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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 isolationsystems. 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 horizontalflexibility of the system, together with providing appropriate damping. In this research we use some codes forthe design examples of elastomeric bearings. Experimental results indicate the effectiveness our approach.©JASEM

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

During earthquake attacks, the traditional building structures in which the base isfixed to the ground, respond with a gradual increase from ground level to the top ofthe building, like an amplifier. This may result in heavy damage or total collapse ofstructures. To avoid these results, while at the same time satisfying in-servicefunctional requirements, flexibility is introduced at the base of the structure, usuallyby placing elastomeric isolators between the structure and its foundation. Additionaldamping is also needed to control the relative displacement between the structure and the ground.

Typical earthquake accelerations have dominant periods of about 0.1-1.0 sec. withmaximum severity often in the range 0.2-0.6 sec. Structures whose natural periods of vibration lie with in the range 0.1-1.0 sec. are therefore particularly vulnerable toseismic attacks because they may resonate. The most important feature of seismicisolation is that its increased flexibility increases the natural period of the structure(>1.5 sec., usually 2.0-3.0 sec.). Because the period is increased beyond that of theearthquake, resonance is avoided and the seismic acceleration response is reduced[1]. The benefits of adding a horizontally compliant system at the foundation levelof a building can be seen in Figure 1.1.

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.

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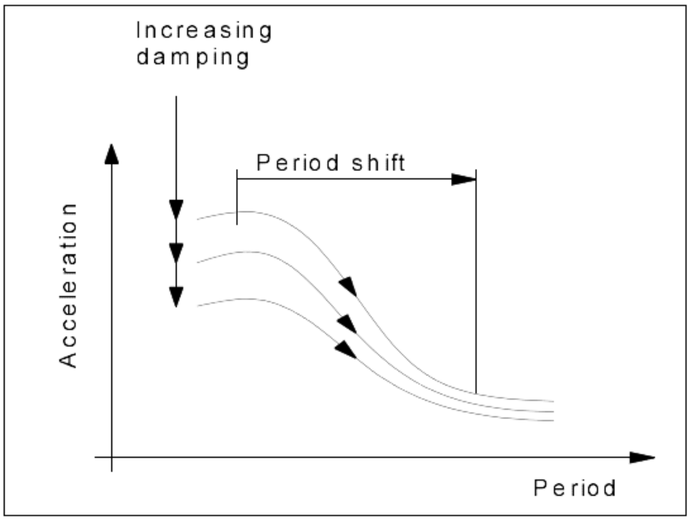


Fig. 1. Acceleration response spectrum

The seismically isolated buildings fall into two broad categories: fragile structures ofhistoric significance and new structures with contents, which need to be protected orcontinue to operate during and immediately after the earthquake. It is seen that mostbase isolated buildings around the world are important buildings such as hospitals,universities, schools, firehouses, nuclear power plants, municipal and governmentalbuildings, 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 housingin developing countries have been completed in Chile, the People's Republic ofChina, Indonesia, and Armenia [3].In the United States the most commonly used isolation system is the lead-plug rubberbearing. Although some projects are isolated solely with lead-plug bearings, they aregenerally 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 analysisof the seismic responses of isolated structures, which is oriented to give a clearunderstanding 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 anddifferences, are presented. Case studies illustrate their use in both static and dynamicanalyses. The static equivalent lateral force of analysis, response spectrum analysisand time history analysis are carried out in case studies. Design procedures used forbase isolated systems are discussed and form the basis for preliminary designprocedures. Using a consistent set of design criteria, a commercial computer programSAP2000 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. Thereforethe seismic base isolation provisions of the FEMA [4] have beenutilized in the design examples. Nevertheless, the discussion of the case study resultsis done by considering the Turkish seismic code and some important conclusions foruse in possible future version of the Turkish seismic code are drawn.

Mathematical modeling

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

$$K_H = \frac{(GA)}{t_r}$$

Where G is the shear modulus of the elastomer, A is the total cross-sectional area, and tris the total thickness of the rubber only. Another design characteristic of an isolatoris the vertical stiffness KV which is the dominant parameter controlling the verticalfrequency of an isolated structure. The vertical stiffness of a rubber bearing is given by the formula 1:

$$K_V = \frac{(E_C A)}{t_r}$$

whereEcis the instantaneous compression modulus of the rubber-steel compositeunder the specified level of vertical load.
The compression modulus of a circular bearing (Ec) is defined by different formulasin FEMA-356 [16] and Naeim and Kelly study [1].

$$E_C = (\frac{1}{6GS^2} + \frac{4}{3K})^{-1} \quad \text{[FEMA-356]}$$

$$E_C = (\frac{1}{6GS^2} + \frac{1}{K})^{-1} \quad \text{[Naeim and Kelly]}$$

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

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

The non-linear force-deformation characteristic of the isolator can be replaced by anequivalent linear model through effective elastic stiffness and effective viscousdamping. The equivalent linear elastic stiffness for each cycle of loading iscalculated from experimentally obtained force-deformation curve of the isolator andexpressed 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 Δ^-,respectively. Thus, the *keff*is the slope of the peak-to-peak values of the hysteresisloop as shown in Figure 2.4.

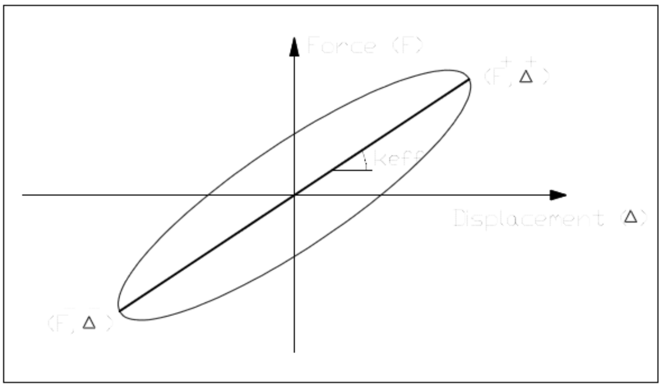


Fig.2. Force displacement relationship of equivalent linear model [6]

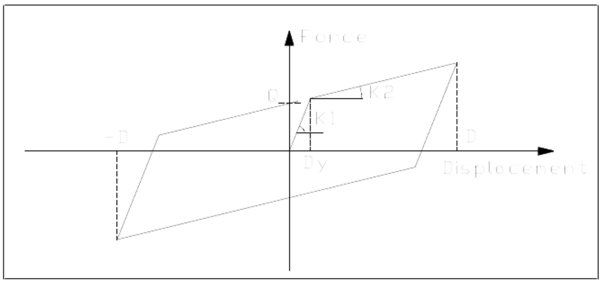
The effective viscous damping ratio of the isolator calculated for each cycle ofloading is expressed as [11]:

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

Where Eloop is the energy dissipation per cycle of loading.

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

The non-linear force-deformation behavior of the isolation system is modeledthrough 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). Thecharacteristic strength, Q is related to the yield strength of the lead plug inserted inthe elastomeric bearing or friction coefficient of the sliding type isolation system
[20].



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

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

whereDyis 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 buildingsisolated by bilinear and equivalent linear isolator models, a five-story symmetricalbuilding, 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 linearmodeling. The nonlinear time history method is used for the analyses by the help of acommercial computer program SAP2000. The earthquake motions selected for thestudy are S50W component of 1979 Imperial Valley earthquake (IMPERIAL), EWcomponent of 1999 Kocaeli earthquake (KOCAELI), HORIZ0 component of 1989Loma 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 for2% damping are shown in Figures 2.6 and 2.7. The damping ratio is selected as 2%for the analyses.

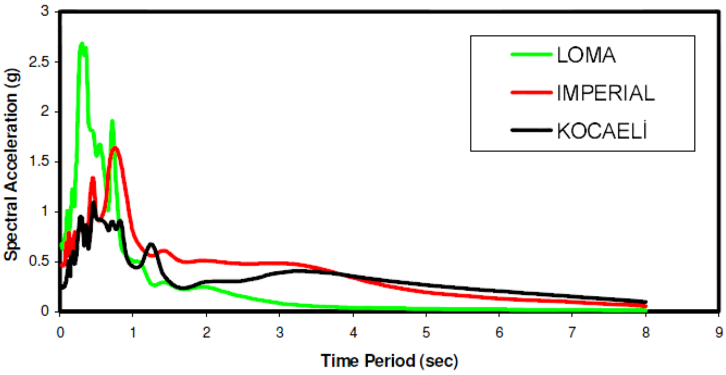


Fig. 3 Acceleration spectra

The investigated response quantities are the top floor acceleration and bearingdisplacement. These response quantities are important because floor accelerationsdeveloped in the structure are proportional to the forces exerted as a result of anearthquake ground motion. On the other hand, the bearing displacements are crucialin the design of isolation systems.

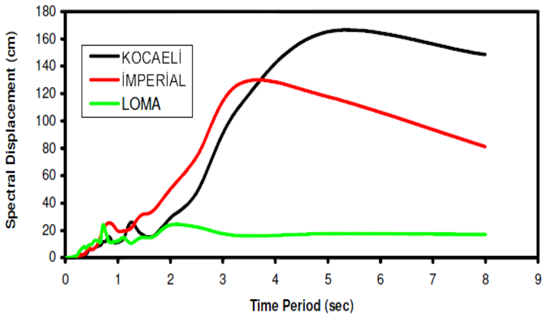


Fig. 4 Displacement spectra

The parameters for the bilinear model isolators are determined according to theparameters of equivalent linear model which are depended on the selected targetperiod, thedesign displacement, D, is also necessary for the determination of the parameters ofbilinear model. The design displacement, equal to the maximum isolatordisplacement, is calculated as a result of the analysis of the structure isolated by theequivalent linear model isolators having the parameters Beff.

Material and methods: The basic motive in the studies is to identify the similarities and differences betweenthe design code IBC2000, and design specification FEMA 273, and make acomparison 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 50/50centimeters in size, and beams of dimension 40/70 centimeters. Each floor slab has15 centimeters thickness and the story height is 3 meters. The critical damping ratioof superstructure is taken as 2% for isolated cases.

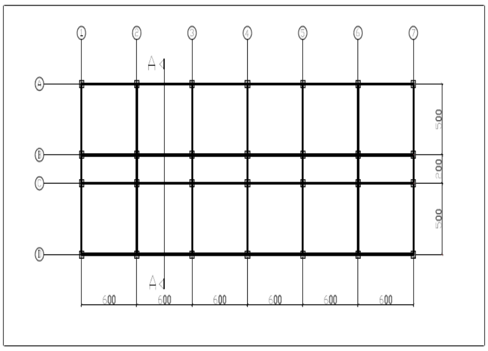


Fig. 5 Plan view of symmetrical building types

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

_i= 0.15 (isolator damping ratio)
G = 500 kN/m2
Kh= 805 kN/m
Kv= 500000 kN/m

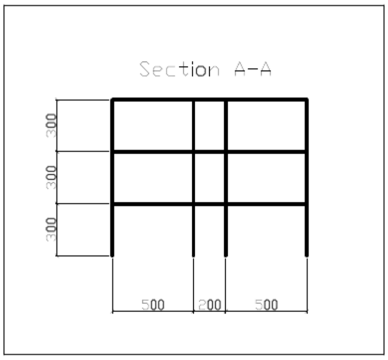


Fig. 6 Section view of building Type-I

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

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

$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{S_{D1}T_D}{B_D}$$

where:

BD = Numerical coefficient related to the effective damping of theisolation 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

EFFECTIVE DAMPING (β_i)	B_D
<2%	0.8
5%	1.0
10%	1.2
20%	1.5
30%	1.7
40%	1.9
>50%	2.0

Table 3.1 Damping coefficient [7]

For damping values other than the one specified in Table 3.1, linear interpolation canbe done to find corresponding BD value. Alternatively, a very close approximation tothe 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:

$$T_D = 2\pi\sqrt{\frac{W}{K_h g}}$$

where W is the total dead load weight of the superstructure.

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

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

where:

d = Shortest plan dimension
b = Longest plan dimension
e = The actual eccentricity measured in plan between the center of massof the structure and the center of stiffness of the isolation system,plus the accidental eccentricity taken as 5% of the longest plandimension of the structure perpendicular to the

direction of seismicloading under consideration (Figure 3.7).

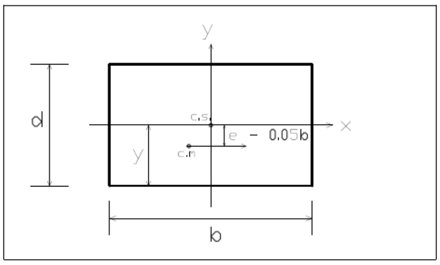


Fig. 7 Plan dimensions for calculation of DTD [8].

The structure above the isolation system must be designed to withstand a minimumtotal shear force, VS:

$$V_S = \frac{K_h D_D}{R}$$

where:
R = 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 inelasticrange specifications, thus the lateral EQ force, applied to the building is not reduced. Onecan easily calculate the corresponding design values of R=2.0 if it is desired.The total shear force, VS, is distributed over the height of the structure as given by:

$$F_x = \frac{V_S W_x h_x}{\sum_{i=1}^{n} W_i h_i}$$

where:
hi= Height above the base to level i.
hx= Height above the base to level x.
Wx= Portion of total dead load that is located at or assigned to level x.
Wi= 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 bothdirections (X-Y) simultaneously. While the component applied from one axis ismultiplied by 1.00; the orthogonal component is multiplied by 0.30. According tothis logic, two different E.Q. combinations are applied to the structure and the resultsare examined for each case. In the results, the one, which causes the most criticalcondition, is taken into account.

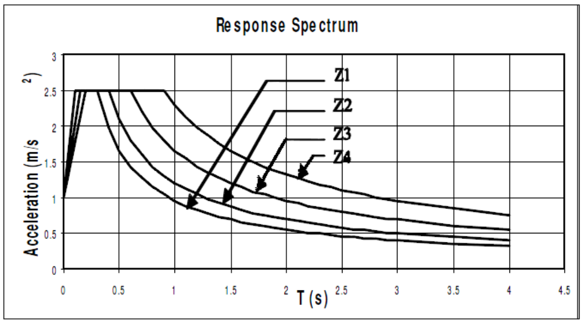


Fig. 8 Response spectrum functions given in Turkish Seismic Code.

RESULT AND DISCUSSION

In this section "scaling" phenomenon mentioned in FEMA-273 & IBC2000 and thedifferences between these two codes from the "scaling" point of view are discussedfor the symmetric buildings. To facilitate a study of the code provisions, buildingTypes I, II and III are selected. The description of the buildings is introduced inSection 3.2. The high damping rubber bearings, HDR, designed in Section 4.1 areused for the isolation of the all buildings. Response spectrum analysis, described inSection 3.3.2, is carried out on building Types I, II and III. In addition, staticequivalent lateral force and time history analyses, described in Section 3.3.1 and3.3.3, are performed for Type II which typifies the class of symmetrical structure thatis encountered in design. The analyses of the isolated buildings are done for each soiltype 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 asmentioned 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 equivalentlateral 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 fora 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 theresults of the analysis are scaled according to the mentioned limit. For the calculationof the lateral seismic force, VT, the procedure described in Turkish Seismic Code isused.

$$V_T = \frac{W_T \times A(T_1)}{R(T_1)} > 0.10 \times I \times W_T$$

$$A(T_1) = A_0 \times I \times S(T_1)$$

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

	S(T)	A(T) (Equation 5.2)	V_T (kN) (Equation 5.1)	V_S (kN) (Equation 3.5)	Scaling Factor
Z1	0.529	0.296	826	5432	no need to scale
Z2	0.666	0.373	1041	6790	no need to scale
Z3	0.921	0.516	1440	9670	no need to scale
Z4	1.274	0.713	1990	11027	no need to scale

	S_{D1}	D_D (cm) (Equation 3.1)	$D_{D'}$ (cm) (Equation 3.7)	$0,9{*}D_{TD'}$ (cm) (Equation 3.4)	$D_{analysis}$ (cm)	Scaling Factor
Z1	0.64	18.09	17.84	20.39	15.14	1.347
Z2	0.80	22.62	22.30	25.49	19.06	1.337
Z3	1.14	32.23	31.78	36.33	26.36	1.378
Z4	1.30	36.75	36.24	41.42	36.46	1.136

Scaling for Response Spectrum Analysis: Building Types I, II and III are analyzed with response spectrum analysis and theresults of the analysis are scaled according to both FEMA-273 and IBC2000. To becomprehendible, the parameters needed for the calculation of scaling factors aregiven below. The damping coefficient, BD, is taken as 1.38 for the calculations sincethe HDR, bearings designed in Section 4.1, are used for the isolation. As a result ofthe modal analysis the fixed based period T, and isolated period TD of the buildingsare determined as:
T(sec)=0.27, T_D(sec)=1.57,
Scaling according to IBC2000:

When IBC2000 is considered, the design displacement determined by response spectrum analysis, Danalys is, must be greater than 90% of DTD' as specified in Equation 3.4. On the other hand, the design base shear force on the structure above theisolation system must be greater than 80% of VS as prescribed by Equation 3.5. Otherwise, all response parameters, including inertial forces and deformations, must be adjusted proportionally upward. When the results of the analyses are examined, it is seen that the first scaling limit, Danalysis> 0.9×DTD', is more critical than the second one and results in greater scalingfactors. Therefore, displacement dependent scaling limit is used in the scaling factorcalculations.

The parameters used for design purposes show great modification depending uponthe used scaling factor. The following figures are prepared to be able to comprehendthis effect. The relevant comments, in Section 5.3, on comparison of IBC2000 andFEMA-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 Figure5.1. Before scaling and after scaling values are presented. As it is seen for soil typeZ1 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.

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 theequation 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.

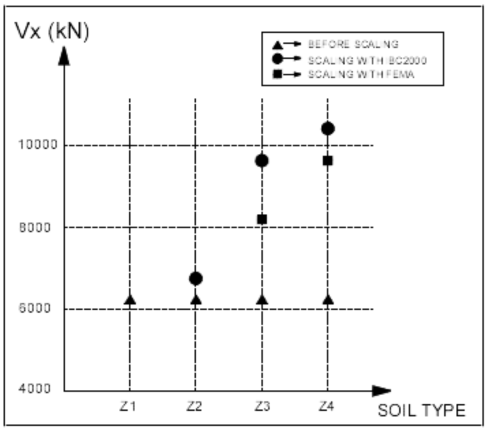


Fig.5.1 Base shear in X direction, (Type-II, time history analysis)

The scaling factors for response spectrum analyses are given in Tables 5.3-8, 5.16-17. When these tables are examined, it is realized that the scaling factors for each soiltype are nearly constant, very close to each other, and do not fluctuate much fordifferent soil types except soil type Z4. Actually, this is the expected trend since theeffect of site condition on the scaling factor is already taken into account by assigning different spectrum functions for each soil type.

In FEMA-273 and IBC2000 site classes are categorized into six different groups asA, B, C, D, E and F. On the other hand, in Turkish Seismic Code site classes aregrouped as Z1, Z2, Z3 and Z4. Although these groups do not match with each otherexactly, for the determination of scaling factors, it is assumed that A stands for Z1, Bstands for Z2, C stands for Z3 and D stands for Z4. The decrease in the scaling factor for soil type Z4 when compared with Z1, Z2 and Z3 basically results from thisassumption. Because, Z4 is assumed to be identical with site class D for the analyses,however it represents weaker soil conditions and stands for somewhere between siteclasses D, E and F. Consequently, scaling factor Z4 decreases when compared withZ1, Z2 and Z3.

In this study, the design of seismic isolation systems is explained and the influence ofbase isolation on the response of structure is examined in details. Various types ofisolators are introduced and one of the most commonly used type, high dampingrubber bearing, is used in the case studies. Both alternatives of modeling an isolatorfor design purposes, linear and bi-linear, are discussed; also advantages anddisadvantages of them are stated. The analyses of isolated buildings, symmetrical andnon-symmetrical in plan, are performed according to the related chapters of thedesign codes FEMA and IBC2000. According to these analyses, the codes arecompared 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 theFEMA and IBC2000 design codes; underestimates the peak superstructureacceleration 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.

When time history analysis is used, the site condition where earthquake datais 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 musthave been recorded on similar soil condition with the site where the structureis located. It means that site condition must be also taken into account inaddition to the mentioned parameters in IBC2000 and FEMA (fault distance, magnitude and source mechanism type).

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

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

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

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