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DYNAMIC DESIGN PROCEDURE FOR THE DESIGN OF BASE ISOLATED STRUCTURES LOCATED ON THE MEXICAN PACIFIC COAST

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SUMMARY

This paper presents a methodology for the design of base isolated structures located in the Mexican Pacific Coast using dynamic principles. The dynamic method is based on the one proposed by the UBC-97 code, but including several modifications to take into account the philosophy of local codes and regional seismicity. For example, the basic equation for the design displacement was obtained from the displacement design spectra (DDS). The DDS were computed using basic probabilistic and statistical criteria based on the displacement response spectra of several ground motions recorded at stations located on rock sites. Some of the records were scaled to an earthquake magnitude compatible with the maximum event considered in Mexican codes, basically, a Ms = 8.1 subduction earthquake that may occur in the Mexican Pacific Coast anytime, this is, a similar event to the 1985 Michoacán earthquake. The DDS were defined for different damping ratios (ξ = 0.05, 0.10, 0.15, and 0.20) to consider that there are both low damping and high damping base isolators currently available in the market. The dynamic design procedure was calibrated with the design of the base isolation system and the superstructure of two buildings. The proposed design using DDS was compared with the dynamic response obtained from time-step nonlinear dynamic analyses of the structures when subjected to the action of the acceleration records used in the definition of the DDS.

INTRODUCTION

Base isolation has been widely accepted in recent years as an effective system to protect structures from earthquakes. Several structures have been built with this system all around the world; however, in Mexico only two buildings have base isolation, a church and a school, those structures were built in the 70’s using a system designed by González-Flores. More recently, one bridge and the press machine of the Reforma Newspaper were isolated, using elastomeric bearings for the bridge and GT-BIS devices for the press [Tena-Colunga *et al.* 1997]. Analytical research has been conducted in Mexico by few researchers, and these studies are reported in Villegas [1999]. It is hoped that some building developers in México will soon consider to use base isolation in future projects, taking advantage of the experience gained from these works. This paper presents some of the required modifications that have to be made in order to adapt the UBC isolation design philosophy to the design philosophy of Mexican codes, among them how to address local seismicity.

It is of paramount importance to point out the correct identification of suitable soil profile types before consider using base isolation as a seismic design (retrofit) strategy. For example, in soft soils, an increment in the fundamental period may lead the structure to a zone where maximum dynamic amplifications may occur. For this reason, this work deals with rock sites for zones identified to have the highest seismic hazard in the Mexican Pacific Coast.

METHODOLOGY

The design procedure for the base-isolated structures using the dynamic method is based on the recommendations provided by the UBC-97 code. However, since the seismicity of the United States and México are different, as well as the core of seismic building codes [i.e., Tena-Colunga 1999], several adaptations were

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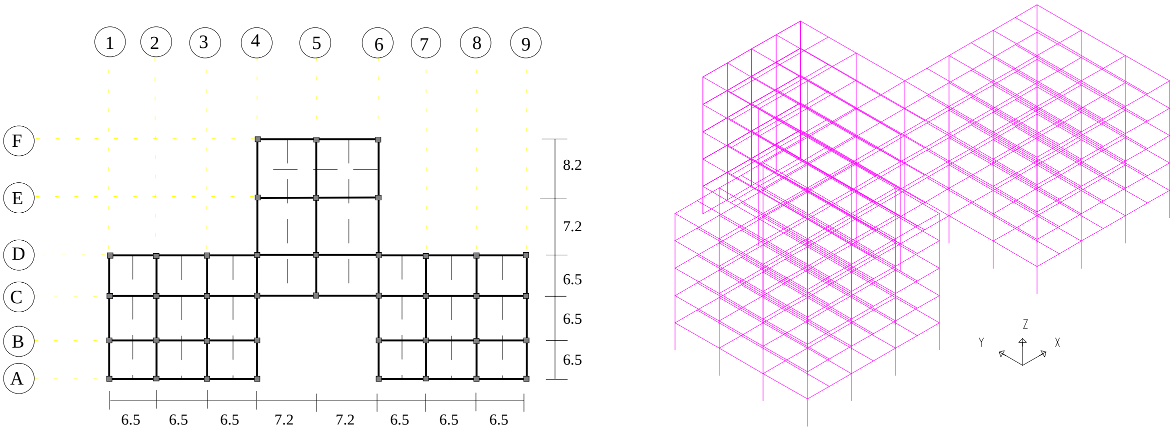
made in order to follow the general procedure outlined by UBC-97 code for base isolation. Perhaps the most important modification is that a general equation to obtain the design displacement was defined from an acceleration database of important earthquake events (M_s=6.9 to M_s=8.1) recorded on rock stations along the Mexican Pacific Coast. In addition, the design process of the isolations units was based on analytical models. In this study, bilinear isolators with a postyielding stiffness of 10% (k_2/k_1) were considered to fulfill the requirements specified on the UBC-97 code. According to UBC-97 code, the effective stiffness of the isolation system at the design displacement must be greater than one third of the effective stiffness at 20% of the maximum design displacement. A complete iterative procedure was developed for the design of base isolated structures using and adapted version of the UBC-97 code to Mexican codes design philosophy, which are presented in detail in Villegas [1999].

SUBJECT BUILDINGS

Two buildings were studied, a hospital (HGZ) and an office building (EBA). The dynamic properties of both structures were obtained using ETABS program. A brief description of the structures is given bellow.

Hospital Building (HGZ)

The structure is a typical project for government hospitals of the 1980's. HGZ consists of five stories, it has an Y shaped plan layout, therefore, it is classified as an irregular building according to ruling Mexican codes. The structural systems used for lateral loading are a dual system in one direction (moment resisting frames and shear walls) and moment resisting frames in the other direction. The typical story height is 3.5 m. Two designs strategies were used for the design of the building: (a) a conventional design of a fixed-base structure according to the seismic code of Guerrero [RCGS-90 1990] and, (b) a base-isolated design using the method briefly discussed in this article. The main purpose of it was to compare the use of base isolation against traditional design methods. The impact of the reduction of the design base shear for the superstructure on the amount of steel reinforcement of columns and beams was assessed. The architectural model is depicted in Figure 1.



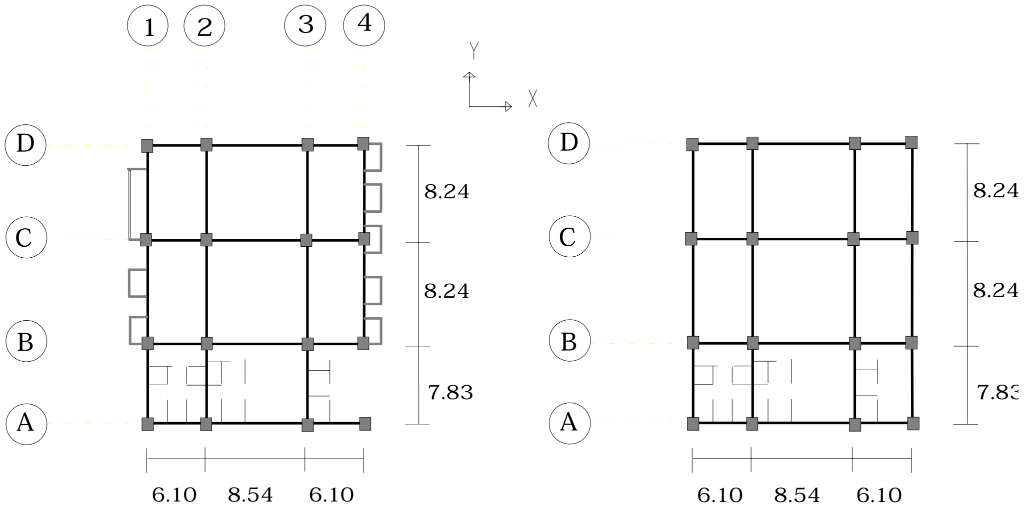
a) Plan view

b) Isometric view

Figure 1. HGZ Building

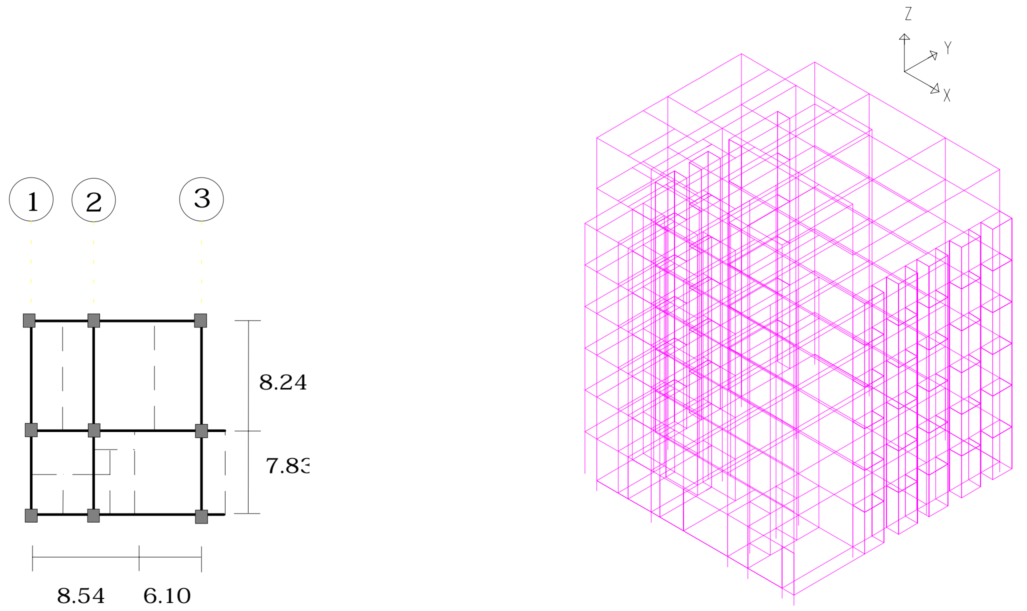
Office Building (EBA)

EBA building has eight stories including a heliport. This building was chosen because it has an irregular configuration on elevation, as some beams are missed in frame 1 from levels 1 to 8. Besides, a sudden change of stiffness occurs from the first to the second level because the shear walls are eliminated on the second floor. The typical story height is 4.03 m from the first level to the roof and 4.9 m in the heliport. The plan and elevation of the building are depicted in Figure 2.



a) Plan view from level 1 to 6

b) Plan view level 7



c) Plan view level 8

d) Isometric view

Figure 2. EBA Building

ACCELERATION RECORDS

Typical accelerograms for the Mexican earthquakes recorded on rock sites during recent earthquakes were used for this work. A set of nine stations was selected; however, some stations were used more than once because they have important accelerograms recorded during different earthquake events. Five of the acceleration records (AZIH, CALE, PARS, UNIO and VILE) were obtained during the September 19, 1985 earthquake (M_s=8.1), three (AZIH, PAPN and VILE) for the September 21, 1985 aftershock (M_s=7.6), and four (CPDR, MSAS, SMR2 and VIGA) for the April 25, 1989 earthquake (M_s = 6.9). The records for the September 21, 1985 and April 25, 1989 earthquakes were scaled to an earthquake magnitude M_s=8.1 using a method proposed by Mario Ordaz, which is based on the seismological, model ω^2. Response spectra were calculated for each record for different levels of damping (ξ = 0.05, 0.10, 0.15, 0.20) and using a basic statistical criteria. Displacement spectra were obtained using a median plus one and a half times the standard deviation criterion (σ+1.5S_{dev}). The design spectra for different damping levels are shown in Figures 3 to 6. Considering that is widely recommended in the literature on base isolation that the effective period (T_D) for a base-isolated structure must be located in a period range between 1.5 s and 3.0 s (1.5s<T_D<3s), displacement equations for this interval were estimated. For simplicity, a linear function dependent of the effective period and the damping level was considered.

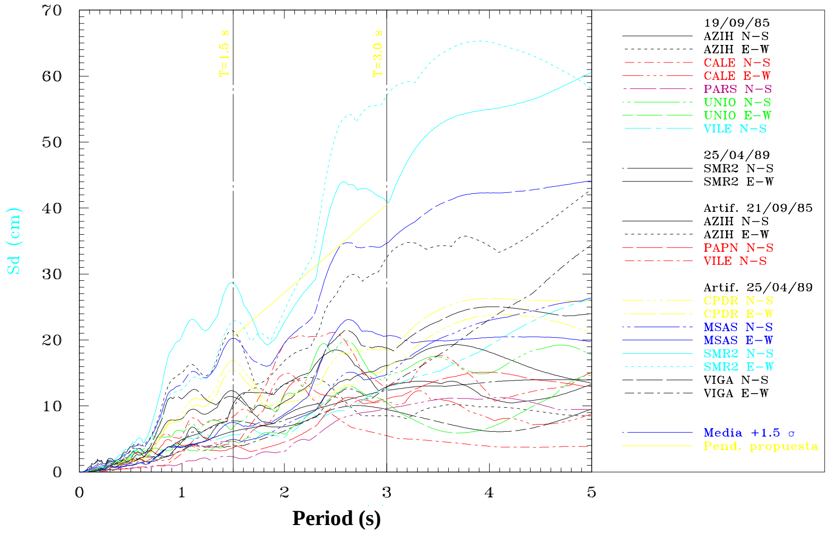


Figure 3. Displacement Spectra for 5% of Critical Damping

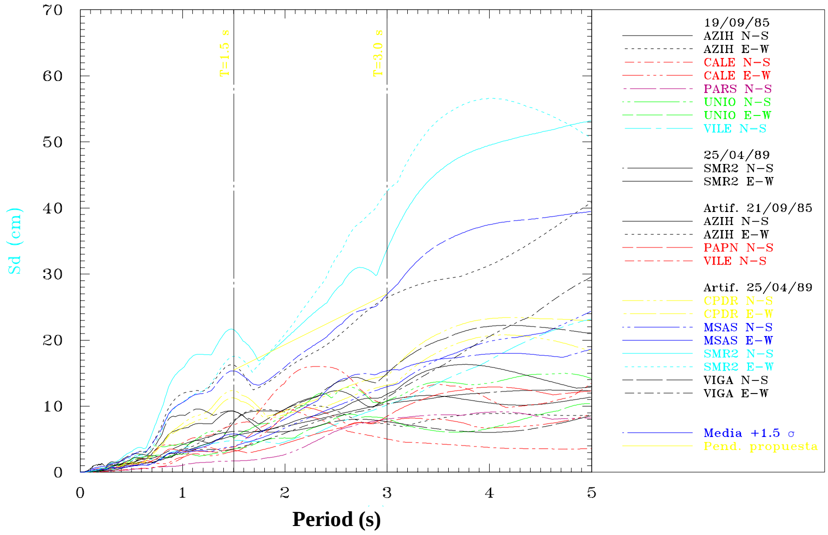


Figure 4. Displacement Spectra for 10% of Critical Damping

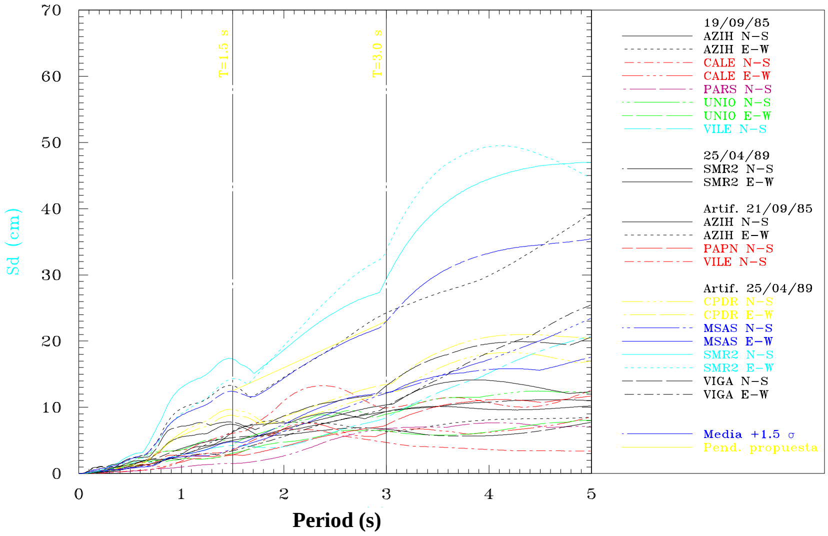


Figure 5. Displacement Spectra for 15 % of Critical Damping

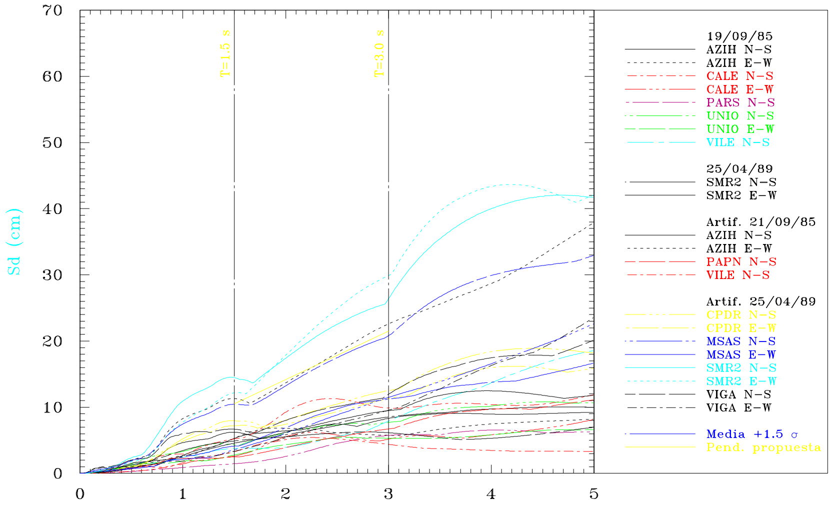


Figure 6. Displacement Spectra for 20% of Critical Damping

DYNAMIC DESIGN PROCEDURE

The procedure is based on the equations of the UBC-97 but some modifications were made to include the design philosophy of Mexican codes. The first step in the design procedure is to select a trial effective isolated period (T_D), then, considering a bi-directional action of earthquakes (assumed to act on the two main axes of the structure), the maximum displacement for the isolation system is computed and the stiffness of the isolation system is estimated. The ratio between the stiffness of the isolation system and the number of required isolators, (preferably one beneath a column), is the stiffness of each base isolator. Based on the mathematical model for bilinear isolators, it is possible to define the mechanical characteristics of each isolator (pre-yield and post-yield stiffnesses, yield displacement and yield force) to comply with the requirements of the UBC-97 code. With this information at hand, it is possible to do a preliminary design of elastomeric bearings with or without a lead plug. The design displacement (D, in centimeters) for the isolation system is estimated using the following general equation:

$$D = m(T_D - 1.5) + b \qquad \text{...(1)}$$

Being T_D the period (in seconds) of base-isolated structure and the values of m and b are parameters which depend on the damping values given in Table 1:

Table 1. Displacement parameters

ξ (%)	***m***	***B***
5	13.40	20.5
10	7.67	15.5
15	7.00	12.5
20	7.33	10.5

The design displacement calculated above considers only one direction of earthquake loading. For design purposes, torsional and bidirectional effects must be considered, so according to the 1997 UBC code, they can be accounted in the following way:

The displacement calculated above consider only one direction, for design purposes torsional and bidirectional effects must be considered:

$$D_{TMD} = D\left[1 + \frac{12e}{b^2 + d^2}\right] \qquad \text{...(2)}$$

$$D_{TMR} = \mathrm{Max}\left(D_{TSMVY}, D_{TSMVX}\right) \qquad \text{...(3)}$$

$$D_{TMSVY} = \sqrt{\left(D_{TMDY}\right)^2 + \left(0.3D_{TMDX}\right)^2} \qquad \text{...(4)}$$

$$D_{TMSVX} = \sqrt{(0.3D_{TMDY})^2 + (D_{TMDX})^2} \qquad ...(5)$$

Where "*e*" is the eccentricity from the mass center of the structure to the stiffness center of the isolation system, "*b*" and "*d*" are the minimum and maximum plan dimension of the structure, respectively. Based on the total maximum displacement, the period and the mass, the global stiffness of the system can be estimated as:

$$k = \frac{4\pi^2 W}{T_D{}^2 g} \qquad ...(6)$$

Knowing the number of isolators (N_{ais}), the effective stiffness can be calculated:

$$k_{eff} = \frac{k}{N_{ais}} \qquad ...(7)$$

Then, the pre (k_1) and post (k_2) yield stiffness are estimated:

$$k_1 = 5k_{eff} \qquad ...(8)$$

$$k_2 = 0.5k_{eff} \qquad ...(9)$$

Based on the analytical model, the yield displacement can be known as follows:

$$\Delta_y = 0.111D_{TMR} \qquad (10)$$

The maximum shear on the isolator is calculated based on the displacement and the stiffness:

$$V_{ais} = k_{eff} D \qquad (11)$$

then, the yield shear can be assessed:

$$V_y = 0.555V_{ais} \qquad (12)$$

Considering that the isolator has a cylindrical plan, the diameter and the height of the unit is calculated as:

$$\varphi = 3D_{TMR} \qquad ... \qquad (13)$$

$$h = \frac{\pi\varphi^2 G_{ais}}{4k_{effM}} \qquad ... \qquad (14)$$

In case that the bearings have a lead plug, the height is estimated based on the postyield stiffness:

$$h = \frac{\pi\varphi^2 G_{ais}}{4k_2} \qquad ... \qquad (15)$$

Finally, the lead plug diameter is calculated:

$$A_{pb} = \frac{V_y - k_2\Delta_y}{\tau_{pb}} \qquad ... \qquad (16)$$

Two restrictions are imposed for the design of the elastomeric bearings. The first is that the ratio between the height and the diameter of the bearing should be no more than 0.8 and no less than 0.25 ($0.25 \leq h/\phi \leq 0.8$). This condition prevents the isolator of being too slender or too short. The second applies only to bearings that have lead plugs, and also limits the ratio of the diameter of the lead core with respect to the diameter of the rubber bearing to a minimum of 0.1 and a maximum of 0.3 ($0.1 \leq \phi_{pb}/\phi \leq 0.3$). Besides, the design yield base shear of the isolation system should be no more than 10.5% of the weight of the structure ($V_{yw} \leq 0.105$) for strong earthquakes (M_s>7.5) in order to have nonlinear behavior of the isolation system. It should be noted that the selection of optimal yielding forces for the isolation unit strongly depends on the characteristics of the ground motions and earthquakes sources, so smaller values must be used for low magnitude earthquakes.

Once these criteria has been satisfied, the base shear transmitted to the structure is calculated, depending on the isolation system stiffness or the code design spectrum, as follows:

$$V_{bme} = \mathrm{Max}(V_s, V_{br}) \qquad ... \qquad (17)$$

$$V_S = 0.80 \frac{k_D D_D}{Q_a'} \qquad \ldots \qquad (18)$$

where Qa’ is the response modification reductive factor for base-isolated structures dependent on the characteristics of structural system and Q’ is the response modification reductive factor for fixed base structures The spectral ordinate must be obtained using the base isolated period T_D.

$$V_{br} = \frac{aW}{Q'} \qquad \ldots \qquad (19)$$

RESULTS

As the design procedure is iterative, a Fortran program was done to perform the design of the isolation system for each building. The final design for the isolations system of the HGZ building consist of a total of 40 circular lead-rubber bearings 61.5 cm in diameter and 37.5 cm in height, with a lead core diameter of 13.8 cm. The total maximum isolator displacement (considering bidirectional effects) was 20.5 cm and the yield displacement was 2.27 cm. The yield strength was 10.1% of the total weight for the structure. On the other hand, the isolation system designed for EBA building consist of a total of 16 lead-rubber bearings of 80 cm in diameter and 54.41 cm in height, with a lead core of 17.8 cm in diameter. These units were designed for a total maximum displacement of 26.64 cm and a yield displacement of 2.96 cm. The yield strength was 10.2% of the total weight for the structure. Details on the design can be consulted in Villegas [1999].

Table 2. Peak dynamic displacements shear vs allowable limits. LRB base isolation project for HGZ

Event	Station	Max relative roof displacements with the isolators (cm)		Peak LRB isolator displacements		Base Shears (Ton)		V_x ------	V_y -----
		Δx_{max}	**Δy_{max}**	**Δ_a/Δ_M**	**θ**	**V_x**	**V_y**		
09/19/85	AZIH	3.2	5.8	.283	31.6	661.1	587.6	.108	.096
	PARS	1.9	4.2	.097	72.2	381.0	446.3	.062	.073
	VILE	3.4	4.4	.268	11.4	679.9	475.2	.111	.077
09/21/85	AZIH	3.9	4.4	.607	22.35	797.0	435.7	.130	.071
	PAPN	1.9	5.2	.161	54.95	346.3	510.0	.056	.083
	VILE	1.8	5.5	.156	80.67	359.5	597.1	.058	.097
04/25/89	CPDR	2.9	6.4	.605	46.41	600.2	639.5	.098	.104
	SMR2	5.1	8.6	1.397	41.25	1036.8	940.7	.169	.153

Table 3. Peak dynamic displacements shear vs allowable limits. LRB base isolation project for EBA

Event	Station	Max relative roof displacements with the isolators (cm)		Peak LRB isolator displacements		Base Shears (Ton)		V_x ------	V_y -----
		Δx_{max}	**Δy_{max}**	**Δ_a/Δ_M**	**θ**	**V_x**	**V_y**		
09/19/85	AZIH	30.5	36.0	.270	41.13	370.9	437.1	.055	.065
	CALE	24.1	36.3	.304	68.61	307.4	455.7	.046	.068
	PARS	13.4	22.2	.065	65.72	199.7	244.4	.029	.036
09/21/85	AZIH	28.1	46.2	.885	68.81	308.1	697.0	.046	.103
	PAPN	14.0	21.5	.116	59.13	194.2	322.1	.029	.048
	VILE	27.2	30.4	.157	1.10	403.8	319.5	.060	.055
04/25/89	CPDR	32.4	22.2	.553	46.41	432.5	425.6	.064	.063
	SMR2	54.7	43.7	1.64	44.81	769.2	794.0	.114	.118

To verify the peak dynamic responses for the isolation system of both buildings, nonlinear dynamic analyses were done using the 3-D Basis program [Nagarajaiah *et al.* 1991]. Some results are summarized in Tables 2 and 3. As it can be observed, dynamic responses of HGZ and EBA buildings are stable when subjected to most of the acceleration records; however, for the 1989 scaled record of the SMR2 station, the dynamic displacement was greater than the total maximum displacement obtained using the equations mentioned above. This phenomenon is presented because the SRM2 acceleration record of the 1989 event is epicentral and perhaps the scaling procedure overestimates the expected ground motions for larger earthquakes. In any event, it is clear that the proximity to the epicentral area has a great importance and has to be addressed independently in the estimation of the maximum displacements, as currently done in the 1997 UBC code. The normalized shear in the isolation system for this case (SMRZ station, M_s=8.1 subduction earthquake) was 0.17 and 0.15 for HGZ and EBA buildings respectively. Therefore, these results would suggest that the yield strength for bilinear isolation systems of structures that may be located in epicentral areas should be more than 10% the total weight of the structure for large earthquakes (M_s>8.0).

In both buildings, the isolation system yield for all M_s=8.1 records, except PARS station for the 0919/1985 earthquake. PARS records have not as much energy as the one of the remaining stations because the station is located far away from the epicenter for the 09/19/85 earthquake, among other reasons. The maximum dynamic displacements of the isolators are within reasonable bounds when subjected to the other acceleration records, this is, even though the isolators yield, no one got close to the maximum allowable displacement. The design of HGZ building as base-isolated structure produced savings in steel weight of about 20%, nevertheless, in this case there was no savings in concrete weight because the same beams and columns geometry was used in both cases.

CONCLUSIONS

The study presented herein suggest that an adapted version of the dynamic design procedure outlined in the UBC-97 code could be used in the Mexican Pacific Coast if the regional seismicity and the design philosophy of Mexican seismic codes are carefully assessed. To promote base isolation technology, displacement design spectra must be defined for different seismic zones of Mexico in order to incorporate these spectra and design guidelines for base-isolated structures in the principal seismic codes of Mexico. Steps are currently taken in this direction. The proximity to an epicentral area or a fault must be considered in the estimation of the design displacements for base isolators in an explicit and independent way, as currently done in the UBC-97 code. Displacement design spectra (DDS) for Mexican codes must be based on detailed studies where the seismic hazard must be evaluated using both deterministic and probabilistic approaches and being compatible with the remaining seismic design criteria for these codes. Steps are being taken in this direction. The use of base isolation technology is still an art in many countries. Therefore, the knowledge of the earthquake sources, the soil profile types and the estimation of the possible ground motions that frame the earthquake risk and hazard are very important factors to determine the potential use of base isolation for particular buildings.

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