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Ground motion input for NLRHA: practical limitations of NZS 1170.5 and comparison to US standards

G.J. Morris & A.J. Thompson
Holmes Consulting, Christchurch.

J.N. Dismuke
Golder Associates, New Zealand.

B.A. Bradley
University of Canterbury, New Zealand.

ABSTRACT

Nonlinear response history analysis (NLRHA), or so-called "nonlinear time history analysis", is adopted by practicing structural engineers who implement performance-based seismic design and/or assessment procedures. One important aspect in obtaining reliable output from the NLRHA procedure is the input ground motion records. The underlying intention of ground motion selection and amplitude-scaling procedures is to ensure the input for NLRHA is representative of the ground shaking hazard level, for a given site and structure.

This paper provides a summary of the salient limitations of the ground motion selection and scaling requirements in Sections 5.5 and 6.4 of the New Zealand (NZ) loading standard NZS 1170.5 (2004). Also discussed within, there are implications for more modern guidance documents in NZ, such as the draft and the 2017 "Assessment Guidelines" for existing buildings, which cite NZS 1170.5. To emphasize the above issues with NZS 1170.5, this paper presents a summary of contemporary approaches in the US standards ASCE 7-16 (new buildings) and ASCE 41-17 (existing buildings).

This paper presents a truncated version of an article submitted for publication in the New Zealand Society for Earthquake Engineering Bulletin. The reader is encouraged to refer to the journal paper for more detailed discussion, including other subjects (not discussed within, for brevity).

1 INTRODUCTION

Nonlinear response history analysis (NLRHA), or so-called "nonlinear time history analysis", is an increasingly common analysis approach used by consulting engineers for performance-based seismic assessment and design. It is the most sophisticated analysis method available. Actual ground accelerations are applied to the base of a computation model which explicitly model the non-linear force and deformation response of structural components. The resulting damage and time-varying properties of the non-linear components are continually updated within this process.

The greater level of sophistication associated with NLRHA requires considerable technical knowledge of structural behaviour and earthquake engineering, processes within the analysis software itself, as well as skills to critically review resulting behaviour and output. This is required to define the proper inputs for NLRHA—and confidence in the quality of resulting design decisions or advice relies on this.

One critical input "ingredient", and the focus of this paper, is the ground motion (i.e. acceleration time series) selection, scaling and application procedure. Ideally, when paired with appropriate and compatible methods of response measurement (usually considered as part of the procedure), procedures should provide a sufficiently accurate representation of seismic demands at the selected hazard level—neither overly conservative nor unconservative—and which are specific to the site and structure which is being evaluated.

Acknowledging their exclusion from the NZ Building code verification method B1/VM1, specific requirements for ground motion selection and scaling are given in Sections 5.5 and 6.4 of the New Zealand Standard (NZS) for seismic loading, NZS 1170.5 (2004). From a regulatory perspective therefore, these provisions have been generally straightforward to apply as part of an alternative solution using NLRHA. However, it is now over 16 years since these clauses were drafted. The purpose of this paper is to highlight some frequently encountered issues and limitations of NZS 1170.5, given more recent developments in the literature, and in application in a practitioner environment.

US standards ASCE 7-16 "Minimum design loads for new buildings", and ASCE 41-17 "Seismic Evaluation and Retrofit of Existing buildings (ASCE, 2017) have adopted more contemporary methods than NZS 1170.5, which makes them attractive to practitioners as alternative solutions (for reasons which will be discussed within). Although similar requirements exist in other international standards (such as Eurocode 8), a global review is beyond the scope of this paper.

This paper is written for consulting engineers in NZ for both new design work and assessment of existing buildings following the NZSEE (2017). It is also noted however that the research community often adopts NLRHA and inputs "code-based" ground motion selection and scaling procedures. The paper is organised into the following sections:

- General overview of the three main "tasks" for determining suitable ground motion input for NLHRA. The tasks are: i) ground motion selection, ii) scaling, and iii) application to the computer model.
- Summary of the relevant NZ requirements in NZS 1170.5 and NZSEE Assessment Guidelines (2017), with discussion of the various limitations
- Summary of US Standards ASCE 7-16 and ASCE 41-17, along with brief mention of some practical issues.

1.1 "Tasks" For Determining Suitable Ground Motion Input for NLRHA

Suitable ground motions for NLRHA should provide a relatively unbiased representation of the design-level seismic hazard. This section briefly lists the three main "tasks" of determining suitable ground motion input prior to performing NLRHA.

1.1.1 Task 1: Hazard Analysis and Ground Motion Selection

Prospective ground motions are selected based on the design-level seismic hazard of the site. First, a probabilistic Seismic hazard analysis (PSHA) is performed for a specific site to define the ground motion intensity with annual probability of exceedance (APE) consistent with the APE design criteria in NZS 1170.0. PSHA is typically used to define the seismic hazard in NZ, although deterministic analyses or checks are sometimes used (particularly for "near-fault" high seismicity regions). This paper herein refers specifically to PSHA.

Disaggregation of the seismic hazard is then required to identify the dominant fault (or faults) rupture mechanisms, magnitudes, and rupture source-to-site distances to inform the selection of prospective ground motions. This "rupture scenario information" implicitly ensures that the intensity measures of the selected motions, such as amplitude and duration, are notionally consistent with those expected from the rupture scenario(s) that governs the seismic hazard for a given site and structure. The rupture scenario information is used as the basis for selecting ground motions from publicly available datasets of historical earthquake records, such as the PEER NGA-West2 Strong Ground Motion Database (https://ngawest2.berkeley.edu/). The ground motion selection procedure lends itself towards sophisticated algorithms, such as the Conditional Mean Spectrum (CMS) (Baker et al., 2011) or Generalised Conditional Intensity Measure (GCIM) algorithms (Bradley, 2010).

There are no strict regulatory frameworks for seismic hazard analysis and ground motion selection thus, the current practical norm relies on self-regulation using general specifications to meet the fundamental objectives alluded to above. Generally, this task is outside of the expertise or means of practising structural engineers, and often requires specialist input from a consulting engineering seismologist.

1.1.2 Task 2: Ground Motion Scaling

Once the catalogue of prospective ground motions is collated, the ground motions must be scaled to be compatible with the design response spectra. "Task 2" is essentially a calculation procedure to determine the linear scale factors which are then used for "Task 3". The general intent is to ensure the ground motion response spectra is scaled to equal/exceed the code design response spectra over the structure's vibration period range of interest, as illustrated schematically in Figure 1.

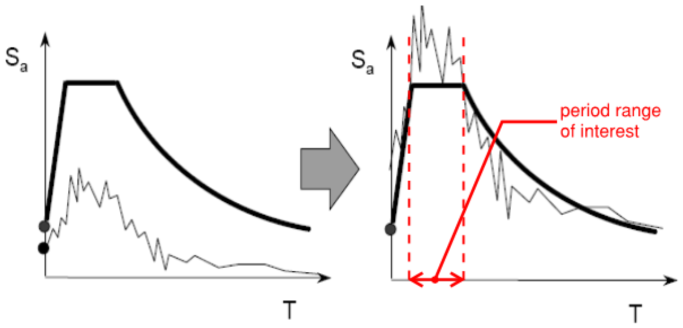

Figure 1: Schematic illustration of amplitude-scaling the ground motion response spectrum to the design spectrum over a range of vibration periods.

Seismic loading standards generally contain prescriptive requirements for ground motion amplitude scaling. The most notable difference between different seismic loading standards is whether "envelope scaling" or "mean scaling" is applied (discussed later herein). Most available scaling methods are based on the 5% damped elastic response spectral accelerations. As the prescribed scaling requirements are focussed solely on matching the target spectra, there is an implicit assumption that other ground motion intensity measures (such as duration) will be notionally consistent with the seismic hazard. This assumption is conditional on "Task 1" being completed appropriately however, this is often not the case, as illustrated in Bradley (2010), and Tarbali and Bradley (2016).

From the perspective of life safety or collapse avoidance, it is often the non-linear engineering demand parameters which control the evaluation outcome, however this is not necessarily consistent with the scaled elastic response spectra. This essentially means that Task 2 is based on the fundamental assumption that scaling the elastic response spectra will provide a sufficient level of inelastic demands on the structure.

1.1.3 Task 3: Application to the Computational Model

Before running NLRHA, the last step is to apply the one- or two- components of horizontal ground acceleration at the base level of the computational model. In some cases, a third component of vertical motion may also be applied (although vertical ground motions are not discussed further herein).

The most important aspect of this task is to ensure that each axes of a building's lateral load resisting system is subjected to a consistent amplitude of ground shaking such that unintended "directional bias" in the analysis is minimised. Directional bias is treated differently for sites that are classified as being "far-field", or "near-fault". This classification is based on the hazard disaggregation results.

In some standards, "near-fault" sites require the horizontal components to be rotated to the fault-normal (FN) and fault-parallel (FP) directions of the causative fault and be applied to the building in such orientation. The rotation of as-recorded motions can have a marginal increase the spectral accelerations in FN orientation, though the main effect of this rotation is to represent the large velocity pulses which tend to occur near-fault.

2 NZ PROCEDURE FOR GROUND MOTION SELECTION AND SACLING

2.1 NZS 1170.5 (2004) Requirements

Ground motion record selection and scaling requirements are laid out in Sections 5.5 and 6.4 of NZS 1170.5. The authors believe it is an important reminder that the overall NLRHA framework in NZS 1170.5 is tailored towards evaluation of the Life Safety performance objective. There are no explicit requirements or modifications for assessment of Collapse Prevention.

2.1.1 Maximum Response of 3 (or More) Ground Motions

A minimum of three ground motions is required, and the amplitude scaling is based on the "Maximum of 3" records. A similar requirement exists in Eurocode 8 (a standard which also permeants the "mean of 7" approach). For evaluating the NLRHA output, the maximum overall response parameter from all three ground motions is used. The specification of a minimum of 3 records dates back to NZS 4203 (1992) which, in part, was to deal with the trade-off in output reliability and analysis run times. However, within the past 30 years, computational efficiency has improved significantly. In today's consulting offices, analysis run times are less constrained due to multi-core processors and cloud-computing capabilities.

Seismic demands have a large record-to-record variability. As stated earlier, the demand parameters of interest in NLRHA are usually non-linear parameters such as component strains; not the elastic spectral accelerations or spectral displacements. There is a significant (and undesirable) probability that the "envelope of 3" demand can actually be lower than the true mean seismic demand, reasonably expected to be at least 0.15 to 0.30 (Bradley, 2011, Hancock, 2008). The poor handling of variability in demand parameters is a significant shortcoming of the maximum of three approach.

Even if greater than 3 ground motions are used, the specific wording is such that, in order to comply with NZS 1170.5, the evaluation must be based on the maximum response. This requirement provides a major disincentive for including greater variability in the analysis. By increasing the number of ground motions, statistically the maximum response will also increase, which can ultimately shift from the evaluation from being potentially unconservative, to being systematically over conservative by an unknown amount (Bradley, 2014). In attempt to mitigate the above issues, it is not uncommon for consulting engineers in NZ to consider the mean response from at least 7 ground motions based on ASCE 7-10 (2010, now superseded) as an alternative method. The latest version of the standard ASCE 7-16 requires a minimum of 11 records (discussed later herein), and results in substantially less scatter about the true value (in comparison to the maximum of three approach).

2.1.2 Ground Motion Selection

The ground motion selection methodology must follow the requirements of Section 5.5; a section which is relatively vague. It generally accepted that the nature of the seismic hazard (i.e. the so-called '*seismological signature*') underlying the design spectrum should be ascertained based on hazard disaggregation. Disaggregation results are not directly available without a site-specific seismic hazard analysis study being performed.

Site-specific hazard analysis and ground motion selection is an area of the NZ earthquake engineering profession that is currently self-regulated. NZ Territorial authorities (TA's) generally do not require site-specific hazard analysis to independently peer reviewed. There are a growing number of seismology/geotechnical engineering consultants offering services of seismic hazard analysis and ground motion selection.

Given that Section 5.5 is somewhat open to interpretation, the authors believe that the potential risks to consistency and quality from self-regulation could be better mitigated by having an acceptable framework procedure introduced to NZ practice – particularly if site specific spectra are proposed to be used to set the seismic demands rather than simply to aid in selection of ground motions. For efficiency, the proposed framework could be adopted as interim guidance in the first instance, and later cited in future versions of NZS 1170.5.

2.1.3 Prescribed Period Range for Scaling Calculations

The period range for scaling calculations is prescribed as (0.4-1.3)T_1. The upper bound period (T_{UB}) should implicitly account for period lengthening due to material yielding and should be a function of the level of inelastic behaviour that is expected. If the secant period is used, the upper bound 1.3T_1 corresponds to a generic system with a global system displacement ductility of approximately 1.7. Whilst perhaps on the low side, in many cases this is likely to be reasonable, as actual global system displacement ductility for many buildings will be substantially lower than those of the governing components corresponding to the language of force-based design procedures in NZS 1170 (and its predecessor standards).

The lower bound period, T_{LB} intends to account for higher mode effects. Higher modes are important either for their own response in isolation, or for their contribution to linear or non-linear fundamental mode behaviour. For typical frame structures, the second mode is approximately 1/3 of the fundamental mode (0.33T_1), while for a wall structures the second mode is often 1/6 of the fundamental mode (0.17T_1). The prescribed lower value 0.4T1 in NZS 1170.5 does not encompass the higher modes of vibration for either cases, and so perhaps implicitly presumes that the most damage occurs from response in the fundamental mode.

The prescribed period range warrants consideration for non-generic buildings, such as URM buildings, and for assessments at other levels of seismic hazard (such as assessing Collapse Prevention).

2.1.4 Prescribed D_1 Limit vs. Spectrum Short-Period Plateau

The specified limit is $D_1 \leq \log(1.5)$, yet the commentary states this is *"not very restrictive"* and better fit based on log(1.3) should be aimed for. A requirement of Section 5.5.2 (c), vii) is to *"Reject records that are not of reasonable fit"*. The authors note D_1 values sometimes exceed this limit where the ground motion response spectra coincide with the 'artificial' (i.e. non-physical) plateau of the target spectrum at short-periods. In the author's experience, this can lead to apparent trade-offs between the prescriptive limits for D_1 and $k_{1,}$ and the prescribed period range. Holistically this trade-off is considered (by the authors) to be unimportant, as variability in the procedure is more important. The authors recommend that the causal parameters M_w-R_{rup} are treated as a higher priority, and some leniency in the values of D_1 is necessary. There is no equivalent D_1 goodness-of-fit parameter specified in ASCE 7-16 or in Eurocode 8.

2.1.5 Reasons for Large Scale factors (k_1 and k_2)

Typically, the prescribed lower limit of $k_1 > 0.33$ is not problematic, although upper limits of $k_1 < 3.0$ and/or $k_2 < 1.3$ are often exceeded for a variety of reasons, as listed:

1. High-importance structures designed for rare ground motion intensity levels.
2. Subduction-source ground motions, of which there are few historic earthquake events with ground motion data of sufficient quality.
3. Sites which there are inconsistencies between the NZS 1170.5 design spectrum and the site-specific seismic hazard spectrum.
4. Evaluating the Collapse Prevention performance level based on ASCE 41 Tier 3 Assessments, including the requirements in C1.6.2 of the NZ Seismic Assessment Guidelines (2017) for an additional 1.8 factor (or 1.5, for Importance Level 4 buildings).

Further discussion on the above is given in Morris et al. (in press).

2.1.6 Application to the computational model

Sections 6.4.3 & 6.4.4 requires that records are applied twice, meaning the analysis is repeated for the same ground motion but with the primary and secondary horizontal components "flipped" with respect to the building axis. This essentially means that applying a minimum of three ground motions actually requires six separate analysis (per each mass eccentricity). NZS1170.5 states that:

"Both the principal component and the scaling factors will usually be different for each analysis because T_1 is different for both situations [orthogonal directions]."

In the authors' experience, different scale factors are generally not applied for each direction when using 3D models. Instead the period range is bounded for the fundamental periods in each direction (elongating the period range), and the same scale factor used for both components. There is not the technical basis to be confident that separate scale factors would not alter the characteristics and directional bias of the records.

2.2 NZSEE (2017) Assessment Guidelines for Existing Buildings: Requirements for Ground Motion Input

For complex existing buildings, consulting engineers might adopt NLRHA as a means for conducting Detailed Seismic Assessments (DSAs) to the NZ Seismic Assessment Guidelines (2017), herein referred to as the *guidelines*. The *guidelines* directly cite Sections 5.5 and 6.4 of NZS 1170.5 for ground motion input for NLRHA. Progress in ground motion selection and scaling methods since the publication of NZS 1170.5 is recognised in the Appendix Section C2C.2 commentary of the *guidelines*. Whilst it is helpful that the "currency" of NZS 1170.5 is identified as a limitation of *guidelines*, defining the reviewer's scope and qualification is left to the project team to determine. Aside from Morris et al. (in press), along with publications by the last author, there is shortage of guidance available to consulting engineers which has been presented in the context of NZS 1170.5 and NZ practice.

2.2.1 Alternative Verification Methodology: ASCE 41-13

Clause C1.6.2 of the *guidelines* facilitates the use of the ASCE 41-13 (2013) "Tier 3 Assessment" procedure using NLRHA as an acceptable alternative verification methodology. While ASCE 41-13 is stipulated by the *guidelines*, it is now the predecessor to ASCE 41-17.

Using this alternative verification methodology can be attractive due to the more modern approach for NLRHA as outlined in ASCE 41. The *guidelines* require that:

"The acceptance criteria and recommendations given in ASCE 41, unless specifically modified for NLTHA in these guidelines, should be used in their entirety this includes the process of selection and scaling of strong motion records."

This alternative approach results in a building risk rating which is calibrated at two return periods on the hazard spectrum; Life Safety (LS) at ULS, and Collapse Prevention (CP) under higher shaking. This varies from the one ULS check required by the Assessment Guidelines. In many cases this can provide a more transparent and robust measure of resilience to shaking—as the fragility of controlling system mechanisms to some higher level of demand is reviewed directly, rather than by reliance on margins in the material/component strain limits applied at the ULS.

The ground motion requirements in ASCE 41-13 are similar to those from previous standards from the decade prior, whereas ASCE 41-17 includes significant modifications to be consistent with ASCE 7-16, which incorporates a more contemporary approach to ground motion input for NLRHA. For this reason, the ASCE 7-16 / ASCE 41-17 combined methods have been applied to some NZ projects.

3 SUMMARY OF US STANDARDS ASCE 7-16 & ASCE 41-17

ASCE 7-16 and ASCE 41-17 are the current seismic loading and design standards developed by the American Society of Civil Engineers (ASCE). ASCE 7-16 *"Minimum design loads for new buildings*" contains the most contemporary and non-prescriptive guidance available for ground motion input for NLRHA. ASCE 41-17 *"Seismic Evaluation and Retrofit of Existing Buildings*" includes evaluations of both Life Safety and Collapse Prevention, along with other performance objectives (as outlined in Sections 2.2 and 2.3 of the standard). For Tier 3 evaluations, the input ground motion requirements cite those in Section 16.2 of ASCE 7-16, along with some modifications to better represent existing buildings (discussed below).

For context, it is worth noting that the current 2016 California Building Code (CBC) currently cites the respective forerunners standards; ASCE 41-13 and ASCE 7-10, and it's anticipated that the latest standards will be cited in the 2019 CBC. This means that, at the time of writing this paper, consulting engineers in California have varying (and often limited) practical experience with applying the ground motion requirements in ASCE 41-17 and ASCE 7-16.

3.1 Mean Response of a Minimum of 11 records

Earlier versions of ASCE 7 permitted the use of either the "mean of 7, or maximum of 3" ground motions, with practitioners preferring to use the "mean of 7". In US practice, it was not uncommon for consulting engineers to increase the number of ground motions to 10 (or more) in order to improve the overall reliability of the NLRHA outputs. More recently, it became apparent that the mean of 7 ground motions may be un-conservative (Bradley, 2014), while a minimum of 11 greatly increases the confidence of seismic response predictions, without a significant increase in computational effort (FEMA, 2012).

Whilst using a minimum of 11 records is perceived to be a major increase in the required computational workload relative to NZS 1170.5, it is offset by the fact that records only need to be applied once to the computational model. Compared to the NZS 1170.5 requirement in Section 6.4.4, the records would be applied twice with the primary record components flipped in orthogonal directions, meaning six analyses are required. Ultimately this means using 11 records per ASCE 7-16 only increases the minimum level of computational effort from NZS 1170.5 (i.e. using 3 records) by a factor of two.

3.2 Section 16.2.2: Ground Motion Selection

Commentary section C16.2.2 outlines the selection methodology in more detail, with reference to NIST GCR 11-917-15 (2011) "*Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analysis*". This NIST guidance document was originally prepared to address the needs from the profession to have *"improved procedures for selecting and scaling earthquake ground motions for performing response-history analysis."*

Peer review of seismic hazard analysis and ground motion selection varies in the US. Some authorities having jurisdiction have preferred peer reviewers, while others rely on the peer reviewer to be nominated by the consulting engineering seismologist.

3.3 Section 16.2.3: Ground Motion Modification (Scaling)

Compared to NZS 1170.5, the US standards contain fewer prescriptive requirements. There are no specific limits on scale factors as a basis for rejecting records. Scale factors between 0.25-4.0 are recommended as initial target values (Haselton et al., 2017), though the final scale factors are treated overall as being less important than the casual M_w-R_{rup} properties, along with maintaining other ground motion intensity measures (such as duration). There is no goodness of fit requirement (like D_1 in NZS 1170.5).

The most prescriptive aspect of ASCE 7-16 and ASCE 41-17, respectively, are the defined period ranges, as summarised below:

Standard	Lower bound, T_{LB}	Upper bound, T_{UB}
ASCE 7-16	$\min(0.2T_{min},\ T_{90})$	$2.0T_{max}$[a]
ASCE 41-17	$0.2T_{min}$	$1.5T_{max}$[b]

T_{min} = minimum value of $T_{1,x}$ and $T_{1,y}$ (the fundamental period in two orthogonal directions).

$T_{90\%}$ = the period at which 90% mass participation is obtained (mass of the super-structure).

T_{max} = the maximum fundamental period (including both translational and torsional modes).

[a] The upper bound period in ASCE 7-16 can be reduced, but not less than $1.5T_1$, provided there is justification based on the response reported from the NLRHA at the MCE_R level of shaking.

[b] The upper bound period shall not be less than 1.0 sec

The ASCE 7-16 period range is generally consistent with Eurocode 8 (Part 1) but, in contrast, is evidently much larger than that specified in NZS 1170.5.

As shown above, ASCE 41-17 makes two main modifications to the period range prescribed by ASCE 7-16. Firstly, the upper-bound period is relaxed on the basis that existing buildings do not develop the same degree of global ductility compared to a new designed ductile structure. Secondly, there is minimum upper bound period of 1.0 sec which, evidently, influences buildings where $T_1 \leq 0.66$ sec. Relatively brief commentary is given in the Standard and the authors are not aware of any technical insight or basis presented for this requirement. For a given short period building, if the scaling procedure is governed by the upper bound period, then this requirement leads to increases scale factors, which results in additional challenges for seismic assessments and retrofit.

For long period buildings, the scaling calculations are constrained by the broad period range, which can lead to overly conservative scale factors. An example of this is illustrated in Figure 2 (a) and described here. The prescribed period range for the structure is 1.2 to 9.6 sec. Figure 2 (a) shows the initial response spectrum scaling of ground motions is governed by the relative short-fall in the mean spectra at the band of periods from 1.2 to 2.0 sec. An initially large family scale factor of $k_2 = 2.40$ is calculated. At the fundamental periods, the ratio of scaled response spectrum to the code target spectrum, $SA(T_1)_{mean} / SA(T_1)_{code}$, is approximately 2.4, hence the initial ground motion scaling results are not suitable for NLRHA.

The initial scaling calculations were corrected by expanding the ground motion suite to contain 13 records. The two supplementary records have an increased response spectra for T = 1.2 to 2.0 sec. The re-scaled response spectrum is shown in Figure 2(b). The k_2 scale factor reduced to 1.4, and at the fundamental periods the ratio $SA(T_1)_{mean} /SA(T_1)_{code}$ was reduced to approximately 1.3. Although not shown, the corresponding spectral displacement demands at long periods were significantly reduced from the initially excessive values. Increasing the number of input ground motions had relatively few implications for this structure due to limited non-linear response, therefore analysis run times were not a constraint. Although there is an amplification of higher modes in the additional ground motions, these were not problematic for the structure.

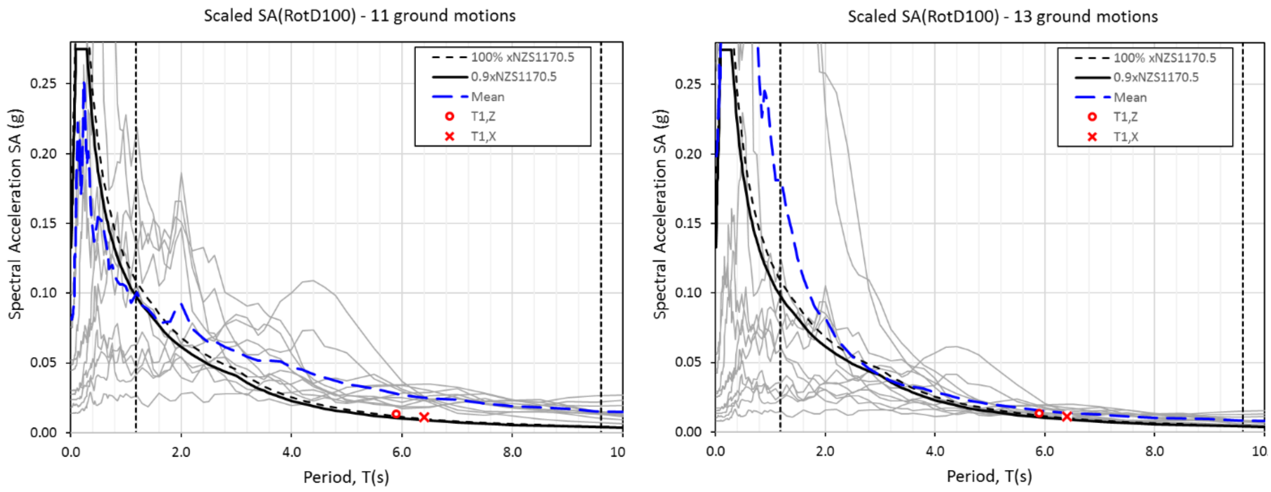

Figure 2: (Left) Scaled mean response spectrum governed by the lower bound period. (Right) Re-scaled response spectrum with additional ground motions.

3.4 Section 16.2.4: Application to Computational Model

For "far-field" sites, the as-recorded horizontal components applied to the model should not introduce a directional bias greater than ±10% in each orthogonal direction (this applies to all periods within the prescribed period range). This requirement is favourable as it means records do not need to be applied twice with the primary record components flipped (as is common in NZ practice to NZS 1170.5). This requirement represents the fact that the record-to-record variability in the suite of 11 records is far greater than the variability associated with flipping the horizontal components, therefore there is almost no benefit in performing 22 analyses compared to 11 analyses which meet the ±10% rule.

For "near-fault" sites; horizontal components are to be rotated to the fault-normal (FN) and fault-parallel (FP) directions of the causative fault and be applied to the building in such orientation. There are some practical challenges associated with these "near-fault" requirements;

1. Rotating the entire suite of records to be FN/FP may be inadequate, on the basis that only a sub-set of the selected motions will contain pulse-like characteristics. Internationally, it is common practice, but not mandatory, to rotate only the pulse-like motions.
2. Many high seismicity regions have several causative faults in the near-fault region. In such cases the fault orientations may vary, which may justify performing NLRHA with a greater number of ground motions to represent more than one "scenario" FN/FP input.
3. Forward-directivity and pulse-like effects are better understood for shallow crustal earthquake hazards, whereas near-fault subduction hazards are more complex. In Wellington (NZ), the subduction hazard is off-shore, and there is a relative mis-alignment of slip direction, rupture propagation direction, and source-to-site distances in the relevant directions. For practical applications, the as-recorded subduction ground motions may be more suitable (in lieu of the prescribed fault-normal / fault-parallel motions).

4. Basin and topographic effects in near-fault regions (such as Wellington) is a complex subject that influences seismic wave propagation. The uncertainties associated with basin and topographic effects may be greater than the greater "detail" which the near-fault prescriptions are focussed on.

4 OTHER CONSIDERATIONS

This paper presented a truncated version of an article submitted for publication in the New Zealand Society for Earthquake Engineering Bulletin. The bulletin article includes discussion of:

- Examples of the varying applications of NLRHA in NZ practise.
- Reference to the relevant requirements in the draft NZ base-isolation guidelines (currently in development).
- Examples of "above-minimum" requirements for the ground motion input used for NLRHA of tall buildings in the US.
- List of other items not discussed (frequency scaling procedures, simulated ground motions, and considerations related to risk-targeted demands or risk-adjusted hazard (which have been used in US standards since 2010).

5 CONCLUSIONS

This paper summarised the ground motion selection and scaling requirements of the NZ loading standard NZS 1170.5, the NZSEE (2017) *Assessment Guidelines*. Some of the salient limitations that often need to be addressed on an ad-hoc basis when conducting NLRHA were discussed within. As NLRHA is becoming increasingly popular, there will be greater needs to have contemporary guidance available for determining the ground motion input. This paper has discussed the following specific issues for NZ practice:

- Ground motion selection and scaling requirements are relatively out-dated; however, these have been cited in more modern documents such as the NZSEE (2017) *Assessment Guidelines* for existing buildings.
- Self-regulation of seismic hazard analysis and ground motion selection is the current norm in NZ practice. The requirements for ground motion selection are relatively open to interpretation, whereas it would be beneficial to have an accepted framework procedure.
- Scaling and applying records to the computational model may require leniency from the prescriptions given in NZS 1170.5, in favour of more fundamentally important factors such as causal magnitude and rupture distances.
- The US standards ASCE 7-16 and ASCE 41-17 were summarised in this paper. These standards offer an attractive alternative to NZS 1170.5, as these standards were developed based on relatively modern research.

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