The Seismic Assessment of Existing Buildings

Technical Guidelines for Engineering Assessments

Draft for Sector Briefings June 2016

Part C3: Earthquake Demands

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NEW ZEALAND
GEOTECHNICAL
SOCIETY INC

New Zealand Society for
Earthquake Engineering

MINISTRY OF BUSINESS,
INNOVATION & EMPLOYMENT
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Document Status and Amendments

Version	Date	Purpose/Amendment Description
Draft Version 2016_SB	30 June 2016	Draft for Sector Briefings

This document is likely to be incorporated by reference to the Earthquake Prone Buildings (Chief Executive's) Methodology to be developed under the provisions of the Building (Earthquake-prone Buildings) Amendment Act. It will also be endorsed by MBIE for use as guidance under section 175 of the Building Act to the extent that it assists practitioners and territorial authorities in complying with the Building Act.

Document Access

This document may be downloaded from www.EQ-Assess.org.nz in the following file segments:

1 Contents

2 Part A – Assessment Objectives and Principles

3 Part B – Initial Seismic Assessment

4 Part C – Detailed Seismic Assessment

Updates will be notified on the above website.

The document will be formally released in early 2017, when the final form of the regulations and EPB Methodology associated with the Building (Earthquake-prone Buildings) Amendment Act 2016 is established.

Document Management and Key Contact

This document is managed jointly by the Ministry of Business, Innovation and Employment, the Earthquake Commission, the New Zealand Society for Earthquake Engineering, the Structural Engineering Society and the New Zealand Geotechnical Society.

Please contact the New Zealand Society for Earthquake Engineering via questions@EQ-Assess.org.nz if you require further information on these draft Guidelines, or if you wish to provide feedback.

Acknowledgements

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Funding for the development of these Guidelines was provided by the Ministry of Business, Innovation and Employment and the Earthquake Commission.

Contents

C3. Earthquake Demands

C3.1 General

C3.1.1 Outline of this section

This section sets out the intended method for deriving the ULS seismic demand, which is needed to evaluate the *%NBS* seismic rating in accordance with Sections C1.5.1 and C1.5.6. It also lists the available representations of the ULS seismic demand and explains what is intended for these.

C3.1.2 Definitions and abbreviations

ADRS	Horizontal acceleration-displacement response spectra
IL	Importance level of a building, as defined in AS/NZS 1170.0:2002
PGA	Peak ground acceleration
Site subsoil class	Categorisation of the soil profile under the building in accordance with NZS 1170.5:2004
ULS	Ultimate Limit State as defined in NZS 1170.5:2004
SLaMA	Simple Lateral Mechanism Analysis (refer to Section C2)
100%ULS seismic demand	Seismic demand used in the calculation of *%NBS*. Can be represented in a number of ways depending on the aspect under consideration.

C3.1.3 Notation

Symbol	Meaning	Comments
%NBS	Percentage of new building standard (refer to Section C1)	
$k\mu$	Inelastic spectrum scaling factor	As defined in NZS 1170.5:2004
R	Return period factor	Will typically be R_{u} in accordance with NZS 1170.5:2004
S_{a}	Spectral acceleration	
S_{d}	Spectral displacement	
S_{p}	Structural performance factor	Determined in accordance with NZS 1170.5:2004
T	Period(s) of vibration for the building	
T_1	First mode period of vibration of the building	
U_{eff}	Lateral displacement at the effective (equivalent) height	Refer to Section C2
V	Base shear	
W	Weight of the structure	
K_{ξ}	Spectral damping reduction factor	Refer to Section C3.3

Symbol	Meaning	Comments
$K_\delta\ (T)$	Displacement spectral scaling factor	Varies depending on the building period, *T*
ξ_{sys}	Equivalent viscous damping of the system	

C3.2 Method for Deriving ULS Seismic Demand

C3.2.1 General

The basis for the derivation of ULS seismic demand is the New Zealand earthquake loadings standard NZS 1170.5:2004 and Module 1 of the New Zealand Geotechnical Society's "Geotechnical Earthquake Engineering Practice" series (NZGS, 2016). These are assumed to define 100%ULS seismic demand or, in other words, the seismic demand that would be used to design a new building at the time the assessment is completed.

Alert:

Seismic demand for the purposes of defining an earthquake-prone building in accordance with these guidelines has been set in legislation as that which would have been obtained for the design of a new building from NZS 1170.5:2004 (including amendment X.) and Module 1 of the Geotechnical Earthquake Engineering Practice series dated March 2016. These documents define the seismic demand that was current at the time the legislation was enacted, which is the relevant basis for the ULS seismic demand used to calculate the earthquake-prone threshold adopted in these guidelines of 34%*NBS*.

It is intended that the basis for setting the seismic demand for determining *%NBS* generally is the demand determined in accordance with the versions of the above documents that are current at the time the assessment is completed.

The importance level (IL) used for the evaluation of the ULS seismic demand shall be derived from AS/NZS 1170.0:2002 based on the use/intended use of the building.

For the purposes of deriving the ULS seismic demand, the design life shall not be taken as less than 50 years unless a lower design life has been formally established with the relevant building consent authority.

Note:

An argument can be raised that life safety risks should not be affected by the design life of the building. The rationale for this is that the life safety risk exists at any point in time (say, expressed as an annual risk) and is not affected by the total exposure period, whereas the exposure period is relevant when considering the potential economic losses (for example) over the life of the building.

While the concept of a design life less than 50 years is allowable under AS/NZS 1170.0:2002, this is on the assumption that the building will be removed when this period expires and that this intention will be noted on the building file held by the building consent authority/territorial authority. This should also apply if a building is assessed from a regulatory point of view or a consent for alteration (retrofit) is applied for. It is not intended that a chosen design life of less than 50 years is simply rolled over in perpetuity. In accordance with the intent of the New Zealand Building Code a 50 year exposure period (design life) is considered to represent an indefinite design life.

C3.2.2 Available representations

Representation of the ULS seismic demand will vary depending on the method of analysis and the particular aspect being assessed.

The range of available representations includes:

- acceleration response spectra
- displacement response spectra
- acceleration-displacement response spectra (ADRS)
- ground acceleration, velocity or displacement strong motion records
- peak ground acceleration (PGA), ground displacements, characteristic earthquakes, numbers of cycles for geotechnical considerations, and
- inter-storey drifts and total deformation between supports for elements supported on ledges.

When using time history analysis techniques it may be appropriate to determine the *%NBS* by scaling input motions. In these circumstances the scaling should only be applied to the ground accelerations and displacements and not to the duration of shaking, which should remain as appropriate for the ULS.

Likewise, when running traditional analysis for a target *%NBS* (say 34*%NBS* for a simple earthquake-prone check) it is only the response spectral ordinates that are scaled. The duration of shaking remains unchanged from that implied by the 100%ULS seismic demands.

Note:

While it is acknowledged that some assessors will be more familiar with the elastic based representations of NZS 1170.5:2004 and the allowance for ductility through application of an assumed global ductile capability, the thrust of these guidelines is to take account of the nonlinear deformation capability of the building directly using the displacement based simple lateral mechanism analysis (SLaMA) approach and the ADRS representation of the seismic demand.

C3.3 Horizontal Acceleration Response Spectra

When a horizontal acceleration response spectrum is used to establish the ULS seismic demand, the spectrum shall be derived in accordance with NZS 1170.5:2004 Clauses 5.2.2.1 and 5.2.2.2 including an appropriate value for S_p, which may vary depending on the particular aspect being assessed (refer Section C3.9.2).

When required, horizontal acceleration response spectra for different damping values may be obtained by multiplying the spectral ordinates of the 5% damped elastic spectrum determined as above (i.e. setting $k_{\mu} = 1$) by the spectral damping reduction factor, K_{ξ}:

$$K_{\xi} = [7/(2+\xi_{\mathrm{sys}})]^{0.5} \qquad \text{…C3.1}$$

where:

ξ_{sys} = equivalent viscous damping of the system (refer Section C2.5.11)

Note:

Priestley et al. (2007) provides some guidance on damping and the resulting reduction in spectral demand for seismic assessment. Equation C3.1 is presented as part of this guidance.

While Kong and Kowalsky (2016) have recently noted that the above equation appears to be quite reasonable for large magnitude events, studies such as those by Akkar et al. (2014) and Rezaeian et al. (2014) indicate that the actual damping-dependent spectral scaling factor should be a function of several factors including magnitude, epicentral distance (and depth) and period of vibration.

Pennucci et al. (2011), on the other hand, demonstrated that more representative inelastic (effective period) spectra for use with the displacement-based design/assessment approach could be obtained by scaling the displacement spectrum using ductility-dependent, as opposed to damping-dependent, spectral scaling factors. However, Pennucci et al. (2011) also point out that scaling factors should be a function of spectral shape and the results presented by Stafford et al. (2016) indicate that such inelastic spectra should again depend on magnitude and period.

For sites affected by near-field ground motions containing velocity pulses, Priestley et al. (2007) recommended changing the exponent within Equation C3.1 from 0.5 to 0.25 to account for the limited benefit of hysteretic energy dissipation characteristics on inelastic displacement demands induced by velocity pulse characterised near-field motions.

However, results presented in Sullivan et al. (2013) suggest that when the effective period of a structure is assessed to be less than the velocity pulse period for the site then no change is required to the scaling recommended for far-field motions. In contrast, when the velocity pulse period is equal to or larger than the pulse period, the inelastic displacement demands tend to be equal to the elastic spectral displacement demands (suggesting no benefit of hysteretic response).

Near-fault effects have traditionally been associated with larger magnitude earthquakes. However, Bradley (2015) indicated that near-fault effects were also discernible in the moderate magnitude Christchurch near-fault events.

NZS 1170.5:2004 currently adjusts the acceleration response hazard spectrum for near field effects using the near-fault factor. This addresses the increased amplitude of the expected motion for larger magnitude earthquakes (also taking into account the directional nature on the expected frequency of occurrence) but does not otherwise address the effect of the reduction in the ability to dissipate energy, and therefore the reduced effect of the ability of nonlinear behaviour (ductility) to reduce a building’s response.

It is clear that additional research is needed to determine how best to account for near-field effects in design and assessment and the extent to which this phenomenon needs to be allowed for. It might be expected that future revisions of NZS 1170.5:2004 will need to address this issue which may increase demand requirements. This could also lead to the need to reconsider the level of damping that might be available and the expected effect of this. However, in the interim, it is recommended that Equation C3.1 continue to be used for all sites.

C3.4 Horizontal Displacement Response Spectra

For displacement based methods, a displacement response spectrum is required. For the purposes of these guidelines it is considered appropriate to derive the 5% damped spectral displacement spectrum by multiplying the ordinates of the 5% damped elastic acceleration spectrum from Section C3.2 by the factor:

$$K_{\delta}(T) = 9800T^2/4\pi^2 \qquad \text{…C3.2}$$

Displacement spectra for different damping values may be obtained by multiplying the 5% damped displacement spectrum by the factor, K_{ξ}, calculated using Equation C3.1.

Figure C3.1 illustrates the shape of the resulting displacement spectra for Wellington, Christchurch and Auckland for different subsoil conditions. The effect of the application of K_{ξ} is illustrated in Figure C3.2.

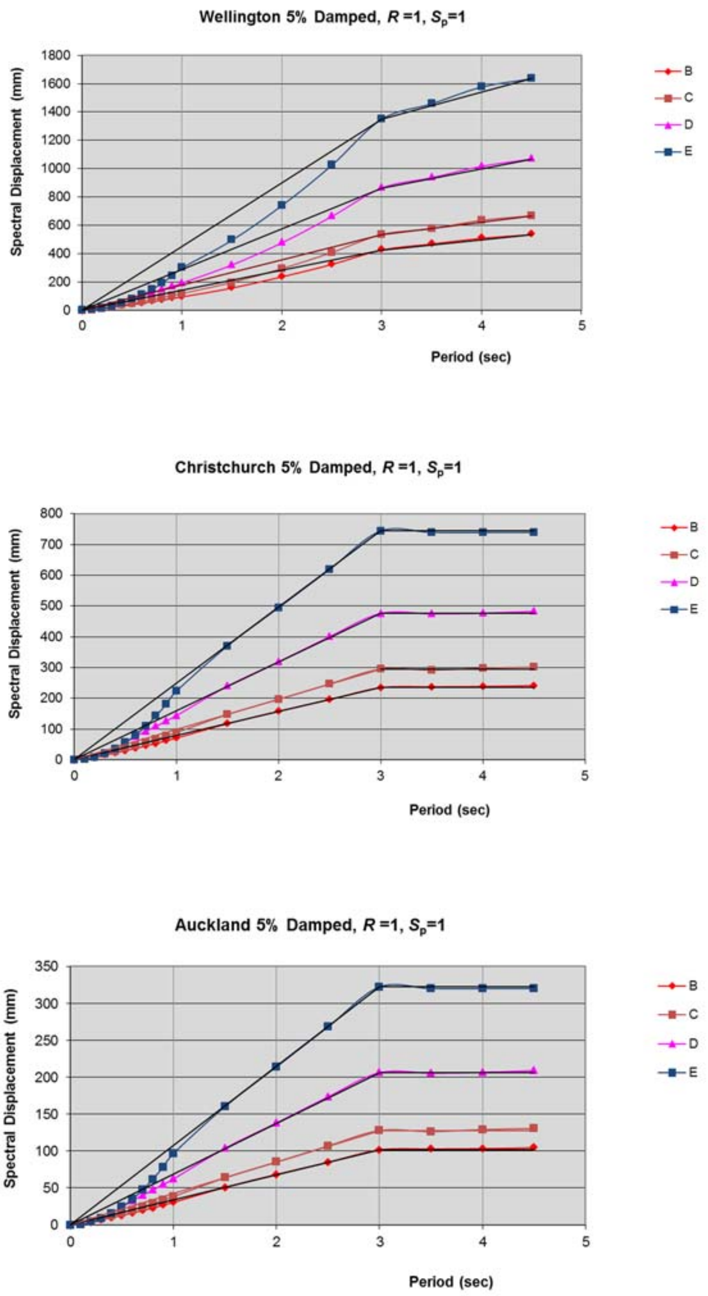

Figure C3.1: Displacement spectra at 5% damping for R = 1, S_{p} = 1 for various site subsoil classes and including appropriate near fault factor

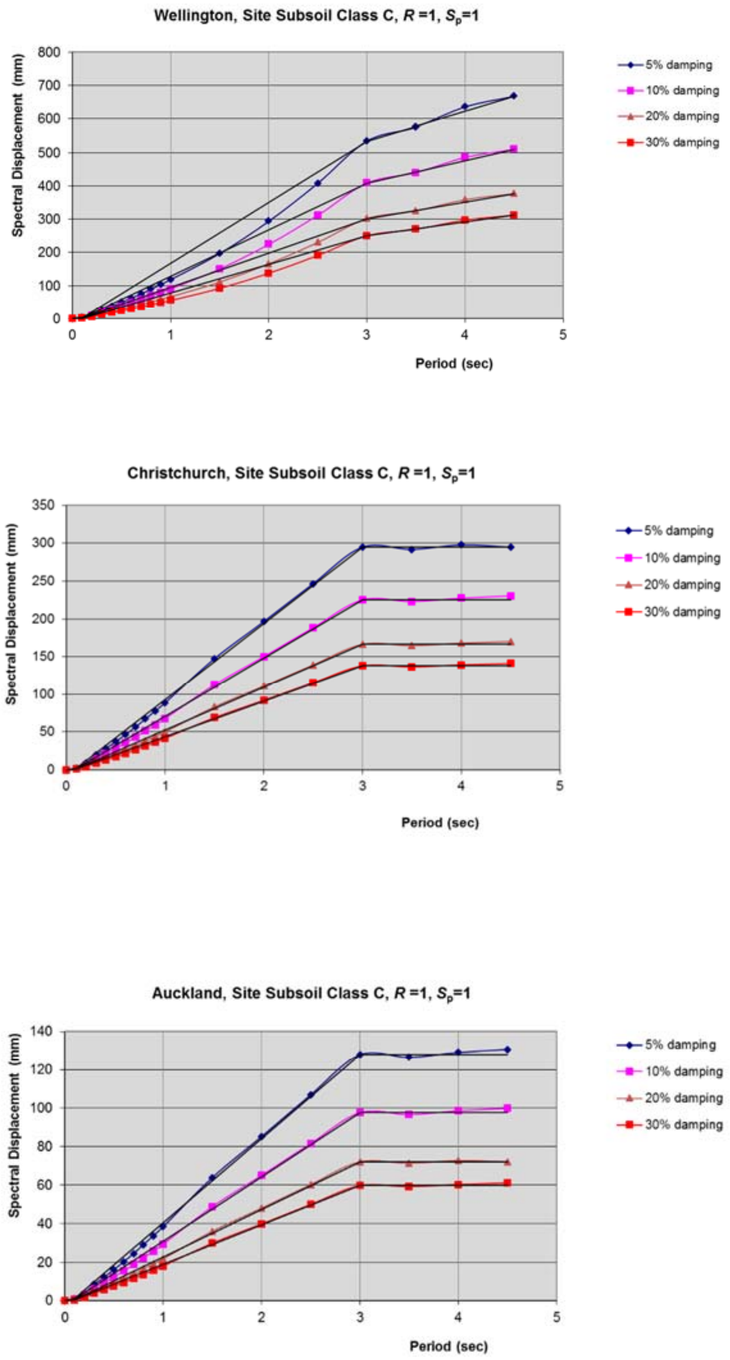

Figure C3.2: Displacement spectra for different damping levels and site subsoil class C and including appropriate near fault factor

Examination of the displacement spectra in Figures C3.1 and C3.2 reveals several interesting points.

First, the significance of the soil type is much more apparent when seismicity is expressed in terms of displacement, rather than acceleration, spectra.

Second, apart from some nonlinearity for low periods, the curves are well represented by straight lines from the origin as shown on Figure C3.2. For sites where near-fault effects are not an issue the displacement spectra are well represented by a bilinear relationship pivoting around the displacement at T = 3 seconds and with a horizontal leg beyond 3 seconds. For a site where near-fault effects are specified the displacement spectra can be approximated by a bilinear relationship between T = 0, 3 and 4.5 seconds. These are approximations, the validity of which will need to be confirmed. It is expected that the straight-line approximations indicated are sufficiently accurate to be used as the basis for assessments and design of retrofit works. However, this should not preclude a more precise or direct evaluation should circumstances warrant or allow.

Third, the displacement spectra obtained do not represent the tendency of the spectral displacement to converge to the peak ground displacement at long periods but maintain the spectra conservatively at constant peak displacement response values (or increase these for sites where near-fault effects are specified).

C3.5 Horizontal Acceleration-Displacement Response Spectra (ADRS)

The acceleration and displacement spectra derived in the previous two sections for a particular site and level of damping can be usefully presented in the form of an acceleration-displacement response spectrum (Mahaney et al., 1993). The ordinates of such a spectrum are spectral acceleration and spectral displacement. An example of such representations is shown in Figure C3.3 for Wellington, Christchurch and Auckland for a 500 year return period (R_u = 1), S_p = 1 and site subsoil class C.

When constructing an acceleration-displacement spectrum for a particular level of damping both the acceleration and the displacement ordinates must be multiplied by K_ξ and the appropriate value of S_p.

Acceleration-displacement spectra are particularly useful when assessing the *%NBS* of a building from the results of a nonlinear pushover analysis. The acceleration and displacement results from a pushover analysis need to be converted to spectral acceleration and spectral displacement (as described below) before comparisons are possible with the acceleration-displacement spectra described above.

Alert:

When a pushover curve has been derived from the combination of various structural systems of different ductile capability (using, for example, the SLaMA method), it may be more useful to incorporate the various S_p factors into the combined system pushover curve and compare against the ADRS calculated assuming S_p = 1. Refer Section C3.9.2.

The conversion can be carried out as follows, assuming that elastic response is a good predictor of inelastic response (this will not always be the case):

$$S_{\mathrm{a}} = V/W \quad \ldots\text{C3.3}$$

$$S_{\mathrm{d}} = U_{\mathrm{eff}} \quad \ldots\text{C3.4}$$

where:

V = base shear consistent with U_{eff}
W = total weight of the structure
U_{eff} = lateral displacement at the effective (equivalent) height (refer Section C2)

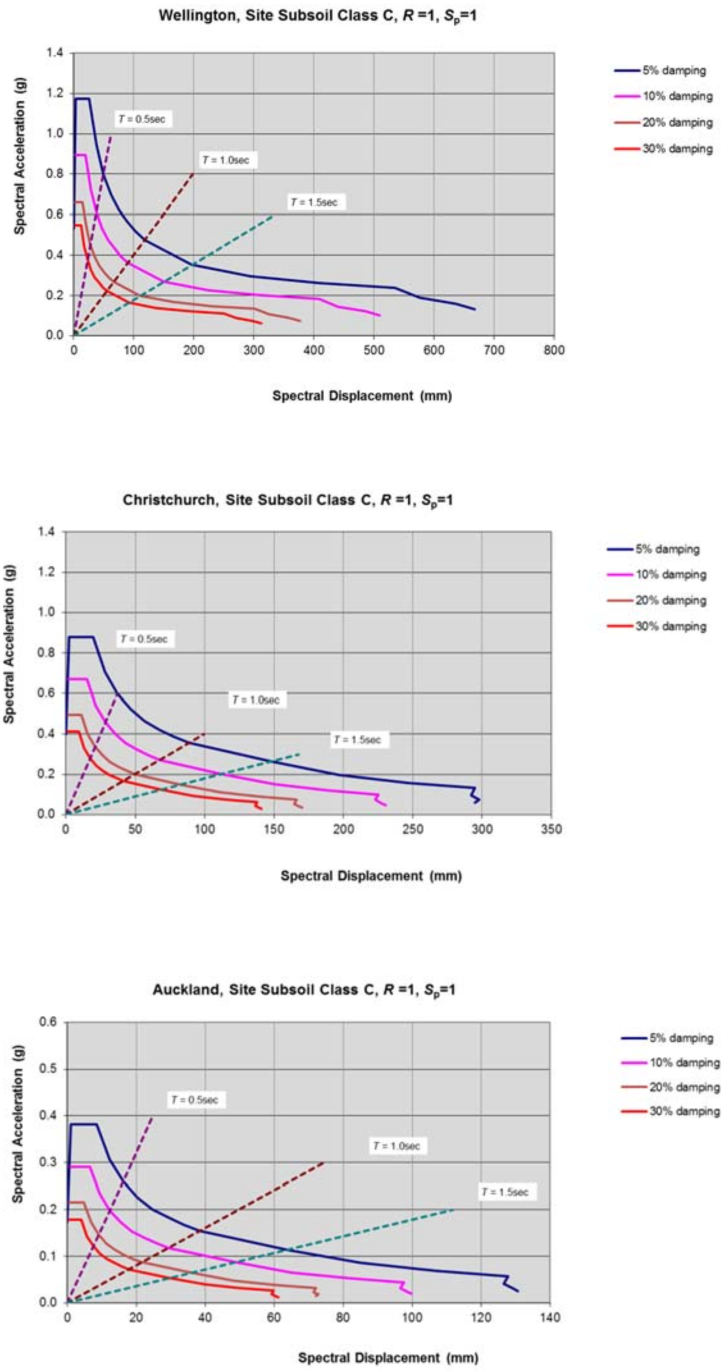

Figure C3.3: Acceleration-displacement spectra for different damping levels for R = 1, S_p = 1 and site subsoil class C

Note that the first mode period, T_1, can be approximated (assuming predominantly first mode response) from the relationship:

$$T_1 \;=\; 2\pi\,\sqrt{(S_\mathrm{d}/S_\mathrm{a})} \qquad \ldots\text{C3.5}$$

where:

S_a, S_d are as defined above.

Thus the stiffness of the building (T) can be represented by radiating lines from the origin of the acceleration-displacement spectrum. These lines, for example periods of 0.5, 1.0 and 1.5 sec, are shown in Figure C3.3.

Note:

ATC 40 (1996) presents an excellent discussion on the way in which the acceleration-displacement spectrum can be derived and used to assess the performance of buildings. Refer to Section C2 for the use of ADRS with nonlinear static pushover analysis.

C3.6 Vertical Acceleration Response Spectra

When a vertical response spectrum is required to establish the ULS seismic demand, the spectrum shall be derived from NZS 1170.5:2004, Clause 5.4.

C3.7 Acceleration Ground Motion Records

When acceleration ground motion records are required, their selection and scaling shall meet the requirements of NZS 1170.5:2004, Clause 5.5.

Appropriate artificial time histories can also be used if suitable historical records are not available. In any case, the input earthquake records shall either contain at least 15 seconds of strong motion shaking or have a strong shaking duration of at least five times the fundamental period of the structure, whichever is greater.

All three components of any ground motion records should be used where all components are scaled by the same factor which is determined separately for each direction of application of the principal component. When scaled ground motion records are used to establish a *%NBS* other than 100*%NBS*, only the acceleration ordinates should be scaled. The duration of shaking established for the ULS seismic demand should not be changed.

C3.8 Representations for Geotechnical Considerations

The ULS seismic demand for geotechnical considerations, including PGA, representative (effective) earthquake magnitude and number of cycles, should be derived in accordance with the requirements of Module 1 (Section 5) of the Geotechnical Earthquake Engineering Practice series (NZGS, 2016).

C3.9 Other Issues

C3.9.1 Site-specific probabilistic seismic hazard analysis

Site-specific probabilistic seismic hazard analysis should be completed in accordance with the requirements of NZS 1170.5:2004 and Module 1 of the Geotechnical Earthquake Engineering Practice series (NZGS, 2016) as appropriate. The constraints noted in the Verification Method B1/VM1 (for New Zealand Building Code Clause B1 Structure) regarding the results from a site specific hazard analysis apply.

C3.9.2 Incorporation of the structural performance factor, S_p

The appropriate value of the structural performance factor, S_p needs to be used when assessing the ULS seismic demand for structural considerations. This may require different values for S_p depending on the level of nonlinear deformation possible from the aspect under consideration, as determined in accordance with NZS 1170.5:2004 and this section.

S_p may be used either to reduce the demand spectral values calculated above (this is the approach adopted in NZS 1170.5:2004) or used to enhance the capacity as assessed later in these guidelines. If the latter option is used, then for the purposes of establishing the ULS seismic demand S_p would need to be taken as 1.0.

As S_p is dependent on the structural ductility available it is likely that the S_p factor will only be able to be set once the available global ductility has been determined from the global deformation capacity of the building.

S_p is not used for geotechnical considerations.

C3.9.3 Demands on secondary structural and non-structural elements

The ULS seismic demand on secondary structural and building parts should be determined in accordance with Section 8 of NZS 1170.5:2004. The demand may be in the form of loads/forces or deformations. Further guidance is provided in Section C10.

C3.9.4 Application of ULS loading (actions)

The direction of application of the specified actions and the allowances for accidental eccentricity should meet the requirements of NZS 1170.5:2004, Clause 5.3.

Where the actions for an element are influenced by more than one direction of loading (e.g. a corner column in a moment resisting frame building) and the load on the element cannot be limited by a yielding mechanism, the application of the ULS actions may be as for a nominally ductile structure.

References

AS/NZS 1170.0:2002 – Structural Design Actions – Part 0: General Principles, *Australian/New Zealand Standard*, 2002

Akkar, S., Sandikkaya, M.A. and Ay, B.O. (2014) Compatible ground-motion prediction equations for damping scaling factors and vertical-to-horizontal spectral amplitude ratios for the broader Europe region. *Bull. Earthquake Engineering.* Vol 12 pg 517-547.

ATC 40 - Seismic evaluation and retrofit of concrete buildings, Vol 1 & 2 Applied Technology Council, Nov 1996.

Bradley, B. (2015). “Period Dependence of Response Spectrum Damping Modification Factors due to Source- and Site-Specific Effects” *Earthquake Spectra*, Vol. 31 (2): 745–759

Kong, C. and Kowalsky, M.J. (2016). “Impact of Damping Scaling Factors on Direct Displacement-Based Design”, Earthquake Spectra, In press.

Mahaney, J. A., T.F. Paret, B. E. Kehoe, and S. A. Freeman, (1993). “The Capacity Spectrum Method for Evaluating Structural Response During the Loma Prieta Earthquake”, *Proceedings 1993 National Earthquake Conference, Earthquake Hazard Reduction in the Central and Eastern United States: A Time for Examination and Action*, May 2-5, 1993, Memphis, Tennessee, Vol. II, 1993

“*Earthquake Geotechnical Engineering Practice Module 1: Overview of the guidelines*”, Geotechnical Earthquake Engineering Practice series, March 2016.

NZS 1170.5:2004 –Structural Design Actions – Part 5: Earthquake Actions – New Zealand, *New Zealand Standard*, 2004

Pennucci, D., Sullivan, T.J., and Calvi, G.M. (2011) “Displacement Reduction Factors for the Design of Medium and Long Period Structures” *Journal of Earthquake Engineering*, Vol. 15, Supplement 1, 1-29.

Priestley M.J.N., Calvi G.M. and Kolwasky M.J. (2007), *Displacement-based seismic design of structures*. IUSSS Press. Pavia, Italy.

Rezaeian, S., Bozorgnia. Y. Idriss, I.M., Abrahamson, N.A., Campbell, K.W. and Silva, W.J. (2014) Damping scaling factors for vertical elastic response spectra for shallow crustal earthquakes in active tectonic regions: “average” horizontal component. *Earthquake Spectra* Vol. 30, page 939-963

Stafford, P., Sullivan, T.J. and Pennucci, D. (2016). “Empirical correlation between inelastic and elastic spectral displacement demands” *Earthquake Spectra*, in press.

Sullivan, T.J., Pennucci, D., Piazza, A., Manieri, S., Welch, D.P. and Calvi, G.M. (2013). “General aspects of the displacement based assessment approach” in *Developments in the Field of Displacement-Based Seismic Assessment, Edited by Sullivan, T.J., Calvi, G.M.*, IUSS Press, Pavia, Italy, ISBN; 978-88-6198-090-7.