DESIGN SPECTRA FOR SEISMIC ISOLATION SYSTEMS IN TURKEY

Aslıhan YOLCU¹, Cüneyt TÜZÜN², Gülüm TANIRCAN³

ABSTRACT

In this study, acceleration-displacement response spectra (ADRS) approach of Whittaker and Jones (2014) is extended considering the new Turkish Building Seismic Design Code (TBSDC, 2018) that will come into force in 2018. In the ADRS approach, series of nonlinear response history analyses are performed for several isolation system parameters and seismic hazard levels. Effective and robust ADRS graphs which facilitate the preliminary design stage of the seismic isolation systems are examined and represented in graphical forms. ADRS graphs provide the base shear and displacement limits of seismic isolation systems in the region under maximum considered earthquake (MCE) and design basis earthquake (DBE) design levels. Shaking levels are obtained from New Probabilistic Seismic Hazard Map of Turkey (TDTH, 2016). The design spectra composition is formed using two site categories (NEHRP C and NEHRP D) and two hazard zones (high and moderate hazard) at each design level. For each design spectra, eleven horizontal ground motion pairs are selected and linearly scaled using the geomean of spectral ordinates. Analyses are performed using a combination of eight site-specific design spectra in total, six effective isolation system periods and five yield levels. Four ADRS charts are presented to reflect the effects of different design levels and site categories on the analysis results.

Keywords: Seismic isolation; Non-linear response history analysis; Acceleration-displacement response spectrum

1. INTRODUCTION

Over the past two decades performance based seismic design concept has been vastly used in earthquake engineering. In this concept, designers are required to fulfill the specific structural requirements that conform to the intended function and life-time of the structure, which is known as performance levels. Among several effective engineering tools, seismic isolation systems are rational alternatives to reach adequate performance levels for protecting both structural and non-structural members of buildings.

Seismic isolation design is based on reducing seismic response of the structure by providing increment of natural vibration period and displacement capability of the structure. Seismic isolators have flexibility in horizontal directions and rigidity in vertical direction. They dissipate large amounts of energy during the earthquake and lessen the shaking of structure as compared to fixed base structures. In recent years, lead rubber and friction pendulum bearing type seismic isolators have been used by the designers.

Hysteretic behavior of seismic isolation systems is defined in accordance with an equivalent linear system with secant stiffness and an equivalent viscous damping approach. The major obstacle in implementing force-displacement hysteresis during the preliminary design of the seismic isolation

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system is that equivalent viscous damping approach is response dependent and hence requires an iterative process which may take a long time.

Whittaker and Jones (2013, 2014) suggested the concept of acceleration-displacement response spectra (ADRS) approach. The concept is based on time history analyses of inelastic single degree of freedom (SDOF) oscillator to represent the nonlinear behavior of the isolation system. It represents realistic behavior of seismic isolation systems, to diminish analyses time by elimination of iterative process and produce an accurate tool. It is easier to obtain nonlinear dynamic analyses results because the approach enables evaluation of seismic isolation system engineering parameters, directly. Moreover, ADRS approach provides a guideline via its visual graphical form for preliminary design stage of seismic isolation system for different buildings which are in the same study. As an important advantage, calculations are weight independent. Properties of seismic isolation systems are independent from amplitude and can be selected by the designers in the preliminary design process.

They further performed case studies in various regions such as New Zealand, the USA and Canada, Turkey and Chile (Jones et al. 2015a, 2015b, 2017) to demonstrate the efficiency of the method. Although only a few buildings in Turkey have been designed and constructed with seismic isolation systems (e.g. hospitals, historical and special buildings) there is an increasing demand on using these systems. For that reason, having a robust and immediate tool on the preliminary design stage may help designers to have a quick point of view about inelastic seismic demands of seismically isolated systems.

In this study above mentioned previous works are extended to Turkey. Regulations of Turkey have been taken into consideration in all analyses. Seismic isolation systems are considered as single degree of freedom (SDOF) oscillators. ADRS approach is applied to high seismic zones of Turkey using different combinations of two shaking levels (MCE, DBE) and site categories (NEHRP C, NEHRP D). MCE and DBE correspond to DD1 and DD2 in TBSDC (2018), respectively. Eleven pairs of ground motion recordings are selected according to geomean spectral ordinate from all around the world to perform nonlinear dynamic analyses. A large range of structural period (2-5 seconds) and yield level (5%-15% of W) are used to represent practical and applicable period and strength ratio levels for a typical isolator (or isolation system). Results are discussed in the following parts of the paper.

2. GROUND MOTION IDENTIFICATION AND METHOD

2.1 Design Hazard Levels

Maximum Considered Earthquake (DD1) and Design Basis Earthquake (DD2) design levels are considered in the study. In order to select the appropriate hazard levels, probabilistic hazard results of Turkey (TDTH, 2016) in terms of spectral acceleration at 1s. structural period (Sₐ₁) have been investigated. For the reference site condition, maximum Sₐ₁ at DD1 hazard level is 1.4g on the active faults (R=0) and sharply decreases to 0.6 g at approximately 15-20 km away from the fault line. It further decreases to 0.4g at 45-50 km epicentral distance. Hence calculations are performed between 0.4g and 0.6g. Hazard is classified into two levels; moderate hazard level (0.4g≤Sₐ₁(DD1)<0.5g) and high hazard level (0.5g≤Sₐ₁(DD1)<0.6g). Average values of these ranges have been used for calculating the elastic response spectra. Corresponding mean Sₐ₁ at DD2 hazard level is 0.25g for moderate hazard and 0.30g for high hazard ranges. Combination of ground motion and isolation system parameters is exhibited in Table 1.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Levels</td>
<td>Maximum Considered Earthquake (DD1)</td>
</tr>
<tr>
<td></td>
<td>Design Basis Earthquake (DD2)</td>
</tr>
</tbody>
</table>

Table 1. Combination of ground motion and seismic isolation system parameters
Hazard Levels \(0.4 \text{g} \leq S_1(\text{DD}) < 0.5 \text{g}, 0.5 \text{g} \leq S_1(\text{DD}) < 0.6 \text{g}\)

Site Categories NEHRP C, NEHRP D

Elastic Periods (s) 2, 2.5, 3, 3.5, 4.0, 5.0

Yield Levels (W\%) 5.0, 7.5, 10.0, 12.5, 15.0

Table 2. Case studies

<table>
<thead>
<tr>
<th>Case</th>
<th>Design Level</th>
<th>Hazard Level</th>
<th>Site Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>DD1</td>
<td>High</td>
<td>NEHRP D</td>
</tr>
<tr>
<td>Case 2</td>
<td>DD2</td>
<td>Moderate</td>
<td>NEHRP C</td>
</tr>
<tr>
<td>Case 3</td>
<td>DD1</td>
<td>High</td>
<td>NEHRP C</td>
</tr>
<tr>
<td>Case 4</td>
<td>DD2</td>
<td>High</td>
<td>NEHRP D</td>
</tr>
</tbody>
</table>

2.2 Strong Motion Recordings

Strong motion recordings are selected and downloaded from Pacific Earthquake Engineering Research (PEER) Center database (NGA-West2, 2015). The recordings are selected following the procedure of updated Turkish Building Seismic Design Code draft version of which has been released in June 2016 and expected to be enforced in the first quarter of 2018. The magnitude range is assigned as 6.0 to 7.5 and fault mechanism is specified as strike slip considering the two major faulting zones exhibiting the high seismic hazard in Turkey, the North Anatolian and the East Anatolian Fault Zone. Distance (\(R_{jb}\)) of earthquakes is between 15 km - 60 km. 15 km distance is assumed to be the sufficient distance to neglect near field effects. Pulse-like recordings are ignored. Soil types belong to NEHRP C (\(V_{s30}=360, 760 \text{ m/s}\)) and NEHRP D (\(V_{s30}=180, 360 \text{ m/s}\)) categories. 1\textsuperscript{st} order baseline correction is applied to correct data for analyses.

2.3 Analysis

In the analysis, four case studies are investigated. Design, hazard and site categories of these case studies are given in Table 2.

As the first step, horizontal elastic response spectra are obtained for each design case. Recordings are scaled linearly to match the 5% damped elastic horizontal design spectra which are acquired in line with regulations of Turkey. (TBSDC, 2018) The period range is appointed as 1-7 s and hence average of selected ground motions fits the horizontal elastic spectrum between these periods. Eleven selected recordings and their scale factors only for Case-1 and Case-2 are presented in Table 3 and Table 4. %5 damped elastic design spectrum for DD1 and DD2 design levels are given together with elastic response spectra of selected and scaled recordings (Figure 1-2). List of selected ground motion for Case-3 and Case-4 are not given due to page limitation.

Table 3. Selected recordings and scale factors of Case-1.

<table>
<thead>
<tr>
<th>Event</th>
<th>Station</th>
<th>Mw</th>
<th>(R_{jb}) (km)</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Darfield, New Zealand 2010</td>
<td>PPHS</td>
<td>7.00</td>
<td>18.73</td>
</tr>
<tr>
<td>2</td>
<td>Darfield, New Zealand 2010</td>
<td>CCCC</td>
<td>7.00</td>
<td>19.89</td>
</tr>
<tr>
<td>3</td>
<td>Darfield, New Zealand 2010</td>
<td>CHHC</td>
<td>7.00</td>
<td>18.40</td>
</tr>
<tr>
<td>4</td>
<td>Chi-Chi Taiwan-04 1999</td>
<td>CHY101</td>
<td>6.20</td>
<td>21.62</td>
</tr>
<tr>
<td>5</td>
<td>Chi-Chi Taiwan-04 1999</td>
<td>CHY030</td>
<td>6.20</td>
<td>30.46</td>
</tr>
</tbody>
</table>
6  Superstition Hills-02 1987  ICC  6.54  18.20  2.670
7  Imperial Valley-06 2010  DLT  6.53  22.03  2.975
8  Victoria, Mexico 1980  CHI  6.33  18.53  4.334
9  Landers1992  FHS  7.28  26.84  6.951
10 El Mayor-Cucapah, Mexico 2010  CXO  7.20  19.12  2.298
11 El Mayor-Cucapah, Mexico 2010  E11  7.20  15.36  2.370

Table 4. Selected recordings and scale factors of Case-2.

<table>
<thead>
<tr>
<th>Event</th>
<th>Station</th>
<th>Mw</th>
<th>Rjb(km)</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hector Mine 1999</td>
<td>ABY</td>
<td>7.13</td>
<td>41.81</td>
<td>1.480</td>
</tr>
<tr>
<td>2 Hector Mine 1999</td>
<td>JTN</td>
<td>7.13</td>
<td>50.42</td>
<td>8.224</td>
</tr>
<tr>
<td>3 Hector Mine 1999</td>
<td>29P</td>
<td>7.13</td>
<td>42.06</td>
<td>9.584</td>
</tr>
<tr>
<td>4 Darfield, New Zealand 2010</td>
<td>HVS</td>
<td>7.00</td>
<td>24.36</td>
<td>2.770</td>
</tr>
<tr>
<td>5 Darfield, New Zealand 2010</td>
<td>CSHS</td>
<td>7.00</td>
<td>43.60</td>
<td>4.126</td>
</tr>
<tr>
<td>6 Chi-Chi Taiwan-04 1999</td>
<td>CHY006</td>
<td>6.20</td>
<td>24.58</td>
<td>2.725</td>
</tr>
<tr>
<td>7 Chi-Chi Taiwan-04 1999</td>
<td>CHY024</td>
<td>6.20</td>
<td>19.67</td>
<td>3.409</td>
</tr>
<tr>
<td>8 Chi-Chi Taiwan-04 1999</td>
<td>CHY029</td>
<td>6.20</td>
<td>25.75</td>
<td>2.719</td>
</tr>
<tr>
<td>9 Landers 1992</td>
<td>FVR</td>
<td>7.28</td>
<td>25.02</td>
<td>4.781</td>
</tr>
<tr>
<td>10 El Mayor-Cucapah, Mexico 2010</td>
<td>CISWSHN</td>
<td>7.20</td>
<td>31.79</td>
<td>6.772</td>
</tr>
<tr>
<td>11 Düzce, Turkey 1999</td>
<td>LAMONT 362</td>
<td>7.14</td>
<td>23.41</td>
<td>8.284</td>
</tr>
</tbody>
</table>

In the second step, nonlinear analyses are performed using the PRISM for Earthquake Engineering Software (PRISM, 2018) for seismic response analysis of SDOF systems. The bi-linear hysteresis curve model is used to represent nonlinear behavior of a typical seismic isolation system. Analyses are performed for each horizontal component of ground motion pairs for each strength ratio and post-yield stiffness combinations.

The flow chart of analysis steps are shown in Figure 2.

![Figure 1](image1.png)

Figure 1. Target acceleration spectrum and spectra for scaled ground motions for Case-1 (left), Case-2 (right)
Figure 2. Target acceleration spectrum and spectra for scaled ground motions for Case-3 (left), Case-4 (right)

Figure 3. Flow chart of the study

Based on the information from the manufacturers and practicing engineers, it is assumed that the elastic stiffness ($k_1$) is 10 times greater than characteristic stiffness ($k_2$) in analyses hence, the properties of seismic isolation system are dominated by the assigned post-yield stiffness ($k_2$) and yield level ($Q_d$). $Q_d$ can also be called as “strength ratio on yield force” and it expresses “characteristic strength” of a seismic isolator. $Q_d$ is the lead core yield force for lead rubber bearings and friction force for friction pendulum bearings. $k_2$ is the “characteristic stiffness” of a seismic isolator and is expressed as the second slope of force-displacement graph of bilinear curve. As such, the seismic isolation system can be defined in terms of the yield level and the post-yield stiffness period of vibration.

In PRISM (PRISM, 2018) bi-linear curve description is done by parameters; $T_1$, SR and $\alpha$. The calculation of post-to-pre-yield stiffness ratio ($\alpha$) by the Equation 1, the first slope period of vibration ($T_1$) by the Equation 2 and strength ratio (SR) by the Equation 3 is shown below:

$$\alpha = \frac{k_2}{k_1} \quad (1)$$

$$T_1 = T_2 \sqrt{\alpha} \quad (2)$$

$$SR = \frac{Q_d}{W} \quad (3)$$

where, $W$ is the system weight and $T_2$ is the second slope period of vibration.
Square root of sum of squares (SRSS) of two response displacements at period $t_{\text{max}}$, which is the period corresponding to the largest response displacement in a horizontal direction, is calculated. The largest of the SRSS is considered as the maximum response displacement of the system excited with the scaled ground motion pair and averages of 11 ground motion pairs are calculated. Base shear which is transferred to superstructure is calculated from the Equation 4, in line with the TBSDC (2018), Chapter 14.

$$V_M = \frac{S_{ae}^{(DD1)}(T_M)W\eta M}{R}$$  \hspace{1cm} (4)

Base shear is expressed as $V/W$ to make it weight independent. In the Equation 4, $S_{ae}^{(DD1)}$ is spectral acceleration for maximum ground motion level at $T_M$. $T_M$ is the effective vibration period of seismically isolated building at maximum displacement. All indices in Equation 4 are given for MCE level. R is earthquake force reduction factor and is taken as 1.2 as recommended in TBSDC, (2018). Damping scaling coefficient ($\eta$) and damping ratio ($\xi$) are expressed in Equation 5 and Equation 6, respectively.

$$\eta = \frac{10}{\sqrt{5 + \xi}} \hspace{1cm} (5)$$

$$\xi = \frac{2}{\pi} \left( \frac{\mu}{\mu + \frac{D}{R_c}} \right) \hspace{1cm} (6)$$

In Equation 6, friction coefficient ($\mu$) is assumed as 0.05 for this study. D is average displacement which is obtained from nonlinear response analysis. Radius of seismic isolation unit on surface ($R_c$) is given in Equation 7.

$$R_c = \frac{T^2g}{4\pi^2} \hspace{1cm} (7)$$

g is the acceleration of gravity, $T$ is period.

A total 5280 nonlinear analyses are performed and ADRS are obtained for eleven ground motion pairs, with six structural periods ($T_2=2$, 2.5, 3, 3.5, 4, 5 s.) and five yield levels (5%, 7.5%, 10%, 12.5, 15% of W) defined.

3. RESULTS

The analyses results are represented as four ADRS graphs which are shown in the following pages, in Figure 4-7.

As expected, for the given shortest period ($T=2$ s) and given smallest yield ratio (5%W) base shear ratio of the systems has its highest value and vice versa. Besides, for the given shortest period ($T=2$ s) and the greatest yield ratio (15%W) displacements are the smallest and for the longest period ($T=5$ s) and the smallest yield ratio (5%W) displacement values are the highest in all cases. Higher structural periods enable the structure to have higher displacement capacity.

Case-1 and Case-2 show the two extreme results of the system and worth comparing. Figure 4 shows the response of the system under Case 1. Maximum base shear ratio is 0.4(V/W). Displacement range is between 210 mm and 760 mm. Figure 5, on the contrary, shows the response of the system under Case-2. Maximum base shear ratio is around 0.12(V/W) and displacement range is limited to 90 mm - 237 mm. There is a similar proportional reduction in minimum base shears, from 0.1 to 0.035. There is a three times difference in maximum and minimum base shears of Case-1 and Case-2. The maximum
displacement value of Case-2 is nearly equal to the minimum displacement of Case-1. The effect of yield levels which are above 10% is not significant on ADRS chart in Figure 6 when the period is 3 s.

Figure 4. DD1 / High Hazard / NEHRP D (Case-1)

Case-1 in Figure 4 and Case-3 in Figure 6 portray the change in the response of the system when the soil type switches from NEHRP D to NEHRP C. In the stiff soil condition maximum and minimum base shear values decrease 25%. Maximum displacement is reduced by 170 mm by the different soil type property. When period gets longer, the effect of yield level increases and horizontal displacement lines are lengthened. When the soil gets stiffer, the effects of period and yield level diminish. Consequently, at soft soil, seismic isolation systems with high fundamental period necessitate very high displacement capability which might not be feasible in terms of seismic isolator production. In this case, designers may reduce the period of structure for a better performance.

Figure 5. DD2 / Moderate Hazard / NEHRP C (Case-2)
Figure 6. DD1 / High Hazard / NEHRP C (Case-3)

Figure 7 shows the response of the system under Case-4. For the smallest period and yield ratio, base shear is around 0.210 (V/W) and for the biggest period and yield ratio base shear is around 0.057 (V/W). Displacements are between 105 mm and 409 mm.

The effect of yield levels which are above 12.5% is not significant on ADRS chart when the period is 4 seconds. On the other hand, for 2.5 and 3 seconds, differences in yield level dominate the responses of seismic isolation system.

Comparison of ADRS graphs for Case-1 (Figure 4) and Case-4 (Figure 7) reveals that, for the same soil condition, DD2 design level imposes approximately half of the DD1 design level base shear values.

Figure 7. DD2 / High Hazard / NEHRP D (Case-4)

In DD1 level, the maximum base shear reaches 0.4 (V/W) and in the worst case (Case-1) base shear
never decrease under 0.1 (V/W). As expected, the minimum period (T=2 s) and minimum yield level (5%) combination give the maximum base shear results. Higher structural periods enable the structure to have a higher displacement capacity.

In T=2.5-4.0 seconds range, the effect of increasing period decreases the increment ratio of base shear. In Case-3, the effect of yield level diminishes in low period ranges and consequently the line which represents displacement range shortens with increasing base shear values. On the other hand, all periods are highly affected by yield level in Case-1. The average displacement range is 190 mm between 2.5 and 4 seconds.

Results indicate that, periods between 2.5s and 4s are suitable for seismic isolation systems. Above 4 s, intolerable deformation and base shear values are observed. Such values may require extremely large diameter seismic isolators which may not be feasible.

4. CONCLUSIONS

Nonlinear time history analyses are performed for different post-elastic periods and yield levels of seismic isolation systems and displacement and acceleration values are obtained. Ground motion sets composed of eleven pairs of earthquake recordings are scaled according to TBSDC (2018). Characteristic seismic isolation parameters are evaluated and inscribed in graphical form.

The ADRS methodology is practical tool for preliminary design of seismic isolation systems. The methodology enables to observe and evaluate demands and overall behavior of the system.

The ADRS charts can be used for all typical seismic isolation systems because the calculations are based on post-elastic periods and yield levels. The comparison of the different type of systems can be made in the same single chart and this feature makes it more feasible to evaluate all alternatives in decision process.

It is worth noting that, only for Case-2; at T=3 s periods, displacement responses are almost constant at yield level equal or higher than 10%. In further studies, analyses might be repeated using different ground motion data set to see if such an issue is raised by the excitation characteristics of the ground motion.

The ADRS graphs which make it possible to rapidly obtain the required parameters for preliminary design of seismic isolation systems quickly can be improved and standardized by making further analyses with vast ground motion data set.

5. ACKNOWLEDGEMENTS

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