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SEISMIC DESIGN CRITERIA: CONSIDERATIONS FOR VERY SOFT SOILS

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ABSTRACT

Some problems associated to specification of earthquake design spectra for very soft sites are discussed, having Mexico City as an example. The following issues are explored: 1) the effect of earthquake sources in the selection of design earthquakes; 2) the fact that spectral shapes at soft sites change with earthquake magnitude, which presents complexities if a multi-level design approach is desired; 3) the geographical variability of spectral shapes throughout the city for a given earthquake, a fact that leads to the necessity of a careful microzoning for design purposes; 4) the estimation of reduction factors due to ductility at soft soils; 5) the importance of the long strong-shaking duration usually associated to soft sites. Although for some of the problems possible solutions are discussed, for others, the problem is just stated.

INTRODUCTION

Specification of earthquake design spectra has historically been a mixture of science and engineering judgment. The size of future earthquakes can not be deterministically predicted, so design must be made to resist a reasonably unfrequent event. There is not, however, an agreement on how unfrequent this event has to be. Some values of return periods or annual probabilities of exceedance are commonly regarded as reasonably safe. But it is very likely that these values have been adopted because its use leads to design levels that have been shown reasonable when structures have been subjected to severe earthquakes. Few people would occupy a building whose real strength had a 10% probability of exceedance in 50 years. Design base-shear coefficients of, say, 0.2 are considered reasonable for certain classes of buildings even when large reductions (a factor of 10 in some cases) with respect to elastic response spectra have to be invoked. Then, why a design coefficient of 0.2 is considered reasonable? Mainly because structures designed with this capacity have resisted severe ground motions.

Moreover, even if the size of the design earthquake is known, a careful dynamic analysis could give indications about the required structural strength, but most theories would have trouble answering the question of what design parameters should be used to attain that strength. Ductility plays a role and so does overstrength. But quantification of their effects and implications in design are still controversial. In view of this, engineering judgment has historically been, and still is, of extreme importance in deciding which response spectra should be included in codes. Engineering judgment enriched, of course, with careful observation and analysis of damage induced by earthquakes to buildings of known design.

Even when the presence of soft soils is now recognized as a key factor affecting structural performance, it turns out that a great deal of experience on damaged buildings and observed ground motions has come from hard sites, so many design recommendations, especially those of empirical nature, may not be appropriate for soft sites. These sites present special problems that prevent the extrapolation of criteria (the engineering judgment) derived from other soil conditions.

In this paper we explore some of the particular problems associated to specifying design spectra at very soft sites. Examples of Mexico City are used, perhaps an extreme case in this sense; however, some of the difficulties discussed here are common to other cities in the world. First it is shown how the existence of very soft sites complicates the selection of design earthquakes, in the sense that different earthquake sources can produce motions of different nature in a given site, so there can not be, in fact, one design earthquake. Second, a discussion is included on the fact that spectral shapes at soft sites change with earthquake magnitude, which presents complexities if a multi-level design approach is desired. The geographical variability of ground motion throughout the city for a given earthquake is also examined, a fact that leads to the necessity of a careful microzoning for design purposes. The estimation of reduction factors due to ductility at soft soils is also explored; there are, in this sense, large differences with respect to predictions of commonly used rules, and a new one is propossed that fits observed reduction factors better. Finally, we discuss the importance of long strong-shaking duration, a fact usually associated to soft sites. At this respect, a possible way of accounting for the effect of dissipated energy in the design procedure is proposed.

GROUND MOTION CHARACTERISTICS

In this section, problems related with shapes of response spectra at very soft sites are discussed. We show how changes in shape, derived from several factors, affect the specification of design spectra.

Effect of different earthquake sources

Historically, Mexico City has been affected mainly by earthquakes originating along the Pacific coast. To this group belongs the damaging Michoacan event of September 19, 1985. In the last years, however, the destructive potential of other types of earthquakes has been recognized (Rosenblueth et al., 1989). This is the case of intermediate-depth, normal-faulting events which occur inland. The largest of these events recorded in Mexico City is the October 24, 1980 Huajuapan earthquake (M=7), which produced some damage in the city.

The approach that has proven more accurate to estimate ground motion in the Valley of Mexico from coastal earthquakes is essentially empirical (Ordaz *et al.*, 1988; Singh *et al.*, 1988; Ordaz *et al*, 1994). It consists on: 1) estimation of the motion, in terms of its Fourier amplitude spectrum, at a reference station; 2) estimation of Fourier amplitude spectra at about 100 accelerographic sites in the Valley by multiplying the reference spectrum by an empirical transfer function (ETF) characterizing each site; ETF's are average Fourier spectral ratios with respect to the reference station; 3) computation of elastic response spectra at each instrumented site by means of random vibration theory. For non-instrumented sites, an interpolation scheme has been developed which permits estimation of response spectra at arbitrary points.

Although ETF's are roughly constant, for a given site, from earthquake to earthquake, the absolute values and the shape of the response spectrum at each site depend, of course, on the frequency contents of the input motion (the motion at the reference station). And this content changes very much depending on earthquake characteristics (*e.g.*, focal mechanism, magnitude and distance).

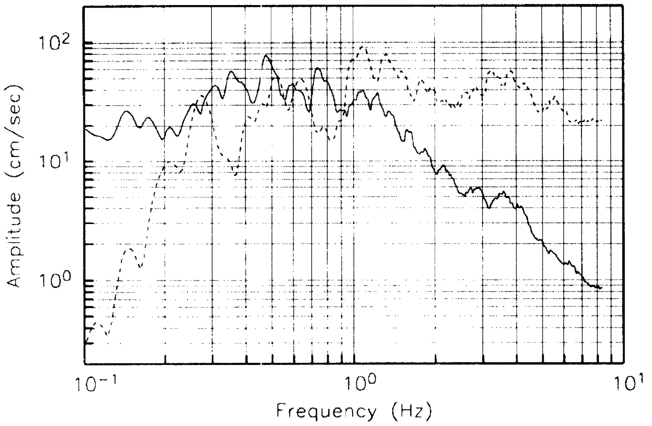

Figure 1. Fourier acceleration spectra at station CU in Mexico City from two earthquakes. Solid line: September 19, 1985 (M 8.1); dotted line: October 24, 1980 Huajuapan event scaled to R=80 km

To illustrate the differences in expected ground motion in Mexico City due to differences in the incoming motion, and therefore to source and path effects, we selected two cases: the 1985 Michoacan earthquake (M 8.1) and a hypothetical normal-faulting earthquake like the October 24, 1980 Huajuapan event (M=7, R=220 km) but located at 80 km of Mexico City. Figure 1 depicts their corresponding Fourier acceleration spectra at the reference station; note the differences in spectral contents, in particular, the larger high-frequency level for the normal-faulting earthquake.

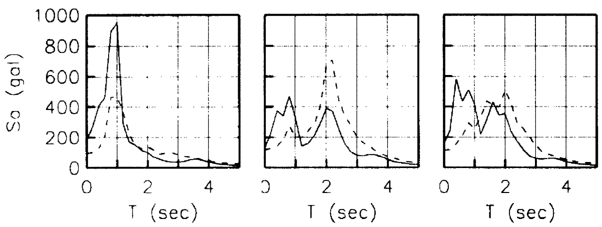

Figure 2. Expected response spectra at selected sites in Mexico City, computed for the two scenarios discussed in the text. Solid line: normal-faulting event; dotted line: coastal earthquake

Expected response spectra (pseudoacceleration, 5% damping) were computed, for the two cases, at sites throughout the city, using the procedure described above. Figure 2 shows response spectra at selected sites for the two earthquakes. At sites with low predominant period ($T_g < 1$ sec; left frame in Fig. 2), amplitudes are larger for the normal-faulting event, but spectral shapes are similar; at softer sites, however, spectral shapes differ very much. This presents a problem for the specification of design spectra: for economic reasons it would seem desirable to choose peaked design spectra at soft sites, in view of the peaked shapes of the response spectra of the (frequent) coastal events; but additional peaks could appear at shorter periods during normal-faulting earthquakes. On the other hand, these events are much less frequent than coastal earthquakes, so a very broad design spectrum covering both short- and long-period peaks could be overconservative. A rational solution is, perhaps, to compute a constant-risk response spectrum and to specify the design spectrum accordingly. But, in any case, the process of assigning design spectra to the different zones in the city is complex and requires careful analysis of the implications of having several earthquake sources.

Spectral shapes for a multi-level design

Source effects produce also another complication. It is now well known that spectral values for long period grow faster with magnitude than spectral values at short period. Regarding spectral shapes at hard soils, this is generally of no concern, because energy is concentrated at frequencies greater than a few Hz so, essentially, spectral shapes do not change with earthquake magnitude. For soft soils, where the crucial spectral band is centered at a fraction of a Hz (0.2-1 Hz), scaling with magnitude becomes relevant. Figure 3 depicts normalized (a_{max}=1) response spectra at very soft sites (T_g >3 sec, where T_g is predominant soil period) for three earthquakes: April 25, 1989 (M=6.9), May 31, 1991 (M=6.0) and (only for one station) October 9, 1995 (M=7.6). It can be noted that spectral shapes change with earthquake size, showing, for the larger events, relatively larger amplitudes for longer periods. Note that this happens while the ETF's at the sites remain constant from earthquake to earthquake; thus, changes in shape must be attributed to source effects.

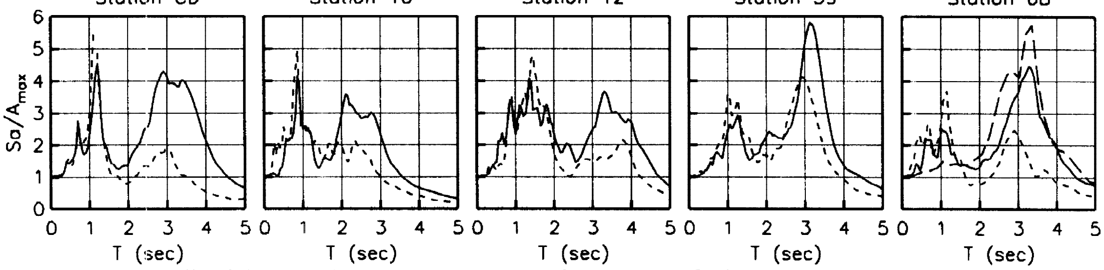

Figure 3. Normalized (amax=1) response spectra at three very soft sites (Tg > 3 sec) in Mexico City for two (three at station 68) earthquakes. Solid line: April 25, 1989 (M=6.9); dotted line: May 31, 1990 (M=6); dashed line: October 9, 1995 (M=7.6)

The dependence of spectral shape on magnitude is observed mainly for sites with $T_g > 3$ sec. It implies that, if a multi-level design approach is to be used, design spectra for the various levels should differ not only in amplitude but also in shape. In other words, it would not suffice to multiply by a constant the design spectrum of, say, the service level to obtain the design spectrum against collapse. Solutions to this problem for the case of Mexico City are currently under discussion.

Geographical variability

Figure 4 shows response spectra of recorded motions at seven sites in Mexico City during the same earthquake (April 25, 1989, M 6.9). From this figure it can be appreciated that the shapes of response spectra vary widely within the Valley of Mexico. This complicates the specification of design spectra according to soil type, or, in other words, there are too many soil types. There exist, at least, the following possibilities to solve this problem:

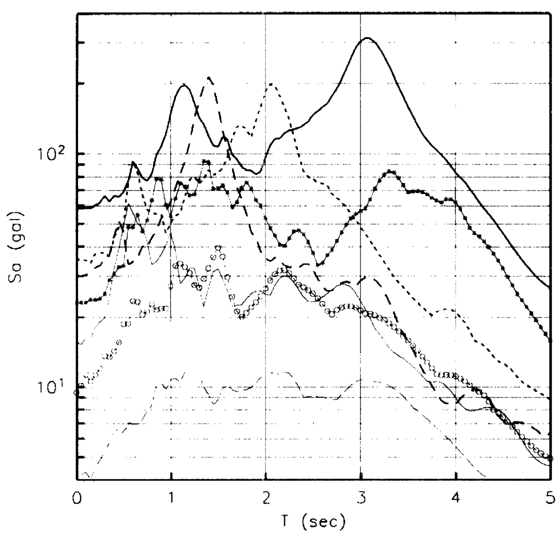

Figure 4. Observed response spectra for seven stations in Mexico City during the April 25, 1989, M 6.9 event. Note the large variations both in amplitude and in shape

1) The solution adopted in the current Mexico City Building Code (MCBC), which consists on the use of a single design spectrum for the whole lake-bed zone. This spectrum is a conservative envelope of response spectra for all sites with predominant ground periods between 1 and 4 sec. In view of the peaked shapes of the response spectra, this single design spectrum is generally too conservative for structures with periods far away from the soil's predominant.

2) To index the shape and amplitude of the design spectrum to T_g. This possibility is also contemplated in the MCBC, where the design spectrum depends on three parameters. Rules are given to find these parameters as functions of T_g, and a map of this quantity is provided in the code. These rules, however, do not take into account the fact that, due to source effects, the shape of the design spectrum to prevent collapse is generally different than that of the service earthquake (see previous section).

3) To construct a microzoning map for the purpose of assigning design spectra. In the case of the MCBC this means to increase the number of zones from three to a larger, reasonable number. Perhaps infinity, which would amount to having a geographical continuum of design spectra. This could hardly be done using conventional maps and tables, but could be easily accomplished with a simple digital map included in

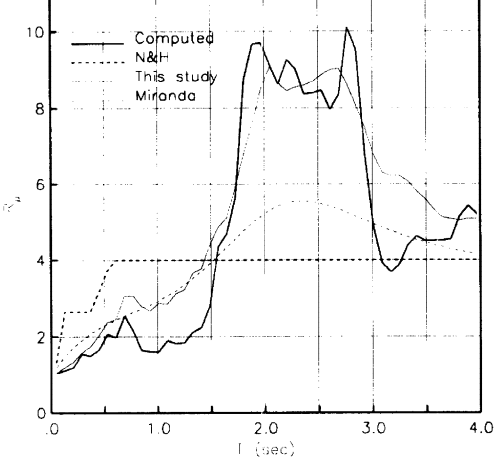

Figure 5. Strength reduction factor, R_μ, for the EW component of the SCT, Mexico, recording of the September 1985 Michoacán earthquake. Computed: the actual values of R_μ; N&H: $R\mu$ as predicted by Newmark and Hall's rule (1973); Miranda: as predicted by Miranda (1993) for soft soils; This study: as predicted by equation 1.

the code. It is very likely that possibility 3 above will be adopted in the new version of the MCBC with a still undefined number of microzones. The topic, however, is presently a matter of discussion

ESTIMATION OF INELASTIC SEISMIC DEMANDS

The usual approach for fixing seismic design parameters includes the estimation of the strength required to limit the ductility demand to an specified value, μ. This is generally accomplished by reducing the elastic design spectrum with *strength reduction factors*, R_μ. Rules to find R_μ have a long history. Miranda and Bertero (1994) made a thorough review of the various efforts in this direction. With the exception of the rule proposed by Miranda (1993), there are no specific considerations for soft soils, a problem previously pointed out by Krawinkler and Rahnama (1992). Miranda's rule, on the other hand, clearly shows that, at soft sites, R_μ is a function of the ratio T/T_g, where T is structural period. In any case, it is clear that a successful design depends on our ability to predict inelastic seismic demands, so accurate rules to estimate R_μ are required.

Many building codes include an extremely simplified version of Newmark and Hall's (1973) rule to find R_μ, given by $R_\mu=\mu$, regardless of period and soil conditions. Some others, like the MCBC, recognize the inefficiency of ductility at short periods, and propose rules in which $R_\mu=\mu$ for periods above some characteristic value, and R_μ decreases linearly for shorter periods, down to unity at T=0.

Figure 5 shows R_μ for $\mu=4$ as a function of T, for the SCT (Mexico City) EW recording of the September 19, 1985 Michoacan earthquake, along with estimations of R_μ carried out using Newmark and Hall's rule (1973), the one proposed by Miranda (1993) for soft soils, and a rule proposed in the present study. It must be noted that the rule by Miranda includes an uncertainty of 10% on the ratio T/T_g, a factor not included in the other rules. We recall that site SCT is located in Mexico City's lake-bed zone, on soils with S-wave velocities as low as 50 m/sec for several meters, with a predominant period of 2 sec. As pointed out by several authors (*e.g.*, Meli and Ávila, 1988; Krawinkler and Rahnama, 1992), R_μ is grossly underestimated by Newmark and Hall's rule for periods close to the predominant one. This underestimation is conservative, since the predicted required strength would be higher than the real one, but the opposite happens at shorter periods, for which R_μ is overestimated. But for most of the periods, both the required strength and the inelastic displacement would not be correctly estimated. R_μ is better predicted by the curve labeled "This study" in Fig. 5, which was obtained with the following expression:

$$R_\mu = 1+[V(T)/V_{max}]^\alpha(\mu-1) \qquad (1)$$

μ	α
1.5	0.42
2.0	0.54
4.0	0.65
8.0	0.72

Table 1. Values of α in eq. 1 for several values of μ

where V(T) is the velocity spectrum for the appropriate damping, V_{max} is the peak ground velocity, and α is a function of μ (see Table 1). Note that: 1) as T goes to zero so does V(T), hence R_μ tends to 1, regardless of μ; 2) as T grows, V(T) tends to V_{max}, so R_μ tends to μ; 3) for $T=T_g$, the predominant period of the motion, defined as that for which V(T) is maximum, R_μ is also maximum, as noted by Miranda (1993). In Fig. 6 we show some examples of the performance of eq. 1 to predict R_μ using recordings obtained at 12 sites in Mexico City during the April 25, 1989 (M 6.9) event. Note how eq. 1 with α=0.65 closely follows the computed R_μ values, even when they show a bimodal character, which of course is also present in the velocity spectrum. In particular, R_μ values of the May 31, 1990 recording at station CD have two very clear peaks, which could not have been predicted by other rules.

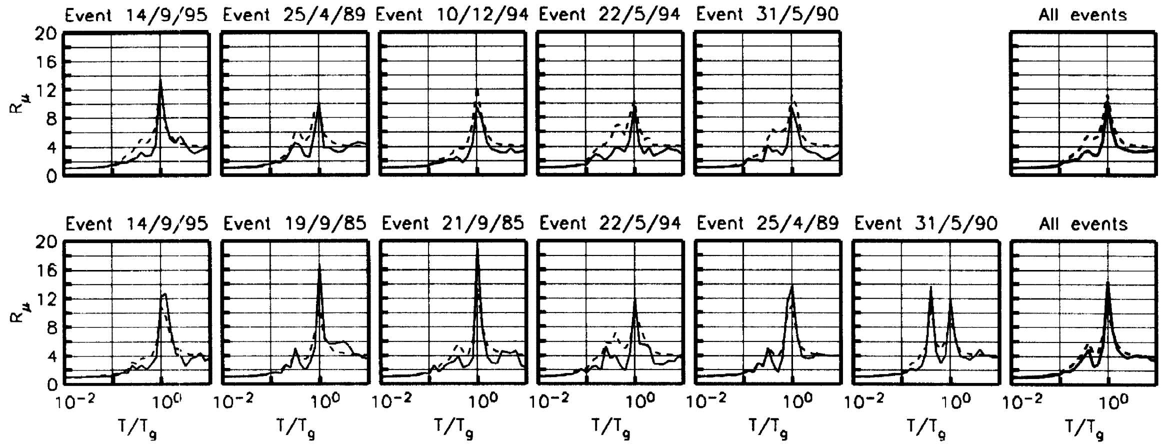

Figure 6. Solid line: R_μ (μ=4) for the EW component of ground motions recorded at two stations in Mexico City. Top row: station 56; bottom row: station CD. Dashed line: R_μ predicted with equation 1. The title in each frame indicates date of the event

Results are shown only for soft sites, but the rule given in eq. 1 works reasonably well also for firm sites. Note that although eq. 1 seems adequate to go from elastic to inelastic <u>response</u> spectra, a somehow smoothed version should be used to reduce elastic <u>design</u> spectra. In any case, eq. 1 appears to be a good alternative to estimate the required strengths to limit ductility demand, having the elastic design spectrum as a starting point.

DURATION OF STRONG MOTION AND DISSIPATED ENERGY

In the preceding section it was noted that common rules to reduce elastic spectra to account for inelastic behavior are usually conservative for periods around the predominant one in the case of soft soils; one might be satisfied with things as they are. But on the other hand, ground motions at soft soils are longer, and sometimes much longer, than those recorded at firmer sites, and this translates into more loading cycles and larger amounts of energy input to the structures. Since values of strength reduction factors (or allowable ductility demands, or overstrength factors) have been adopted after observing the performance of structures mainly at firm sites, it is reasonable to think that some corrections should be made to account for the longer strong-motion durations at soft sites. But current design approaches are based on peak values -of ductility demand in this case- and there is no room to directly include energetic considerations into our force-based design methods.

One possibility to include dissipated energy into the design process, inspired on a work by Fajfar (1992), was discussed by Ordaz and Faccioli (1996). It is based on the use of Park and Ang's (1985) damage index, D, defined, for a single-degree-of-freedom oscillator and assuming elastoplastic behavior, as

$$D = \frac{x_{max}}{x_u} + \beta \frac{E}{F_y x_u} \qquad \textbf{(2)}$$

where x_{max} is the peak inelastic displacement of the structure during the earthquake loading, x_u is the maximum allowable displacement <u>during monotonic loading</u>, β is a parameter measuring strength degradation, E is the dissipated hysteretic energy, and F_y is the oscillator's yielding force. Note that, while x_u, F_y and β are design parameters, x_{max} and E are structural responses. A structure is considered safe as long as D<1.

Assume that a structure is safe when, under monotonic loading, ductility demand is limited to μ_u, for which D=1. The same structure would be unsafe under dynamic loading when $\mu=\mu_u$, and also for some smaller values of μ, due to the effect of the dissipated energy, measured with the second term of the right-hand side member of eq. 1; how unsafe would depend on the values of E, F_y and β. For a given ground motion, however, a value of F_y can be found that, for known x_u and β, leads to D=1. Figure 7 shows values of F_y/W for different ductility levels, using again the SCT recording (EW component) of the 1985 Michoacan earthquake. Note that if a given value of μ is considered safe under monotonic loading, a higher (and sometimes much higher) design force must be used under earthquake loading in order that the structure remains safe. This could also be interpreted in the following way: the structure should be designed to withstand a displacement larger than the expected elastoplastic demand; the additional capacity, so to speak, will be consumed in dissipating hysteretic energy.

For simplicity in the computations and in explaining the approach, β was fixed to 0.15 -a value previously used by other researchers (e.g., Fajfar 1992) structures- and assumed that x_u and T -the structural period- are independent of strength, measured with F_y. The first assumption implies that ductile capacity decreases as strength grows. However, more reasonable assumptions can be made about the relations among T, x_u and F_y and more realistic spectra, similar to those in Fig. 7, could be constructed. Also, the starting point is that some values of (global) ductile capacity <u>under monotonic loading</u> have been considered reasonable for some types of structures. Reality is that those capacities have been judged reasonable after observing the performance of structures with known design under earthquake loading, that is, including some amount of dissipated energy, and not none, as it was assumed. Thus, results presented here are, in the best case, upper limits to the increases in required design forces.

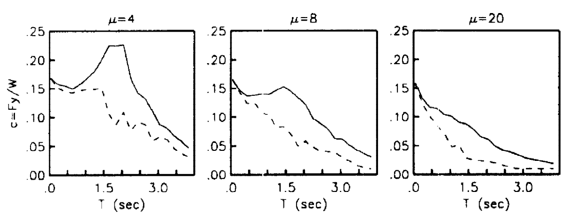

Figure 7. Required strength, $c=F_y/W$, to attain D=1 (see eq. 3) assuming different levels of ductility capacity μ_u, for the EW component of the SCT recording, in two cases: dashed line: when damage due to dissipated energy is not accounted for (conventional computation of inelastic response); solid line: when the effect of dissipated energy is included according to eq. 3

Even when the approach presented here is simplified and merits much more research, it is believed that it can help in finding clues as to how to correct usual design spectra to account for the effect of duration and dissipated energy.

CONCLUSIONS

Several problems associated to the specification of design spectra for very soft soils have been discussed. These problems are, in general, of little concern when constructing design spectra at firm sites.

The first group of problems has to do with the very strong changes that response spectral shapes can suffer due to source effects or, in general, effects derived from the frequency contents of the input motion. This implies that: 1) while design spectra must be constructed to cover the response spectra associated to frequent, large, and distant earthquakes of one type, they must also reasonably cover the effects of less frequent, smaller and closer earthquakes from other origins. This presents complexities, because response spectral shapes of the different groups of events can differ very much; 2) if a multi-level design is desired, provisions must be taken to account for the fact that, due to effects of earthquake size and the presence of very soft soils, response spectra of the service and collapse events can differ, not only in amplitude, but also in shape.

The geographical variability of response spectra throughout the Valley of Mexico was also discussed. It leads, if economy is a constraint, to the necessity of a detailed microzoning for design purposes. A well-thought set of site-specific spectra, or, in other words, the existence of a relatively large number of "soil types" is perhaps the better solution.

Some characteristics of strength reduction factors at very soft soils were also presented. Its study is relevant, since contemporary design approaches need an accurate estimation of ductility demands. It was shown how their behavior differs greatly from the one observed at firm soils, so the strength reduction factors at soft soils are not correctly predicted by standard rules. An empirical equation is proposed to compute reduction factors which, in general, works better than previously published rules.

Finally, the importance of accounting for the effect of the very long strong-motion durations at soft soils was pointed out. A possible way in which this effect might be incorporated in the design practice was presented. Although extremely simplified, the approach could help in this direction.

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