A Practical Approach to Designing Supplementary Damped Isolation Systems

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ABSTRACT

With an update to the NZS1170.5 design hazard anticipated in 2023, New Zealand designers will need to explore innovative solutions to manage potentially significant increases in design hazard, particularly for structures located in the lower North Island.

Seismic base isolation has been increasingly utilized in New Zealand over the past few decades, particularly for new buildings of high importance and in regions of moderate to high seismicity. The reduction in seismic base shear is proportional to an increase in the displacement of the isolation system. However, as seismic hazard increases, this inherent trade-off becomes more challenging. Larger isolator displacements require wider moat widths, more complex flexible service connections, and larger stabilizing structures to cope with P-delta effects. It is crucial to achieve a careful balance between increasing displacement and feasibility of detailing these interfaces.

Base isolation with supplemental damping is an effective way to achieve both increased superstructure period, an effective stiffening behaviour at larger hazards, and provide additional energy dissipation to control displacements. This approach has been recently implemented on a high-importance project in Wellington, New Zealand by Holmes and (to the author's knowledge) is set to be the first of its kind in New Zealand.

This paper presents a practical approach for designing supplementarily damped isolation systems to meet base shear and isolation displacement targets. Interim recommendations for adapting the approach in near-fault regions, as well as early design steps to mitigate common concerns associated with highly damped solutions, are also discussed.

1 INTRODUCTION

The concept of incorporating dampers across the isolation plane in base isolation systems is not new and has been successfully implemented in other regions of high seismicity around the world, for both new construction and seismic retrofit projects.

Traditional base isolation systems, such as lead rubber bearings with sliding pot bearings or curved surface sliding bearings, have been widely adopted in New Zealand over the past decade. However, with the expected update to the NZS1170.5 (Standards New Zealand 2004) design hazard in 2023, there is a need for innovation to manage potential increases in displacement demand.

Innovative systems do not necessarily require costly analysis during the early design phases. A practical design approach that leverages conventional isolation design methods and familiar concepts for practicing engineers is crucial in promoting the use of this technology. This approach should allow the designer to gain a fundamental understanding of the expected parameters, accelerations, and displacements of the system before proceeding to more detailed and compliant analysis methods, such as Nonlinear Time History Analysis (NLTHA).

A traditional design approach has been adapted to consider the influence of velocity-dependent damping devices, particularly in the context of curved surface sliding bearings in combination with fluid viscous dampers. This was in response to a significant displacement demand in a recent Holmes design that utilised a site-specific hazard assessment to provide the uniform hazard spectra. The reduced correlation between yield and design displacement in curved surface sliding bearings is a notable characteristic that makes them an advantageous option for this type of design. It is believed that this approach could also be adapted for lead rubber bearing systems, particularly when the displacement demands of the system are lower.

The approach also includes recommended adaptations for near-fault sites, as well as an investigation into highly damped structures (with a heavy podium and light superstructure).

In applying the proposed design approach, the designer should have a good understanding of key isolation system parameters, such as the yield force and post-yield stiffness of the isolators, non-linear damping coefficient and velocity exponent of the dampers, as well as spectral accelerations and displacements of the equivalent single degree of freedom system for relevant performance objectives.

2 DISPLACEMENT DEMANDS

Figure 1 illustrates a comparison of the displacement spectrum obtained from a probabilistic site-specific hazard assessment and that derived from the NZS1170.5 standard (including modifications from the draft NZSEE seismic isolation guidelines (NZSEE 2019) for a recent IL4 Holmes project. The comparison is made at the Ultimate Limit State (ULS) level.

It is observed that there is an overall increase in displacement demand across all period ranges. This is consistent with the expected changes in seismic hazard in the region. It is anticipated that the 2023 update to the NZS1170.5 design hazard will capture a similar increase in displacement demand.

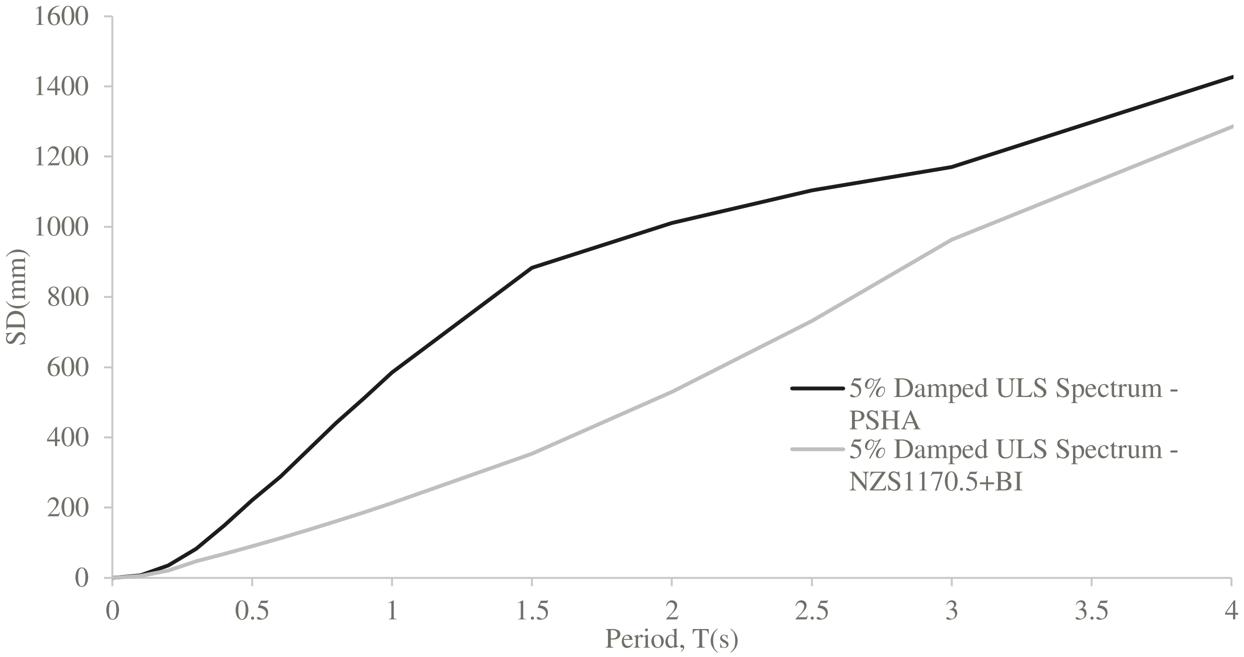


Figure 1: Displacement-Period Comparison between PSHA and NZS1170.5 hazard including NZSEE Seismic Isolation guidelines modifications, for an IL4 site in Wellington, New Zealand

3 TRADITIONAL SCHEME DEVELOPMENT

3.1 Draft NZSEE Seismic Isolation Guidelines

There are various methods for designing traditional systems, but the approach outlined in the draft NZSEE seismic isolation guidelines is commonly used as the basis for the SDOF ADRS method. This approach involves an iterative process to converge on an effective secant stiffness, with the damped ADRS demand curves. For this reason, the details of the approach are not repeated.

A crucial aspect of this approach is accounting for uncertainty. The uncertainty bounds (either from BS-EN15129 (British Standard 2018) or ASCE7 (ASCE Standard 2016) have a significant impact on the design scheme, depending on the isolation system adopted. It is not always practical to further rationalise these bounds at the early stages of design, which often limits optimisation of schemes.

3.2 Limitations when large displacements are present

Where large displacements are present, traditional design approaches can be limiting.

For example, lead rubber bearings require a minimum overlap area of the lead core at design displacement, which influences the yield force and the maximum reduction in seismic base shear that the structure can achieve.

In contrast, solutions with larger displacements are more feasible with curved surface sliding bearings, as their yield is a function of axial load, which is less dependent on design displacement. However, energy dissipation (hysteretic hoop area) under lower bound solutions is often low, with most of the reduction in seismic demand attributed to elongating the period. To control displacements, a minimum yield force (in the form of increased friction coefficient) is required. In conflict to this displacement-based target, when solving upper bound conditions, the maximum reduction in seismic base shear achieveable is often limited.

The limitation of traditional design is that it can generally only control one performance objective well, such as displacement, at the expense of others, such as design base shear coefficient.

4 SUPPLEMENTAL DAMPING

As previously mentioned, the use of supplementary damping in base isolation systems is not a novel concept and has been adopted internationally. The incorporation of damping across the isolation plane provides an opportunity for additional control over key performance objectives and helps to overcome the limitations of traditional design approaches.

The combined system acknowledges that one component (isolators) is displacement-dependent, while the other (viscous dampers) is velocity-dependent. Supplementary damping is a useful method to both enhance energy dissipation and effectively stiffen response during critical lower bound performance scenarios – such as collapse avoidance (CALS), when system velocities are high. This does not necessarily lead to an increase in seismic base shear at upper bound performance objectives, such as the ultimate limit state (ULS), as system velocities is lower, thus reducing the effective stiffening attributed from the dampers.

Additionally, it offers an opportunity to manage hazard and design uncertainty by enabling the derivation of key parameters with confidence during the early design phases, such as moat clearance and superstructure design base shear, with some flexibility.

5 PROPOSED METHODOLOGY

5.1 Process

The proposed methodology for designing supplementarily damped isolation systems is an iterative approach that leverages familiar concepts for practicing engineers. It does require careful judgement when making initial assumptions to converge on a solution.

To simplify the process, it is recommended to initially target a displacement-critical constraint, such as a rattle space size. Additionally, using lower bound properties for the isolator system and nominal properties for the dampers will reduce the number of unknowns. The resulting converged solution can then be used to determine performance at all relevant hazards.

The methodology has been written assuming a curved surface sliding bearing. For bearings with more than one sliding surface, the intent is that μ_{nom} represents the averaged dynamic seismic nominal friction.

Equations to calculate energy dissipated by a non-linear viscous damper per each cycle (area under the force-displacement curve, $A_{hyst,FVD}$) are available (Christopoulos and Filiatrault 2006).

Given the initial steps are conducted with nominal damper properties, the true converged lower bound displacement at CALS will often be larger than initial estimate – the designers should consider this effect and adjust targets accordingly. It is reccomended to investigate the full combination of bounding pairs (e.g UB_{FVD}:$LB_{isolators}$) to determine the true worst-case bounds for design.

Effective single pendulum radius, $R_{eff,iso}$, which is a simplistic representation of the response at peak displacement, is often a useful parameter to discuss across multiple isolator providers who have various staged performances of their system.

For extreme seismic events, a further degree of control can be realised through implementation of a velocity cap in the dampers (generally acknowledging the step change in velocity of dampers between ULS and CALS hazards). In some special scenarios, implementation of staged non-linear damper could be beneficial.

Target Performance Objectives

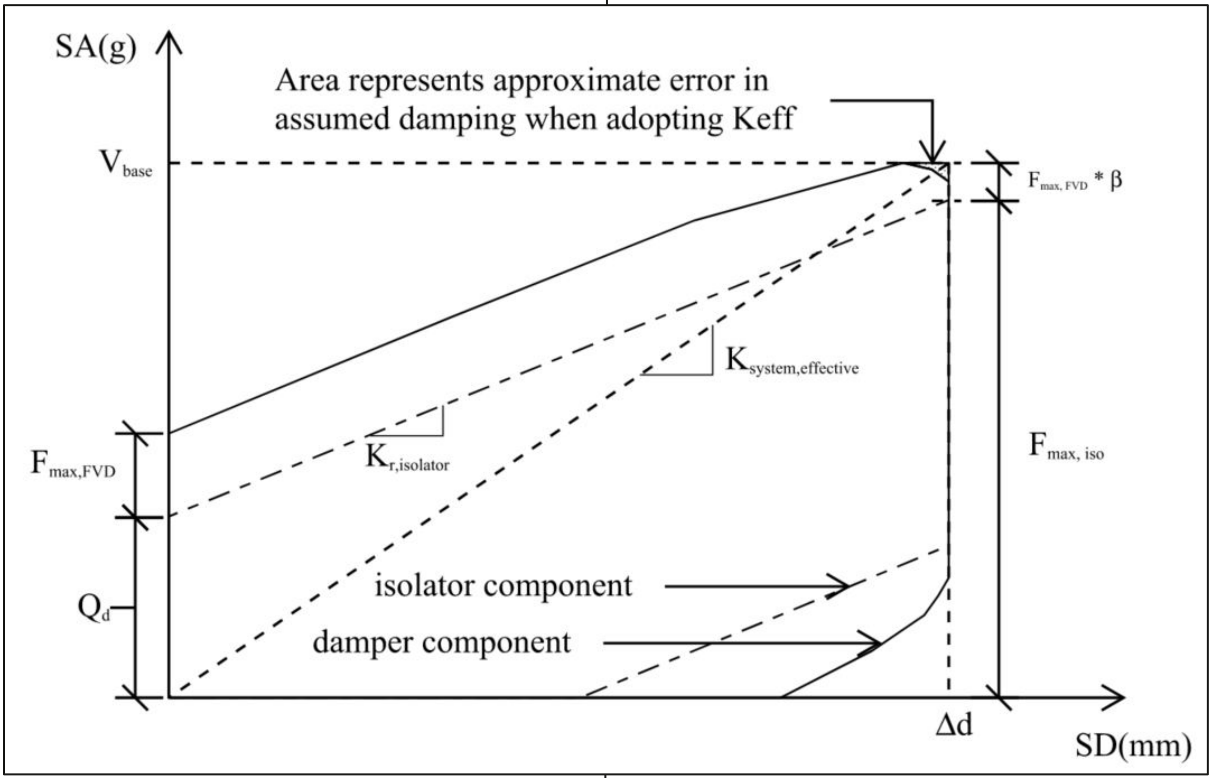
$SA(g)_{DCLS,nom}$, $SD(mm)_{DCLS,nom}$, $SA(g)_{ULS,UB}$, $SD(mm)_{CALS,LB}$

Additional performance objective targets may be appropriate.

Determine the 5% Damped Acceleration Displacement Response Spectrum

Estimate Key Parameters

$$\mu_{nom}\,,\gamma = \frac{Fmax_{FVD}}{Fmax_{iso}}\,,\beta, \alpha_{vd,FVD}, \xi_{system,effective}, T_{system,effective}$$

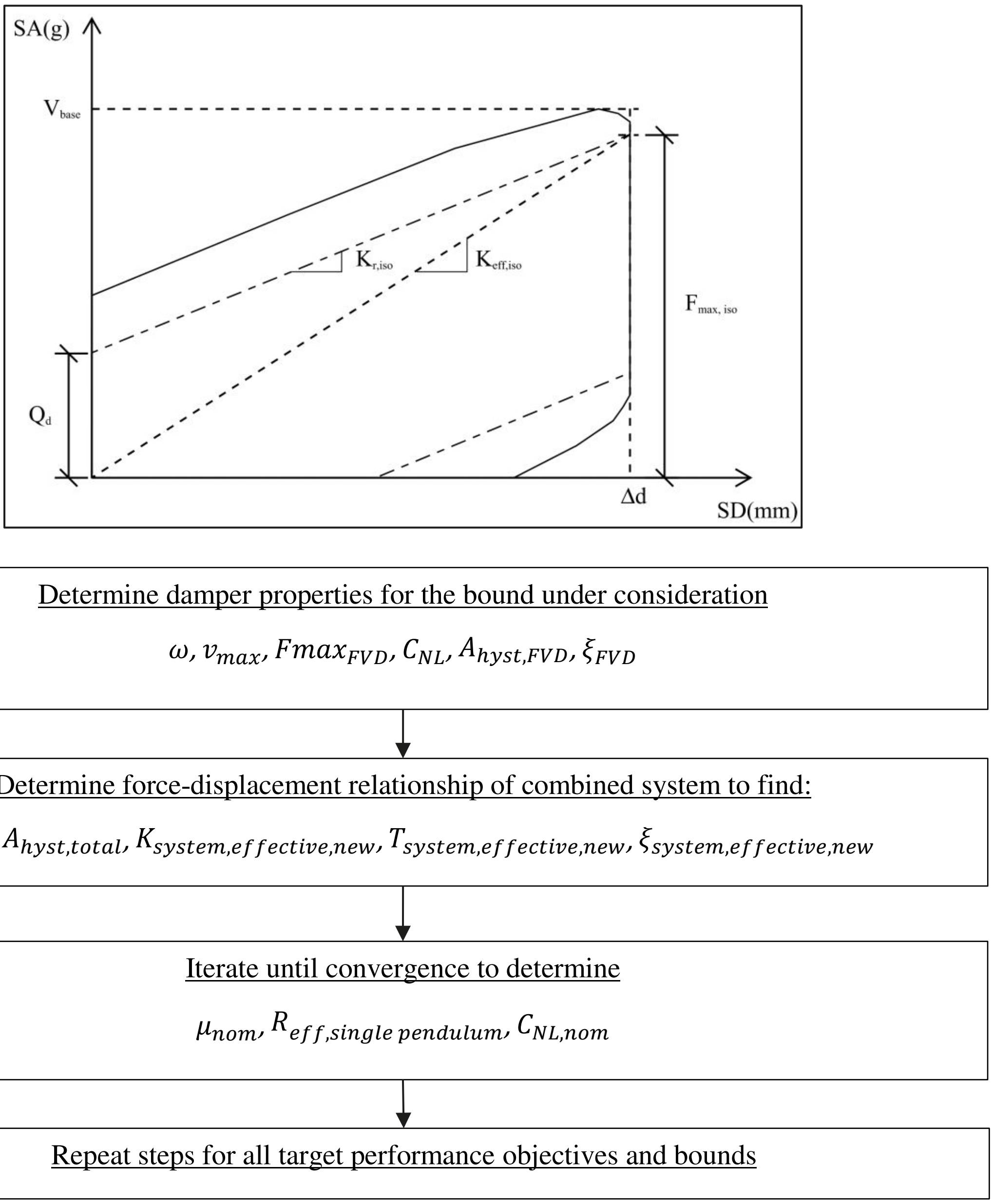


Determine Initial V_{base} and Δ_d

Determine isolator properties for the bound under consideration

$$Q_d, Fmax_{iso}, K_{r,iso}, K_{eff,iso}, R_{eff,single\ pendulum}\frac{W_{tot}}{K_{r,iso}}\,, A_{hyst,iso}, \xi_{iso}, T_{iso}$$

Figure 2: Proposed Supplementary Damped Iterative Design Approach



Determine damper properties for the bound under consideration

$\omega, v_{max}, Fmax_{FVD}, C_{NL}, A_{hyst,FVD}, \xi_{FVD}$

Determine force-displacement relationship of combined system to find:

$\beta_{new}, A_{hyst,total}, K_{system,effective,new}, T_{system,effective,new}, \xi_{system,effective,new}$

Iterate until convergence to determine

$\mu_{nom}, R_{eff,single\ pendulum}, C_{NL,nom}$

Repeat steps for all target performance objectives and bounds

Figure 2 Continued: Proposed Supplementary Damped Iterative Design Approach

5.2 Example Building

A SDOF example of a high importance 5-floor structure in a high seismic region is discussed. This is compared to an equivalent isolator only system. A 5% damped acceleration and displacement spectrum has been provided in Figure 3 below which includes the corresponding damped spectrum at relevant hazards. Table 1 provides a summary of the key parameters in the system, adopting the approach outlined in Section 5.1. For this example, torsional effects have been ignored. Table 2 provides a summary of system performance and a comparison against a traditional approach.

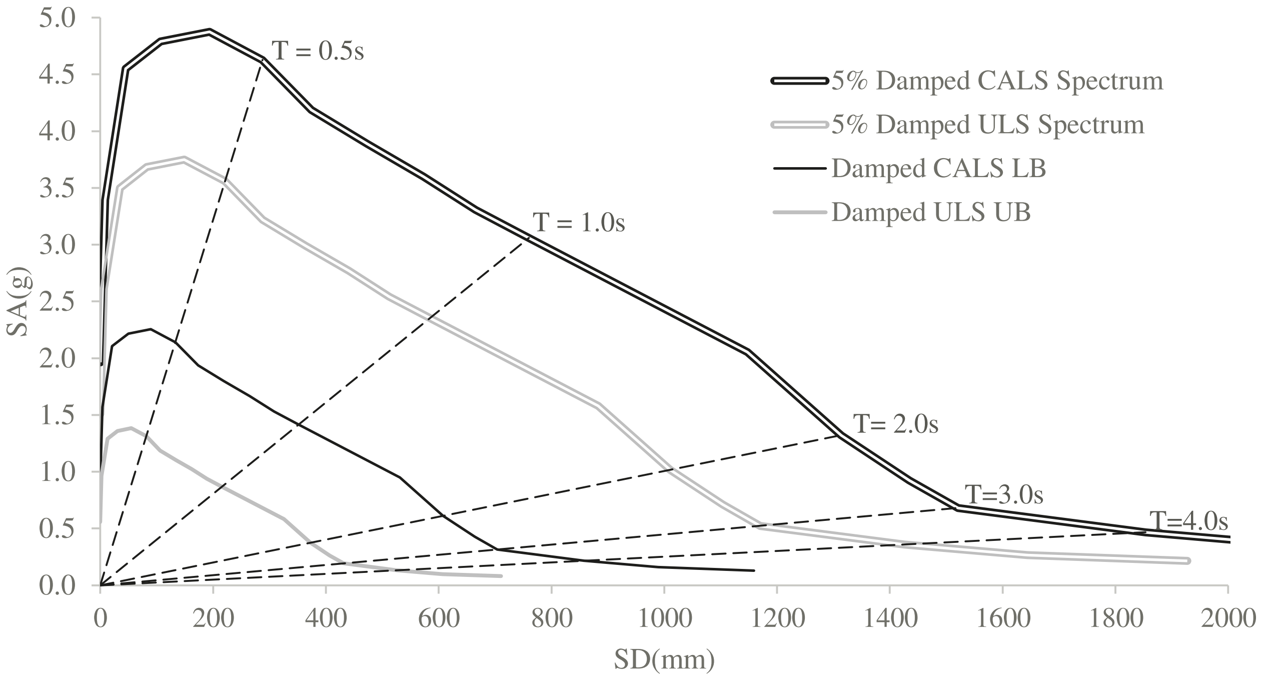


Figure 3: Acceleration-Displacement Response Spectra for Supplementarily Damped Example Building

The draft NZSEE seismic isolation guidelines (NZSEE 2019) recommend considering a maximum damping of 30% when conducting a Modal Response Spectrum Analysis (MRSA). ASCE7-16 (ASCE Standard 2016) adopts a similar limit for its Equivalent Lateral Force Procedure. For this reason, the comparison targets the same base shear when damping is capped at 30%.

The limitations highlighted in Section 3.2 can be observed when comparing the spectral displacement at CALS LB for an equivalently damped ULS UB system (Table 2) – or against a converged system with comparable friction coefficients (Table 3). Friction coefficients closer to 5-8% are more achievable in practice. Therefore, the true traditional system will have spectral displacements approaching Table 3. In contrast, the supplementarily damped system controls displacement demands at CALS LB as well as accelerations at ULS UB. The traditional system could reduce displacements at CALS LB performance objectives by accepting larger ULS UB seismic base shears.

Table 1: System Parameters for Example Supplementarily Damped Building

Parameters	**ULS UB**	**CALS LB**
W_t (kN)	50910	
μ_{nom} (%)	5	
K_r (kN/m)	7926	
γ	0.57	0.41
β	0.55	0.48
α_{vd}	0.7	0.7
$v_{max}^{(1)}$ (m/s)	1.09	

C_{NL} (kNs/m)	4604	3403

Note 1 - Velocity cap in dampers to further control performance

Table 2: Comparison Summary of System Performance of an IL4 structure in a high seismic region for an equivalently damped ULS UB system targeting same ULS base shear

	ULS UB		**CALS LB**	
	Supplementarily Damped System	Traditional System $^{(1)}$	Supplementarily Damped System	Traditional System $^{(1)}$
SA (g)	0.19	0.19	0.22	0.19
SD (mm)	432	432	**854**	**1045**
$\xi_{effective}$ (%)	49.5	49.5	30.7	26.8
$T_{effective}$ (s)	2.99	2.99	3.92	4.87
SA (g), ξ_{max} – 30%	**0.25**	**0.25**	0.23	
SD (mm), ξ_{max} – 30%	547	547	863	

Note 1 – μ_{nom} of 14.8% and K_r of 4981kN/m to achieve comparable ULS UB performance

Table 3: Comparison Summary of System Performance of an IL4 structure in a high seismic region with comparable friction coefficients targeting same ULS base shear

	ULS UB		**CALS LB**	
	Supplementarily Damped System	Traditional System $^{(1)}$	Supplementarily Damped System	Traditional System $^{(1)}$
SA (g)	0.19	**0.25**	0.22	0.44
SD (mm)	432	728	**854**	**1750**
$\xi_{effective}$ (%)	49.5	20.8	30.7	5.9
$T_{effective}$ (s)	2.99	3.40	3.92	4.01
SA (g), ξ_{max} – 30%	**0.25**		0.23	
SD (mm), ξ_{max} – 30%	547		863	

Note 1 – μ_{nom} of 5.0% and K_r of 11535kN/m

6 RECOMMENDATIONS FOR SUPERSTRUCTURE DESIGN

There is literature (York and Ryan 2008) which suggests high levels of isolation system damping can amplify higher mode effects in the superstructure. Supplementarily damped isolation systems can result in total equivalent viscous damping higher than more conventional systems, particularly for upper bound ULS conditions which determine superstructure design forces.

The draft NZSEE seismic isolation guidelines (NZSEE 2019) outline four equivalent lateral force distributions (Methods A through D) – with only method D incorporating the effective equivalent viscous damping, ξ_{sys}, as a factor. Method D is intended to be used for buildings with three storeys or less where a large percentage of the building's seismic mass is in the base slab. The equations that incorporate ξ_{sys} is repeated below to support discussion.

$$V_{st} = V_b \left(\frac{Ws}{W}\right)^{(1-2.5\zeta_{sys})} \tag{1}$$

$$C_{vx} = \frac{w_x {h_x}^k}{\sum_{i=1}^{n} w_i {h_i}^k} \tag{2}$$

$$k = 14\zeta_{sys} T_{1,fixed-base} \tag{3}$$

where:

V_{st} *= base shear for superstructure above the isolation plane.*
V_b *= base shear of the SDOF isolation system.*
W *= effective seismic weight about the isolation plane.*
W_s *= effective seismic weight excluding effective seismic weight of base level.*
w_i, w_x *= portion of seismic weight that is located at or assigned to Level i or x.*
h_i, h_x *= height above the isolation interface of Level i or x.*
C_{vx} *= vertical distribution factor;* ζ_{sys} *= effective damping of the isolation system at the maximum displacement.*
$T_{1,fixed-base}$ *= fixed base fundamental period of the superstructure.*

The factor 'k' has an impact on lateral load distributions by affecting the effective height of the superstructure. High damping will result in a higher overturning moment for the same base shear when adopting Method D.

Figure 4 and Figure 5 show the results of simplified time history analyses where a lightweight 5-storey superstructure is above a heavy isolated podium. The aim of this analysis was to determine the validity of the equations above, and to ensure that all equivalent lateral load distributions (Methods A through D) were representative. Two fixed base periods were investigated; a stiff superstructure ($T_{effective}/T_{1,fixed-base} = 5$) and a more flexible ($T_{effective}/T_{1,fixed-base} = 3$). The effective system damping was varied between 35-40%.

From the results it was observed that varying the damping had minimal impact on the overturning moment. It further highlighted that for a supplementary damped isolated system with high damping, adopting ‘k’ as derived above was conservative, and a value of 1 more appropriate. Additionally, it highlighted that Method D is appropriate to consider even though it exceeded the three-storey limit.

It is recommended to conduct a representative, but simplified time history analysis for highly damped superstructures. The purpose is to determine the applicability of Methods A through D (including modifications) when undertaking an equivalent static analysis prior to NLTHA validation.

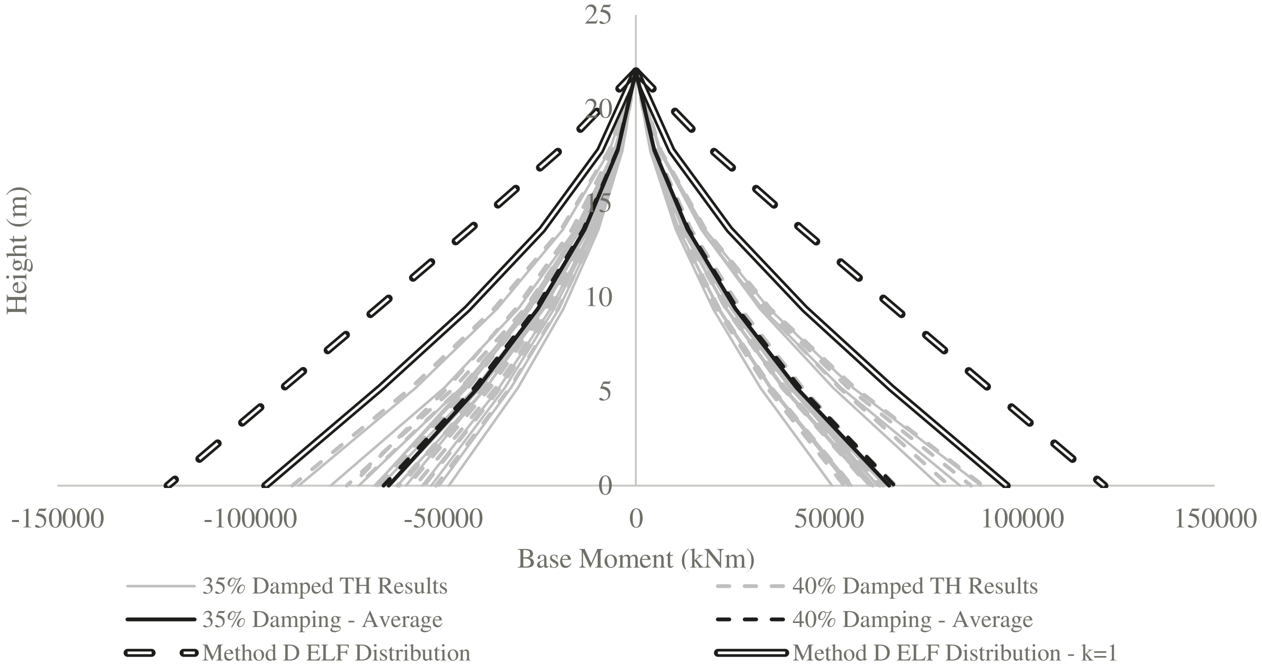


Figure 4: Overturning moment of averaged time history results against the Method D equivalent lateral force application, with $T_{effective}/T_{1,fixed\text{-}base}$ =5

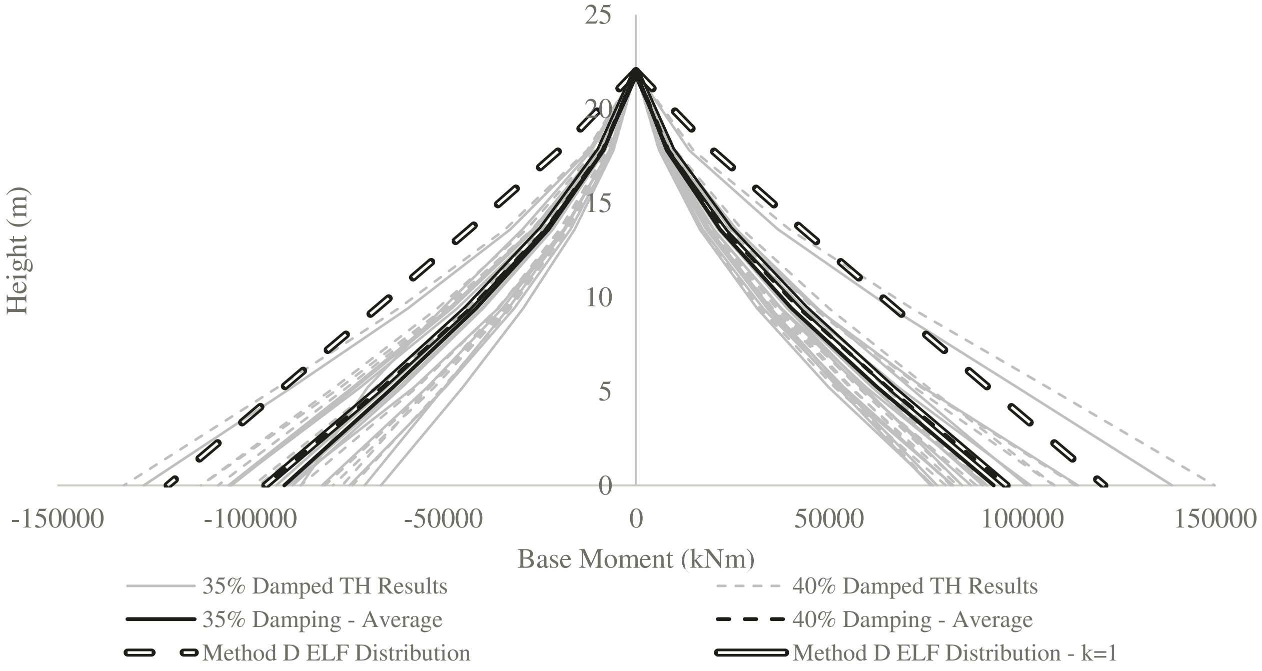


Figure 5: Overturning moment of averaged time history results against the Method D equivalent lateral force application, with $T_{effective}/T_{1,fixed\text{-}base}$ =3

7 ACCOUNTING FOR NEAR-FAULT EFFECTS ON RESPONSE

Near-fault ground motion characteristics, such as directivity and pulse-like behaviour, are distinct from those of far-field events. Adopting the iterative approach in this paper for near fault sites without adequate consideration of these effects is not reccomended.

When designing supplementarily damped isolation systems to account for these conditions, it is expected that the displacement response from single degree of freedom (SDOF) analysis will be underestimated if near-fault effects on damping are ignored. Equation 5-5 in the draft NZSEE seismic isolation guidelines has been reproduced below, with the exponent replaced with the symbol, α. A suggested value for sites with forward directivity is 0.25, however, this is based on limited data *(Priestley, Calvi and Kowalsky 2008).*

$$B_{\zeta} = \left(\frac{0.07}{0.02+\zeta_{system}}\right)^{\alpha} \tag{4}$$

Figure 6 illustrates the results of simplified time history analyses of a lightweight 5-storey superstructure above a heavy isolated podium under CALS LB conditions. The analyses include a suite of earthquake records, including near-fault events. The parameters for the isolation system were derived targeting a spectral displacement of approximately 860mm. The results from the averaged Nonlinear Time History Analyses (shown as solid black triangles) indicate that the expected displacements are approximately 25% higher than the target displacement.

This potential impact on displacement was identified early in the design process. To address this, an allowable movement was established, and a target Single Degree of Freedom (SDOF) spectral displacement was determined by scaling down the allowable displacement. For instance, given a maximum vector displacement of 1070mm, an 860mm target for SDOF iteration was deemed appropriate. This approach, although simplified, was found to yield a suitable solution without the need for excessive analysis. The validity of this estimation was reinforced by conducting simplified lumped mass time history analyses.

Additional research is necessary to fully comprehend the effects of the exponential term in the damping reduction equations when supplementarily damped isolation systems are applied to near-fault sites. Figure 6 illustrates the damped hazards for the same system damping, with varying alpha factors. This suggests that there may be benefits to determining an appropriate alpha factor through iterative scheme development. However, it is important to carefully weigh the value of this analytical effort against the potential outcome, as the simplistic approximation used in this case appears to effectively address the critical concern.

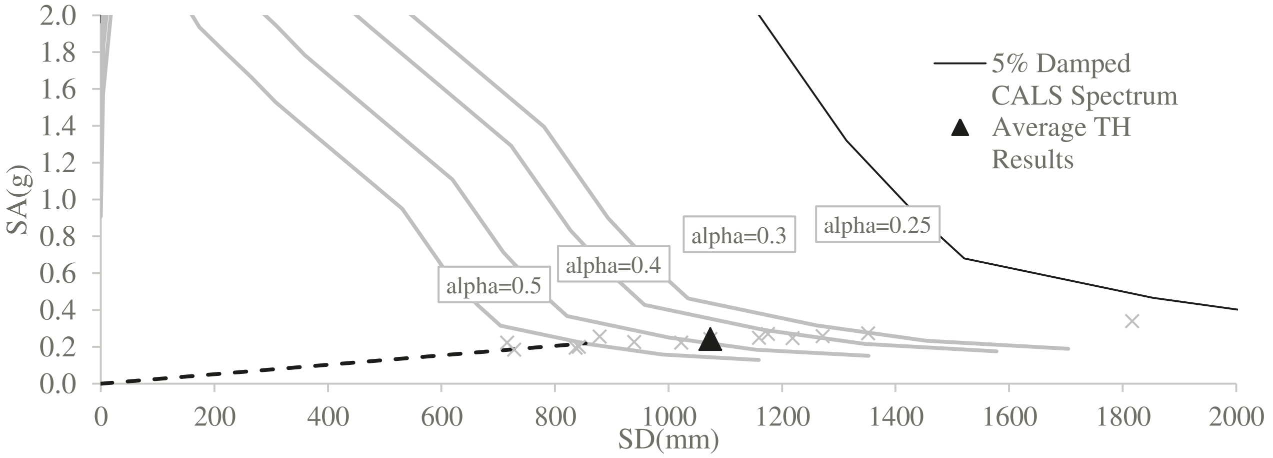


Figure 6: Damped CALS LB Spectrum adopting various alpha values and a total equivalent viscous damping ratio, ξ_{eq}, of 30.7%

8 CONCLUSIONS

The updated NZS1170.5 design hazard is expected to result in significant increases in design hazard, particularly for structures located in the lower North Island. There are practical limitations when continually increasing design displacement to control seismic demands. Where large displacements are present, traditional isolation design methodologies can be limiting. Supplementarily damped isolation systems provide additional control over both displacement and accelerations.

A practical method to scheme supplementarily damped isolation systems has been presented, with an emphasis on understanding key parameters and performance objectives prior to more detailed Nonlinear Time History Analyses. Near-fault ground motion characteristics, such as directivity and pulse-like behaviour, need careful consideration, particularly for effective damping reductions to displacements – but indications from the work completed to-date is that current literature may be too conservative in determining this reduction factor. Furthermore, the influence of high levels of isolation plane damping on superstructure design needs careful consideration, however the potential for significant increases in overturning moment when high system damping is used did not prove problematic, and regular and well-proportioned superstructures do not seem affected by the high damping introduced by viscous dampers.

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