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Evaluating the Characteristics of Vertical Design Spectrum in Egyptian Seismic Design Code

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Abstract: The vertical design spectrum was defined in modern seismic design codes as a ratio from horizontal response spectra for different levels of seismic intensity. These spectra are important for some special structural systems which are indicated in the seismic design codes. In this study, 268 sets of shallow crustal earthquakes in three magnitude levels of earthquakes were selected to evaluate the characteristics of the vertical design spectrum in the Egyptian design seismic code (ECP-201, 2012). The database records of strong motions were taken from Pacific Earthquake Engineering Research Center (PEER) for diverse areas in the world. Four types of soil (A, B, C and D) based on ECP-201 are used in the evaluations. The first type of elastic response spectrum for shallow crustal earthquakes was recommended according to the ECP-201. The evaluation indicated that significant differences between the mean vertical spectral response spectra and individuals derived from the ECP-201 code for different seismicity. The V/H ratio is sensitive to both earthquake magnitude levels and soil types.

Keywords: Vertical Design Spectrum; the Egyptian design code; earthquake magnitude;Strong-Motion; Seismic Site Classification

I. INTRODUCTION

Three perpendicular directions of earthquake ground motions are typically recorded. These recorded are two horizontals and one vertical ground motion. Vertical ground motions have become one of the most discussed topics in recent decades in designing structures, especially after ignoring it in designing earthquakes for many years. It was believed that vertical ground motions are always less than horizontal ground motions and that damage from earthquakes was due to horizontal ground motions. Also, mostly the peaks in vertical and horizontal accelerations do not happen together. Extensive research has initiated since the 1994 Northridge earthquake in California with the impact of the vertical earthquake component [1]. Fardis [2] indicated that the vertical seismic component effects are usually covered by the design of gravity loads.

Many analytically and experimentally studies are performed to predict the performance of structures under the horizontal with the vertical components of earthquakes. Kima et al. [3] investigated experimentally the effect of vertical and horizontal ground motion on the piers in RC bridge. The test results are indicated that the axial force and the strain of the spiral increase with the vertical ground motion. Djarir and Abdelkrim[4] evaluated the non-linear dynamic analysis of 5- and 9-story RC frames on shallow foundations under horizontal with vertical components of earthquakes. The results indicated that horizontal displacements in the case of the vertical ground motion with the soil-structure interaction decreases compared to the status of the horizontal component only. Kuleli and Elnashai[5] evaluated the performance of medium to long span for cable-stayed bridges in two cases of the input motions. The first case with the horizontal motion only, whiles the second case with both horizontal and vertical component of earthquakes. The results obtained indicated that the moment and rotation requirements along the bridge deck increase as the vertical ground motion is taken into consideration in the analysis. Also, the effect of horizontal acceleration and both horizontal and vertical acceleration on three steel frames are investigated by Abdollahiparsa et al. [6]. Two types of soil (E and D) with shear waves 100 and 250 m/s are used in the analysis. The analysis showed that the axial force on columns, the story drift and foundation rotation are increased by effect vertical component. In addition, the column axial forces with the inclusion of a seismic vertical component in type D soils are greater than those in type E soils.

Farsangi and Tasnimi[7] investigated the horizontal and vertical ground motions investigations on four RC-MRFs which have been designed according to ACI building code. Special and intermediate of RC-MRFs are used in the analysis. The results indicated that the ductility demand is increased in the case of horizontal and vertical ground excitations. Elhifnawy et al. [8] investigated the inelastic performance of 6-, 10- and 20-story RC frames under the three components of earthquakes. The results indicate that the column axial forces and strain ductility factors in columns are affecting under the three components of the earthquakes. Wibowo and Sritharan[9] also investigated the seismic response of medium- and long-span bridges under vertical ground accelerations. The results indicated that the displacement and moments have effected due to the vertical ground acceleration.

It is now easy to analyze the structures in three directional models, especially with the great development of computers. So, both two horizontal component and vertical components of earthquakes can be used in the analysis. There is a spectral acceleration with different values for each component of earthquakes. However the only response spectrum for the horizontal component (H) is found in seismic design codes while the vertical response spectrum (V) was taken as (V/H) ratio from horizontal component. Newmark et al. [10] considered the V/H ratio as a constant value and equals to 2/3. While Abrahamson and Litehiser[11] indicated that the constant rule of V/H ratio (2/3) is unreasonable. Also, Niazi and Bozorgnia[12] indicated that in the very near field, the V/H equals to 2/3 appears un-conservative. As for the far field, the V / H decreases by less than a value equal to 1/2.

Ambraseys and Simpson [13] indicated that with short periods, the V/H is greater than one while at both medium and long periods, these ratios are less than one. Collier and Elnashai [14] noted that in 5 kilometers from the earthquake source, the V/H is greater than 1.0, and greater than 2/3 within a radius of 25 km. Bozorgnia and Campbell [15] mention that the source to site distance, natural period, and site situations have a strong influence on V/H ratio; while the magnitude of earthquake and faulting mechanism have a little effect on V/H ratio. Furthermore, in firm soil sites, the V/H ratio can exceed the unit value, approaching factor 1.8 in short periods, close distances, and great magnitudes. Bozorgnia and Campbell [16] develop that at short periods, V/H ratio exceeds 2/3 value in near fault areas.Additionally, different empirical models were estimated to find a V/H ratio. These models are presented the equations to calculate approximately a vertical response spectrum from a horizontal response spectrum. Many variables such as site class, source to site distance, and style of faulting and moment magnitude were used in these models [17]-[21].

From previous studies and research, it is clear to us that the approach for estimating the structural response due to the seismic vertical ground motion as a percentage of structural response due to the horizontal earthquake component is an approximation because the frequency content of the seismic vertical ground motion is usually greater than the horizontal ground motion. Moreover, the estimates of the V/H ratio in the literatures and ECP-201code [22] are varied and cannot be reached to a single value. Also, the vertical spectral shape did not clearly the effects of magnitude earthquake levels and the soil types in ECP-201code [22]. Hence, it is important to assess adequacy of the provisions design outlined in the building codes for spectra of response to the vertical component of earthquakes. The characteristics of the vertical design spectrum in the Egyptian seismic design code are evaluated in this study. 268 sets of shallow crustal earthquakes for three magnitude levels of earthquakes were selected. Four types of soil based on Egyptian's seismic design code are suggested. The first type of elastic response spectrum for shallow crustal earthquakes was recommended according to the ECP-201 [22].

II. VERTICAL TO HORIZONTAL RESPONSE SPECTRUM RATIO IN SEISMIC DESIGN CODES

Several design seismic codes derived a vertical response spectra shape as a ratio (V/H) from horizontal response spectrum. This means that both response spectrum shapes of the vertical and horizontal shape have identical frequency content. In many design seismic codes, the ratio V/H is constant and equivalents 2/3 as the Iran’s practical building code [23] and FEMA-356 [24]. Some codes such as Caltrans [25], AASHTO [26], and ASCE 7-16 [27] are increasing or decreasing the quantity of dead load to consider the influence of the vertical ground motion. Based on the earthquake magnitude, Type 1 and Type 2 of the spectrum are recommended in Euro code [28]. Type 2 spectrum is implemented for earthquakes with a surface-wave magnitude not transgress 5.5, and contribute significantly to the site-specific seismic risk for the purpose of assessing probabilistic risk. For that, the V/H ratios are considered equal to 0.45 and 0.9 for Types 1 and 2 spectra, respectively.

The pseudo vertical peak ground acceleration (PGA) was recommended two values in the ECP-201[22] as a portion of horizontal PGA. The first value is 0.45 which used in the coastal region on the Mediterranean Sea while the second value is 0.9 which used in all regions of the republic of Egypt. The vertical response spectrum in ECP-201did not considers the soil type, but depend on the peak ground acceleration. The vertical component in ECP-201 was considered for all structures that in case a_{vg} is larger than 0.25 g; Horizontal structural members or semi-horizontal with spanning equal or greater than 20 m; Horizontal or semi-horizontal cantilever with span more than 5 m, Horizontal pre-stressed beams or semi-horizontal and base-isolated structures. The elastic vertical response spectrum in ECP-201 is defined as[22]:

$$0 \le T < T_B \qquad S_{ve}(T) = a_{Vg} \cdot \gamma_1 \cdot \left(1 + \frac{T}{T_B} \cdot (\eta \cdot 3.0 - 1)\right) \quad (1)$$

$$T_B \le T \le T_C \qquad S_{ve}(T) = a_{vg} \cdot \gamma_1 \cdot \eta \cdot 3.0 \quad (2)$$

$$T_C \le T \le T_D \qquad S_{ve}(T) = a_{vg} \cdot \gamma_1 \cdot \eta \cdot 3.0\left(\frac{T_C}{T}\cdot\right) \quad (3)$$

$$T_D \le T \le 4\sec \qquad S_{ve}(T) = a_{vg} \cdot \gamma_1 \cdot \eta \cdot 3.0 \cdot \left(\frac{T_C T_D}{T^2}\right) \quad (4)$$

Where, S_{ve} is the elastic response spectrum, ηcorrection damping factor with reference value, a_{vg} is the design vertical ground motion, T is the natural period of vibration; T_B, T_C, T_D are theendsof the spectral acceleration constant branch, dependent on ground type.

III. STRONG-MOTION DATABASE

268 sets of ground motions for shallow crustal earthquakes were chosen to cover a various collection of frequency, duration and amplitude. Three classifications of earthquake magnitude are included with Joyner–Boore distance (R_{JB}) less than 30 km from near-source earthquake records and from 30 to 250 km for far-source earthquake records. These magnitudes are with M_W< 5.5, 5.5 ≤ M_w ≤ 6.5 (M5-6) and M_w> 6.5 as shown in Fig.1. The ECP-201 code was suggested four types of soil (A, B, C and D). These types of soils are rocky, or very stiff (V_{S30} ≥ 800 m/s), very dense sand/gravel or of stiff clays (360 m/s ≤ V_{S30}< 800 m/s), dense or medium dense sand/gravel (180 m/s ≤ V_{S30}< 360 m/s), and loose-to-medium cohesion less soil, (V_{S30}< 180 m/s)[22]. For evaluation drives, the maximum horizontal response spectrum for each earthquake was selected in calculating the ratio of vertical to horizontal response spectra. The database records of strong motions were taken from Pacific Earthquake Engineering Research Centre (PEER) for diverse areas in the world [29].

The first type of spectrum for shallow crustal earthquakes in the ECP-201 has used in the evaluation, as it covers most of Egypt's regions. The seismic maps of the ECP-201 code present six different seismic PGAs of 0.1g, 0.125g, 0.15g, 0.2g; 0.25g and 0.3g are considered to covering a varied range of seismic designed structure. These response spectra did not depend on the type of soil as the horizontal response spectrum according to the ECP-201 code.

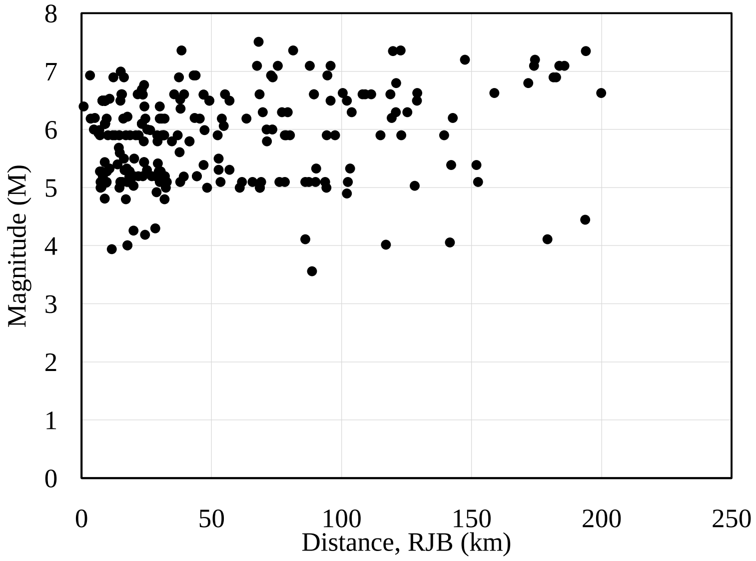

Figure 1: Distribution of magnitude with distance for earthquake records

IV. EFFECT OF EARTHQUAKE MAGNITUDE

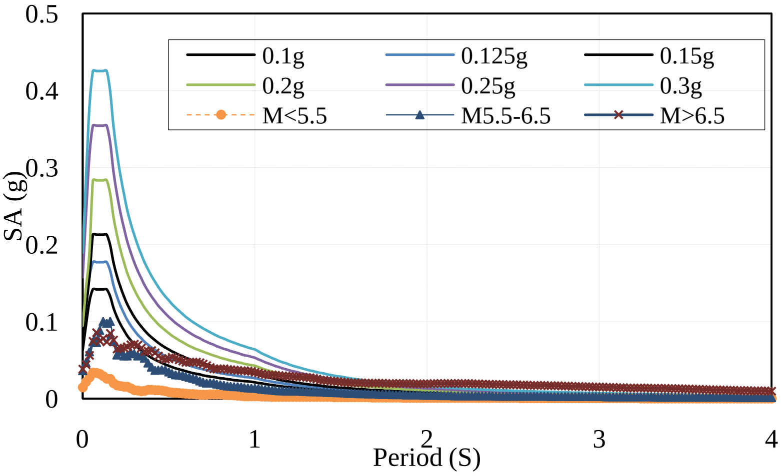

Figure 2: Mean vertical response spectra versus the periods for soil type (A) to three earthquake magnitude levels

The mean vertical spectral response spectra versus the periods of soil type (A) for three earthquake magnitude levels are shown in Fig. 2. The vertical response spectra for different seismicity levels of the ECP-201 conditions are also showed in this figure. The figure indicates that a significant difference between the mean vertical spectral response spectra of earthquakes and individuals derived from the ECP-201 code. The mean vertical spectral response spectra developed from different magnitudes levels also show different tendencies with each other. The vertical design spectra of ECP-201 code for different seismicity levels are overestimating the mean vertical spectral response spectra in cases of M < 5.5 and M5.5-6.5. In case of M > 6.5, the mean vertical spectral response spectra are underestimating the vertical design spectra of ECP-201 code for different seismicity levels with period less than 0.3S.

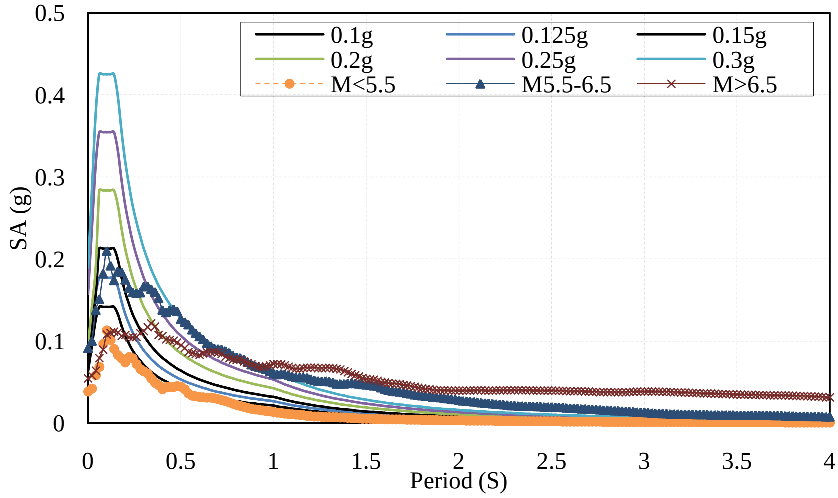

Figure 3: Mean vertical response spectra versus the periods for soil type (B) to three earthquake magnitude levels

The mean vertical spectral response spectra versus the periods of soil type (B) for three earthquake magnitude levels are shown in Fig. 3. The vertical response spectra for different seismicity levels of the ECP-201 conditions are also showed in this figure. The figure indicates that significant differences between the mean vertical spectral response spectra of earthquakes and individuals derived from the ECP-201 code. The mean vertical spectral response spectra established for different magnitudes moreover show different tendencies with each other. The vertical design spectra of ECP-201 code for different seismicity levels are overestimating the mean vertical spectral response spectra in case of M < 5.5. In case of M > 6.5, the mean vertical spectral response spectra are underestimating the vertical design spectra of ECP-201 code for different seismicity levels with period less than 0.2S. In case of M5.5-6.5, the vertical design spectra of ECP-201 code (0.2g, 0.25g and 0.3g) are overestimating the mean vertical spectral response spectra for short periods. The performance of ECP-201 vertical design spectrum for 0.1g is accessible with the case of M< 5.5.

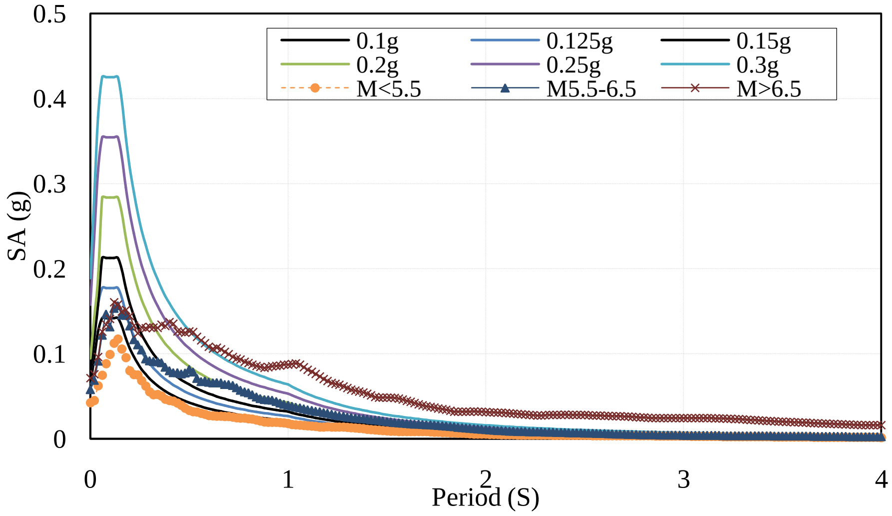

Figure 4: Mean vertical response spectra versus the periods for soil type (C) to three earthquake magnitude levels

The mean vertical spectral response spectra versus the periods of soil type (C) with for earthquake magnitude levels are displayed in Fig. 4. The vertical response spectra for different seismicity levels of the ECP-201 conditions are also showed in this figure. The figure indicates that significant differences between the mean vertical spectral response spectra of earthquakes and individuals derived from the ECP-201 code. The mean vertical spectral response spectra established for different magnitudes moreover show different tendencies with each other. The vertical design spectra of ECP-201 code for different seismicity levels are overestimating the mean vertical spectral response spectra in case of M < 5.5. In case of M5.5-6.5 and case of M > 6.5, the vertical design spectra of ECP-201 code (0.125g, 0.2g, 0.25g and 0.3g) are overestimating the mean vertical spectral response spectra for short period.

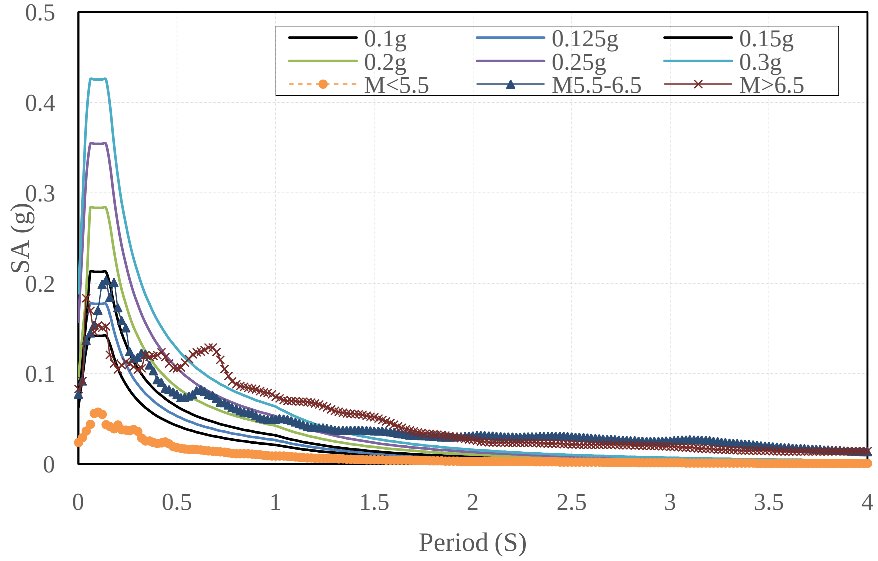

Figure 5: Mean vertical response spectra versus the periods for soil type (D) to three earthquake magnitude levels

The mean vertical spectral response spectra versus the periods of soil type (D) for three earthquake magnitude levels are shown in Fig. 5. The vertical response spectra for different seismicity levels of the ECP-

201 conditions are also showed in this figure. The figure indicates that significant differences between the mean vertical spectral response spectra of earthquakes and individuals derived from the ECP-201 code. The mean vertical spectral response spectra established for different magnitudes levels moreover show different tendencies with each other. The vertical design spectra of ECP-201 code for different seismicity levels are overestimating the mean vertical spectral response spectra in case of M < 5.5. In case of M5.5-6.5, the vertical design spectra of ECP-201 code (0.125g, 0.15g, 0.2g, 0.25g and 0.3g) are overestimating the mean vertical spectral response spectra for short period. In case of M > 6.5, the vertical design spectra of ECP-201 code (0.2g, 0.25g and 0.3g) are overestimating the mean vertical spectral response spectra for short period. The above comparisons indicate that a vertical response spectrum is sensitive to both magnitude levels of earthquakes and the soil type. Also, the differences between the mean vertical spectral response spectra and individuals derived from the ECP-201 code for different seismicity levels.

V. EFFECT OF VERTICAL TO HORIZONTAL RESPONSE SPECTRUM RATIO

The effect of soil type on the vertical to horizontal response spectrum ratio (V/H) was analyzed in three levels of earthquake magnitude. Fig. 6 shows the relationships between the mean vertical to horizontal (V/H) response spectrum ratio and the periods for the three earthquake magnitude for soil type (A). The constant value of V/H ratio to Newmark et al. [10] and the ECP-201 code [22] are also displayed in this figure. The results offered in the figure indicate that the V/H ratios of the three earthquake magnitude levels are not constant as set in the Newmark et al. and the ECP-201 code. The maximum mean V/H ratios are 0.75, 0.688 and 0.757 for earthquakes in cases M< 5.5, M5.5-6.5 and M> 6.5, respectively. The maximum mean V/H ratios are greater than both ratios of Newmark and ECP-201 for all cases of earthquake magnitude levels.

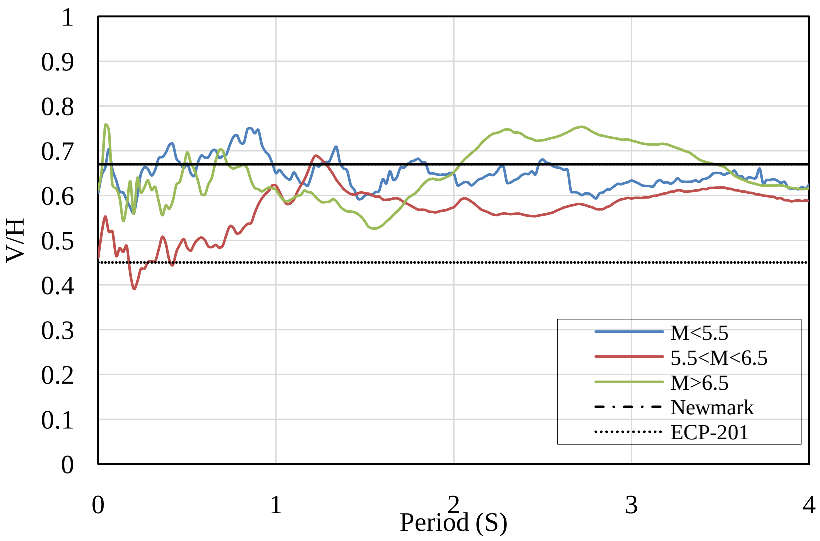

Figure 6: The mean vertical to horizontal response spectrum ratio (V/H) variation for three earthquake magnitude levels to soil type (A)

The effect of soil type on the vertical to horizontal response spectrum ratio (V/H) was analyzed in three levels of earthquake magnitude. Fig. 7 shows the relationships between the mean vertical to horizontal (V/H) response spectrum ratio and the periods for the three earthquake magnitude of soil type (B). The constant value of V/H ratio to Newmark et al. [10] and the ECP-201 code[22] are also displayed in this figure. The results offered in the figure indicate that the V/H ratios of the three earthquake magnitude levels are not constant as set in the Newmark et al. [10] and the ECP-201 code [22]. The maximum mean V/H ratios are 0.7, 0.69 and 0.75 for earthquakes in cases M< 5.5, M5.5-6.5 and M> 6.5, respectively. The maximum mean V/H ratios are greater than both ratios of Newmark and ECP-201 for all cases of earthquake magnitude levels.

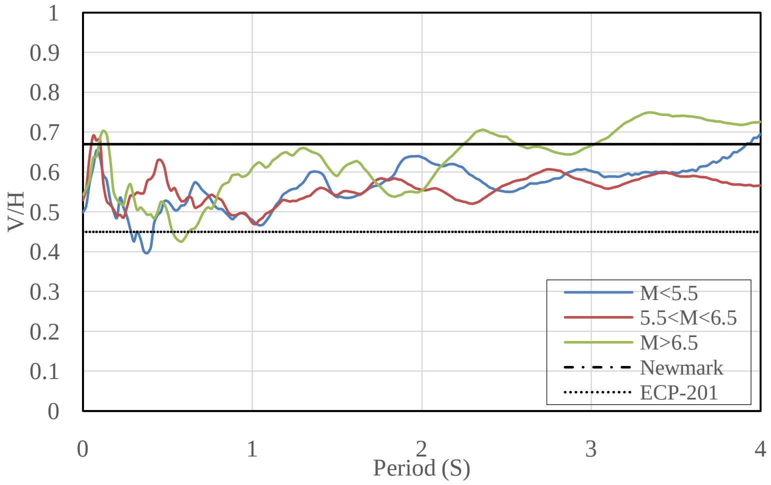

Figure 7: The mean vertical to horizontal response spectrum ratio (V/H) variation for three earthquake magnitude levels to soil type (B)

The effect of soil type on the vertical to horizontal response spectrum ratio (V/H) was analyzed in three levels of earthquake magnitude. Fig. 8 shows the relationships between the mean vertical to horizontal (V/H) response spectrum ratio and the periods for the three earthquake magnitude of soil type (C). The constant value of V/H ratio to Newmark et al. [10] and the ECP-201 code [22] are also displayed in this figure. The results offered in the figure indicate that the V/H ratios of the three earthquake magnitude levels are not constant as set in the Newmark et al. [10] and the ECP-201 code [22]. The maximum mean V/H ratios are 0.57, 0.74 and 0.68 for earthquakes in cases M< 5.5, M5.5-6.5 and M> 6.5, respectively. The maximum mean V/H ratios are greater than the ratios of Newmark in cases M5.5-6.5 and M> 6.5. The maximum mean V/H ratios are greater than the ratios of ECP-201 for all cases of earthquake magnitude levels.

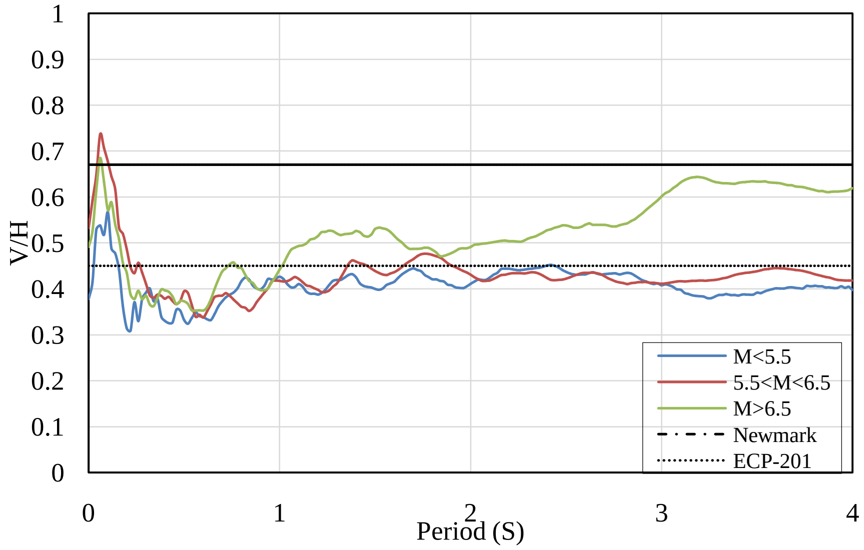

Figure 8: The mean vertical to horizontal response spectrum ratio (V/H) variation for three earthquake magnitude levels to soil type (C)

The effect of soil type on the vertical to horizontal response spectrum ratio (V/H) was analyzed in three levels of earthquake magnitude. Fig. 9 shows the relationships between the mean vertical to horizontal (V/H) response spectrum ratio and the periods for the three earthquake magnitude of soil type (D). The constant value of V/H ratio to Newmark et al. [10] and the ECP-201 code[22] are also displayed in this figure. The results offered in the figure indicate that the V/H ratios of the three earthquake magnitude levels are not constant as set in the Newmark et al. and the ECP-201 code. The maximum mean V/H ratios are 0.65, 0.87 and 0.73 for earthquakes in cases M< 5.5, M5.5-6.5 and M> 6.5, respectively. The maximum mean V/H ratios are greater than the ratios of Newmark in cases M5.5-6.5 and M> 6.5. The maximum mean V/H ratios are greater than the ratios of ECP-201 for all cases of earthquake magnitude levels. From Figs. 6-9, the results indicate that V/H ratio is sensitive to both soil type and magnitude level.

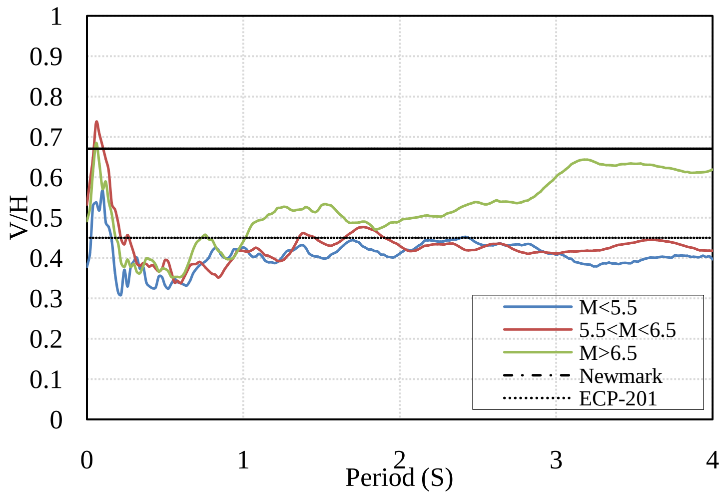

Figure 9: The mean vertical to horizontal response spectrum ratio (V/H) variation for three earthquake magnitude levels to soil type (D)

VI. CONCLUSIONS

In this study, the characteristics of the vertical design spectrum in the Egyptian design seismic code are evaluated. 268 sets of three magnitude levels for shallow crustal earthquakes were selected. Four types of soil based on Egyptian's seismic design code (ECP-201, 2012) are suggested. The first type of elastic response spectrum for shallow crustal earthquakes was recommended according to the ECP-201. The following conclusions are:

1) There is a difference between the mean vertical response spectra and the individuals derived from the ECP-201 code for different seismicity levels.
2) The vertical response spectrum is sensitive to both magnitude levels and the soil type.
3) The vertical design spectra of ECP-201 code are overestimating the mean vertical spectral response spectra in the case of M< 5.5 for all types of soils.
4) There is a need for investigated the Egyptian code formulas to calculate the vertical response spectrum with taken the effect of earthquake magnitude levels and type of soils.

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