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ORIGINAL ARTICLE

Vertical elastic response spectra for low and high seismicity regions

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Abstract

This paper is focused on the definition of the vertical elastic response spectra. This study follows the recent development of the horizontal response spectrum in the framework of the revision of the Algerian seismic code RPA99 (Laouami and Slimani 2025). The same ground motion database is used, which comprises 773 3-component records, from magnitude ranging from 3.0 to 7.4, and hypocentral distances less than 200 Km. A statistical method is used to estimate constant spectral acceleration branch limits, attenuation indexes, and the ratio of the vertical to horizontal response spectra, at two seismicity levels: weak to moderate seismicity (wms) and moderate to high seismicity (mhs). The results of the analysis showed significant differences between the control periods of the elastic response spectra as a function of both the site class and the magnitude. The results reveal that the control period T_{Cv} increases as the site moves from rock to soft classes and from low to high earthquake magnitude, whereas the attenuation index decreases with increasing earthquake magnitude. The findings reveal also that the vertical to horizontal spectral ratio increase with magnitude and can exceed unity at near field for vertical vibration periods in the range 0.05–0.1 s. The recommended values of the ratio of vertical to horizontal design acceleration, $C_{v/h}$, for wms and mhs seismicity levels, are 0.60 and 0.80 respectively. Comparison to the vertical spectra of the ASCE7-16 and the new generation EC8-draft2022 standards, reveals that period Tc of the proposed spectra is in agreement with the ASCE7-16 for the wms seismicity level, and with EC8-draft2022 for the mhs seismicity level. Finally, two spectral shapes are proposed for the two seismicity levels wms and mhs. This solution enables a significant upgrade over the present version of the national seismic design code RPA99, which does not offer elastic response spectra for the vertical component of seismic motion.

Keywords Vertical elastic response spectra · Seismic design code · Strong motion database · Attenuation index · Ratio of vertical to horizontal design acceleration

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1 Introduction

During an earthquake, buildings are subject to three-dimensional ground movements. However, most of the current state of the art have analysed and researched horizontal motion widely, but vertical movements have typically been overlooked and scarcely evaluated. However, according to observations made after an earthquake like the ones that struck Chi-Chi, Taiwan (1999), Kobe, Japan (1995), and Northridge, California (1994) abundant evidences are provided that the large-scale damage was caused by the vertical component of the recorded earthquakes (Papazoglou and Elnashai 1996; Kunnath et al. 2008; Haji-Soltani et al. 2017). The effects of the vertical excitation on horizontal response of structures is largely treated in the literature which highlight that the vertical component of the earthquake plays a fundamental role in defining the crack pattern of the elements and their collapse (Sorrentino et al., 2014; Bradley et al. 2014; Ghaffarzadeh et al., 2015; Di Michele et al. 2020).

During the design of structures, the vertical component is usually taken as 1/2 or 2/3 of the horizontal component's peak ground acceleration (PGA), assuming that all ground motion components have the same frequency, which is incorrect based on recorded frequency data for the respective ground motion.

Several researchers proposed V/H ratio values, which are considered an important parameter in seismic design. Newmark (1973) achieved one of the main investigations on V/H ratio as 2/3 value based on records from the USA. Using a consequent strong motion database, Laouami (2019) shows that the relationship between vertical and horizontal (V/H) response spectra is highly dependent on the period, the magnitude and site distance from the seismic source.

According to the Algerian seismic code RPA99 (2003), the vertical maximum acceleration (PGA) of the seismic action is considered as the half of the horizontal one, regardless of the spectral period. However, in recent years, in various seismic codes like Eurocode 8 (2004) and NEHRP BSSC (2009) it is recommended vertical spectra that are distinct from horizontal spectra.

The current research aims to propose improved parameters and normalized shapes at two seismicity levels: weak to moderate seismicity (wms) and moderate to high seismicity (mhs).

2 Strong motion database and site classification (details in Laouami and Slimani 2025)

In this study, the same strong motion database considered for developing the horizontal elastic response spectra (Laouami and Slimani 2025) is used. It consists of 153 earthquakes with a total of 773 3-component records from events with magnitudes ranging from 3.0 to 7.4 and hypocentral distances less than 200 Km. Figure 1 illustrates the record distributions as a function of magnitude and hypocentral distance, vertical PGA and magnitude and vertical PGA and hypocentral distance. Peak vertical ground accelerations are often less than 300 m/s^2 due to the lower vertical accelerations compared to horizontal accelerations (see to section Ratio of vertical to horizontal design acceleration). All data come from shallow crustal earthquakes and reverse faults in active regions (e.g., Algeria, western North America, Italy, Greece, and so on) with depths less than 30 km.

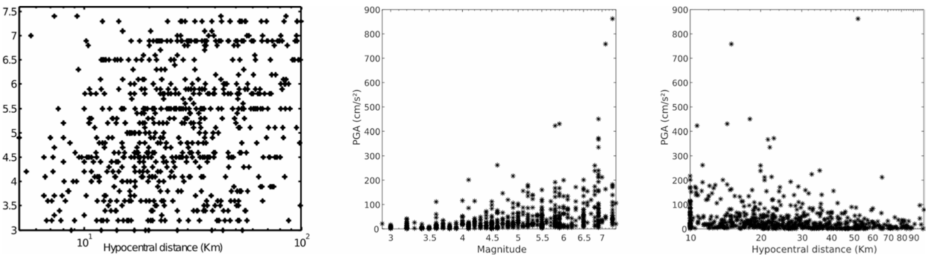

Fig. 1 Distributions of the records as a function of magnitude and hypocentral distance (left)), PGA and magnitude (center) and PGA and hypocentral distance (right)

Table 1 Definition of the soil classes based on shear wave velocity and distribution of the strong motion database with respect to soil class and seismicity level

Soil Category	SCA		SCB		SCC		SCD	
Soil profile	Rock		Very dense soil and soft rock		Stiff soil		Soft soil	
Shear wave velocity (m/s)	> 800		360–800		180–360		100–180	
RPA99/2003	S_1		S_2		S_3		S_4	
Magnitude class	wms	mhs	wms	mhs	wms	mhs	wms	mhs
Number of 3-component records	159	42	184	103	113	78	56	38
S/Total	201		287		191		94	
Total	773							

The strong motion database has been divided into two subgroups according to the magnitude. The first subgroup covers all earthquake records with magnitude M > 5.5 (mhs). It allows elaborating the seismicity level 1 spectra. The second subgroup covers all earthquake records with magnitude M <= 5.5 (wms). It allows elaborating the seismicity level 2 spectra. This subdivision of the database into magnitude classes allows normalizing the spectra with regard to seismic hazard. The magnitude M = 5.5 is used to differentiate between the two seismicity levels wms and mhs. For engineering purposes, it is preferable to examine a differentiation based on a horizontal ground motion amplitude measure, such as the pick ground acceleration or short spectral acceleration Ss (T = 0.2s). Based on the ground motion prediction equation developed for Algeria and the surrounding region (Laouami et al., 2018), if we assume nearfield conditions adequate for vertical component (Rhypo = 10 Km) and for M = 5.5, we get a $pga_{Horizontal}$=1,5 m/s² and Ss(T = 0.2s) = 3,75 m/s².

Table 1 shows the definition of the soil classes based on shear wave velocity and the distribution of the strong motion database by soil class and seismicity level. It demonstrates a good distribution of 3-component records across the 4 soil classes, with 201, 287, 191, and 94 records for SCA, SCB, SCC, and SCD, respectively. Table 1 shows that records from wms are more numerous because low magnitude earthquakes are the most frequent.

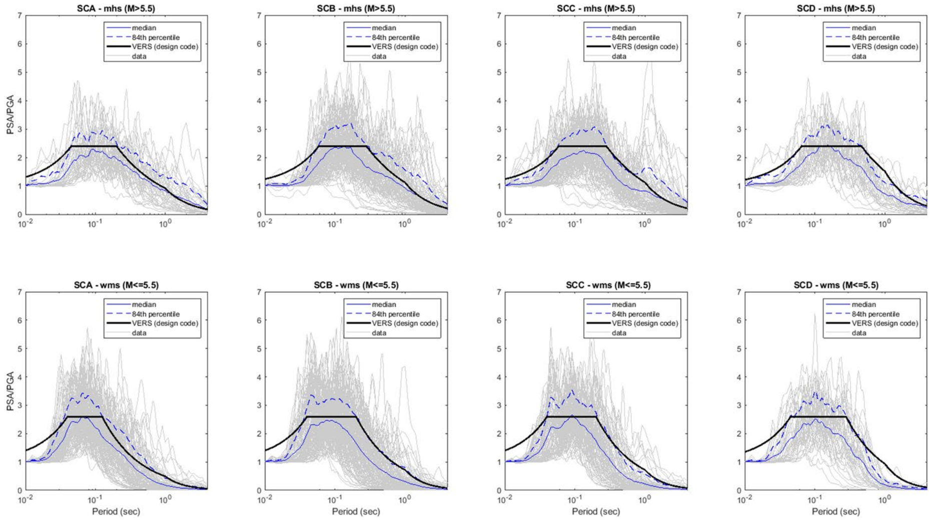

Fig. 2 The recorded vertical PSA/PGA normalized spectra (in grey) for the 4 soil class and 2 seismicity levels, the median normalized acceleration spectra (solid blue line), and the 84th (average plus one standard deviation, dashed blue line) percentiles, and the proposed VERS for design code (solid black line)

Table 2 The values of the coefficient of variation and average amplitude of the plateau level (β in Eq. 9) for the 4 soil class and 2 seismicity levels, mhs and wms

Seismicity level	wms				mhs			
Soil class	SCA	SCB	SCC	SCD	SCA	SCB	SCC	SCD
Cov (%)	31	32	28	38	27	32	30	25
β	2.6	2.48	2.67	2.50	2.30	2.38	2.25	2.44
Mean (β)	2.56				2.34			
Std (β)	0.09				0.08			
Recommended (β)	2.60				2.40			

3 Normalized vertical acceleration elastic response spectra

According to soil and seismicity level classification in Table 1, the vertical strong motion records were normalized to a value of unity at zero period and grouped into four soil classes and two seismicity levels. For each soil class and seismicity level, the median of the corresponding normalized spectra was calculated, as well as the 16th and 84th percentiles, respectively. Figure 2 depicts the normalized spectra (PSA/PGA in grey) for the four soil classes (SCA, SCB, SCC, SCD) and two seismicity levels (wms and mhs), as well as the median and the 84th percentiles (in solid and dashed blue lines respectively).

In order to appreciate the dispersion of the normalized vertical response spectra, Table 2 shows the coefficient of variation (Cov) at T = 0.1 s for the eight families of spectra presented in Fig. 2. It appears that the covariance ranges between 27% and 32% and between 28% and 38% for mhs and wms seismicity level respectively. The average coefficient of variation is around 30%, which is relatively acceptable according to epistemic and aleatory uncertainties characterizing the strong motion.

In Table 2, the values of the plateau spectral amplitude of the constant spectral acceleration (β in Eq. 1), which is the maximum of the normalized response spectra, are dressed for the four soil classes and two seismicity levels. The highest plateau amplitudes appear for wms level around 2.56, whereas it is around 2.34 for mhs level. Recommended values of 2.60 and 2.40 are assumed in the following for wms and mhs seismicity levels respectively. In a recent study, Pavel et al. (2024) found that the mean value of the amplification factor (β) computed for ground motion database of about 500 ground motions recorded during moderate and large Vrancea intermediate-depth earthquakes, was about 2.5, which represent the average value of the recommended ones.

4 Shape of vertical elastic response spectra

According to several relevant seismic design codes (Eurocode 8, 2004; BSSC, 1995). The fitted general formula, Eq. (1), is utilized to derive the characteristic parameters by calibrating the normalized vertical response spectra.

$$S_{ev}\left(T\right)=\begin{cases} a_gC_{v/h}\left[1+\frac{T}{T_B}\left(\beta\,\eta\,-1\right)\right] & 0\leq\,T\leq\,T_B \\ \beta\,a_gC_{v/h}\eta & T_B\leq\,T\leq\,T_C \\ \beta\,a_gC_{v/h}\eta\,\left[\frac{T_C}{T}\right]^{\alpha} & T_C\leq\,T\leq\,T_D \\ \beta\,a_gC_{v/h}\eta\,\left[\frac{T_CT_D}{T^2}\right]^{\alpha} & T_D\leq\,T\leq\,4s \end{cases} \tag{1}$$

where:

$S_{ev}(T)$ is the elastic vertical response spectrum; T the vibration period of a linear single-degree-of-freedom system; a_g the design horizontal ground acceleration (RPA2024) scaled to 1; $C_{v/h}$ is the ratio of vertical to horizontal design acceleration, $\mathrm{T_B}$ and $\mathrm{T_C}$ are the limits of the constant spectral acceleration branch to be estimated by fitting the general form by the experimental normalized acceleration response spectra; T_D is the value defining the beginning of the constant displacement response range of the spectrum $(T_D\ =\ 1.0$ for vertical component of seismic motion, EC8 (2004)); η is the damping correction factor, its reference value is $\eta\ =1$ for 5% viscous damping, β is the amplitude of the flat portion given in Table 2, and α is the attenuation index.

In this part, we study the fluctuation of the period interval where the PSA/PGA plateau remains constant, with the seismicity levels and with the soil classes. The first step is to fit the 84th percentile normalized acceleration spectra (dashed blue line in Fig. 2) to the general formula (Eq. 1), accounting for as many uncertainties as feasible. The standard form of the proposed normalized acceleration elastic response spectra (VERS solid black line in Fig. 2) is obtained from the 84th percentiles normalized acceleration spectra (dashed blue line in Fig. 2) by setting the amplitude of the plateau equal to β=2.4 for mhs and 2.6 for wms, respectively. The limits of the constant spectral acceleration branch $(\mathrm{T_B}\text{-}\,\mathrm{T_C})$ are the intersections between the plateau's ordinate (β=2.4 for mhs and 2.6 for wms) and the 84th percentile normalized acceleration spectra (dashed blue line in Fig. 2). Table 3 shows the calculated $\mathrm{T_B}$ and $\mathrm{T_C}$ values for the two seismicity levels (wms and mhs), as well as the four soil classes (SCA, SCB, SCC, and SCD).

For comparative considerations, Yang et al. (2020) investigated the features of vertical design spectrum in Japan using differential evolution on the KiK-net database, which

Table 3 Comparison of the period values of T_B and T_C obtained by the current study with those from Yang et al. (2020), for the four soil classes SCA, SCB, SCC and SCD and the two seismicity levels wms and mhs

		This study		This study (Recommended values)		Yang et al. (2020)*
Soil Class	Magnitude Class	T_B	T_C	T_B	T_C	T_C
SCA	wms	0.04	0.13	0.05	0.15	-
	mhs	0.05	0.20	0.05	0.20	-
SCB	wms	0.04	0.20	0.05	0.20	0.18
	mhs	0.06	0.28	0.05	0.30	0.31
SCC	wms	0.04	0.23	0.05	0.25	0.30
	mhs	0.06	0.35	0.05	0.40	0.50
SCD	wms	0.05	0.28	0.05	0.30	0.33
	mhs	0.07	0.46	0.05	0.50	0.60

* The comparison with Yang et al. (2020) takes M_w=5.5 for wms and M_w=7.0 for mhs

comprises roughly 10,000 records. The authors use Eq. 14 to obtain empirical relationships between period T_C and moment magnitude (Mw) for soil classes SCB, SCC, and SCD. The predicted mean periods T_C of Eq. 2 for the two seismicity levels wms and mhs, and the three soil classes (Table 3) demonstrate that T_C grows with site class from SCB to SCD, although it is highly impacted by earthquake magnitude.

$$T_C = \begin{cases} 0.0851M_w - 0.2904 & for\ SCB \\ 0.1299M_w - 0.4119 & for\ SCC \\ 0.1772M_w - 0.6403 & for\ SCD \end{cases} \quad (2)$$

Table 3 compares the derived constant spectral acceleration branch limits T_B- T_C to those from Yang et al. (2020) for the two seismicity levels, wms and mhs, and the four soil classes. The current study reveals a slight variation of T_B with seismicity level, with mean values of 0.06 and 0.043 for mhs and wms respectively. In terms of soil class effect, there is no substantial difference in T_B across the four soil classes. An average value of 0.05 is adopted for both wms and mhs seismicity levels.

According to the current analysis, the period T_C is significantly influenced by the type of seismicity and soil classes. The value of T_C increases with soil class as it changes from SCA to SCD; this variation is more pronounced for mhs and ranges from 0.20 for SCA to 0.50 for SCD, while for wms, it ranges from 0.15 for SCA to 0.30 for SCD. Yang et al. (2020) found similar variations for mhs and wms seismicity levels, respectively, from 0.31 for SCB to 0.60 for SCD and from 0.18 for SCB to 0.33 for SCD.

We also look at the impact of seismicity type on the attenuation index, α, since the American Society of Civil Engineers (ASCE7-16, 2017) design code and the EC8 (2004) recommend different values of 0.7 and 1 respectively. The values found for wms and mhs are 0.8 and 0.6, respectively, with an average value of 0.7, which matches the ASCE suggested one.

Kale and Akkar (2020) have suggested a new formula for a code-based vertical design spectrum. They established a relationship between the attenuation index and the period of the upper corner of the constant vertical acceleration plateau, T_C. A large magnitude produces a longer period and a relatively low attenuation index of around 0.47, whereas a small magnitude produces a shorter period and a relatively high attenuation index of around 0.8.

Table 4 Parameters values recommended for the proposed vertical elastic response spectrum

Parameters		wms (M≤5.5)				mhs (M>5.5)			
		β	T_B	T_C	α	β	T_B	T_C	α
Soil classes	SCA	2.6	0.05	0.15	0.8	2.4	0.05	0.20	0.6
	SCB	2.6	0.05	0.20	0.8	2.4	0.05	0.30	0.6
	SCC	2.6	0.05	0.25	0.8	2.4	0.05	0.40	0.6
	SCD	2.6	0.05	0.30	0.8	2.4	0.05	0.50	0.6

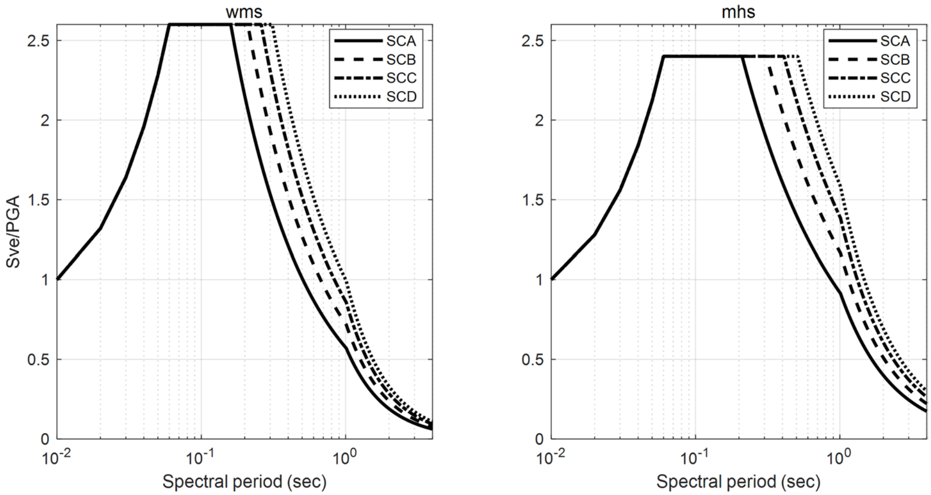

Fig. 3 Normalized vertical response elastic spectra for the two seismicity levels, wms and mhs, and for the four soil classes, SCA, SCB, SCC and SCD

Table 4 presents the suggested parameter values for the proposed vertical elastic response spectra in the current revision of the national design code, whereas Fig. 3 illustrates the comparison of normalized vertical elastic response spectra across the two seismicity levels, wms and mhs, and among the four soil classes, SCA, SCB, SCC, and SCD.

5 Ratio of vertical to horizontal design acceleration $C_{v/h}$

To determine the ratio of vertical to horizontal design acceleration $C_{v/h}$, the ratio of the vertical to horizontal response spectra is investigated using the vertical (Laouami 2019) and the horizontal (Laouami et al. 2018b) GMPEs derived from a same database. A parametric study is carried out to evaluate the fluctuation of the V/H spectral ratio vs. magnitude M, hypocentral distance Rhypo, and vertical vibration period T. Previous research has revealed that the vertical component of seismic motion can have greater amplitudes than the horizontal one, particularly in near field. Therefore, the parametric investigation is focused specifically for near field conditions (R_{hypo}=10Km).

Figure 4a shows the variation of V/H with Rhypo for M_w=7.0 and T=0.01, 0.05, 0.1, 0.2 and 1.0 s. The V/H ratio decreases generally with distance, with the exception of the longer periods T=0.2 and 1.0s. Up to about 50 km, the V/H ratio reaches its maximum for T=0.05s.

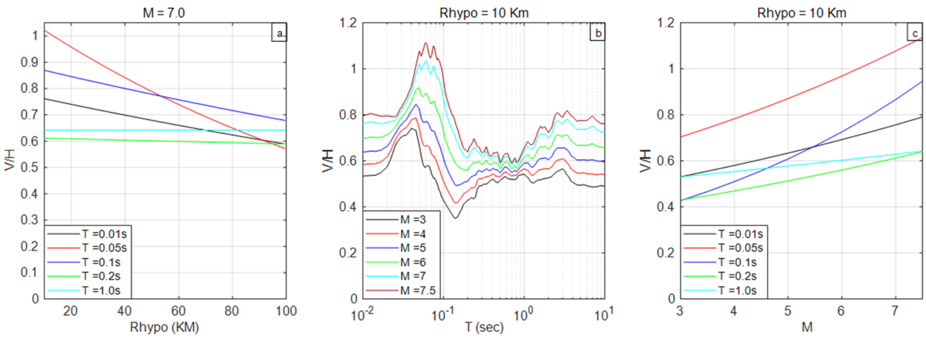

Fig. 4 Variation of the ratio of the vertical to horizontal response spectra with distance, magnitude and vibration period

It surpasses unity in the near field (Rhypo = 10 km), but thereafter rapidly drops. It is followed by V/H ratio for T = 0.1s, which has value in near field close to 1, and decreases more slowly than for T = 0.05s. Beyond 50 Km, the V/H ratio for T = 0.1s is at its highest. According to this result, the greatest V/H spectral ratios for the whole distance range are found in the period interval 0.05–0.1 s, which range from 0.7 (T = 0.1 s and Rhypo = 100 km) to 1.02 (T = 0.05 s and Rhypo = 10 km). This finding might have a significant impact on the seismic behavior of stiff buildings whose vertical fundamental periods fall between 0.04 and 0.15 s.

Figure 4b shows the variation of V/H with period for Rhypo = 10 Km and Mw = 3, 4, 5, 6, 7 and 7.5. The results indicate that V/H ratio reaches its maximum at T = 0.04 (V/H = 0.74), T = 0.045 (V/H = 0.79), T = 0.045 (V/H = 0.85), T = 0.05 (V/H = 0.92), T = 0.06s (V/H = 1.04) and T = 0.07s (V/H = 1.10) for M = 3, 4, 5, 6, 7 and 7.5, respectively. Between T = 0.2s and T = 1.0s, V/H ratios fluctuate between 0.5 and 0.6.

Figure 4c shows the variation of V/H with M for Rhypo = 10 Km and T = 0.01, 0.05, 0.1, 0.2 and 1.0 s. The V/H ratio increase with magnitude for the different values of the period. The increase is more pronounced for T = 0.05 and 0.1s than for T = 0.01, 0.2 and 1.0s. The results indicate that the largest amplitude of V/H spectral ratios for the whole magnitude range, in the near field (Rhypo = 10Km), is found at the period T = 0.05s (red line), which range from 0.7 (M = 3) to 1.14 (M = 7.5). Then, for the remaining periods, for wms ($M \leq 5.5$), the amplitude of the V/H spectral ratio is the most greater at T = 0.01s (black line) and ranges between 0.53 (M = 3) to 0.66 (M = 5.5). For mhs ($M > 5.5$), the amplitude of the V/H spectral ratio is the most greater at T = 0.1s (blue line), and ranges between 0.66 (M = 5.5) to 0.95 (M = 7.5).

According to the previous analysis, the vibration periods that give the most significant amplitudes of the V/H spectral ratio are T = 0.05 and 0.1s, and to a lesser degree T = 0.01s. In the current seismic codes (EC8, 2004) the ratio of PGA (vertical) to PGA (horizontal) determines the vertical to horizontal scaling factor. This is equivalent to T = 0.01s in the current investigation, which is not the worst-case scenario. Thus, we suggest calculating the ratios of the vertical to horizontal response spectra at the five previously described periods (columns 2 to 7 in Table 5). For each Period, we then average the values that correspond to M = 3, 4, and 5 in the case of the wms seismicity level (column 8 in Table 5), and the average of the values that correspond to M = 6, 7, and 7.5 in the case of the mhs seismicity level (column 9 in Table 5).

Table 5 Ratio of the vertical to horizontal response spectra from the present study and comparisons with Malhotra (2006), Cauzzi and Faccioli (2008), and Pavel et al. (2024)

M	3	4	5	6	7	7.5	Average for wms	Average for mhs	mean	Malhotra (2006)	Cauzzi and Faccioli (2008)	Pavel et al. (2024)
T (s)	V/H											
0.01	0.53	0.58	0.63	0.69	0.76	0.79	***0.58***	***0.75***	*0.67*	0.6	1	0.62
0.05	0.70	0.78	0.87	0.97	1.08	1.14	***0.78***	***1.06***	*0.92*	0.8	1	-
0.1	0.43	0.51	0.61	0.73	0.87	0.95	***0.52***	***0.85***	*0.69*	0.7	1	-
0.2	0.43	0.47	0.51	0.56	0.61	0.64	*0.47*	*0.60*	*0.54*	0.55	0.67	0.50
1.0	0.53	0.55	0.58	0.60	0.63	0.64	*0.55*	*0.62*	*0.59*	0.40	0.67	0.40
Mean values							*0.58*	*0.78*				
Recommended values for $C_{v/h}$							***0.60***	***0.80***				

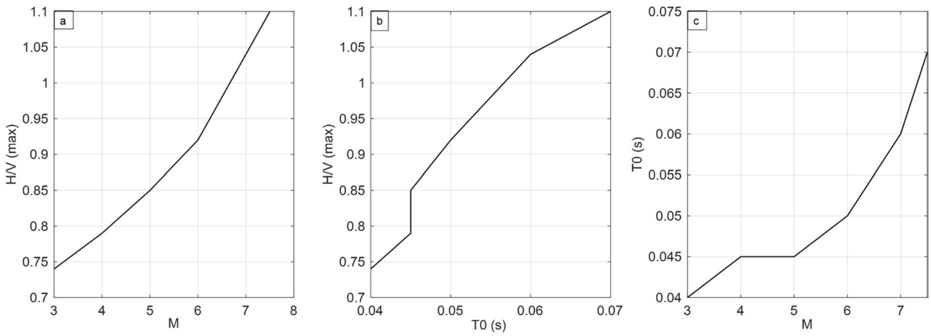

Fig. 5 Variation of the ratio of the vertical to horizontal response spectra versus the magnitude (**a**), the period T_0 (**b**), and variation of T_0 with M (**c**)

Table 5 presents, for each period, the mean ratios of the vertical to horizontal response spectra for the wms and mhs seismicity levels. First, we see that there are variations in the average values of the V/H ratios across periods for the two levels, wms and mhs. Then, for the wms and mhs levels, high and low ratios are obtained at T = 0.05 s and T = 0.2 s, respectively. For T = 0.01s, the PGA period, the maximum V/H ratios are 0.58 and 0.75 at wms and mhs levels, respectively. The recommended values of the ratio of vertical to horizontal design acceleration $C_{v/h}$, for wms and mhs seismicity levels, is the averaged value over the five periods, 0.60 and 0.80 respectively.

Table 5 presents also comparisons with the mean ratios of the vertical to horizontal response spectra from Malhotra (2006), Cauzzi and Faccioli (2008), and Pavel et al. (2020), who used 63, 1155 ($5.0 \leq M_W \leq 7.2$), and 500 ($M_W \geq 5.2$) strong motion data, respectively. The comparison reveals similar V/H ratios from the present study for mhs seismicity level with those of Cauzzi and Faccioli (2008), while the mean V/H ratios from the present study are close to those from Malhotra (2006) and Pavel et al. (2024) except at T = 1.0s.

Finally, from Fig. 4b, findings allow us to plot in Fig. 5 the variation of the ratio of the vertical to horizontal response spectra versus the magnitude (Fig. 5a) and versus the associated period T_0, at which the maximum is attained, (Fig. 5b), and the variation of T_0 with the magnitude M (Fig. 5c). It is clearly apparent that the ratio of the vertical to horizontal response spectra increases with both the period T_0 and M, and that the period T_0 increases with M.

6 Comparison with ASCE7-16 and draft of the EC8 (2022)

In this part, we compare the derived vertical elastic response spectra to the vertical spectra of the ASCE7-16 and the new generation EC8-draft2022 standards given by Eqs. 3 and 4 respectively.

$$\begin{array}{ll} S_{aMv} = 0.3.C_v S_{MS} & T_v \leqslant 0.025\,s \\ S_{aMv} = 20.C_v S_{MS}\,(T_v - 0.025) + 0.3.C_v S_{MS} & 0.025 < T_v \leqslant 0.05\,s \\ S_{aMv} = 0.8.C_v S_{MS} & 0.05 < T_v \leqslant 0.15\,s \\ S_{aMv} = 0.8.C_v S_{MS}\left(\frac{0.15}{T_v}\right)^{0.75} & T_v > 0.15\,s \end{array} \tag{3}$$

with S_{MS} is the MCER spectral response acceleration at short period, T_v is the vertical period of vibration in sec, and C_v is given in Table 6.

$$S_{\alpha\,v} = f_{v\alpha}\,S_{\alpha} \text{ and } S_{\beta\,v} = f_{v\beta}\,S_{\beta} \tag{4}$$

S_{α} and S_{β} are the spectral acceleration at short period and at T = 1 s respectively in m/s² with

$$f_{v\alpha} = 0.6 \qquad S_{\alpha} < 2.5$$

$$f_{v\alpha} = 0.04 S_{\alpha} + 0.5 \qquad 2.5 \leqslant S_{\alpha} \leqslant 7.5$$

$$f_{v\alpha} = 0.8 \qquad S_{\alpha} > 7.5$$

and

$$f_{v\beta} = 0.6$$

Figures 6 show the comparison between the derived vertical elastic response spectra to the vertical spectra of the ASCE7-16 and the new generation EC8-draft2022 standards, for 4 soil classes and 6 short period spectral acceleration values at T = 0.2 s.

For wms (Ss = 1.75, 2.5, and 3.75 m/s²) and mhs (Ss = 5.0, 6.25, and 7.5 m/s²) seismicity levels, the comparison reveals:

The amplitude of the proposed spectra is in agreement with the ASCE7-16 and with EC8-draft2022 except the mhs level and soil class SCA revealing some difference with ASCE7-16.

The period Tc of the proposed spectra is in agreement with the ASCE7-16 for the wms seismicity level (Ss ≤ 3.75 m/s²), and with EC8-draft2022 for the mhs seismicity level (Ss ≥ 5.0 m/s²).

Table 6 Values of vertical coefficient C_v (ASCE7-16)

Mapped MCER spectral response parameter at short period	Site class A, B	Site class C	Site class D, E,F
S_S≥2.0	0.9	1.3	1.5
S_S=1.0	0.9	1.1	1.3
S_S=0.6	0.9	1.0	1.1
S_S=0.3	0.8	0.8	0.9
S_S≤0.2	0.7	0.7	0.7

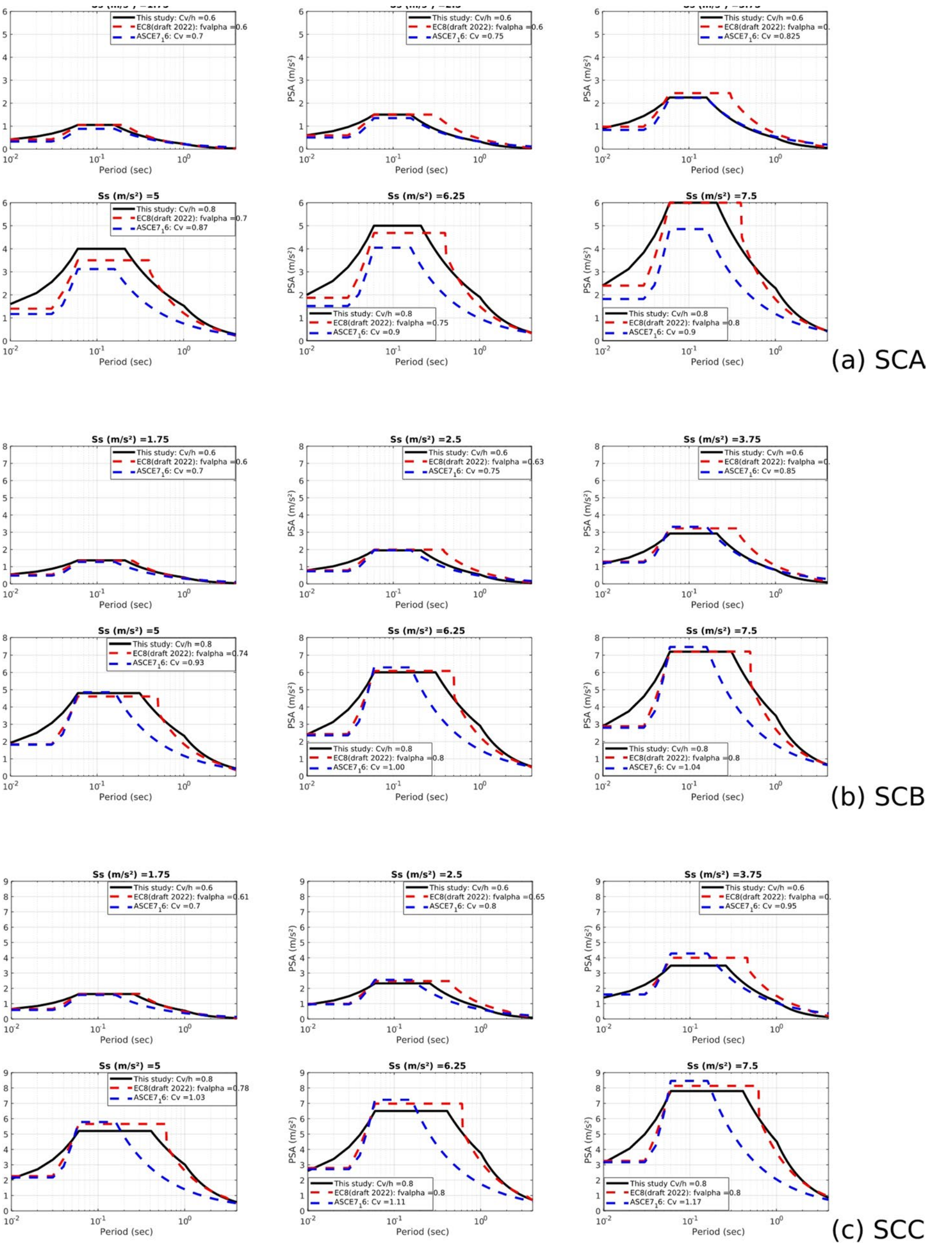

Fig. 6 Comparison between the derived vertical elastic response spectra to the vertical spectra of the ASCE7-16 and EC8-draft2022 standards for soil class SCA (**a**), SCB (**b**), SCC (**c**) and SCD (**d**)

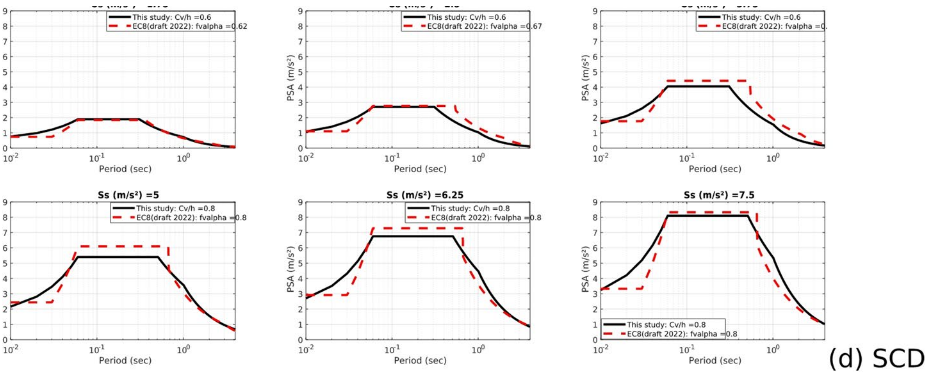

Figure 6 (continued)

7 Conclusion

This paper has focused on the definition of the vertical elastic response spectra in the framework of the ongoing revision of the current Algerian seismic code RPA99 (2003). A large accelerometric database from Algeria and surrounding regions of 773 3-components records, with magnitudes ranging from 3.0 to 7.4, is used to develop vertical elastic acceleration response spectra for four soil classes (rock, firm, soft, and very soft soils) and two seismicity levels, mhs ($M > 5.5$) and wms ($M \leq 5.5$).

Firstly, the plateau spectral amplitude of the constant spectral acceleration, which is the maximum of the normalized response spectra, is investigated. The obtained results recommend values of 2.60 and 2.40 for wms and mhs seismicity levels respectively.

The period limits of the constant spectral acceleration branch are then investigated, which can be estimated by fitting the general form with experimental normalized acceleration response spectra at the 84th percentiles. The current study reveals that both the type of seismicity and the soil class have significant impact on T_C, whereas theirs influences T_B is minor. This result supports our interest in proposing two types of spectra for the two seismicity levels.

The impact of seismicity level on the attenuation index is analyzed, since the American Society of Civil Engineers (ASCE7-16, 2017) design code and the EC8 (2004) recommend different values of 0.7 and 1 respectively. The values found for wms and mhs are 0.8 and 0.6, respectively, with an average value of 0.7, which matches the ASCE suggested one.

Finally, the ratio of the vertical to horizontal response spectra is investigated since previous research has revealed that the vertical component of seismic motion can have greater amplitudes than the horizontal one, particularly in near field. A parametric study is carried out to evaluate the fluctuation of the V/H spectral ratio vs. magnitude M, hypocentral distance R_{hypo}, and vertical vibration period T. The main results show that:

- For a given magnitude, the V/H ratio decreases generally with distance,
- For a given distance, the V/H ratio increase with magnitude,
- The greatest V/H spectral ratios for the whole distance range are found in the period interval 0.05–0.1 s. This finding might have a significant impact on the seismic behavior of stiff buildings whose vertical fundamental periods fall between 0.04 and 0.15 s,

- Comparison reveals similar V/H ratios from the present study for mhs seismicity level with those of Cauzzi and Faccioli (2008), while the mean V/H ratios from the present study are close to those from Malhotra (2006) and Pavel et al. (2024) except at T = 1.0s.
- The obtained results clearly show that the ratio of the vertical to horizontal response spectra increases with both the period T_0, at which the maximum of the ratio V/H is attained, and M, and that the period T_0 increases with M.

Comparison between the derived vertical elastic response spectra to the vertical spectra of the ASCE7-16 and the new generation EC8-draft2022 standards, for 4 soil classes and for wms (Ss = 1.75, 2.5, and 3.75 m/s²) and mhs (Ss = 5.0, 6.25, and 7.5 m/s²) seismicity levels, reveals:

- The amplitude of the proposed spectra is in agreement with the ASCE7-16 and with EC8-draft2022 except the mhs level and soil class SCA revealing some difference with ASCE7-16.
- The period Tc of the proposed spectra is in agreement with the ASCE7-16 for the wms seismicity level (Ss ≤ 3.75 m/s²), and with EC8-draft2022 for the mhs seismicity level (Ss ≥ 5.0 m/s²).

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Author contributions Laouami Nasser contributed to the study conception and design, material preparation, data collection and analysis, and manuscript writing.

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Data availability The Algerian dataset analysed during the current study is available in the CGS repository, http://www.cgs-dz.org/index.php/fr/reseau-accelerometriques.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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