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Characterization of the Elastic Displacement Demand: Case Study - Sofia City

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CHARACTERIZATION OF THE ELASTIC DISPLACEMENT DEMAND: CASE STUDY - SOFIA CITY

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ABSTRACT

The results of the study on the seismic site response of a part of the metropolitan Sofia are discussed. The neo-deterministic seismic hazard assessment procedure has been used to compute realistic synthetic waveforms considering four earthquake scenarios, with magnitudes M=3.7, M=6.3 and M = 7.0. Source and site specific ground motion time histories are computed along three selected cross sections, making use of the hybrid approach, combining the modal summation technique and the finite differences scheme. Displacement and acceleration response spectra are considered. These results are validated against the design elastic displacement response spectra and displacement demand, recommended in Eurocode 8. The elastic response design spectrum from the standard pseudo-acceleration, versus natural period, *Tn*, format is converted to the $Sa - Sd$ format. The elastic displacement response spectra and displacement demand are discussed with respect to the earthquake magnitude, the seismic source-to-site distance, seismic source mechanism and the local geological site conditions.

CONSTRUCTION AND CHARACTERIZATION OF THE SYNTHETIC EARTHQUAKE GROUND MOTION SET

Geological Outline.

The input data, necessary for the earthquake ground motion simulation using the hybrid approach, consist of the regional bedrock model, the laterally heterogeneous local model, and the earthquake source model. To prepare the input data for this study, a broad range of information recently collected for the Sofia valley has been analyzed and assessed (Tzankov and Nikolov 1996; Shanov *et al.*, 1998; Ilieva and Josifov, 1998; Solakov et al., 2001). Sofia City is situated in the central southern part of the Sofia kettle, a continental basin in southern Bulgaria, filled with Miocene-Pliocene sediments. The bedrock is represented by heterogeneous (in composition) and different (in age) rocks, which outcrop within the depression. The Sofia kettle is filled with Neogene and Quaternary sediments and its thickness reaches 1200 m near the town of Elin Pelin. From the structural point of view, the Sofia kettle represents a complex, asymmetric block structure graben, located in the West Srednogorie region, with an average altitude of about 550m (Frangov, 1995; Ivanov, 1997; Ivanov et al., 1998).

Details on the tectonics and the local seismicity of the region, and on the construction of the structural models used in the computations are provided in Tzankov and Nikolov, 1996; Christoskov et al., 1989; Paskaleva, 2002; Paskaleva et al., 2007. Sketch of the investigated profiles is given in Figure 1. The characteristics for the laterally varying part 2D models along the profiles in WE and SN directions are specified according to Paskaleva, 2004b.

The Earthquake Scenarios.

When a scenario earthquake characterizes the ground motions for the evaluation and design, the primary earthquake source parameter is its magnitude or seismic moment. In the deterministic analysis, the scenario earthquake is typically the largest earthquake that controls the seismic hazard around the City. Alternatively, a possible scale of scenario earthquakes is: disastrous (average return period about 500 years), very strong (average return period 200 - 250 years), strong (average return period 120-140 years) and frequent (average return period 50 - 60 years).

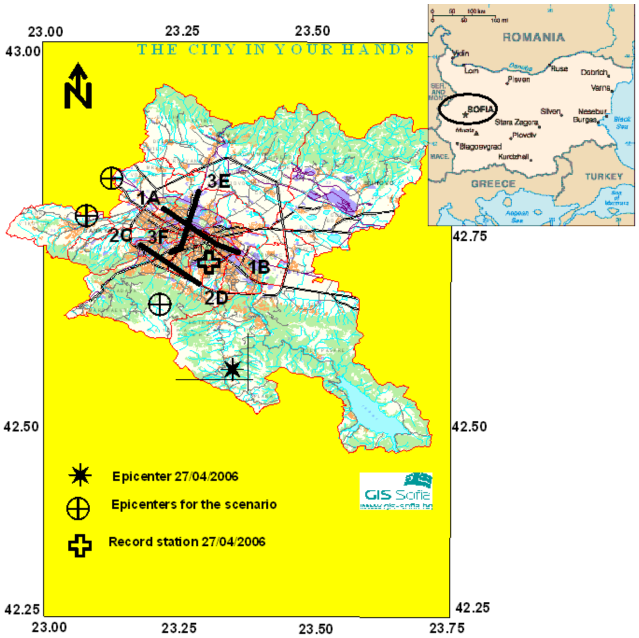

Figure 1. City sketch with the location of the profiles used in the numerical simulations: 1A-1B and 2C-2D are parallel and are about 3.5km apart. The ticks on the frame of the figure are: ⊕ locations of the epicentre for the scenario M=7.0; ✷ - location of the epicentre of the first recorded accelerogram M=3.7 (preliminary assessment); ✚ - location of the recording station of the seismic event 27/04/2006

The maximum macroseismic intensity at Sofia, I = IX (MSK), observed in 1858 (Watzov, 1902; Bonchev et al., 1982), can be expected to occur with a return period of 150 years (Christoskov et al., 1989), i.e. it could correspond to the strong earthquake scenario. Recently seismic hazard maps of the Circum - Pannonian Region (Panza and Vaccari 2000; Gorshkov et al., 2000), show that Sofia is placed in a node having potential for the occurrence of an earthquake with M> 6.5 and that it could suffer macroseismic intensity up to X. In the Sofia region, the seismicity is limited to the uppermost 20 - 30 km of the lithosphere. A maximum macroseismic intensity I = VIII can be expected at Sofia (Glavcheva and Dimova, 2003), if an earthquake with magnitude M_{max} = 7 (Bonchev et al., 1982) occurs at a depth of about 20 km, and a maximum macroseismic intensity IX (and higher) can be provoked by an event with M_{max} = 7 and focal depth around 10 km.

The earthquake scenarios considered in this study, are chosen to correspond to a seismic source, located at 10 km distance west or southwards from the City center, correspondingly (Christoskov et al., 1989; Alexiev and Georgiev 1997; et al., 1999, Slavov, 2000, Matova 2001; Solakov et al., 2001). To construct comprehensive earthquake scenarios, the conservative combinations of information, available in the literature (Alexiev and Georgiev 1997; Shanov et al., 1998; Slavov, 2000) is considered. The assumed source parameters, common to the first three cases in table 1, are chosen to approximate the seismic event, which hit Sofia in 1858. The chosen earthquake scenarios with respect to the investigated models are summarized in table 1. To estimate the effect of the change of the seismic source mechanism on the site response, one more set of seismic source parameters have been used - Sce3a in table 1. Both focal mechanisms, Sce1, 2 and 3 in table 1, are consistent with the available geological studies performed within the epicentral area (Christoskov, 1989; Solakov et al., 2001; Slavov et al., 2004).

Table 1. Earthquake scenarios used for the computations*.

SCE	PRF	Mw	strk (°)	dip (°)	rak (°)	H (km)	L (km)
Sce 1	M1, M2, M3	3.7	340	77	285	2	8
Sce 2	M1, M2, M3	6.3	340	77	285	10	10
Sce 3	M1, M2, M3	7.0	340	77	285	10	10
Sc3A	M3	7.0	00	44	309	10	10

*SCE – Scenario name; PRF - Name of the Geological Profile; Mw – Magnitude; Strk – strike angle; Dip – dip angle; Rak – rake angle; H – focal depth; L – Epicentral distance to the nearest point of the fault.

The synthetic ground motion data base.

The synthetic ground motions along the three selected geological cross sections (Figure 1) are generated applying the neo-deterministic hybrid technique (Fäh et al., 1993; Fäh et al., 1995a; Fäh et al., 1995b; Panza et al., 2001). It combines the modal summation technique (Panza, 1985; Panza and Suhadolc, 1987; Panza and Vaccari, 2000; Panza et al., 2001), used to describe the seismic wave propagation in the anelastic bedrock structure with the finite difference method (Virieux, 1984; Virieux, 1986; Levander, 1988) used for the computation of wave propagation in the anelastic, laterally inhomogeneous sedimentary media (Stein and Wysession, 2003). Thus synthetic ground motion data base (Panza et al., 2001), containing more than 2700 accelerograms, velocigrams and seismograms has been built up. The synthetic records are consistent with the only existing record of the earthquake of April 27, 2006, M=3.7, I = IV – V MSK, which epicentre is shown in Figure 1, (Koleva, 2008).

The signals for magnitudes M = 3.7 and M = 6.3 are computed considering the frequency dependent response of point seismic sources (Gusev, 1983). For magnitude M = 7.0 the extended source with bilateral rupture propagation is considered, and the observation point is on a line at 90^o from the propagation direction of the rupture (Gusev and Pavlov, 2006).

DISCUSSION OF THE RESULTS.

The seismic input at Sofia is characterized by the computed source and site dependent seismic signals. These signals have been grouped accordingly with the site-to-source distance as follows: 10-12 km, 12-16 km and 16-20 km. Elastic displacement and acceleration response spectra for 5% damping have been extracted from the synthetic accelerograms. The generalized horizontal response spectra has been computed as the square root of the sum of the squares of the two horizontal components, $SA_H = SQRT (TRA^2 + RAD^2)$.

Characterization of the Elastic Displacement Spectra.

The important effect of the source-to-site distance, $\mathbf{d_s}$, the magnitude and the local geological conditions on the spectral displacements is shown in Figures 2a-2b, where the mean elastic displacement spectra, along the three models M1, M2 and M3, considering scenarios Sce 1 (M=3.7), Sce 2 (M=6.3) and Sce 3 (M=7.0) for periods up to 2.5 s, are plotted. The elastic displacement spectral amplitudes in the near field (ds = 10-12 km) is larger than those obtained in the far field as can be seen along the three models considering earthquake scenarios Sce 1 (M=3.7) and Sce 2 (M=6.3). This trend is observed also for model M1, Sce 3 (M=7.0). The results, obtained for model M2, Sce 3 (M=7.0) and model M3, Sce 3 and Sce 3a (M=7.0) show that the local geological conditions also contribute significantly to the seismic input. The comparison of the spectral displacements, plotted in figure 2, computed for model M3, scenarios Sce3 and Sc3a, shows the visible effect of the seismic source mechanism on the spectral amplitudes, particularly at periods T > 1.25 s.

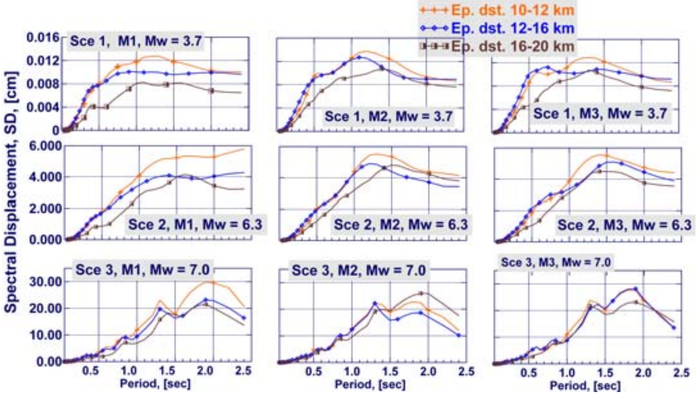

Fig. 2a. Mean elastic displacement spectra computed for models M1, M2, M3 considering Sce 1, Sce 2, Sce 3 according Table 1.

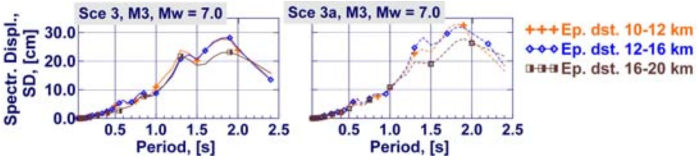

Fig. 2b. Mean elastic displacement spectra computed for model M3 considering Sce 3 and Sce 3a according Table 1.

The synthetic seismic signals are computed for period T = 0.05 - 10 s. The period interval T < 4 s has been chosen as the most interesting for the engineering practice and the comparisons of the computed displacements response spectra with the Eurocode 8 ones have been performed over this period. The comparisons of the computed displacement design spectra with the recommended EC8 design spectra (Figure 3) show that the synthetic spectral values for all models follow the Eurocode 8 amplitudes for the period range T = 0.05-1 s. The synthetic amplitudes overestimate the EC 8 ones for periods T = 1 – 2 s.

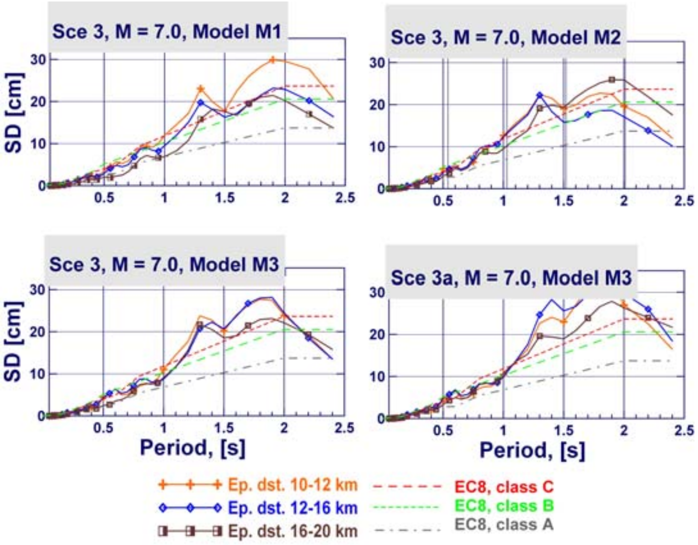

Fig. 3. Comparison between the computed elastic displacement spectra (mean values) for magnitude M = 7.0 for M1, M2, M3 and the recommended in Eurocode 8 code design displacement spectra. The dashed line graphs correspond to peak ground acceleration 270 cm/s^2 (BG code 1987) and soil conditions class A (rock), class B (stiff soil) and class C (soft soil), respectively.

The comparison between the maximum displacement $\mathbf{d_s}$ and the corresponding corner period **Tc** (models M1, M2 and M3) obtained in this study and the results of Decanini et al. (2003) for stiff soil (S1), at distances from the source less than 5 km and larger than 30 km, magnitude 6.5 < M <7.1, is shown in Figures 4a, b.

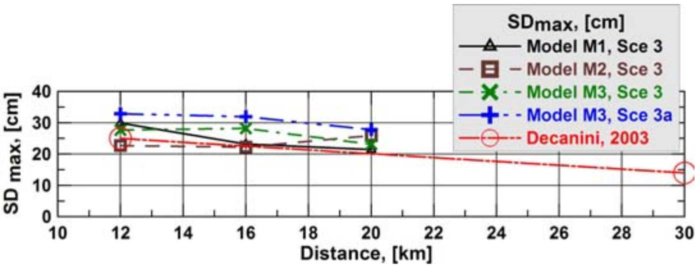

Figure 4a. Comparison of the maximum spectral displacement SD (models M1, M2 and M3) with the data of Decanini et al., 2003 for stiff soil (S1), magnitude range 6.5<M<7.1.

The comparison between the results derived from the real data bank (Decanini et al., 2003) and the results obtained from the synthetic data base compiled using the neo-deterministic approach is fully satisfactory for displacements and corner periods as well.

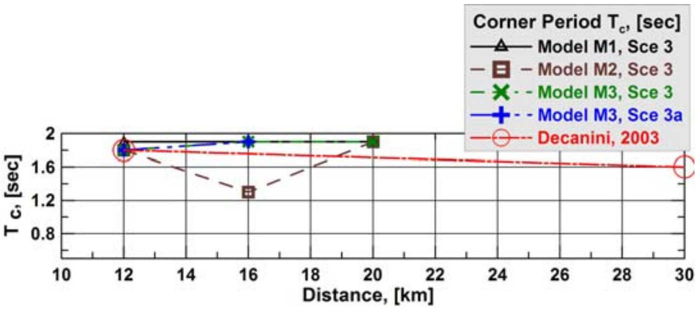

Figure 4b. Comparison of the corner period Tc corresponding to the maximum spectral displacement SD (models M1, M2 and M3) with the data of Decanini et al., 2003 for stiff soil (S1), magnitude range 6.5<M<7.1.

Relative Displacement Spectra Attenuation. The concept of the displacement relative attenuation, expressed by the parameter Att, was introduced by Decanini et al. (2003). It has been used to evaluate the influence of the distance from the source to the particular site. For the spectral displacement SD the parameter Att (relative attenuation) is given by the following ratio: Att = $\{Sd_{si}$ (T)$\}$/ $\{Sd_{s0}$ (T)$\}$, where Sd_{si} (T) represents the spectral displacement value d_s considering intervals of distance ($10< d_s <$ 12km, $12 < d_s <$ 16km, $16 < d_s <$ 20km) to the source; Sd_{s0} (T) - is the spectral displacement for the lowest interval distance ($d_s =$ 10km). Obviously, low Att values indicate fast attenuation and high Att values denote slow attenuation with distance.

The influence of the magnitude, the geological conditions along the profiles and the seismic source mechanism on the relative displacement attenuation is illustrated in Figures 5a – 5b. Generally, the displacement relative attenuation in the far field along all investigated models, considering all scenarios, is visibly faster than the attenuation in the near field. The fastest relative attenuation of displacement has been observed for model M3 and the slowest one has been observed for model M2. Analysing the relative displacement spectra along Model M1 (the left column in Figure 5), the Att parameter shows increasing values with increasing magnitude, more visibly at periods T > 1 s. The far field attenuation, d_s > 16 km, is visibly faster compared to the near field one. The significant contribution of the geological conditions to the earthquake site response and to the relative displacement attenuation at the site is illustrated by the comparison between the plotted displacement relative attenuation for model M1 (left columns in Figure 5), model M2 (middle column) and model M3 (right column). Figure 5b shows the influence of the seismic source mechanism on the displacement relative attenuation for model M3 - the displacement relative attenuation follows the same trend, but with higher amplitudes.

ELASTIC DEMAND DIAGRAM

An extensive numerical analysis has been carried out on SDOF systems with natural periods *T* in the range of 0–2 s. The elastic spectral displacement ***Sd*** and strength demand ***Sa***, which represent the structural performance, have been extracted from all the computed accelerograms assuming a constant damping ratio 5%. The results for the Earthquake scenarios M = 7.0 are plotted in Sa–*S*d format in Figure 7. In the same figure it is shown the comparison of the mean elastic acceleration-displacement diagram with the Sa-Sd diagram, recommended in Eurocode 8, corresponding to the case-study of Sofia City - design acceleration 0.27g, “B” soil conditions. The plot in Figure 7 shows a good correlation between the compared data in the period range 0.4 < T < 0.8 s, while for longer periods (0.8 < T < 2.0 s) the synthetic signals are dominant for all considered distances.

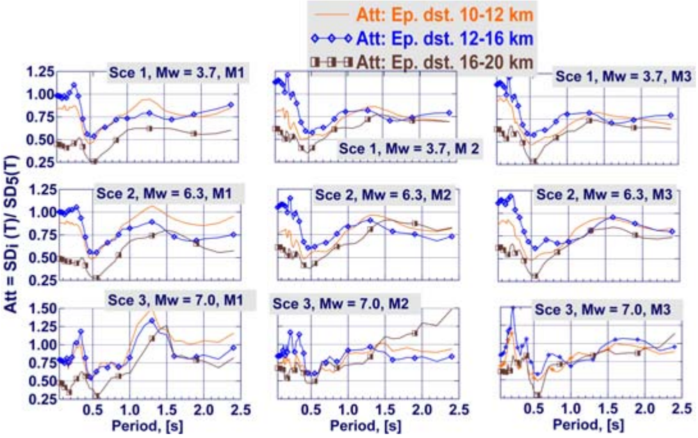

Figure 5a. Relative Displacement Spectra Attenuation, computed along all investigated models M1, M2 and M3 considering all scenarios Sce1, Sce2, Sce3.

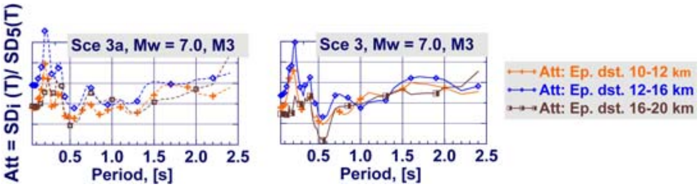

Figure 5b. Relative Displacement Spectra Attenuation, computed along all investigated model M3 considering scenarios Sce3 and Sce3a.

Figure 6 shows the comparison of the design displacements relative attenuation Att obtained from the synthetic data base computed for Sofia with the Att values, extracted from observations (e.g. Decanini et al., 2003; Bommer and Elnashai, 1999). The attenuation coefficient obtained in this study, using the computed seismic input shows visibly higher Att values, which indicate faster attenuation along the investigated site. This result calls our attention to perform more parametric analyses in order to clarify the contribution of the different characteristics of the computation model and the input information on the Att coefficient.

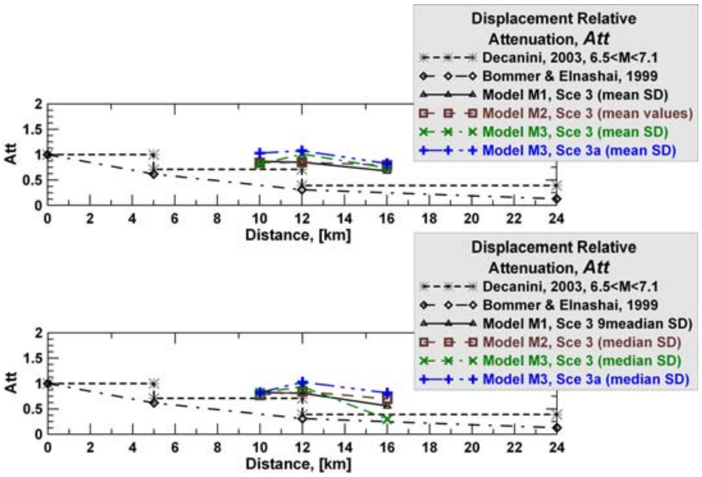

Figure 6. Relative attenuation coefficient Att: Comparison between the results, obtained in this study for the generalized horizontal component (median values) with the data of Decanini, et al. (2003) 6.5<M<7.1 and Bommer and Elnashai, 1999 (magnitude independent).

FINAL REMARKS AND CONCLUSIONS

The task and the results, discussed in this work have been provoked by the need of reliable procedures, capable of predicting realistic demands imposed by earthquakes. The capability of demand estimations for buildings exposed to seismic loading is a major challenge of the design and engineering and particularly for the prognostic estimates of the seismic behaviour of these buildings. The elastic demand information is very useful for the further development of the design procedures, incorporating different advanced sub-procedures, e.g. (1) specific serviceability level performance evaluation procedure, (2) verification of the reliability of the buildings, representative of different structural systems, which reliability has to be consistent with both, the code provisions and the developing analytical evaluation procedures capable of predicting building performance with reduced uncertainty.

A synthetic ground motion data base, containing 2700 site and source dependent seismograms (accelerations, velocities and displacements) is now available for the city of Sofia. One of the many possible uses of the data base has been shown in this study. Elastic displacement spectra and displacement demand, extracted from the available data base, are analyzed grouping the results accordingly to earthquake magnitude, local geological conditions and earthquake source mechanism. The results obtained theoretically are validated against the corresponding observed quantities, recommended in Eurocode 8. The results show that the earthquake source and the local geological conditions influence significantly the displacement design spectra and the displacement attenuation along the investigated profiles.

The case study of the city of Sofia has shown that the neo-deterministic seismic hazard assessment procedure is a capable tool for the construction of realistic synthetic strong motion data base, particularly for regions, which are characterized by high seismicity and lack of instrumental earthquake record.

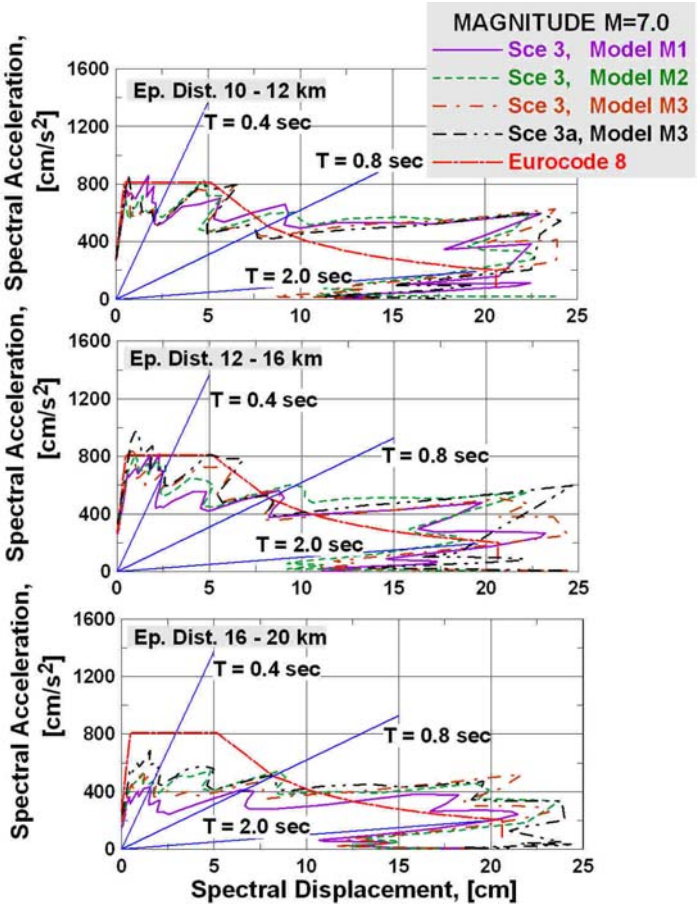

Figure 7. Elastic demand spectra. Comparison of the synthetics and the Eurocode 8 values.

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