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PROBABILISTIC SEISMIC HAZARD ANALYSIS FOR INELASTIC STRUCTURES ON SOFT SOILS

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ABSTRACT

The mean and the mean plus one standard deviation attenuation relations, appropriate for Vrancea intermediate foci (60-170 km) were established by non-linear multi-regression of the available set of peak ground accelerations, as a function of magnitude, azimuth, hypocentral distance and focal depth. The total data base contains more than 310 accelerograms from four Vrancea events.

The normalized elastic acceleration response spectra having 0.1 and 0.5 probability of exceedance were codified, according to the Eurocode 8 format, for the soft soil conditions of Bucharest and for the medium soil conditions in Romania.

For each type of soil category, the elastic to inelastic response factor $1/R_\mu$ is computed. For narrow frequency band motions recorded on soft soil conditions characterized by a long predominant period, the $1/R_\mu$ factor is a function of the ratio of the structure period to the site period (T_g).The practice-in-codes of scaling the elastic spectrum to obtain the inelastic spectrum through a factor, which is not dependent on the width of the frequency band of the excitation, is contrary to the results provided by nonlinear analysis.

KEYWORDS

Europe, intermediate depth earthquakes, seismic hazard, magnitude, probability of exceedance, peak ground acceleration, non-linear multiregression, narrow frequency band motions, predominant period, soft soil condition, response spectra, building codes, elastic to inelastic response factor.

1. PROBABILISTIC HAZARD ASSESSMENT FOR INTERMEDIATE DEPTH EARTHQUAKES

The Vrancea region, situated in South-East of Europe where the Carpathian Arc bends, is the source of an intermediate depth (60-170 km) seismic activity which affects more than 2/3 of the territory of Romania, an important part of the Republic of Moldova and a small area in Bulgaria.

The Gutenberg-Richter law for the recurrence intervals of earthquakes with magnitude greater than or equal to M was determined from C. Radu's catalogue of the Vrancea intermediate depth magnitudes occurred during this century (1901-1994). For the magnitude interval of interest in the civil engineering ($M \geq 6$), the average number of earthquakes per year (N) with a magnitude equal or greater than M is :

$$\log N(M \geq 6) = 3.489 - 0.720M \tag{1}$$

Attenuation relations for Vrancea intermediate depth foci were obtained through non-linear multi-regression of the peak parameters of the ground motions. A Joyner-Boore model was applied to a data base containing more than 310 accelerograms from four Vrancea events recorded in Romania, Republic of Moldova and Bulgaria, Table 1.

Table 1. Characteristics of the recorded Vrancea earthquakes

Date	Origin time	Lat. Long.	Focus depth, h, km	Richter magnitude, M	Seismic moment, M_0	Moment magnitude, M_w	Strike of fault plan Φ^0	Time of fracture, s	Seismic stations with records
1977, March 4	Source 1 19:21:56	45.78 26.78	93		$9.1x10^{26}$		220	20	
	Source 2 19:22:15	45.48 26.30	109	7.2	$7.1x10^{26}$	7.5	194	10	2
1986, Aug. 30	21:28:37	45.53 26.47	133	7.0	$8.1x10^{26}$	7.2	227	7	45
1990, May 30	10:40:06	45.82 26.90	91	6.7	$3.2x10^{26}$	7.0	232	5	64
1990, May 31	00:17:49	45.83 26.89	79	6.1	$3.5x10^{25}$	6.3	308	3	42

Taking into account : (i) the deep structure in Vrancea, where three tectonic units come in contact, (ii) the stability of the angles characterizing the fault plane and the motion on this plane and (iii) the ellipse-shape of the macroseismic field produced by the Vrancea source, the attenuation analysis was performed on two orthogonal directions corresponding to an average direction of the fault plan (N45E) and to the normal to this plane (N135E).

As a result , three circular sectors , of $90^{0,}$ each, centered on these directions, were established :

a) the Moldova sector on the East European platform (centered on NE direction);

b) the Cernavoda nuclear power plant sector (centered on SE direction);

c) the Bucharest sector on the Moesian Platform, oriented to the S-SE.

Using the modification of the Gutenberg-Richter relationship, proposed by Hwang and Huo (1994) in order to satisfy the propriety of the probability distribution :

$$N(\geq M) = e^{\alpha-\beta M} \frac{1 - e^{-\beta(M_{max}-M)}}{1 - e^{-\beta(M_{max}-M_o)}} \qquad (2)$$

where :

M_{max} is the maximum credible magnitude of the Vrancea source

M_0 - the threshold magnitude (M_0=6.0)

$\alpha = 3.489\ln10$ and β=0.720ln10

one gets :

$$N(\geq M) = e^{8.036-1.658M} \frac{1 - e^{-1.658(7.8-M)}}{1 - e^{-1.658(7.8-6.0)}} \qquad (3)$$

The maximum credible magnitude of the Vrancea source is estimated by seismologists to be at least 7.5 and at most 8.0.

The 50 yr. return period magnitude is $M_{50yr.}$=7.1 and the magnitude with a 10 percent probability of exceedance in 50 yr. is $M_{475yr.}$=7.6.

The mean and the mean plus one standard deviation attenuation relations, appropriate for Vrancea intermediate foci were established by non-linear, multi-regression of the available set of peak ground accelerations, as function of magnitude, azimuth (sector), hypocentral distance and focal depth. The following Joyner -Boore model was applied :

$$\ln PGA = c_1 + c_2 M + c_3 \ln R + c_4 h + \sigma_{\ln PGA} P \quad (4)$$

where : PGA is the maximum peak ground acceleration at the site, M - the magnitude, R - the hypocentral distance, h - the focal depth, $\sigma_{\ln PGA}$ - the standard deviation of the lnPGA variable, P - a binary variable (0 for mean attenuation curve and 1 for mean plus one standard deviation attenuation) and c_1, c_2, c_3, c_4 are data dependent coefficients.

Considering one event only, equation (4) becomes :

$$\ln PGA = c_1 + c_3 \ln R + \sigma_{\ln PGA} P \quad (5)$$

The attenuation characteristics of the observed maximum peak ground accelerations from the 1990, 1986 and 1977 Vrancea events are given in Table 2 and 3. These results can be used to predict 50 and 84 percentile of PGA, produced by a magnitude with a specified return period and a specified focal depth.

Table 2. Attenuation coefficients for intermediate depth (90-133 km) Vrancea earthquakes, Eq.(5)

Sector	Aug. 30, 1986			May 30, 1990			May 31, 1990		
	c_1	$-c_3$	$\sigma_{\ln PGA}$	c_1	$-c_3$	$\sigma_{\ln PGA}$	c_1	$-c_3$	$\sigma_{\ln PGA}$
Moldova	11.987	1.370	0.551	6.887	0.395	0.215	9.725	1.071	0.417
Cernavoda	18.678	2.711	0.368	11.280	1.298	0.296	11.367	1.474	0.464
Bucharest	14.864	1.954	0.328	9.084	0.884	0.341	9.959	1.295	0.477
All data	15.565	2.092	0.458	10.562	1.138	0.315	10.347	1.315	0.533

Table 3. Coefficients of directional attenuation for Vrancea earthquakes, Eq.(4).

Coefficients	Complete data set	Bucharest sector	Moldova & Bucharest	Cernavoda NPP sector
c_1	5.432	4.726	3.953	5.560
c_2	1.035	0.976	1.020	1.154
c_3	-1.358	-1.146	-1.069	-1.561
c_4	-0.0072	-0.0066	-0.0060	-0.0070
$\sigma_{\ln PGA}$	0.397	0.353	0.376	0.372

The May 31, 1990, earthquake, of very small magnitude and very short return period, is not included in the multi-regression analysis for the attenuation prediction.

2. RESPONSE SPECTRA AND ELASTIC TO INELASTIC RESPONSE FACTOR

More than 200 seismic records from four Vrancea events were analyzed to identify the frequency bandwidth. It was established that in the South, East and center of Bucharest, capital of Romania, the principal peak of the narrow frequency band spectral density indicates site conditions of 1.4 - 1.6 s long predominant period. The 30 meter layer of wet, soft clay, in the uppermost 50 meter depth, offers the explanation for the long period in the soil condition at INCERC station in the East of Bucharest. The long predominant period was experienced during the severe 1977 and the moderate 1986 earthquakes, Table 4, but not during the small 1990 event. This can be explained by both nonlinear behavior of the soil profile at this site and the source mechanism (magnitude, time of fracture). Opposite to the Bucharest narrow frequency band records, the records in Moldova have broad and intermediate frequency bandwidth and a negligible mobility of the spectral shapes to different magnitudes.

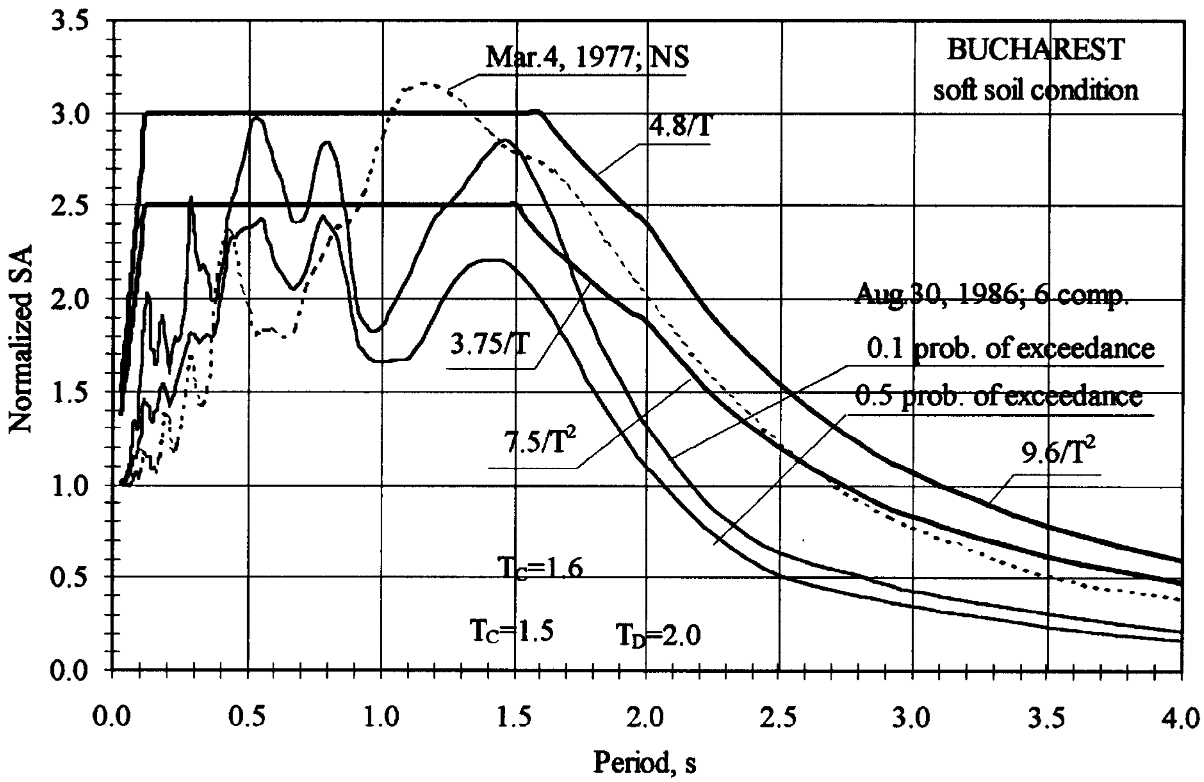


Fig. 1a Site dependent elastic response spectra for soft soil condition

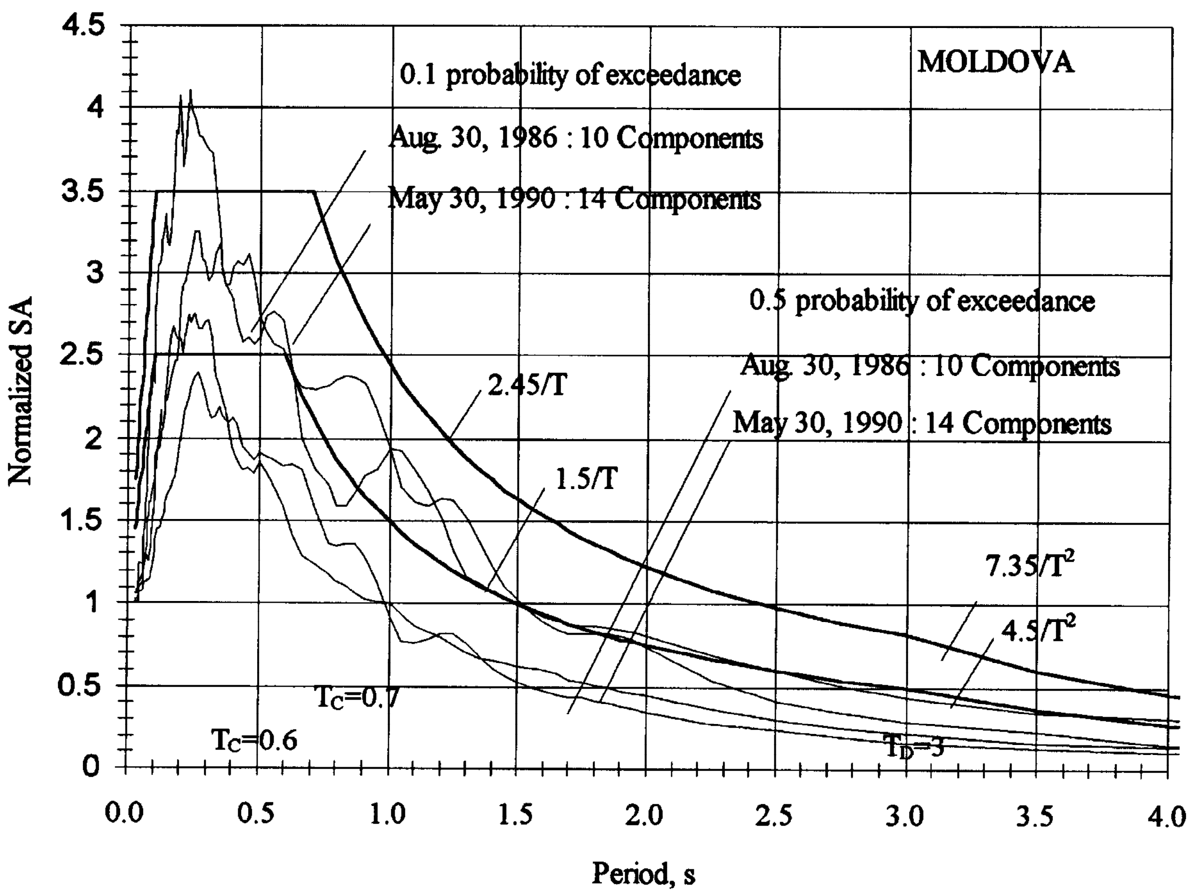


Fig. 1b Elastic response spectra for medium soil condition

Table 4. Long predominant period records produced by the Vrancea source in Bucharest

Station and location		Event	Comp	PGA, cm/s2	ε	PSD frequencies, Hz			RS control periods, s	
						f_{10}	f_{50}	f_{90}	T_C	T_D
INCERC	East of Bucharest	Mar.4, 1977	NS	194.9	0.97	0.4	0.69	2.0	1.34	1.90
		Mar.4, 1977	EW	162.3	0.91	0.4	1.44	4.1	1.19	2.02
		Aug.30,1986	NS	88.7	0.95	0.5	0.74	3.8	1.26	1.58
Carlton	Center of Bucharest	Aug.30,1986	N30W	68.6	0.90	0.5	1.37	4.9	0.95	1.61
ISPH		Aug.30,1986	N15E	86.7	0.92	0.5	1.25	4.0	1.22	1.66
Metalurgiei	South of Bucharest	Aug.30,1986	W32S	69.8	0.94	0.5	0.88	2.7	1.33	1.60
Metro IMGB		Aug.30,1986	N60E	72.7	0.92	0.6	1.12	3.8	1.49	1.52
Buc.Magurele		Aug.30,1986	NS	135.4	0.94	0.5	1.25	3.7	0.98	1.46

The normalized elastic acceleration response spectra having 0.1 and 0.5 probability of exceedance were codified, according to the Eurocode 8 format, for the soft soil conditions of Bucharest (in Romanian Plain) characterized by narrow frequency band records of 1.4-1.6 s long predominant period and for other soil conditions.

For the narrow frequency band motions from Bucharest, the median and the 0.1 probability of exceedance normalized acceleration elastic response spectra are presented in Fig.1a and Table 5 (for ζ=0.05). The results obtained for Bucharest indicates that the median normalized response spectrum recommended by Eurocode 8 for extreme soil class (T_C=0.8) are not conservative, at least for the Romanian case of soft soil deposits.

The control (corner) periods of the response spectra are defined as :

$$T_C = 2\pi\, SV_{max} / SA_{max} \qquad T_D = 2\pi\, SD_{max} / SV_{max} \tag{6}$$

where SD, SV and SA are the structure relative displacement, relative velocity and absolute acceleration spectral values.

Table 5. Design response spectra for various soil conditions in Romania (Eurocode 8 format)

Soil category		Soft soil condition, Bucharest		Medium soil condition	
Control periods of response spectra	T_A	0.12	0.12	0.1	0.1
	T_B	1.5	1.6	0.6	0.7
	T_C	2.0	2.0	3.0	3.0
Probability of exceedance		0.5	0.1	0.5	0.1
$T<T_B$		1+12.5 T	1+16.7 T	1+15 T	1+25 T
$T_B<T<T_C$		2.5	3.0	2.5	3.5
$T_C<T<T_D$		3.75 / T	4.8 / T	1.5 / T	2.45 / T
$T>T_D$		7.5 / T^2	9.6 / T^2	4.5 / T^2	7.35 / T^2

The response modification factor due to the nonlinear behavior of the structure , 1/R is generally the product of two factors, Fig.2 :

$$1 / R = (1 / R_\mu)(1 / R_{ov}) \tag{7}$$

where: $1/R_\mu$ is the factor to reduce the base shear force from the elastic level to the collapse level

$1/R_{ov}$ - the overstrength factor.

The $1/R_\mu$ factor based on the Newmark format ($1/R_\mu = (2\mu-1)^{1/2}$ is given as function of ductility in Fig.3 and Table 6:

$$1/R_\mu = [c_1\, \mu - (c_1 - 1)]^{c2} \tag{8}$$

Table 6. Elastic to inelastic response factor $1/R_\mu$, Eq.(8)

Probability of exceedance	Bucharest, soft soil condition (T_g = 1.5 s)		Medium soil condition	
	c_1	c_2	c_1	c_2
0.5	4.580	-0.274	2.794	-0.400
0.1	3.943	-0.229	1.603	-0.349

The values of $1/R_\mu$ are clearly dependent on the spectral content of the seismic input, i.e. soil category.
In Table 7, for each type of soil category, the elastic to inelastic response factor $1/R_\mu$ is computed in terms of displacement ductility (μ) and initial period (T) and damping (ζ=0.05) of the structure.
For the wide and intermediate frequency band motions recorded on medium soil conditions, the $1/R_\mu$ factor does not depend on the structure period for T≥0.5.
For narrow frequency band motions recorded on soft soil conditions characterized by a long predominant period, the $1/R_\mu$ factor is a function of the ratio of the structure period (T) to the site period (T_g), Hwang and Hsu, 1991. The coefficient of variation of $1/R_\mu$ factor has a peak for the structure period approximately equal to the site period. The higher the structure lateral ductility ,μ the larger the coefficient of variation of $1/R_\mu$.

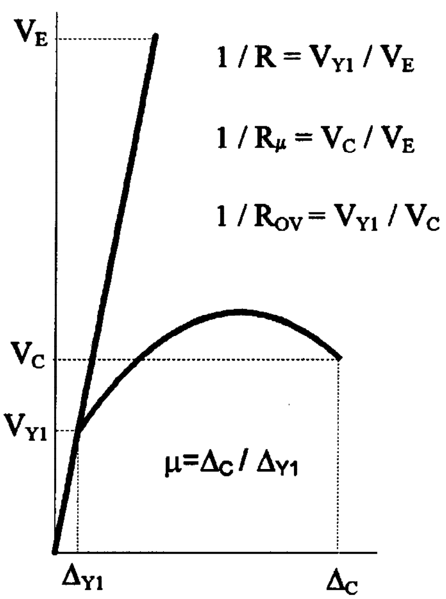


Fig.2 The response modification factor 1/R

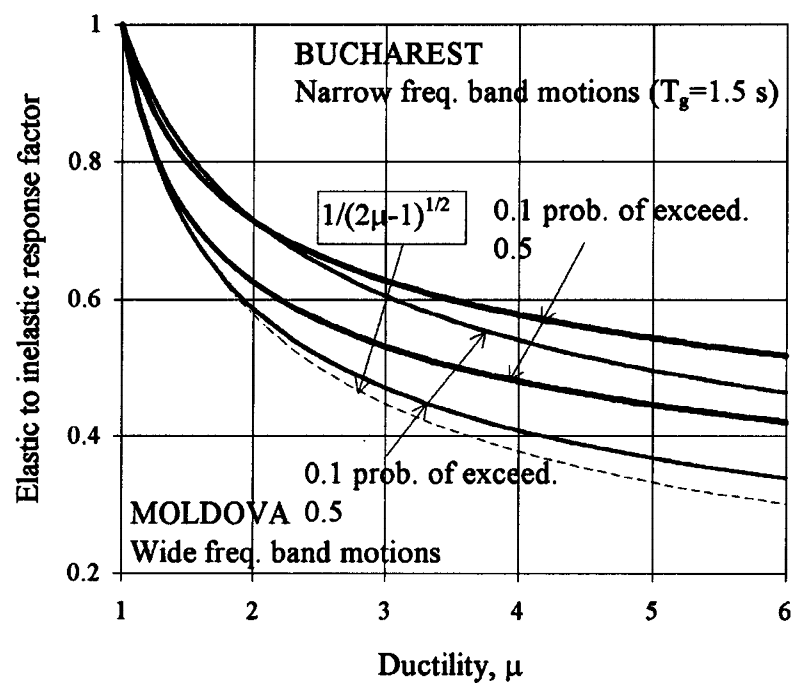


Fig. 3 $1/R_\mu$ factor as function of structure lateral ductility

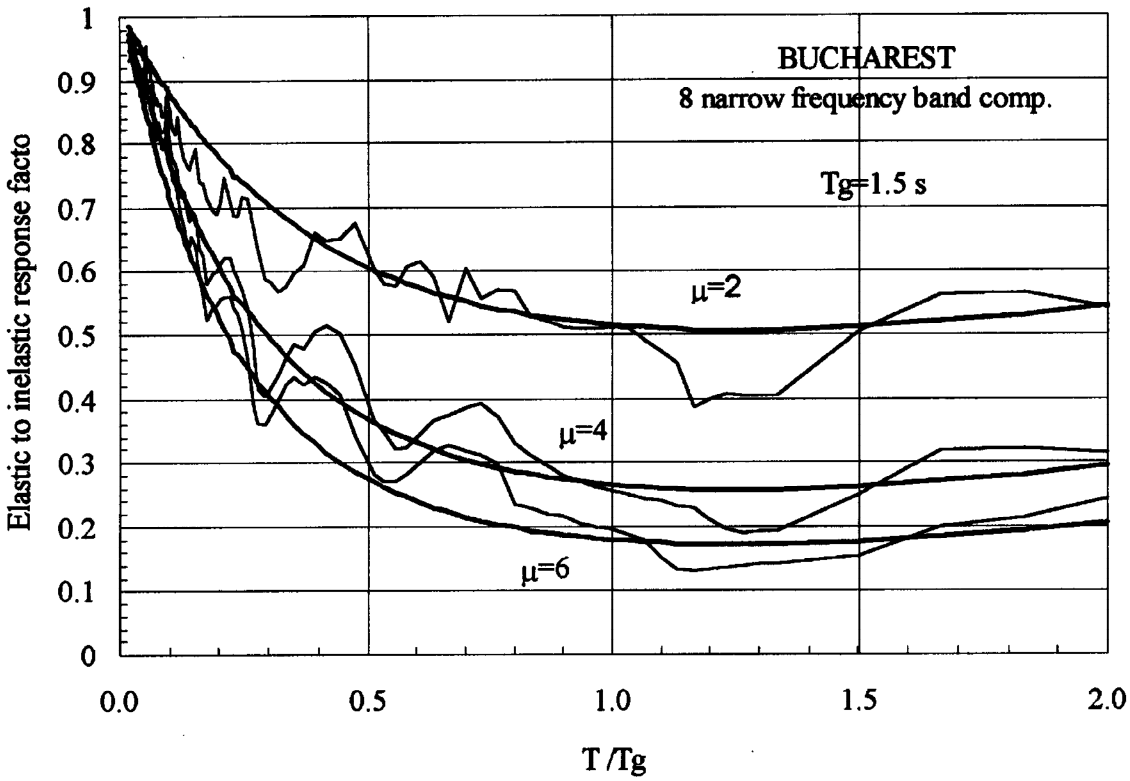
The statistical analysis of the nonlinear response ordinates uses the lognormal model. Median and 10% probability of exceedance $1/R_\mu$ factor are shown in Fig.4 as a function of the spectral content of the ground motion, i.e. soil category:

(i) Narrow frequency band motions on soft soils:

$$1/R_\mu=\mu^{c1[c2+\exp(-c3\ T/Tg)-\exp(-c4\ T/Tg)]} \qquad (9)$$

(ii) Wide and intermediate frequency band motions on medium soils :

$$1/R_\mu=\mu^{c1[c2+\exp(-c3\ T)-\exp(-c4\ T)]} \qquad (10)$$



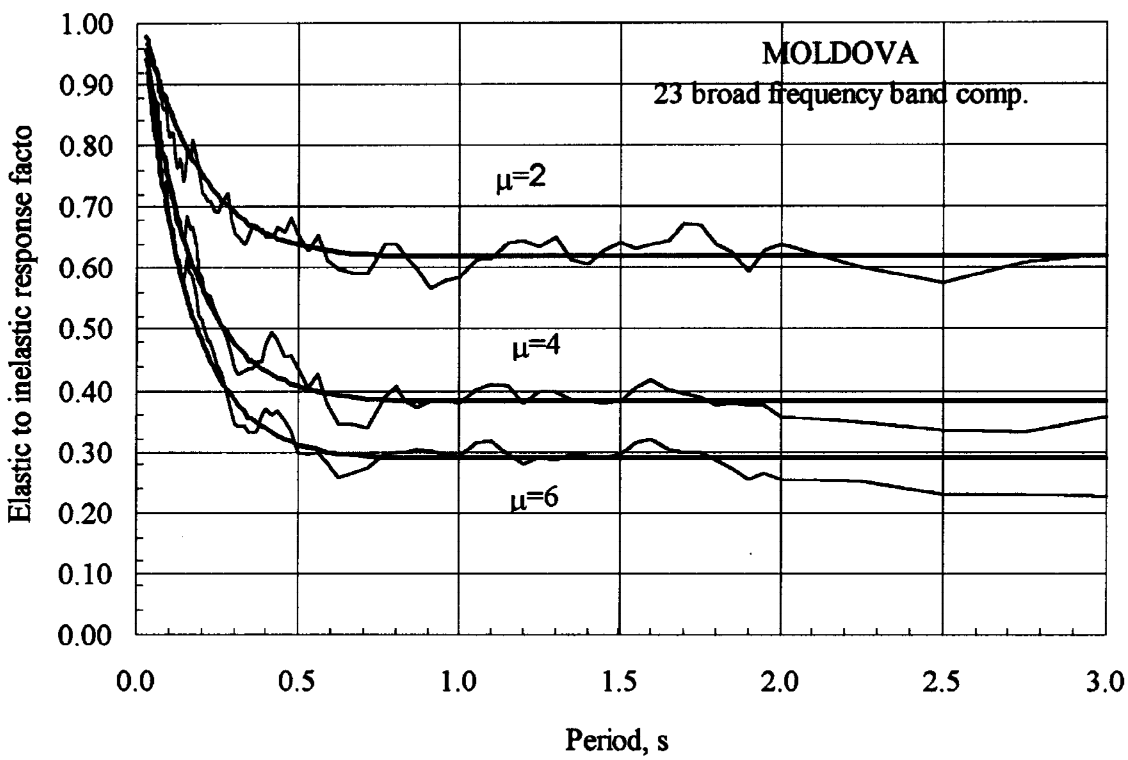


Fig.4 Elastic to inelastic response factor, 1/Rμ with 0.1 probability of exceedance

Table 7. Elastic to inelastic response factor, $1/R_\mu$ coefficients, Eq.(9) and Eq.(10)

Probability of exceedance	Bucharest, soft soil condition (T_g=1.5 s)				Medium soil condition			
	c_1	c_2	c_3	c_4	c_1	c_2	c_3	c_4
0.5	1.858	-0.010	1.959	0.231	1.151	0.1207	6.216	-0.00089
0.1	2.415	0.0105	1.362	0.409	0.780	0.106	4.967	-0.00161

The scaling of the elastic spectrum to obtain inelastic spectrum through a factor which is not dependent on the width of the frequency band of the excitation is neither rational nor appropriate. For the narrow frequency band motions, the practice-in-codes of scaling using a period-independent factor is contrary to the results provided by nonlinear analysis.

CONCLUSIONS

A probabilistic hazard evaluation for intermediate-depth (60-170 km) Vrancea source as a function of azimuth, hypocentral distance, magnitude and focal depth was performed. The diagnosis of narrow frequency band motions of long (1.5 s) predominant period on wet, soft clay in Bucharest was achieved by stochastic measures. Normalized acceleration elastic response spectra having 0.5 and 0.1 probability of exceedance, for soft and intermediate soil conditions in Romania are established (Eurocode 8 format). The statistical study of nonlinear response presents elastic to inelastic response factors computed for 0.5 and 0.1 probability of exceedance as a function of the structure lateral ductility and the width of the frequency band of the ground motion (i.e. soil category).

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