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GUIDELINE FOR DESIGN OF BUILDINGS WITH SEISMIC ISOLATION IN NEW ZEALAND

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Abstract

A guideline for design of buildings with seismic isolation in New Zealand was published in 2019 for trial use by the industry. The guideline was prepared by a group of specialist practitioners with experience in design of base-isolated buildings and reviewed by several international experts. The project was funded by New Zealand government agencies and technical societies. The guideline provides a methodology for designing isolated buildings in accordance with the NZ national building code and associated compliance standards for structural design of buildings. The document contains sections on isolated building types, performance objectives, design limit states and design philosophies, design spectra for acceleration and displacement demands, analysis methods, design of the superstructure, the isolation system and substructure, detailing of isolation plane, specification for procurement of isolators and recommendations for inspection and maintenance. The recommended design methodology is a displacement-based approach. Acceleration-displacement response spectra (ADRS) and capacity spectra methods are proposed for design of simple structures and preliminary design of more general isolated systems. A number of examples are given of displacement and acceleration demands for major New Zealand cities, with various building importance levels, ground conditions and isolation system properties. The examples show a wide range of acceleration and displacement demands which will be useful preliminary design guidance for engineers designing buildings with seismic isolation.

Keywords: seismic isolation; New Zealand; design guideline

1. Introduction

A draft guideline (the Guideline) for the design of seismic isolation systems for buildings in New Zealand has recently been completed for trial use by the industry [1]. This paper summarises the content of the Guideline and also provides results of a limited parametric study of displacement and acceleration demands for typical isolation systems located in the main cities of New Zealand.

Primary funding for the project was provided by government agencies, the Ministry of Business Innovation and Employment (MBIE) and The Earthquake Commission (EQC), with additional support from professional technical societies, the New Zealand Society for Earthquake Engineering (NZSEE), Structural Engineering Society (SESOC) and New Zealand Concrete Society (NZCS).

The Guideline was prepared by specialist practitioners from the major New Zealand science agencies and engineering consultancies with experience in designing base-isolated buildings and it was reviewed by international experts from the USA, Japan and Italy.

2. Recent damaging earthquakes in New Zealand

In 2010 and 2011 the city of Christchurch was severely impacted by a sequence of strong earthquakes. The sequence started with a M_w7.1 Darfield Earthquake with fault rupture within 20 km from the central business district (CBD) of Christchurch. Peak ground accelerations (PGA) in the CBD from that event were in the order of 0.3g and there was widespread damage to buildings, but no loss of life. The Christchurch Earthquake aftershock with magnitude M_w6.2 was centred within 3 km of the CBD and caused very strong ground shaking with peak ground accelerations in the order of 0.7g. This event caused widespread damage, collapse of several buildings and, sadly, the loss of 185 lives. Several other moderate aftershocks had PGA shaking intensities of around 0.2g and caused further damage. The direct cost of damage was in the order of US$40B and around 1500 buildings in the CBD were demolished. A Royal Commission of Inquiry was set up by the New Zealand Government to report on the effects of the earthquakes [2]. In the aftermath of these earthquakes many buildings have been rebuilt and some owners and engineers have chosen more earthquake resistant and resilient systems such as base-isolation and other energy dissipative systems.

In 2016 the M_w7.8 Kaikoura earthquake caused strong and prolonged ground shaking across a substantial area of the northern part of the South Island and in Wellington City. The earthquake caused extensive land-sliding and disruption to transportation infrastructure along the Kaikoura Coast. The main highway and railway infrastructure were severely disrupted and required major repair work to restore service. Significant damage was caused to a number of buildings in the Wellington area, particularly several on reclaimed land around the Wellington City waterfront. Around ten buildings were demolished as a result of severe damage that was uneconomic to repair. Buildings in Wellington with seismic isolation or other protective systems generally performed well with little damage reported. The effects of the Kaikoura Earthquake have been reported in the NZSEE Bulletin publication [3].

As a result of these recent damaging earthquakes, there is a heightened interest in developing more earthquake resilient (ie damage-resistant and readily repairable) buildings in New Zealand, especially seismic isolation.

3. Recent New Zealand projects with seismic isolation

As at 2019 there are more than 100 isolated structures in New Zealand. Fig. 1 shows the approximate growth in numbers of isolated structures over time, including the types of structures and isolation types. Most isolated structures are bridges and there is a steady increase in the number of isolated structures since 2010.

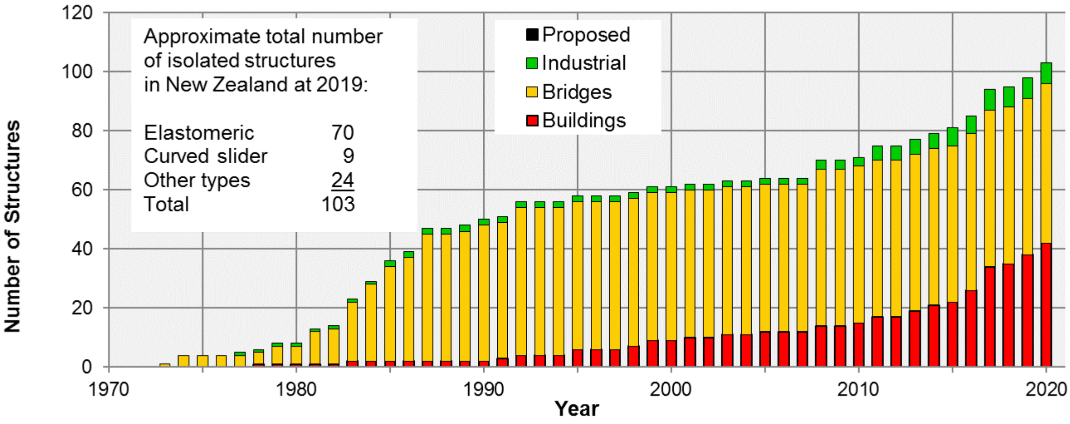

Fig. 1 – Growth in numbers of structures with seismic isolation in New Zealand

4. Guideline for design of seismic isolation systems for buildings

NZSEE has recently published a new guidance document *Guideline for Design of Seismic Isolation Systems for Buildings* [1].

The Guideline sets a framework and recommendations for designing buildings with seismic isolation, generally in accordance with New Zealand Building Code and the Structural Loading Standard NZS 1170.5. It provides recommendations that supplement the requirements for normal buildings to take account of the special nature of isolation systems, in particular the period elongation and additional damping available once the isolation system is activated.

The Guideline contains chapters outlining four prescribed isolated building types, performance objectives for designing isolated buildings, design limit states and design philosophies, design spectra for acceleration and displacement demands, analysis methods, design approaches to be used for the various components of an isolated building; ie superstructure, isolation system and substructure, detailing of the isolation plane, guidance on preparing technical specifications for procurement of the isolation system and isolator devices, as well as recommendations for inspection and maintenance of the isolation system and components. Each Chapter is presented as recommendations and associated commentary.

The content of the Guideline chapters is summarised in the following sections.

4.1 Chapter 1 - Introduction

The Introduction outlines the purpose, scope and exclusions of the Guideline.

The Guideline is intended for isolation systems with bilinear type hysteretic behaviour comprising combinations of elastomeric (including lead-rubber) and flat slider isolators, or curved surface slider systems. Supplementary viscous damper devices may also be included.

Four isolated building types are proposed, and designers must select, within specified criteria limits, which type they will design for and follow all of the requirements for that type. The four isolated building types are summarised as follows:

Type 1	**Simple** - regular and low-rise superstructures. Equivalent static analysis is permitted, and structural elements are to be designed to remain elastic.
Type 2	**Normal** – more general isolated building layouts not meeting Type 1 requirements. Modal response spectrum analysis methods and structural design and detailing for nominally ductile behaviour are required as a minimum.

Type 3 **Complex** – isolated buildings where some inelastic deformation in the superstructure may be expected, or the isolation plane does not provide for the full displacement demand on the system. Numerical Integration (nonlinear) Time History Analysis and capacity design is required.

Type 4 **Brittle** – for brittle superstructures including existing structures. Numerical Integration Time History Analysis and design for elastic response is required.

The Chapter outlines how compliance with the Building Code is intended to be achieved and limit states that are recommended to be considered. It is recommended that designs for buildings with seismic isolation should be independently peer reviewed.

4.2 Chapter 2 - Isolated building system and design philosophy

Chapter 2 sets out the detailed criteria and limitations for the four isolated building types which determine the approach to be used for analysis and design of each. It also identifies the functions and design philosophy for the five key components of an isolated building: foundation and substructure, isolator system, isolation gap, isolator stability elements and superstructure.

4.3 Chapter 3 - Building performance

Chapter 3 provides guidance to engineers and owners on the performance objectives and criteria to be considered in addition to Building Code requirements for normal buildings, in particular performance related to the reduction of damage and downtime in buildings.

In addition to NZS 1170 Serviceability (SLS) and Ultimate (ULS) Limit States, the Guideline recommends that a Damage Control Limit State (DCLS) and a Collapse Avoidance Limit State (CALS) are considered for isolated buildings. It is recommended that building isolation systems should be shown explicitly to be capable of surviving displacement demands for the rare earthquake event referred to in NZS 1170.5 (generally assumed to be 1 in 2,500 years) without collapse. The rare earthquake in NZS 1170.5 is similar to the Maximum Considered Earthquake (MCE) used in other international codes.

The approach recommended in the Guideline is consistent with “low damage design” philosophies. The expected performance will generally exceed the minimum required by the national building code. An important principle is to communicate and agree the intended performance objectives with the building owner and to record these objectives in a Design Features Report.

A “Star Rating” system is suggested, including “minimum” (4-Star) and “recommended” (5-Star) performance levels.

4.4 Chapter 4 - Seismic Hazard spectra and ground motions

Chapter 4 provides recommended seismic hazard spectra, both acceleration and displacement, for isolated structures, based on the acceleration response spectra (hazard spectra) in NZS 1170.5. A response modification factor is included to account for the effects of increased levels of equivalent viscous damping compared with the 5% viscous damping value assumed in NZS 1170.5.

Using the recommended displacement spectra provided allows designers to represent seismic demands in acceleration-displacement response spectra (ADRS) format. This format is convenient for graphically presenting the behaviour of isolated structures using simplified capacity-demand methods for determining base shear and displacement response demands on the isolation system.

The Guideline includes changes to the long period portions of the NZS 1170 acceleration spectra, which typically govern the design of isolated buildings. The corner period T_L, at which the constant displacement part of the spectrum starts, has been extended from 3 seconds to 5 or 10 seconds for most of the country. This has the effect of increasing displacement demands on isolation systems with periods greater than 3 seconds in most areas.

For the CALS limit state a scaling factor is provided to increase the ultimate limit state acceleration and displacement earthquake demands to be considered for the rare earthquake event. A factor of 1.5 is proposed for buildings of Importance Level 2 (normal occupancy) and 3 (buildings of higher than normal importance containing crowds) and a factor of 1.3 is proposed for Importance Level 4 (requiring post-disaster functionality) buildings. The CLS scaling factor may be reduced by a Robustness Factor “α” , ranging from 1.0 to 1.2, reflecting the expected robustness of the isolation system configuration.

Guidance is also provided on procedures for site-specific seismic hazard studies, selection and scaling of ground motion records for numerical integration time history analysis, and use of conditional hazard spectra methods for analysis and design of isolated structures.

4.5 Chapter 5 - Analysis requirements and methods

Chapter 5 sets out the requirements for the seismic structural analysis of isolated buildings, including both linear and non-linear methods. Recommended analysis methods include single degree of freedom and equivalent lateral force (static) analysis, plus modal response spectrum and numerical integration time history (response history) analysis. The method of analysis to be used is determined based on the isolated building type specified in Chapter 1.

Preliminary analysis for all isolated building types is recommended to start with single degree of freedom analysis of an assumed rigid building on a flexible isolation layer, followed by more detailed analysis using equivalent static, modal response spectrum or numerical integration time history analysis, depending on the type and complexity of the building.

Consideration of isolator property variability (upper and lower bound) is required in addition to target isolator system properties. Generally upper bound properties give maximum force demands on the structure, and lower bound properties give maximum displacement demands on the isolators. The isolator variability parameters from both ASCE 7Chapter 17 [4] and EN 15129 [5] are referenced.

4.6 Chapter 6 - Design

Chapter 6 provides design flow charts are provided for each isolated building type that address design of the isolated building overall, including design of the substructure and superstructure, isolation system, adjacent stability structure, isolation plane and isolation gap clearances. Checklists are provided for designers to check that the design remains within the criteria applicable to each building type.

For most isolated structures the Structural Performance Factor S_p, used by NZS 1170.5, is recommended to be 1.0 and the superstructure is recommended to be designed to remain elastic or perhaps nominally ductile. Guidance is provided for design parameters for materials standards for design of foundation, substructure and superstructure. A minimum level of ductile detailing and capacity design will generally be required in the superstructure to allow for possible inelastic demands that are possible under extreme earthquakes.

4.7 Chapter 7 - Detailing of the isolation plane

Chapter 7 establishes performance requirements for the isolation plane and isolation system as whole and individual isolators. It also provides detailing guidance for structure, secondary structure and non-structural components which cross the isolation plane. The isolation plane should be detailed to ensure construction, maintenance and operation during the life of the building continue to meet the appropriate performance requirements.

An example part-diagram from the Guideline, showing a cross-section through a lift shaft with adjacent non-structural elements and seismic gaps that would be required, is shown in Fig. 2.

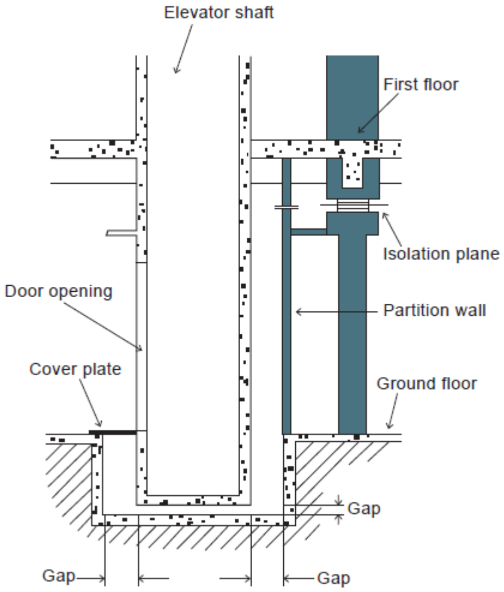

Fig. 2 – Example of diagram showing seismic clearances required at a suspended lift shaft (part of Figure 7-4 from the Guideline)

4.8 Chapter 8 - Specification for procurement of isolation system and isolators

Chapter 8 provides recommendations for preparing a performance-based specifications for procurement of the isolation system and isolator devices, largely based on ASCE 7 Chapter 17 and EN 15129.

Designers are recommended to select the type and number of isolators required and to prepare a performance-based specification giving the combinations of design forces and displacements that isolators are to withstand. It is strongly recommended that detailed design of the isolators is left to the supplier in accordance with an approved international standard. Qualification, prototype and production testing sequences and acceptance criteria are to be specified. Full-scale testing of isolators or similar prototypes is generally required, as is testing of production units. Load testing of 100% of production units is desirable, together with suitably qualified independent technical overview.

4.9 Chapter 9 - Inspection and maintenance

Chapter 9 recommends that an inspection and maintenance programme including reporting requirements should be established and agreed with the client. The planned programme should include warning signage, a maintenance manual, installation of displacement recorders or other instrumentation, as well as type and frequency of inspections for the entire isolation system and its various components.

4.10 Appendix C - Sample specification for seismic isolation system components

Appendix C of the Guideline provides a generic technical specification for procuring isolator systems and various device types. Sections include a General specification for the system, and specific technical sections for curved-surface slider devices, elastomeric isolators including lead rubber bearings, flat slider bearings and supplemental viscous damping devices (used in conjunction with other elastomeric devices).

6. Design acceleration and displacement spectra

6.1 Spectral shape functions

The Guideline provides acceleration and displacement spectra for design of isolated structures. The design spectra are based on NZS 1170.5 elastic hazard (acceleration) spectra and derived displacement spectra. The design base shear coefficient and displacements are given in Equations 1 and 2.

$$C(T) = C_h(T)\ Z\ R\ N(T, D)\ B_\xi \tag{1}$$

$$\Delta(T) = \Delta_h(T)\ Z\ R\ N(T, D)\ B_\xi \tag{2}$$

where $C(T)$ is the design base shear coefficient

$C_h(T)$ is the spectral shape factor (for acceleration)

$\Delta(T)$ is the elastic site displacement in mm

$\Delta_h(T)$ is the displacement spectral shape factor

B_ξ is the spectrum scaling factor to account for damping (less than or equal to 1.0)

Z is the hazard factor, R is the return period factor and N(T, D) is the near-fault factor according to NZS 1170.5.

An example acceleration Ch(T) versus displacement $\Delta_h(T)$ spectral shape for deep or soft ground (subsoil category D) is plotted in Fig. 3. The effect of the variable corner period T_L on the spectrum can be seen, where the solid red curve changes to dashed and dotted lines for periods exceeding 3 seconds or 5 seconds. In those cases, for long periods, spectral displacements increase beyond the normal constant displacement assumed in the standard NZS 1170.5 spectrum.

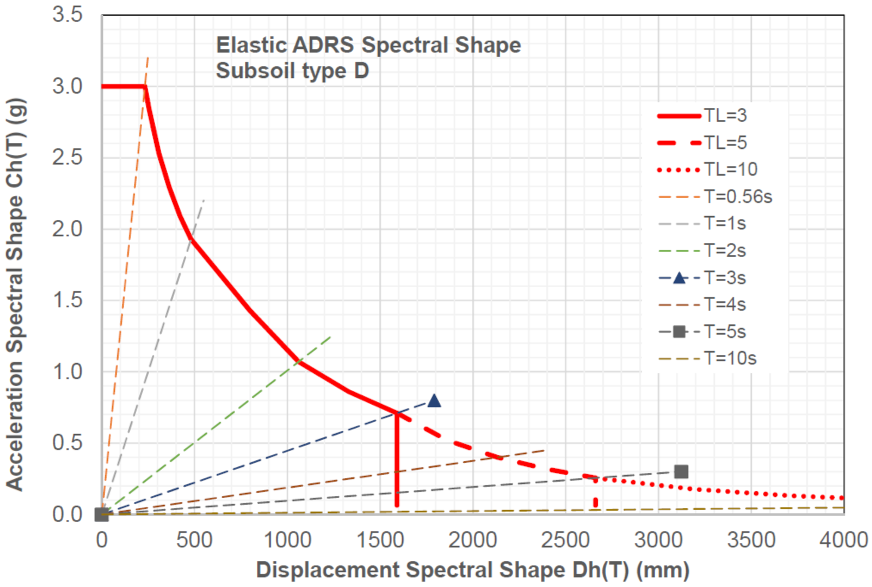

Fig. 3 – Example acceleration versus displacement spectral shape for deep or soft ground conditions (subsoil category D)

The behaviour of the isolation system is assumed to be a yielding bilinear hysteretic system represented by the generalised expression for a curved surface slider system given in Equation 3. The system behaviour for an elastomeric system, for example using lead rubber bearings, can be easily expressed in a similar equation form representing overall yield force and elastic restoring force terms.

$$V_b = fW + \Delta/R \tag{3}$$

where V_b is the base shear force

Δ is the lateral displacement of the isolation system

f is the friction coefficient,

W is the isolated weight, and

R is the radius of curvature for a curved surface slider system.

The isolation system behaviour can be conveniently shown on an acceleration versus displacement response spectrum (ADRS) plot for the purposes of calculating capacity-demand diagrams and predicting acceleration and displacement response demands on the isolation system. An example is shown in Fig. 4.

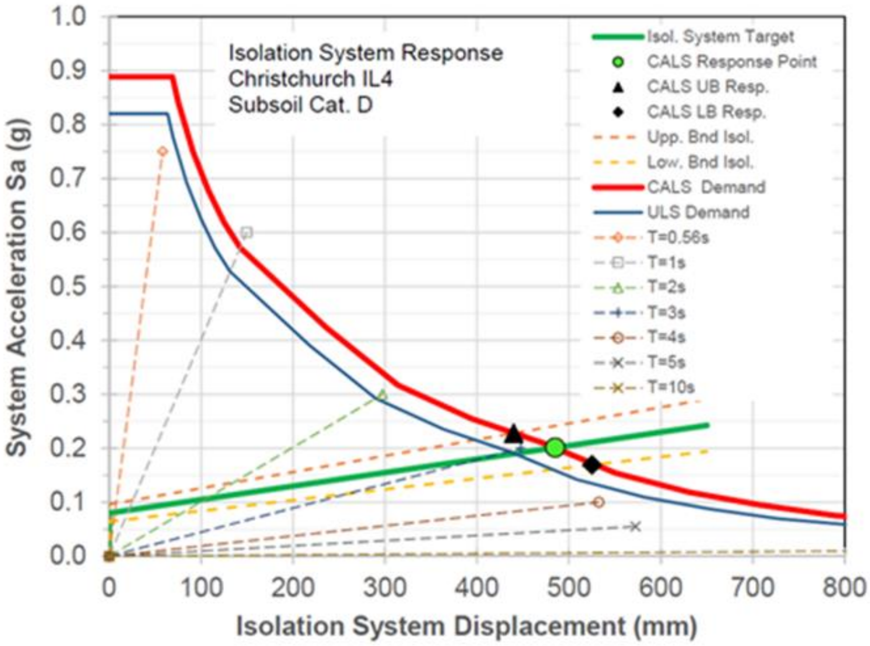

Fig. 4 - Example capacity–demand diagram for a high importance (IL4) building in Christchurch on deep or soft ground and 1 in 2500 year (MCE) code demand for a curved surface slider isolator system with f=0.08 and R=4m

6.2 Parametric study of acceleration and displacement demands

A simple parametric study was carried out by the author to determine the acceleration and displacement spectra in the four main cities of New Zealand, Auckland, Wellington, Christchurch and Dunedin, according to the recommendations in the Guideline, using a range of isolation system parameters. These comparisons are a useful indication of demands for isolated buildings in each location.

The study considered a limited number of combinations of importance levels of buildings and ground conditions according to the New Zealand code, as well as equivalent curved surface slider isolation system properties, as follows:

- Slider system friction coefficient f = 6%, 8%, 10% and 12%, or an equivalent base shear yield level
- Slider system radius R = 2000, 4000 and 6000 mm, or equivalent elastomeric stiffness. (these radii correspond to second-slope periods of 2.8s, 4.0s and 4.9s).

Some results of the study are shown in Figs. 5, 6 and 7. The diagrams show acceleration and displacement demands calculated using the Guideline for various combinations of location, building importance, ground condition, slider radius and friction coefficient. The plotted points were each calculated using an iterative graphical procedure similar to that depicted in Fig. 3. Lines have been drawn through various groups of points to show the effect of holding either curved surface slider yield level or radius constant while varying the other parameter. For the purposes of initial design, an additional displacement of up to 20% of these values could be assumed for isolators in the building corners, to allow for torsional response effects.

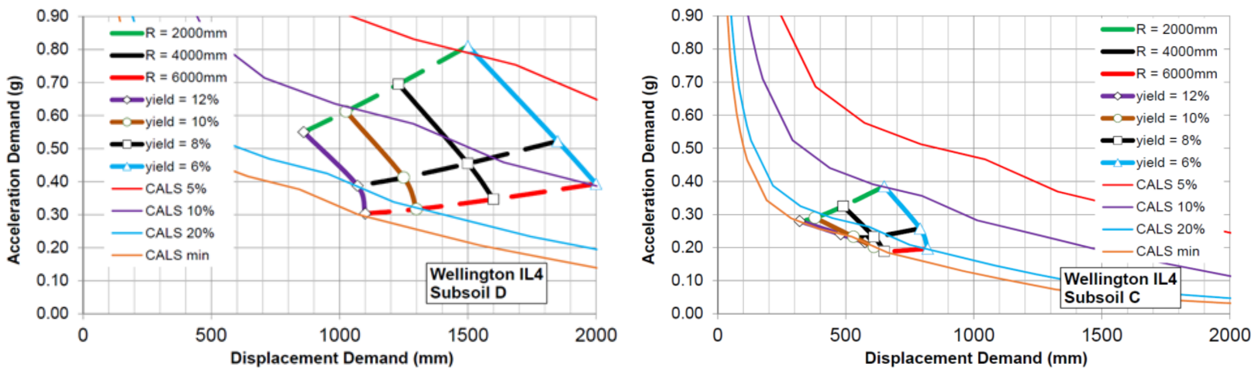

Fig.5 - Acceleration-displacement demand plots for Wellington for post-disaster functional buildings on: (left) deep or soft subsoil D and (right) shallow soil ground conditions

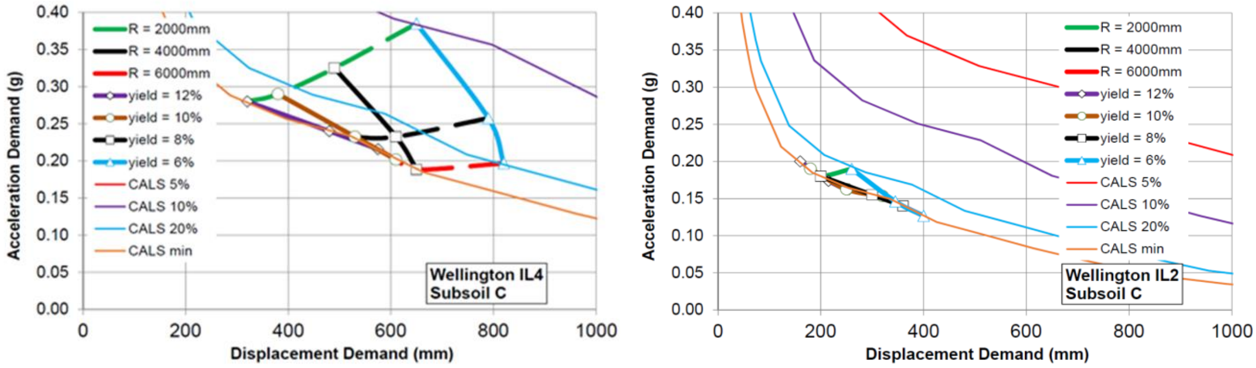

Fig. 6 - Acceleration-displacement demand plots for Wellington buildings on shallow soil ground conditions for: (left) post-disaster functional buildings and (right) normal importance buildings

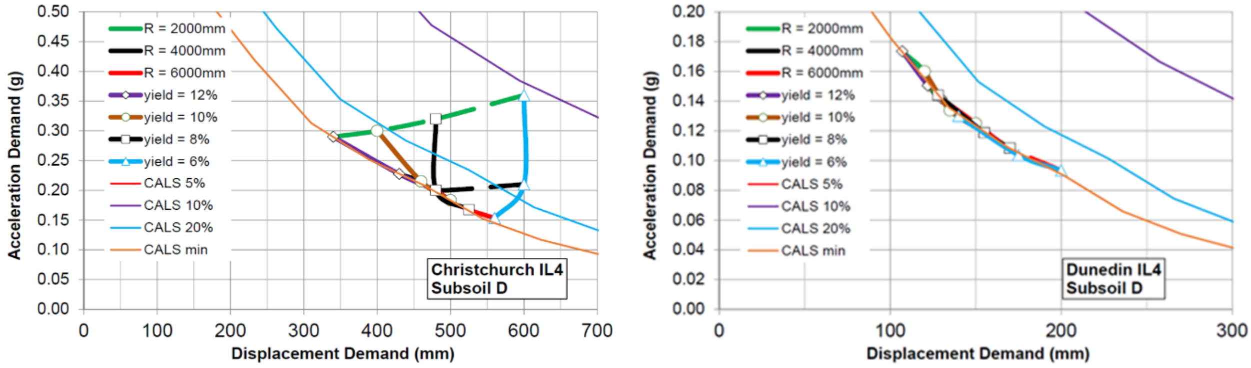

Fig. 7 - Acceleration-displacement demand plots for post-disaster functional buildings on deep or soft ground conditions located in: (left) Christchurch and (right) Dunedin

6. Conclusions

A recently published draft New Zealand guideline for design of buildings with seismic isolation will help ensure that design of isolated buildings is carried out in a consistent manner across the industry and in alignment with the requirements of the New Zealand national building code and associated design Standards. The recommendations draw on content from relevant US and European codes of practice. The Guideline provides a methodology for determining displacement spectra demands for isolated systems with long periods of vibration and appropriate levels of equivalent viscous damping.

A simple parametric study showed the range of isolation system acceleration and displacement demands for various ground conditions and importance level buildings located in the main cities of New Zealand which have a wide range of seismic hazard. The resulting displacement and base shear forces demands vary considerably.

The rate of application of seismic isolation and other energy dissipation technologies has increased markedly in New Zealand following recent severe and damaging earthquakes. Owners and engineers are increasingly recognising the significant performance and life-cycle cost benefits that seismic isolation brings to earthquake protection and functional recovery of buildings and their contents. The benefits include increased in safety, as well as reductions in the frequency and severity of damage, disruption and downtime to repair any damage that does occur. As a result of this recognition of improved seismic resilience, seismic isolation and other energy dissipation earthquake protection systems are expected to be used much more frequently in New Zealand in the future.

The draft Guideline will be updated in due course once practitioners have had the opportunity to trial and comment on it.

7. Acknowledgements

The author gratefully acknowledges the contributions of all of the authors of the Guideline and also the funders, especially the principal funding agencies MBIE and EQC.

8. References

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