nzsee
NEW ZEALAND SOCIETY FOR
EARTHQUAKE ENGINEERING

Implementing the NZSEE Seismic Isolation Guidelines: A practitioners view over three new designs

R.H. Ballagh, A.G. Cattanach & C.R. Speed
Dunning Thornton, Wellington.

ABSTRACT

The draft seismic isolation guidelines provide a significant step forward in promoting a consistent NZ approach to designing and demonstrating compliance in isolated buildings. This paper provides a practitioners' point of view of implementing of the guidelines on three new structures currently in design/peer review. Achieving consistency across the chapters, structure types and philosophies takes some interpretation. This paper is intended to provide some assistance to other practitioners navigating the guidelines, and note some important aspects where further development/clarification may be appropriate. Key topics include the scaling of records and the non-directional nature of isolated buildings, scaling ADRS spectra for damping, simplified methods for getting parts/floor specta, and matching risk philosophy with the application of Sp and alpha.

1 INTRODUCTION

The draft seismic isolation guidelines were drafted with the intention of making consistent NZ's approach to design, and to capture modern refinements to design methodologies. Dunning Thornton have completed the design of three building since the draft guidelines were published, each different and having a different Peer Review consultant.

The Wellington Conference and Exhibition Centre (WCEC) is a large footprint three storey structure, with each floor double height with areas of mezzanine floors. Superstructure bracing is a hybrid diagrid/CBF and the isolation system is LRB's with flat slider bearings.

Victoria Lane Apartments is a 16 storey mixed use structure with offices on the lower floors and apartments above. The superstructure is braced by a diagrid on the lower floors up to a CBF in the upper apartment floors and the isolation system is LRB's under the tower and LRB's and some flat sliders under the office extension at the front.

Site 9 is a four storey office, the superstructure is a two way stiff steel moment frame. Seismic Isolation is on top of cantilever columns at high level ground floor, consisting of LRB's with flat sliders.

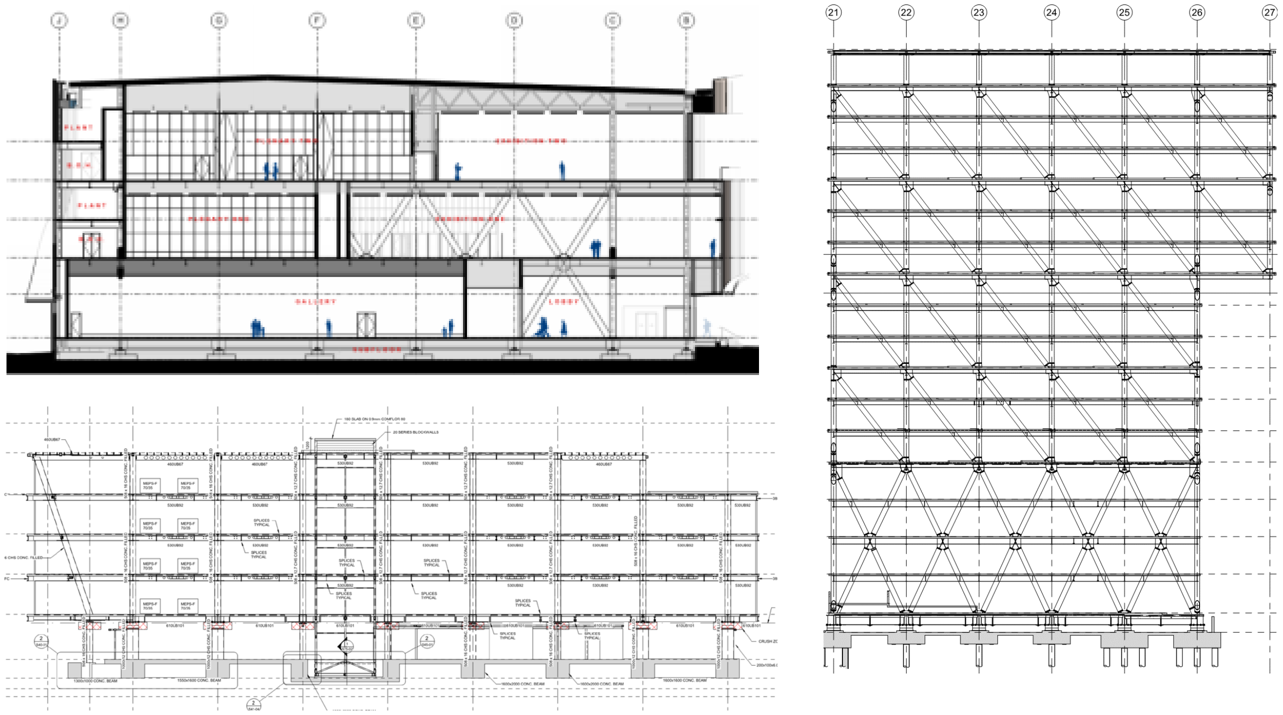

Figure 1: Structural views through WCEC, VLA and Site 9 respectively (clockwise from top left).

This paper summarises issues where applying the guidelines appeared inconsistent with their underlying science or principles.

2 GROUND MOTION DIRECTIONALITY

2.1 Relationship to Base Isolation Hardware Design

Hazard Spectra in NZS 1170.5 represent the larger spectral acceleration of two orthogonal ground motion directions (SA_{Larger})[1]. By contrast, US design codes have recently changed from using the geometric mean to the maximum direction of any possible record orientation ($SA_{RotD100}$) as the design parameter[2].

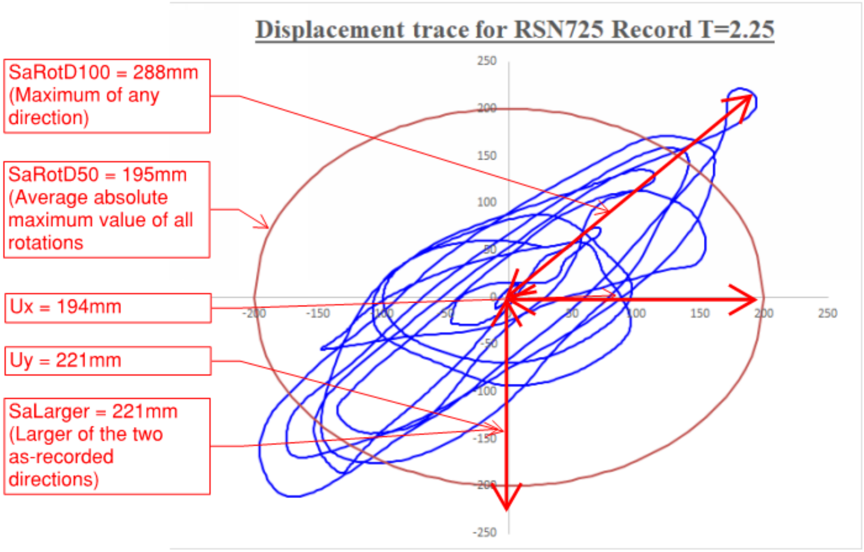

Figure 2: Plots of X and Y Displacements and parameter definitions for RSN725 Record

Use of SA_{Larger} for design of torsionally stable frame buildings, where the two orthogonal structural systems are distinct from one another, will provide a system that inherently has the capacity for the net actions at angles to the principle frames. For a base isolated building, stiffness at the isolation plane is generally azimuth independent, that is the isolation system maximum displacement is likely to be at an angle to the superstructure above. The actual angle, and the magnitude of the difference, will vary depending on the nature of the ground motions and the period of the isolation system. There is no confidence that designing to SA_{Larger} as the parameter will achieve the exceedance level desired for the isolation system if performing ADRS/ Equivalent static checks for an NZS1170.5 spectra.

Using NLTHA in New Zealand, this is overcome (to a certain degree) by scaling the larger of two records in its raw, randomly chosen direction, to the NZS 1170.5 spectra, which represents a similar parameter. One will then output the square root of the sum of the squares for the x and y displacement directions at each analysis timestep to get the maximum value. This process has two downsides:

It requires careful consideration of the relationship between the SA_{Larger} and $SA_{RotD100}$ spectra. Known studies [3,4]use large datasets with a large range of rupture distances, which may not match the a hazard at a given site, particularly when near- source effects are dominant. Individual records can have significant scatter and a disproportionate effect on results. The ratio of $SA_{RotD100}$ to SA_{Larger} is typically around 1.05-1.25. It tends to be lower for far field than near field ground motions: near field motions giving more directional motions where far field motions typically result in more non-directional rounder loops

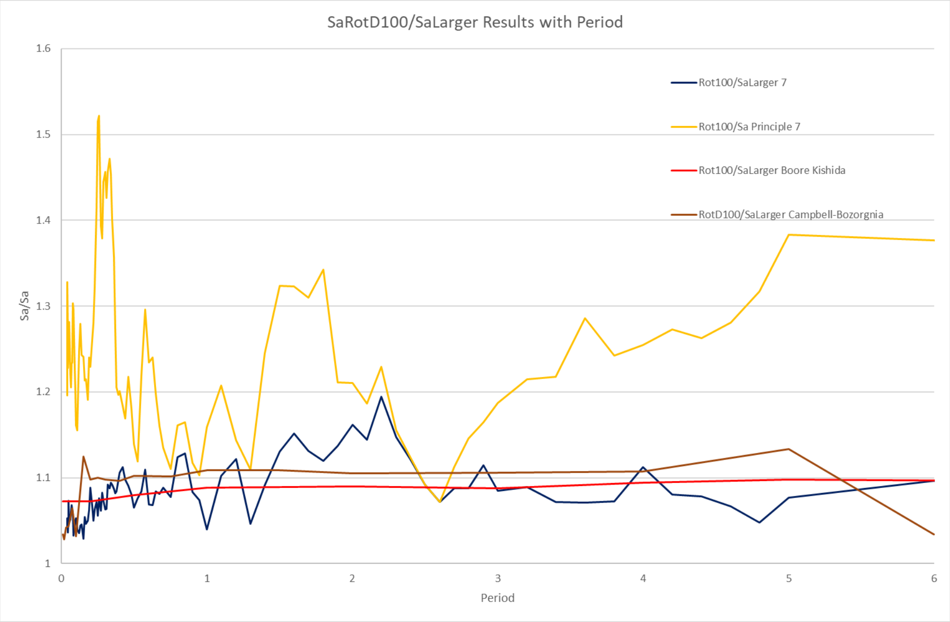

Figure 3: Ratios of SaRot100 to SaLarger from sample record set and from academic research

More subtly, and significantly, NZS1170.5 scaling is not a direct like for like scaling, as one is scaling the usually larger of two record spectra to the SA$_{\text{Larger}}$ design spectra over a period band (not SA$_{\text{Larger}}$ to SA$_{\text{Larger}}$, which would require enveloping the two record spectra). Because the principle direction is not the larger of the two records of the full scaling band, to match spectra the individual scaling factors have to be significantly increased. This has a disproportionate effect on the SA$_{\text{RotD100}}$ ratio as can be seen in the yellow/ orange lines in Figure 2 above, where the SA$_{\text{RotD100}}$ to SA$_{\text{Principle Direction}}$ ratios are much higher.

The sum total of the above points is significant scatter and potential over-conservatism in the analysis results. As per acceleration/displacement plot below, this can be up to a 30% increase in design displacements (note this shows 5% damped spectra which accentuates the effect, whereas this will be correspondingly damped for a typical isolated system)

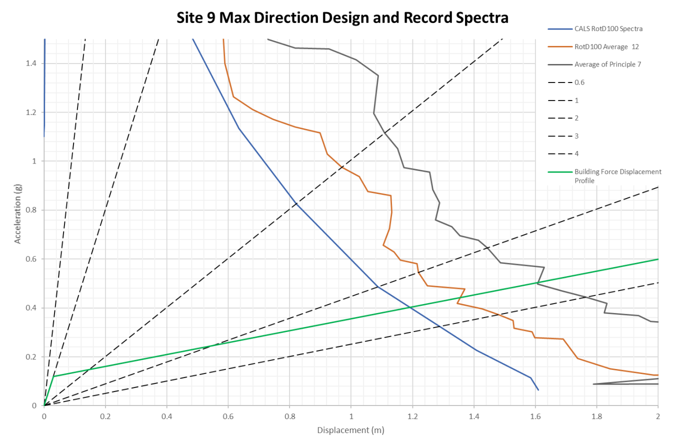

Figure 1: ADRS for Site 9 Building, showing the effect of scaling on building displacement

2.2 ASCE 7-16 Approach and Relationship to Superstructure design

The ASCE 7-16 NLTHA (Chapter 16) requires selection of 11 records to achieve a reasonable statistical balance, with scaling done between RotD100 design spectra and RotD100 record spectra, eliminating any directional bias. Each record pair is then applied to the model in a single arbitrary orientation (rather than each record pair being applied in one direction, then at 90 degrees, as in NZS1170.5). This has a computation advantage over a suite of 7 record pairs applied in each direction (14 cases, vs 11). There are, however, some departures from philosophies of NZS1170.5 (i.e. use of SA_{Larger})

1. The ASCE7-16 approach means effectively designing to SARotD50, a more statistically exact but averaged design value. Sa_{Larger} may be more consistent with a basic ULS design philosophy- that is not that a building has an inherent robustness beyond the design level of shaking. We suggest that ASCE7-16 be applied to both isolator and superstructure design, but with larger Sp values and more conservative combination rules (eg 100/100 rather than 100/30). There is a similar issue with positive/ negative earthquake directionality. RotD50 is defined as the 50th% value of the maximum absolute values from the time history for each record orientation between 0 and 90 degrees. When extracting tension in an isolator from one side of an unsymmetric building, the average value from time history could be not quite RotD50, but a lower value. The designer is then left with the choice of either doubling the number of record cases run (i.e. applying each forwards and backwards), or attempting to convert time history base shears and moments into values to apply statically. A example of this process for one building, derived from acceleration values is discussed below.
2. Applying the records in arbitrary directions means they only coincide with the most torsional direction approximately half the time (which will reduce torsional displacements by approximately the square of the torsion factor – designated δxi in the Guidelines). Again, this may match the exceedance level targeted better, but potential reduced robustness to a certain type of attack needs to be understood.

SaLarger	(g)	RotD50	(g)	Single Dctn (g)		SaLarger/ RotD50	RotD50/ RotD50.360	SaLarger/ RotD50.360
0.60	0.63	0.55	0.55	0.53	0.50	1.10	1.04	1.14
0.46	0.42	0.41	0.38	0.39	0.35	1.11	1.06	1.18
0.35	0.31	0.32	0.29	0.29	0.27	1.09	1.09	1.19
0.37	0.33	0.34	0.30	0.32	0.28	1.08	1.07	1.16
0.45	0.40	0.41	0.36	0.39	0.33	1.11	1.04	1.15

Figure 5: Tabulated values for 5 different records showing scaling relative effect. (360 = all directions)

3 EQUIVALENT STATIC ANALYSIS

3.1 Isolation System Displacements:

Simple, accurate hand calculations are critical design and checking tools, and are most useful if they offer a glimpse into the complex nonlinear behaviour which underpin then, and have been benchmarked against comprehensive nonlinear time history analysis.

There is a form of this for determining isolator displacements in the NZSEE Seismic Isolation Guidelines. This is similar to the ESM in ASCE7-16, which itself has remained largely unchanged since the UBC of 1997 and has a long (and occasionally chequered) history of verification against nonlinear time history analysis (NLTHA)[5,6] Both methods use effective stiffness based effective period, full Jacobsen area based equivalent viscous damping, and a formula to reduce displacements based on the amount of equivalent viscous damping. The only significant departure is in the damping reduction formula; ASCE 7-16 uses tabulated values and the draft NZSEE Seismic Isolation Guidelines use the viscous damping reduction factor from a draft version of Eurocode 8:

$$\eta = \sqrt{\frac{0.07}{0.02+\xi}}$$

Damping reduction are significantly greater for the NZSEE formula compared with ASCE7-16. Isolator designs from the author's own office show non-conservatism of the NZSEE procedure but good correlations between ESA based on the formula from the final Eurocode 8, based on the work of Bommer [7]:

$$\eta = \left(\frac{0.1}{0.05 + \xi}\right)^{0.5}$$

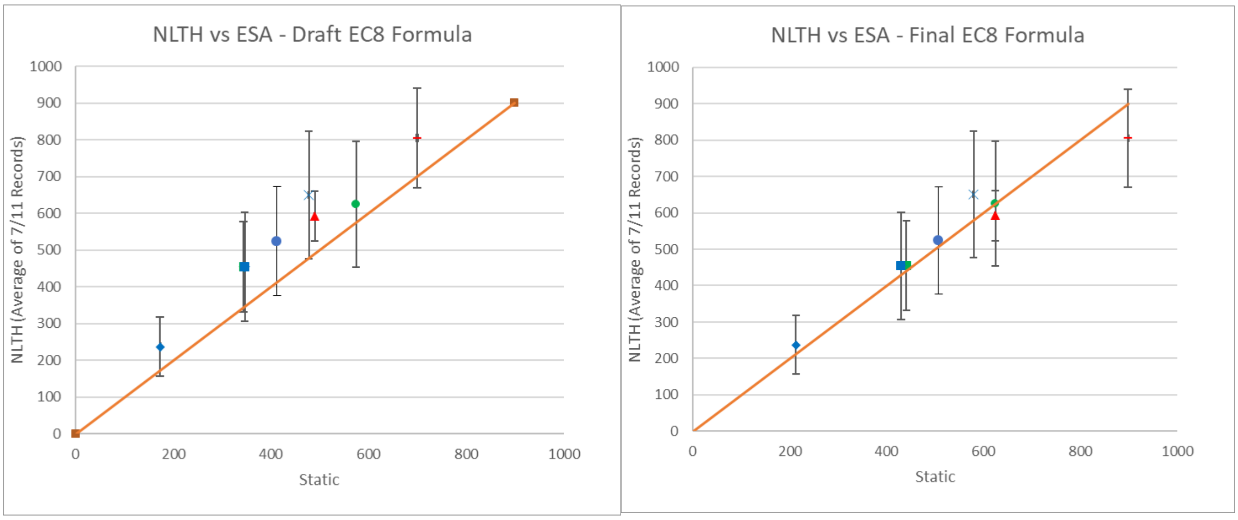

Figure 6: Predictive power of equivalent viscous damping formulae. Colours of dots represent different isolator systems from different Dunning Thornton building designs. Error bars denote scatter of NLTH results for earthquake records within a set. Note values above the line denote nonconservative predictions.

3.2 Vertical distribution of lateral force in the superstructure

In an ideal base isolated structure, the structure remains still and the ground moves around it. The acceleration is low and due to the large stiffness differential between the isolators and the superstructure, constant up the building. In real situations, the use of high damping and flexible superstructures this is frequently not realised and the nonlinearity amplifies the response of higher building modes.

This phenomenon has been studied extensively by Ryan for moment frame buildings up to 9 storeys[8]. As can be seen in this graph below, this method offers excellent predictions relative to other distributions.

Where Ryan is not applicable is for overturning moments (as it is an envelope of shears) and non shear deflection dominated buildings, such as braced frames. The latter have lower participation of higher modes when base isolated, and distributions revert instead closer to idealised squares.

Without comprehensive extra study, we are reluctant to propose a more accurate distribution, but simply note it will be significantly closer to square than for moment frame (difficulties in providing generalised rules are acknowledged in Ch 5.8 of the guidelines). However we believe the process in producing and understanding the distribution is an integral part of the design process:

- It demonstrates the balance achieved by the level of damping selected – enough to limit isolator displacements' as necessary but often at the expense of increasing superstructure accelerations
- It provides a set of accelerations that can be used in benchmarking parts accelerations, and for static checking processes as described later in this paper.

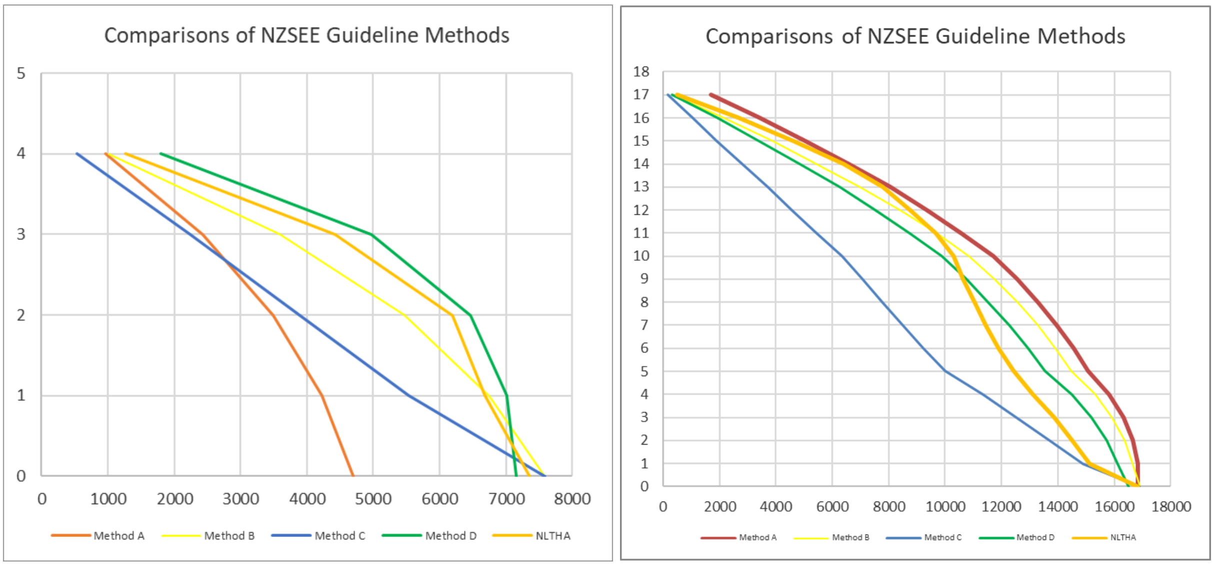

Figure 7: Shear by Storey for Site 9 building (left) and VLA (right).

3.3 Parts Spectral accelerations:

The response of parts of a building, for example building services, can be affected significantly by subtleties in the isolation system in ways that are not captured by analysis of the first modal response. System damping, the superstructure and isolation system natural periods and hysteretic loop shape can have a significant effect on floor spectra[9], with effective $C_i(T_p)$ factors greater than 2 for highly damped systems and less than 2 for lowly damped systems. DTC have had success matching spectral accelerations using formulas for $C_i(T_p)$ based on system damping and shapes based on the isolator and superstructure periods, and C_{Hi} factors based on the Ryan distribution rather than the NZS 1170.5 distribution used in the guidelines Ch 5.8.

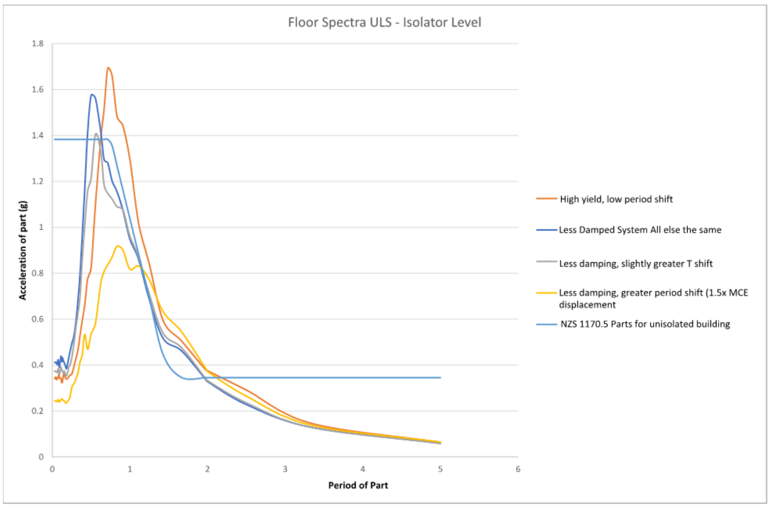

Figure 8: Comparison of superstructure acceleration above isolator level using different damping levels.

4 DESIGN CRITERIA, LIMIT STATES AND APPLICATION OF REDUCTION FACTORS

The new New Zealand Seismic Isolation Guidelines have two primary limits states, two potential demand reduction factors (one of which, the Sp factor may be applied to both isolator and superstructure demands), a 5% accidental eccentricity (to be applied in the least favourable direction). Combined with 11 or 14 records, and a couple of design iterations, this results in many NLTH runs, a lot of output to process, and therefore in the opinion of the authors, increased scope for mistakes. All the various scenarios that could be envisaged for complex structures are almost impossible to explicitly analyse for. For example 2 Sp x 11 records x upper and lower bound x 4 accidental eccentricity directions = 172 NLTH runs for one limit state, and even that may not address principle axis differences between the sub and superstructure alluded to in the first section of this paper.

Tables 6-1 through 6-5 attempt to provide a summary of how to navigate this process. In reality such tables will never be able to address all the different situations a designer may encounter with real buildings that rarely in the authors' experience conform to textbook examples. There is intended difference in how they are applied across the analysis types to reflect different uncertainties, but these will not always match risks and consequences in the wide range of real buildings. The table only mentions removal of strength reduction factors (ideal properties), where for some limit states the use of probable properties (as defined in the NZSEE assessment guidelines) may be more appropriate.

The Sp, α, and to a lesser degree kμ are actually empirical fudge factors intended coarsely modify risk against consequence. Purely mathematically they aren't consistent. For example, an alpha of 1.2 will reduce the displacement demand to approximately 70% of the theoretical value. This means if the moat is sized as reduced by alpha, in the design CALS event, the structure will collide with the moat wall with approximately 70% of its kinetic energy. Instead they make more sense when applied directly to the output demands than to the hazard. This also does not obscure the relationship between demand and capacity.

We therefore suggest the following three strategies:

- Limit the number of actions that need explicit checking against NLTHA results. Analyse where non-linear and/or higher mode dynamic actions are significant. Benchmark the remainder against simple performance summary criteria like storey acceleration/shear and drift.
- Analyse critical structural assemblies statically using these summary criteria of storey accelerations and drifts applied statically. It is far easier to check unknowns such as varying soil springs or stiffness from composite action in static models to understand the effects, than to plough through masses of NLTHA data to get the same.
- Summarise the behaviours of critical sub-assemblies in the summary language implied by the guidelines. For example 'ensure LRB performance at CALS by deriving the maximum displacement from lower bound properties and prototype testing at these, verifying dependable performance to justify the combination of Sp and α used in this displacement'. The implication here is that probable capacity performance would be adequate to cover no reduction with Sp and α. These statements will typically be in Design Features Report summaries, and in Peer Review query interactions. We suggest the use of dependable, ideal, and probable to describe capacities in these descriptions.

5 CONCLUSION

The draft base isolation guidelines are a huge step forward in achieving consistency in approach for isolation design in NZ. Although Peer Reviewed from the USA, Japan and Europe, it is only through use in the variety of structures we design here that their strengths and weaknesses can be brought out. As no programme is currently underway to update the guidelines to final status, it is important we practitioners capture our comments for the time the future update can occur. It is important, as we have discovered in concluding these issues for ourselves in our designs, that we ensure that we design Seismically Isolated buildings with an appropriately equivalent level of risk so that the public can benefit from this greater level of performance without a 'gold standard' premium of structural life safety conservatism that reduces the performance in smaller likely more regular events, or could render them uneconomic.

REFERENCES

1. Mcverry G, Zhao J, Abrahamson N, Somerville P. New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes. *Bull New Zeal Soc Earthq Eng*. 2006;39:1-58. doi:10.5459/bnzsee.39.1.1-58
2. ASCE. Minimum design loads for buildings and other structures. *ASCE/SEI Stand*. January 2010:7-10.
3. Boore D, Kishida T. Relations between Some Horizontal-Component Ground-Motion Intensity Measures Used in Practice. *Bull Seismol Soc Am*. 2016;107. doi:10.1785/0120160250
4. Campbell KW, Bozorgnia Y, Center. PEER. *Campbell-Bozorgnia NGA Ground Motion Relations for the Geometric Mean Horizontal Component of Peak and Spectral Ground Motion Parameters*. Berkeley, Calif.: Pacific Earthquake Engineering Research Center; 2007.
5. Winters CW, Constantinou MC. Evaluation of static and response spectrum analysis procedures of SEAOC/UBC for seismic isolated structures. 1993.
6. Pant D, Constantinou M, Wijeyewickrema A. Re-evaluation of equivalent lateral force procedure for prediction of displacement demand in seismically isolated structures. *Eng Struct*. 2013;52:455–465. doi:10.1016/j.engstruct.2013.03.013
7. Bommer JJ, Mendis R. Scaling of spectral displacement ordinates with damping ratios. *Earthq Eng Struct Dyn*. 2005;34(2):145-165.
8. York K, Ryan KL. Distribution of Lateral Forces in Base-Isolated Buildings Considering Isolation System Nonlinearity. *J Earthq Eng*. 2008;12(7):1185-1204. doi:10.1080/13632460802003751
9. Skinner RI, Robinson WH, McVerry GH. *An Introduction to Seismic Isolation*. Wiley; 1993. https://books.google.co.nz/books?id=QMhRAAAAMAAJ.