Displacement and acceleration design spectra for seismic isolation systems in Christchurch

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ABSTRACT: The paper extends previous work by the authors on displacement and acceleration spectra for analysis and design of seismic isolation systems in Christchurch, in accordance with the requirements of NZS 1170.5.

A suite of earthquake records has been selected based on expert recommendations and scaled to match the NZS 1170.5 hazard spectra. The assumptions and method for scaling the earthquake records is discussed. A range of typical isolation system parameters for lead rubber or concave slider systems were identified, including yield level and post-elastic stiffness or equivalent period, both of which can be directly selected by the designer.

Single degree of freedom inelastic time history analyses were carried out using the selected isolation system parameters and the suite of earthquake records to determine the displacement and acceleration demands on isolation systems. The results are presented in displacement and acceleration spectra, as well as in “direct inelastic acceleration-displacement spectra” format. These charts provide designers with a powerful tool to directly determine displacement and acceleration demands on isolated structures in Christchurch, based on a range of practical isolation bearing system characteristics. The methodology can easily be applied in other locations.

1 INTRODUCTION

The destructive earthquakes of 2010 and 2011 in Christchurch caused widespread building damage which led to many being economic write-offs and their demolition. As a result there is now a wave of new buildings being designed and constructed. Owners and designers are seeking more effective seismic protection systems in buildings that will greatly reduce earthquake damage. While seismic isolation has generally been well recognised as the best available technology for minimising damage and ensuring post-disaster operability, only a few buildings of special importance have until recently enjoyed the benefits of earthquake protection using isolation. Now, however, many new commercial buildings are being designed with seismic isolation.

Common isolator technologies such as lead rubber or concave slider bearings exhibit very full force–displacement hysteresis that dissipates large amounts of seismic energy. The hysteretic behaviour is often approximated as an equivalent linear system based on the secant stiffness and effective viscous damping level. The longer effective period of vibration and significant equivalent viscous damping both lead to substantially lower response of an isolated structure compared with the same fixed base structure. The seismic forces that are attracted can be controlled to a large extent to prevent damage in structures, while significant displacements are accepted in the isolator elements that can sustain large movements substantially without damage.

The New Zealand structural design standards do not give specific guidance on how to design isolated structures or what earthquake design loads should be used. Designers are adopting various design approaches such as using displacement based design methods, or selectively adopting requirements from design codes from other countries (eg ASCE or Eurocode). As the use of seismic isolation becomes more prevalent, it will be necessary to develop more standardised approaches to design and associated building consent processes for isolated buildings.

Previous work by the authors (Whittaker and Jones 2013) examined how the codes (eg NZS 1170.5) for conventional (fixed base) buildings could be adapted to determine suitable seismic design spectra for isolated buildings. Code elastic acceleration spectra were modified using so-called “B Factors”, accounting for the increased levels of damping, to obtain the reduced acceleration response for isolated structures. Various B Factor relationships are available from different international codes and guidelines, such as NZSEE, ASCE and Eurocode.

The 2013 work also examined the elastic acceleration and displacement response spectra determined using a 25% elastic damping and how the resulting response spectra compared with the 5% elastic response used in our structural codes. The elastic highly-damped (and inelastic) response spectra both showed significant reductions of displacement and acceleration response, and clearly showed that peaks in the 5% spectra from the Canterbury earthquakes did not affect typical isolated structures.

The concept of Acceleration Displacement Response Spectra (ADRS) was also shown to be a very useful method by which designers can graphically overlay the structural response of an isolated structure and earthquake demand to determine an effective operating point (acceleration, displacement and effective viscous damping) of the isolated system.

The paper examined the inelastic response behaviour of simple isolation systems responding to some of the actual strong motion records obtained from the Canterbury earthquake sequence. The inelastic response studies were based directly on isolation system properties that are explicitly known - yield level and post-elastic stiffness (or elastic period). The approximations and iterative design process inherent in the “equivalent viscous damping” approach are eliminated. It was noted that the inelastic seismic demands on isolated systems can conveniently be presented in graphical form as a direct inelastic acceleration-displacement response spectrum.

In this paper the 2013 analysis methodology is extended to give isolation system designers a direct method of estimating structure lateral load demands and isolation displacement demands to a set of code compliant strong motion records. The approach involved the following steps:

- 7 strong motion records were selected including 4 Christchurch CBD records and 3 overseas records that represent large magnitude far source to site distances. The records were scaled in accordance with the requirements of NZS 1170.5.
- Isolation system parameters representative of practical system behaviour were selected.
- A series of inelastic time history analyses were carried out using the scaled records and the results are presented in a graphical form showing system demands directly.

Finally, the effects of residual displacement of bilinear isolation systems are examined to understand whether there may be cumulative ratcheting effects that might detrimentally affect the performance of typical isolation systems in Christchurch.

2 STRONG MOTION RECORDS

A suite of seven strong motion earthquake records for Christchurch CBD sites has been selected based on recommendations of Dr Brendon Bradley (Bradley 2013). The suite consists of four Christchurch records (two each from 2010 and 2011) and three overseas records. The latter were included to represent “large magnitude events at regional and far source-to-site distances” which are not represented in the 2010 and 2011 records. It is understood that this suite of records has been used for a number of Christchurch rebuild projects.

The records were scaled following the procedure of NZS 1170.5 to provide a match to the code design response spectrum (5% damped) for Z=0.3, N=1, Soil type D. For the present study, single degree of freedom analyses were performed and therefore only one (dominant) horizontal component was selected and scaled. Amplitudes corresponding to R=1.3, 1.8 and 2.25 were considered, corresponding to shaking intensities of 1 in 1,000, 1 in 2,500 and 1 in (approximately) 7,500 years. The last level is in excess of intensities considered in NZS 1170.5, but was included for reference as it might be considered for design of critical structures, such as Importance Level 4 facilities.

Scaling was performed considering the period range of 2.5 - 4.0 seconds, which covers the effective period of the maximum response of typical base-isolation systems that might be utilized in Christchurch. The record scale factor K_1 for each of the seven records is determined to provide a best fit of the 5% spectrum of the record being scaled with the target spectrum. A second K_2 ("family") scale factor is applied to all records to ensure that the target code spectrum is enveloped by the envelope of the spectra of the records being scaled. The ground motion records and scale factors (for the R=1.8, 2,500yr) used in the study are presented in Table 1. The resulting acceleration and displacement spectral match showing both the mean and envelope spectra are shown in Figure 1.

Table 1. Selected strong motion records and scaling to NZS 1170.5 for R=1.8.

Record	NGA ID# (PEER)	Event	Station	Component	K1 Record	K2 Family	Scale Factor
1		ChCh 2010	CBGS	2	1.66	1.12	1.86
2		ChCh 2010	CHHC	1	1.62	1.12	1.81
3		ChCh2011	CBGS	1	1.05	1.12	1.18
4		ChCh 2011	CHHC	2	1.12	1.12	1.25
5	1207	Chi Chi, Taiwan	CHY044	2	3.98	1.12	4.46
6	1187	Chi Chi, Taiwan	CHY015	2	2.58	1.12	2.89
7	1177	Kocaeli, Turkey	Zeytinburnu	1	7.08	1.12	7.93

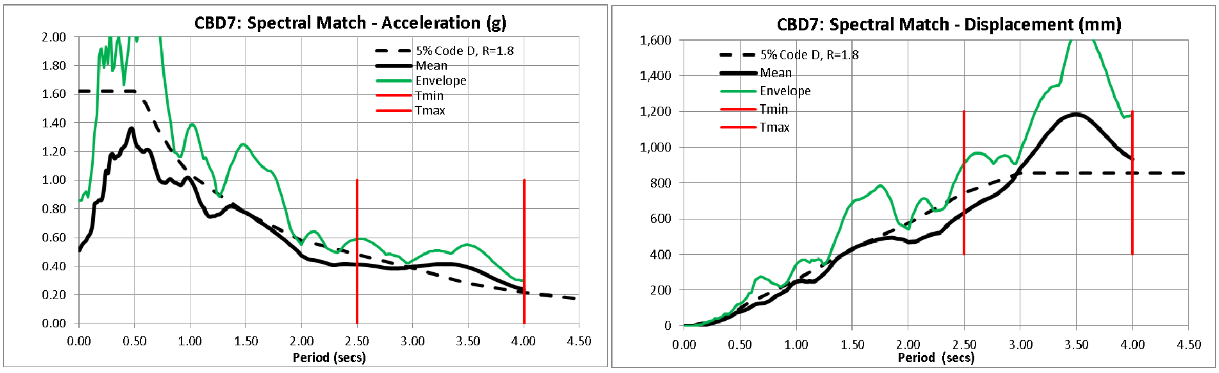


Figure 1. Comparison of scaled strong motion acceleration and displacement spectra with NZS 1170.5 (R=1.8).

3 ANALYTICAL STUDIES

Base isolation systems are often modelled using a bi-linear hysteresis model as shown in Figure 2. For elastomeric bearing isolators (including lead-rubber bearings) the yield force (Q_d) is the result of yielding of the lead core, and the elastic stiffness (K_d) results from elastic shear deformation of the rubber material. For isolator types involving sliding (curved or flat sliders) of a friction material against a smooth surface, the yield force arises from the sliding friction force (Q_d) at the interface. The post-elastic stiffness K_d is purely a function of the curvature of the surface supporting the sliding element (and is zero for flat sliders). A period T_2 corresponding to the post-elastic stiffness can be determined. Isolator properties are conveniently defined by the zero displacement yield level (Q_d/W) and the post-elastic period (T_2), as these are amplitude independent and can be directly selected and specified by the designer. Note that for elastomeric bearing systems, knowledge of the tributary mass is also needed in order to determine either isolator properties or equivalent overall isolation system properties.

For the present study, T_2 values of 3.0, 4.0 and 5.0 seconds are selected, representing a typical range from stiffer to more flexible. Yield levels of 6%, 8%, 10% and 12%W were chosen. For each combination of isolator parameters, non-linear time history analyses (NLTHA) have been performed for each of the seven strong motion records scaled to each of three return periods. The representative response of a given response parameter is taken as the average of the results for each strong motion record. For brevity, detailed results presented here are for the R=1.8 (1 in 2,500 year) analysis only.

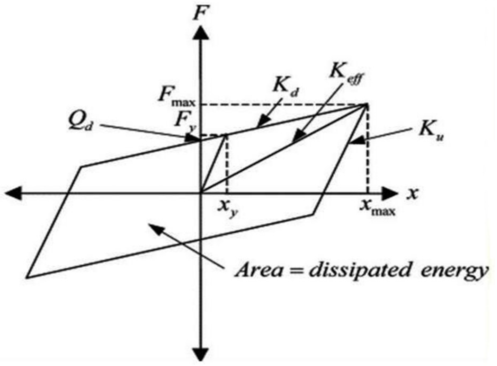


Figure 2. Typical bilinear shear force versus displacement behaviour for isolators.

Figures 3 (a) and (b) show the inelastic analysis displacement and base shear demands, for the 1 in 2,500 year case, presented in the form of spectra plotted against T_2 on the horizontal axis. It is evident that, the displacement demand is fairly constant across the T_2 range for a given yield level. This is somewhat surprising given that it is commonly assumed that a more flexible system (ie greater T_2) will produce greater displacement demand. To some extent the explanation is in the fact that, for a given yield level, the equivalent viscous damping (EVD) increases with reduced stiffness (ratio of hysteretic to elastic strain energy increases). Of course, the basic design displacement spectrum is also constant for periods greater than 3.0 seconds, which will also influence this behaviour. Figure 3 (c) shows the equivalent viscous damping (EVD) value.

The plots on the right hand side of Figure 3 show the same data plotted versus yield level. Again it can be seen that the shear (ie the force transmitted to the structure) is primarily dependent on the T_2 value and remains fairly constant with yield level. Observations such as these clearly show the important effects of isolator properties. Using these charts, overall design of an isolation system is quite straightforward and avoids the need for iteration or extensive overall system analysis.

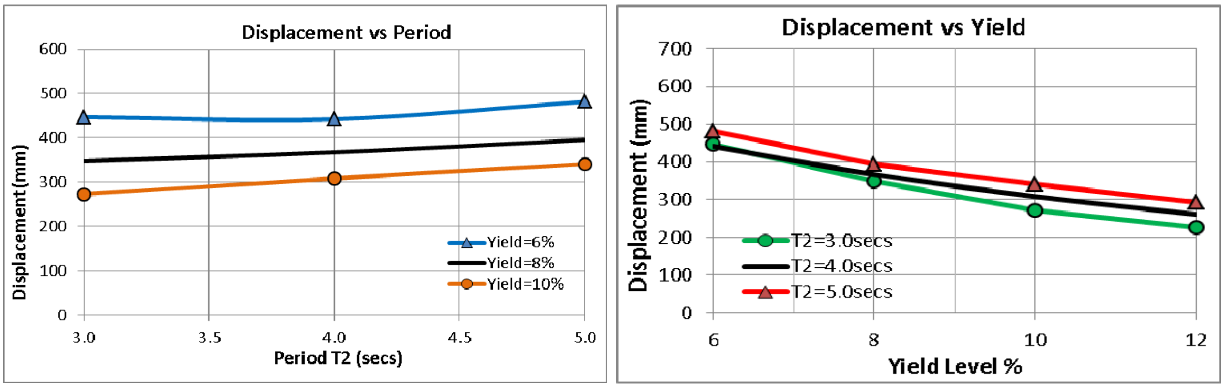
Figure 4 consolidates the displacement response values in a single chart showing displacement demand for the 1 in 1,000 year (R=1.3), 1 in 2,500 year (R=1.8) and 1 in 7,500 year (R=2.25) values- for each T_2 value for yield levels ranging from 6% to 12%.

4 COMPARISON OF INELASTIC SPECTRA WITH CODE SPECTRA AND B-FACTORS

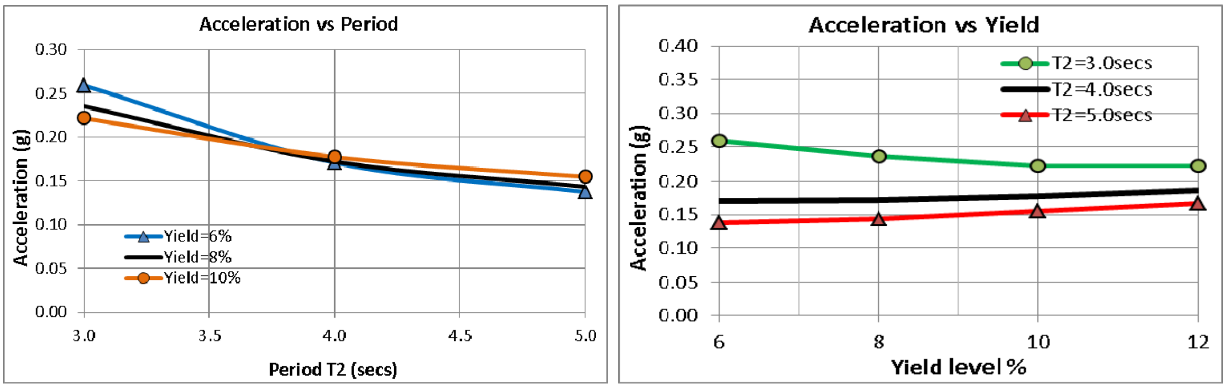
A common approach to estimating response of isolated systems, or other systems with significant levels of damping, is to modify the code 5% damping elastic acceleration response spectra with a damping adjustment factor ("B-Factor"). Figure 5 shows the results of the calculated inelastic displacement response spectra discussed above, compared with elastic displacement response inferred from NZS 1170 5% damped spectra with various B-Factor type damping adjustments applied according to NZSEE 2006, ASCE 7-10 and Eurocode. The B-Factor scaling of the code elastic response spectra generally over-estimate the displacements (by as much as 50%) compared with the calculated inelastic spectra.

5 EFFECT OF ISOLATOR YIELD DISPLACEMENT

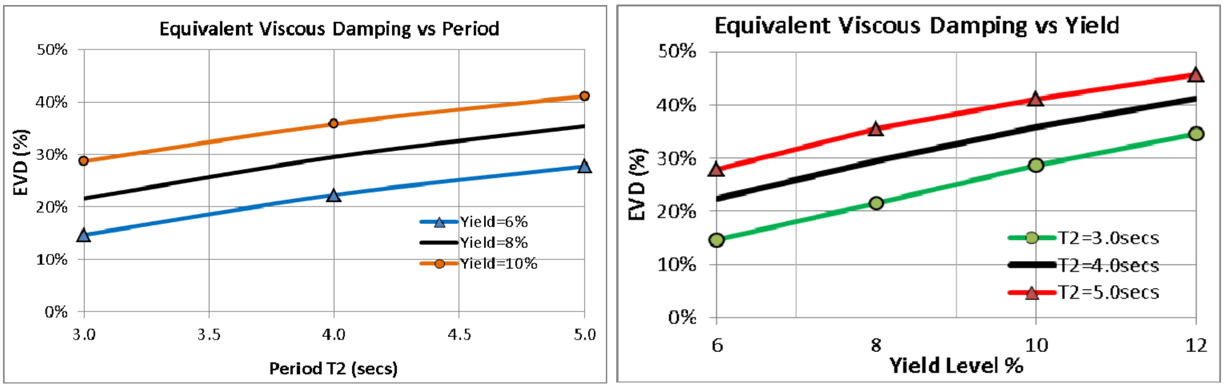
The displacement response of the isolation system is also dependent to some degree on the initial stiffness F_y/X_y and corresponding yield displacement. The steeper the initial elastic slope, the greater will be the area enclosed by the hysteresis loop and hence greater energy dissipation and effective viscous damping. The results presented in this paper are all based on an approximately 2-5mm yield displacement which is typical of a sliding system. For an elastomeric isolator (such as lead-rubber), the yield displacement is typically larger than this (20-50mm).



(a) Inelastic displacement response.



(b) Inelastic acceleration response.



(c) Equivalent viscous damping.

Figure 3. Inelastic response versus period T_2 and yield level (1 in 2,500 year).

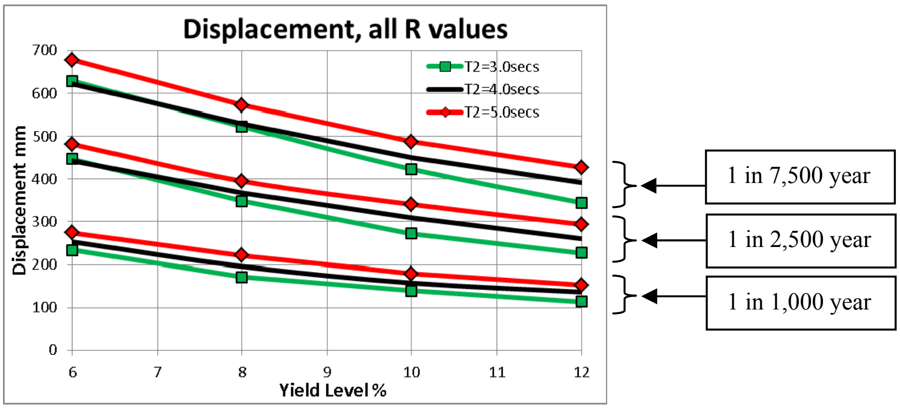


Figure 4. Inelastic displacement response versus isolator yield level.

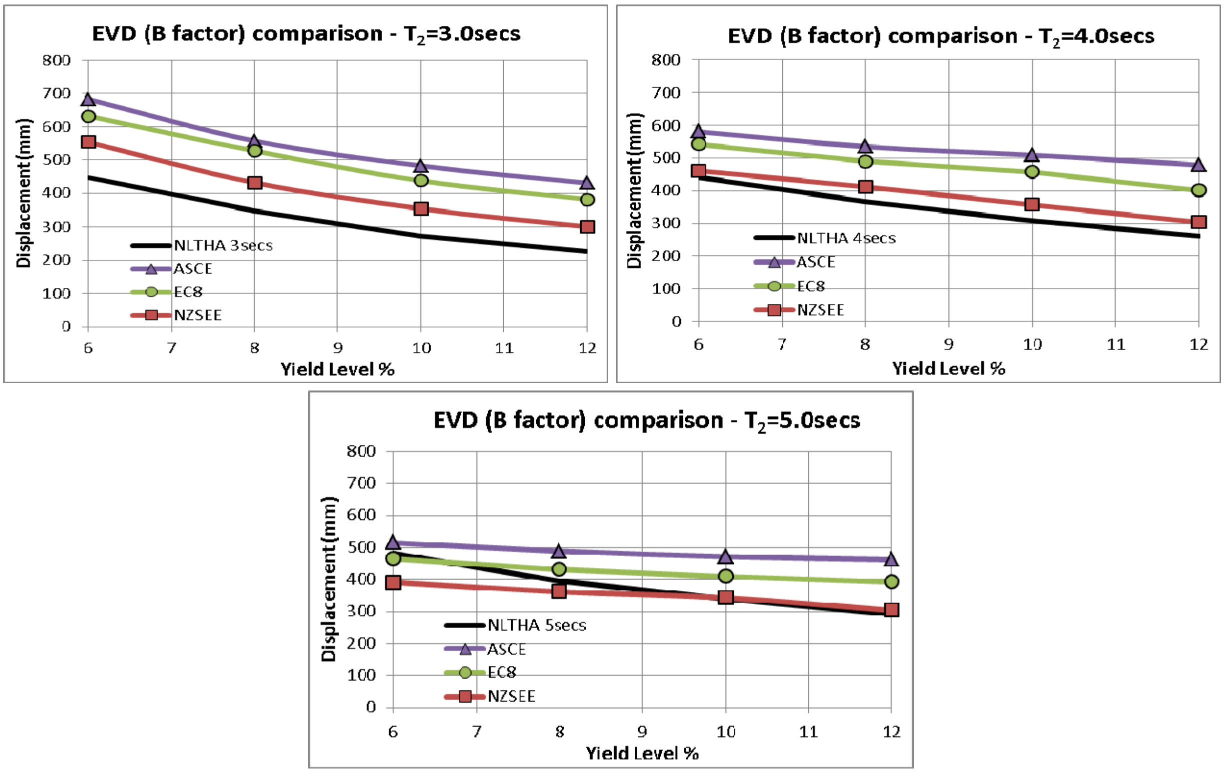


Figure 5. Comparison of inelastic displacement response spectra with “B-Factor” spectra.

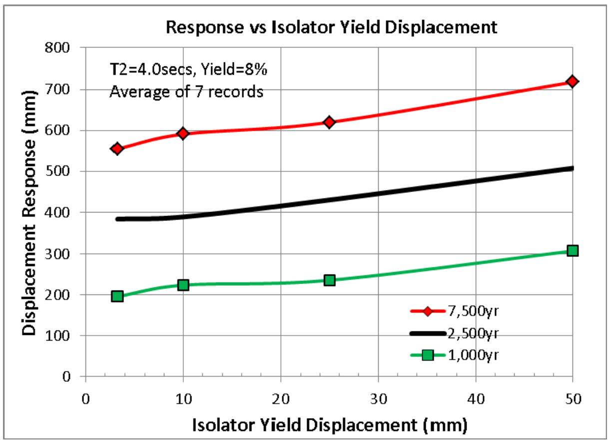


Figure 6. Effect of isolator yield displacement on displacement demand.

Figure 6 illustrates the effect of isolator yield displacement on the maximum displacement demand. The results are for an isolation system with T_2=4.0secs and a yield of 8%W. Each data point represents the average of the maxima of seven time-history analyses. It can be seen that the response increases with increasing yield displacement quite linearly (and consistently between earthquake shaking return periods). For a system with yield displacement of 50mm the displacements predicted by the ADRS charts presented here need to be scaled by a factor of up to 1.3. Further investigation of this behaviour is necessary.

6 DIRECT INELASTIC ACCELERATION-DISPLACEMENT RESPONSE SPECTRUM

The authors (2013) presented the concept of a direct inelastic acceleration–displacement response spectrum, which further consolidates the inelastic spectral demands on to a single diagram.

Figure 7 shows a completed direct inelastic acceleration–displacement response spectrum graph presenting the results from section 3 for 1 in 1000 and 1 in 2,500 year earthquake demands. The overall system acceleration and displacements can be determined directly based on selected yield level and T_2 period properties of the isolation system.

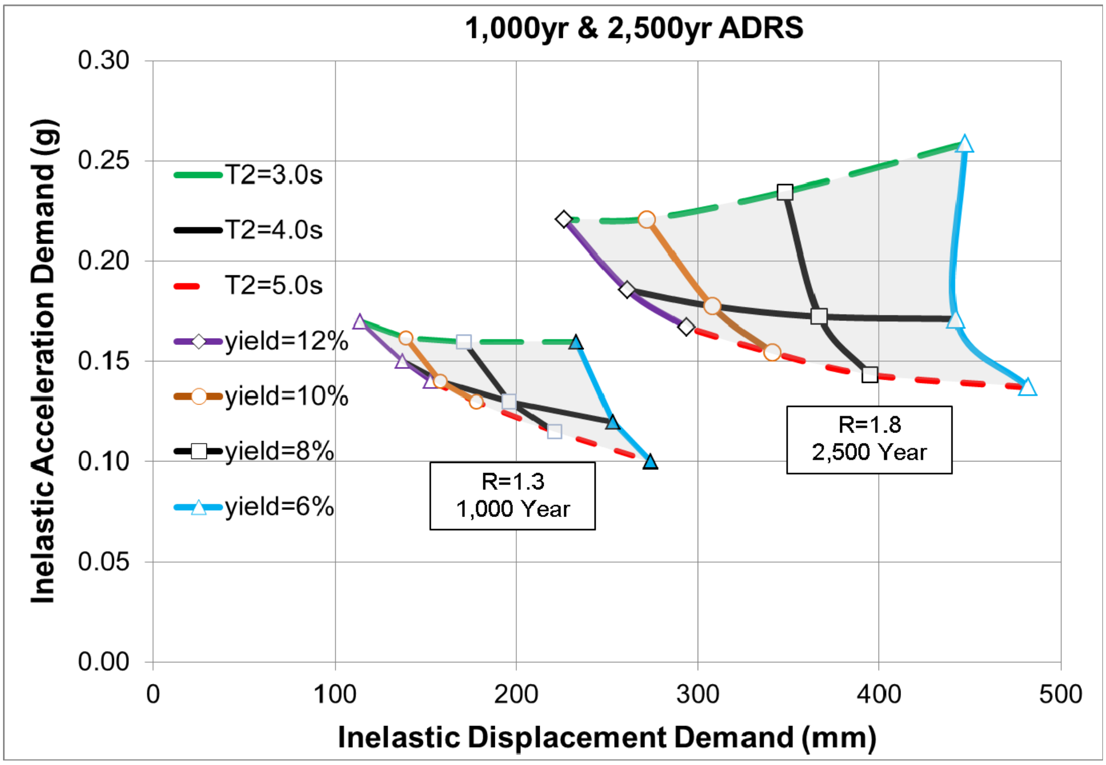


Figure 7. Direct inelastic acceleration-displacement response spectra for isolated structures in Christchurch.

7 ISOLATOR RECENTERING PERFORMANCE

Adequate re-centring performance of an isolator is a function of both the earthquake ground motion and the isolator properties. It is important that residual displacement does not compound and in effect "use up" the available displacement capacity. Given the very large number of aftershocks that have occurred in Christchurch, it is useful to look at their impact. As part of this investigation a preliminary study has looked at these effects.

To prevent significant residual displacement behaviour it is necessary to avoid system designs that are a combination of long period (T_2) and high yield level. This has not been well addressed in the codes although recent studies are bringing a better understanding to the issue. One such study (Katsaris 2006) used a wide range of earthquake records to develop "generic" guidelines. However, many of the seismic records used may not be appropriate for application in Christchurch.

Residual displacements were calculated for an example isolation system with at T_2=4.0 seconds, yield level = 0.08W and yield displacement of 5mm. For each of the 7 CBD records selected for this study, scaled to R=1.8, the residual displacement at the end of each analysis was noted. The variation of residual offset over the seven records is shown in Figure 8. The maximum residual was 25mm (7.9% of the maximum displacement response) for the scaled 2011 CHHC record.

In order to check if there was likely to be any cumulative residual effects for this record (CHHC), the analysis was repeated twice in succession, using the residual offset from the first event as an initial offset for the second event. The final residual displacement from two identical events was the same as from one event. This was repeated scaling the record by 1.25 and 1/1.25 and in each case no cumulative effect was observed.

The impact of a substantial initial offset was also considered (irrespective of its origin). The 2011 Botanical Gardens record (CBGS) scaled to R=1.8 was used and initial displacement offsets of 0, +100mm and -100mm were applied. The results shown in Figure 9 show that the impact of the initial offsets is eliminated in little more than one complete cycle. Clearly this system is exhibiting very good re-centring behaviour for this earthquake record. Additional studies will be carried out using the other records.

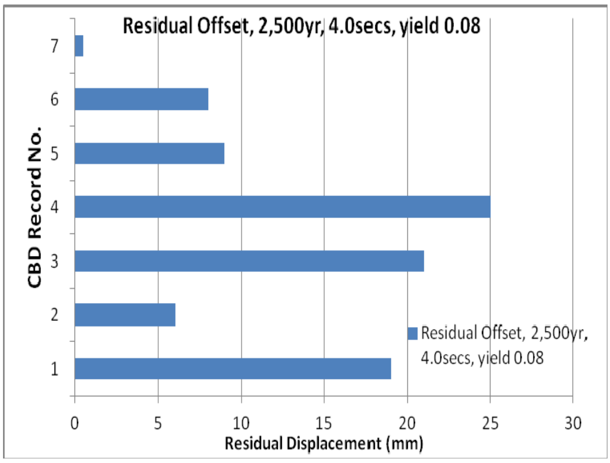


Figure 8. Isolator Residual displacements.

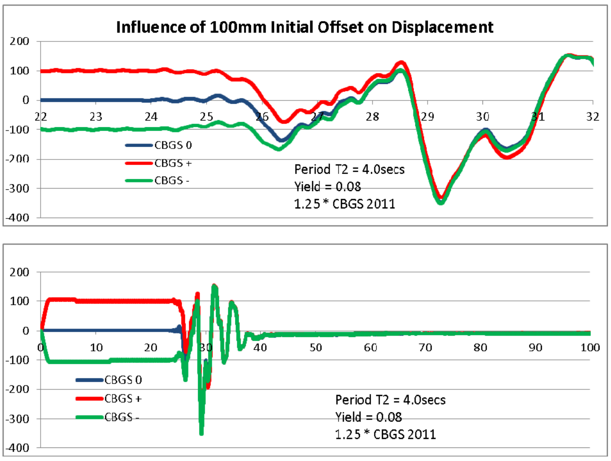


Figure 9. Effect of initial residual offset response.

8 CONCLUSIONS

A suite of strong motion earthquake records has been selected and scaled to the NZS 1170.5 code spectra, suitable for typical Christchurch central city sites.

Using the suite of scaled strong motion records an extensive number of inelastic time history analyses were carried out to determine the displacement and acceleration responses of isolation systems with a practical range of yield and post-elastic system properties applicable to real lead rubber or concave slider bearing systems.

The direct inelastic acceleration–displacement response spectra presented enable estimation of acceleration and displacement response demands directly based on yield level and post-elastic period of the isolation system. The results are presented in a convenient graphical form that will inform designers and isolator suppliers of the demands and overall behaviour of practical isolation systems.

Isolator re-centring performance has been examined and current indications are that, for the range of isolators properties considered herein under the effect of multiple earthquake events, isolators desirably tend to re-centre rather than ratchet to large displacement offsets.

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