Design Spectra for Seismic Isolation Systems in Christchurch, New Zealand

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ABSTRACT: Acceleration and displacement spectra for analysis and design of seismic isolation systems in Christchurch are presented, in accordance with the requirements of NZS 1170.5.

Seismic isolation design strategy consists of increasing the natural vibration period and effective damping such that the seismic response of the building is substantially reduced compared with conventional fixed base building. This requires acceptance of increasing displacement demands across the isolators where they can easily be accommodated. The code spectrum shape at long periods, based on a constant displacement assumption, provides a limit on the displacement demand.

The Christchurch CBD ground motion records from the 2010 and 2011 earthquakes showed significant peaks in the elastic 5% damped spectra at periods between 2.0 and 3.5 seconds. Both linear and nonlinear time history analyses were undertaken to quantify the impact of these earthquake records on isolated structures with realistic damping levels. The results clearly indicate that the additional spectral “bumps” from the strong motion records are effectively damped out and do not affect the behaviour of typical isolation systems.

A new “direct capacity spectrum method” is presented which, with some further development, will allow designers to directly determine acceleration and displacement demands on isolated structures in Christchurch, based on chosen characteristics of typical isolation bearings.

1 INTRODUCTION

The 2010/2011 Christchurch earthquakes caused significant damage and economic loss in buildings with conventional structural systems. Ground motions recorded from the earthquakes were extreme and the acceleration response spectra for structures with periods greater than 2 seconds, typical of isolated structures, have been noted as being potentially significantly higher than the NZS 1170.5 design spectra. This has also raised questions about the suitability of isolated structures in Christchurch, if more earthquakes of similar type occur in the future.

Christchurch Women’s Hospital was the only building in Christchurch built incorporating seismic isolation. It is understood to have performed very well during the recent earthquakes with little damage. There is now significant interest in use of seismic isolation to provide a superior low damage design strategy in both new buildings and retrofit of existing buildings in Christchurch.

The New Zealand Building Code and the New Zealand Standards for structural design do not specifically cover design of isolated structures. Therefore, as the use of isolation becomes more widespread, Building Code compliant standards and codes are required to allow designers to deal more readily with these structures. This paper provides a first step to show how the NZS 1170.5 acceleration and associated displacement design spectra can be determined for design of structures with seismic isolation in Christchurch.

The Christchurch rebuild presents a unique situation in that numerous new structures will be built (and retrofits carried out) in close proximity to each other. The seismic criteria for each project will be very similar (if not identical). It makes sense to provide useful design information to enable engineers to quickly assess seismic isolation without each having to repeat essentially the same calculations and “reinvent the wheel”.
2 DESIGN SPECTRA FOR ISOLATED STRUCTURES BASED ON NZS 1170

NZS 1170 spectra are based on uniform hazard estimation for typical structures with 5% damping, and the additional damping available in isolated structures can be accounted for by simple scaling of the response spectra.

The horizontal earthquake design action coefficient $C_d(T)$ in accordance with NZS 1170.5 is given by equations 1 and 2.

$$C(T) = C_h(T) Z R N(T,D)$$  \hspace{1cm} (1)

$$C_d(T) = C(T) \frac{S_p}{\mu}$$  \hspace{1cm} (2)

where $Z =$ hazard factor (now 0.3 for Christchurch), $R =$ return period factor ($R_u = 1.0$ for 1 in 500 year earthquake actions, $R_u = 1.3$ for 1 in 1000 year actions and $R_u = 1.8$ for 1 in 2500 year actions), $N(T,D) =$ near fault factor (taken as 1.0 in Christchurch), $S_p = $ structural performance factor (conservatively could be assumed to be 1.0 for isolated structures but could be less depending on the structure type), $\mu =$ structural ductility factor (also assumed to be 1.0 for isolated structures).

Adjustment for additional damping can be done, for example, using the NZSEE damping correction factor $K_x$ (NZSEE 2006 Equation 5(1)). This adjustment is commonly also referred to as the “B factor” and therefore B(d) is adopted as the terminology here. The design base shear coefficient $C_{dd}(T,d)$ and design spectral displacement $D_{dd}(T,d)$ for an isolated structure with effective period $T$ and damping $d$, can be determined from Equations 3 and 4.

$$C_{dd}(T,d) = C_{dd}(T) Z R B(d)$$  \hspace{1cm} (3)

$$D_{dd}(T,d) = \frac{C_{dd}(T,d)}{\omega^2}$$  \hspace{1cm} (4)

$$B(d) = (\frac{7}{2+d})^{0.5}, > 0.50$$  \hspace{1cm} (5)

Where $\omega =$ circular frequency $= 2\pi/T$, $d =$ effective damping percentage, B(d) is the B factor that adjusts for level of damping (the minimum value of 0.50 is suggested by the authors).

The resulting base shear acceleration coefficient versus period and displacement versus period for typical Christchurch buildings, for effective damping values of 5%, 10%, 20% and 30% are shown in Figure 1. An alternative “capacity spectrum” representation of the base shear coefficient versus displacement spectra is shown in Figure 2. The capacity spectrum presentation is very useful as the chosen force versus displacement behaviour of the isolation system can be plotted on the same graph, and an “operating point” of the system response can be determined, where the earthquake demand curve intersects with the isolation system behaviour (Whittaker 2007).

Figure 1. Displacement and acceleration response spectra for isolated structures in Christchurch
Figure 2. Acceleration versus displacement spectra for isolated structures in Christchurch

The charts represent the standard approach for estimating the global acceleration and displacement demands on isolated structures in Christchurch. The charts show that, for high levels of damping in the order of 25-30% of critical, the acceleration and displacement response is reduced to around half of the 5% damped response. The NZSEE B factor equation has a minimum value of 0.5 meaning the response is not less than 50% of the 5% spectrum values.

3  SPECTRAL DEMANDS ON ISOLATED STRUCTURES FROM CHRISTCHURCH CBD EARTHQUAKE RECORDS

Many strong motion records were obtained in Christchurch during the recent 2010/2011 Canterbury earthquake sequence, including some of the largest ground accelerations ever recorded in the world. The highest recorded ground accelerations and associated 5% response spectra generally exceeded the NZS1170.5 1 in 500 year design values and in some cases exceeded the 1 in 2500 year values. The significant peaks in the 5% response spectra suggest that there may have been special features of the earthquake source mechanisms, directivity effects and possible amplification due to the nature of the geology under Christchurch.

The 5% damped acceleration response spectra from the Christchurch CBD records show particular amplification in the 2 to 4 second period range. These records and response spectra raise questions regarding the response and performance of long period structures such as those using seismic isolation. However, isolated structures typically have high levels of damping, well in excess of the 5% used for normal code spectra and assumed for conventional structures. In order to ascertain the effects of the earthquake records on isolated structures and other structures with substantially greater than 5% damping, elastic and inelastic response spectra have been calculated using simple single degree of freedom time history analysis.

Figure 3 shows the elastic spectral envelopes for displacement and acceleration using the most severe of the 2010 and 2011 records obtained at the four CBD (Central Business District) sites (Carr 2012). The 2011 records produced the highest spectral ordinates in the period range of interest. Linear elastic 5% and 25% viscous damping spectra are shown – the latter being typical of base isolation systems. The 2,500yr NZS 1170.5 spectra are also shown, and also a modification to the design spectral shape proposed by GNS (GNS 2012) to account for the significant “bumps” observed in the 5% damped elastic response spectra derived from the recorded ground motions.

While there are no specific code provisions for design of base-isolation systems, the concept of “equivalent viscous damping” for hysteretic systems is commonly used as noted above. The “B” factor is used to scale the 5% damped design spectra to account for the more highly damped system incorporating isolation. The application of this approach implicitly assumes that the 5% and 25% (for example) damped shapes are the same and only the amplitude requires scaling.
Based on the acceleration and displacement response plots presented in Figure 3, a number of important observations can be made.

- Over the range of effective Period $T_{\text{eff}} = 2.5$ to $3.5$ seconds, typical of practical isolation systems, the spectra from the most severe recorded CBD motions envelope the NZS 1170.5 2,500 year design spectrum.

- The significant spectral peaks at about $3.3$ seconds that appear in the $5\%$ damped curves are completely damped out in the $25\%$ damping response spectra and would not adversely affect the response of isolation systems.

- The shape of the $5\%$ design spectra and the $25\%$ spectra obtained from recorded motions are quite consistent. This implies that the use of the B factors (discussed above) to scale down the $5\%$ curved is a valid approach.

- A “B” factor of $2.0$ applied to the NZS 1170.5 spectra shows very good consistency with the $25\%$ damped elastic spectra from the most severe Christchurch CBD recorded motions.

- The spectral shape modification suggested by GNS to account for “bumps” in the $5\%$ damped response spectra is not necessary for base-isolation system design, but may well require further consideration for structures with less available damping.

4 DIRECT CAPACITY SPECTRUM METHOD FOR ESTIMATING RESPONSE OF ISOLATED SYSTEMS

As noted above, the methodology commonly used in the analysis and design of seismic isolation systems (and incorporated into some codes) is based on the “equivalent linear” concept. The basis of the design is a conventional $5\%$ damped, linear response spectrum scaled to account for system damping. Because typical isolation systems are inherently non-linear, the concept of an “effective period $T_{\text{eff}}$” is necessary. Traditional linear response spectra are based on viscous damping, whereas common isolation systems employ hysteretic energy dissipation (damping) and so the linear “equivalent viscous damping EVD” is used (based on hysteresis loop area). But neither of these parameters is a direct property that can be designed for an isolator. Both the $T_{\text{eff}}$ and the EVD parameters are response amplitude (displacement) dependent and an iterative process is therefore required to develop an isolator design having the required properties.

An alternative innovative approach is suggested that presents isolation system performance in terms of primary engineering properties of an isolation system. It enables the presentation of non-linear dynamic analyses results to be presented in a way to enable direct assessment of isolation system design properties without iteration.

The most common types of seismic isolation system are modelled using a bi-linear hysteretic loop
similar to that shown in Fig. 5. The important properties are the yield level $Q_d$ and the elastic stiffness $K_d$, neither of which is amplitude dependent. For example, for a lead-rubber isolator, the $Q_d$ represents the lead core yield force and the $K_d$ represents the elastic rubber shear stiffness. For a friction, pendulum type isolator the $Q_d$ is the friction force and the period $T$ is related to the sliding surface curvature (mass independent). Using the known structure mass, an elastic isolation period can be determined for systems using either type of bearing.

![Figure 5. Bilinear force-displacement behaviour of a typical seismic isolator](image)

Figures 6 and 7 show the calculated displacement and acceleration response spectra of systems to the actual 2010 and 2011 earthquake records from the Christchurch Hospital site. The 5% damped elastic response spectrum curves for both earthquakes show a pronounced peak. It is interesting to note that the spectrum peaks occur at different natural periods. The peak of the 2010 earthquake spectrum is at about 2.6 seconds and the peak of the 2011 earthquake spectrum is at about 3.3 seconds.

![Figure 6. Elastic and inelastic displacement and acceleration spectra for Christchurch Hospital 2010 record](image)

![Figure 7. Elastic and inelastic displacement and acceleration spectra for Christchurch Hospital 2011 record](image)
Also shown on each plot is the 25% elastic damped spectrum for that record (ie not an envelope) and the calculated non-linear hysteretic response for a system having a yield level of 10% of the system weight (ie 0.1g yield). The shapes of these two spectra are remarkably similar. The acceleration demand curves fall consistently with increase in isolator period and displacement demand curves are fairly flat, indicating that reduced shears can be reliably obtained by lengthening the isolation system period without incurring significant variation in displacement demand. It should again be emphasized that the horizontal axis Period (T2) is the elastic period (ie related to rubber stiffness or curved slider effective pendulum period) and is a system property that is not displacement amplitude dependent.

Figure 8 shows inelastic displacement and acceleration spectra demands for the most severe Christchurch CBD earthquake records plotted against isolator elastic period for isolator yield levels equal to 5%, 10% and 15% of isolated system weight, representing practical system yield levels. Also shown on the plots is the calculated elastic response spectrum for 25% damping.

![Figure 8](image_url)

Figure 8. Inelastic Displacement and Acceleration “Spectra” for Christchurch CBD 2011 Earthquake Records

From these plots the relationship between displacement and acceleration (shear force) response can be clearly seen. For example, looking at the 10% yield level, it is seen that the spectral displacement curve is quite flat at a value between 350mm and 400mm and increasing the period from 2.5 seconds to 4 seconds reduces the shear forces by around 50%. The designer can use these demand curves to select a suitable isolation system and to allow for the resulting force demands on the building structure, and also the displacement demand on the isolators and necessary separations around the building. Note that the curves presented here have been generated using only the unscaled, recorded ground motions from the Christchurch earthquakes and therefore should not be confused with the NZS 1170 code demands in their present form.

Figure 9 shows the inelastic capacity spectrum which directly shows the inelastic acceleration and displacement demands on systems, based on the isolator properties of yield level and post-elastic period. The dashed lines represent the actual force-displacement behaviour of the isolation system. As for the elastic capacity spectrum method shown in Figure 2, the operating point for a given level of isolator yield and isolator period is where the force-displacement behaviour of the isolation system intersects with the inelastic spectrum.

The results shown in Figure 9 are based only on the maximum Christchurch CBD earthquake records. The authors have proposed the name “Direct Capacity Spectrum Method” to describe the process used to derive this diagram. The approach can easily be extended to provide NZS 1170.5 code compliant design charts for structures with seismic isolation in Christchurch or other locations. The analyses in this paper need to be extended using a suite of earthquake records scaled in accordance with the time history scaling requirements of NZS 1170.5. The direct capacity spectrum method would provide an invaluable design tool whereby inelastic displacement and acceleration spectra have already been determined. In effect the time history analyses would have already been run and designers of regular structures with seismic isolation would have direct and reliable estimates of demands on the isolated
structures they are designing. The information presented in this paper already gives a good indication of the levels of displacement and acceleration demand on typical isolated structures in Christchurch.

Figure 9. Inelastic Capacity Spectra for Christchurch CBD 2011 Earthquake Record

5 CONCLUSIONS

Engineers and owners should have confidence that seismic isolation provides the best level of earthquake protection for structures in Christchurch.

A simple method was presented for determining NZS 1170.5 seismic design acceleration and displacement spectra for the high damping levels available in isolated structures. The NZS 1170.5 acceleration and displacement design spectra presented for Christchurch will provide designers with estimates of acceleration and displacement demands for typical isolated structures using either concave friction type slider bearings or lead rubber bearings.

Inelastic spectra derived for the most severe of the Christchurch CBD records from the 2010 and 2011 earthquakes show demands on isolated structures that compare closely with the code level spectra that are scaled for effective level of damping.

Inelastic spectra calculated from the Christchurch earthquakes demonstrate that recent proposals for introducing “bumps” in the code spectra for Christchurch to reflect responses measured from the Christchurch earthquakes are not necessary for structures with significant damping (or ductility).

A new direct capacity spectrum method is presented that, with some further development, will allow direct prediction of NZS1170.5 earthquake demands on typical isolation systems.

A New Zealand Standard or amendment to an existing Standard for design of structures with seismic isolation is needed to enable professional engineers to prepare designs meeting the performance objectives and requirements of the New Zealand Building Code.

The Christchurch rebuild presents a unique situation where, in the near future a number of structures will be designed incorporating base-isolation, all essentially being governed by the same seismic criteria. Thus, it is clearly beneficial to extend this work to produce design charts that are fully compliant with the NZS 1170.5 criteria for nonlinear, time history analysis. This approach will provide a valuable tool for designers to quickly and directly assess performance of buildings with seismic isolation.

REFERENCES


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