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HAZARD-CONSISTENT SPECTRA AND FRAGILITY ANALYSIS

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SUMMARY

An advanced method for computing hazard-consistent seismic demand spectra is recently developed. It is based on extended seismic hazard analysis performed in the following steps: 1) delineation of the seismic sources; 2) estimation of the seismic activity parameters through complex management of earthquake catalogue; 3) definition of hazard-consistent events using quadriparametric seismic hazard disaggeregation for predefined seismic hazard return periods; and 4) computation of hazard-consistent elastic acceleration spectrum as an attenuation of the hazard-consistent magnitude and distance. The hazard-consistent inelastic acceleration and displacement spectra are defined as constant ductility inelastic response spectra. The mean hazard-consistent ADR spectra, to be used for estimation of the seismic fragility and performance of buildings in the City of Skopje are computed for return periods of 43, 72, 475 and 970 years.

INTRODUCTION

The most rational analysis and performance evaluation methods for practical structural applications are the simplified inelastic procedures. They use the non-linear quasistatic (pushover) analysis of MDOF system and the response spectrum approach of equivalent SDOF system.

The earthquake engineering community has not paid an appropriate attention to simplified non-linear approaches until mid of 1990s, when a breakthrough of these approaches occurred. The advanced methodologies on seismic evaluation of existing buildings such as FEMA/NIBS HAZUS, 1997 and ATC40, 1996 assess the seismic fragility of buildings using the capacity spectrum method, Freeman [5]. This technique requires estimation of the both seismic demand and building capacity spectra in ADRS format and the performance point is defined as an intersection between these two spectra.

The demand spectra are basically code design or model-defined (ATC40, HAZUS, Newmark & Hall, 1972) site response spectra. HAZUS methodology characterizes the ground shaking using standard response spectrum shape representing rock, stiff soil and soft soil conditions taking into consideration the distance from scenario earthquake. The demand spectrum is based on the 5% damped elastic response

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spectrum at the building's site modified to higher damped response spectrum to account for hysteretic nonlinear response of the structure.

Recent investigations Chopra [2], Fajfar [4], Vacareanu [12] revealed the fact that the utilization of higher damped response spectrum can significantly underestimate the structural response in particular in low frequency range. Consequently, the modification of site elastic response spectrum into constant-ductility inelastic response spectrum by means of strength reduction factors is preferred by the scientific community.

METHOD FOR COMPUTING HAZARD-CONSISTENT SEISMIC DEMAND SPECTRA

Taking into consideration the importance of the seismic demand spectra in the simplified non-linear approaches, a method for computing hazard-consistent seismic demand spectra is recently developed, Trendafiloski [11]. It is based on extended seismic hazard analysis performed in the following steps: 1) delineation of the seismic sources; 2) estimation of the seismic activity parameters through complex management of earthquake catalogue; 3) definition of hazard-consistent events using quadriparametric seismic hazard disaggeregation for predefined seismic hazard return periods; and 4) computing hazard-consistent spectra as an attenuation of the hazard-consistent magnitude and distance.

The analyses are performed for each seismic zone separately and the seismic hazard parameters are estimated as mean values. Hence, the disaggragates of the seismic hazard define a physically realizable event, i.e. the event is placed within the borders of the seismic zone and the hazard-consistent magnitude belongs to the range of the minimum (level of completeness of the catalogue, m_o) and maximum expected magnitude (m_{max}). The proposed concept, based on the estimation of the mean parameters of hazard-consistent earthquakes, is compatible with the methods for fragility analysis.

Seismic zone activity parameters

The seismic zones are delineated using the technique of clustering of earthquake epicenters. Their activity parameters: 1) maximum expected magnitude m_{max}; 2) frequency of the catalogue's level of completeness (λ_o); and, 3) seismic severity (β) are determined by parametric-historic seismic hazard analysis method (K-S method), Kijko [8] combining the earthquake catalogues with historic, macroseismic and instrumental data. The magnitude frequency is modeled by doubly truncated Gutenberg-Richter distribution.

The K-S method includes several attractive features as the following: 1) Possibility to combine different types of data from the earthquake catalogues (instrumental and historical); 2) Possibility to use data with different level of completeness; 3) Possibility to include large historical events which donot belong to the earthquake catalogue; 4) Exceeding the problem with time gaps in the earthquake catalogue; and, 5) Resolving the problem with the magnitude heterogeneity in the earthquake catalogue taking into consideration the magnitude uncertainty. By its application, the seismic activity parameters can be computed taking into consideration the earthquake catalogue data only with no regard to the geo-tectonic characteristics of the region.

Hazard-consistent earthquake

The hazard-consistent earthquake is defined with the following parameters: 1) hazard-consistent magnitude (energetic quantificator of the event) and 2) hazard-consistent epicenter (location of the event). The hazard-consistent epicenter is determined in polar coordinates (hazard-consistent distance and angle).

In order to define the parameters of a hazard-consistent earthquake, a procedure for quadriparametric disaggregation of the seismic hazard is recently developed, Trendafiloski [11]. It does a probabilistic re-evaluation of the magnitudes and the distances which contribute to the seismic hazard level at certain location and defines the parameters of the event as mean values of the conditional probability distribution, Ishikawa [7].

The quadriparametric disaggregation refers to hazard-consistent magnitude $\overline{M}(p)$, distance $\overline{\Delta}(p)$, angle $\overline{\Theta}(p)$ and predominant period $\overline{T}(p)$.

$$\overline{M}(p) = \frac{\sum_i \sum_j m_i \, P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}{\sum_i \sum_j P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}$$

$$\overline{\Delta}(p) = \frac{\sum_i \sum_j \delta_i \, P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}{\sum_i \sum_j P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}$$

$$\overline{\Theta}(p) = \frac{\sum_i \sum_j \Theta_i \, P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}{\sum_i \sum_j P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}$$

$$\overline{T}(p) = \frac{\sum_i \sum_j T(m_i, \delta_j) P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}{\sum_i \sum_j P(Y \geq y(p) \mid m_i, \delta_j) \, P_k(m_i) \, P_k(\delta_j)}$$

where $P_k(m_i)$ and $P_k(\delta_j)$ are probabilistic mass functions of the magnitude and epicentral distance, $T(m_i, \delta_i)$ is an attenuation relationship for the predominant period.

The hazard-consistent predominant period $\overline{T}(p)$ appears as an additional condition in determination of the epicenter of a hazard-consistent earthquake. The epicenter of the event defined by the quadriparametric disaggregation is an event which cause seismic motions at particular site with predominant period $\overline{T}(p)$.

The parameters of the hazard-consistent earthquake $\overline{M}(p_o)$, $\overline{\Delta}(p_o)$, $\overline{\Theta}(p_o)$ and $\overline{T}(p_o)$ are determined for predefined seismic hazard level p_o following an iterative procedure: 1) $\overline{M}(p_o)$, $\overline{\Delta}(p_o)$, $\overline{\Theta}(p_o)$ and $\overline{T}(p_o)$ are determined for coefficients of the spectral accelerations pertinent to T=0; 2) In the next iterations the parameters of the hazard-consistent earthquake are determined for the attenuation coefficients of spectral accelerations pertinent to $T=\overline{T}(p_o)$ from the previous step.

Hazard-consistent seismic demand spectrum

The hazard-consistent seismic response spectrum is defined as seismic response spectrum at certain location caused by the hazard-consistent earthquake, Trendafiloski [11]. It refers to mean elastic acceleration spectrum $\overline{S}_{A,el}(T, p_o)$.

$$\overline{S}_{A,el}(T, p_o) = f_T\left[\overline{M}(p_o), \overline{\Delta}(p_o) \mid \overline{T}(p_o)\right]$$

where f_T is attenuation of spectral accelerations, p_o is seismic hazard level.

The proposed hazard-consistent seismic response spectrum takes into consideration the type of soil conditions and its frequent characteristics are dependent on the hazard-consistent earthquake parameters, particularly to the hazard-consistent magnitude when local seismic sources are analyzed. The maximum spectral acceleration refers to the spectral acceleration corresponding to the mean predominant hazard-consistent period of the ground motion. The hazard-consistent elastic displacement spectrum is computed as follows

$$\overline{S}_{D,el}(T, p_o) = \frac{\overline{S}_{A,el}(T, p_o)}{4\pi^2} T^2$$

The elastic response spectra can be converted into constant-ductility inelastic spectra using strength reduction factor, Vidic et al. (1994)

$$\overline{S}_A(T, p_o) = \frac{\overline{S}_{A,el}(T, p_o)}{R_\mu} \qquad \overline{S}_D(T, p_o) = \frac{\overline{S}_{D,el}(T, p_o)}{R_\mu}\mu$$

where μ is ductility ratio and R_μ is the strength reduction factor.

The ADR coordinates of the mean hazard-consistent seismic demand spectrum are the parameters $\overline{S}_A(T, p_o)$ and $\overline{S}_D(T, p_o)$.

HAZARD-CONSISTENT SEISMIC DEMAND (HCD) SPECTRA FOR THE CITY OF SKOPJE

The HCD spectra for the City of Skopje are computed for the seismic hazard return periods defined by SEAOC Vision 2000, Bertero [1] (Table 1) taking into consideration the seismicity of the local seismic source Skopje-Vitina only. In delineation of the seismic zone the existing seismic source zoning in the Republic of Macedonia is used (Fig. 1).

Table 1. Seismic Hazard Return Periods

Earthquake	Return period (yrs)	Probability of exceedance p_o (%)
Frequent	43	50% in 30 yrs
Occasional	72	50% in 50 yrs
Rear	475	10% in 50 yrs
Very rear	970	10% in 100 yrs

The earthquake catalogue pertinent to the considered seismic source, Milutinovic [9] is divided into three subcatalogues with the following levels of completeness ($m_{o,i}$) and magnitude uncertainty (δ)

1. subcatalogue of historic data (δ=0.5);
2. subcatalogue of the instrumental data - period 1900-1937 (m_{o2}=4.0, δ=0.3); and,
3. subcatalogue of the instrumental data - period 1956-1996 (m_{o3}=4.0, δ=0.1).

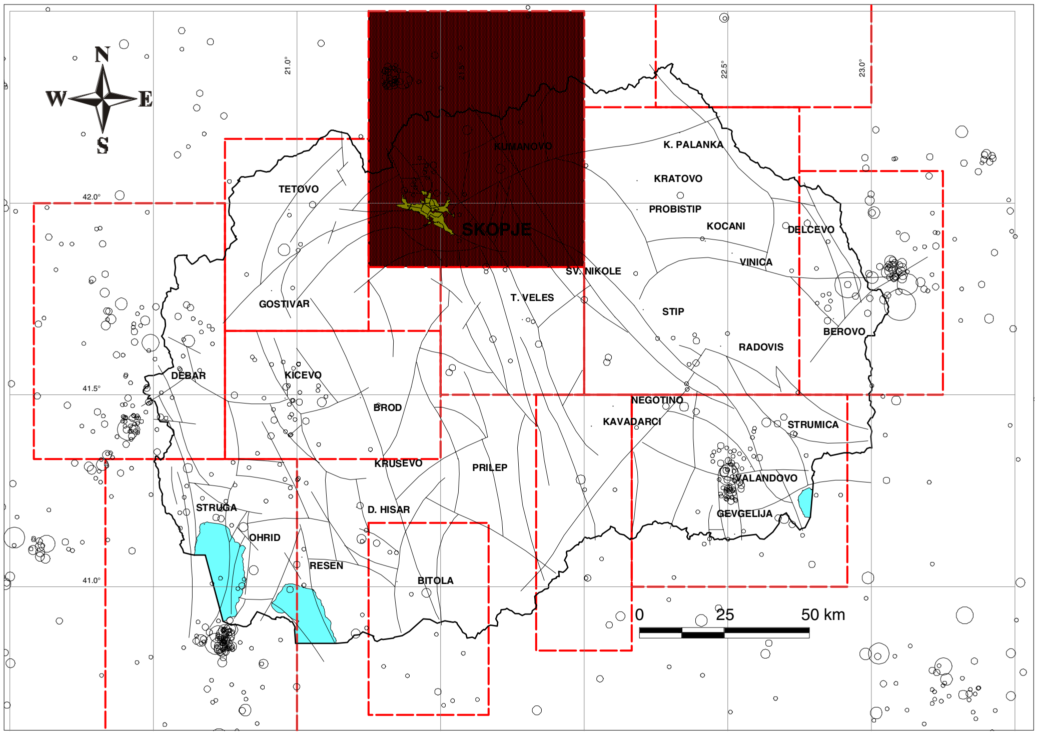

Fig. 1. Local Seismic Source Skopje-Vitina

The local magnitudes M_L are converted into surface wave magnitudes M_S by the Ambraseys, 1991 relationship $0.8\ M_L - 0.6\ M_S = 1.04$.

The magnitude frequency distribution and the seismic activity parameters of the Skopje-Vitina seismic source are presented in Fig. 2.

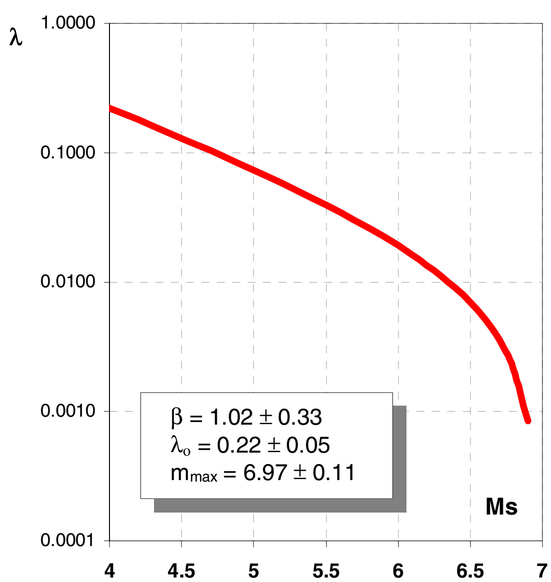

Fig. 2. Magnitude Frequency Distribution for Skopje-Vitina Seismic Source

The quadriparametric disaggregation of the seismic hazard is performed using the Ambraseys, 1996 spectral acceleration attenuation relationship as well as the Seed and Idriss, 1975 predominant period attenuation relationship.

The parameters of the hazard-consistent events and the disaggregates of the seismic hazard for the City of Skopje are presented in Table 2 and Fig. 3.

Table 2. Parameters of the Hazard-Consistent Events for the City of Skopje

RP (yrs)	p_o	$\overline{M}(p_o)$	$\overline{\Delta}(p_o)$ (km)	$\overline{\Theta}(p_o)$ (°)	$\overline{T}(p_o)$ (sec)
43	0.023	5.05	12.70	138.39	0.19
72	0.014	5.18	10.60	141.90	0.20
475	0.002	5.73	5.92	148.83	0.24
970	0.001	5.91	4.76	151.10	0.25

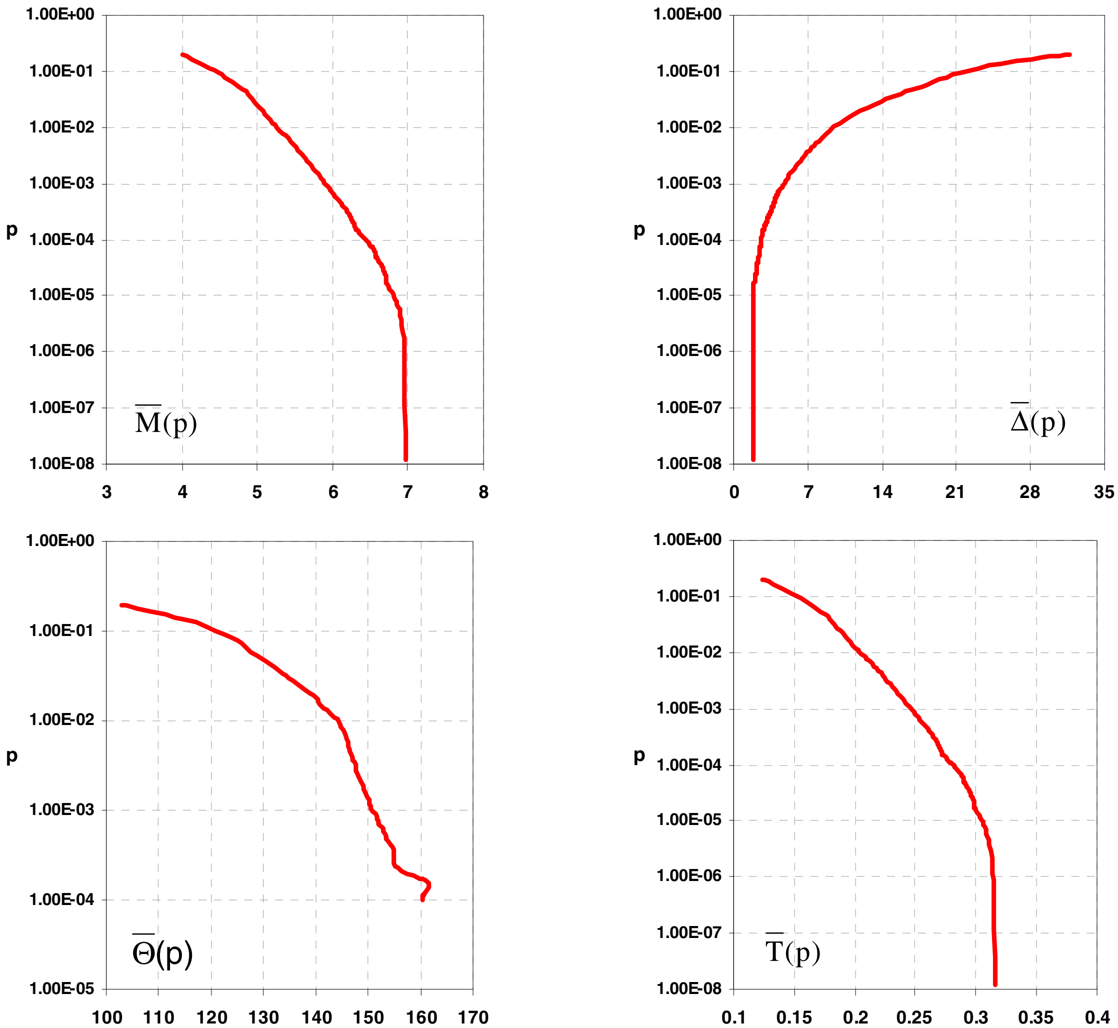

Fig. 3. Disaggregates of the Seismic Hazard for the City of Skopje

The mean hazard-consistent elastic ADR spectra (5% damping, return periods of 43, 72, 475 and 970 years) for the City of Skopje are presented in Fig. 4.

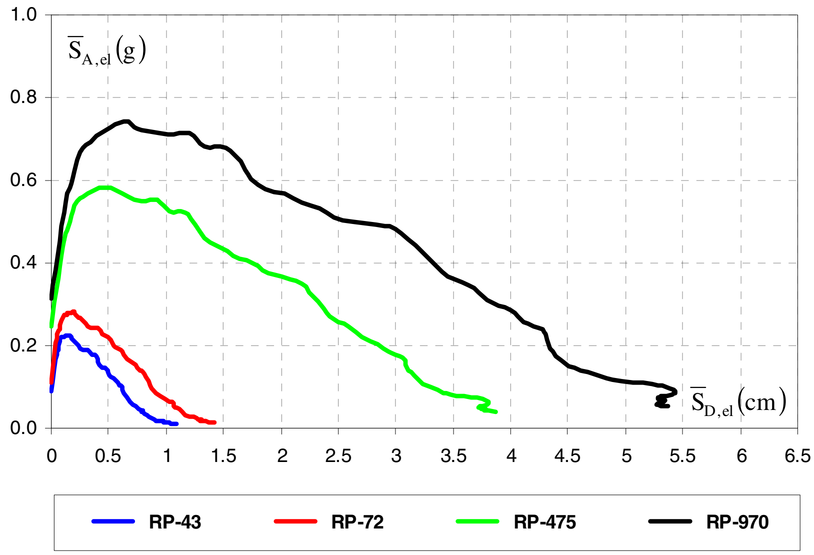

Fig. 4. Mean Hazard-consistent Elastic ADR Spectra for the City of Skopje

The mean hazard-consistent inelastic ADR spectra for the City of Skopje to be used as seismic demand spectra for fragility analyses are computed using bilinear spectrum for the strength reduction factor R_μ proposed by Vidic et al. (1994) and Fajfar [4]

$$
\begin{aligned}
R_\mu &= (\mu - 1)\frac{T}{T_c} + 1 && T < T_c \\
R_\mu &= \mu && T \geq T_c
\end{aligned}
$$

where T_C is a characteristic period of the ground motion (default value of T_C = 0.6 s is adopted).

The mean HCD spectra for the City of Skopje for return periods of 43, 72, 475, 970 years and ductility demand μ=4 are presented in Fig 5.

CONCLUSIONS

An advanced method for computing hazard-consistent seismic demand (HCD) spectra is recently developed. The HCD spectra refer to mean hazard-consistent constant ductility inelastic site response spectra. They are compatible with the recent fragility and performance estimation approaches and particularly are convenient for elaboration of probabilistic earthquake scenarios.

The quadriparametric disaggregation of the seismic hazard provides parameters for computing of response spectrum with single risk index pertinent to particular (hazard-consistent) event, hence overpassing one of the main disadvantages in the classical PSHA which tends to eliminate information on the physical characteristics of earthquakes in evaluation of site ground motions. The spectrum amplitude and frequent content are basically determined with the parameters of the event: hazard-consistent magnitude, distance and predominant period. The proposed disaggregation technique can be extended in order to include ground motion duration and other earthquake parameters for the stated needs.

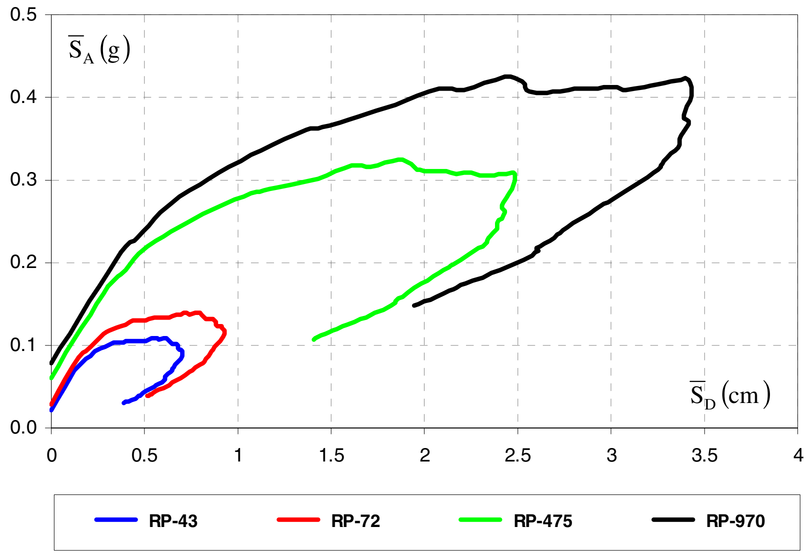

Fig. 5. Mean HCD Spectra for the City of Skopje

Due to the fact that in computation of demand spectra for the City of Skopje only the seismicity of the local seismic source Skopje-Vitina was considered, it can be concluded that HCD spectrum better represents the frequency and amplitude content of the expected site response spectrum if compared to code design ADC-81 [3] or HAZUS spectrum (Fig. 6). The application of code design and other model-defined spectra can cause certain overestimation of the expected seismic response of the structures.

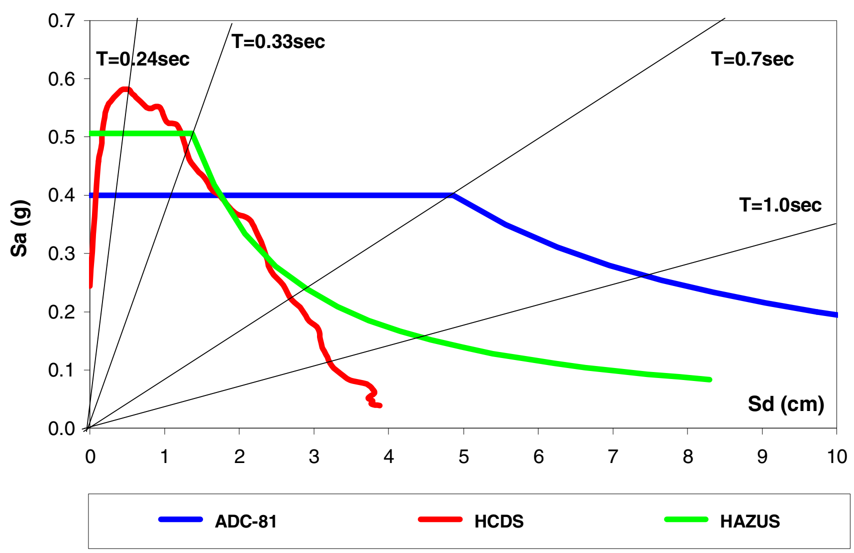

Fig. 6. Elastic Site Response Spectra for the City of Skopje (RP-475)
1) ADC-81 ground category II and zone seismicity IX; 2) HCDS -
2) Hazard-consistent demand spectrum (stiff soil conditions);
3) HAZUS response spectrum (soil category C)

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