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ANALYSIS OF VERTICAL GROUND MOTIONS OF NEAR SOURCE RECORDS IN MEXICO

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SUMMARY

A brief state-of-the-art about vertical ground motions is compiled. Recommended provisions to include the vertical ground motion in the seismic design of structures available in some international building codes are discussed. The vertical component of the ground motion recorded near the source (epicentral records) in earthquakes originated in the subduction zone of the Mexican Pacific Coast is studied. The curves for the spectral displacement ratios of vertical to horizontal components are analyzed and adjusted to an envelope function for the mean response. Artificial records obtained from the proposed spectral intensity functions are compared with the records that gave rise to them. Furthermore, the design spectra proposed by some seismic codes in Mexico to account for the vertical effects are compared with the forecast spectra obtained from the horizontal spectral intensity with the described envelope function. Finally, qualitative recommendations for the election of the spectral design intensity in the vertical direction are provided.

INTRODUCTION

In the beginning, the solution to the problem of the seismic design of structures started with the practical consideration of applying equivalent lateral forces, which are proportional to the weight of the structure. With the gain of knowledge in structural dynamics and the development of computer software, structural engineers started to take into account, among other considerations, the dynamic properties of the structure, the influence of both horizontal components for the site, and soil-structure interaction effects. However, a reasonable consensus exists for the need of incorporating into the design process other variables that could influence the structural response of certain type of constructions located in regions of high seismic hazard. An example of these variables is the consideration of the vertical component of the ground motion in the design process, which most seismic codes worldwide omit or include in a very simplistic and superficial way.

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The first studies on the vertical seismic component proposed to obtain ratios of the peak absolute values of the horizontal and vertical components of the seismic ground acceleration and thus, to estimate the vertical design intensity in function of the parameters established in the codes for the design of lateral forces. In the lack of other alternative, this methodology was adopted in many seismic codes worldwide, mainly where the probability of a high vertical seismic intensity was supposed.

BACKGROUND

Most of the studies on vertical ground motion are limited to obtaining relationships between the vertical and the horizontal ground motion components, in order to predict the vertical intensity through the horizontal intensity, with or without relation to other variables such as magnitude, distance, frequencies or periods. However, as it will be commented below, other studies have been focused on estimating the vertical seismic intensity without relating it to the horizontal.

Newmark et al. [1] accomplished one of the first studies on vertical ground motion. They proposed to obtain vertical to horizontal quotients (maximum ground acceleration, velocity and displacement). This study indicates that, based on the analysis of 33 records mainly of the United States, the vertical acceleration is 2/3 of the horizontal. This value has been adopted in many seismic design codes with no other alternative. Some researches (Kawashima et al. [2]; Ambrasays and Simpson [3]; Boomer and Martinez [4]; Mohammadioun [5]) have continued with this trend, in order to estimate the maximum vertical intensity in function of its corresponding horizontal intensity. In Table 1, different proposed vertical-to-horizontal ratios based on maximum ground acceleration are shown.

Table 1. Vertical-to-horizontal acceleration ratios proposed

Reference	Records	V/H
Newmark et al. [1]	33 records from USA	2/3
Kawashima et al. [2]	Records from Japan	1/5
Ambrasays & Simpson [3]	104 records from the world, R<15km, M>6, V>0.1g	1.75
Boomer and Martinez [4]	130 records, V>0.2g	1.00
Mohammadioun [5]	Alluvium soil, near source	0.75

Relationships of vertical to horizontal motion of records associated with granite were studied by Abe and Watanabe [6]. They concluded that vertical motion is strongly affected after the arrival of S waves.

Other authors (Singh [7], Hudson et al. [8], Bozorgnia, Niazi and Campbell [9], Perea and Esteva [10]) emphasize that the ratio of peak values of vertical to horizontal accelerations is highly dependent on epicentral distance, with high values in short distances and low in far distances. Others (Singh [7], Hudson et al. [8], Ohno et al. [11], Kusunoki [12], Bozorgnia, Campbell and Niazi [13]; Perea [14]) emphasize that quotient is furthermore highly dependent of the vertical period, with high values in short periods and low values in high periods.

Spectral attenuation relationships for vertical ground motion, based on the seismic records analysis, were obtained by Sharma [15], Bozorgnia, Campbell and Niazi [13], and Perea and Esteva [10]. Spectral quotients from vertical to horizontal, based on the attenuation relationships, were presented in the first two publications. Their results show a great dependency between both horizontal and vertical components on the oscillation period, the distance from source to site, and the soil local conditions, but not on the magnitude and mechanism type. Nevertheless, the results of the last two groups of authors show a great dependency of the spectral extent of both components with the magnitude and the epicentral distance, and the site effects are mainly controlled by the differences between both spectral amplitudes.

Acceleration records of the vertical component have been generated by Saragoni and Hart [16] and Perea, Alamilla and Esteva [17]. The algorithm proposed by the former authors consists in passing white noise through a filter that represents consecutive segments of a ground accelerations record by different uniformly modulated stationary processes. The second generates vertical story acceleration on firm ground by means of an amplitude-and-frequency modulation model (generalized attenuation functions). Each acceleration time history is considered as a realization of a non stationary gaussian stochastic process, with statistical parameters that depend on the magnitude and the site-to-source distance. Semi-empirical functions, designated as generalized attenuation functions, have been determined to relate those parameters with the magnitude and the source-to-site distance. These functions are based on ground motion time histories of earthquakes generated at several sources near the Mexican Pacific Coast and recorded at different sites near the coast. The dispersion in the values of the parameters is interpreted as a measure of the uncertainty associated with the statistical properties of a randomly selected record. This dispersion is associated with the characteristics of the acceleration time histories included in the study and with the intervals of the parameters of the seismic sources that generated the records.

CONSIDERATIONS IN THE CODES FOR THE VERTICAL MOTION

Several seismic design codes include recommendations related to the effects of the vertical component of the ground motion. Currently in Mexico, only three codes request the consideration of the vertical motion in design (RCEG-90 [18], MDOC-93 [19], RCMP [20]).

A brief summary of the analytical expressions proposed in some building codes to consider the influence of the vertical component of the ground motion on structural response (both static and dynamic methods), is shown in Table 2.

In order to have homogeneous expressions for comparison, the notation used in the expressions is the following: F_H and F_V are the inertial forces produced by the horizontal and vertical motion respectively. C_H & C_V are the seismic coefficients. $A_H(T_H)$ & $A_V(T_V)$ are the design spectrum's accelerations. I & Z are factors that depend on the building importance and the zone. Rμ is a reduction factor of the elastic forces, which depends on the ductility on the system, energy absorption, inelastic behavior, over-strength, etc. FC is the load factor. SW, DL & LL are the gravity loads (self weight, dead load, and live load), which integrate the total load W.

Table 2. Summary of expressions in some codes to consider vertical ground motion

COUNTRY	**REFERENCE**	**STATIC METHOD**	**DYNAMIC METHOD**
Canada	NBCC, 1990	Do not apply	Do not apply
USA	UBC, 1997	$\uparrow F_V = 0.7 \cdot C_H \cdot I \cdot DL$ Cantilever on 3 & 4 seismic zones	$A_V(T_V) = 2A_H(T_H)/3$ $m^* > 90\%$
	FEMA-368, 2000	$\uparrow F_V = 0.2 \cdot DL$ Beams, cantilever and prestressed $\updownarrow F_V = 0.2 \cdot C_V \cdot DL$ Building beams	$A_V(T_V) = 2A_H(T_H)/3$ Other structures

Table 2. Summary of expressions in some codes to consider vertical ground motion (continued)

Mexico	RCEG, 1990	$\updownarrow F_V = 2 \cdot C_H \cdot W / 3$	$A_V(T_V) = 2 \cdot A_H(T_H)/3$
	MDOC, 1993	$\updownarrow F_V = 2 \cdot C_H \cdot W / 3$	$A_V(T_V) = C_{V/H} \cdot A_H(T_H)$ $C_{V/H}$=2/3; $C_{V/H}$=3/4 (industries)
	RCMP, 1999	$\updownarrow F_V = 2 \cdot C_H \cdot W / 3$	$A_V(T_V) = 2 \cdot A_H(T_H)/3$
	NTCDS-RCDF, 2000	Do not apply	Do not apply
Cuba	NC53-114, 1999	$\updownarrow F_V = 0.75 \cdot C_H \cdot I \cdot DL$ Cantilevers, balconies, arches, prestressed, span>20m.	Do not apply
El Salvador	NTDS-RSECES, 1997	$\uparrow F_V = 0.50 \cdot C_H \cdot DL$ Horizontal cantilevers	$A_V(T_V) = 2 \cdot A_H(T_H)/3$
Nicaragua	NSN, 1990	$\updownarrow F_V = 0.40 \cdot W$	$A_V(T_V) = A_H(T_H)$
Costa Rica	CSCR, 1986	$\updownarrow F_V = 2 \cdot C_H \cdot W / 3$ Flat slab, long span beams, cantilevers, and columns with high compression.	$A_V(T_V) = 2 \cdot A_H(T_H)/3$
Ecuador	CEC, 2000	$\updownarrow F_V = 2 \cdot C_H \cdot I \cdot S \cdot W / 3$	$A_V(T_V) = 2 \cdot A_H(T_H)/3$
Peru	NDS-RCP, 1977	$\updownarrow F_V = C_V \cdot W$ C_V = 0, 0.2 ó 0.3	Do not apply
Chile	INN, 1989	Do not apply	Do not apply
Argentina	INPRES-CIRSOC 103, 1991	$\updownarrow F_V = C_{V/H} \cdot W$ $C_{V/H}$ = 0.4 a 0.6	$A_V(T_V) = C_{V/H} \cdot A_H(T_H)$ $C_{V/H}$ = 0.4 a 0.6
Europe	CEN, 1994	$\updownarrow F_V = C_{V/H}(T_V) \cdot W$ $C_{V/H}$ = 0.70: T_V<0.15; $C_{V/H}$ = 0.40: T_V>0.50; $C_{V/H}$ = +11/14 - 4T_V/7: 0.15<T_V<0.50	$A_V(T_V) = C_{V/H}(T_V) \cdot A_H(T_H)$
Spain	P.D.S.-1, 1974	$\updownarrow F_V = FC \cdot A_H(0.5s) \cdot W$	$A_V(T_V) = 0.7 \cdot A_H(T_H)$
France	PS, 1982 $\alpha = 2^{(IMM-9)}$	$\updownarrow F_V = C_V \cdot W$ All elements: $C_V = C_H / \sqrt{\alpha}$ Only cantilevers: $C_V = 0.15\alpha / T \leq 0.4\alpha \leq 1$	Do not apply
	AFPS, 1990	$\updownarrow F_V = C_H \cdot W$	$A_V(T_V) = A_H(T_H)$
Italy	NTRCS, 1986	$\updownarrow F_V = C_V \cdot I \cdot W$	Do not apply

Table 2. Summary of expressions in some codes to consider vertical ground motion (continued)

Hungary	TGPH, 1978	$\updownarrow F_V = 2 \cdot C_H \cdot W / 3$	$A_V(T_V) = 2 \cdot A_H(T_H)/3$
Rumania	P100, 1991	$\updownarrow F_V = 2 \cdot C_H \cdot W$	Do not apply
Yugoslavia	YNBC, 1987	$\updownarrow F_V = 0.7 \cdot C_H \cdot W$ Long span elements	Do not apply
Bulgaria	CDBSSR, 1987	$\updownarrow F_V = FC \cdot W$ Buildings: FC=0.15 ó 0.30 $\updownarrow F_V = 2 \cdot C_H \cdot I \cdot W$ Cantilevers	Do not apply
Greece	GSC, 1992	$\updownarrow F_{Vi} = W \cdot C_V \cdot m_i u_i \Big/ \sum_{i=1}^{n} m_i u_i$ $T = 2\pi \sqrt{\sum_{i=1}^{n} m_i u_i^2 \Big/ \left(g \sum_{i=1}^{n} m_i u_i \right)}$	Do not apply $Cv = 0.7 \dfrac{\alpha \cdot I \cdot \beta(T_V)}{R\mu_V} n$
Israel	IC-413, 1994	$\updownarrow F_V = 2 \cdot C_H \cdot DL / 3$ Cantilevers $\updownarrow Fv = SW - 1.5 \cdot C_H \cdot I \cdot S \cdot DL$ Prestressed beams	Do not apply
Iran	IC-SRDB, 1988	$\updownarrow F_V = \dfrac{2 \cdot C_H \cdot I}{R\mu} W$	Do not apply
China	GBJ-11, 1989	$\updownarrow F_{Vi} = F_V \cdot \dfrac{W_i \cdot H_i}{W \cdot H}$ Tall buildings and chimneys $F_V = 0.65 C_H \cdot 0.75 W$	Do not apply Deck w/span>24m, cantilevers, etc. $F_V = C_V \cdot W$
India	IS:1893, 1994	$\updownarrow F_V = 2.5 \cdot C_H \cdot W$	$A_V(T_V) = 0.5 \cdot A_H(T_H)$
Japan	BSLEO, 1981	Do not apply	Do not apply
	SSCECJ, 1980	Do not apply	Do not apply
	AIJ, 1990	$\updownarrow F_V = 0.5 \cdot C_H \cdot W$	$A_V(T_V) = 0.5 \cdot A_H(T_H)$
Australia	AS 1170.4, 1993	$\updownarrow F_V = 0.5 \cdot C_H \cdot W$	$A_V(T_V) = 0.5 \cdot A_H(T_H)$
New Zeeland	NZS-4203,1992	Do not apply	Do not apply

Regarding the recommended provisions presented in Table 2, it is observed that the seismic intensity for vertical design is obtained, as a rule, applying a factor to the seismic intensity for horizontal design. However, some discrepancies are observed; for example, some of them only consider the effects of the vertical seismic component in structural elements that are supposedly sensitive to such component. Others suppose that the problem is solved increasing the gravity loads with static loads equivalent to those that would be produced by the vertical acceleration of the ground motion. In addition, others propose to accomplish dynamical analysis with a factored horizontal response spectrum. Few codes clarify the need of including in the analysis vertical degrees of freedom that simulate the load distributed with the aim of estimating vertical periods and to make rational modal combinations. No one implicitly proposes design spectra for the vertical component, compatible with the seismic hazard at the site.

The Mexican codes that consider the vertical seismic component (RCEG-90 [18]; MDOC-93 [19]; RCMP-99 [20]) present recommended provisions and common practices that, as other international codes, are prone to wrong interpretations, which causes that the effect of such component will be either wrongly understood or ignored.

In current design practice, where the consideration of the vertical quakes component is required, it is common to obtain the vertical design coefficient by multiplying the corresponding horizontal coefficient by a factor, regardless of the differences between the dominant periods that characterize each component. This factor is usually obtained from the ratio of vertical to horizontal peak ground accelerations. However, it is not considered that this quotient is highly dependent of the period and not constant, as most of the codes propose. To omit this observation implies to overestimate the effects of the vertical component, which does not necessarily lead to a higher level of structural safety, in particular if a possible change in the collapse mechanism is produced if beams are made stronger without checking their interaction with columns.

In order to obtain vertical design coefficient, it is necessary to estimate the natural periods of vibration in the vertical direction. However, ordinary commercial computer programs only account for horizontal accelerations. A few of them have the option of considering the contribution of both rotational and vertical mass, and permit the simulation of continuous distributed mass by means of discrete models. This implies an increase in the number of degrees of freedom that must be considered in the dynamic analysis.

Other common consideration in most of codes is not to permit the reduction by inelastic behavior, and the reasons are not clarified. In addition, on the values of the percentage of critical damping (ξ) associated with the vertical vibration may not be available.

Based on this framework, it can be stated that codes are not transparent regarding the vertical ground motion and its variation with the vertical periods of vibration; rules to combine the responses to horizontal and vertical ground motion are also missing. It should be possible to compare the design recommendations with the results of dynamical step-by-step analysis that use real or simulated acceleration time histories of representative and independent movements, with characteristic of intensity, duration and frequency that are consistent with the seismic hazard at the site.

ANALYSIS OF VERTICAL GROUND MOTION RECORDS OBTAINED IN THE SOUTHERN COAST OF MEXICO

As previously stated, available ground motion records show that the ratio of the peak amplitudes of the vertical to the horizontal components are very sensitive to the epicentral distance, the focal depth and the type of soil. An analysis of this ratio for some records on firm soil in the Mexican Pacific Coast was presented by Perea and Esteva [10] (Figure 1).

Spectral ratios of the pseudo-accelerations, as well as ratios of vertical to horizontal displacement of ten Mexican Pacific records were studied. According to the authors, under certain circumstances the vertical component becomes very important for sites near the generating source (hypocentral distance smaller than 115 km; Perea [14]). The characteristics of the selected records are summarized in Table 3, and their pseudo-acceleration response spectra (ξ=5%) are illustrated in Figure 2. The record names (EEEEYYMMDD) mean station name (EEEE), last two digits of year (YY), month (MM) and day (DD) of the earthquake.

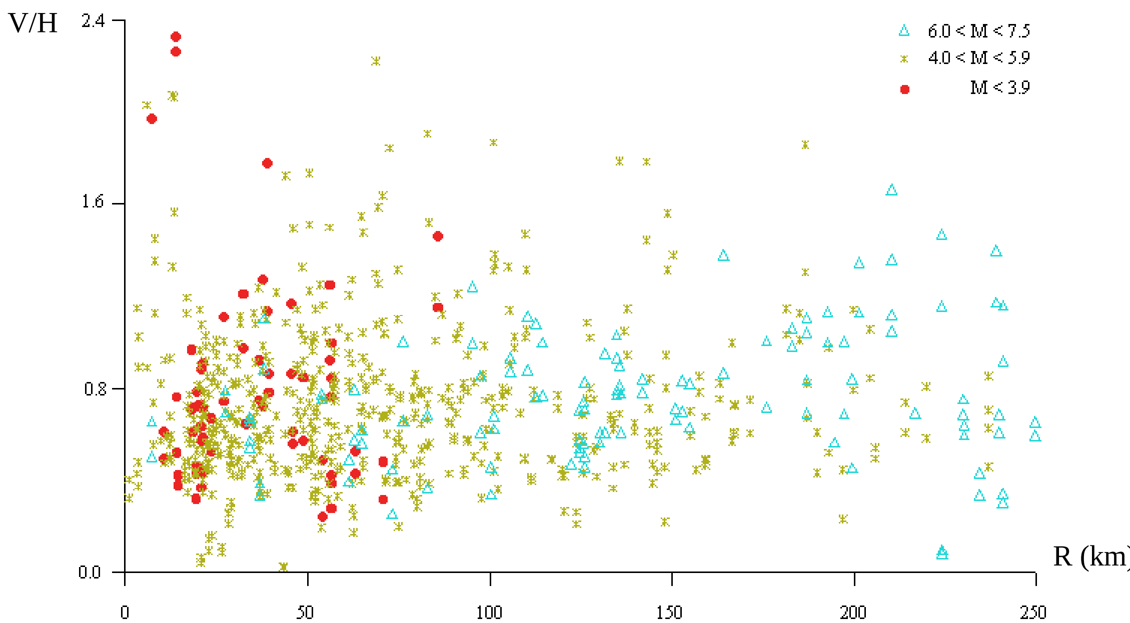


Figure 1. Quotients V/H of Mexican Pacific records

Table 3. Information of Mexican records selected

RECORD	M	R	H	D	SOIL	LOCATION
VCPS870207	5.4	6	6	8	Volcanic rocks	Mexicali Valley, Baja California
IAGS791015	6.6	3	10	10	Sediments (alluvium)	Mexicali Valley, Baja California
VICS800609	6.1	10	12	15	Sediments (alluvium)	Mexicali Valley, Baja California
COPL931025	6.6	7	19	20	Rock	Copala, Guerrero
CALE850919	8.1	21	15	25	Rock	Caleta de Campos, Michoacán
CALE970111	6.9	30	16	40	Rock	Caleta de Campos, Michoacán
BALC941210	6.3	38	20	43	Rock	El Balcón, Guerrero
ACAC890425	6.9	56	15	58	Sand, limo, clay	Acapulco, Guerrero
ZACA850919	8.1	84	15	86	Compact clay	Zacatula, Michoacán
RIXC951021	6.5	54	98	112	Limestone	Tuxtla Gutiérrez, Chiapas

M: Magnitude; R: Epicentral distance (km); H: Focal depth (km); D: Hypocentral distance (km).

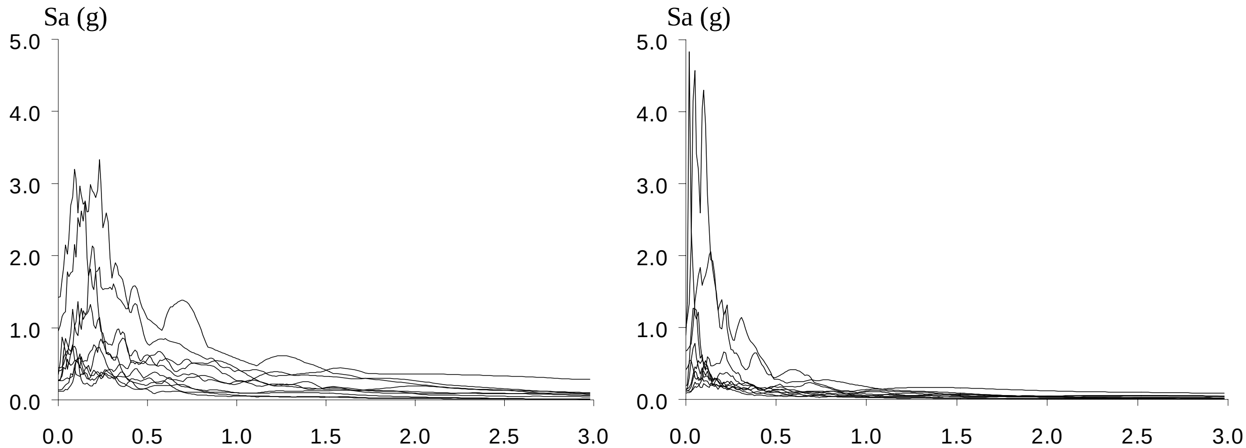
For the sample of records selected, the calculated vertical-to-horizontal spectral ratios (Figure 3: a, b) show a considerable dispersion. However, it is distinguished that the greater dispersion occurs in the low-period interval, where the vertical ground motion may even have a greater intensity. On the other hand, for periods longer than 0.5 s, the vertical seismic component is lower than 40% of the horizontal component, in contradiction with the percentages proposed in some codes (67%, 75% or 80%) based on the calculation of the quotient V/H for the maximum ground motion accelerations.

The mean values (μ) of the spectral ratios, and the corresponding standard deviations (σ), are calculated and shown in Figures 3c, d. Upper and lower bounds for the probable values of those means are presented in the figure (Figure 3c, d; Equation 1). For periods shorter than 0.05 s, the vertical component reaches values up to 140% of the horizontal component; the highest standard deviations occur in this interval of short periods (T_v<0.1s). In contrast, for periods longer than 0.5 s, the vertical seismic component is lower than 40% of the horizontal component. Although the envelope proposed underestimates periods higher than 1s, it covers most of the practical and real cases of beams. In Equation 1, T is the vibration period, and V & H are the spectral value of vertical and horizontal component, respectively.

In Figure 4, the vertical response spectra (ξ=5%) of ground motions are compared with that obtained by multiplying the horizontal spectrum by 2/3 factor, as well as with the envelope. The vertical response spectra obtained from the horizontal product by a factor function of the period (envelope) are reasonably close to those obtained from the records, except in some short-period cases, where greater deviations are observed. The constant scale factor 2/3 does not lead to correct forecasts, particularly for high vertical periods.

In Figure 5, as an illustration, the vertical design spectrum proposed for a Mexican code is compared with that obtained from the period-dependent factor. The figure shows that the code is conservative for structures designed with vertical periods longer than 0.2 s; nevertheless, a great number of beams could have a vertical period shorter than this value. Code requirements seem to be insufficient for that interval.

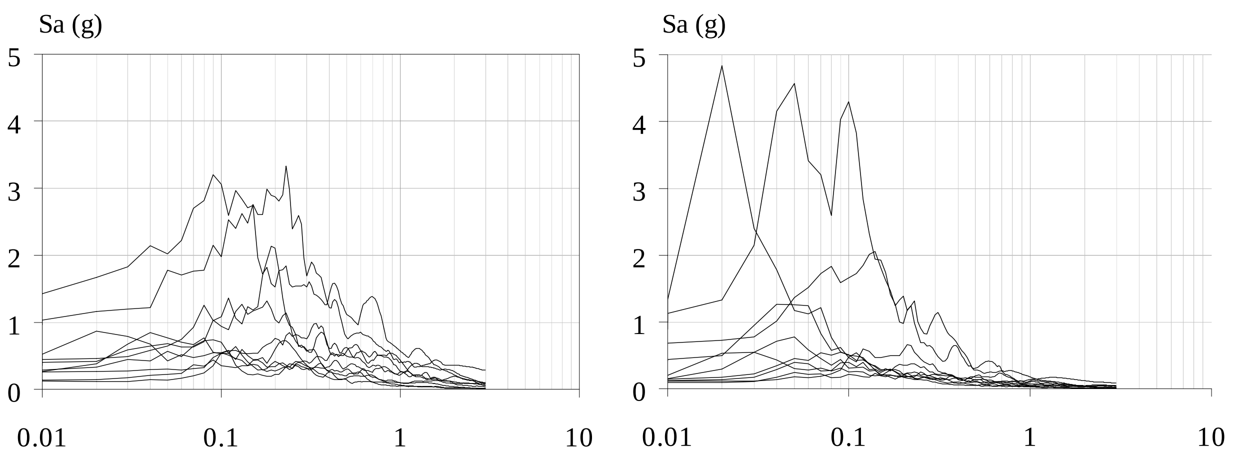
$$\frac{V(T)}{H(T)} = +1.40 \quad : \quad T \leq 0.05 \quad ; \quad \frac{V(T)}{H(T)} = +1.40\left(\frac{0.05}{T}\right)^{\frac{2}{3}} \quad : \quad T > 0.05 \qquad (1)$$



a) Horizontal component

b) Vertical component

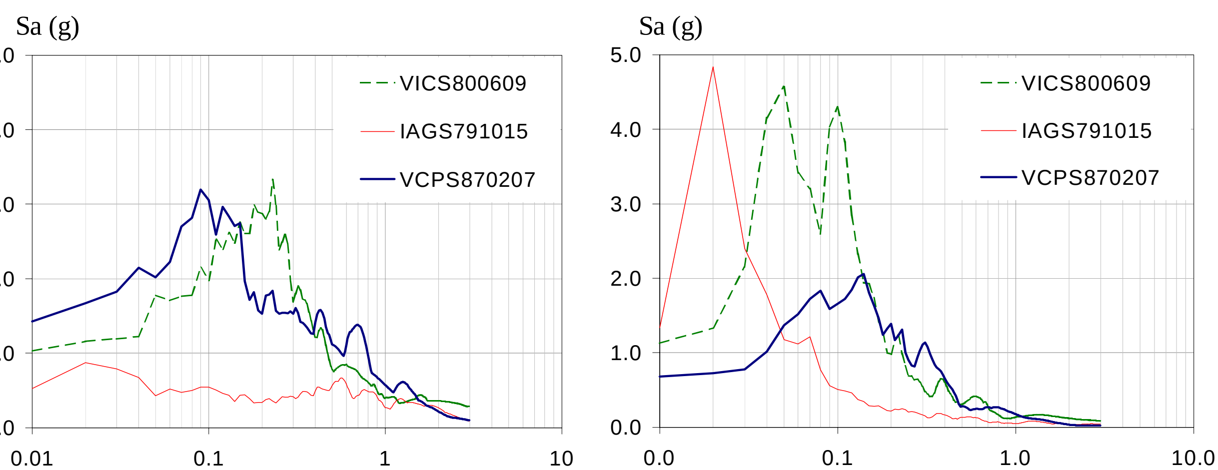
i) Records selected (decimal scale)



a) Horizontal component

b) Vertical component

ii) Records selected (logarithmic scale)



a) Horizontal component

b) Vertical component

iii) Records selected with the highest vertical intensity

Figure 2. Response spectra of pseudo-accelerations

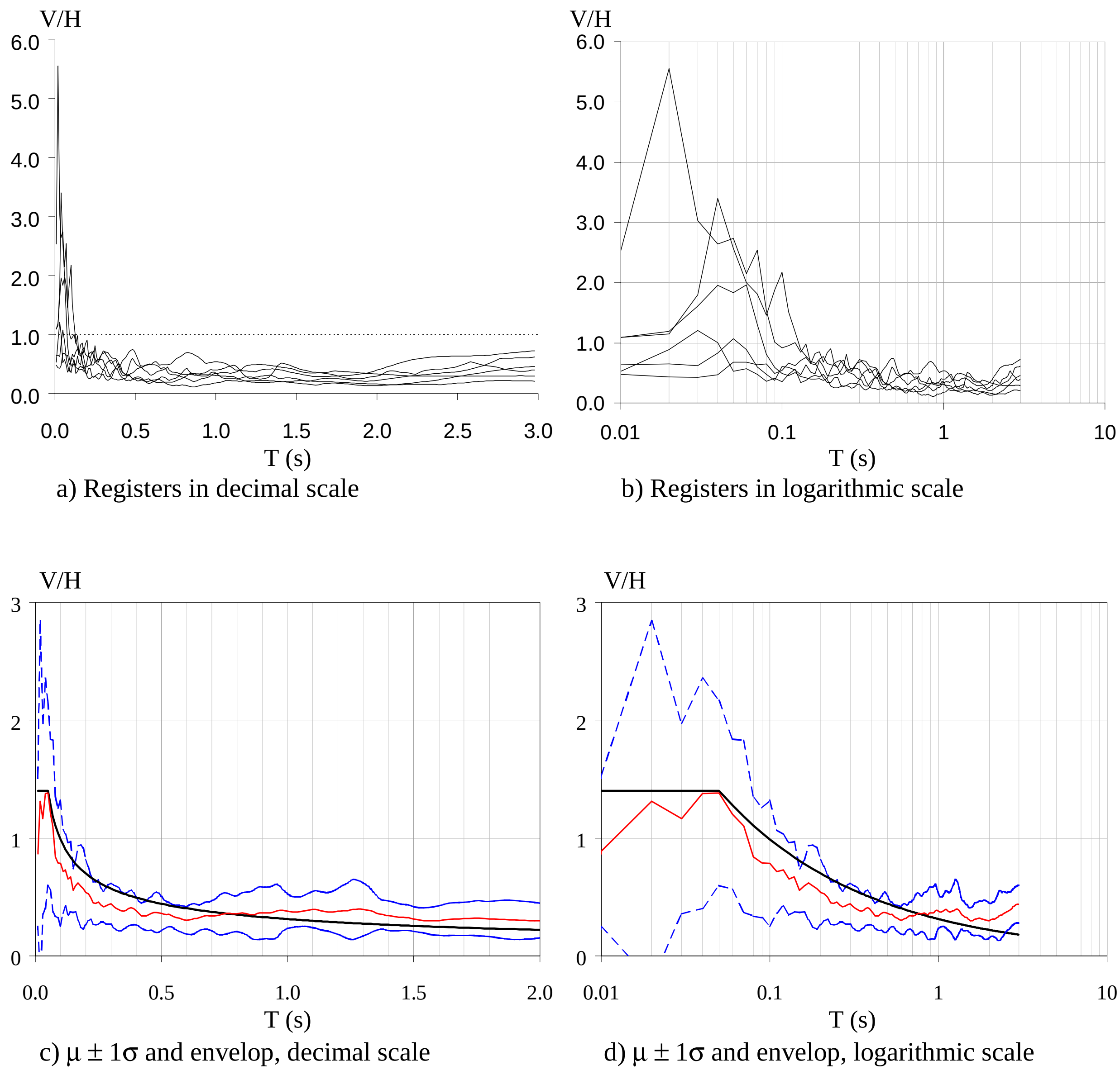


Figure 3. Spectral quotients V/H

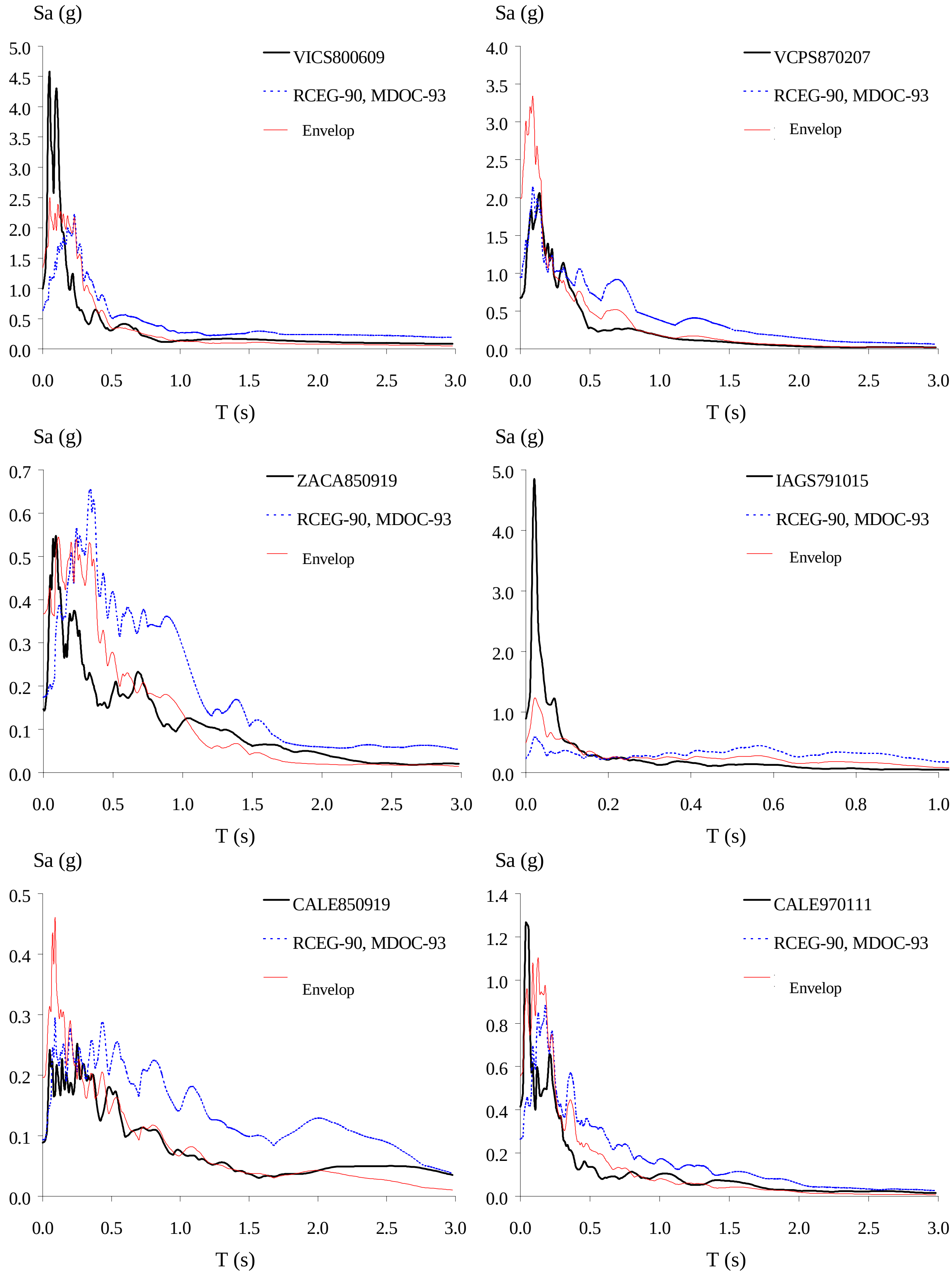


Figure 4. Vertical response spectrum vs. the estimated

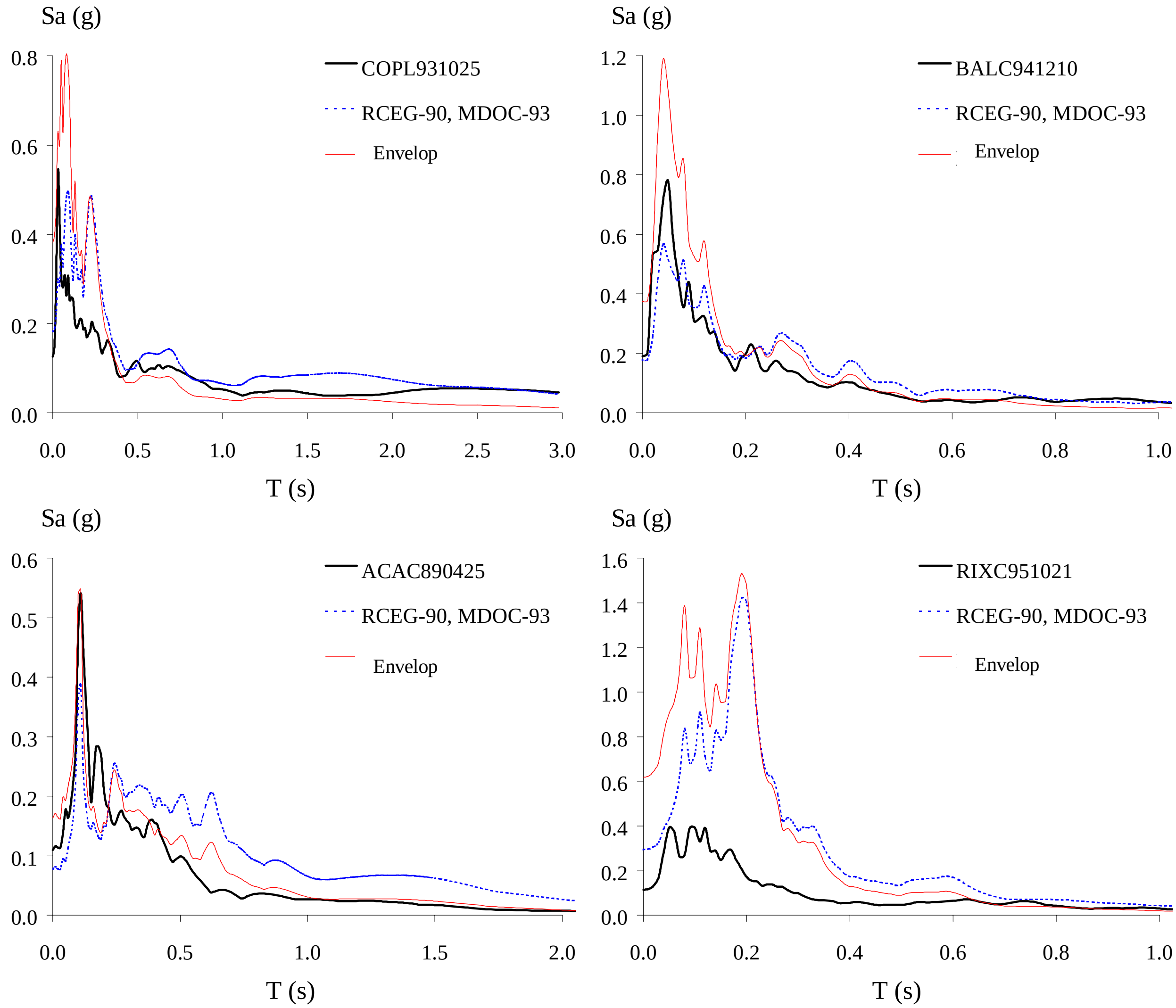
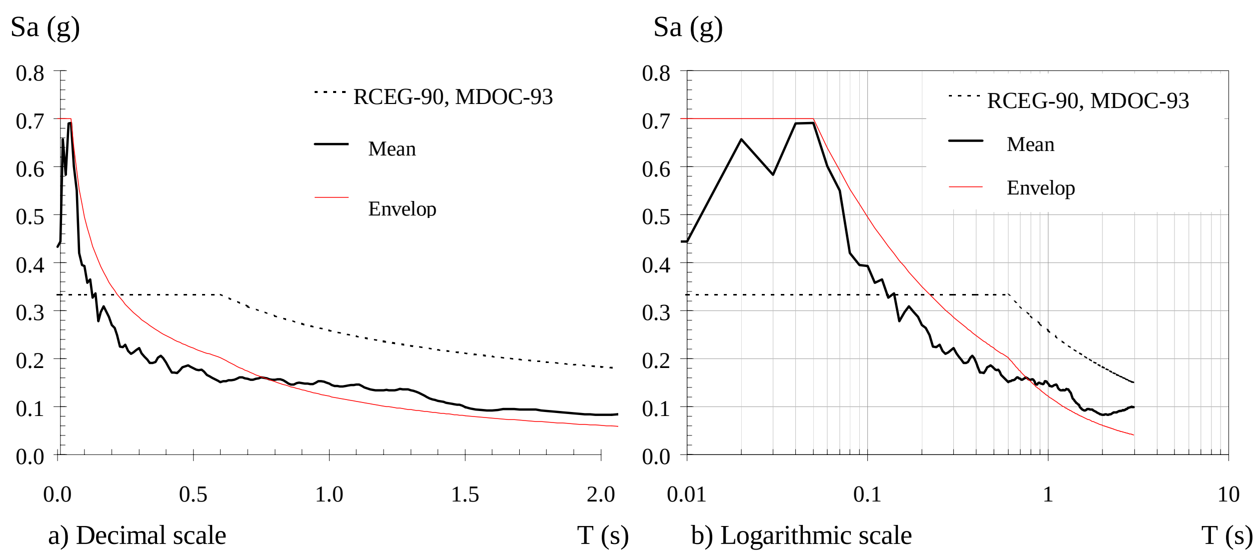


Figure 4. Vertical response spectrum vs. the estimated (continued)



a) Decimal scale

b) Logarithmic scale

Figure 5. Vertical design spectrum vs. the estimated

CONCLUSIONS

From the analysis of Mexican records, it is observed that the relationship between vertical and horizontal ground motion presents large dispersions; its magnitude is a function of the epicentral distance, the focal depth, and the vertical vibration period.

The constant factor that is normally applied to obtain the vertical spectrum from the horizontal one results from the vertical-to-horizontal ratios of the maximum ground motion accelerations. Scaling the horizontal spectrum by a factor that varies with the period would result in a more realistic and transparent vertical spectrum; however, it is necessary to verify the adjustment with more data. The epicentral records selected, which were used to obtain the period-dependent factor, have a high energy for both vertical and horizontal ground motions.

The high intensity vertical response spectra (ξ=5%) (Figure 2.iii) correspond to stations IAGS, VICS and VCPS, which according to Table 3 correspond to the greatest epicentral distances and focal depths and are located in Mexicali Valley, California. Future projects will use similar records, in order to study their implications on the dynamic response of soil and structure. Emphasis will be placed on near-source and shallow-depth earthquakes, similar to those often obtained in California, in the United States.

Future studies should also be aimed at the definition of vertical response spectra for given return intervals. Attention should also be given to some structural response concepts, such as the differences in the structural dynamic properties relevant for horizontal and vertical vibration (damping, energy dissipation, inelastic behavior, etc.).

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