A Survey study on design procedure of Seismic Base Isolation Systems

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ABSTRACT: Adding shear walls or braced frames can decrease the potential damage caused by earthquakes. We can isolate the structures from the ground using the Seismic Base Isolation Systems that is flexible approach to decrease the potential damage. In this research we present information on the design procedure of seismic base isolation systems. In addition, we analyze the seismic responses of isolated structures. The seismic isolation includes the installation of mechanisms, which decouple the structure. This decoupling is achieved by increasing the horizontal flexibility of the system, together with providing appropriate damping. In this research we use some codes for the design examples of elastomeric bearings. Experimental results indicate the effectiveness of our approach.

Seismic isolation, also known as base isolation in structures, is an innovative design strategy that provides a practical alternate for the earthquake resistant design of new structures and the seismic rehabilitation of existing buildings, bridges and industrial establishments. The concept of seismic isolation is based on the premise that a structure can be substantially decoupled from damaging horizontal components of earthquake ground motions. Thus, earthquake induced forces may be reduced by factors of five to ten from those that a conventional fixed-base structure would experience.

In Figure 1.1, note the rapid decrease in the acceleration transmitted to the isolated structure as the isolated period increases. This effect is equivalent to a rigid body motion of the building above the isolation level. The displacement of the isolator is controlled (to 100-400 mm) by the addition of an appropriate amount of damping (usually 5-20 % of critical). The damping is usually hysteretic, provided by plastic deformation of either steel shims or lead or ‘viscous’ damping of high-damping rubber. For these isolators strain amplitudes, in shear, often exceed 100%. The high damping has the effect of reducing the displacement by a factor of up to five from unmanageable values of ~1.0 m to large but reasonable sizes of <300 mm [2]. High damping may also reduce the cost of isolation since the displacements must be accommodated by the isolator components and the seismic gap, and also by flexible connections for external services such as water, sewage, gas and electricity.
The seismically isolated buildings fall into two broad categories: fragile structures of historic significance and new structures with contents, which need to be protected or continue to operate during and immediately after the earthquake. It is seen that most base isolated buildings around the world are important buildings such as hospitals, universities, schools, firehouses, nuclear power plants, municipal and governmental buildings, and some high technology buildings that house sensitive internal equipment or machinery.

There are many examples of base-isolated structures in the United States and Japan. A number of base-isolated buildings have been built in New Zealand and in Italy. Demonstration projects that apply low-cost base isolation systems for public housing in developing countries have been completed in Chile, the People’s Republic of China, Indonesia, and Armenia [3]. In the United States the most commonly used isolation system is the lead-plug rubber bearing. Although some projects are isolated solely with lead-plug bearings, they are generally used in combination with multilayered elastomeric bearings without lead plugs.

The aim of this study is to investigate the effects of seismic base isolation systems, especially rubber bearings, on the response of structures. The study includes analysis of the seismic responses of isolated structures, which is oriented to give a clear understanding of the processes involved and discussion of various isolators.

The notes introduce the related chapters of FEMA and IBC2000 regulations for theseismic isolated structures. These provisions and formulas, their similarities and differences, are presented. Case studies illustrate their use in both static and dynamic analyses. The static equivalent lateral force of analysis, response spectrum analysis, and time history analysis are carried out in case studies. Design procedures used for base isolated systems are discussed and form the basis for preliminary design procedures. Using a consistent set of design criteria, a commercial computer program SAP2000 demonstrates the ease with which the design for isolated systems may be executed.

No specific provisions are included in the Turkish seismic code (ABYYHY-98) [3] for the earthquake resistant design of buildings with seismic base isolation. Therefore, the seismic base isolation provisions of the FEMA [4] have been utilized in the design examples. Nevertheless, the discussion of the case study results is done by considering the Turkish seismic code and some important conclusions for use in possible future version of the Turkish seismic code are drawn.

Mathematical modeling

The horizontal stiffness of a bearing is given by [1]:

\[ K_H = \frac{G A}{t_r} \]

Where \( G \) is the shear modulus of the elastomer, \( A \) is the total cross-sectional area, and \( t_r \) is the total thickness of the rubber only. Another design characteristic of an isolator is the vertical stiffness \( K_V \), which is the dominant parameter controlling the vertical frequency of an isolated structure. The vertical stiffness of a rubber bearing is given by the formula:

\[ K_V = \frac{(E_c A)}{t_r} \]
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where Ec is the instantaneous compression modulus of the rubber-steel composite under the specified level of vertical load.

The compression modulus of a circular bearing (Ec) is defined by different formulas in FEMA-356 [16] and Naeim and Kelly study [1].

\[ E_c = \left( \frac{1}{6GS^2} + \frac{4}{3K} \right)^{-1} \] [FEMA-356]

\[ E_c = \left( \frac{1}{6GS^2} + \frac{1}{K} \right)^{-1} \] [Naeim and Kelly]

Ec: Compression Modulus
S: Shape Factor (5 < S < 30)
K: Bulk Modulus (1000MPa < K < 2500 MPa)
G: Shear Modulus (0.5MPa < G < 2.5 MPa)

Figures 2.1 – 2.3 are prepared in order to demonstrate how the compression modulus of a circular pad changes according to these two different formulas for given intervals of shape factor (S), bulk modulus (K), and shear modulus (G).

The non-linear force-deformation characteristic of the isolator can be replaced by an equivalent linear model through effective elastic stiffness and effective viscous damping. The equivalent linear elastic stiffness for each cycle of loading is calculated from experimentally obtained force-deformation curve of the isolator and expressed mathematically as [5]:

\[ k_{eff} = \frac{(F^+ - F^-)}{(\Delta^+ - \Delta^-)} \]

where F+ and F− are the positive and negative forces at test displacements \( \Delta^+ \) and \( \Delta^- \), respectively. Thus, the \( k_{eff} \) is the slope of the peak-to-peak values of the hysteresis loop as shown in Figure 2.4.

![Figure 2. Force displacement relationship of equivalent linear model [6]](image)

The effective viscous damping ratio of the isolator calculated for each cycle of loading is expressed as [11]:

\[ \beta_{eff} = \frac{(2E_{loop})}{\pi k_{eff} (\Delta^+ - \Delta^-)^2} \]

Where Eloop is the energy dissipation per cycle of loading.

Bilinear model can be used for all isolation systems used in practice. In fact only bilinear hysteretic model can reflect the non-linear characteristics of the lead-plug bearings and friction-pendulum systems that are commonly used isolation systems.

The non-linear force-deformation behavior of the isolation system is modeled through the bilinear hysteresis loop based on the three parameters (i) elastic stiffness, K1 (ii) post-yield stiffness, K2 (iii) characteristic strength, Q (Figure 2.5). The characteristic strength, Q is related to the yield strength of the lead plug inserted in the elastomeric bearing or friction coefficient of the sliding type isolation system [20].

![Figure 2.5: Characteristic strength, Q](image)

At specified design displacement, D, the effective stiffness for a bilinear system is expressed as [1]:

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$$k_{eff} = K_2 + \left(\frac{Q}{D} \right)$$

where $D_y$ is the yield displacement. In terms of the primary parameters [1]:

$$D_y = \frac{Q}{(K_1 - K_2)}$$

The Beffis expressed as [1]:

$$\beta_{eff} = \frac{4Q(D - D_y)}{(2\pi k_{eff}D^2)}$$

To investigate and compare the differences in the seismic responses of buildings isolated by bilinear and equivalent linear isolator models, a five-story symmetrical building, introduced in Section 3.2.2, is chosen. Two different types of isolators, lead-plug bearings (LPB) and friction pendulum system (FPS), are used for bilinear modeling where as type of the isolator is not important for equivalent linear modeling. The nonlinear time history method is used for the analyses by the help of a commercial computer program SAP2000. The earthquake motions selected for the study are S50W component of 1979 Imperial Valley earthquake (IMPERIAL), EW component of 1999 Kocaeli earthquake (KOCAELI), HORIZ0 component of 1989 Loma Prieta earthquake (LOMA). The peak ground acceleration (PGA) of Imperial Valley, Kocaeli and Loma Prieta earthquake motions are 0.46g, 0.23g and 0.63g, respectively. The acceleration and displacement spectra of the ground motions for 2% damping are shown in Figures 2.6 and 2.7. The damping ratio is selected as 2% for the analyses.

The investigated response quantities are the top floor acceleration and bearing displacement. These response quantities are important because floor accelerations developed in the structure are proportional to the forces exerted as a result of an earthquake ground motion. On the other hand, the bearing displacements are crucial in the design of isolation systems.

Material and methods: The basic motive in the studies is to identify the similarities and differences between the design code IBC2000, and design specification FEMA 273, and make a comparison between them from the design of base isolated structures point of view.

Description of the Structures: The structures, used for the analyses, are assumed to be serving as school buildings. The detailed descriptions of the buildings are as follows: The three-storey building has a regular plan (36m x 12m) as shown in Figure 3.1.

The structural system is selected as concrete frames with identical columns of 50/50 centimeters in size,
and beams of dimension 40/70 centimeters. Each floor slab has 15 centimeters thickness and the story height is 3 meters. The critical damping ratio of superstructure is taken as 2% for isolated cases.

28 units High Damping Rubber bearings (HDR) are used for the isolation of the building. The detailed calculations of isolation system design are explained in Section 4.1. The bearings have the following linear properties accordingly:

\( i = 0.15 \) (isolator damping ratio)
\( G = 500 \text{ kN/m}^2 \)
\( K_h = 805 \text{ kN/m} \)
\( K_v = 500000 \text{ kN/m} \)

Analysis Methods: In this section, static equivalent lateral force procedure, response spectrum analysis and time history analysis are discussed.

The isolation system should be designed to withstand minimum lateral earthquake displacements, DD, that act in the direction of each of the main horizontal axes of the structure in accordance with the following [6]:

\[
D_D = \left( \frac{g}{4\pi^2} \right) \frac{S_{DI} T_D}{B_D}
\]

where:

BD = Numerical coefficient related to the effective damping of the isolation system at design displacement, as set forth in Table 3.1

\( g = \) Acceleration of gravity

SD1 = Design 5% damped spectral acceleration at 1 sec. period

TD = Isolated period at design displacement

<table>
<thead>
<tr>
<th>EFFECTIVE DAMPING (( \beta ))</th>
<th>BD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2%</td>
<td>0.8</td>
</tr>
<tr>
<td>5%</td>
<td>1.0</td>
</tr>
<tr>
<td>10%</td>
<td>1.2</td>
</tr>
<tr>
<td>20%</td>
<td>1.5</td>
</tr>
<tr>
<td>30%</td>
<td>1.7</td>
</tr>
<tr>
<td>40%</td>
<td>1.9</td>
</tr>
<tr>
<td>&gt;50%</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 3.1 Damping coefficient [7]

For damping values other than the one specified in Table 3.1, linear interpolation can be done to find corresponding BD value. Alternatively, a very close approximation to the table values is given by:

\[
\frac{1}{B_D} = 0.25(1 - \ln \beta)
\]

The effective period of the isolated structure, TD, is determined as:

\[
T_D = 2\pi \sqrt{\frac{W}{K_b g}}
\]

where \( W \) is the total dead load weight of the superstructure.

"The total design displacement, DTD, of elements of the isolation system shall include additional displacement due to actual and accidental torsion calculated considering the spatial distribution of the lateral stiffness of the isolation system and the most disadvantageous location of mass eccentricity. DTD must satisfy the following condition." [8]:

\[
D_{TD} \geq D_D \left( 1 + \left( \frac{12e}{b^2 + d^2} \right) \right)
\]

where:

\( d = \) Shortest plan dimension

\( b = \) Longest plan dimension

\( e = \) The actual eccentricity measured in plan between the center of mass of the structure and the center of stiffness of the isolation system, plus the accidental eccentricity taken as 5% of the longest plan dimension of the structure perpendicular to the
direction of seismic loading under consideration (Figure 3.7).

The structure above the isolation system must be designed to withstand a minimum total shear force, $V_S$:

$$V_S = \frac{K_b D_d}{R}$$

where:

- $R$ = Seismic load reduction factor.
- $K_b$ = Seismic load reduction factor.
- $D_d$ = Seismic load reduction factor.

While FEMA 273 assumes $R$ as equal to one for isolated structures (the structure deforms only in elastic range), IBC2000 takes it as if the structure goes into inelastic range specifications, thus the lateral EQ force, applied to the building is not reduced. One can easily calculate the corresponding design values of $R=2.0$ if it is desired. The total shear force, $V_S$, is distributed over the height of the structure as given by:

$$F_x = \sum_{i=1}^{x} \frac{V_i W_i h_i}{h}$$

where:

- $h_i$ = Height above the base to level $i$.
- $h_x$ = Height above the base to level $x$.
- $W_i$ = Portion of total dead load that is located at or assigned to level $i$.
- $W_i$ = Portion of total dead load that is located at or assigned to level $i$.

Response Spectrum Analysis The 5% damped spectrum, given in Turkish seismic code (ABYYHY-98, [8]), is used for the analysis of building and the spectrum is modified for each of the soil types (Z1, Z2, Z3, Z4). Spectrum is assumed to be acting on the building from both directions (X-Y) simultaneously. While the component applied from one axis is multiplied by 1.00; the orthogonal component is multiplied by 0.30. According to this logic, two different E.Q. combinations are applied to the structure and the results are examined for each case. In the results, the one, which causes the most critical condition, is taken into account.

RESULT AND DISCUSSION

In this section “scaling” phenomenon mentioned in FEMA-273 & IBC2000 and the differences between these two codes from the “scaling” point of view are discussed for the symmetric buildings. To facilitate a study of the code provisions, building Types I, II and III are selected. The description of the buildings is introduced in Section 3.2. The high damping rubber bearings, HDR, designed in Section 4.1 are used for the isolation of all buildings. Response spectrum analysis, described in Section 3.3.2, is carried out on building Types I, II and III. In addition, static equivalent lateral force and time history analyses, described in Section 3.3.1 and 3.3.3, are performed for Type II which typifies the class of symmetrical structure that is encountered in design. The analyses of the isolated buildings are done for each soil type that is given in the Turkish Seismic Code (Z1, Z2, Z3, and Z4).

Scaling of the Results: The results of the analyses are scaled according to both FEMA-273 and IBC2000 as mentioned in Section 3.4. The detailed calculation of scaling factors for each analysis method is given below.

The limits of scaling mentioned in FEMA-273 and IBC2000 for static equivalent lateral force procedure are the same except that an additional limit is defined in IBC2000: “The base shear must be greater than the lateral seismic force required for a fixed-base structure of the same weight and a period equal to the isolated period”. Building Type-II is analyzed with static equivalent lateral force procedure and the results of the analysis are scaled according to the mentioned limit. For the calculation of the lateral seismic force, $V_T$, the procedure described in Turkish Seismic Code is used.
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\[ V_T = \frac{W_T \times A(T_I)}{R(T_I)} > 0.10 \times I \times W_T \]

\[ A(T_I) = A_0 \times I \times S(T_I) \]

A0 = 0.40
I = 1.4
R = 8 (Seismic load reduction factor for non-isolated building)
WT = 22330 kN
TD = 2.09 sec.

Table 5.1 Calculation of scaling factor for Type-II according to IBC2000

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>S(T) (Equation 5.2)</th>
<th>A(T) (Equation 5.1)</th>
<th>VT (kN) (Equation 5.1)</th>
<th>VS (kN) (Equation 3.5)</th>
<th>Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1</td>
<td>0.529</td>
<td>0.296</td>
<td>826</td>
<td>5432</td>
<td>no need to scale</td>
</tr>
<tr>
<td>Z2</td>
<td>0.666</td>
<td>0.373</td>
<td>1041</td>
<td>6790</td>
<td>no need to scale</td>
</tr>
<tr>
<td>Z3</td>
<td>0.921</td>
<td>0.516</td>
<td>1440</td>
<td>9670</td>
<td>no need to scale</td>
</tr>
<tr>
<td>Z4</td>
<td>1.274</td>
<td>0.713</td>
<td>1990</td>
<td>11027</td>
<td>no need to scale</td>
</tr>
</tbody>
</table>

Scaling for Response Spectrum Analysis: Building Types I, II and III are analyzed with response spectrum analysis and the results of the analysis are scaled according to both FEMA-273 and IBC2000. To be comprehensible, the parameters needed for the calculation of scaling factors are given below. The damping coefficient, BD, is taken as 1.38 for the calculations since the HDR, bearings designed in Section 4.1, are used for the isolation. As a result of the modal analysis the fixed based period, T, and isolated period TD of the buildings are determined as:

\[ \text{T(sec)} = 0.27, \text{T}_{D}\text{ (sec)} = 1.57 \]

Scaling according to IBC2000:

When IBC2000 is considered, the design displacement determined by response spectrum analysis, \( D_{\text{analysis}} \), is more critical than the second one and results in greater scaling factors. Therefore, displacement dependent scaling limit is used in the scaling factor calculations.

The parameters used for design purposes show great modification depending upon the used scaling factor. The following figures are prepared to be able to comprehend this effect. The relevant comments, in Section 5.3, on comparison of IBC2000 and FEMA-273 are made in the light of following figures.

Base shear values in X direction as a function of soil types are given above in Figure 5.1. Before scaling and after scaling values are presented. As it is seen for soil type Z1 there is no need of scaling for both methods. For Z2 type only, scaling according to IBC2000 is needed. The significance of scaling is increased as the soil becomes softer.

Equivalent Lateral Load Analysis: It can be seen from the Tables 5.11 & 5.20 that IBC2000 and FEMA-273 gives identical results since the results are not needed to be scaled.

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FEMA-273 gives more critical values for the design when response spectrum analysis is considered. The reason depends on the difference between the accepted scaling thresholds, which are defined in FEMA-273 and IBC2000.

While IBC2000 takes 0.9×DTD’ as limit for scaling, FEMA-273 takes DTD. If the equation for DTD’, Equation 3.7, is examined; it is realized that the inequality of“0.9×DTD’ < DTD” is always valid, Therefore it is concluded that FEMA-273 is more conservative than IBC2000 when response spectrum analysis is concerned.

In this study, the design of seismic isolation systems is explained and the influence of base isolation on the response of structure is examined in details. Various types of isolators are introduced and one of the most commonly used type, high damping rubber bearing, is used in the case studies. Both alternatives of modeling an isolator for design purposes, linear and bi-linear, are discussed; also advantages and disadvantages of them are stated. The analyses of isolated buildings, symmetrical and non-symmetrical in plan, are performed according to the related chapters of the design codes FEMA and IBC2000. According to these analyses, the codes are compared for each type of analysis method.

In the light of the results obtained from the case studies, the following conclusions can be stated:

The assumed equivalent linear model of isolators which is accepted by the FEMA and IBC2000 design codes; underestimates the peak superstructure acceleration and overestimates the bearing displacement when compared to the bilinear model.

For the bilinear model isolators with the increase in isolator yield displacement, Dy, the bearing displacement also increases.

Time history analysis is used, the site condition where earthquake data is recorded has a great influence on the design parameters of the structure.

That is as the soil becomes softer, the response of the structure increases.

Therefore the selected ground motion data sets for time history analysis must have been recorded on similar soil condition with the site where the structure is located. It means that site condition must be also taken into account in addition to the mentioned parameters in IBC2000 and FEMA (fault distance, magnitude and source mechanism type).

When compared with IBC2000, FEMA gives more critical values for the design if response spectrum analysis is used. The reason depends on the difference between the accepted scaling limits in FEMA and IBC2000.

When compared with FEMA, IBC2000 gives more critical values for the design if time history analysis is used. The reason depends on the difference between the accepted scaling limits in FEMA and IBC2000.

The scaling factor for response spectrum analysis does not change for different site conditions except for soil type Z4. The decrease in the scaling factor for soil type Z4 when compared with Z1, Z2 and Z3.

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basically results from the differences between the defined site conditions in IBC2000, FEMA and Turkish Seismic Code.

The scaling factor for time history analyses increases as the site condition worsen.

**REFERENCE**


