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SMOOTH SPECTRA OF HORIZONTAL AND VERTICAL GROUND MOTIONS FOR IRAN

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ABSTRACT

In this study, several practical limitations of the current building code of Iran are addressed with respect to seismic hazard analysis (SHA) projects. The main concern of the present study is to propose a practical procedure for constructing smooth response spectra from the peak values of ground motion. The dynamic amplification factors are calculated for horizontal and vertical components, considering a selection of Iran's strong-motion records, and are compared with those proposed in the previous studies. The results and conclusions of this study are effective in the evaluation of the Iranian code and can be used in the SHA projects in Iran.

KEYWORDS: Smooth Response Spectra, Seismic Hazard Analysis, Iran

INTRODUCTION

Iranian plateau has long been known as an active seismic area in the world, which from time to time has suffered from destructive and catastrophic earthquakes, causing heavy loss of human lives and widespread damage. Recently, after the destructive earthquakes of Avaj in the year 2002, Bam earthquake of 2003, etc., there has been a considerable increase in the demand for performing site-specific seismic hazard analysis (SHA). While SHA provides the occurrence rate of future earthquake ground motions, the evaluation of the effects of these ground motions on the structural response is also strongly needed. The response of a structure to an earthquake motion can be evaluated using response spectra, which are defined as the graphic relationship between the maximum responses of single-degree-of-freedom (SDOF) systems and their natural periods. However, the individual response spectra of strong-motion records have jagged shapes with significant peaks and valleys and differ remarkably; hence, they can only be used to evaluate the seismic forces during specific earthquakes at certain sites (Newmark and Hall, 1969). As opposed to the response spectra, design response spectra, as suggested by several building codes, are extremely effective in identifying the loads during the probable earthquake ground motions in future.

Recent studies (e.g., Tehranizadeh and Hamedi, 2003; Ghodrati Amiri et al., 2003) on design response spectra in Iran are limited to the influence of ground motion parameters of Iran earthquakes and local site conditions on the design spectra. In the previous studies in Iran, the response spectra were normalized to peak ground accelerations (PGAs); however, as shown in several studies (Malhotra, 2006; Newmark and Hall, 1969; Hall et al., 1976), such normalization schemes are not proper for all frequency ranges. Furthermore, in the previous studies in Iran only horizontal (and not the vertical) components of ground motions were considered. In this study, the modified methodology proposed by Malhotra (2006) is followed in order to construct smooth response spectra for both horizontal and vertical components. Furthermore, smooth spectra are adjusted for different damping values. The data, recorded in Iran, is also used to establish relationships between the peak ground motion parameters, PGA, PGV, and PGD. In the current SHA projects in Iran, the most ordinary output parameter is PGA; however, to construct the smooth spectra, based on the methodology proposed by Malhotra (2006) and those described in several other studies (Newmark and Hall, 1969; Mohraz, 1976), it is indicated that peak ground motion parameters (PGA, PGV, and PGD) should be determined and due to weak correlation between these parameters, it is necessary that they be estimated independently.

The main motivation of this study is presented after a brief introduction to Iranian Code of Practice for Seismic Resistant Design, Standard No. 2800 (BHRC, 2003). The main characteristics of the selected strong-motion data bank are described thereafter. Then, the methodology as followed is described, and the results are presented. Subsequently, the results are compared with those of the similar studies, and the concluding remarks are given. Finally, a practical example on constructing smooth response spectrum, by using the proposed methodology, is presented.

LIMITATIONS OF STANDARD NO. 2800

Iran has had an earthquake code since the destructive earthquake of Boeen Zahra in the year 1962. Iranian code of practice for the seismic-resistant design of buildings (i.e., the so-called Standard No. 2800) (BHRC, 2003) was revised by the Building and Housing Research Center (BHRC) in 1987. It became mandatory after the Roodbar-Manjil earthquake in the year 1990. It has been revealed that most of the severely damaged and/or collapsed constructions due to the moderate-to-large earthquake ground motions were the ones, which had not followed the code (Zare, 2004).

In Standard No. 2800 (BHRC, 2003), the building factor (i.e., the normalized spectral acceleration) is calculated as follows:

$$B = \begin{cases} 1 + S\left(\dfrac{T}{T_0}\right) & ;\ 0 \le T \le T_0 \\ 1 + S & ;\ T_0 \le T \le T_S \\ (1+S)\left(\dfrac{T_S}{T}\right)^{2/3} & ;\ T \ge T_S \end{cases} \tag{1}$$

where T is the natural period of the building, T_0 and T_S are the control periods having fixed site-dependent values, as listed in Table 1; and S is the parameter that depends on the site class and hazard level. The corresponding S values for each category are listed in Table 1. The design response spectrum of the horizontal ground motion is obtained for each site by multiplying the building factor by PGA, which is based on the probabilistic seismic hazard analysis.

Table 1: Values for the T_0, T_S and S Factors Recommended in Standard No. 2800 for Different Site Categories

Site Class	T_0	T_S	S	
			Low-Moderate Hazard Level	High-Very High Hazard Level
I	0.10	0.4	1.50	1.50
II	0.10	0.5	1.50	1.50
III	0.15	0.7	1.75	1.75
IV	0.15	1.0	2.25	1.75

As mentioned above, PGA is recommended in Standard No. 2800 to derive design values for the entire period range. However, in some building codes the design response spectrum consists of two or three regions, for example, short, long, and very-long period ranges (e.g., ICC, 2003, 2006). In these codes, the design response spectrum is characterized in terms of spectral acceleration (SA) at specific periods, e.g., 0.2 and 1 s in ICC (2003). Actually, it is outlined in previous studies (e.g., Mohraz et al., 1973; Newmark and Hall, 1969) that the response spectra for earthquake ground motions can be divided into three general regions, namely, acceleration-sensitive, velocity-sensitive, and displacement-sensitive. It is assumed that SAs in each region are reasonably well-correlated to the corresponding peak ground motion parameters; hence, to construct each region, corresponding peak ground motion parameter, i.e., PGA, PGV, or PGD, should be used. This method of constructing response spectrum is better than the one, which uses spectral accelerations at the specified periods (say, 0.2 and 1 s), because PGA, PGV, and PGD, being the fundamental ground motion parameters, are much more intuitive to an engineer than SA at 0.2 or 1 s. Another reason for using PGA, PGV, and PGD is that this makes the selection of site-specific ground motions much easier. Hall et al. (1976) and Mohraz (1976) suggested the ranges, T < 0.33 s, 0.33 < T < 3.33 s, and T > 3.33 s for the acceleration-, velocity-, and displacement-sensitive regions. Figure 1 shows the correlations between SA at various periods and PGA, PGV, and PGD. It is seen that, for the selected set of strong ground motions, SAs are best correlated to PGA for the periods up to 0.2 s, to PGV for the periods between 0.2 and 3.0 s, and to PGD for the rest of the periods. A comparison of the outcomes indicates that the results of this study are different from and slightly lower than those obtained by Hall et al. (1976) and Malhotra (2006), due to difference in the datasets used. Here, the approach proposed by Malhotra (2006) is used. The main advantage of this approach lies in making no prior assumption for the cut-off periods.

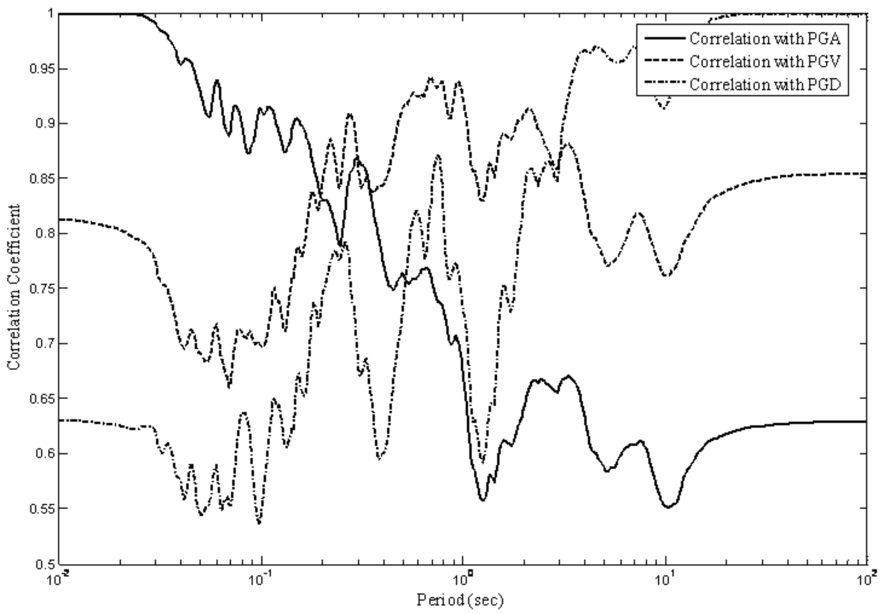

Fig. 1 Correlation of SA at various periods to peak ground motion parameters

Another issue that is not addressed in Standard No. 2800 is the evaluation of response spectrum for different damping ratios. In other words, the design spectra can be constructed only for the 5% damping. However, it is indicated that a broad range of damping ratios can be given for each type of structure, as many factors and design details have influence on the damping. In this study, a functional form of amplification factors is derived to evaluate the amplifications for any damping ratio.

The last issue addressed in this study is of smooth response spectra for the vertical component of ground motion. Conventional building structures have considerable inherent strengths in the vertical direction, and therefore, the effects of vertical components of ground motions are relatively unimportant. Probably, this is the main reason why the vertical ground motion and corresponding building factor are not included in Standard No. 2800. However, for certain types of structures (e.g., dams), the effects of vertical component may be of some significance (Chopra, 1966). In this study, a smooth response spectrum for the vertical ground motions is proposed. In addition, the corresponding amplification factors for the vertical component are also provided for different damping values.

THE ACCELEROMETRIC DATA BANK

Most of the high-populated cities in Iran are close to active faults and have been severely damaged during past moderate-to-large earthquakes. Such vulnerability to earthquakes is also evident in other historical reports. However, strong ground motions could be registered only after the installation of Iranian Strong Motion Network (ISMN) in 1973. Since 1973, the network has gradually been expanded, and at present it consists of 1065 digital and 29 analog accelerographs. Considering the locations of the severely affected regions as well as the magnitudes of the past destructive earthquakes, a set of strong-motion records, located at the near-field regions during the earthquakes with moment magnitudes equal to or larger than 6, is selected for this study. To consider the effects of strong motions, only those records for which the maximum horizontal ground accelerations are greater than 0.05*g* are used. The locations of stations and the corresponding seismological information for each record are given in Appendix. The geographical distribution of the stations and epicenters of the earthquakes are shown in Figure 2. The assigned site classes, based on Zare et al. (1999) and Sineian (2006), for each station are also listed in Appendix. In these studies priority is given to Vs30 and surface geology data, whenever available. Those stations, for which these parameters were not available, are classified by estimating the fundamental frequency at each station, by using Nakamura's technique. However, as it is clear from the recent studies, the site classification based on an empirical scheme should be used with care, and it should be noted that the accuracy may decrease rapidly as the number of records decreases (Zhao et al., 2006; Ghasemi et al., 2009).

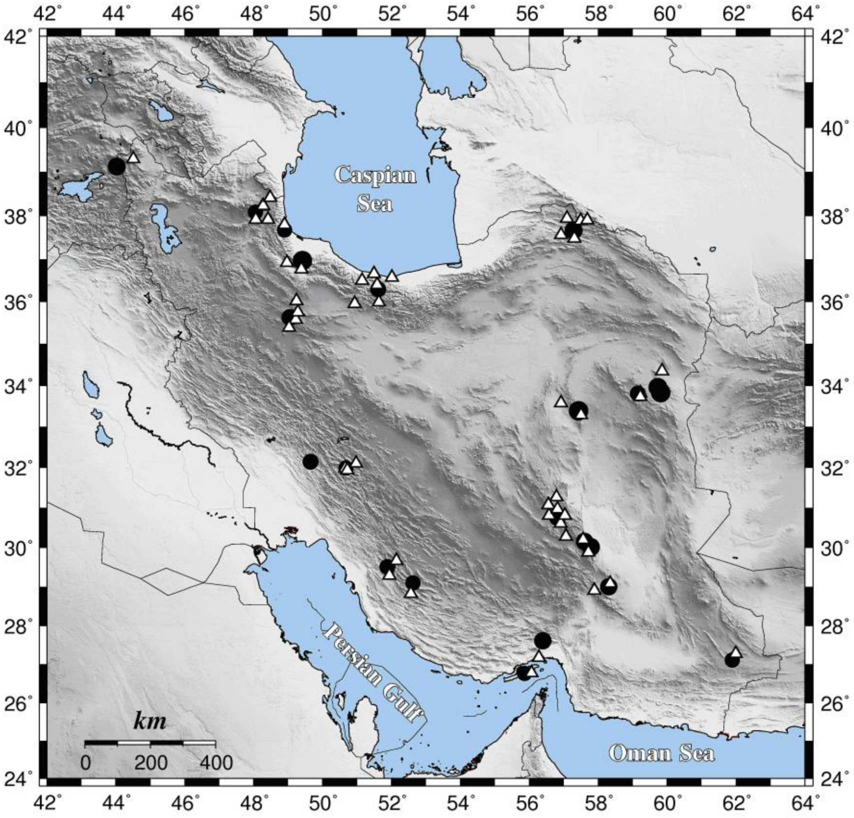

Fig. 2 The geographical distribution of the strong-motion stations (shown as triangles) and epicenters of the events (shown as circles) considered in this study

Almost all strong-motion records in the datasets show clear baseline shifts, and the records are contaminated by long-period as well as high-frequency noise. The reasons of such shifts were well addressed in the previous studies (e.g., Boore and Bommer, 2005). In this study, the procedure proposed by Boore et al. (2002) and Boore and Bommer (2005) is followed. The scheme involves fitting a quadratic polynomial to the velocity baseline followed by filtering. The processed accelerogram and the corresponding velocity and displacement time-histories for the records recorded at Bam station during the Bam earthquake of 2003 are shown in Figure 3(a). The peak ground motion parameters, PGA, PGV, and PGD, and the significant durations of strong-motion records, as considered in this study, are tabulated in Table 2. The listed PGA, PGV, and PGD are the geometric mean values of the two horizontal components, and the duration values are the averages of the significant durations in two horizontal directions. The compatible response spectrum of each component is then calculated using the methodology described in Malhotra (2001). In this method, the short-, medium-, and long-period spectral values are derived from the processed acceleration, velocity, and displacement histories, respectively. This method guarantees the correct asymptotic behavior of the computed response spectrum. Figure 3(b) demonstrates the computed response spectra, of different damping values, from the time-histories shown in Figure 3(a). In this figure all spectral quantities, like displacement, velocity, and acceleration, are displayed in a single graph (on log-log scale), known as the tripartite graph. As can be seen, the response spectrum shows the correct asymptotic behavior, i.e., the spectral acceleration approaches PGA at the short periods and the spectral deformation approaches PGD at the long periods.

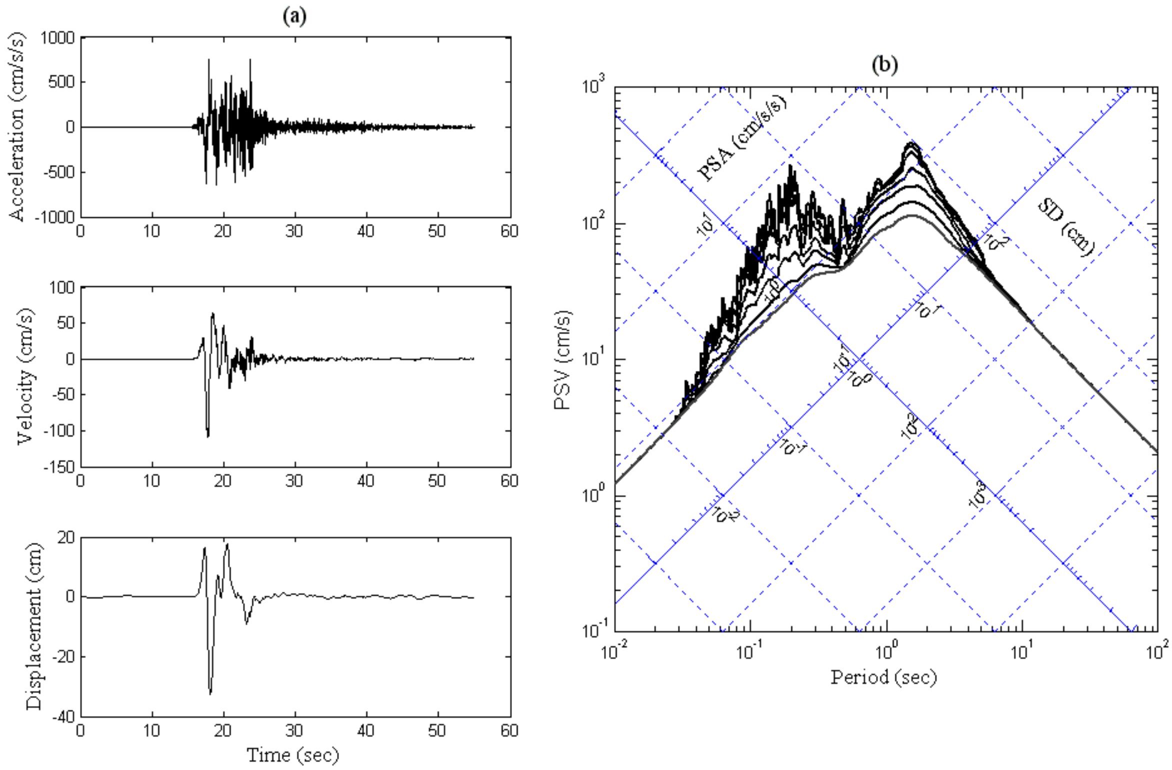

Fig. 3 (a) Processed acceleration, velocity, and displacement time-histories of the ground motion registered during the 2003 Bam earthquake at the Bam station; (b) Response spectra for several damping values computed from the time-histories at the Bam station

Table 2: Corresponding Peak Ground Motion Parameters, Significant Duration T_{cg}, and Normalized Peak Ground Velocity, of Strong-Motion Records Considered in This Study

Station	PGA (cm/s/s)	PGV (cm/s)	PGD (cm)	Duration (s)	T_{cg} (s)	$\overline{\text{PGV}}$
Kariq	541.74	14.28	0.80	4.83	0.24	0.69
Vendik	519.29	7.98	0.87	0.12	0.26	0.38
Naghan-1	81.62	2.23	0.19	0.63	0.30	0.57
Avaj	438.98	20.49	1.54	6.41	0.37	0.79
Hasan Keyf	650.28	40.28	3.23	2.18	0.44	0.88
Baraqan	93.01	3.76	0.59	9.68	0.50	0.51
Namin	89.25	2.27	0.59	13.13	0.51	0.31
Razan	193.60	9.39	1.38	13.55	0.53	0.57
Garmabdar	70.68	3.14	0.55	11.95	0.55	0.50
Poul	213.45	7.75	1.81	13.85	0.58	0.39
Shirinrood Dam1	305.84	16.71	2.70	9.28	0.59	0.58
Manjil	434.84	10.38	4.10	1.76	0.61	0.25
Sib Sooran	86.88	5.83	0.83	6.37	0.61	0.69
Suza	265.07	10.61	2.56	7.41	0.62	0.41
Balaadeh	343.32	11.58	3.41	7.61	0.63	0.34
Qasem Abad	164.93	11.93	1.93	4.78	0.68	0.67

Talesh	53.32	1.99	0.72	2.22	0.73	0.32
Khan Zeynioun	140.76	9.28	2.02	13.34	0.75	0.55
Qadrooni Dam	170.01	12.68	2.95	14.14	0.83	0.57
Deyhuk	343.01	23.32	6.55	34.25	0.87	0.49
Bojnoord	155.96	8.42	3.06	6.05	0.88	0.39
Abgarm	128.47	10.75	2.83	13.30	0.93	0.56
Naghan-1	669.47	43.45	14.89	3.06	0.94	0.44
Ravar	89.10	7.68	2.10	20.49	0.96	0.56
Dastgerd	97.62	3.30	2.39	4.80	0.98	0.22
Darsejin	63.66	3.54	1.60	12.61	0.99	0.35
Noor	56.09	6.95	1.53	28.34	1.04	0.75
Raz	88.12	5.42	2.41	14.11	1.04	0.37
Maku	83.56	3.94	2.33	18.39	1.05	0.28
Ashkhaneh	106.58	7.23	3.00	23.15	1.05	0.40
Kerman	98.95	8.66	2.94	20.32	1.08	0.51
Ghaen	168.53	14.33	5.01	10.31	1.08	0.49
Sirch	564.89	76.02	17.68	5.88	1.11	0.76
Chatrood	68.39	5.44	2.18	13.69	1.12	0.45
Helabad	67.98	5.95	2.19	12.02	1.13	0.49
Noshahr	85.75	9.19	2.84	26.07	1.14	0.59
Bam1	659.03	81.85	22.26	8.85	1.15	0.68
Zarand	268.95	24.05	9.12	18.87	1.16	0.49
Mohammad Abad-e-Maskoon	88.72	6.24	3.13	18.24	1.18	0.37
Ardebil 2	142.63	14.37	5.13	34.82	1.19	0.53
Robat	117.33	9.91	4.43	14.80	1.22	0.43
Bandarabbas	129.56	11.35	4.98	22.32	1.23	0.45
Gifan	136.40	9.70	5.25	14.69	1.23	0.36
Abbar	568.93	46.48	22.16	30.14	1.24	0.41
Golbaf	250.28	27.18	10.16	38.64	1.27	0.54
Dasht-e-Khak	52.88	4.60	2.27	14.58	1.30	0.42
Ardebil 1	95.92	9.22	4.53	34.12	1.36	0.44
Ghaen	173.44	16.04	9.30	12.74	1.45	0.40
Tabas	852.93	94.05	52.60	18.86	1.56	0.44
Firouzabad	105.73	10.90	8.75	10.37	1.81	0.36

RELATIONSHIPS BETWEEN PEAK GROUND MOTION PARAMETERS

The seismic macrozonation hazard map in Standard No. 2800 suggests only the base acceleration values for the zones with different hazard levels; however, as mentioned before, to construct a design response spectrum, PGV and PGD estimates are also needed. Mohraz (1976) and Hall et al. (1976) used two different ratios to estimate PGV and PGD from the specified design acceleration. These ratios are PGV to PGA ratio, called as v/a ratio, and PGA-PGD product to PGV-squared ratio, called as ad/v^2 ratio; the latter ratio represents the frequency bandwidth of the ground motion. For each site category, Mohraz (1976) considered the horizontal components with larger and smaller peak ground accelerations and the vertical components of records as separate groups. The desired ratios were then derived statistically for the individual groups. In this study, strong-motion records are also grouped according to this criterion. Figure 4 shows box and whisker plots for v/a and ad/v^2 ratios for each site category; the boxes have lines at the lower, median, and upper quartile values, while the whiskers are the lines extending from each end of the box to show the extent of the rest of the data. The ratios shown in the figure are computed from the horizontal components of records with larger peak ground accelerations. For 50 percentile, the v/a values are 0.054, 0.039, 0.082, and 0.075 s for the SC-I, SC-II, SC-III, and SC-IV sites, respectively. Generally, the rock sites (i.e., SC-I sites) show lower v/a values than the soil sites (i.e., SC-III, SC-IV sites), which indicates a shift toward the longer-period motions on softer soil sites. The corresponding values for the ad/v^2 ratio are 5.53, 5.51, 4.33, and 4.20. The highest value is obtained, on average, for the rock sites, indicating that the average spectrum for such sites has a broader bandwidth.

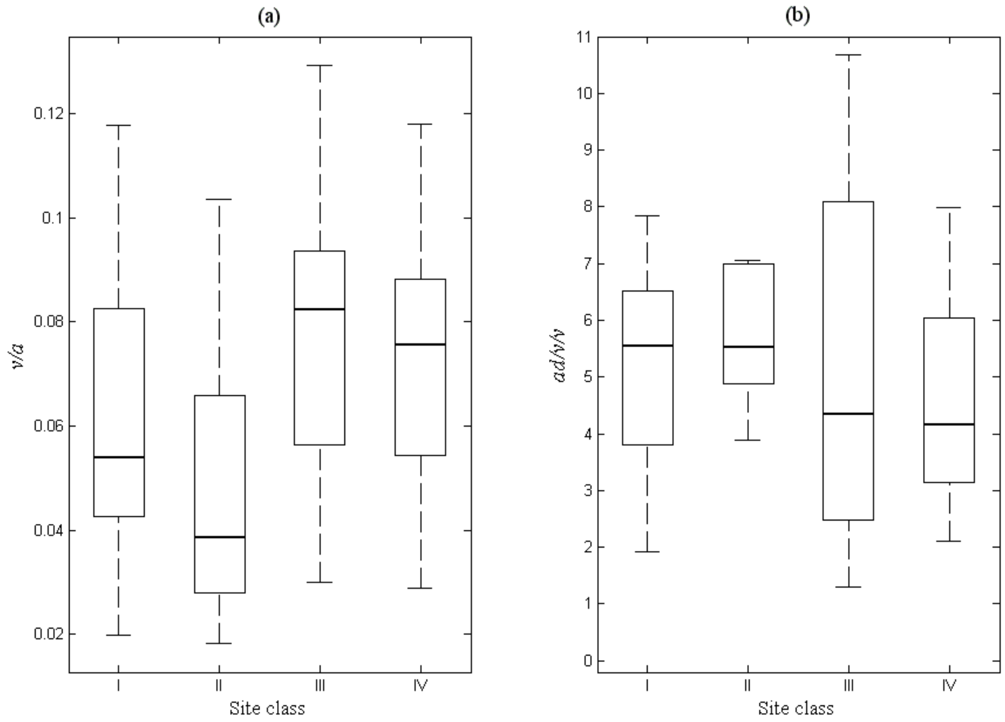

Fig. 4 Box and whisker plots for the (a) v/a and (b) ad/v^2 ratio, for each site category

Although the strong-motion records are grouped according to the criterion of Mohraz (1976), the consequences of a balanced one-way analysis of variance indicate that the results for the horizontal components of records with larger peak ground accelerations are not significantly different from those with smaller peak ground accelerations. The same conclusion can be made for the ratios calculated for each site condition. Therefore, only one set of the desired ratios for the horizontal and vertical components is proposed in this paper. The 50 and 84.1 percentile values for the v/a and ad/v^2 ratios are tabulated in Table 3. The median and median plus one standard deviation of the peak vertical to peak horizontal acceleration ratio are 0.6 and 0.9, respectively. For engineering purposes, the peak vertical acceleration is often assumed to be two-third of the peak horizontal one, which is slightly less than the 84.1 percentile and higher than the median values obtained in this study.

Table 3: 50 and 84.1 Percentiles of the v/a and ad/v^2 Ratios for Horizontal and Vertical Ground Motions

Component	v/a (s)		ad/v^2	
	Percentile		Percentile	
	50	84.1	50	84.1
Horizontal	0.068	0.1	4.8	8.3
Vertical	0.067	0.1	5.8	9.7

It is important to bear in mind that the relationships between PGA and PGV and between PGA and PGD depend on the magnitude of the earthquake and the distance of the site from the source; hence, in practice, the three peak ground motion parameters should be estimated independently.

SMOOTH SPECTRUM OF GROUND MOTIONS

Different response spectra, as calculated from different strong-motion records, can be compared by normalizing those to the same scale. The normalization involves defining cutoff periods for the acceleration-, velocity- and displacement-sensitive regions, and then dividing the spectral values at each period to the corresponding peak ground motion parameter. However, such a scheme needs a prior assumption of the cutoff periods (Newmark and Hall, 1982; Hall et al., 1976; Mohraz, 1976), which can change from one set of ground motions to another. In this study, the normalization scheme proposed by Malhotra (2006) is followed. This scheme has an advantage that it needs no prior assumption of the cutoff periods. It involves normalization of the period scale by dividing all periods by

$$T_{cg} = 2\pi\sqrt{\frac{\text{PGD}}{\text{PGA}}} \tag{2}$$

where T_{cg} marks the boundary between the high- and low-frequency regions (Malhotra, 2001, 2006). Next, the spectral velocity (SV) and PGV are normalized by the $\sqrt{\text{PGA}\times\text{PGD}}$ factor.

Normalized peak ground velocity, $\overline{\text{PGV}}$, is related to the reciprocal of ad/v^2 ratio, and hence, higher values of normalized peak ground velocity are generally expected for the ground motions on softer soil sites. This implies that the ground motions on soil sites have narrower bandwidths. The values of T_{cg} and normalized peak ground velocity of the records considered in this study are listed in Table 2. The reported values are geometric means of the two horizontal components. Figure 5 shows the normalized 5%-damping response spectra of the horizontal and vertical components of ground motions included in the data bank. The values of T_{cg} for the horizontal ground motions range from 0.2 to 2.2 s; similar ranges are obtained for the vertical ground motions. However, Malhotra (2006) obtained shorter values of T_{cg} for the vertical ground motions than those for the horizontal ones. The similarities between the central periods of vertical and horizontal motions, as observed in this study, could be due to the closeness of the sites of all records (selected for this study) to the sources of events. Therefore, vertical motions are comparable to the horizontal ones in high and low frequencies. The median values of normalized peak ground velocities for the horizontal and vertical ground motions are 0.46 and 0.4, respectively. As the normalized peak ground velocity is a measure of the spectral width, lower values for the vertical motions in comparison with the horizontal ones implies that the average spectrum of vertical motions is flatter than that of the horizontal ones. The normalized 5%-damping median spectra of the horizontal and vertical ground motions in the data bank are shown in Figure 6. The shaded area in this figure corresponds to ± 1 standard deviation about the median. Idealized forms of the normalized median spectra for different damping values are shown in Figure 7. As expected, the spectra of vertical motions are flatter than those of the horizontal ones, and the amplification factors decrease with an increase in the damping value. The acceleration, velocity, and displacement amplification factors, α_A, α_V, and α_D, respectively, for the median horizontal and vertical spectra of different damping ratios are listed in Table 4. The amplification factors for different site conditions are also calculated; however, the differences between different site conditions are statistically insignificant according to the variance analysis. The horizontal amplification factors obtained in this study are compared with those reported by Mohraz (1976), Newmark and Hall (1982), and Malhotra (2006), as shown in Figure 8. The α_A values obtained in this study are up to about 10% higher in comparison with those reported by Mohraz (1976), 13% higher as compared to those given by Newmark and Hall (1982), and 3% higher than the values reported by Malhotra (2006). Similarly, the α_V values are about 10% higher than the values reported by Mohraz (1976), 28% lower than those reported by Newmark and Hall (1982), and 18% lower than those given by Malhotra (2006). Further, the α_D values are up to about 4% higher than those given by Mohraz (1976), 23% higher than those reported by Newmark and Hall (1982), and 4% lower than those given by

Malhotra (2006). The present results for α_A and α_D factors are mostly consistent with those obtained by Malhotra (2006), and for α_V values with those of Mohraz (1976). Malhotra (2006) considers the prior assumption of cutoff periods in the studies of Mohraz (1976) and Newmark and Hall (1969, 1982) as the possible source of differences between the calculated amplification factors. The functional form of amplification factors considered in this study is

$$\alpha(\xi) = a + b \ln \xi \tag{3}$$

where α denotes α_A, α_V, or α_D, and ξ denotes the percentage of critical damping. The coefficients, a and b, in Equation (3) are determined through least-squares fitting of the data points in Table 4 and are given in Table 5. The higher-order terms have been considered in Equation (3) elsewhere (e.g., see Malhotra, 2006); however, the coefficients for such terms seem to be statistically insignificant.

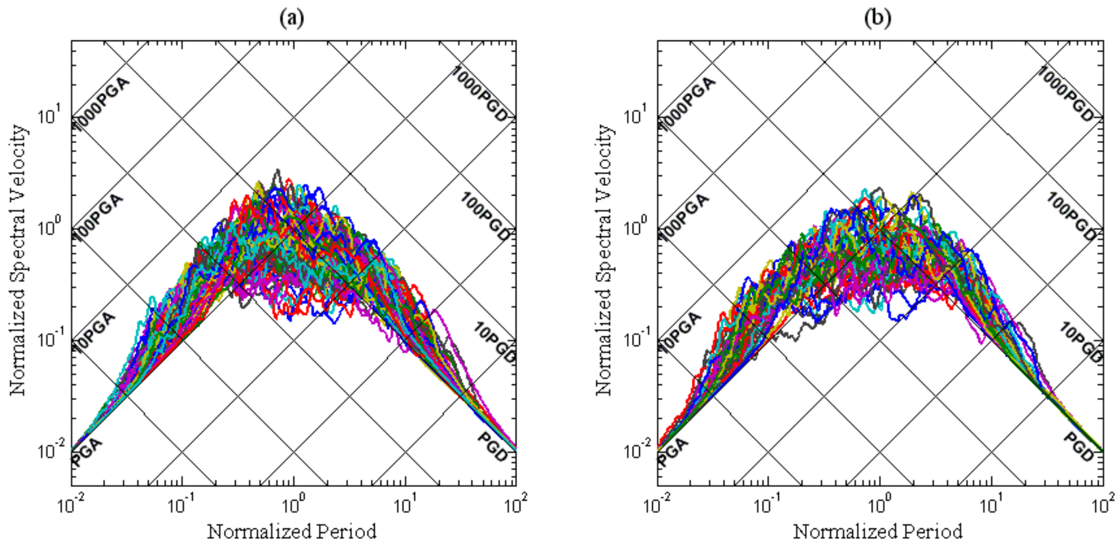

Fig. 5 Normalized 5%-damping response spectra of (a) horizontal and (b) vertical components

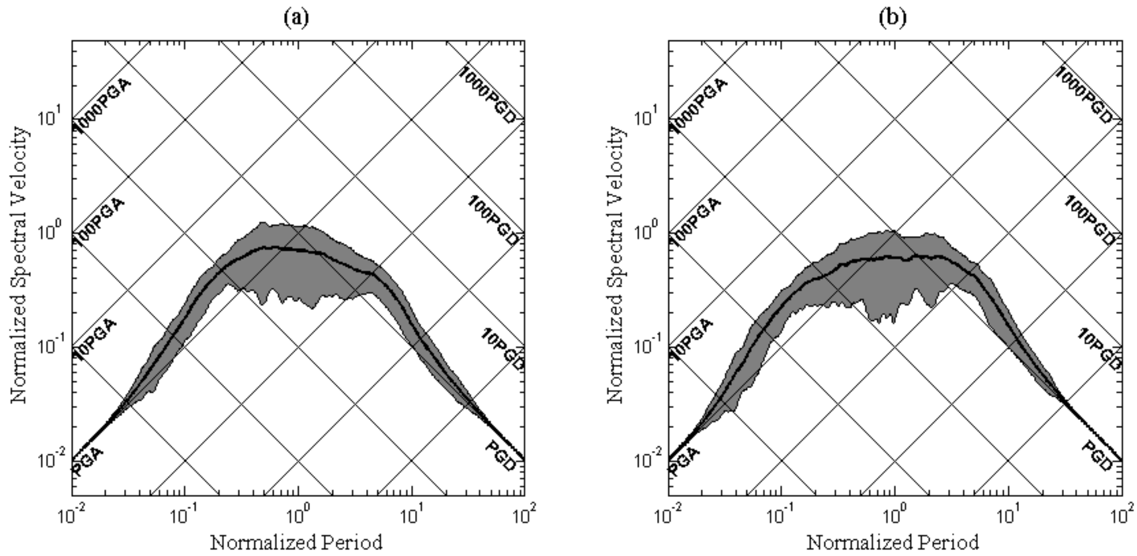

Fig. 6 Normalized 5%-damping median spectra of (a) horizontal and (b) vertical ground motions (the shaded area corresponds to ± 1 standard deviation about the median)

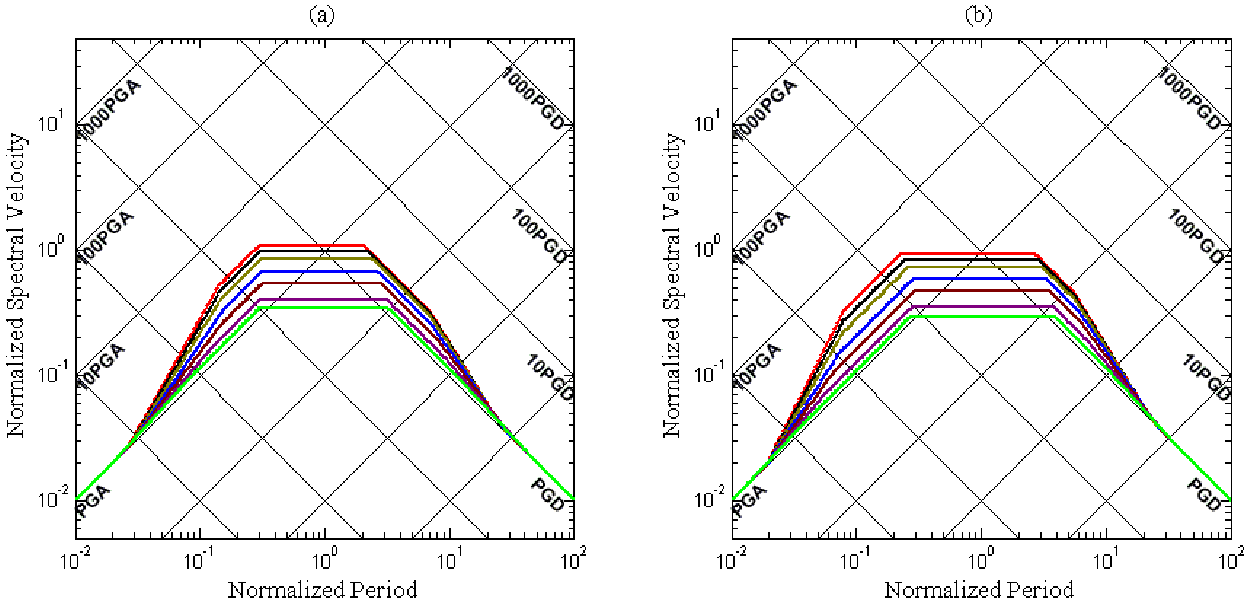

Fig. 7 Idealized forms of the normalized median spectra for different damping values in (a) horizontal and (b) vertical component

Table 4: Acceleration, Velocity and Displacement Amplification Factors for the Median Horizontal and Vertical Spectra of Different Damping Ratios

Damping Ratio (%)	Horizontal			Vertical		
	α_A	α_V	α_D	α_A	α_V	α_D
0.5	3.70	2.22	2.26	4.16	2.18	2.53
1	3.25	2.00	2.19	3.47	1.98	2.43
2	2.78	1.75	2.06	2.83	1.74	2.27
5	2.17	1.38	1.80	2.09	1.39	1.98
10	1.74	1.10	1.54	1.63	1.11	1.67
20	1.35	0.84	1.26	1.27	0.85	1.34
30	1.16	0.70	1.11	1.10	0.70	1.15

The procedure for constructing a smooth response spectrum at the site of interest consists of (a) first estimating three peak ground motion parameters (i.e., PGA, PGV, and PGD) and three amplification factors for the acceleration-, velocity- and displacement-sensitive regions at the site, and (b) then obtaining the spectrum ordinates in each region from the product of the relevant ground motion parameter and its amplification factor. Generally, PGA, PGV, and PGD can be determined by using the results of SHA studies in the region. The amplification factors for the specified damping value can be obtained by using Table 4.

In this study, following the procedure described above, the smooth spectra of numerous horizontal and vertical ground motions are computed via their corresponding peak ground motion parameters. The spectral ordinates for these ground motions are calculated by the method suggested by Malhotra (2006), and the results are presented in this study. In order to validate the results, as obtained by analyzing the Iranian strong-motion records, the ratio between the smoothed and actual response spectra is calculated for each ground motion. Figure 9 shows the median spectral ratio for horizontal and vertical ground motions; the shaded area corresponds to ± 1 standard deviation about the median. The closeness of the median ratio of actual and smoothed SVs to unity for all natural periods confirms accuracy of the results obtained in this study. Here, a t-test of the hypothesis is also performed, i.e., the data points in each period range come from a united distribution. The results indicate that the null hypothesis cannot be rejected in wide period ranges.

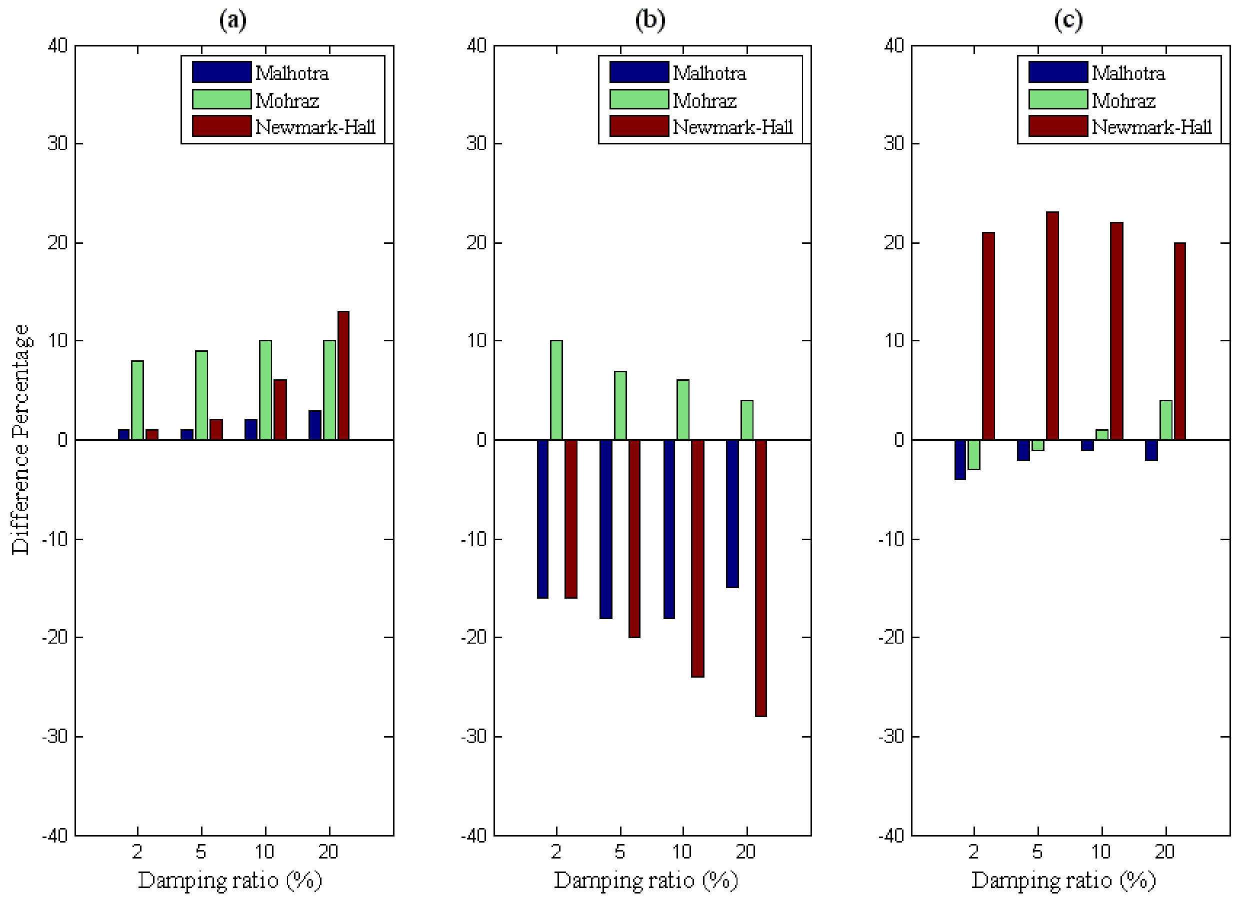

Fig. 8 Comparison between the amplification factors obtained in this study and those suggested by the previous ones: (a) acceleration, (b) velocity, (c) displacement (the values obtained here are shown in the form of percentage differences from the previous studies)

Table 5: Functional Form of the Amplification Factors for Horizontal and Vertical Spectra

	Horizontal	Vertical
α_A	$-0.628\ln\xi+3.233$	$-0.748\ln\xi+3.466$
α_V	$-0.379\ln\xi+1.985$	$-0.368\ln\xi+1.964$
α_D	$-0.291\ln\xi+2.175$	$-0.345\ln\xi+2.419$

AN EXAMPLE ON CONSTRUCTING SMOOTH RESPONSE SPECTRA

Here, the construction of smooth design spectrum using peak ground motion parameters is presented in an example. Based on the seismic hazard map prepared for the Tehran metropolitan (Zare, 2004), the expected PGA value is 0.45*g* (441 cm/s/s) for a 475-year return period. The PGV and PGD values are 30 cm/s and 9.8 cm, respectively. To construct the smooth spectrum for 5% damping and for horizontal component, the desired amplification factors are obtained from Table 3, and the control periods which are the beginning and end points of the acceleration-, velocity- and displacement-sensitive regions, are computed as follows:

$$T_3 = 2\pi \frac{\mathrm{PGV}\times\alpha_V}{\mathrm{PGA}\times\alpha_A} = 2\pi \frac{30\times1.38}{411\times2.17} = 0.29\,\mathrm{s} \tag{3}$$

$$T_4 = 2\pi \frac{\mathrm{PGD}\times\alpha_D}{\mathrm{PGV}\times\alpha_V} = 2\pi \frac{9.8\times1.8}{30\times1.38} = 2.7\,\mathrm{s} \tag{4}$$

$$T_1 = \frac{T_3}{10.8} = \frac{0.29}{10.8} = 0.026\,\text{s} \tag{5}$$

$$T_2 = \frac{T_3}{2} = \frac{0.29}{2} = 0.14\,\text{s} \tag{6}$$

$$T_5 = 2.7T_4 = 2.7 \times 2.7 = 7.3\text{s} \tag{7}$$

$$T_6 = 10.8T_4 = 10.8 \times 2.7 = 29.16\,\text{s} \tag{8}$$

The desired smooth spectrum can be drawn on a tripartite paper (see Figure 10) as follows. Take SA = PGA for $T < T_1$ and SA = α_A ×PGA for $T_2 < T < T_3$. Join SA(T_1) = PGA and SA(T_2) = α_A ×PGA by a straight line. Take SV = α_V ×PGV for $T_3 < T < T_4$, SD = PGD for $T > T_6$, and SD = α_D ×PGD for $T_4 < T < T_5$. Join SD(T_6) = PGD and SD(T_5) = α_D ×PGD by a straight line.

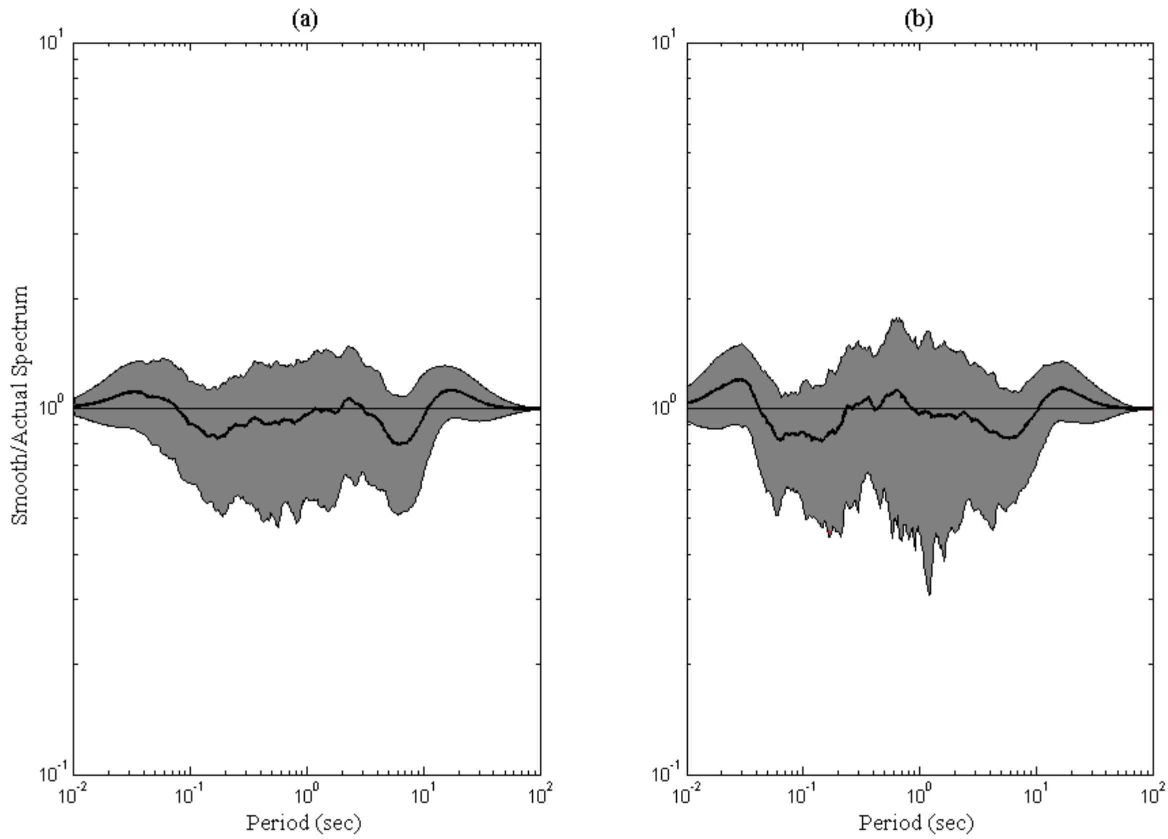

Fig. 9 Median ratios between the 5%-damping smooth spectrum and the actual spectra of (a) horizontal and (b) vertical ground motions (the shaded area corresponds to ± 1 standard deviation about the median)

Such a smooth response spectrum characterizes the earthquake loading and can be used in a pseudo-static analysis, which is needed for a majority of structures. However, for some specific design situations a suite of strong-motion records is required for input into the time-domain nonlinear analysis of structures. These time-histories can be selected from a data bank of real accelerograms; however, the selected ground motion records should be modified to be compatible with the seismic hazard level determined for the target region. Such a modification can be applied by scaling and stretching the selected time-histories. Scaling, which is the multiplication of the accelerogram by a scale factor, makes the peak value of the accelerogram (e.g., PGA) equal to the design value. Hence, scaling affects only the PGA, not T_{cg} and the normalized velocity. In contrast, stretching accelerograms along the time axis changes the duration of the record and frequency content and can be used to change T_{cg}. In practice, it is desirable to combine the scaling-stretching technique to match the PGA, PGV, and PGD with the target values.

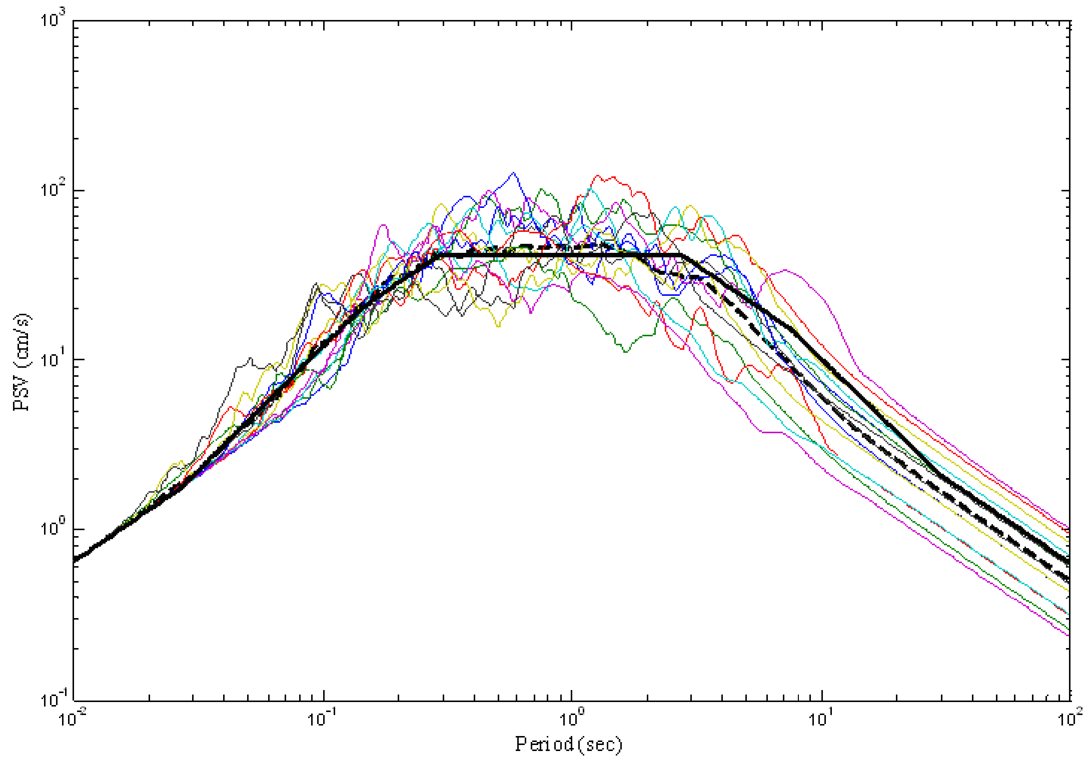

Fig. 10 5%-damping response spectra (in thin lines) of the scaled accelerograms selected to derive design spectra in the Tehran region (the black dotted curve is the geometric-mean spectrum; the black thick curve is the smooth design spectrum calculated using the procedure described in this study)

In the above example, based on the calculated PGA, PGV and PGD for the Tehran region, six time histories are selected that have peak ground motion parameters close to these values. The selected accelerograms are scaled and stretched to meet the demand at the site. Figure 11 shows the horizontal component of the ground motion recorded at the Zarand station during the Zarand earthquake of 2005 as well as the corresponding scaled and stretched time-histories. The PGA of the scaled and stretched accelerogram exactly matches the target value, and the corresponding PGV and PGD values are close to the target ones. In fact, PGA should be matched exactly in the stiff structures, PGV in the moderately stiff structures, and PGD in the flexible structures. The 5%-damping geometric mean spectrum of the selected time-histories is shown in Figure 10. It can be seen that the proposed smooth spectrum for the Tehran region, as obtained by using the described procedure, is consistent with the one determined based on the strong-motion records.

CONCLUDING REMARKS

This study summarizes the results of a comprehensive statistical study on constructing smooth response spectra in Iran. A total of 51 Iranian near-field (three-component) strong-motion records, recorded during 10 moderate-to-large earthquakes, are considered in this study. The main reason for focusing on Iranian plateau is because this region is one of the most seismically active regions in the world, and also has considerable number of strong-motion records which can be used to propose region-specific smooth response spectra. The near-field records are used mainly because of the fact that most of the high-populated cities in Iran are located in the near-field regions. The following conclusions are drawn from the results obtained in this study:

1. The cutoff periods for each region are slightly lower than the values reported in Mohraz (1976) and Malhotra (2006), indicating that those can change from one set of ground motions to another.
2. The ratio of velocity to acceleration and that of acceleration-displacement product to velocity squared are calculated to state the relationships between the peak ground motion parameters.
3. Generally, SC-I sites show lower v/a values and higher ad/v^2 values than the other site categories. This is consistent with the results obtained by Mohraz (1976) and Malhotra (2006).

4. The results of analysis of variance indicate that the differences between the ratios obtained at different site categories are statistically insignificant.
5. The amplification factors for the median horizontal and vertical spectra of different damping ratios are calculated and compared with the results obtained in the previous studies. The amplification factors, α_A and α_D, as obtained in this study are mostly consistent with those obtained by Malhotra (2006), and the α_V values are consistent with the results obtained by Mohraz (1976).
6. The amplification factors for the median horizontal and vertical spectra of different damping ratios are close together, however, the shape of the median vertical spectrum is much flatter than the horizontal one.
7. The results of analysis of variance indicate that the differences between the amplification factors obtained at different site categories are statistically insignificant.
8. In this study, no significant statistical difference is obtained between the desired parameters for different site conditions, which might be due to errors in the initial assignment of site classes. Site classes are initially assigned by using the empirical classification schemes. However, the results from the recent studies indicate that the accuracy of such empirical schemes may decrease rapidly with a decreasing number of records at each station.
9. The comparison between the smoothed and actual response spectra for the horizontal and vertical components validates the results of this study.
10. The smooth response spectrum, as constructed by using the procedure proposed in this study, is consistent with the mean response spectrum, which has been computed based on the response spectra of the accelerograms of the ISMN data bank.
11. The results of this study are effective in the evaluation of the present Iranian seismic code and can be used directly in future SHA projects in Iran. This study could be used as the basis for a more comprehensive study in developing the design response spectra by increasing the number of strong motions in the accelerometric data bank and by discussions on standard deviations in the spectral amplitudes in very low and very long periods.

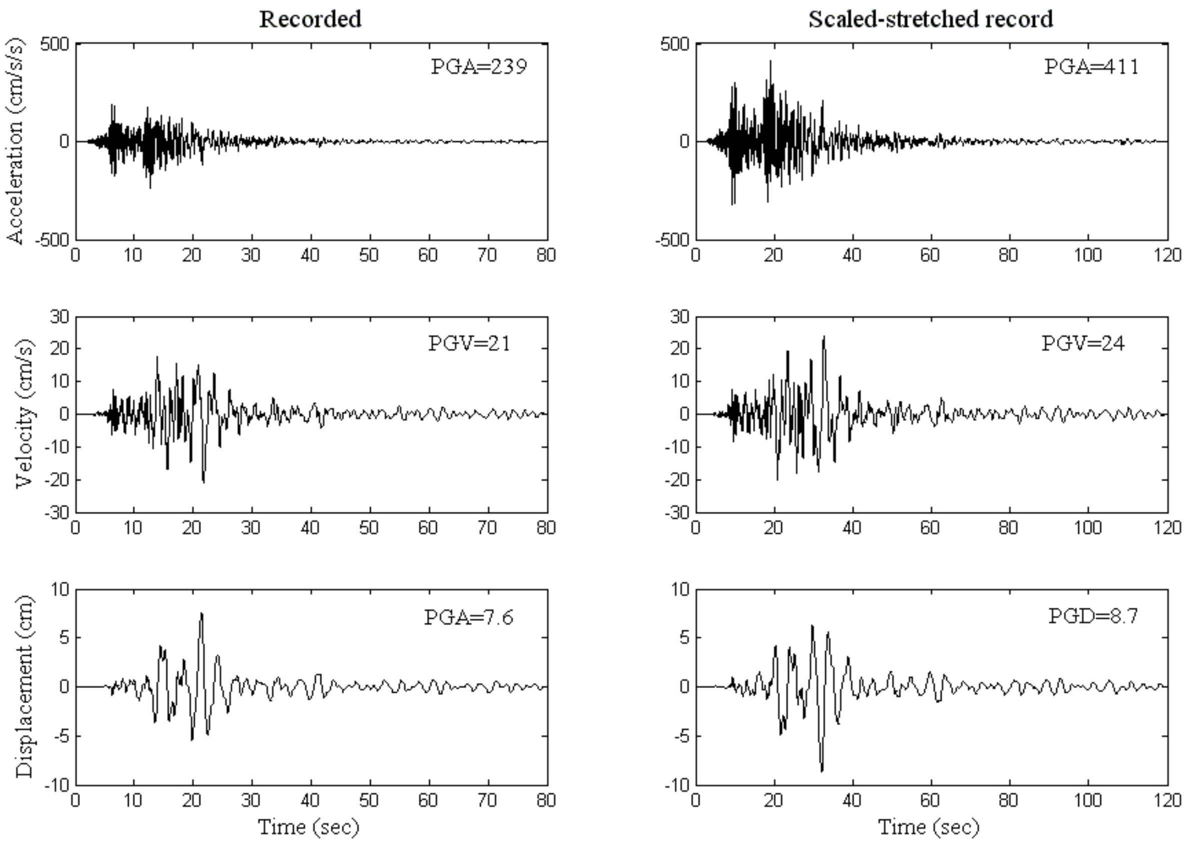

Fig. 11 Acceleration, velocity and displacement time-histories of the Zarand earthquake of 2005, as recorded at the Zarand station, and the corresponding scaled and stretched time-histories

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APPENDIX: LOCATIONS OF RECORDING STATIONS, ASSIGNED SITE CLASSES, AND CORRESPONDING SEISMOLOGICAL INFORMATION

No.	Station	Lat.	Long.	Site Class	Date	M_w	*R* (km)
1	Vendik	33.82	59.23	II	11/7/1976	6.4	11
2	Ghaen	33.73	59.22	I	11/7/1976	6.4	10
3	Maku	39.29	44.51	II	11/24/1976	7.3	48
4	Bandarabbas	27.18	56.28	II	3/21/1977	7.0	52
5	Naghan-1	31.93	50.72	I	4/6/1977	6.1	7
6	Dastgerd	32.10	50.98	II	4/6/1977	6.1	18
7	Ardal	31.98	50.66	IV	4/6/1977	6.1	21
8	Deyhuk	33.29	57.50	I	9/16/1978	7.4	36
9	Tabas	33.58	56.92	I	9/16/1978	7.4	27
10	Talesh	37.80	48.90	III	11/4/1978	6.2	20
11	Naghan-1	31.93	50.72	I	12/14/1978	6.1	5
12	Ghaen	33.73	59.22	I	11/27/1979	7.1	44
13	Golbaf	29.88	57.72	III	7/28/1981	7.1	12
14	Kerman	30.28	57.07	IV	7/28/1981	7.1	48
15	Abbar	36.92	48.97	I	6/20/1990	7.3	40
16	Manjil	36.76	49.39	II	6/20/1990	7.3	12
17	Firouzabad	28.83	52.56	III	3/1/1994	6.0	31
18	Bojnoord	37.48	57.31	III	2/4/1997	6.5	10
19	Gifan	37.89	57.49	IV	2/4/1997	6.5	29
20	Ashkhaneh	37.56	56.92	III	2/4/1997	6.5	56
21	Robat	37.90	57.69	IV	2/4/1997	6.5	41
22	Raz	37.94	57.10	III	2/4/1997	6.5	42
23	Kariq	37.92	48.06	II	2/28/1997	6.1	26
24	Ardebil 2	38.22	48.26	III	2/28/1997	6.1	37
25	Ardebil 1	38.23	48.28	I	2/28/1997	6.1	37
26	Namin	38.42	48.48	II	2/28/1997	6.1	58
27	Helabad	37.92	48.42	IV	2/28/1997	6.1	37
28	Qasem Abad	34.35	59.86	IV	5/10/1997	7.1	55
29	Sirch	30.20	57.56	III	3/14/1998	6.3	12
30	Balaadeh	29.29	51.94	I	5/6/1999	6.2	49
31	Khan zeynioun	29.67	52.15	I	5/6/1999	6.2	30
32	Avaj	35.58	49.22	I	6/22/2002	6.4	30
33	Razan	35.39	49.03	IV	6/22/2002	6.4	34
34	Abgarm	35.76	49.28	IV	6/22/2002	6.4	37

35	Darsejin	36.02	49.24	II	6/22/2002	6.4	38
36	Bam1	29.09	58.35	III	12/26/2003	6.5	9
37	Mohammad Abad-e-Maskoon	28.91	57.89	II	12/26/2003	6.5	59
38	Hasan Keyf	36.5	51.15	III	5/28/2004	6.3	43
39	Poul	36.401	51.586	IV	5/28/2004	6.3	17
40	Baraqan	35.953	50.935		5/28/2004	6.3	69
41	Noshahr	36.654	51.494	IV	5/28/2004	6.3	39
42	Garmabdar	35.987	51.634		5/28/2004	6.3	35
43	Noor	36.574	52.011	IV	5/28/2004	6.3	51
44	Chatrood	30.605	56.911	II	2/22/2005	6.2	36
45	Ravar	31.263	56.791	III	2/22/2005	6.2	66
46	Zarand	30.81	56.577	III	2/22/2005	6.2	40
47	Dasht-e-Khak	31.066	56.555	IV	2/22/2005	6.2	36
48	Qadrooni Dam	30.962	56.819	IV	2/22/2005	6.2	29
49	Shirinrood Dam1	30.811	57.031	II	2/22/2005	6.2	33
50	Sib Sooran	27.286	61.998		3/13/2005	6.0	53
51	Suza	26.782	56.07	I	11/27/2005	6.1	17

REFERENCES

1. BHRC (2003). "Iranian Code of Practice for Seismic Resistant Design of Buildings, Standard No. 2800", Publication No. S-374, Building & Housing Research Center, Tehran, Iran.
2. Boore, D.M. and Bommer, J.J. (2005). "Processing of Strong-Motion Accelerograms: Needs, Options and Consequences", Soil Dynamics and Earthquake Engineering, Vol. 25, No. 2, pp. 93–115.
3. Boore, D.M., Stephens, C.D. and Joyner, W.B. (2002). "Comments on Baseline Correction of Digital Strong-Motion Data: Examples from the 1999 Hector Mine, California, Earthquake", Bulletin of the Seismological Society of America, Vol. 92, No. 4, pp. 1543–1560.
4. Chopra, A.K. (1966). "The Importance of the Vertical Component of Earthquake Motions", Bulletin of the Seismological Society of America, Vol. 56, No. 5, pp. 1163–1175.
5. Ghasemi, H., Zare, M., Fukushima, Y. and Sinaeian, F. (2009). "Applying Empirical Methods in Site Classification Using Response Spectral Ratio (H/V): A Case Study on Iranian Strong Motion Network (ISMN)", Soil Dynamics and Earthquake Engineering, Vol. 29, No. 1, pp. 121–132.
6. Ghodrati Amiri, G., Zahedi, M. and Taghdir, A. (2003). "Evaluation of Soil Type Classification of the 2800 Code Based on Response Spectrum Study", Proceedings of the Third Conference on Iranian Code for Seismic Resistant Design of Buildings, Tehran, Iran, Vol. 1, pp. 111–120 (in Persian).
7. Hall, W.J., Mohraz, B. and Newmark, N.M. (1976). "Statistical Studies of Vertical and Horizontal Earthquake Spectra", Report NUREG-0003 (prepared for U.S. Nuclear Regulatory Commission, Washington, DC, U.S.A.), Nathan M. Newmark Consulting Engineering Services, Urbana, U.S.A.
8. ICC (2003). "International Building Code", International Code Council, Washington, DC, U.S.A.
9. ICC (2006). "International Building Code", International Code Council, Washington, DC, U.S.A.
10. Malhotra, P.K. (2001). "Response Spectrum of Incompatible Acceleration, Velocity and Displacement Histories", Earthquake Engineering & Structural Dynamics, Vol 30, No. 2, pp. 279–286.
11. Malhotra, P.K. (2006). "Smooth Spectra of Horizontal and Vertical Ground Motions", Bulletin of the Seismological Society of America, Vol. 96, No. 2, pp. 506–518.
12. Mohraz, B. (1976). "A Study of Earthquake Response Spectra for Different Geological Conditions", Bulletin of the Seismological Society of America, Vol. 66, No. 3, pp. 915–935.

13. Mohraz, B., Hall, W.J. and Newmark, N.M. (1973). "A Study of Vertical and Horizontal Earthquake Spectra", Report WASH-1255 (prepared for U.S. Atomic Energy Commission, Washington, DC, U.S.A.), Nathan M. Newmark Consulting Engineering Services, Urbana, U.S.A.
14. Newmark, N.M. and Hall, W.J. (1969). "Seismic Design Criteria for Nuclear Reactor Facilities", Proceedings of the Fourth World Conference on Earthquake Engineering, Santiago, Chile, Vol. 2, pp. B-4: 37–50.
15. Newmark, N.M. and Hall, W.J. (1982). "Earthquake Spectra and Design", Earthquake Engineering Research Institute, Okland, U.S.A.
16. Sinaiean, F. (2006). "Study on Iran Strong Motion Records", Ph.D. Thesis, International Institute of Earthquake Engineering and Seismology, Tehran, Iran.
17. Tehranizadeh, M. and Hamedi, F. (2003). "Influence of Iran's Earthquake Ground Motion Parameters on Design Spectra Using Deterministic and Probabilistic Approaches", Journal of Earthquake Engineering, Vol. 7, No. 2, pp. 275–295.
18. Zare, M. (2004). "Seismic Hazard Analysis for Tehran Metropolitan", Research Report, International Institute of Earthquake Engineering and Seismology, Tehran, Iran (in Persian).
19. Zare, M., Bard, P.-Y. and Ghafory-Ashtiany, M. (1999). "Site Characterizations for the Iranian Strong Motion Network", Soil Dynamics and Earthquake Engineering, Vol. 18, No. 2, pp. 101–123.
20. Zhao, J.X., Irikura, K., Zhang, J., Fukushima, Y., Somerville, P.G., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T. and Ogawa, H. (2006). "An Empirical Site-Classification Method for Strong-Motion Stations in Japan Using H/V Response Spectral Ratio", Bulletin of the Seismological Society of America, Vol. 96, No. 3, pp. 914–925.