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Evaluation of displacement design spectra for base isolated systems

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ABSTRACT: Several accelerograms from the last largest italian eaerthquake event have been analyzed for deriving, by means of a special filtering process, displacement spectra reliable also in the long period range. The normalization with respect to *PGV* has been then proved to be, for these events, and consistently with the technical literature, an effective mean. Finally relative design displacement spectra, based on attenuation law have been proposed and proved to be more adherent to the recorded accelerograms than the ones suggested by current code provisions.

1 INTRODUCTION

Base isolation is today considered an effective technique in earthquake-resistant design, and the concept behind it is gaining worldwide acceptance among the design professionals. In the last ten years, many isolated structures have been constructed, particularly in USA and Japan. In Italy, isolation bearings coupled with mechanical energy absorbers have been used in highway bridges, and recently a certain number of isolated buildings have been completed. Nevertheless, hesitation from the engineering profession still remain, and this prevents the development of applications on a vast scale. We think that the main reason of this situation is the fear toward the adoption of an unconventional technique, in absence of adequate design guidelines at both the national and European level.

A fundamental step in the development of recommendations for seismically isolated structures is the definition of the design input motion. For a conventional earthquake-resistant structure, in which the seismic energy input is dissipated by means of controlled inelastic deformations of the structural elements, engineering seismology studies have led to the definition of the ground motion input to be considered in the design. Design response spectra have been proposed and included in current seismic codes. These spectra usually refer to an equivalent viscous damping ratio of 5%, which represents a good estimate of the damping value expected in a conventional structure under the action of a severe earthquake.

In an isolated construction, a significant reduction of the energy input is achieved through the interposition of the isolation devices at the base of the structure. Perplexities have been raised regarding the applicability of current code design spectra to a seismically isolated structure. This because the presence of the isolation system shifts the fundamental period toward values longer than 1 s, i.e. toward the long period range where numerous uncertainties still remain regarding the reliability of the usually adopted strong motion processing methods, and present knowledge of earthquakes having a long predominant period is still insufficient to provide data to be included in code provisions. Moreover, the intrinsic energy dissipation capacity of the isolation devices increases the equivalent viscous damping ratio, up to 10 ÷ 20% of critical. While appropriate reduction factors for the 5% design response spectra have been proposed to account for larger damping ratios, their adequacy need to be checked before they are applied to the design of an isolated structure.

Finally it has to be underlined that, while in conventional structures it is well established that the transformation of a response spectrum into a design spectrum passes through the definition of overstrength and ductility factors, gathered into the structural factor, in the case of isolated structures the design philosophy is not yet consolidated. In particular, in the most advanced provisions some inelastic deformations are allowed in the structure but not in the device, the scientific debate being still open on this point.

In this paper 16 accelerograms from the last italian major earthquake event have been analyzed for obtaining the displacement spectra up to 4.0 seconds. A new filtering process has been adopted for deriving significant values also in the low-frequency range. This analysis allowed to evidence some pitfalls in the actual provisions where the normalization with respect to Peak Ground Acceleration (*PGA*) has proved to lead to a larger scatter in the frequency range of interest for Base Isolation Systems (BIS) (Chaloub & Kelly 1990) if compared to a normalization with respect to Peak Ground Velocity (*PGV*). The normalization proposed in this paper, with respect to *PGV* has proved that the attenuation laws set up for italian earthquakes can represent an efficace tool for developing design spectra for BIS. The comparison between the italian and north-american attenuation laws suggested the need for defining new design spectra for BIS since the existing ones, developed for conventional structures, don't seem to be appropriate in the long period range where BIS applies.

2 RELATIVE DISPLACEMENT DESIGN SPECTRA

Response spectra have proven to be a very useful concept in earthquake-resistant design, as they take into account the natural period and intrinsic damping of the structure. Current seismic codes for conventional earthquake-resistant structures provide absolute acceleration spectra, which immediately allow to derive the inertia forces to be used in the design analysis. Usually, these spectra implicitly include a reduction factor to take into account of the non-linear structural behavior under the action of a strong earthquake. On the other hand, a quantity of major interest in the design of an isolated structure is represented by the maximum relative displacement at the isolation interface. This quantity has an immediate physical meaning, and allows to derive the total base shear once the stiffness of each isolator is known. If the structure above the isolation devices is expected to respond elastically, and this is certainly the case when the isolated structure is an essential facility from the seismic point of view prescribed to suffer no damage even after the action of an extreme earthquake, no reduction factors need to be applied to compute the forces acting on the superstructure. The tentative provisions for seismic isolated structures included in appendix to the latest edition of the Californian "Blue Book" (SEAOC 1990) provide a relative design displacement when a static analysis is performed, and a reduction factor R_w^I, accounting for overstrength and inelastic ductility, for the total base shear which depends on the type of lateral force resisting system used for the superstructure. The reduction factor is assumed equal to one for design of the device while for the superstructure is assumed andapproximately equal to one third of the ones adopted for conventional construction, though some researchers advise to prudentially take it equal to one until a full understanding of the effect of the yield in the superstructure is reached (Chalhoub & Kelly 1990). The same author, in a more recent paper (Kelly 1991), suggests "...that collapse concept applies also to isolated buildings since the isolation systems are not the weakest elements in the overall structural system".

From the discussion above it is clear the advantage of prescribing the design input motion for an isolated structure in terms of a relative displacement spectrum. The adoption of a standard spectral shape scaled with respect to Peak Ground Acceleration (*PGA*), as is done in the SEAOC reccomendations, can lead to significant errors, because the shape of the response spectrum is strongly dependent on magnitude, and this problem is particularly serious in the longer period range characteristic of an isolated construction (Serino & De Luca 1991). An experimental evaluation of the actual shear forces acting on an isolated system subjected to shaking table tests (Chalhoub & Kelly 1990) has suggested to adopt the A_v coefficient for adjusting this inconsistency of scaling with respect to *PGA*. A certain improvement is obtained if spectral ordinates are scaled with respect to *PGA* in the short period range (up to 0.30÷0.70 s), Peak Ground Velocity (*PGV*) in the intermediate period range (up to 2.0÷4.0 s), and Peak Ground Displacement (*PGD*) in the long period range, as first suggested by Newmark and Hall (1969).

However, studies by McGuire (1977) indicated that a constant proportionality factor between and intermediate period response may lead to design spectra which are inconsistent in terms of seismic hazard. Based on these investigations, ATC-3-06 (1978) introduced two new ground motion parameters to characterize the intensity of the design ground motion: the Effective Peak Acceleration (*EPA*) and the Effective Peak Velocity (*EPV*). These paramenters were considered as normalizing factors for construction of smoothed elastic response spectra for ground motion of normal duration. The *EPA* is obtained by averaging the 5% damping spectral acceleration ordinates between the periods 0.1 and 0.5 and then reducing the average by a factor 2.5. The *EPV* is equal to the 5% spectral velocity at 1 s period reduced by the same factor 2.5. The *EPA* and *EPV* values thus obtained are related to *PGA* and *PGV*, but are not necessarily the same or even proportional to them. As it will be shown in the next paragraph, attenuation laws of spectral ordinates derived from regression analyses on recorded accelerograms indicate the efficacy of adopting other parameters, i.e. magnitude and fault distance for predicting spectral values.

3 ANALYSIS OF ITALIAN RECORDS

3.1 *General data and filtering process*

Displacement response spectra for four different values of damping (undamped, 5, 10, 15 and 20%) have been computed from the sixteen strongest horizontal accelerograms recorded during a recent Italian earthquake (Campano-Lucano 1980). The quake was a shallow event (focal depth of 16 km), with a normal-slip fault rupture mechanism. The computed surface magnitude M_S was 6.8, and local magnitude M_L was 6.5. Table 1 lists the epicentral distance, the fault distance (defined as the shortest distance between the instrument and the surface projection of the fault rupture) and the local site geology at each recording station, as well as the values of *PGA* and *PGV* for each record. The peak ground motion values and the response spectra have been computed from the corrected acceleration time histories. The records were baseline and instrument corrected with the SACP (Stanford Accelerogram Correction Procedure) frequency domain routine (Khemici & Shah 1982), which uses a band-pass filter with transition bands tapered with a half-cosine wavelength on each side. The cutoff frequencies were 25.0 and 27.0 Hz for the low-pass filtering, and varied from 0.03 to 0.18 Hz for the high-pass filtering. In Table 1, the values of the high-pass filter cutoff frequencies adopted for each record are also given. These values have been obtained through visual inspection of the response spectra computed from the uncorrected records and seismological considerations regarding the duration of the strong motion part of the record. It is important to point out that these frequency values are lower than those usually adopted in standard correction procedures performed on Italian earthquake data (Basili & Bongiovanni 1990), and thus allow to obtain the full acceleration signal in the long period range up to and above 4.0 s, which is the longest period value considered in the present study.

Table 1. General data for the analyzed Italian records of the 1980 Campano-Lucano earthquake.

Recording Station	R_{epi} [km]	R_{fli} [km]	Site Geology*	*PGA* [cm/s²]		*PGV* [cm/s]		High-pass Cutoff Frequencies F_1 [Hz]		F_2 [Hz]	
				NS	WE	NS	WE	NS	WE	NS	WE
Bagnoli Irpino	23.0	8.0	0	128.	102.	27.2	34.9	0.09	0.09	0.10	0.10
Brienza	41.3	17.6	1	217.	174.	12.6	9.8	0.14	0.09	0.15	0.10
Mercato San Severino	47.8	33.0	2	105.	137.	7.7	13.2	0.17	0.15	0.18	0.16
Sturno	34.1	19.0	0	224.	312.	38.4	73.1	0.09	0.06	0.10	0.07
Calitri	21.0	20.5	2	155.	173.	26.1	28.3	0.04	0.09	0.05	0.09
Auletta	25.6	20.3	1	55.	56.	5.4	6.1	0.09	0.09	0.10	0.10
Rionero in Vulture	35.8	35.6	2	99.	94.	15.7	7.6	0.05	0.09	0.06	0.10
Bisaccia	30.2	26.7	0	94.	83.	23.9	16.2	0.03	0.03	0.04	0.04

* Site geology clasification: 0 = rock/stiff soil; 1 = shallow soil deposit; 2 = deep soil deposit.

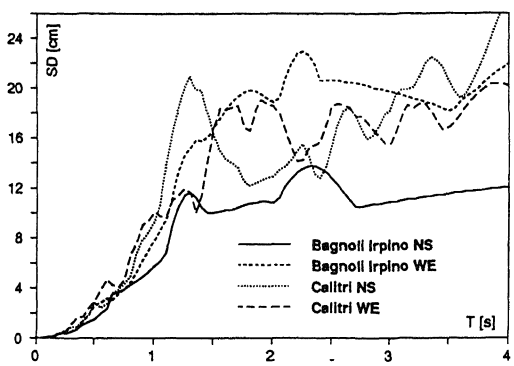

Figure 1. Displacement spectra for 5% damping.

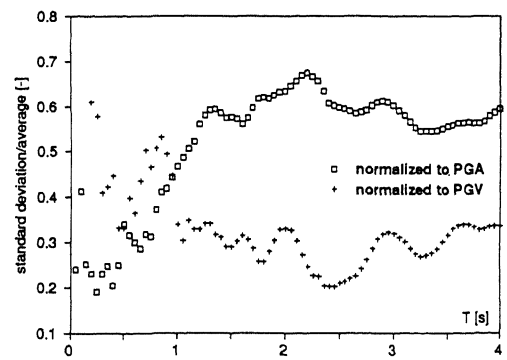

Figure 2. Standard Deviation/Average ratio from analyzed records.

3.2 *Displacement spectra and importance of PGV*

As an example of the computed spectra, Figure 1 shows the 5% damped displacement response spectra obtained from the Bagnoli Irpino and Calitri records. A total of 80 period values were considered, equally spaced between 0.05 and 4.0 s. The spectral ordinates increase is observed in the short and intermediate period range up to approximately 1.5 s, then the spectra tend to oscillate around a constant value.

In order to check the adequacy of *PGA* and *PGV* as scaling parameters for the displacement spectra, the mean and standard deviation of the 5% spectral ordinates scaled with respect to *PGA* and *PGV* have been computed for the 16 records at each period value. The ratio between the standard deviation and the average are plotted in Figure 2. Although the number of records is limited, they are sufficient to clearly indicate that *PGA* is a better scaling parameter up to approximatively 1.0 s, but in the long period range is certainly *PGV* the scaling parameter leading to smaller errors. The main factors responsible for the differences among the computed scaled spectra are distance and local site conditions, considering that earthquake magnitude is the same for all the accelerograms, as they have been recorded during the same event.

3.3 *Damping reduction factor*

In view of the development of appropriate reduction factors for the 5% damped spectrum to account for larger damping ratios, the ratios between the 10, 15 and 20% damped spectral ordinate and the 5% damped one have been computed for all the records at each period. The mean of these ratios are shown in Figure 3. It is apparent from the plot that the reduction factors are practically constant throughout the whole period range, except at very low period values .The ratios to the 5% damped spectrum are approximately 0.80, 0.69 and 0.61 for the 10, 15 and 20% damped spectra, respectively.

4 EMPIRICAL ESTIMATE OF RESPONSE SPECTRA

In the recent years, great advances have been made in the field of strong earthquake ground motion prediction. As new acceleration data became available, reliable empirical methods have been developed for the prediction of spectral ordinates. Theoretical seismological models of the seismic source and wave propagation have also been devised for the estimation of ground motion parameters and simulation of time series. An excellent

review of the latest empirical and theoretical methods is given in a recent paper by Joyner and Boore (1988).

Among the empirical procedures, the simplest method would be to select, from a strong motion database, a certain number of accelerograms which are characterized by magnitude, source-to-site distance and local site conditions as close as possible to the design earthquake. If necessary, the accelerograms may be appriopriately scaled to account for the differences in the above factors. Response spectra are computed from the corrected records, and their envelope then used in the design.

A more general and probably more reliable method would be to use the results of regression analyses performed on strong motion accelerograms recorded in the same tectonic region where the isolated stucture is going to be built. Up to today, a considerable number of empirical predictive relationships have been developed. These formulas, commonly referred as attenuation relations, express strong motion parameters (e.g. *PGA*, *PGV*, spectral ordinates) as a mathematical function of parameters characterizing the earthquake size, travel path and geology. Most of these studies indicate magnitude, distance, and local site conditions as the main elements affecting the strong motion paramenters, and use these three quantities only as independent variables in their attenuation relations. Though it has been proven that other factors (like fault type, hypocentral depth, repeat time, directivity, radiation pattern) may influence ground motion amplitude to a certain extent, they are rarely included in the predictive formulas. Examples of predictive relationships can be found in Joyner & Boore (1988), Sabetta & Pugliese (1989) and Kawashima *et al.* (1984), for western North America, Italy and Japan earthquakes, respectively.

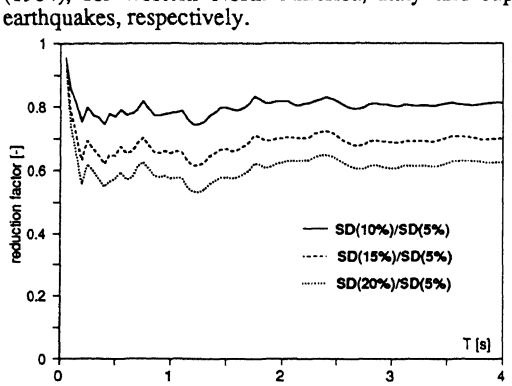

Figure 3. Damping reduction factor vs. period from analyzed records.

4.1 Attenuation relations for Italian earthquakes

In our country, the increasing number of available accelerograms recorded during recent earthquakes allowed to develop attenuation relations specific for the Italian seismotectonic environment. Predictive relations have been proposed for peak ground horizontal acceleration and velocity (Sabetta & Pugliese 1987) and for pseudo-velocity spectral ordinates (Pugliese & Sabetta 1989).The strong motion data base consists of records obtained by the accelerometric network installed and maintained since 1976 by the ENEA-ENEL Commission for the Study of the Seismic Problems. The accelerograms used in the regression analyses were only those believed to represent free-field conditions, for which the triggering earthquake was reliably identified, had a magnitude greater than 4.5, was recorded by at least two stations, had an epicenter determined to an accuracy of 5 km or less, and had a magnitude accurate to 0.3. The application of the above criteria resulted in the selection of a total of 95 recordings from 17 earthquakes having a magnitude between 4.6 and 6.8 occurred in Italy between 1976 and 1984. On the basis of geological and geotechnical information, the local site conditions were divided into three categories: rock/stiff soil, shallow soil deposit and deep soil deposit.

The predictive equation adopted to model attenuation of the pseudo-velocity spectral values was the following:

$$\log PSV = a + bM - \log(r^2 + h^2)^{1/2} + s \qquad (1)$$

where *PSV* is the 5% damping ratio pseudo-velocity response at a certain period *T*, and *r* is the epicentral distance or the closest distance to the vertical projection of the rupture on the surface of the earth, the latter being also briefly indicated as "fault distance". *M* is the surface wave magnitude M_S when both M_S and local magnitude M_L are greater than or equal to 5.5, and M_L otherwise. The regression coefficients *a*, *b* and *h* are functions of period *T*, while the soil coefficient *s* depends on *T* and on the local site category. Two sets of coefficients were determined for fourteen period values ranging from 0.04 to 4.0 s, one set being valid when *r* is the epicentral distance, and the other when *r* is taken as fault distance. Attenuation relations of similar form were developed to predict peak ground horizontal acceleration and velocity. The computed values of the regression coefficients may be found in the original paper (Pugliese & Sabetta 1989). They refer to the randomly oriented horizontal component of the ground motion, as both horizontal components from a certain earthquake and recording station were included in the regression analysis, thus considering them as independent data.

Once *PSV* is known as a function of magnitude, distance and local site condition, the product $(T/2\pi)PSV$ gives the spectral relative displacement *SD*.

From equation (1) it can be seen that by making use of the attenuation law the parameters affecting the expected spectrum are Magnitude and fault distance. It is also well-known that the Magnitude is a measure of the Energy input and therefore related to the velocity of the accelerogram (*PGV*). It was therefore decided to plot in Figure4 the Spectral Relative Displacement *SD* nondimensionalized with respect to *PGV*, also in consideration of the results delivered in section 3 of this paper. In this figure are reported the displacement spectra of two recorded accelerograms, together with the expected spectrum for a magnitude M=6.5 and for different fault distances going from 10 to 100 Kilometers.

Two main conclusions can be derived by this figure: the first one is that with this representation there is no effect of the fault distance for the italian recorded accelerograms; the second result is that the shape of the relative displacement spectrum is practically constant for values of period greater than 1.5 seconds, i.e. in the range of interest of BIS.

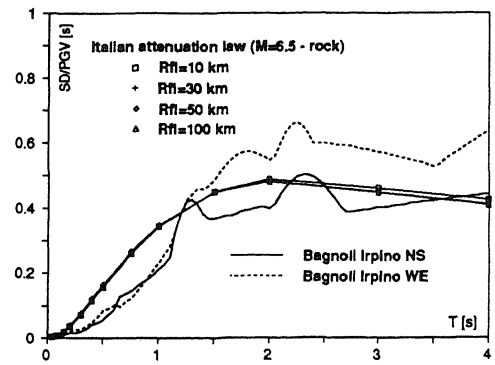

Figure 4. Comparison between attenuation law, for different fault distances, and computed spectra.

The good accordance between the two input motions and the spectrum as derived by the attenuation law (1), suggests to adopt a procedure for the expected spectrum in which the main parameter is the expected Magnitude. For this reason in Figure 5 are plotted 2 accelerograms together with the attenuation law derived for 3 different magnitudes: respectviely 6.0, 6.5 7.0 and for a fault distance equal to 30 Km.

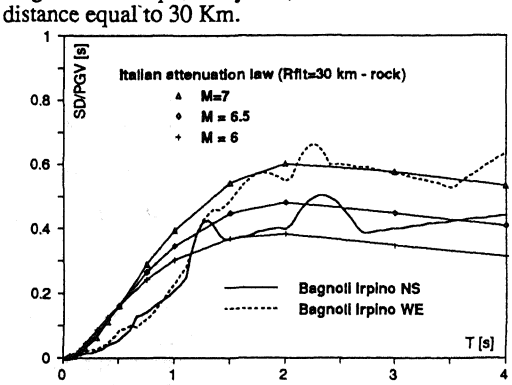

Figure 5. Comparison between attenuation law, for different magnitudes, and computed spectra.

4.2 Attenuation laws for western Norh America

It is interesting to compare the predicted spectral displacement relative to Italian earthquakes with those relative to other seismotectonic regions. Attenuation relations for peak ground horizontal acceleration, velocity and pseudo-velocity spectral ordinates have been developed by Joyner & Boore (1988) analyzing data from western North America earthquakes. The data set was restricted to shallow events, for which the fault rupture lay mainly above a depth of 20 km, with moment magnitude greater than 5.0. Only earthquakes for which the data were adequate for estimating source distance to an accuracy better than 5 km were considered.

The attenuation relation for the pseudo-velocity spectral values was:

$$\log PSV = a + b(M-6) + c(M-6)^2 + d\log R + kR + s \quad (2)$$

where $R = (r^2 + h^2)^{1/2}$, r is the fault distance, M the moment magnitude, and s is a site correction coefficient for soil sites (sites with 5 m or more of soil). The quantities a, b, c, d and k are the other regression coefficients. The equation above is applicable only when $5.0 \leq M \leq 7.7$. Two sets of regression parameters were determined for twelve period values ranging from 0.1 to 4.0 s, one set being relative to the randomly oriented horizontal component of the ground motion, and the other to the larger of the two horizontal components. Attenuation relations of similar form were developed to predict peak ground horizontal acceleration and velocity. The computed values of the regression coefficients may be found in the original paper (Joyner & Boore 1988).

In Figure 6 is delivered the relative displacement spectrum nondimensionalized with respect to *PGV* as provided by attenuation law (2). The different curves, all referring to magnitude 6.5 and to rock site evidence two major differences with the analogous representation of Figure 4 related to Italian earthquakes. The first difference is that, in case of USA recordings, the fault distance cannot be neglected as design parameter. The second difference is that the relative displacement spectrum does not show a constant behaviour in the range of periods exceeding 1.5 seconds. A quasi-linear behaviour is evidenced instead in the entire range of periods hence justifying the design spectrum proposed by SEAOC Recommendations.

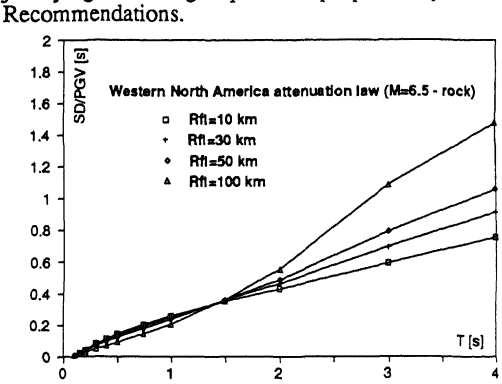

Figure 6. Western North America attenuation law, for different fault distances.

5 COMPARISON WITH CURRENT CODES AND CONCLUSIONS

The numerical results derived in this paper on the basis of the spectra obtained by the 16 accelerograms recorded during the Irpinia earthquake allow to derive some conclusions in terms of design spectra to be used for dimensioning Base Isolated Structures in Italy.

The first conclusion is that an approach which makes use of attenuation laws for predicting the relative displacement spectrum seems very appropriate expecially if the *PGV* is adopted as nondimensional design parameter. The second conclusion is that the italian accelerograms as well as the attenuation law derived on the basis of major italian earthquakes have proved to show a significantly different behaviour with respect to the USA ones. This difference is cleared out in Figure 7 where

the spectra derived by the two attenuation laws (1) and (2) are given. In this figure are provided the spectra obtained for Magnitudes M=6 and M=7 and for rock site.

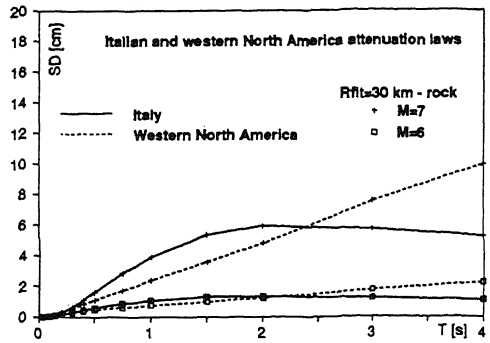

Figure 7. Comparison between attenuation laws.

These conclusions call for a specific design spectrum to be used in Italy for BIS which should be more coherent with the expected values expecially in the long period range. The existing italian and european specifications (CNR-GNDT 1984 & EC8 1989), actually set up for conventional buildings, don't seem to fulfill this requirement as it can be seen in Figure 8. In this figure the mean *SD* and the 0.16 & 0.84 fractile as derived by equation (1) are presented and compared to the code spectrum. From this figure it is evident that the code spectra, both the CNR and the EC8 ones, which are close in shape to the USA ones, are excessively conservative in the long period range since they provide spectral ordinates even larger than the higher ones given in the figure and corresponding to the 0.84 fractile. The same results have been obtained also for the case of rock site even though they are not presented here for brevity.

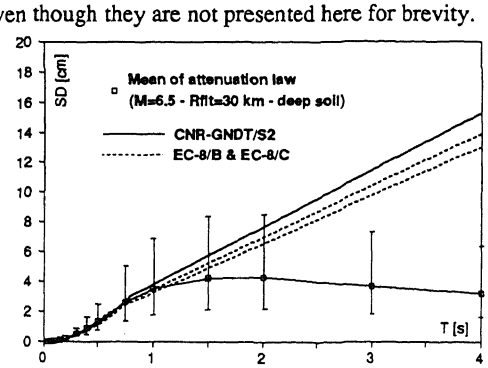

Figure 8. Comparison between attenuation laws and code provisions.

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REFERENCES

ATC-3-06 1978. *Tentative provisions for the development of seismic regulations for buildings.* Applied Technology Council. Palo Alto, California.

Basili, M. & G. Bongiovanni 1990. Data acquisition and processing in strong motion seismology: an overview. *European Earthquake Engineering 2*: 38-39.

Chaloub, M.S. & J.M. Kelly 1990. Comparison of SEAONC base isolation tentative code to shake table tests. *Journal of Stuctural Engineering, Proc. ASCE 116-ST4:* 925-938.

CNR-GNDT 1984. *Norme tecniche per le costruzioni in zone sismiche.* Ingegneria Sismica, Anno II, n.1.

Eurocode No.8 1989. *Structures in seismic regions - Design Part 1 General and Building, May 1988 edition.* Commission of the European Communities. Brussels.

Joyner, W.B. & D.M. Boore 1988. Measurement, characterization, and prediction of strong ground motion. *Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground Motion Evaluation, ASCE Geotechnical Special Publication No. 20:* 43-102. Park City, Utah.

Kawashima, K., K. Aizawa & K. Takahashi 1984. Attenuation of peak ground motion and absolute acceleration response spectra. *Proc. 8th World Conf. on Earthquake Engineering vol. 2*: 257-264. San Francisco, California.

Kelly, J.M. 1991. Recent experimental studies of isolation systems for nuclear and civil structures. *Proc. of Int. Meeting on Earthquake Protection*: 33C-56C. Ancona, Italy.

Khemici & Shah 1982. Frequency domain corrections of earthquake accelerograms with experimental verifications. *Report No. 55, John A. Blume Earthquake Engineering Center.* Stanford, California.

Mc Guire, R.K. 1977. Seismic design spectra and mapping procedures using hazard analysis based directly on oscillator response. *International Journal of Earthquake Engineering and Structural Dynamics 5*: 211-234.

Newmark, N.M. & W.J. Hall 1969. Seismic design criteria for nuclear reactor facilities. *Proc. 4th World Conf. on Earthquake Engineering B-4*: 37-50. Santiago, Chile.

Pugliese, A. & F. Sabetta 1989. Stima di spettri di risposta da registrazioni di forti terremoti italiani. *Ingegneria Sismica 6-2*: 3-14.

Sabetta, F. & A. Pugliese 1987. Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records. *Bulletin of the Seismological Society of America 77-5*: 1491-1513.

SEAOC 1990. *Recommended lateral force requirements and commentary.* Seismology Committee, Structural Engineers Association of California. Sacramento, California.

Serino, G. & A. De Luca 1991. La definizione degli spettri di progetto nelle strutture isolate alla base. *Proc. of the 5th Italian National Conf. on Earthquake Enginering vol. 2.* Palermo, Italy.