UPDATED GUIDELINES FOR THE SEISMIC DESIGN OF BUILDINGS IN THE MOC-2008 CODE OF 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. A major update is performed in the chapter for the seismic design of building structures from the previous one that is dated back in 1993. This paper summarizes the most relevant changes of this building code and their relations to research efforts conducted in Mexico and worldwide to improve the seismic design of building structures. One goal was to make the guidelines as transparent as possible to users, so the design process will be clearer and enriching to structural engineers.

KEYWORDS: Building codes, seismic codes, seismic guidelines, design spectra, response modification factors

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 previous version for this manual dates from 1993 (MOC-93 1993, Tena-Colunga 1999), so an in-depth review was mandatory. The new version of the manual and all their chapters are going to be tentatively published in the first semester of 2008 (MOC-2008 2008).

MOC-2008 (2008) is, like ASCE-7 (2005), a very comprehensive code, that addresses specifically the design of several structural systems (buildings, bridges, dams, power stations, industrial facilities, chimneys, silos, pipelines, tanks and deposits, vessels, inverted pendulums, retaining walls, etc.) to accidentals actions such as earthquakes and winds. Modern technologies such as base isolation and passive energy dissipation are now addressed, as well as the use of modern materials such as carbon fibers and composites. Specialized topics such as soil-structure interaction, monitoring of structures, evaluation and rehabilitation of existing structures are also covered.

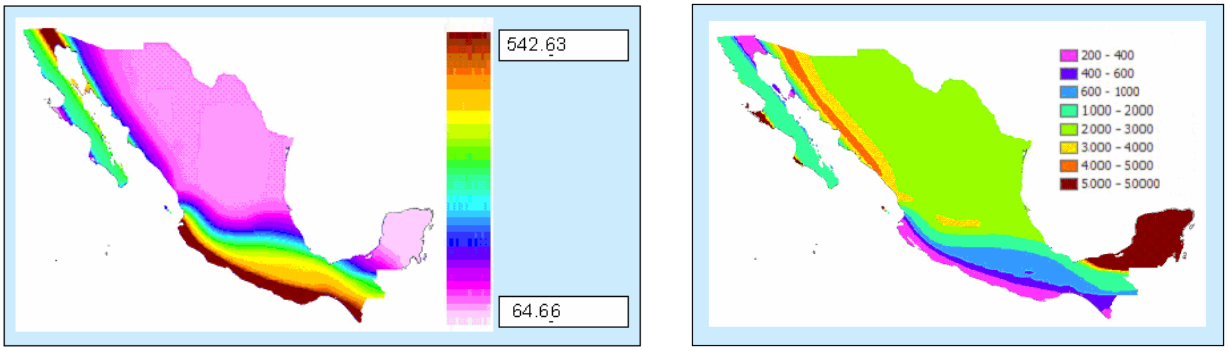
The following sections summarize only some of the most important updated provisions that impact the seismic design of building structures. Some background in the bases and design philosophy of former seismic provisions of MOC-93 code in English language can be found elsewhere (Tena-Colunga 1999).

2. SEISMIC ZONATION

One of the major changes in MOC-2008 with respect to previous MOC-93 code is the concept of the seismic zonation. In MOC-93 code, Mexico was divided in four seismic zones (A, B, C and D, Figure 1), for which there were three different soil profile types: I (firm soils), II (“transition” soils) and III (soft soils), as explained in greater detail elsewhere (MOC-93 1993, Tena-Colunga 1999).

In MOC-2008 code, the seismic hazard of Mexico is defined as a continuum function where peak accelerations in rock are defined (Figure 2a). These peak accelerations are associated to return periods (Figure 2b) that were obtained using an optimization design criterion to define the seismic coefficients for the plateaus of the elastic design spectra for standard occupancy structures as explained in detail elsewhere (MOC-2008 2008, Ordaz *et al.* 2007). All known earthquakes sources for the different regions of seismic risk of Mexico and their maximum credible earthquake (MCE) scenarios expected using updated information were taken into account. The seismic hazard was evaluated using both deterministic and probabilistic approaches.

Figure 1. MOC-93 seismic zone map of Mexico (courtesy of Servicio Sismológico Nacional)



a) Peak ground accelerations in rock a_0^r (cm/s^2)

b) Associated return periods, T_r (years)

Figure 2. Peak ground accelerations for MOC-2008 associated to return periods obtained using an optimal design criteria

3. ELASTIC DESIGN SPECTRA

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 as briefly described in the previous section.

This major conceptual change of having such refinement was taken as: (1) Important progress has been attained in the fields of seismology and seismicity, where more reliable information is available and, (2) practicing engineers and researchers in Mexico often noted that the definition of seismic forces for design for different structures across the Mexican Territory cannot be done in a rational and transparent way with the collection of 12 design spectra as per MOC-93, as relevant information about site effects and structural dynamics are lost, unless site-specific design spectra would be allowed for design and, (3) the impressive development in computer technology and its availability to practically anyone in the workplace allows now such approach, as it is planned to make available user-friendly software to define the design spectrum for any given site according to MOC-2008.

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. Spectral amplifications and nonlinear effects due to the characteristics of the soil profile and its relation with the seismic intensity incidence are considered in the site effect modeling (MOC-2008 2008, Pérez-Rocha *et al.* 2007). A soil model based on a homogeneous layer with nonlinear behavior supported by an elastic half space was used for such purpose (Pérez-Rocha *et al.* 2007).

The detailed steps that have to be taken in order to define the elastic acceleration design spectra for a given site for the MCE related to the collapse prevention performance level are presented elsewhere (MOC-2008 2008, Tena-Colunga *et al.* 2008). For space constraints, this paper focuses in presenting some of the most relevant information only.

The elastic acceleration design spectra for 5% equivalent viscous damping for structures of the group B (standard occupancy) for MOC-2008 code, schematically depicted in Figure 3, is defined with the following general expressions:

$$a = \frac{S_a(T_e)}{g} = \begin{cases} a_0 + (\beta c - a_0)\dfrac{T_e}{T_a}; & \text{if } T_e < T_a \\ \beta c; & \text{if } T_a \le T_e < T_b \\ \beta c\left(\dfrac{T_b}{T_e}\right)^r; & \text{if } T_b \le T_e < T_c \\ \beta c\left(\dfrac{T_b}{T_c}\right)^r \left[k + (1-k)\left(\dfrac{T_c}{T_e}\right)^2\right]\left(\dfrac{T_c}{T_e}\right)^2; & \text{if } T_e \ge T_c \end{cases} \qquad (3.1)$$

where a is the spectral acceleration ordinate for the design spectrum (S_a) expressed as a fraction of the acceleration of gravity (g), a_0 is the ground acceleration coefficient, c is the seismic coefficient that defines the plateau, T_e is the structural natural period of interest, T_a and T_b are control periods that define the plateau of the spectrum, T_c is a control period that defines the descending branch of the acceleration spectrum in order that the displacement design spectrum computed from the acceleration design spectrum will converge to the ground displacement at long periods, r is the parameter that defines the descending branch of the acceleration spectrum in the period range $T_b \le T_e < T_c$, k is the parameter that defines the descending branch of the acceleration spectrum when $T_e \ge T_c$ and β is a damping factor.

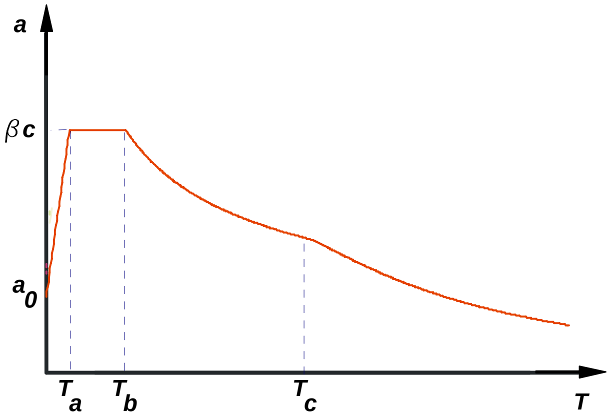


Figure3. Schematic representation of elastic acceleration design spectra for MOC-2008

The control period T_c and the parameters r and k that define the descending branch of the acceleration spectrum are defined as follows:

$$T_c = \begin{cases} 2\,s & if\ T_b < 2\,s \\ T_b & if\ T_b \ge 2\,s \end{cases}; \quad r = T_s; \quad 0.5 \le r \le 1.0; \quad k = \begin{cases} 2 - T_s & if\ T_s \le 1.65\,s \\ \max\{0.35,\ \beta / F_r\} & if\ T_s > 1.65\,s \end{cases} \qquad (3.2)$$

where all terms have been already defined.

The damping factor β allow modifying the spectral ordinates for damping ratios different from 5% to account primarily for soil-structure interaction effects and/or supplemental damping and is defined by the following expressions:

$$\beta = \begin{cases} \left(\dfrac{0.05}{\zeta_e}\right)^{0.45}; & \text{if } T_e < T_c \\ 1 + \left[\left(\dfrac{0.05}{\zeta_e}\right)^{0.45} - 1\right]\dfrac{T_c}{T_e}; & \text{if } T_e \geq T_c \end{cases} \tag{3.3}$$

where ζ_e is the effective (target) damping of interest for the structural system. For essential facilities (structures of group A), the spectral acceleration ordinates (*a*) given in Eq. 5 should be multiplied by an importance factor I=1.5.

The acceleration design spectra to check for the serviceability performance level is obtained indirectly from the one defined for the collapse prevention level divided by a factor of 5.5 and assuming linear behavior for the soil profile, therefore F_{nl}=F_v=1.0. Then, a_0, T_a and T_b are computed as:

$$a_0 = \frac{F_s\ a_0^r}{5.5g}; \quad T_a = 0.35T_s \geq 0.1s; \qquad T_b = 1.2T_s \geq 0.5s \tag{3.4}$$

The remaining parameters used to define the acceleration design spectra remain unchanged. The described spectra should be used to review damage prevention (linear behavior) for the structural system for both essential and standard occupancy building structures. The importance factor is neglected for essential facilities (no amplification for this concept).

Displacement design spectra $S_d(T_e)$ is obtained indirectly from acceleration design spectra based upon standard relation from structural dynamics:

$$S_d(T_e) = \frac{T_e^2}{4\pi^2} S_a(T_e) \tag{3.5}$$

It can be demonstrated that when $T_e \rightarrow \infty$, the maximum spectral displacement converges to the peak ground displacement D_{max} (MOC-2008, 2008, Tena-Colunga *et al.* 2008) as schematically depicted in Figure 4. The shape of the displacement design spectra depends on several parameters that define the absence or presence of site effects, but three of them are particularly important: the *k* parameter, the site factor F_s and the fundamental site period T_s. For relatively firm to firm soils or rocks (T_s<0.8s, F_s<1.5), design displacement spectra converge to the peak ground displacement in an asymptotic manner (“firm soils”, Figure 4), whereas for relatively soft to very soft soils (T_s>1.3s, F_s>1.5), design displacement spectra reach a peak value when $T_e = T_c$ and decay to converge to the ground displacement (“soft soils”, Figure 4).

4. REDUCTION OF ELASTIC RESPONSE PARAMETERS FOR DESIGN

In sake of transparency in the design process, there is an important conceptual adjustment in the reduction of elastic response parameters for design in MOC-2008 with respect to previous MOC-93. In MOC-93, the elastic design spectra were reduced by dividing the spectral ordinates by a somewhat obscure reductive seismic force factor *Q´* that accounted for everything (ductility, redundancy, overstrength, etc.). In MOC-2008, it is established that for the collapse prevention limit state, the reduced spectral ordinates *a´* should be computed as (Figure 5):

$$a' = a(\beta) / Q'R\rho \tag{4.1}$$

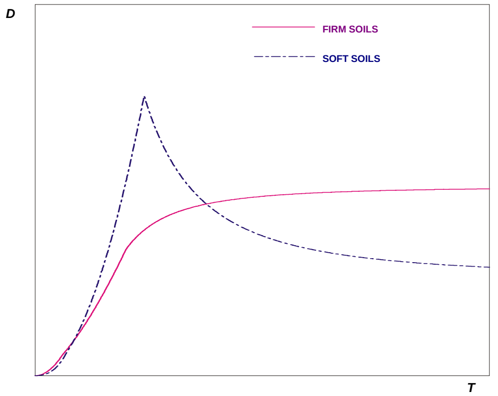


Figure 4.Schematic representation of elastic displacement design spectra for MOC-2008

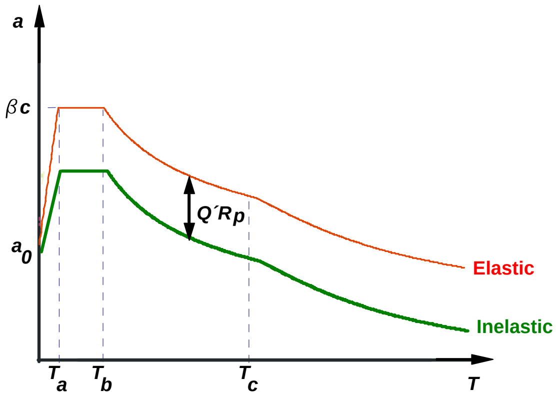


Figure 5. Schematic representation of inelastic acceleration design spectra for MOC-2008

where $Q´$ is a seismic reduction force factor that accounts primarily for ductility (deformation) capacity, R is an overstrength factor that depends on the structural system and the structural period and ρ is the redundancy factor; it is essentially a correction factor of $Q´$ and R to account for how redundant is the lateral load structural system in a given direction of analysis. For structural systems with stiffness and/or strength degrading characteristics under cyclic loading located in soft soils, the reduced spectral ordinates $a´$ should be computed as:

$$a' = a(\beta)A_{cd} / Q'R\rho \qquad (4.2)$$

where A_{cd} is a modification factor to account for stiffness and/or strength degradation in soft soils. All these parameters are explained in greater detail elsewhere (MOC-2008 2008, Tena-Colunga *et al.* 2008) and for space constraints will be briefly described in following sections.

4.1. Seismic response modification factor Q

The definition, requirements and proposed values for the seismic response modification factor Q remain practically unchanged in MOC-2008 with respect to previous MOC-93 code. The values for Q established by all modern Mexican codes are 1, 1.5, 2, 3 and 4, and they depend on the selected structural system (Tena-Colunga 1999). For example, in order to use Q=3 or Q=4 for dual systems, the designer has to demonstrate that the dual system satisfies specific requirements related to the strength and stiffness balances of frames with respect to shear walls and/or braced frames. The Q factors of Mexican codes account primarily for the deformation capacity of the structural system and its relation with its displacement ductility, redundancy and overstrength.

4.2. Seismic reduction force factor Q´

In MOC-2008 code, the seismic reduction force factor $Q´$ stands now only for the approximate ductility deformation capacity of the selected structural system, given in terms of the seismic response modification factor Q. For any given structural system, $Q´$ should be computed as follows, where p is a factor to define the descendent curve of the inelastic response spectra and all remaining terms have already been defined:

$$Q' = \begin{cases} 1 + (Q-1)\sqrt{\beta/k}\,\dfrac{T_e}{T_a}\ ; & if\ \ T_e \le T_a \\ 1 + (Q-1)\sqrt{\beta/k}\ ; & if\ \ T_a < T_e \le T_c\ ; \qquad p = k + (1-k)\left(\dfrac{T_c}{T_e}\right)^2 \\ 1 + (Q-1)\sqrt{\beta p/k}\ ; & if\ \ T_e > T_c \end{cases} \qquad (4.3)$$

Therefore, it can be observed from Eqs. 4.3 that the proposed *Q´* factor is not constant and depends on the structural period T_e and the site period T_s (in terms of parameters T_a, T_c and k). In fact, the proposal for *Q´* coincides with the proposal available in Appendix A of the seismic provisions for current Mexico's Federal District Code (NTCS-2004 2004). This proposal is based on the study of SDOF systems with elastoplastic hysteretic behavior as explained in greater detail elsewhere (MOC-2008 2008, Tena-Colunga *et al.* 2008). *Q´* is the ratio between the minimum strength required to limit a structural system to an elastic response $C(T_e, 1)$ and the strength required for a structural system to limit its ductility capacity to a given *Q* value $C(T_e, Q)$.

As it can be deducted from Eqs. 4.3, several *Q´* curves can be obtained for MOC-2008. Typical normalized *Q´/Q* ratio vs the normalized T_e/T_s ratio curves for soft soil sites and firm soil sites are depicted in Figure 6 and compared with that one defined by MOC-93. These curves were computed considering Q=4 for all curves; in addition T_s=2s was taken for soft soils and T_s=0.5s for firm soils for MOC-2008. In contrast to the proposal of previous MOC-93 (i.e., Tena-Colunga 1999), it is observed in Figure 6 that *Q´* can be larger than *Q*, this is, $Q'/Q>1$ in a given period range. These higher values are obtained for soft soil sites ($k<1$); that is a fact that has been reported before in previous studies that considered a large number of acceleration records typical of soft soils (Miranda 1993, Ordaz and Pérez-Rocha 1998). In contrast, for firm soils, *Q´* is usually smaller than or equal to *Q*, this is, $Q'/Q<1$ in a wide period range. For all soil profile types, *Q´* converges to *Q* as $T_e \rightarrow \infty$, this is, $Q'/Q \rightarrow 1$ as $T_e/T_s \rightarrow \infty$ (Figure 6).

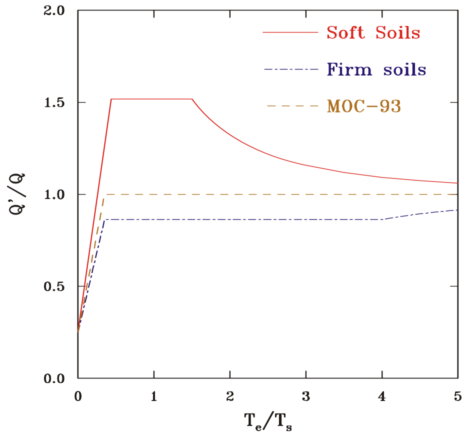


Figure 6. Normalized *Q´/Q* curves

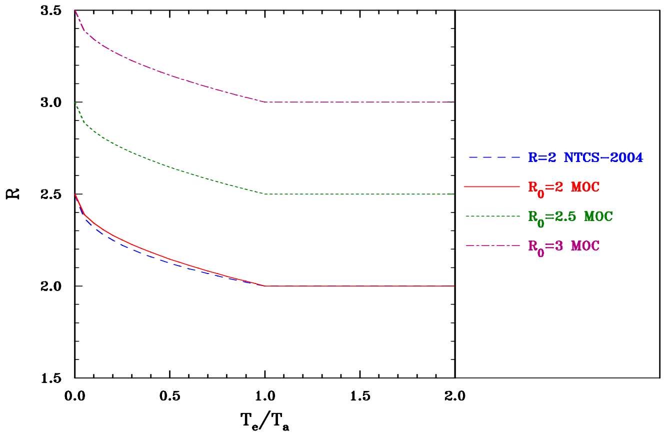


Figure 7. Overstrength reduction factors *R* for MOC-2008

4.3. Overstrength reduction factor R

The introduction of an overstrength reduction factor *R* in MOC-2008 is a new concept for this manual as MOC-93 did not include it. However, the *R* factor was first introduced in the seismic codes of Mexico in Mexico's Federal District Code (NTCM-2004 2004). In fact, the proposal of the *R* factor for MOC-2008 is an improved version of the one presented in NTCM-2004.

The proposal for *R* in MOC-2008 is given by the following equations:

$$R = \begin{cases} R_0 + 0.5\left(1 - \sqrt{\mathrm{T_e/T_a}}\right); & \text{if } \mathrm{T_e} \le \mathrm{T_a} \\ R_0\,; & \text{if } \mathrm{T_e} > \mathrm{T_a} \end{cases} \tag{4.4}$$

where R_0 is an overstrength index value that depends on the structural system. For example, R_0=2 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_0=2.5 for special moment-resisting frames, intermediate moment-resisting braced frames, and confined masonry wall structures made with solid units; R_0=3.0 is for dual systems built with special moment-resisting frame connections.

The proposed *R* curves for MOC-2008 are depicted in Figure 7, where they are compared with the *R* curve proposed in NTCM-2004. It can be observed that the overstrength reduction factor *R* in Mexican codes is period dependent. 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. In NTCM-2004, *R* is independent of the structural system (Figure 7). This conceptual shortcoming is fixed in MOC-2008, where it is also recognized that the overstrength that a structure can develop under earthquake loading strongly depends on the structural system, as it is done in other modern seismic codes (i.e., ASCE-7 2005). The proposed values for R_0 are based in: (1) analytical studies conducted in Mexico for some structural systems such as ordinary and special moment-resisting RC and steel frames, special moment-resisting concentric braced frames, (2) experimental studies (shaking table tests) conducted for confined masonry structures and, (3) proposed values of NTCM-2004 and U.S. codes such as ASCE 7-05 and IBC-2006. Of course, the current proposal of MOC-2008 has room for improvement as more reliable data regarding the assessment of overstrength for different structural systems will be available in the future.

4.4. Redundancy factor ρ

The introduction of a redundancy factor ρ in MOC-2008 is a new concept for the seismic design codes of Mexico, not only for MOC-2008. The purpose of this “new” factor is recognizing directly that structural systems are able to develop more strength and increase their deformation capacity as they become more redundant. This fact is well-known by the structural engineering community worldwide. However, it seems some seismic codes have came short before, by no recognizing that a more redundant structural system under lateral loading should be allowed to be designed with higher reductions and that weakly-redundant systems should be penalized and be designed with smaller reductions.

In MOC-2008, ρ is a factor that basically corrects the previous assessment of the overstrength factor *R*, as most of the available studies where *R* has been computed have been mostly done in 2D models with different degrees of redundancy. In addition, this factor takes into account unfavorable performances of weakly-redundant structures in strong earthquakes occurred worldwide in the last 30 years. The proposed values for ρ in MOC-2008 are the following:

> $\rho = 0.8$ 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).
>
> $\rho = 1$ 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).
>
> $\rho = 1.25$ 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).

As it can be observed, one-bay framed buildings are now penalized in the design, because they are weakly-redundant and their observed performances during strong earthquakes have been poor; some collapses or partial collapses have been documented in reconnaissance reports. The structural systems where $\rho = 1$ is proposed correspond to those considered in most of the consulted studies to define target values for the overstrength factor *R*. The proposal for $\rho = 1.25$ is based in some recent studies where parallel frames of these characteristics have been studied and where higher *R* factors were obtained. It is also worth noting that the value of ρ may vary in each main orthogonal direction. The assessment of the ρ factor for a given structure is straight-forward as it is illustrated with examples elsewhere (MOC-2008, 2008, Tena-Colunga *et al.* 2008)

4.5. Amplification factor for degrading hysteretic behavior A_{cd}

The introduction of an amplification factor A_{cd} for structures with degrading hysteretic behavior (stiffness and/or strength) located in soft soils is also a new concept for the seismic design codes of Mexico, not only for MOC-2008. The A_{cd} factor is computed as :

$$A_{cd} = 0.8 + \frac{1}{2 + 5\left|2\frac{T_e}{T_s} - 1\right|^5} \tag{4.5}$$

The A_{cd} factor is now introduced as it has been shown that low-cycle fatigue is very important in the seismic behavior of stiffness and strength degrading systems such as RC and masonry structures located in soft soils where long durations of the earthquake motions are observed, such as in the lakebed zone of Mexico City. There are also other soft soil sites in zones of high seismic risk of Mexico besides Mexico City, for example, Ciudad Guzmán in Jalisco state. The proposal is based in the study presented by Terán-Gilmore (2005).

5. FINAL REMARKS

For space constraints, it was impossible to comment about the design of buildings with structural irregularities, which was reviewed and updated and now a more stringent design is set for structures with soft story and torsional irregularities. New rules for the combination of vertical and horizontal ground motions are also proposed. A new vertical spectrum is defined. All methods of analysis were reviewed and updated, incorporating new findings from recent research studies. Design drift limits were reviewed and now they depend on the structural system. Hopefully, this information will be available to the interested readers in English language soon (Tena-Colunga *et al.* 2008).

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