred at Port Waikato on June 24th 1891 [9]. The GNS Active fault map [10] is limited to the Wairoa North Fault in the Hunua ranges, although there have been other studies published of lesser known faults. However, as the Christchurch experience shows, lack of specific knowledge of faults does not equate to a lack of faults.

As a scenario, consider the 1835 earthquake, which by its description, could equate well to a moderate but significant earthquake for Auckland city. The location is shown below in Figure 1. This earthquake could be of a similar scale to the Lyttelton earthquake and the earthquake that is used for scenario 1 in Wellington. Note that the scenario producing a Moderate Earthquake (as defined in the Regulations) for Wellington, may be a severe earthquake in Auckland, due to the relativity of the design actions used to assess it (Auckland design shaking is approximately 33% of Wellington, 60% of Christchurch prior to 2011).

Given the relatively similar magnitude, the area within the 20km radius (defining the Z=0.13 minimum earthquake actions), could experience similar levels of shaking to that felt in Christchurch during the Lyttelton Earthquake. This area is intensively developed, including the Manukau city centre, the Mangere airport, 80% of Auckland's water storage, most of its wastewater treatment capacity and significant concentrations of population. Note that if the epicentre was 10km to the northeast, the whole Auckland CBD would be included within the 20 km radius.

Figure 1: A 20km radius from the centre of the 1835 M_L 6.5 earthquake (from Google Earth).

Outcomes may include:

- The Moderate Earthquake (i.e. 33% of the code earthquake shaking) could likely be exceeded by a considerable margin. This earthquake scenario would likely produce similar shaking effects to the first Wellington scenario, but by definition, that would be approximately 3 times the relative shaking (compared to the shaking levels from the current loadings standard [2]) for Auckland. Therefore, it could be close to 100% of the current code shaking for some sites.
- Again, the resulting response spectra for buildings may be expected to be approximately reflective of the standardised spectra but likely in the range of 33-67% of the current code shaking outside the 20 km radius from the epicentre and significantly higher within. Strong shaking may last only 10-15 seconds, not long enough to excite tall buildings, but enough to cause significant damage for low-to-medium rise buildings.
- Similar shaking scenarios to Christchurch may eventuate, but as modern buildings in Auckland have typically been designed to 60% of the design load of those in Christchurch, greater levels of damage may be expected, including therefore the partial or full collapse of a small number of modern buildings. Damage outcomes may include:
  - URMs that had not been upgraded would suffer typical damage—a few collapses and much loss of facades, parapets and appendages, probably resulting in injuries with some deaths, generally in the street and adjacent lower buildings. As illustrated in Christchurch, the concentration would be low as these buildings typically have relatively low population density (noting that the Christchurch occupant density was artificially low due to the September 4th 2010 earthquake). The damage levels would be on a par with similar buildings in Wellington or Christchurch.
  - URMs that had been upgraded may suffer less damage, but because the upgrading target loads would be 33% of that used in Wellington, it is likely there would be more damage than scenario 1 for Wellington. There is a parallel for this in the observed damage from Christchurch, where it was evident that those URMs secured to the legal minimum, with widely spaced ties, had their connections overwhelmed at relatively low levels of load and suffered similar damage to unsecured buildings.
  - There could be full or partial collapse of particularly poor multi-storey buildings, but these would be ‘outliers’ and most reinforced concrete and steel buildings should suffer only minor to moderate damage, not significantly affecting safety.
  - There could be some areas of liquefaction damage in vulnerable areas, which could include estuarine deposits and reclamation around the foreshore. This could include parts of Auckland International Airport and low-lying waterfront development from St Marys Bay to Judges Bay [11].
  - From this, we might conclude that although the relativity of the %NBS risk indicator holds, the notion of a moderate earthquake is 33%NBS is out of proportion with the damage implications of the type of earthquake that could happen near to Auckland.

A second scenario has not been considered in detail but the distance from Auckland to the major fault lines that run generally from Fiordland to Whakatane and beyond is such that the intensity of shaking from such a large magnitude event may not be as great as from a smaller local event. However, the duration of shaking may be significantly longer. For buildings founded on rock, this is unlikely to be significant, but for those that are on softer ground (category D and E subsoils), local amplification of the shaking may have a significant impact on longer period multi-storey buildings. Due to the relatively low design earthquake shaking assumed by NZS1170.5 [2] in Auckland, the ensuing damage for such buildings may be greater than elsewhere in the country, with the potential for partial collapse and poor performance of precast floors similar to that in Wellington in a few cases.

In conclusion, the current approach to determining acceptable risk in the Auckland region may be quite misleading, if considering the type of event that may actually happen and may have happened in the relatively recent past.

A BRIEF COMPARISON WITH JAPAN

It is interesting to contrast the outcomes of the 2010-11 Christchurch earthquakes with the 2016 Kumamoto earthquakes. The NZSEE structural [12] and geotechnical [13] reconnaissance teams concluded that although the shaking resulting from the Kumamoto earthquakes was similar to Christchurch, the damage outcomes for modern buildings were typically better in Japan and the disruption to the city was considerably less. There are many contributing factors, but some notable points are:

- The Kumamoto region appears to have experienced considerably less liquefaction and related effects.
- The design earthquake load is considerably higher relative to assessed seismicity. There is considerably less variation from highest to lowest seismic design regions in Japan. Note that Kumamoto is in an area of moderate seismicity (zone B, Z=0.9) in Japan and therefore may be equated to Christchurch. In areas of higher seismicity, Z=1.0.
- The reduction in design loading to allow for ductility is less. In Japan the maximum design ductility is 3.3, compared to 6 for New Zealand.

The base seismicity is higher in any case. These effects are illustrated in Figure 2 below from Sarrafzadeh et al [12], which suggests that the design loading for a ten storey building in Kumamoto would have been approximately 40% higher than the current equivalent in Christchurch. However, even the lowest seismic zone in Japan, the same building would be designed for approximately three times the equivalent building in Auckland.

AN ALTERNATIVE APPROACH - EARTHQUAKE SCENARIOS

As an alternative to PSHA, it is proposed that earthquake scenarios (using a combination of deterministic and probabilistic analysis) may be a better way to consider risk, both qualitatively and quantitatively. A ‘scenario approach’ would require that we consider the shaking generated at a site by a range of different types of event that may be experienced there, in order to tailor our designs and assessments to the requirements of the user. There are many benefits to such an approach [14], which would be considered an alternative solution under the current regulations.

Perhaps the most significant overall benefit (and the basis for this paper) would be the increased understanding of both designers and users of buildings, of the possible range of events that a structure may be subjected to and their outcomes. The probability of events occurring is not irrelevant but using it as a primary input may discount the impact of events with outcomes that may be considered unacceptable.

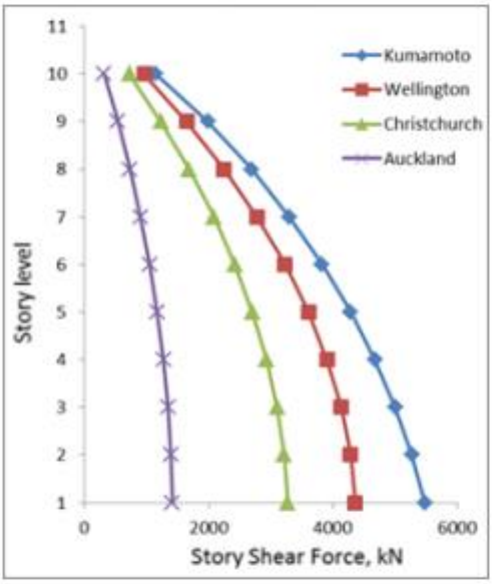

Figure 2: Story Shear Force for Kumamoto (Safety Check, Soil Type 3, Ds=0.3) vs NZS1170 ULS (IL2, Ductility 4, Soil Type E) [12].

It is of course possible to use this approach now, to allow developers, owners and users to determine alternative design objectives. This is a key input to facilitate Low-Damage Design (LDD), done properly. However, as an alternative solution, it may require significant peer review on a case-by-case basis, adding significant compliance cost even while potentially providing 'better' solutions. Consequently it could not be considered a 'mainstream' approach.

If an individual developer/owner determines now that they wish to have a better-performing building, they are free to do so, provided that they can demonstrate code minimum performance or better in their Building Consent application. Many people consider the Building Code as a 'gold standard' but in fact, it should be seen as the minimum acceptable standard. However, this confusion contributes to a reluctance to spend more money on safety as opposed to more obvious benefits for future tenants.

There is a tension between the right of an individual owner to design and construct buildings as they choose, and the need for a public policy on what constitutes the minimum standard. This was apparent in the outcomes from the both the Christchurch earthquake and the Kaikōura earthquake. There has been widespread disappointment expressed at how many modern buildings were demolished or required extensive repair, both in the profession and beyond.

The outcomes from the Christchurch earthquake were probably skewed by the availability of insurance cover, resulting in greater levels of demolition (as opposed to repair) than might have happened had there been less insurance cover available or less favourable conditions. This meant that individual building owners were relatively insulated against the loss of the building and in some cases may have been advantaged. Perversely, this means that owners that had spent more on building to a higher standard or strengthening may have been economically disadvantaged compared to those that did the least and collected the insurance settlements. However, if viewed from a societal perspective, the disruptive effects of the lengthy shut-down of the CBD and the even longer process of demolition and replacement may outweigh the benefits of the insurance settlements, which in the commercial environment flow only to a narrow cross-section of society. If insurance were taken out of the picture, there may be no winners.

Application to Public Policy

In addition to the design of structures, the scenario approach could be extended also to public policy matters such as emergency planning and lifelines, where it is important that those responsible have an understanding of the bounds of what may happen, not simply an averaged outcome resulting from probabilistic hazard analysis. An example of deterministic analysis in practice is in the analysis and design of dams [15].

A further example of the application of the scenario approach to planning may be land use, specifically in completing appropriate risk assessment and mitigation in considering what needs to be done in order to make land acceptable for development or deciding what land should not be developed. Once again, Christchurch offers great insights into some of the mistakes of the past that should not be repeated.

The liquefaction hazard in parts of Christchurch was known long before the earthquake, even if the severity of the exposure was not fully recognised. However, land was developed for residential construction that with the benefit of hindsight should not have been allowed without greater mitigation measures being adopted.

On a probabilistic basis, it is unlikely that the benefit/cost ratio for this mitigation would exceed 1. That is, it would not be justified by conventional economic analysis. However, few would argue that the Christchurch earthquake sequence resulted in an unacceptable outcome in light of what happened in newer suburbs such as Bexley.

Much of this land is now in the Residential Red Zone, vacant pending a decision on its future. Unlike the commercial buildings that were demolished, there were no winners in this (apart from the original land developers); the owners were displaced from their homes and the public bore the cost of paying out the displaced homeowners. It is possible that the mitigation measures may have made the land uneconomic to develop or at least driven up the cost of homeownership in such areas. This in turn may have led to more development on less vulnerable areas for little or no extra cost. With the current focus on housing and reduced compliance, are we confident that this will not all happen again?

PSHA is still a valuable and necessary tool—for example although we need to consider the extreme scenarios, the expected loss scenarios provided by probabilistic analysis are important for central planning and consideration of insurance requirements.

Risk Communication

For the public at large, the communication of risk in terms of outcomes from scenario events is much more tangible and readily understandable. Some communication of the probability of these scenarios is still required, with the accompanying caveat about the inevitability of rupture on known (and unknown) faults. It will be challenging to achieve balance (promoting understanding, not hysteria), but will support better decision making.

For those charged with greater levels of responsibility (including for example regulators, developers, building owners, lessees), this more tangible view will also better inform decision making.

Seismic Loading and Design Approach

A scenario approach could lead to a vastly simplified set of seismic design procedures.

Rather than a seismic hazard map with series of iso-seismals generated by the National Seismic Hazard Model, we could simplify right back to a two-zone approach, with the delineation determined by where the impacts of the major central fault system dilute to the level of the smaller local faults that may exist throughout the country. This may approximate the transition from Zone A to Zone B as used prior to 1992 [7]. It is of note that the superposition of the zone A/B interface captures most of the short recurrence period active faults in the country as may be seen in Figure 3 below.

The location of the delineation between Zone A and Zone B would need re-evaluation to take into account research findings since the 1980s. The zonation shown in Figure 3 is showed simply as a starting point for consideration. However, it would be unlikely that Zone A would be smaller than that shown here.

Modifiers would then need to be added for local site effects (such as soil type, etc) in a similar fashion to the existing Standard [2]; and importance factors.

The key issue is determining what levels of seismic hazard are to be considered. Under the general approach outlined above, this would need calibration according to the agreed outcomes, with consideration of the critical faults. However, rather than being generated by the probabilistic aggregation of all known faults and fault zones contributing to a site, it would be reflective of the controlling fault for the period range of interest and the acceptable outcomes from such an event. From most buildings, this would be a relatively simple set of inputs, with special study required for a limited number of building types, for example long-period structures (T >5 sec) or those with special purpose, as was done for example for the Clyde hydroelectric dam.

Serious consideration should be given to the design approach used in Japan, which could be simplistically summarised as designing initially for serviceability (at a level proportionally higher than the current R=0.25, probably analogous to SLS2 as we currently think of it) and then detailing for ductility with rudimentary checks against life safety criteria for actions generated by the controlling faults [12]. A similar approach is often employed in the design of IL4 buildings and assists in achieving damage reduction objectives.

Such an approach could shift the emphasis from relatively arbitrary selection of design ductility focused on minimising the seismic design impact, to mitigating potential earthquake impacts on the functionality of buildings, that is, moving towards Low Damage Design. If Low Damage Design is intended to satisfy functional recovery or continuous occupation objectives, it is almost imperative that this approach is followed.

Assessment and Upgrading

It may be helpful to shift the emphasis in assessment from quantitative comparative assessment against equivalent new buildings to a pure assessment of identified vulnerabilities to the effects of specific events. Identification of vulnerabilities and consideration of their implications for performance are clearly intended by the recently issued guidelines [6] but that does not always seem to be clearly understood.

A point of difference in a scenario approach is that the impact of large events is not missed or diluted. The current approach of providing a seismic rating expressed as %NBS does not describe potential outcomes and nor does it force consideration of the types of events that a structure may be most vulnerable to. This consideration appears missing from the current debate about precast flooring.

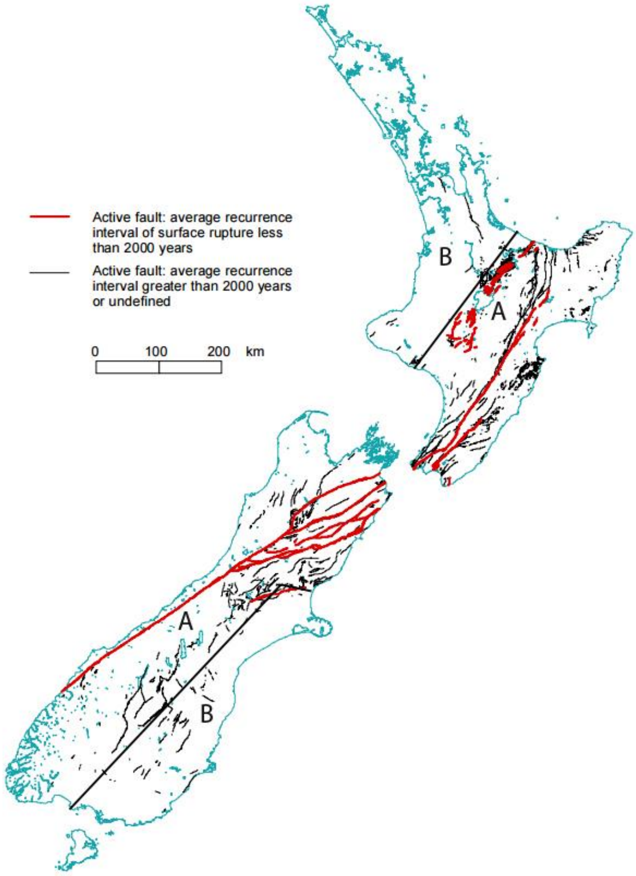

Figure 3: Hypothetical two-zone map overlaid on the NZ fault map (adapted from MFE).

Cost Implications

One of the first points of resistance to change is the perceived negative impact on the existing building stock. In absolute terms, this is a fallacy – the risk associated with existing buildings is not changing, only the lens through which we view it. However, the value of existing buildings will change relative to new buildings, if we choose more generally to design and construct (or improve) to a higher standard in order to mitigate risk from larger events. However, it is not clear whether the resistance owes more to a belief that there are better ways to spend the money or a reluctance of the profession to accept that what has historically been done may not be adequate.

A further concern is the cost of construction, if society were to demand significantly better performance. Intuitively, this will drive up the cost of construction but that is not supported by the evidence:

- For an individual building, the cost will rise with the seismic load as more steel and concrete has to be added to achieve greater levels of resistance in the same structure.
- However, this changes when viewed at a system level, as other factors come into play. For example, (refer to Table 1 below) commercial office construction costs in Auckland are approximately 10% greater than Wellington despite the design seismic load demand being one third as high. Other factors that may have more influence include:
  - Architectural design features (necessary to compete to attract tenants)
  - Construction price inflation (fuelled by higher demand for labour and materials leading to higher unit prices)

- Higher market rents supporting more expenditure on the building
- Higher land value requiring more intense development over which to amortise the land cost

If seismic loads were increased, it is likely that different approaches to design would develop that would bring the cost back to levels that the rental market could support, even at the expense in some cases of architectural design features and configurations that may win awards but are less able to sustain greater seismic demand. In other words, the representative costs that are used for feasibility studies tend to drive the design, rather than the reverse.

Table 1: Representative costs of construction in main centres (supplied by Rhodes and Associates, QS).

Region	Wellington	Queenstown	Christchurch	Auckland
Seismic Hazard Factor (Z)	0.4	0.32	0.3	0.13
Cost/m^2 typical commercial office space	$3,700	$4,000	$3,500	$4000

Conversely, retrofitting buildings to a significantly higher level of resistance most likely would cost significantly more (regardless of location) as designers are generally stuck with the configuration and design of the existing buildings as they are. Recognising this, greater improvements to safety (and potential the cost of repair or replacement) may be better focused on improving behaviour by mitigating vulnerabilities, assessed in the context of the most damaging events, or those that might produce the most unacceptable outcomes.

As noted above, the risk for unimproved existing buildings is not changing, only our appreciation of it and our expectation of outcomes for new buildings. Arguably, this supports changing the relativity of expectation (of the performance of new buildings compared to existing) to something that more closely matches what it should be and would encourage more reinvestment in new buildings that provide greater levels of safety and post-earthquake functionality, another good outcome.

CONCLUSIONS

This paper discusses some of the reasons that probabilistic seismic hazard analysis may provide a misleading view of earthquake risk. In the interests of relative brevity, it provides only a high level review but even at that level, it is possible to see that the outcomes of the combination of PSHA and the seismic design and assessment practices that have been adopted in New Zealand may leave us vulnerable to the more severe earthquakes that may be expected to occur in any region of the country.

It is proposed that a scenario approach to assessing seismic demand is adopted, with the goal of evaluating the outcomes from the most severe events that could be expected for a given site. This should be extended beyond seismic design and construction to planning considerations, especially land use. Better understanding of triggers for large-scale damage from liquefaction or landslide could provide guidance to decision-making to ensure that we do not repeat the mistakes of Christchurch and generate more future Residential Red Zone areas.

Probabilistic Seismic Hazard Analysis must be retained for applications such as insurance loss assessment but its use in mainstream engineering design should be limited.

There may be some small increase in the cost of construction but it will not likely be proportionate to any increase in seismic load and should be accompanied by markedly better performance, as has been illustrated in Japan, at least in the areas of lower seismicity.

All of the changes proposed in this paper should be preceded by an appropriate engagement with the public, including in particular building owners, users and regulators, in informed debate. To approach this properly, engineers must not be burdened with a protective attitude about past established practice.

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