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Computational science and engineering with particular application to earthquake engineering and engineering seismology

Two early events remain vivid in my mind among my many interactions with Luis Esteva. The first experience introduced me to Luis Esteva, the scholar and teacher. The second one, to Luis Esteva, the great companion and fun loving man.

I met Luis for the first time at the beginning of my senior year, as my instructor in a course on Structural Analysis he was teaching at UNAM. Since I liked the way he taught the course very much I thought it would be great if I could write my engineer's thesis under his supervision. Would he agree to serve as my advisor, I asked him? His reply was, 'yes of course, but my research is on earthquake engineering. You will need some background on vibration theory. Have you had vibrations before?" No, I said, as at the time vibrations was not offered at the undergraduate level. Luis turned to his bookcase, pulled out a book and said: here, study it, and come see me when you've learned the material. After recovering from the shock, I saw no alternative, so off I went to study vibrations. His style taught me a great lesson in taking personal responsibility for my own learning. Little did I know that I was now hooked on dynamics. It was all due to Luis. In due course, I finished the thesis, and later learned that Luis had incorporated the results of my research into the Mexico City seismic provisions, in order to address the problem of whip effects in buildings. I was elated.

The second experience occurred upon my return to Mexico after completing my graduate studies in the States. One evening Luis, Ismael Herrera, and I went out together to dinner with our wives. Until then I had known Luis as a great scholar, but quite a serious fellow. We had a great dinner at the Café del Lago, wonderful conversation, laughter and jokes. The last thing I expected is that he would get up and start to dance: not waltzes, but rock-and-roll, mambo and cha-cha-cha. It was quite a sight to see him and Gloria dance the evening away like Fred Astaire and Ginger Rogers. My view of him changed that night. No longer was Luis only the scholar and great engineering practitioner, but also a man full of joy of life.

My experience in working under him during the time I spent at the Institute of Engineering at UNAM also taught me that he is a great humanist and caring human being, a man of great integrity and strong sense of fairness. I learned from him not only technical things which have been with me all my life, but also how to deal with all kinds of expected and unexpected situations.

Thank you, Luis, for your teachings, and most of all for your continuing friendship over the years. It means a lot.

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# SEISMIC DESIGN SPECTRA IN SOFT ZONES OF MEXICO CITY

*Sittipong Jarernprasert* [(1)], *Enrique Bazán* [(2)] *and Jacobo Bielak*[(3)]

**ABSTRACT**

An approach for deriving inelastic design spectra previously developed by the authors is used in this note to examine seismic design spectra for the soft lakebed region of Mexico City. Based on statistical analyses of *inelastic* response spectra, this approach expresses the yield strength, $C_y$, required to produce a mean ductility ratio, $\overline{\mu}$ , as $C_y(T,\overline{\mu}) = C(T)\overline{\mu}^{-n(T)}$ . *C(T)* is interpreted as a mean unreduced inelastic spectrum and the power *n* depends only on the elastic natural period, *T*, of the structure. We use *C(T)* to develop widened spectra for region III b of compressible soil in Mexico City and compare it with the spectra prescribed in the 2003 Mexico City Code. *n(T)* is used to derive reduction factors for considering inelastic behavior. This factor is also compared to the corresponding factors prescribed in the code.

## Introduction

Most buildings in Mexico City are designed under the assumption that they will experience significant nonlinear deformations under strong earthquakes. However, in accordance with the City's building code (NTCDS-RCDF, 2003), the seismic analysis is performed with linearly damped *elastic* models. The seismic base shear force is prescribed in terms of unreduced design spectra associated with 5 percent viscous damping, and the inelastic behavior is considered in design by reducing the "elastic" spectrum by a factor which is greater than unity.
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The seismic provisions of the current Mexico City Building Code are strongly influenced by the experience and knowledge related to the 1985 Michoacán event. In particular, the design spectra were increased and the inelastic reduction factors were decreased for soft soil zones, in light of the widespread damage that was observed in those zones. Figure 1 presents the elastic spectra for the SCT record of the 1985 earthquake for damping ratios $\xi$ = 0.05 to 0.40. For small values of $\xi$, these spectra exhibit large distinct peaks close to a period of 2s. These peaks tend to disappear for high-damping spectra. Figure 2 shows the spectra of the same record for elastic-plastic systems for ductility ratios $\mu$ = 1, 1.3, 1.6, 2 and 4. The inelastic spectra exhibit significant reductions due to hysteresis, even for a moderate $\mu$ = 1.3. The reductions of spectral values due to increasing ductility demands are similar to the reductions of elastic spectra when the percentage of viscous damping is increased. The peaks for higher ductilities tend to shift toward smaller periods, and eventually disappear for $\mu$ = 4, for which the spectrum becomes nearly flat, with slight gradual decrease for increasing period.

The preceding observations prompted a study by Jarenprasert et al (2005) to develop simple rules for establishing inelastic seismic design spectra in the soft lakebed of Mexico City directly from statistical

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analyses of inelastic response spectra, using a sample of 66 normalized accelerograms, with dominant periods of approximately 2 sec. Five percent viscously damped SDF systems with

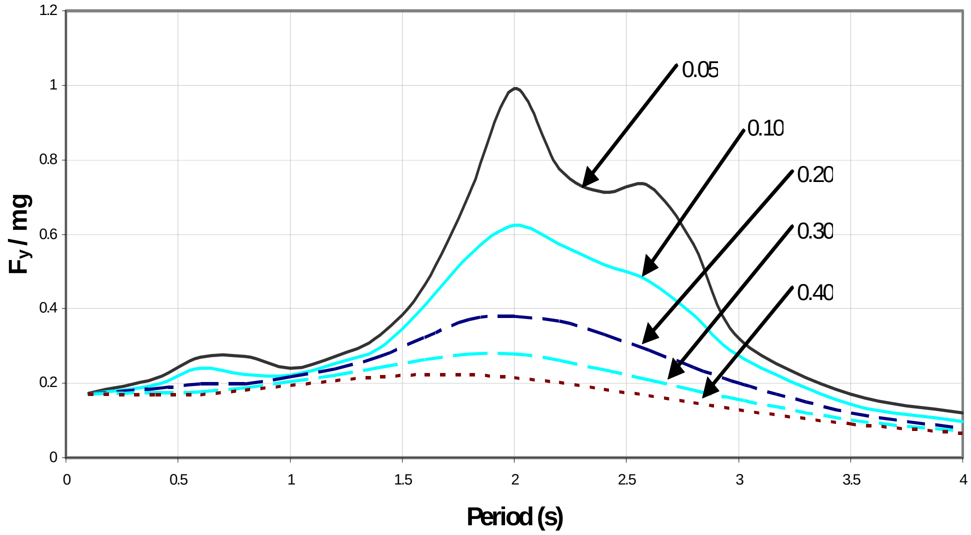


Figure 1. Elastic spectra of the SCT 1985 record for different damping ratios

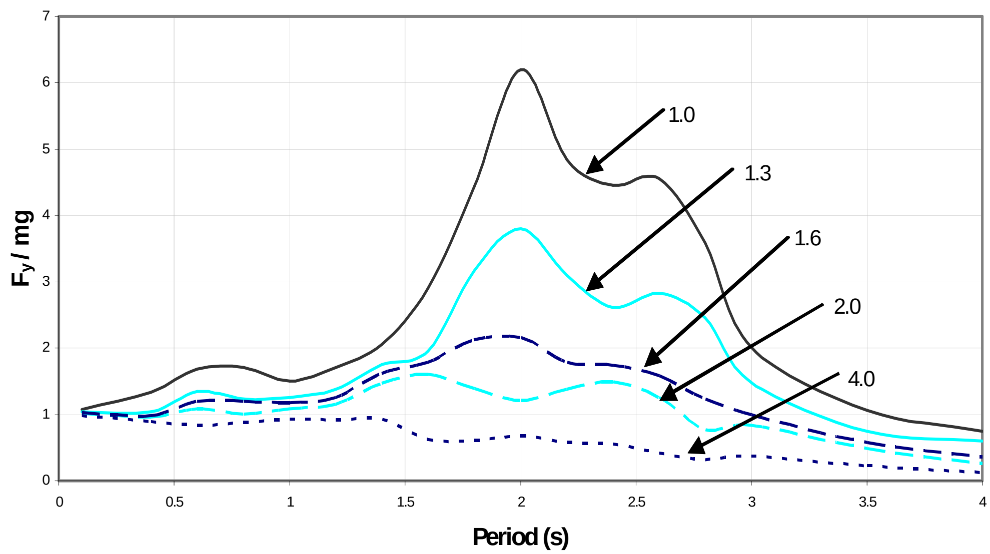


Figure 2. Inelastic spectra of the SCT 1985 record for different ductility ratios

a bilinear hysteretic force-deformation relationship were used in this study, and the hysteretic behavior was defined by the initial elastic period, $T$, the yield displacement, $u_y$, and the slope of the second branch of the force-displacement relationship equal to 2 percent of the initial slope. The seismic coefficient, $C_y$, is such that the yield force is $V_y = C_yW$, where $W = mg$ is the weight of the structure, $m$ its mass, and $g$ the acceleration of gravity. The dimensionless seismic design coefficient $C_y$ can be expressed as:

$$C_y = \frac{4\pi^2}{T^2} \cdot \frac{u_y}{g} \qquad (1)$$

Fig. 3 shows mean elastic spectra of the ensemble of 66 records for damping ratios of 5 to 30 percent and inelastic spectra for mean ductility demands, $\overline{\mu}$ , between 1 and 5, all normalized with respect to the dimensionless mean peak ground acceleration $\overline{\mathrm{PGA}}$/g. Even for moderate ductilities, the mean inelastic spectra are much smoother than the 5 percent mean damped elastic spectrum, exhibiting a relatively flat zone for *T* between 0.6 and 2.0 sec. The peak value for $\overline{\mu}$ = 1.5 is approximately one half that of the elastic spectrum.

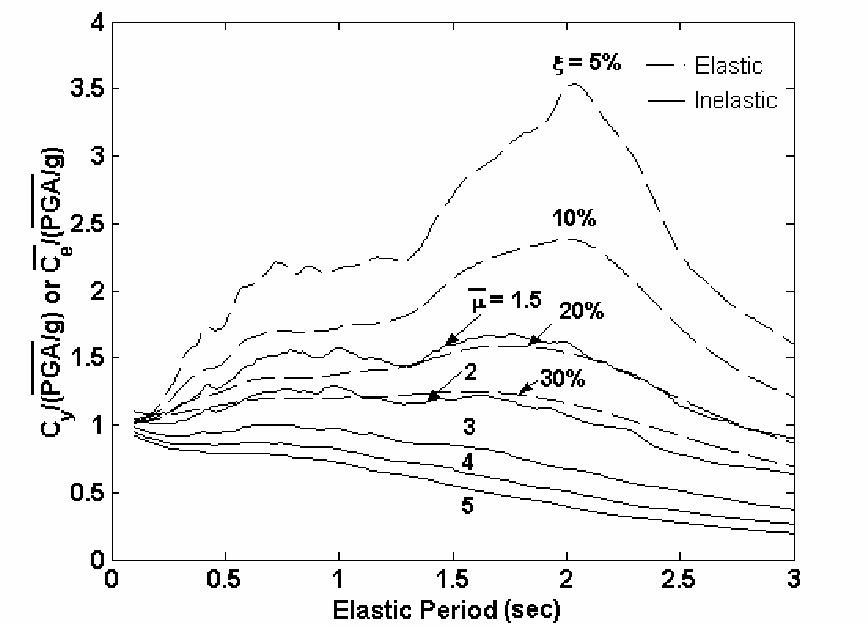


Fig. 3. Normalized spectra $C_y(T, \overline{\mu})$ and $\overline{C_e}$ $(T, \xi)$ for different mean ductility ratios, $\overline{\mu}$ , and critical damping ratios, $\xi$

**Direct inelastic approach for seismic design spectra**

By examining how the inelastic seismic coefficient, $C_y$, changes with $\overline{\mu}$ within 1.5 and 6.0 Jarernprasert (2005) has shown that $C_y$ can be expressed in terms of the natural period of the structure and the ductility factor, as :

$$C_y(T, \overline{\mu}) = \frac{C(T)}{R_{\overline{\mu}}} \qquad (2)$$

where:

$$R_{\overline{\mu}} = \overline{\mu}^{\,n(T)} \qquad (3)$$

*C(T)* is interpreted as a reference *unreduced* spectrum, which divided by a modifying factor, $R_{\overline{\mu}}$ , provides the required inelastic strength $C_y$ that results in a mean target ductility $\overline{\mu}$ . Equation (3) has precisely the format adopted in the Mexico City Building Code (DF, 2003), where a reduction factor Q' is similar to $R_{\bar{\mu}}$ , and accounts for the hysteretic behavior. $R_{\bar{\mu}}$ varies implicitly with *T* through the power *n*. Notice that taking *n* = 1 is similar to the "equal displacement" rule, except that here C*(T)* is not the elastic 5 percent spectrum. Figure 4 shows the values of *C* and *n* obtained from the regression of the numerical results of $C_y$ on $\bar{\mu}$ . A comparison of *C(T)* with the elastic response spectrum for 5 percent damping in Fig. 3 shows that *C(T)* is significantly smaller than the mean elastic spectrum over the entire range of periods. It is also flatter and does not exhibit the strong peak at about the 2 sec dominant period observed in the elastic spectrum. Instead, the peak of the unreduced spectrum is shifted towards the left appearing at T = 1.6 sec.

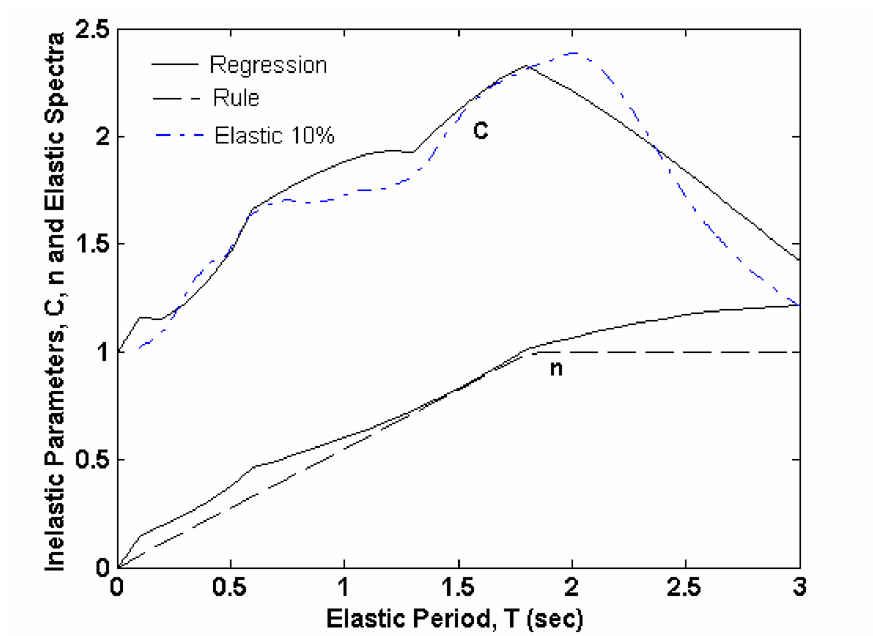


Fig. 4. Unreduced spectrum *C(T)* and power *n(T)* in Eqs. (2) and (3), determined with a regression fit

For the seismic input used by Jarernprasert et al (2005), very good approximations to *C(T)* are provided by (1) the mean elastic spectrum for 10 percent of critical damping, and (2) the mean inelastic spectrum for a ductility demand of 1.2. Fig. 5 compares *C(T)* with these two approximations and shows that all three spectra have a very similar peak value of approximately 2.4 times the zero period value. Another observation by Jarenprasert et al (2005) is that $C_y(T, \bar{\mu})$ for $\bar{\mu}$ = 2 can be closely approximated by the elastic mean response spectrum for 30 percent of critical damping. This approach was called SELIS for Surrogate Elastic Inelastic Spectrum and was also found to be applicable to an ensemble of Californian records (Jarernprasert et al, 2005a).

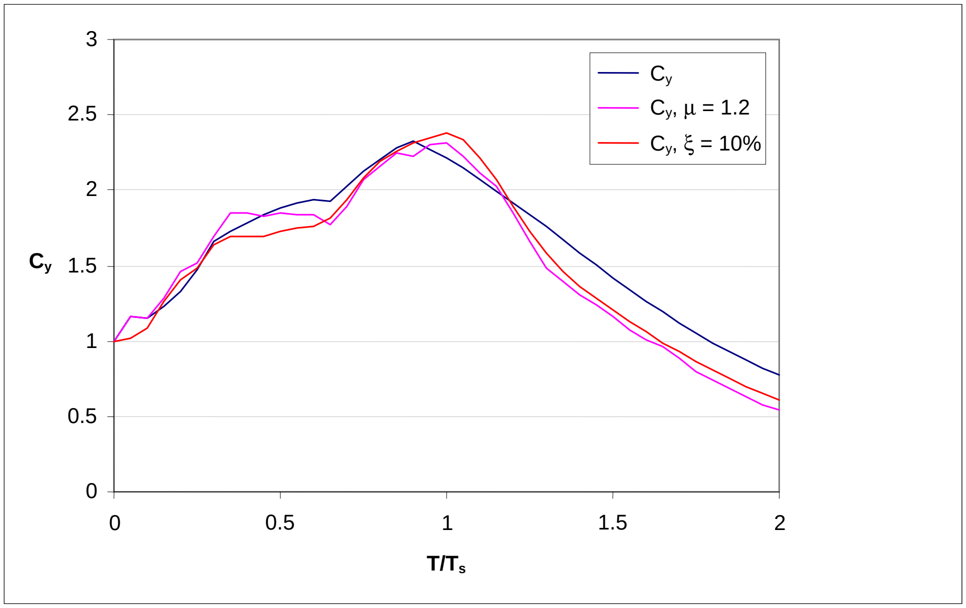


Fig. 5. Unreduced spectrum *C(T)* determined from a regression fit (solid lines), by 10 % elastic spectrum (dashed lines) and inelastic spectrum for $\mu = 1.2$ (dashed-dotted lines).

**Examination of the design spectra in Mexico City**

The maximum values of the design spectra for the soft zones of Mexico City differ appreciably from the peaks of 5 percent damped spectra of actual earthquake records. In particular, the maximum prescribed spectral value of 0.45g for the lakebed region is approximately 45 percent of the peak of the 5 percent elastic spectrum of the 1985 SCT record. This seems to indicate that the "elastic" design spectra implicitly incorporate some reductions due to inelastic behavior. Along these lines, Rosenblueth and Gómez (1991) have commented that reductions already included in the unreduced design spectra account partially for the differences between reduction factors specified in Mexico City and California.

In practice, design spectra are widened to account for uncertainties in the structural vibration period, T, and in the seismic input, especially in the dominant periods of the site and Ts, which changes with the amount of soil deformation. In addition, widening can account for period shifts in the peak value in inelastic spectra. Therefore, a meaningful comparison of *C(T)* with design spectra can be conducted by widening *C(T).* For this purpose, we have considered that the normalized shape of *C(T),* which was derived for a site dominant period of 2 seconds, remains the same for any dominant period between 0.85 and 3.0, which are the limits for the flat region of the design spectrum specified in the Mexico City Code (NTCDS-RCDF, 2003) for zone IIIb. The highest spectral value ($c = 0.45$, $a_o = 0.11$) is prescribed for Zone IIIb, where most of the 66 accelerograms used by Jarernprasert et al (2005) were recorded. The peaks of C(T) in Fig. 6 are equal to 0.45. It can be noted that the decay of the envelope after 3 seconds is slower than in the RDF 2003 Code, for which the design spectrum decreases with the period squared. Another noticeable difference occurs at $T = 0$. Whereas $a_o$, is equal to 0.11 in the design spectrum code, the corresponding value for *C(T)* is 0.19. It seems that for maintaining the plateau at the same value, $a_o$ should be increased to 0.19 to be more consistent with an "unreduced" spectrum that already reflects some reduction due to inelastic behavior.

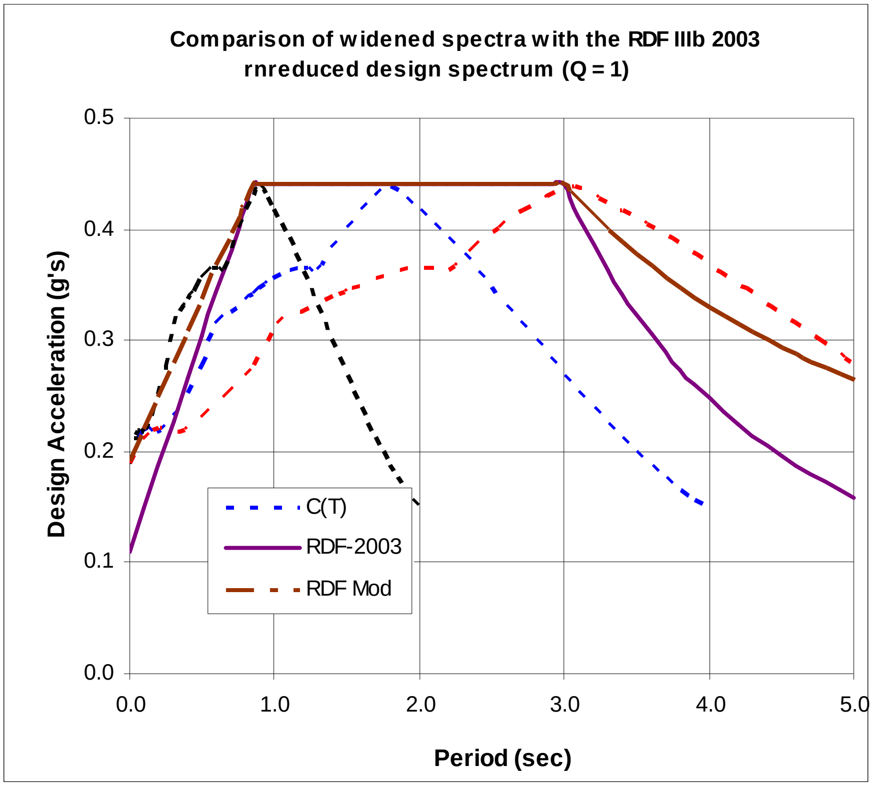


Fig. 6. Widened spectra *C(T)* (dashed lines) and design unreduced spectrum (solid lines

Plotted are The reduced spectra corresponding to the widening of *C(T)* presented in Fig. 6, for $\bar{\mu}$ = 2, 3 and 4, are plotted in Figs. 7, 8 and 9 respectively. The reductions for *C(T)* have been calculated using Eq. 3 with the values of *n(T)* shown in Fig. 4. We have also plotted in these three figures the RDF 2003 Code reduced spectra corresponding to Q equal to 2, 3 and 4, respectively. There are no significant differences between reductions calculated with both procedures. In all cases, at short periods, the code reduced spectra are smaller than the one resulting from Eq. 3. The differences are more noticeable when $\bar{\mu}$ = Q = 4, i.e., when the inelastic behavior is more extensive, particularly for periods smaller than 2.0 s.

Figures 7 to 8 include an example of modifications that could be made to the RDF 2003 Code to attain a better match to the spectra obtained by widening *C(T).* The "modified spectra" are based on increasing $a_o$ from 0.11 to 0.19 and decreasing the spectra for T longer than 3 s, in inverse proportion to *T* rather than to the square of *T*. In addition, the maximum reduction factor has been set as $Q^{0.8}$ rather than Q, and the upper limit for the flat region has been reduced to 2.8, 2.6 and 2.4 s, i.e., [3 – 0.2 (Q-1)] s, for Q = 2, 3 and 4 respectively. These modification lead to a better fit to the widened unreduced spectra based on *C(T)* which constitute the "exact" mean inelastic spectra. We should remark, however, that this was just a matching exercise, aimed to illustrate potential changes. Examination of additional results and consideration of other factors used in design, such as load and strength factors, are required to propose more definitive modifications.

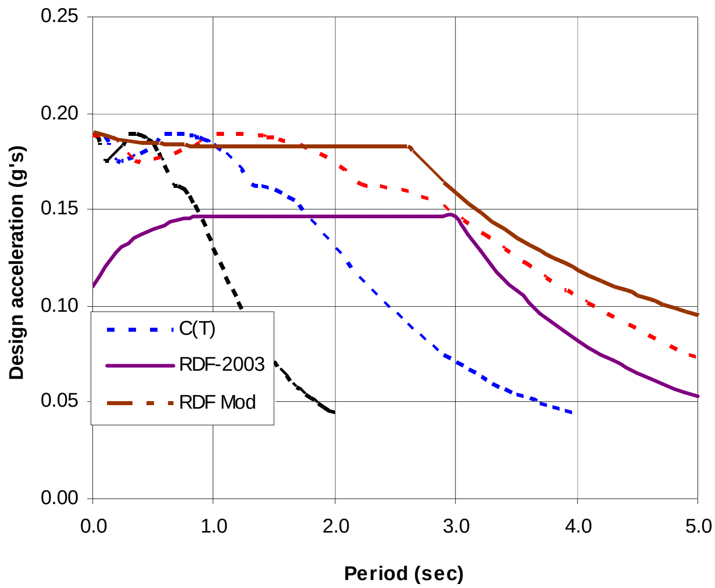


Fig. 7. Widened reduced spectra from Eq. 3 (dashed lines), RDF 2003 design spectrum (solid lines) and an example of a modified design spectrum (dash – solid lines) , for Q = 2.

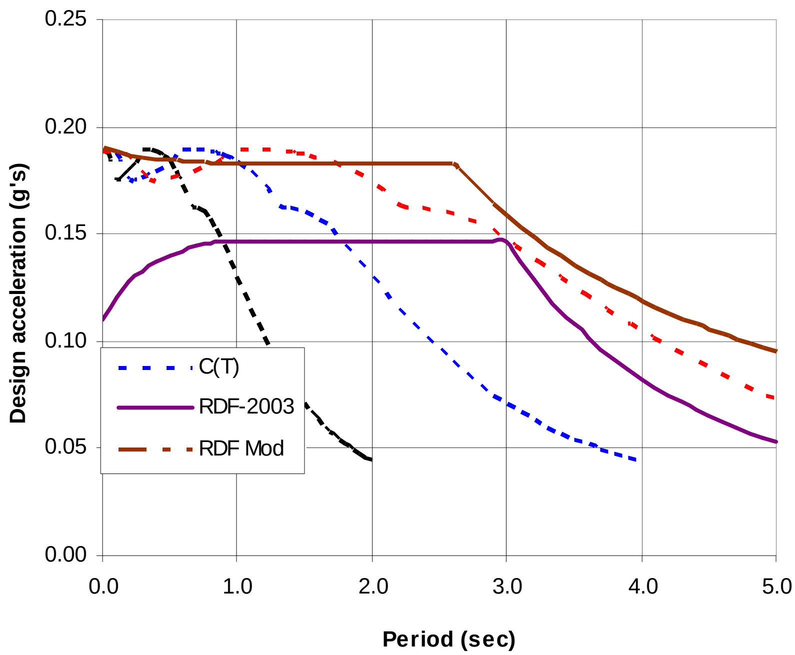


Fig. 8. Widened reduced spectra from Eq. 3 (dashed lines), RDF 2003 design spectrum (solid lines) and an example of a modified design spectrum (dash – solid lines), for Q = 3

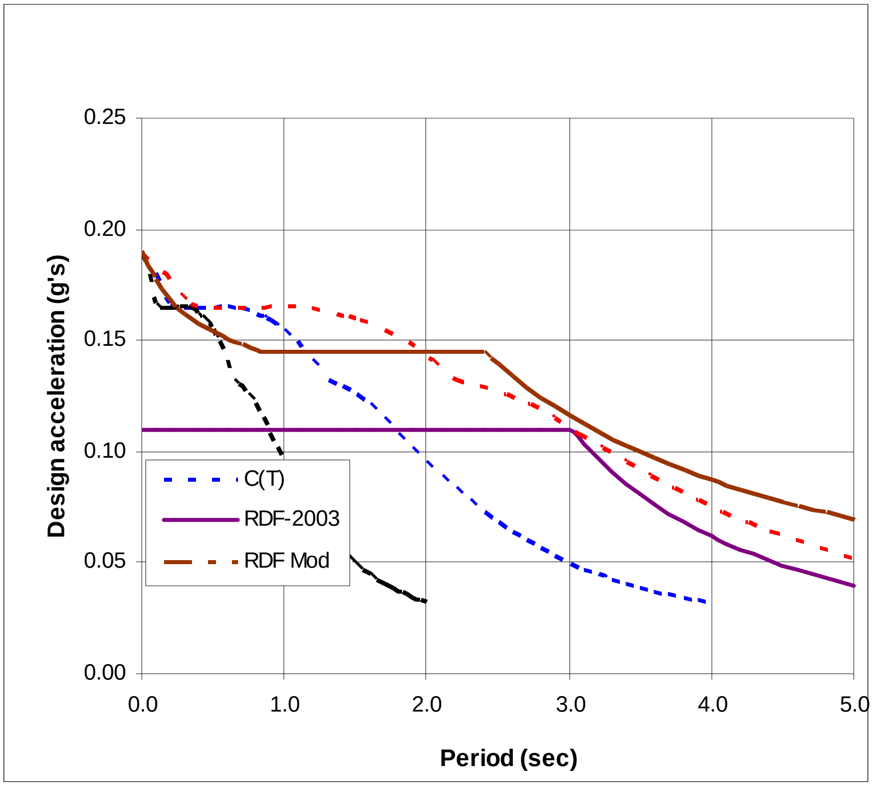


Fig. 9. Widened reduced spectra from Eq. 3 (dashed lines), RDF 2003 design spectrum (solid lines) and an example of a modified design spectrum (dash – solid lines), for Q = 4

## Concluding remarks

The examination of inelastic spectra of SDF bilinear hysteretic systems with 5 percent critical viscous damping, subjected to a sample of accelerograms recorded in the lakebed region of Mexico City shows that mean inelastic spectra can be defined by dividing an unreduced inelastic spectrum by a reduction factor, in the format used by the current Mexico City code. The unreduced spectrum *C(T)* is appreciably smoother than the 5 percent damped mean elastic spectrum. The peak of *C(T)* can be closely approximated by the peaks of the 10 percent damped elastic spectrum or the inelastic spectrum for a mean ductility demand of 1.2. Associated to *C(T)*, the reduction factor for a given mean ductility demand , $\overline{\mu}$ , is given by $\overline{\mu}$ raised to a power n(T) that depends solely on the natural period of the elastic structure (Eq. 3).

*C(T)* has been used to develop a widened spectrum for region IIIb of compressible soil of Mexico City. From the comparison of the widened C(T) with a design spectrum prescribed in the 2003 Mexico City Code, it appears that the "elastic spectrum" already incorporates an appreciable reduction due to inelastic behavior. Consistent with this observation, it might be advisable to increase in the code the zero period spectral values.

A comparison of inelastic reduced spectra obtained from statistical analyses of the seismic response and those specified in the 2003 Mexico City Code, indicates that some modifications in the current provisions might be in order to provide a better fit to the results of inelastic analyses.

## REFERENCES

Jarenprasert, S, (2005). "An inelastic design approach for asymmetric structure-foundation systems," Ph.D. Thesis, Carnegie Mellon University, Pittsburgh, PA, 2005.

Jarernprasert, S, E Bazán and J Bielak (2005). "Inelastic Seismic Design Spectra in Mexico City," XIII National Conference on Seismic Engineering, Mexico, D.F., Mexico

NTCDS-RCDF (2003). "Normas técnicas complementarias para diseño por sismo," *Reglamento de Construcciones para el Distrito Federal*, Gaceta Oficial del Departamento del Distrito Federal, Mexico.

Rosenblueth, E and R Gómez, 1991, "Comentarios a las Normas Técnicas Complementarias para Diseño por Sismo," Series Instituto de Ingeniería No. ES-7, México D.F., México

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