THE NEW GUIDELINES FOR THE SEISMIC DESIGN OF BASE ISOLATED STRUCTURES IN MEXICO

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ABSTRACT

The Manual of Civil Structures (MOC), a model design code in Mexico, is in an updating process. The new version for this code will be published at the end of 2008. This new version of MOC incorporates guidelines for the seismic design of base-isolated structures, being the first Mexican code to include such recommendations. This paper summarizes the most relevant aspects of these guidelines, their relations to other guidelines worldwide and research efforts conducted in Mexico and worldwide to improve the seismic design of base-isolated structures.

KEYWORDS: Building codes, seismic guidelines, seismic isolation, design spectra, base isolation

1. INTRODUCTION

The Manual of Civil Structures (MOC), one of the model design codes in Mexico, is in an updating process. This manual is frequently used in the entire nation in lieu of a specific code for a state or a city. The new version for this manual and all their chapters are going to be tentatively published at the end of 2008 (MOC-2008 2008). Among the new chapters, there is one devoted to the seismic design of base-isolated structures.

The guidelines for base isolation are based in a previous proposal that took care of make them compatible with the design philosophy of the seismic codes of Mexico and that included the seismic risk and hazard of Mexico, to ease their incorporation to model seismic codes of Mexico (Tena-Colunga 2005). However, additional material have been reviewed, adapted and/or included, so the guidelines for base-isolated structures in MOC-2008 are a much improved version from the previous proposal.

Some of the most important provisions that impact the seismic design of base isolated structures are summarized in following sections and presented in greater detail in English language elsewhere (Tena-Colunga 2008). The bases and design philosophy of previous and current seismic design provisions of MOC code in English language can be found elsewhere (Tena-Colunga 1999, Tena-Colunga *et al.* 2008).

2. GENERAL DESIGN CRITERIA

The seismic design of base-isolated structures should satisfy two limit states according to the guidelines available in MOC-2008:

- service limit state, where deformations should be reviewed to prevent damage and warrant that the isolation system is activated and,
- collapse prevention limit state, where strength and deformation capacities of the isolation system and structural elements (below, above and within the isolation interface) will be assessed to check that they can withstand force and displacement demands from the maximum credible earthquake (MCE). The structure above the isolation system should remain essentially elastic or experience very limited damage, and this condition should be checked with the allowable interstory drifts, as specified in other section.

Base-isolated structures should be designed considering the action of three simultaneous orthogonal components for the ground motions (two horizontal and one vertical) and their combinations with other general loading conditions (i.e., gravitational) specified by the manual.

The stability of the isolation system for lateral and gravitational load combinations should be reviewed both analytically and with experimental data from required testing at the design displacement (D_T).

Base-isolated structures should be built in near-firm to rock soil profile types. This must be verified in terms of what it is defined in MOC-2008 as the site factor, F_s, and the site period, T_s, as explained elsewhere (i.e., MOC-2008 2008). The proposed ranges are: $1.0 \leq F_s \leq 1.4$ and $0 \leq T_s \leq 0.7$. Alternatively, the soil profile type could be assessed in terms of: (a) the shear wave velocity, that for the soils under consideration should be $v_s \geq 180\, m/s$ and/or, (b) the number of hits for the standard penetration test, which for the soils under consideration should be equal or greater than 30 ($N_{PE} \geq 30$).

The recommendation to use base isolation systems in competent soil profiles types is justified. The advantages of using base isolation in firm soils or rocks are well-known. The disadvantages of using base isolation in soft soils because of the likeliness of resonant responses and instability of the isolation system have been documented (i.e., Tena-Colunga 1996). In addition, potential problems because of uneven soil settlements can trigger in soft soil sites.

Height limits are specified for the most common structural systems used in buildings and addressed by the code. The proposed height limits are based in base-isolation guidelines of the United States (i.e., ASCE-7 2005), but they were adapted to Mexican design conditions (i.e., Tena-Colunga 2005). However, a window is open in MOC-2008 for special base-isolated structures that may surpass the limiting height values. Taller base-isolated buildings could be built only if a group of experts independent from the original design (peer-review committee) authorizes such projects.

It is also established in MOC-2008 that if the structure above the isolation system contains special elements such as passive energy dissipators or dampers, their design should also met the criteria established for such devices within the Manual and that the proposed design values for effective damping and the seismic reduction factor should be fully justified. This statement is included as it is recognized that such mixed systems are becoming more commonly used worldwide today, so guides should be set for a coherent seismic design.

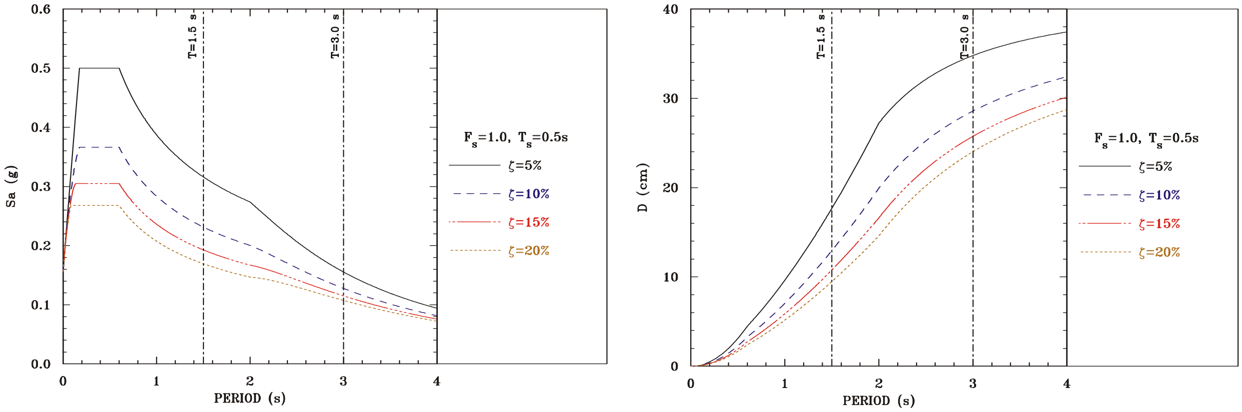
3. ELASTIC DESIGN SPECTRA

As described in further detail in a companion paper presented in this conference (Tena-Colunga *et al.* 2008), the elastic acceleration design spectra for MOC-2008 code is, in theory, an infinite number of discrete functions within the Mexican Territory, as a direct consequence of taking the decision of defining the seismic hazard as a continuum. The proposed elastic acceleration design spectra are transparent in essence, as modification factors are defined exclusively in terms of the seismic hazard and site effects.

For space constraints, the equations needed to define the acceleration and displacement elastic design spectra for the MCE, as well as the damping factor β that allows modifying the spectral ordinates for damping ratios different from 5% to account only for the potential supplemental damping of the isolation system are presented elsewhere (Tena-Colunga *et al*. 2008, Tena-Colunga 2008).

Typical acceleration and displacement spectra for the design of base-isolated structures for effective damping ratios from 5 to 20 percent are depicted in Figure 1. The site profile type is similar to the one defined in former MOC-93 code for zone D-I (Tena-Colunga 1999).

As it is demonstrated elsewhere (i.e., MOC-2008 2008) when the period $T \rightarrow \infty$, the maximum spectral displacement converges to the peak ground displacement D_{max}. This fact is an important improvement in MOC-2008 with respect to their previous version of 1993 and with respect to most international codes, where due to the definition of the descending branch of the acceleration spectra for long periods, displacements grew up irrationally for long periods, as illustrated in Figure 2.



a) Acceleration design spectra

b) Displacement design spectra

Figure 1. Design spectra for MOC-2008 for a site where $a_0^r = 0.157g$, $T_s = 0.5s$ and $F_s = 1$

Different proposals for the displacement design spectra for zone D-I of previous MOC-93 code are compared in Figure 2. It can be observed that displacements grew up irrationally under MOC-93 code. Current MOC-2008 proposal takes care of that problem, as for long periods, defined curves converge to the ground displacement. The guidelines proposed by Tena-Colunga (2005) also converge to the ground displacement. In fact, there is a reasonable correlation in what was proposed by Tena-Colunga (2005) and what is now proposed in MOC-2008 for this site, particularly in the period range of more interest for base-isolated structures ($1.5s \leq T_{as} \leq 3s$). It is worth noting that the proposal in Tena-Colunga (2005) was obtained using a basic probabilistic and statistical criteria based in displacement response spectra of approximately 250 ground motions recorded at stations located on rock sites from the Strong Motion Mexican Data Base for subduction earthquakes of M≥6.4. In contrast, in MOC-2008 all known earthquakes sources for the different regions of seismic risk of Mexico were taken into account, and their maximum credible earthquake (MCE) scenarios were defined using updated information. In addition, the seismic hazard in MOC-2008 was evaluated using both deterministic and probabilistic approaches.

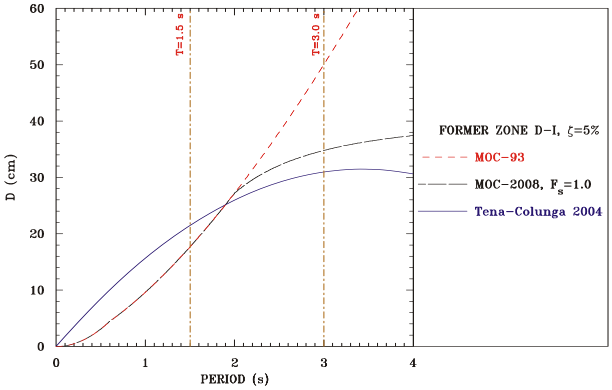


Figure 2. Comparison of displacement design spectra for former zone D-I defined in MOC-93

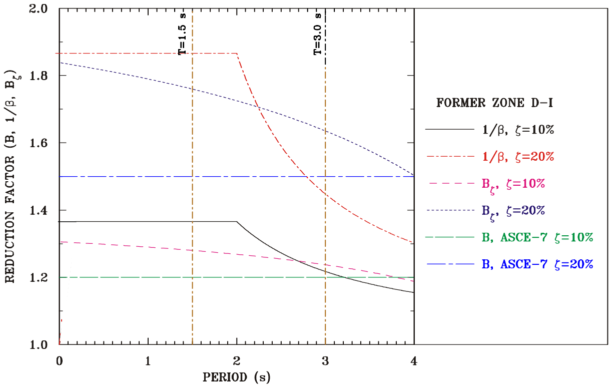


Figure 3. Comparison of different reduction factors to account for supplemental damping

Another relevant aspect of MOC-2008 in the definition of the design spectra is that it is recognized that reductions due to supplemental damping are not constant and they depend on the structural period and the characteristics of the ground motions. Most international guidelines for the seismic design of base-isolated structures (i.e., ASCE-7 2005) specify a constant reduction in sake of simplicity. Proposed reductions for supplemental damping according to MOC-2008 code ($1/\beta$) for former zone D-I of MOC-93 are compared in Figure 3 with the proposal of B_ζ made by Tena-Colunga (2005) and the B constant proposed by the international guidelines of reference. Proposed reductions in MOC-2008 ($1/\beta$) have a spectral shape as they were derived in order that the associated acceleration design spectra will keep their shape. B_ζ curves vary parabollically as they were derived from the quotient between corresponding mean displacement spectra. Granted the differences in their derivation, there is a reasonable agreement between the proposed reduction in ($1/\beta$) and B_ζ curves. It is also worth noting that the constant reduction (B) proposed by international guidelines seem to be somewhat conservative.

4. REDUCTION OF ELASTIC RESPONSE PARAMETERS FOR DESIGN

According to what was presented in previous sections, acceleration and displacement design spectra can be reduced for the supplemental damping provided by the isolation system at the design displacement D_T. Additional reductions are allowed in the acceleration design spectra to account for overstrength and redundancy only (Figure 4), as it is desired that the structure above the isolation system will remain essentially elastic when subjected to the MCE. These additional reductions should be assessed as described in following sections.

4.1 Overstrength reduction factor R_{as}

The proposal for the overstrength reduction factor for base-isolated structures, R_{as}, is given by the following equations:

$$R_{as} = \begin{cases} R_{a0} + 0.3\left(1 - \sqrt{T_E/T_a}\right); & \text{if } T_E \le T_a \\ R_{a0}\,; & \text{if } T_E > T_a \end{cases} \tag{4.1}$$

where T_E is the fixed-base fundamental period of the structure above the isolation system, T_a is the lower boundary limiting period that defined the plateau for the acceleration design spectra and R_{a0} is an overstrength index value for the base-isolated structure that depends on the structural system. For example, R_{a0}=1.4 for ordinary and intermediate moment-resisting frames, ordinary moment-resisting braced frames and confined masonry wall structures made with hollow units (ungrouted or partially grouted); R_{a0}=1.6 for special moment-resisting frames, intermediate moment-resisting braced frames, and confined masonry wall structures made with solid units; R_{a0}=1.7 is for dual systems built with special moment-resisting frame connections.

The proposed R_{as} curves for MOC-2008 are depicted in Figure 5, where it can be observed that they vary with the structural system and the structural period. This is done because it is recognized that for squatty, short period structures ($T_E/T_a<1$), the impact of gravitational load combinations in the design provides structures with additional lateral strength.

4.2 Redundancy factor ρ_{as}

The introduction of a specific redundancy factor for base isolated structures ρ_{as} is a new concept for seismic design codes worldwide, not only for MOC-2008. The purpose of this “new” factor is recognizing directly that base-isolated structures have a better performance under lateral earthquake loading as they become more redundant. This fact is well-known by the structural engineering community worldwide. Therefore, this new ρ_{as} factor allows higher reductions for the design of highly redundant base-isolated structures and penalizes weakly-redundant base-isolated structures with smaller reductions for design. The proposed values for ρ_{as} in MOC-2008 are the following:

$\rho_{as} = 0.8$ for structures with at least two earthquake-resistant parallel frames or lines of defense in the direction of analysis, if such frames are one-bay frames (or equivalent structural systems). The same concept shall be simultaneously satisfied by the base-isolation system.

$\rho_{as} = 1$ for structures with at least two earthquake-resistant parallel frames or lines of defense in the direction of analysis, if such frames have at least two bays (or equivalent structural systems). The same concept shall be simultaneously satisfied by the base-isolation system.

$\rho_{as} = 1.25$ for structures with at least three earthquake-resistant parallel frames or lines of defense in the direction of analysis, if such frames have at least three bays (or equivalent structural systems). The same concept shall be simultaneously satisfied by the base-isolation system.

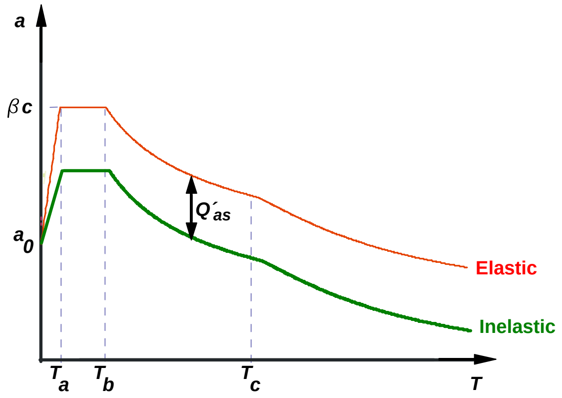


Figure 4.Schematic representation of inelastic acceleration design spectra for base-isolated structures for MOC-2008

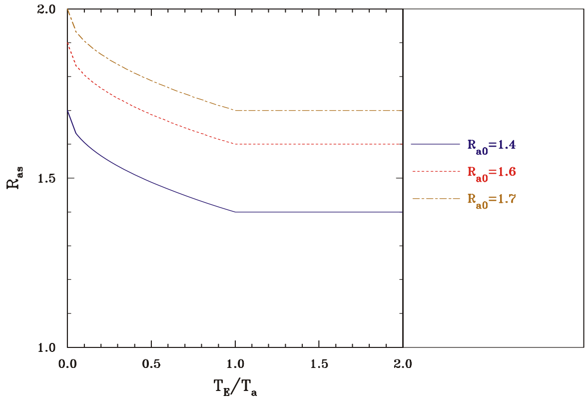
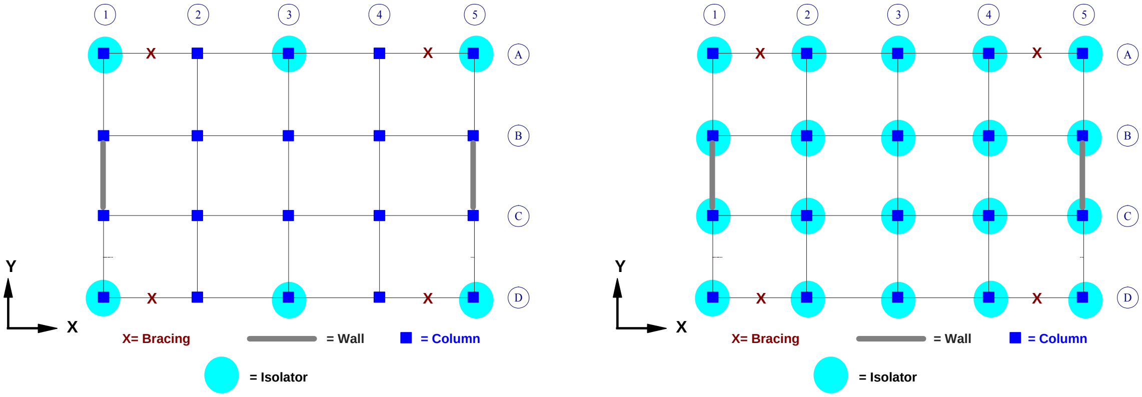


Figure 5. Overstrength reduction factors for base isolated structures R_{as} for MOC-2008

The proposed values for ρ_{as} for base isolated structures coincide with the values proposed for ρ for conventional structures (i.e., MOC-2008 2008, Tena-Colunga *et al.* 2008). This was done for simplicity in lieu of specific studies that may justify differences between ρ and ρ_{as}.



a) Less redundant isolation system
b) More redundant isolation system

Figure 6. Sample buildings to illustrate the assessment of the ρ_{as} factor.

The assessment of the ρ_{as} factor for a given base-isolated structure is straight-forward and it will be illustrated with the buildings which plans are depicted in Figure 6. Often, the number of isolators is equal or less the number of column lines for the building, so usually the definition of the ρ_{as} factor is ruled by the isolation system. For the building plan depicted in Figure 6a, $\rho_{as} = 0.8$ should be taken in the Y direction as the isolation system is forming an equivalent "three parallel one-bay frames system", whereas in the X direction, $\rho_{as} = 1$ because the isolation system is forming an equivalent "two parallel two-bay frames system". In contrast, for the building plan depicted in Figure 6b, $\rho_{as} = 1.25$ should be taken in the Y direction as the isolation system is forming an equivalent “five parallel three-bay frames system”, whereas in the X direction, $\rho_{as} = 1.25$ also because the isolation system is forming an equivalent “four parallel four-bay frames system”.

This simple example illustrates the philosophy behind the new ρ_{as} factor. *A-priori*, most engineers would agree that the base-isolated building which plan is depicted in Figure 6b is more redundant than the base-isolated building which plan is depicted in Figure 6a. It is hoped that this approach would help structural engineers to promote the use of more redundant base-isolated buildings in zones of high earthquake hazard and to limit or avoid the use of weakly-redundant isolation systems (i.e., Figure 6a).

4.3 Seismic reduction factor Q'_{as}

The acceleration design spectra for base-isolated structures could be further reduced for overstrength and redundancy (Figure 4) in terms of a seismic reduction factor for base-isolated structures, Q'_{as}, given by the following expressions:

$$Q'_{as} = \begin{cases} R_{as}\rho_{as} \geq 1; & \text{if } \dfrac{T_{as}}{T_E} \geq 5 \\ R_{as}\rho_{as}\left(0.5 + 0.1\dfrac{T_{as}}{T_E}\right) \geq 1; & \text{if } 2 \leq \dfrac{T_{as}}{T_E} < 5 \end{cases} \tag{4.2}$$

The proposal for Q'_{as} is similar to the one presented in previous recommendations for base isolated structures in Mexico (Tena-Colunga 2005). The normalized $Q'_{as}/R_{as}\rho_{as}$ vs T_{as}/T_E curve is depicted in Figure 7. As it can be observed from Eq. 4.2 and Figure 7, higher reductions are allowed for structures where the effective base-isolated fundamental period T_{as} is considerably higher than its corresponding fixed-base period T_E. It is well known in the literature that when that occurs, the seismic demands in the structure above the isolation system are considerably reduced, but the reductions are not as high when T_E approaches to T_{as}. The limits are based on the observation of amplification curves presented in many studies available in the literature, as well as in studies conducted by the author. The lower limit for $T_{as}/T_E = 2$ is consistent with the minimum value allowed in MOC-2008 guidelines to use the static design force procedure, which is originally based on a recommendation available in Skinner *et al.* (1993), that has been further evaluated, including torsional effects, as reported in Tena-Colunga and Escamilla-Cruz (2007).

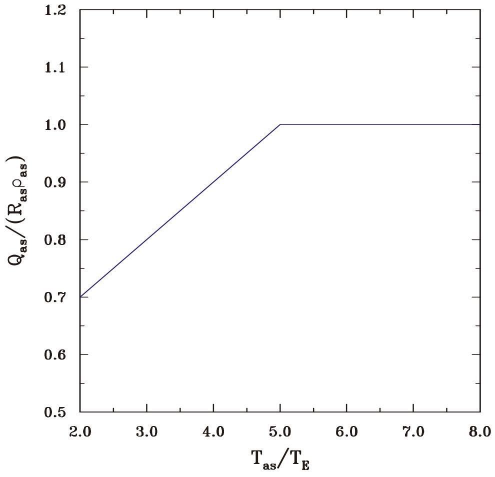


Figure 7. Normalized $Q'_{as}/R_{as}\rho_{as}$ vs T_{as}/T_E curve for base-isolated structures.

From the values specified for R_{as} and ρ_{as} in MOC-2008, it is obtained that the maximum value for the seismic reduction factor for base isolated structure is $Q'_{as} = 2x1.25 = 2.5$ for highly redundant structures when $T_{as}/T_E > 5$ and the minimum value is $Q'_{as} = 1$ for weakly-redundant base-isolated structures, with low overstrength and when the T_{as}/T_E ratio is low. It is worth noting that in base-isolated guidelines of the United States (i.e., ASCE-7 2005) reductions due to redundancy and overstrength for base-isolated structures ranges from 1.4 to 2.0 depending on the structural system, as previously pointed out by Naeim and Kelly (1999). Finally, following the design philosophy of Mexican seismic codes, if the base-isolated structure does not satisfy the conditions of structural regularity, Q'_{as} must be reduced.

5. CONDITIONS OF STRUCTURAL REGULARITY

For the design of base-isolated structures, twelve conditions of regularity are defined and building structures must satisfy them in order to use directly the reductive seismic force factor Q'_{as}. These conditions are mostly the eleven condition of regularity for conventional building specified since MOC-93 (i.e., Tena-Colunga 1999), that mostly remain the same for the design of conventional buildings in MOC-2008, but the statement devoted to prevent a soft story condition (condition # 10) was redefined and now is more conservative than in previous versions. For the design of base-isolated structures, the limits of original structural regularity conditions 2 (slenderness) and 3 (plan aspect ratio) are also lowered, based upon what it is recommended in Naeim and Kelly (1999) and Tena-Colunga (1996). In addition, a new condition of structural regularity 12 is set to limit the static eccentricity in the isolation system which is based in studies devoted to study the torsional response of base-isolated structures (i.e., Tena-Colunga and Zambrana-Rojas 2006). Therefore, the conditions of regularity that have been redefined or inserted for the design of base-isolated structures are:

2. The ratio of the height of the building to the smallest plan dimension shall not exceed 2.0 ($H/L_2 \leq 2.0$).

3. The ratio of the largest to the smallest plan dimensions shall not exceed 2.0 ($L_1/L_2 \leq 2.0$).

10. The lateral shear stiffness or strength of any story shall not exceed more than 50 percent the shear stiffness or strength of the adjacent story below the one in consideration. The top story is exempt from this requirement.

11. The torsional plan eccentricities (e_s), computed for any story from static seismic analysis, shall not exceed 10 percent of the plan dimension in the given direction of analysis.

12. The torsional plan eccentricity for the isolation system (e_{sa}), shall not exceed 5 percent of the plan dimension in the given direction of analysis.

The remaining conditions of structural regularity can be read in English language as outlined elsewhere (Tena-Colunga 1999). Similar to what is done for the design of conventional buildings, if a base-isolated building satisfies all the twelve conditions of structural irregularity, it is defined as a regular structure, so Q'_{as} remains unchanged. However, if at least one condition of structural regularity is not satisfied, the base-isolated building is defined as irregular structure, and then Q'_{as} is reduced for design purposes as follows:

$$Q'_{as-irregular} = \alpha\, Q'_{as-regular} \tag{5.1}$$

where α is a corrective reduction factor that depends on the degree of irregularity according to MOC-2008. If a building does not satisfy one regularity condition (from those numbered 1 to 9), then α =0.9. If a building does not satisfy regularity condition 10 (soft story) or 11 (torsion in the superstructure), or 12 (torsion in the isolation system), or two or more of the remaining regularity conditions (1 to 9) are not satisfied, then α =0.8. If a building has a strong irregularity, then α =0.7. Strong irregularity conditions are defined as follows: (1) If conditions 10 and 11 are not satisfied simultaneously, (2) a strong torsional irregularity in the superstructure is met, evaluated in terms of a static eccentricity greater than 20% of the plan dimension in the given direction of analysis ($e_s > 0.20L$), (3) a strong torsional irregularity in the isolation system is met, evaluated in terms of a static eccentricity greater than 15% of the plan dimension in the given direction of analysis ($e_{sa} > 0.15L$), (4) a strong soft story condition is found, where the lateral shear stiffness or strength of any story exceeds more than 100% the shear stiffness or strength of the adjacent story below the one in consideration. It is recognized in the proposed guidelines that the main source of torsional motions in isolated structures is the isolation system eccentricity, specially when the eccentricity is large. This is why the design of base-isolated structures is severely punished when e_{sa} is greater than 5% or 15%. The limiting values for static eccentricities in the superstructure (e_s) and in the isolation system (e_{sa}) to define when a base-isolated structure should be considered irregular or strongly irregular were proposed after reviewing primarily the results presented in parametric studies reported in the literature, as reported elsewhere (MOC-2008 2008, Tena-Colunga 2008).

6. FINAL REMARKS

For space constraints, it was impossible to comment in detail other important recommendation that are available in the proposed guidelines. A simplified method for the seismic design of low-rise, base-isolated shear wall structures is proposed in MOC-2008. This simplified method is basically a hybrid method, where the design of the isolation system is a simpler but more restrictive version for the static method for base-isolated structures available in US guidelines and the design of the superstructure essentially is the improved simplified method for the seismic design of low-rise shear wall structures of Mexican seismic codes. The static and dynamic methods of analysis mostly coincide with what it is proposed in US guidelines. However, there are some differences worth noting, particularly how torsional response and orthogonal effects, including the action of the vertical component for the ground motions, are accounted for design purposes. The proposal for the vertical distribution of forces in the superstructure in the static method is also somewhat different to what it is available in US guidelines. The review of drift limits for the service earthquake and the MCE for base isolated structures in MOC-2008 is different to what is proposed in US guidelines. The proposed limiting values for the MCE are based on research studies conducted in Mexico for the most common structural systems used within the country. Specialized sections related to the requirements, design, construction, required testing and review for the isolation system are entirely based on US guidelines. However, there are some small modifications that were done to make the base-isolated guidelines coherent as well as compatible with all regulations adopted by MOC-2008. An important modification in the writing of the section entitled “Testing of similar units” was done to try to avoid overregulation on the required prototype testing that may inhibit the application of base isolation for the design and retrofit of buildings in Mexico. It is hoped that these new guidelines in MOC-2008 will help promote the use of base isolation in regions of high seismic hazard in Mexico, then improving their seismic safety. Hopefully, all this information will be available in English language soon (Tena-Colunga 2008).

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