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NONLINEAR RESPONSE SPECTRA FOR ISOLATION SYSTEM DESIGN: CASE STUDIES IN TURKEY, CALIFORNIA AND NEW ZEALAND

Lindsay Jones[1], Ian Aiken[2], Cameron Black[3], David Whittaker[4] and Bahadır Şadan[5]

[1] *President, Maxlide Ltd, Christchurch, New Zealand*
[2] *Principal, Seismic Isolation Engineering, Inc., Emeryville, California, U.S.A.*
[3] *Associate, Seismic Isolation Engineering, Inc., Emeryville, California, U.S.A.*
[4] *Technical Director Structural, Beca Ltd, Christchurch, New Zealand*
[5] *Principal, OBS Project Engineering Consultancy Co., Ltd, Istanbul, Turkey*
Email: linzjonz@maxlide.com

ABSTRACT:

Design displacements and accelerations are determined and compared for typical seismic isolation systems and locations designed in accordance with site-specific seismic demands in New Zealand, California and Turkey. The design demands are estimated by nonlinear time-history analyses using suites of scaled strong motion records following the provisions of ASCE 7-10 for California, NZS 1170.5:2004 for New Zealand and the Specification for Buildings To Be Built In Seismic Zones (2007) for Turkey. Selected isolation system parameters represent a practical range of both typical lead-rubber and pendulum isolation systems. The parameters for the isolation system are the characteristic strength and the post-yield stiffness, herein referred to as the characteristic stiffness (and expressed as a period of vibration), both of which can be directly selected by the designer. These isolation system parameters are independent of response displacement and are therefore preferable over the commonly used "equivalent linear" properties of secant stiffness and equivalent viscous damping which are response dependent. Site locations considered are a central Christchurch NZ location, a near-fault location in the San Francisco Bay Area, and two locations in Turkey: a Seismic Zone 2 near-fault site in eastern Turkey and a Seismic Zone 1 location in the Istanbul area. The displacement and acceleration demands determined from the nonlinear analyses are presented in a convenient and powerful graphical form which can be used by designers to quickly and accurately assess the performance of isolation systems in the design process. The approach also provides a rational, simple means of assessing the impact of material property variations and tolerances rather than relying on arbitrary code-specified values.

KEYWORDS: isolation, design, nonlinear, spectra, analysis

1. INTRODUCTION

Common seismic isolation device technologies such as lead rubber bearings or concave slider bearings exhibit very full force–displacement hysteresis and are able to dissipate large amounts of seismic energy. This type of hysteretic behaviour is often approximated as an equivalent linear system with secant stiffness and equivalent viscous damping.

The longer period of vibration and significant damping of an isolated structure result in substantially lower acceleration (and thus force and damage) response compared with the same fixed base structure. The resulting significant displacements are accommodated in the isolation devices that are designed to sustain such large movements without damage.

Previous work by the authors [Whittaker and Jones 2013, 2014] examined how the design requirements of building codes, such as NZS 1170.5 [NZS, 2004], 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 defined in a number of different international codes and guidelines, such as ASCE, 2010; Eurocode, 2004; NZSEE, 2006.

The previous work also examined elastic acceleration and displacement response spectra determined using 25% equivalent viscous damping and how the resulting response spectra compared with the 5%-damped elastic response implied by building codes. The highly-damped elastic (and inelastic) response spectra both showed significant reductions of displacement and acceleration response compared to the 5%-damped spectra. It clearly showed that the notable long-period peaks in the 5% spectra from the February 2011 Christchurch Earthquake would not be expected to unduly affect typical isolated structures with a moderate level of damping.

The concept of nonlinear Acceleration Displacement Response Spectra (ADRS) was also shown to be a valuable tool for structural designers to graphically define the seismic demand and effective operating point (in terms of base shear and isolation system displacement) of isolation system designs (for a range of characteristic strengths and characteristic stiffnesses). The nonlinear ADRS are developed for the design suite of ground motion time histories. The ADRS are shown to provide a more direct and meaningful approach than the linear one.

The previous papers explored the use of ADRS to understand the response behaviour of single-degree-of-freedom nonlinear isolation systems to a suite of actual strong motion records from the Canterbury earthquake sequence. The ADRS method conveniently, and directly, presents the inelastic seismic demands on isolated systems in graphical form and provides a highly intuitive tool for design.

2. ADRS METHODOLOGY

The properties of an isolator, or isolation system, used in the ADRS response evaluation method are the “characteristic stiffness”, which corresponds to the post-yield stiffness (K_2, or “second slope”) period of vibration, T_2, and the “characteristic strength”, yield level (or friction coefficient), often referred to as Q_d (Figure 1). It is important to note that these are fundamental characteristics of an isolation device (or system) and are not amplitude dependent, as are the effective stiffness (or effective period, T_{eff}) and equivalent viscous damping. These characteristic properties are intuitive to designers, and directly controlled in the design process.

The charts as presented are normalized to be weight independent. Calculation of a corresponding stiffness depends on the type of isolation system being designed. The approximations inherent to, and the necessarily iterative design process required for the “effective (secant) stiffness-equivalent viscous damping” method can be eliminated.

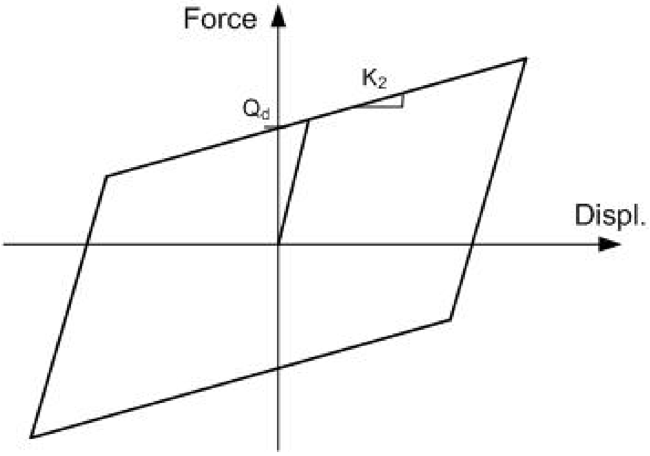


Figure 1. Hysteresis loop parameters used for ADRS development

Seismic responses are calculated for pairs of characteristic strength and isolation period values – and for each of the ground motion records in the suite being considered for design (often seven pairs) scaled to the design spectrum of the applicable code. The resulting contour plot (Figure 2) makes it very easy for a designer to assess the impact of varying either of the two primary isolation system properties and to arrive at the preferred design for the system. The graph can also be useful for establishing rational, acceptable property variations for isolator properties in testing.

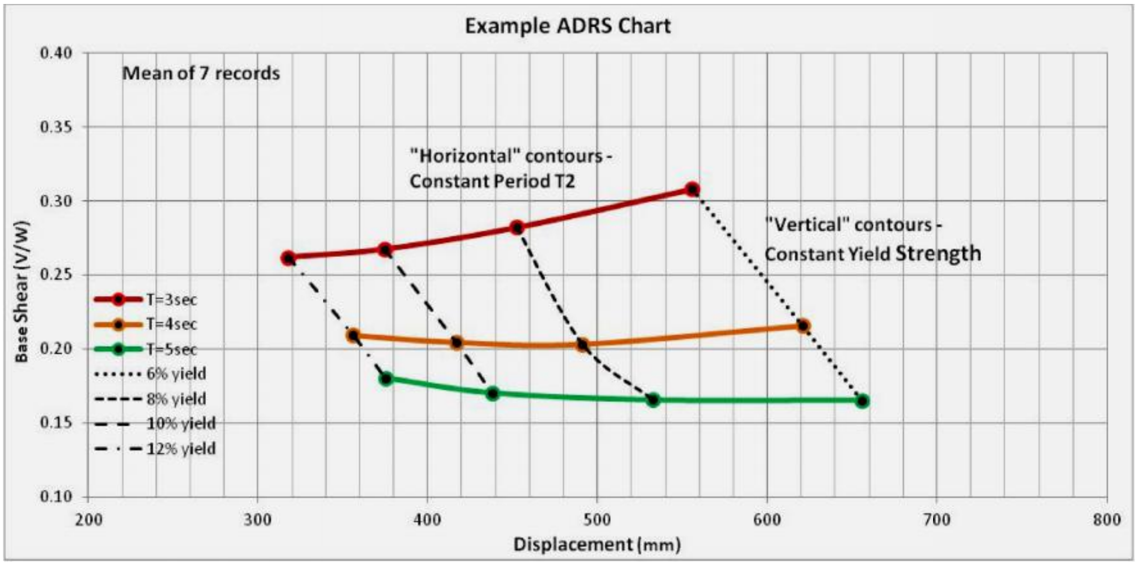


Figure 2. Example ADRS contour plot

2.1 Nonlinear Analysis Procedure

Isolation system response for the development of the ADRS contour is determined through time-history analyses of a Bouc-Wen hysteretic single-degree-of-freedom (SDOF) oscillator to represent the nonlinear behaviour of the isolation devices. The nonlinear equation of motion for the SDOF system was solved directly using Matlab.

An ADRS for seven ground motion pairs, with four period and four characteristic strength values defined, requires a total of 224 analyses. In the case of pairs of ground motions, the maximum displacements in each direction are combined using the SRSS method to determine the maximum response value. When seven or more ground motions (or pairs) are used, the average of these maximum response values is calculated, and when three ground motions (or pairs) are used, the maximum value of the maxima is taken.

Similar ADRS charts can also be easily developed using the simplified linearized or Equivalent Viscous Damping (EVD) approach that is used in a number of codes for seismic isolation. This is presented and discussed as an example case below.

3. CHRISTCHURCH, NEW ZEALAND

The destructive sequence of earthquakes in Christchurch in 2010 and 2011 caused widespread building damage, resulting in many buildings being economic write-offs and the demolition of a large number of buildings in the city. Christchurch was not previously considered at high seismic risk, but the new awareness after the earthquakes has resulted in seismic isolation playing an important role in the rebuild. Owners and designers are seeking more effective seismic protection systems for their buildings that will greatly reduce earthquake damage. This applies not only to important cultural and critical facilities, but also to many new commercial buildings which are being designed with seismic isolation.

The New Zealand structural design standard, NZS 1170.5, does not give specific requirements for the design of seismically-isolated structures or what earthquake design loads should be used for such systems. Engineers are adopting various design approaches such as using displacement-based design methods, or selectively adopting the requirements of design codes from other countries, such as ASCE-7 from the US and EN-15129 from

Europe. A seismic isolation design guideline document is currently under development in NZ [Parker and Whittaker, 2015] and is targeted for completion by the end of 2015.
The isolation system design example presented here is for a typical commercial building located in the Christchurch Central Business District (CBD), the area of the city that suffered major damage in 2010 and 2011.

A suite of seven strong motion earthquake records for design for a Christchurch CBD site was selected based on the recommendations of Dr. Brendon Bradley [Bradley, 2013]. The suite consists of four Christchurch records (two each from the September 4, 2010 and the February 22, 2011 earthquake events) and three worldwide records (two from Chi Chi, Taiwan, 1999, and one from Kocaeli, Turkey, also 1999). The latter three were included to represent "large magnitude events at regional and far source-to-site distances" which are not represented in the 2010 and 2011 Christchurch records.

The records were scaled following the procedure of NZS 1170.5 to provide a match to the code 5%-damped design response spectrum for Z=0.3, N=1 and Soil type D. Following the NZS 1170.5 approach, for each pair of horizontal motions, one is designated as the Principal component based on its amplitude compared with the target spectrum over the period range of 2.5 to 4.0 seconds (which covers the effective period of the maximum response of typical seismic isolation systems). In this paper, the secondary component was not considered. Amplitudes corresponding to R=1.3, and 1.8 were considered, corresponding to hazard levels with return periods of 1 in 1,000 years and 1 in 2,500 years, respectively. ADRS plots (Figure 3) are developed for isolation periods of T_2 = 2, 3, 4 and 5 seconds and characteristic strengths of 4%, 6%, 8% and 10% of the weight of the superstructure, W.

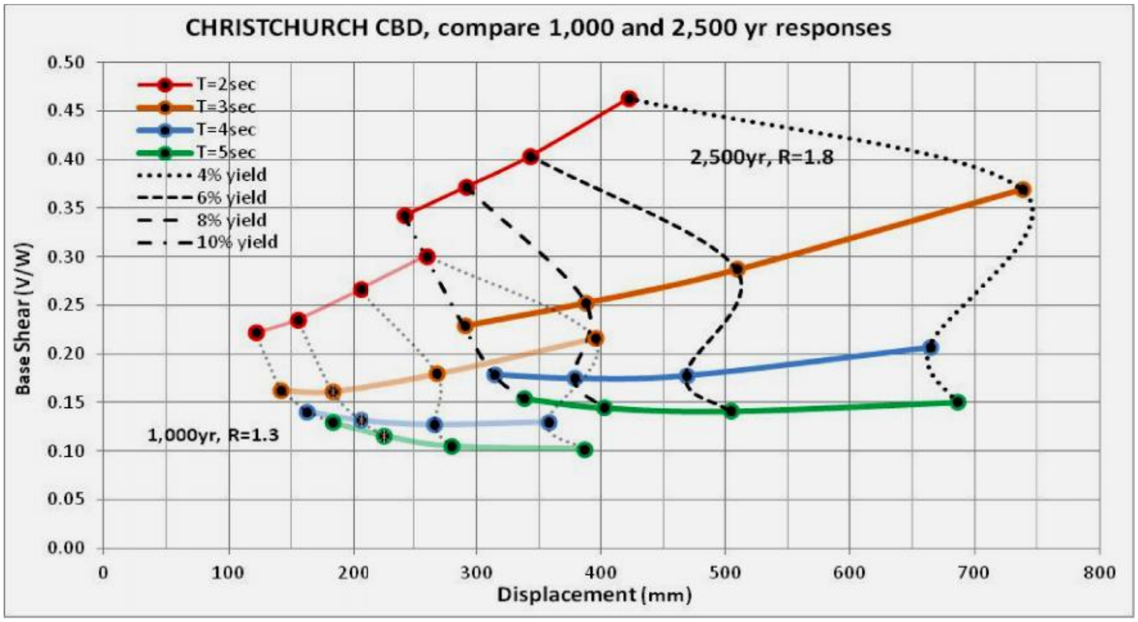


Figure 3. Christchurch ADRS for 1,000 year and 2,500 year hazard levels

An interesting characteristic of the Christchurch ADRS contour is that the displacement demand for 3-second isolation systems (the orange lines in Figure 3) exceeds that of the other three period values (2, 4 and 5 seconds). This is believed to reflect the fact that one of the seven records used (recorded at the Christchurch Hospital in the September 2010 earthquake) showed a pronounced "bump" in the 5%-damped response spectrum in the range of 3 seconds. The ADRS curves clearly show that the impact of this demand "bump" for seismic isolation design is substantially reduced by increased damping in the isolation system [Whittaker and Jones, 2013]. In the above chart, the increased demand of the "bump" is clearly most pronounced for the lowest (4%) yield level, corresponding to the lowest equivalent viscous damping level (about 9%).

4. SAN FRANCISCO BAY AREA, CALIFORNIA

A recent essential facility project in the San Francisco Bay Area, approximately 6 km from the San Andreas Fault, provided the opportunity to apply the ADRS methodology to a suite of ground motions developed for a near-fault, high-seismicity location in California.

Seven sets of two horizontal component ground motion time histories were matched to be spectrum-compatible with the maximum rotated component of the MCE 5% damped design spectrum (2 percent in 50-year probability of exceedance). Starting seed time histories were selected from historically available records, based on the deaggregation of the site-specific probabilistic seismic hazard analysis, and the seed time histories were scaled in the frequency domain such that the square root sum of the squares (SRSS) of the horizontal components from each of the seven sets is greater than or equal to the design spectrum over the period range of interest of 1.05 to 3.0 seconds (per ASCE 7-10 and the project isolation design period). The selected time histories are listed in Table 1.

Table 1. San Francisco Bay Area Strong Motion Suite

Earthquake	**Date**	**Mag.**	**Mechanism**	**Rupture Dist [km]**	**Station**	**Components**
Kocaeli	17/Aug/1999	7.5	Strike-slip	4.8	Yarimca	060 / 330
Duzce	12/Nov/1999	7.1	Strike-slip	6.6	Duzce	180 / 270
Imperial Valley	19/May/1940	7.0	Strike-slip	6.1	El Centro	180 / 270
Landers	28/June/1992	7.3	Strike-slip	23.6	Yermo	270 / 360
Denali	3/Nov/2002	7.9	Strike-slip	2.7	Pump Stn #10	047 / 317
Tabas	16/Sep/1978	7.4	Reverse	2.0	Tabas	Long / Tran
Chi Chi	20/Sep/1999	7.6	Reverse	2.8	TCU076	NS / WE

The ADRS contour plot for the above frequency-domain scaled suite of records are shown in Figure 4. The values plotted are the SRSS for each component pair, and then the mean value determined from the seven pairs.

The same suite of records, alternatively scaled in the time domain, using the scaling tool of the PEER NGA-West2 database [PEER; Ancheta et al., 2013] were also used to compute an ADRS contour plot, and this is shown in Figure 5.

The response contours from both scaling methods show similarly large displacement responses for longer periods, and moderate to high system shear demands across all periods, indicative of the extremely high, near-fault demand at the site. Both plots indicate that in order to limit the maximum base shear to less than about 0.4W, an isolation period of 4 to 5 seconds is required, and a characteristic strength of about 0.09 to 0.10W.

The responses calculated from both frequency and time domain records show reasonable agreement. If it is assumed that the frequency-domain scaled records, in a general sense, provide more “accurate” results, for this suite of motions one might conclude that it is reasonable to construct the ADRS contour with a series of straight lines.

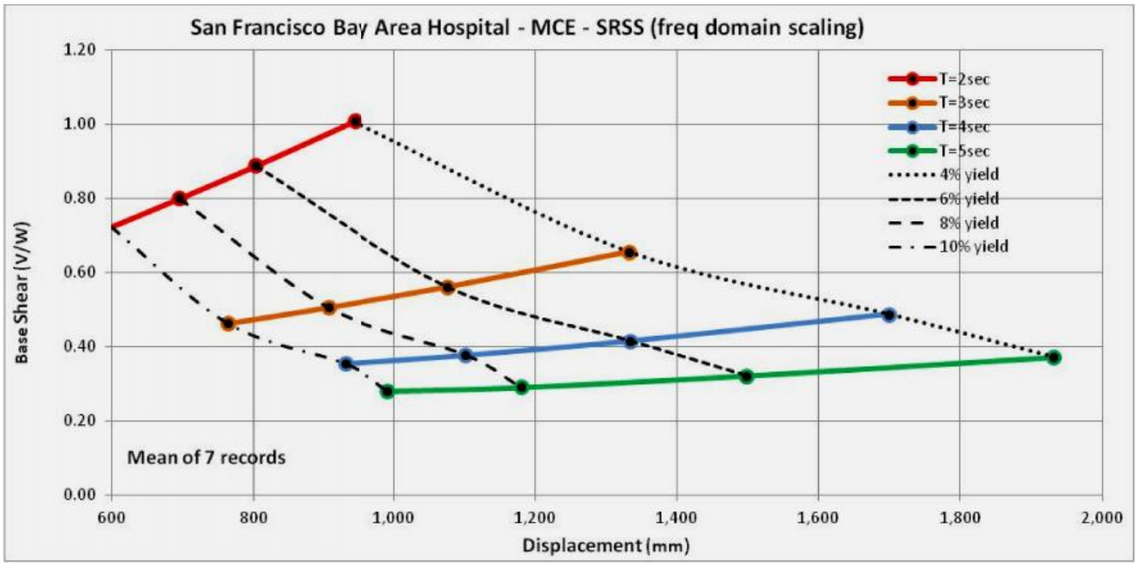


Figure 4. San Francisco Bay Area, ADRS for MCE-level frequency-domain scaled records

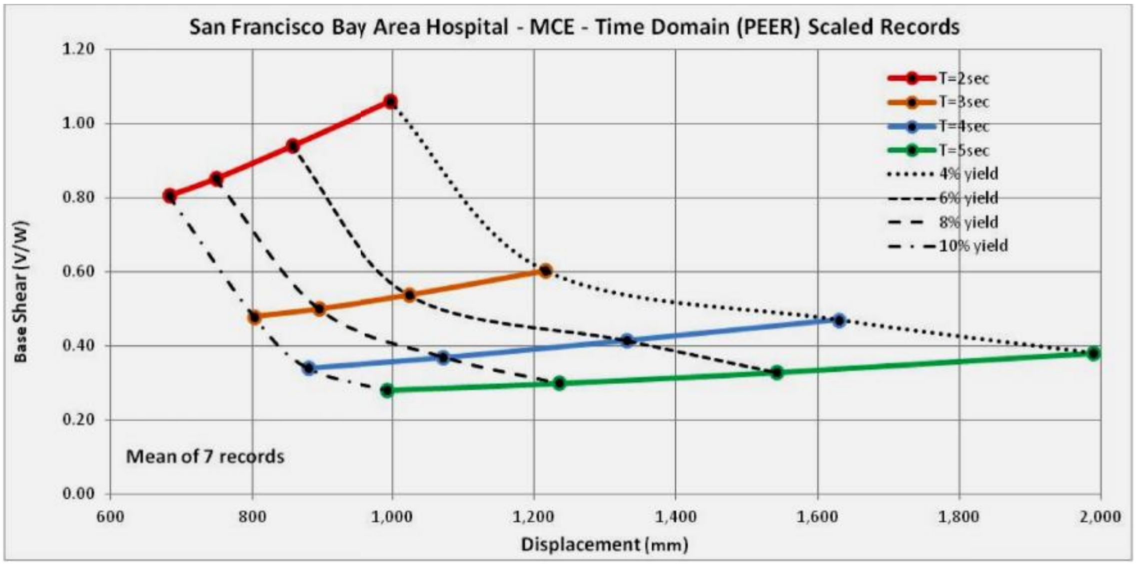


Figure 5. San Francisco Bay Area, ADRS for MCE-level time-domain scaled records

5. TURKEY

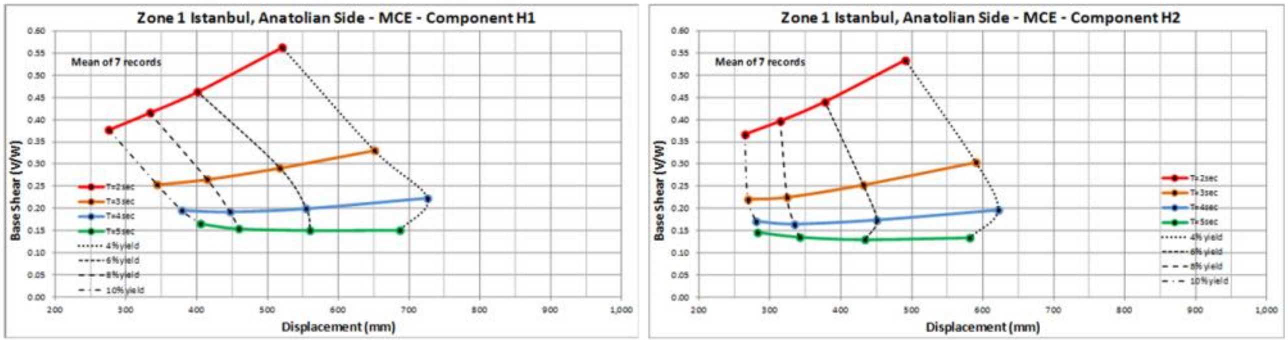
Two recent essential facility projects provided the opportunity to apply the ADRS methodology to suites of ground motions developed as part of probabilistic seismic hazard assessments for Seismic Zone 1 and Seismic Zone 2 sites in Istanbul and eastern Turkey, respectively, according to the Turkish Seismic Code (2007). These studies are described in the following sections.

5.1 Seismic Zone 1 Site, Anatolian Side of Istanbul

A uniform hazard response spectrum in accordance with the IBC (2006) provisions was established, with appropriate spectrum factors for site class C, consistent with the project site conditions. Hazard spectra were separately developed for two levels: 10% probability of exceedance in 50 years (DBE), and 2% probability of exceedance in 50 years (MCE). Suites of seven pairs of horizontal ground motion components were scaled using a time-domain spectral matching approach (Abrahamson, 1998) to the DBE and MCE target spectra, such that the SRSS spectrum of the two components was at least 1.3 times the target spectrum over the period range of interest (ASCE 7, 2010). Earthquake records from Kocaeli and Duzce, 1999; Landers, 1992; Hector Mine, 1999, and Manjil, Iran, 1990, were selected for spectral matching considering the fault mechanism, magnitude and closest distance characteristics of the events.

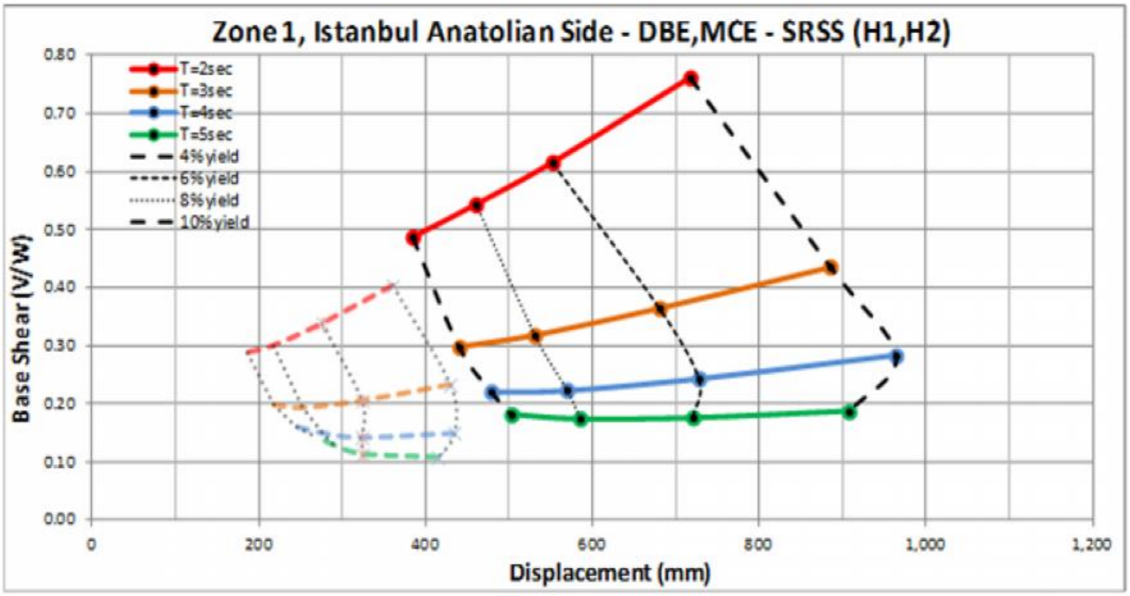
Figures 6(a) and (b) show the MCE level ADRS contours for the two horizontal components separately, and Figure 6(c) shows the DBE and MCE level contours for the mean value response of the two components combined using the SRSS method. The individual component response contours (Figures 6(a) and 6(b)) are similar, with the H1 component showing generally larger responses.

The combined component contour of Figure 6(c) clearly indicates that the lower left region of the ADRS chart is the preferred design parameter region for an isolation system for these particular demand conditions. With the preferred system parameters, or a range thereof, as identified by the ADRS contours, the designer can confidently and efficiently move into the detailed design phase using nonlinear time-history analyses for the complete structural system.



(a) MCE, H1 component

(b) MCE, H2 component



(c) MCE and DBE (SRSS) ADRS contours

Figure 6. Istanbul Zone 1 ADRS contours for separate horizontal components (a) and (b), and combined by SRSS (c), MCE and DBE levels

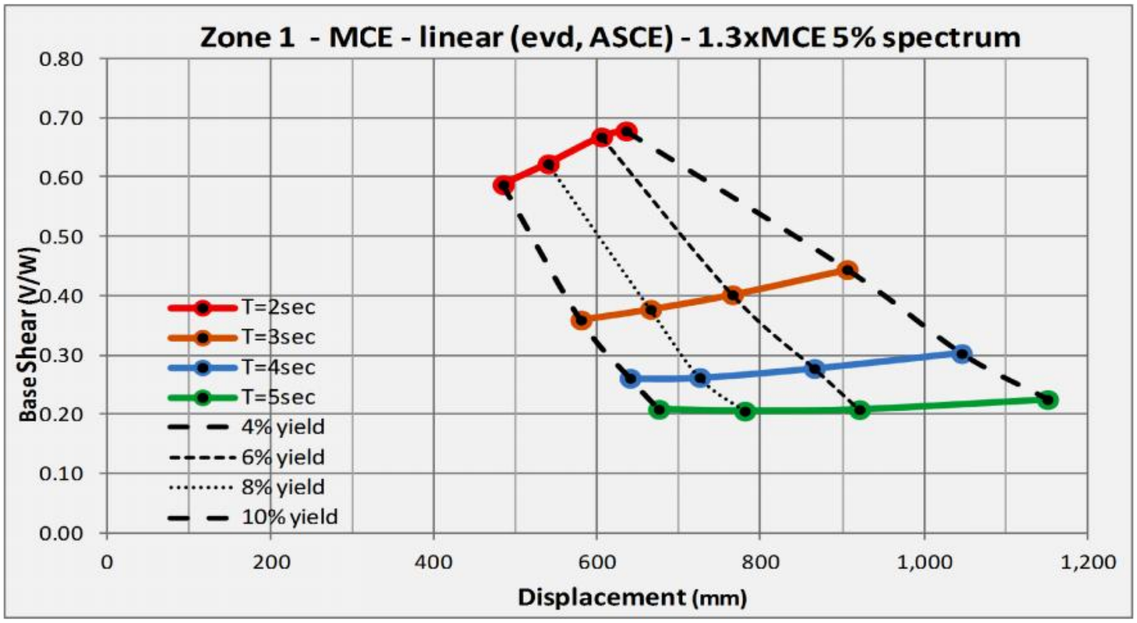


Figure 7. Istanbul Zone 1, MCE ADRS contour, ASCE EVD methodology

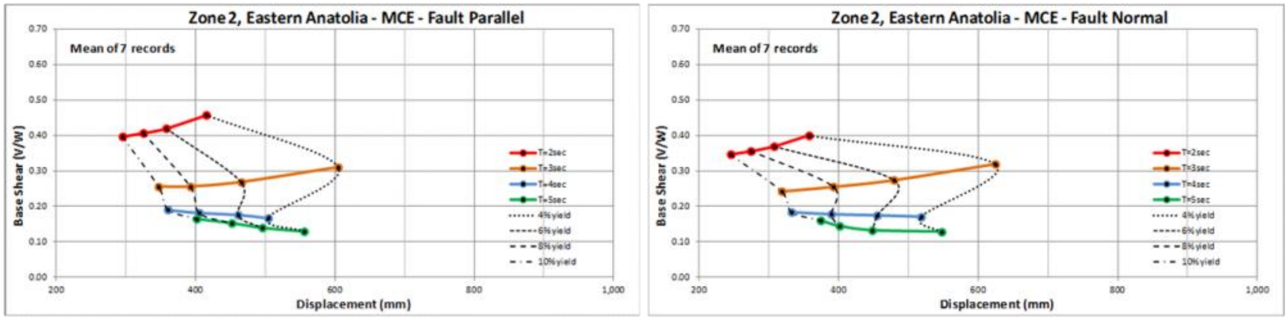
The ADRS contours of Figure 6 were computed using SDOF nonlinear time-history analysis and varying the characteristic strength and stiffness properties of the isolation system. Alternatively, effective stiffness and equivalent viscous damping (EVD) properties to approximate the properties of a bilinear isolation system and damping response reduction factors such as given by ASCE 7 (ASCE, 2010) may be used to achieve a code-based EVD estimation of isolation system response. Figure 7 gives the ADRS chart for such an approach using the Istanbul Zone 1 ground motion suite.

5.2 Seismic Zone 2 Site, Eastern Anatolia

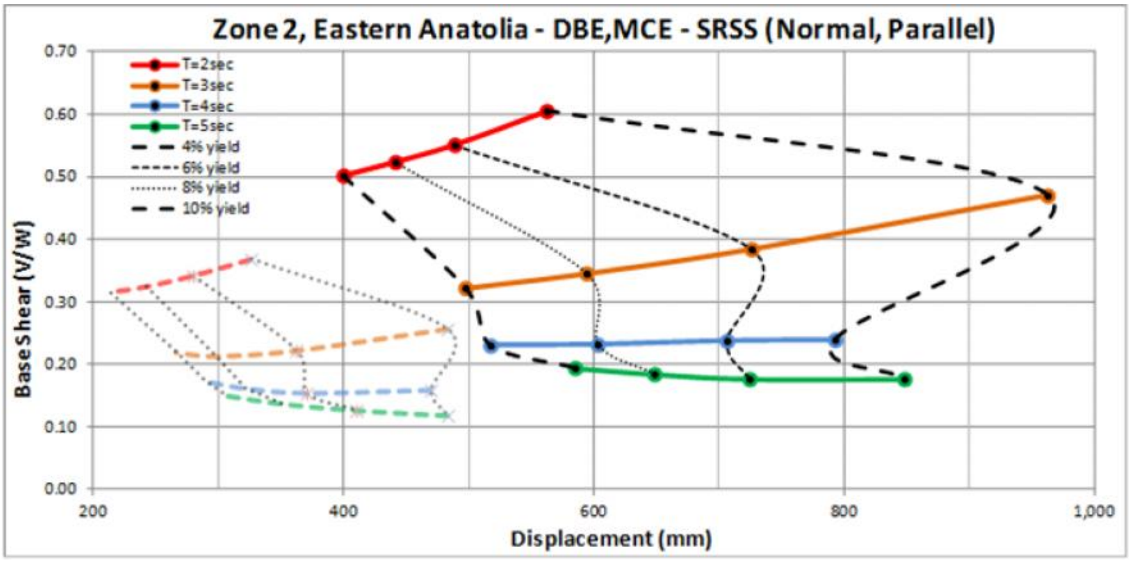
A suite of seven horizontal component pairs of ground motions was developed for the MCE and DBE hazard levels (where the DBE level is taken to be 2/3 times the MCE level). Recorded ground motions from the 1988 Armenia, 1989 Loma Prieta, California, and 1994 Northridge, California, earthquakes were selected based on fault mechanism, site soil conditions (soil class Z3) and closest distance, and scaled in the time domain to the site-specific target spectrum considering the period range of interest for the isolation system design.

Figures 8(a) and (b) show the separate MCE level ADRS contours for the fault parallel and fault normal horizontal ground motions, respectively, and Figure 8(c) shows the MCE and DBE contours for the mean value response of the two components combined using the SRSS method. The response contours indicate similar response trends in the two component directions, with some differences assumed due to directivity.

As was seen with the Istanbul Zone 1 site (Figure 6(c)), the combined component contour of Figure 8(c) clearly indicates that the lower left region of the ADRS chart is the preferred design parameter region for an isolation system for these particular demand conditions, and also clearly identifies systems with less desirable characteristics, namely, with a period of about three seconds and with lower characteristic strength values.



(a) MCE, fault parallel component (b) MCE, fault normal component



(c) MCE and DBE (SRSS) ADRS contours

Figure 8. Eastern Anatolia Zone 2 ADRS contours for separate horizontal components (a) and (b), and combined by SRSS (c), MCE and DBE levels

6. CODE (EVD) METHODOLOGY

As previously discussed, a simplified procedure for determining design actions for isolation systems is provided in major codes such as ASCE-7 and Eurocode 8 [2004]. All of the code methods use an equivalent viscous damping (EVD) relationship to compute and apply a reduction factor to the usual code 5%-damped design response spectrum. While the method is usually considered to over-estimate seismic response (and is hence often referred to as “conservative”) the numerous studies that have been carried recently and a number of relationship formulae proposed indicate a significant degree of unreliability to the approach.

These EVD code methods are, however, amenable to an ADRS approach as is seen in the above example of the Istanbul Seismic Zone 1 site. Other examples have been recently developed and presented by Jones et al. (2015).

7. CONCLUSIONS

With readily available computational power and numerical tools, the development of the ADRS contours using a nonlinear time-history analysis methodology is quite feasible for projects considering the use of seismic isolation. In the absence of NLTHA analyses, system responses estimated by a code equivalent viscous damping approach can also be expressed in this form.

The use of ADRS contours based on characteristic isolation system parameters, whether by nonlinear time-history analysis or code-based equivalent viscous damping methods, represents a significant improvement over the preliminary design approach that has been widely prevalent to date, namely that based on 5%-damped linear elastic response spectra. The resulting charts provide a valuable and intuitive visual tool to enable designers to quickly determine isolation system design parameters likely to be most effective for a given site. The "trade-offs" of different isolation periods and yield values (characteristic stiffness and strength) can be clearly identified. Further, a rational basis for determining acceptable property variations (applicable for the design process, and also for device testing) is provided rather than rely on arbitrary code specified values. The general use of the ADRS methodology should greatly facilitate the rapid, and accurate preliminary design of isolation systems for projects, and will represent another advance in expanding the use of the technology.

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