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CHARACTERISTICS OF RESPONSE SPECTRA FOR RECORDS FROM SOUTH AMERICA

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SUMMARY

Previous studies of the general characteristics of earthquake response spectra have indicated that linear response spectra present three regions of approximately constant response. For relatively short periods, absolute acceleration response is approximately constant with respect to vibration period. For intermediate periods, relative response velocity is relatively insensitive to period. And for relatively long periods of vibration, response may be approximated by assuming constant relative displacements. The ranges of approximately constant response currently used as reference for design and evaluation have been estimated based on statistical studies of linear response spectra calculated for limited suites of records. Previous studies of spectra for records from Chile, Peru and Ecuador have indicated that the ranges of approximately constant response in these spectra differ from those observed for records from the U.S. west coast, which are often used as reference for design elsewhere. The discrepancies between the spectra for records from South America and those for U.S. records have been observed to be related to differences in ground motion frequency content. This note reexamines previous observations regarding the characteristics of spectra for records from South America using recent records obtained in Peru, Chile and Colombia. The trends observed in spectra computed using these records are consistent with previous observations for other records from South America reaffirming what may appear obvious but is often ignored: design or evaluation based on generalizations developed for U.S. records may not produce adequate results elsewhere.

INTRODUCTION

Generic response spectra used today in design and evaluation of structures in different countries share common characteristics. Most of these models classify the response of a single degree of freedom system to ground motion in three distinct ranges of response. The first range corresponds to short periods and, in it, response is approximated by assuming constant absolute acceleration. For long periods, response is estimated assuming relative displacement to be insensitive to change in period. For intermediate periods, response is approximated based on the assumption that relative velocity is constant. Response within each of these ranges is characterized by the ratio of average response to peak ground acceleration, velocity

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or displacement. Definition of the terms "long," "short," and "intermediate," and estimation of amplification factors are possible through examination of ground motion records. Records obtained recently in South America allow a new evaluation of these ranges and amplification factors. Similar studies for previous records from South America [1, 2, 3] and work by Mohraz, Hall and Newmark. [4] are used in this note as point of reference. The latter is included because it is often used as a basis for design.

PROCESSING OF DATA

A total of 28 records of horizontal ground acceleration were included in this study. Table 1 presents details of each record. Ground velocity and displacement histories were obtained by integration of the acceleration records. The records were used as adjusted by the issuing agencies listed in Table 1. No additional adjustments were made except for introduction of an initial velocity as required to avoid monotonic accumulation of displacements with time (Figure 1). This adjustment was made recognizing the fact that the final ground velocity should tend to zero and it does not preclude the possibility of having a nonzero final displacement. Ten records (Table 1) were adjusted in such manner and all of them happen to be records used here for reference because they were included in previous studies [1, 2, 3] while all of the records that did not require additional adjustment are more recent records that were not included in previous investigations. The average assumed initial velocity was 1/40 times the peak ground velocity (PGV), the maximum correction not exceeding ¼ of PGV. Introduction of an initial velocity and displacement cannot be done through adjustment of the acceleration history base line. As a result, response spectra, which are computed based on ground acceleration records, may include an error, which would result in larger calculated relative displacements for relatively large periods of vibration. Figure 2 indicates that, for practical purposes and within the ranges considered, possible errors in the ground acceleration records used may be ignored. However, it is important to emphasize the fact that computations made based on calculated values of peak ground displacement (PGD) are less reliable because of its high sensitivity to the errors and assumptions involved in the process of estimating ground motion.

Linear response spectra were calculated for viscous damping coefficients of 2%, 5% and 10% of the critical damping coefficient. These spectra were normalized with respect to peak ground velocity, displacement and acceleration to allow meaningful comparisons. Amplification factors were computed at each period for which response had been calculated by dividing spectral ordinates by the corresponding ground motion parameter. The mean and the standard deviation of amplification factors for displacement, velocity and acceleration were then computed at each period considered. The amplification factors thus obtained were averaged within ranges selected from average normalized spectra. Average amplification factors were computed within the following ranges.

Acceleration	1/6 to 2/5 sec.
Velocity	2/5 to 1 sec.
Displacement:	1 to 3 sec.

These ranges were chosen through examination of spectra normalized with respect to peak ground velocity. As observed by Mohraz et al. [4], normalization with respect to peak ground velocity yielded a standard deviation that is nearly constant over the entire range of periods considered and, for intermediate frequencies, it is smaller than those obtained by normalizing to either peak ground acceleration or displacement. These ranges, however, do not form an absolute reference but they may be useful as a basis for comparison.

PRESENTATION AND DISCUSSION OF RESULTS

Before examining the computed response spectra, consider the data in Table 1. It is clear that there is not enough information on site characteristics to attempt classification of the records on such basis. However, the ratios v/a and ad/v^2 may serve as reference. Here, a is peak ground acceleration (PGA), v is peak ground velocity (PGV) and d is peak ground displacement (PGD). First, observe that the records from Lima, Peru, have ad/v^2 ratios that are larger than those of other records. In fact, the ad/v^2 ratios for other records appear to be rather low. The average value of ad/v^2 is 4 while Mohraz et al. [4] reported that this ratio may vary between 5 and 15. The average value of v/a (74 cm/s/g; 29 in/s/g) is also lower than the average in reference [4] (114 cm/s/g; 45 in/s/g). The records from Lima do not seem to differ much from the other records in terms of v/a.

Consider now the possible differences in spectral response that may be related to differences in the ratio ad/v^2. Figures 3 and 4 show normalized displacement spectra for records grouped according to the ratio ad/v^2. The records with higher values of ad/v^2, i.e. the records from Lima, seem to be associated with very low displacement amplification. It is clear that we are dealing with sets of data of very different nature. Nevertheless, the data with higher values of ad/v^2 follow a trend similar to that of the rest of the data, which is more evident when normalization is made with respect to PGV rather than PGD. Based on this observation and given the scarcity of information about the sites, it was decided to keep all the records in a single group for computation of amplification factors, keeping in mind that displacement amplification factors for records from Lima may vary substantially from the average.

Let us start the discussion about the response spectra obtained by examining whether spectra for recent records from South America reveal trends similar to those observed for previous records from the region. Figure 2 shows normalized displacement spectra for both sets of records. In this study, special attention is given to displacement spectra because of their relevance in displacement-based design [10]. The similarity between the two sets of displacement spectra in Figure 2 is remarkable and indicates that previous observations made for records from South America may have a range of applicability larger than it may have been suggested before the collection of the data from the Colombia, 1999, and Peru, 2001, earthquakes.

Figures 5 to 7 show displacement spectra obtained using a damping coefficient of 2% and normalizing with respect to PGV, PGD, and PGA respectively. In each figure, two sets of curves are shown: mean values and mean values plus two standard deviations. Each set of curves groups three lines: 1) a thick solid line representing average response obtained by eliminating records from stations Filandia and Arica Casa, 2) a hatched line representing average response for all records, and 3) a thin dotted line representing the response of records that did not require additional adjustments for integration. A sample excluding the records from Filandia and Arica Casa was considered because these records appear to be dominated by signals with frequencies within a very narrow band possibly indicating a strong local effect (Figure 8). In all the cases considered, there seems to be a clear trend regardless the normalization and the "quality" of the records used. Average displacement response is approximately constant for periods exceeding 1 sec. Again, this observation confirms those by Bariola and Fernandez [1], Stark [2], and Wood et al.[3] but it is in conflict with what had been observed before for records from the U.S. west coast [4] and what is commonly assumed for design and evaluation[4]. Figure 9 shows a comparison between average spectra for records from South America and a spectrum constructed from data reported in [4] for records from the U.S. The latter indicates that relative displacement increases almost linearly with period up to a period exceeding of 2 seconds while spectral displacement for records from South America remains nearly

[4] Consider for instance current design recommendations for Colombia [11].

constant for periods exceeding 1 sec. This disparity results in large differences in displacement demands for periods exceeding 1 sec.

Let us examine now the shape of the response spectra and the effect of damping using the traditional log-log format. Figures 10 to 12 show response spectra calculated using all records for three different damping coefficients (2, 5 and 10%) and normalizing with respect to PGA, PGV and PGD. These plots confirm the observation that normalization with respect to PGV results in uniform standard deviation. Normalization with respect to PGA and PGD results in standard deviation increasing outside the ranges of approximately constant acceleration and displacement, respectively. Figure 13 compares the average spectrum obtained for a damping coefficient of 2% and PGV of 50cm/s with a spectrum constructed from data in reference [4]. The logarithmic scale makes the two curves look more similar than in Figure 9. Careful examination of Figure 13 confirms the observation that the range of approximately constant velocity, if there is any in spectra for records from South America[5], could not be bound by the same periods for both curves.

Table 2 shows amplification factors computed in the period ranges described in the previous section. Factors reported in [4] are presented in the same table for comparison. Overall, there does not seem to be a radical difference in response amplification between the records considered here and those considered in [4]. Displacement and velocity amplification factors are of the order of 4/3 of those in [4]. Acceleration amplification factors for the records included in this study are of the same order of those in [4]. Ratios of amplification factors for records from South America to those for records in [4] seem to be insensitive to damping ratio.

The fact that displacement amplification factors are similar to those reported for U.S. records indicates that the difference in displacement response for periods exceeding 1 second is related to differences in peak ground displacement. This observation is in agreement with the observation that peak ground displacements calculated in this study are very low, which reflects the fact that ground acceleration records from South America have been observed to be rich in high frequencies. This can be illustrated by studying the ratios d/a and d/v (Table 3). Study of the data in Table 3 reveals that while the average value of d/a is of the order of 3/4 of meter per g for the records in [4], the records in this study have an average value of d/a of the order of 1/5 of a meter per g. Similarly, while the average value of d/v was of the order of 6/10 of a second for records in [4], the records from South America considered in this study have an average value of d/v of the order of 3/10 sec. In other words, regardless the parameter used as reference for comparison, the average PGD computed for the records in this study does not exceed one half that of the records from the U.S. west coast considered in [4]. Records from Lima show larger ground displacements consistently but this is counterbalanced by small displacement amplification factors in the range of approximately constant displacement response (Figures 3 and 4).

CONCLUSION

Spectra for recent earthquakes confirm previous observations indicating that average response spectra for ground motion records from South America differ substantially from average spectra for records from the U.S. west coast. The difference is related to differences in ground motion frequency content. This observation emphasizes what seems obvious but is often ignored: generalizations for evaluation or design based on records from the U.S. west coast may not yield adequate results elsewhere.

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[5] Stark [2] suggested idealized displacement spectra for records from Chile that do not exhibit a region of approximately constant velocity.

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TABLES

Table 1. Ground acceleration records considered

Earthquake	Date	Station	Source	Magnitude		Distance	Ref.	Comp.	PGA	PGV	PGD	v/a	ad/v^2	Site Conditions
						km			cm/s/s	cm/s	cm	cm/s/g		
Peru	OCT 17,1966	Lima	CISMID §	7.5	Ms	236	[5]	N08E	269	22 †	18 †	79	10	900ft-Deep Alluvial Deposits
						(To Epicenter)		N82W	181	13 †	8 †	72	8	
	MAY 31,1970	Lima	CISMID §	7.8	Ms	372	[5]	L	105	4.7 †	3 †	44	13	900ft-Deep Alluvial Deposits
						(To Epicenter)		T	98	7.0 †	4 †	70	7	
	OCT 3,1974 14:21 GCT	Lima	CISMID §	7.6	Ms	86	[5]	N08E	179	10 †	7 †	56	11	900ft-Deep Alluvial Deposits
						(To Epicenter)		N82W	193	14 †	6 †	73	6	
	JUN 23,2001 20:33:13 UTC	Arica Casa	Universidad de Chile	8.4	Mw	148 (To Falut Plane)	[6]	L	264	20	7	73	4	
								T	308	33	9	104	2	
	JUN 23,2001 20:33:13 UTC	Arica Costanera	Universidad de Chile	8.4	Mw	148 (To Falut Plane)	[6]	L	328	26	7	78	4	
								T	268	25	6	92	2	
	JUN 23,2001 20:33:13 UTC	Cuya	Universidad de Chile	8.4	Mw	206 (To Falut Plane)	[6]	L	132	8.6	1.5	64	3	
								T	154.7	9.3	1.2	59	2	
	JUN 23,2001 20:33 UTC	Moquegua	CISMID §	8.4	Mw	100 (To Falut Plane)	[7]	NS	220	30	7	133	2	Alluvial Deposits
								EW	295	25	5	83	2	
	JUN 23,2001 20:33:13 UTC	Poconchile	Universidad de Chile	8.4	Mw	168 (To Falut Plane)	[6]	L	253	29	7	113	2	
								T	241	29	6	119	2	
	JUN 23,2001 20:33:13 UTC	Putre	Universidad de Chile	8.4	Mw	202 (To Falut Plane)	[6]	L	195	12	2	59	3	
								T	185	11	2	57	4	
Colombia	JAN 25, 1999	Armenia	Ingeominas*	6.2	M_L	13 (To Epicenter)	[8]	NS	580	26	3	43	3	100ft-Deep Volcanic-Ash Deposits on top of 100ft-Deep Volcanic Detritus
								EW	518	27	4	51	3	
	JAN 25, 1999	Pereira	Ingeominas*	6.2	M_L	42 (To Epicenter)	[8]	NS	49	3.4	0.5	68	2	Rock
								EW	83	3.9	0.9	46	5	
	JAN 25, 1999	Filandia	Ingeominas*	6.2	M_L	33 (To Epicenter)	[8]	NS	478	34	5	69	2	Volcanic-Ash Deposits
								EW	554	36	4	63	2	
Chile	MAR 03, 1985 22:47:07	Llolleo	NOAA **	7.8	Ms	50-65 (To Epicenter)	[3], [9]	10	698	40 †	11 †	57	5	Sand [3]
								100	437	23 †	4 †	52	3	Sandstone and Volcanic Rock [9]
	MAR 03, 1985 22:47:07	Viña del Mar	NOAA **	7.8	Ms	50-65 (To Epicenter)	[3], [9]	200	356	31 †	6 †	85	2	Sand [3]
								290	233	26 †	4 †	107	1	Sandstone and Volcanic Rock [9]
Average												74	4.1	

† Initial velocity assumed

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Table 2. Response amplification factors.

	Damping Ratio	Response Amplification			Response Amplification			Ratios		
		Disp.	Vel.	Acc.	Disp.	Vel.	Acc.	Disp.	Vel.	Acc.
		This Study			**Mohraz, Hall and Newmark [4]**			**This Study / Ref. [4]**		
Mean	2%	2.1	3.1	3.1	1.7	2.2	2.9	1.22	1.39	1.08
	5%	1.7	2.3	2.3	1.4	1.7	2.2	1.19	1.33	1.05
	10%	1.4	1.8	1.8	1.1	1.4	1.7	1.20	1.28	1.04
Mean + Stdev.	2%	3.2	4.5	4.1	2.5	3.2	3.8	1.27	1.39	1.09
	5%	2.5	3.2	2.9	2.0	2.4	2.8	1.24	1.31	1.04
	10%	2.0	2.3	2.1	1.6	1.8	2.1	1.26	1.26	1.03
Mean + 2*Stdev.	2%	4.2	5.8	5.1	3.3	4.2	4.7	1.29	1.39	1.09
	5%	3.3	4.0	3.5	2.6	3.1	3.4	1.26	1.31	1.04
	10%	2.6	2.9	2.5	2.0	2.3	2.5	1.29	1.24	1.02

Table 3. Average values of d/a and d/v.

	d/a cm/g	d/v sec	d/a cm/g	d/v sec	d/a cm/g	d/v sec
	This Study		**Reference [4]**		**This Study / Ref. [4]**	
Mean	21	0.28	71	0.56	0.29	0.51
Mean+Stdev.	34	0.47	123	0.84	0.28	0.55
Mean+2Stdev.	48	0.65	175	1.13	0.27	0.58

FIGURES

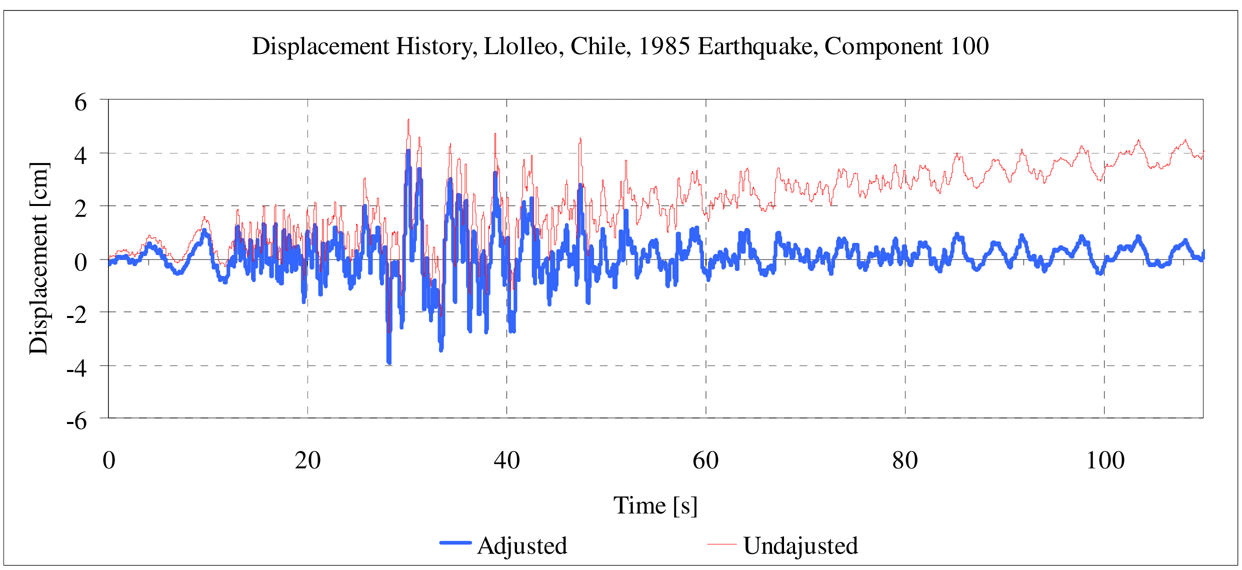


Figure 1. Average displacement response, records normalized with respect to PGV

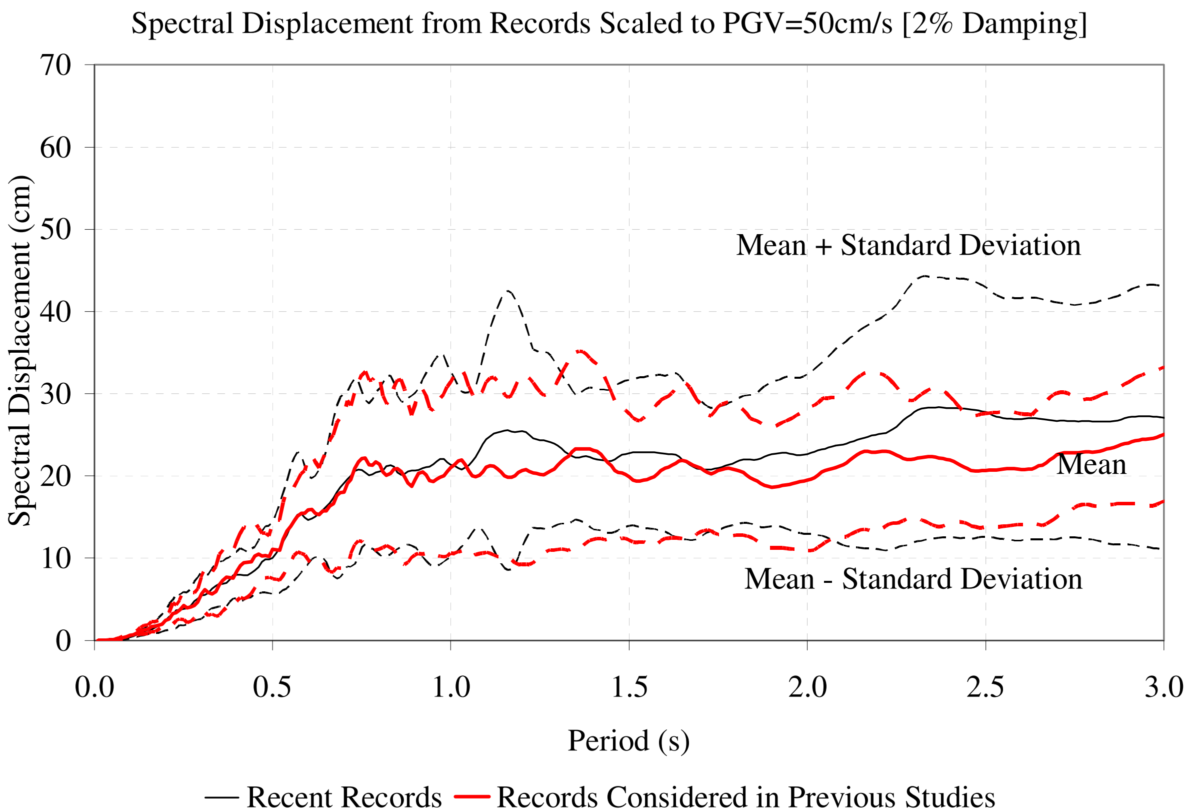


Figure 2. Average displacement response, recent records vs. previous records, normalization with respect to PGV

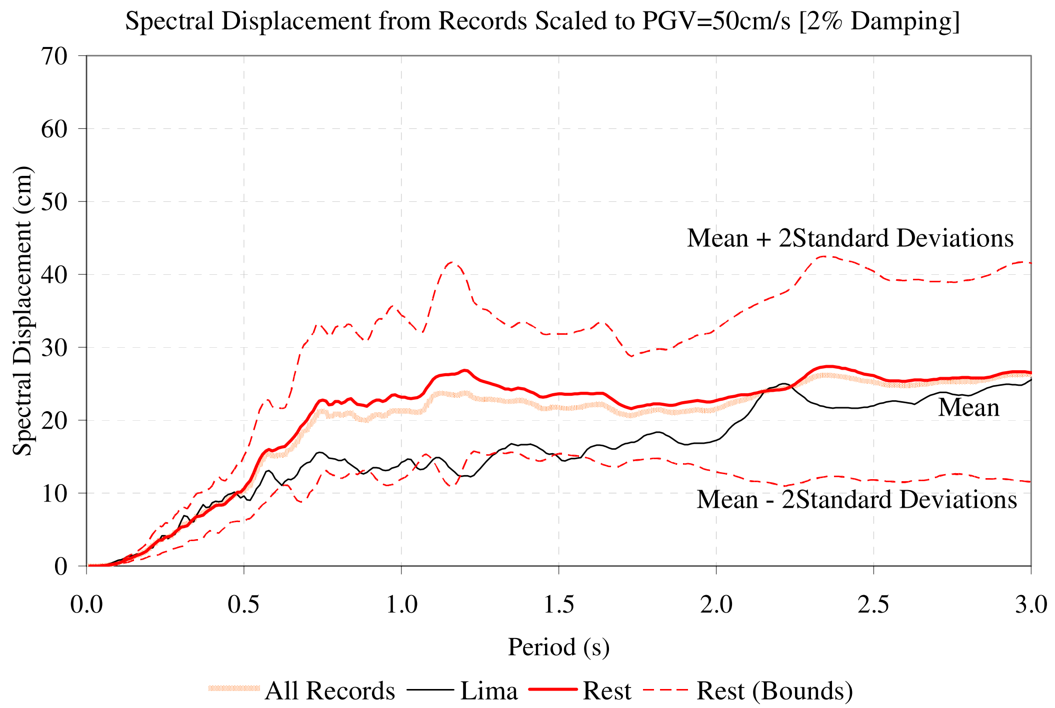


Figure 3. Average displacement response, records normalized with respect to PGV

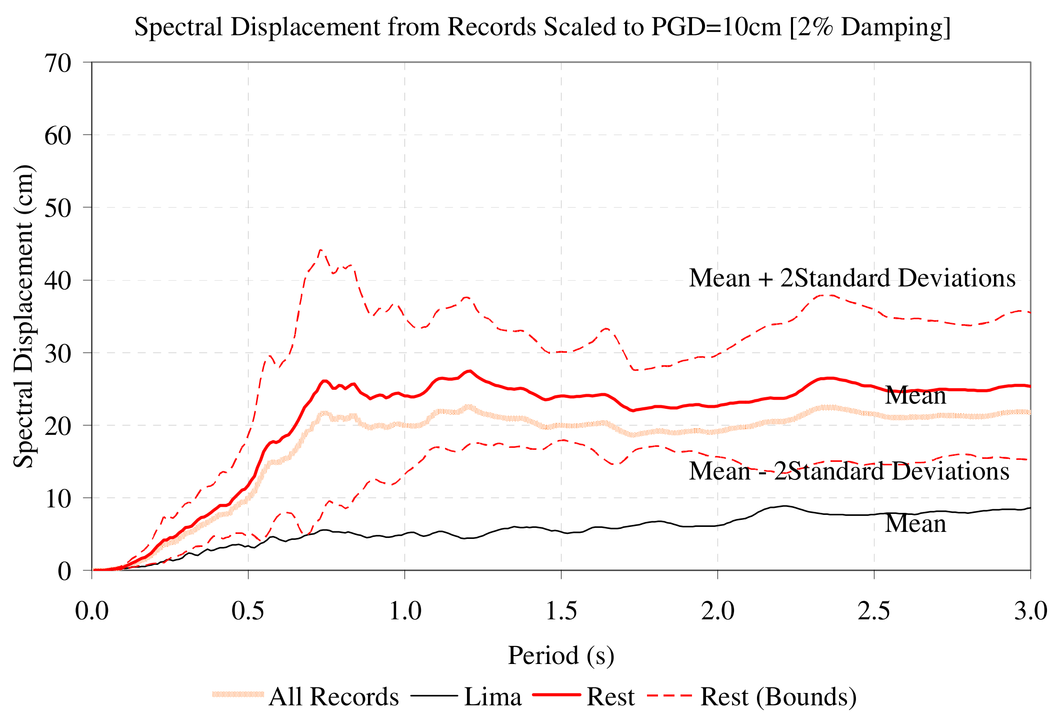


Figure 4. Average displacement response, records normalized with respect to PGD

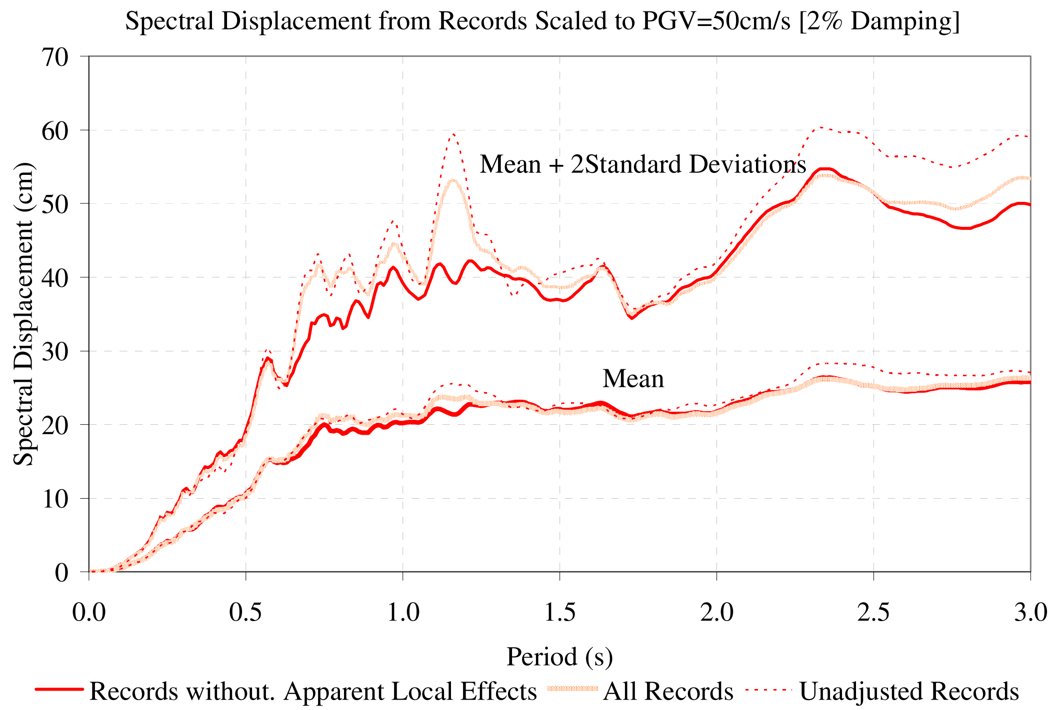


Figure 5. Average displacement response, records normalized with respect to PGV

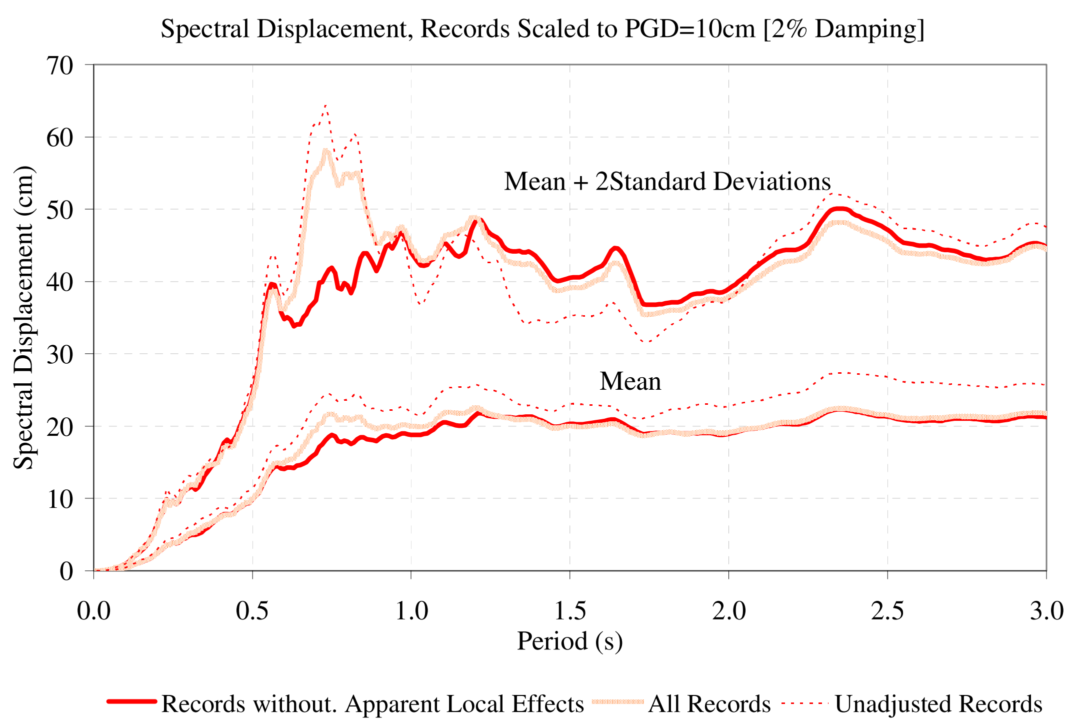


Figure 6. Average Displacement response, records normalized with respect to PGD

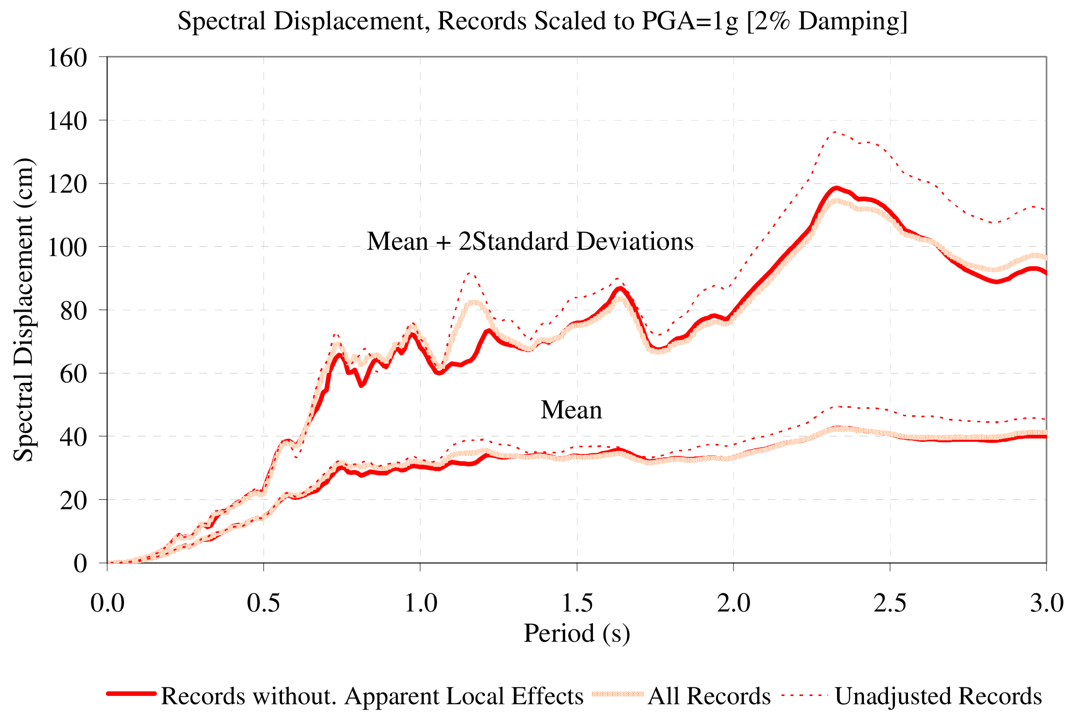


Figure 7. Average displacement response, records normalized with respect to PGA

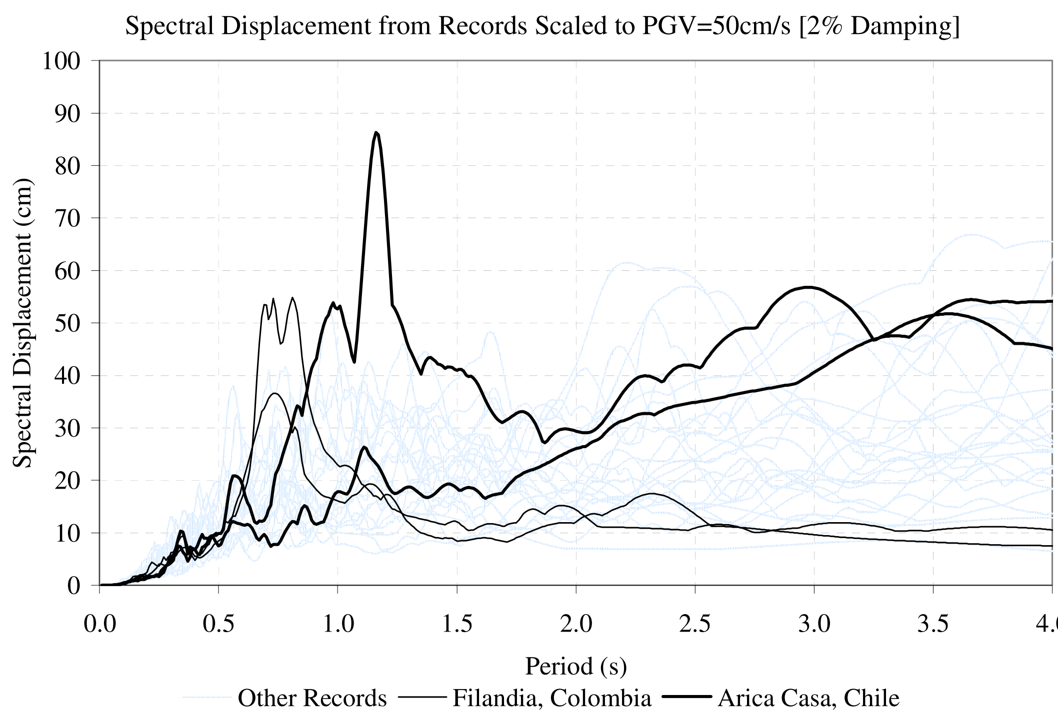


Figure 8. Displacement response, records from stations Filandia and Arica Casa

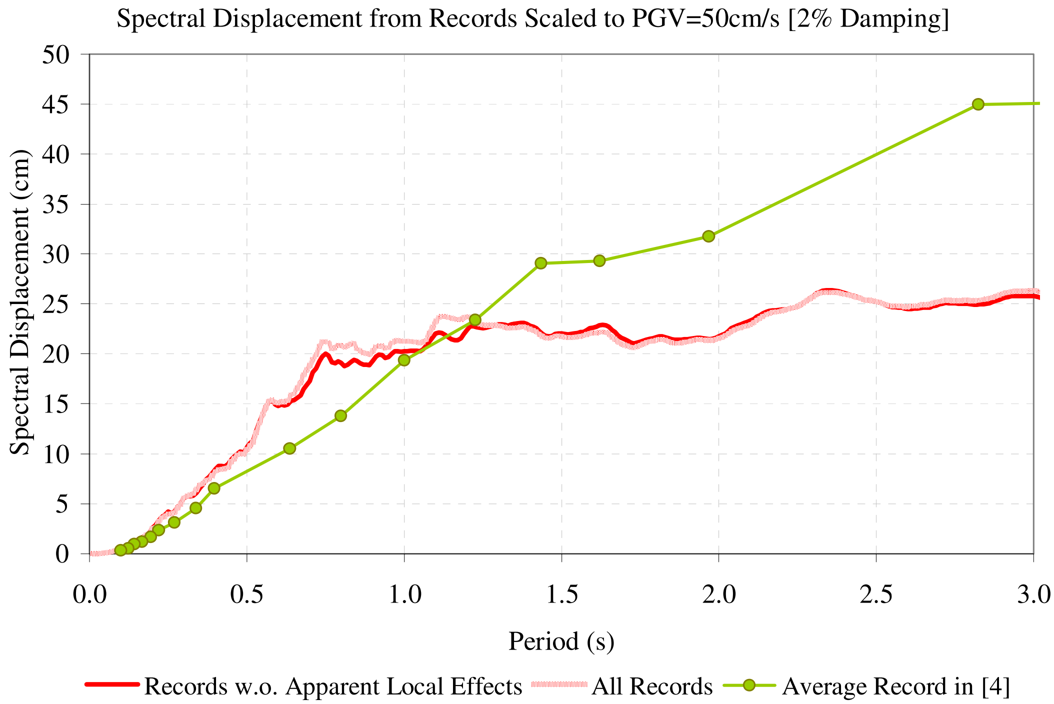


Figure 9. Average displacement response, comparison with values reported by Mohraz et al. [4]

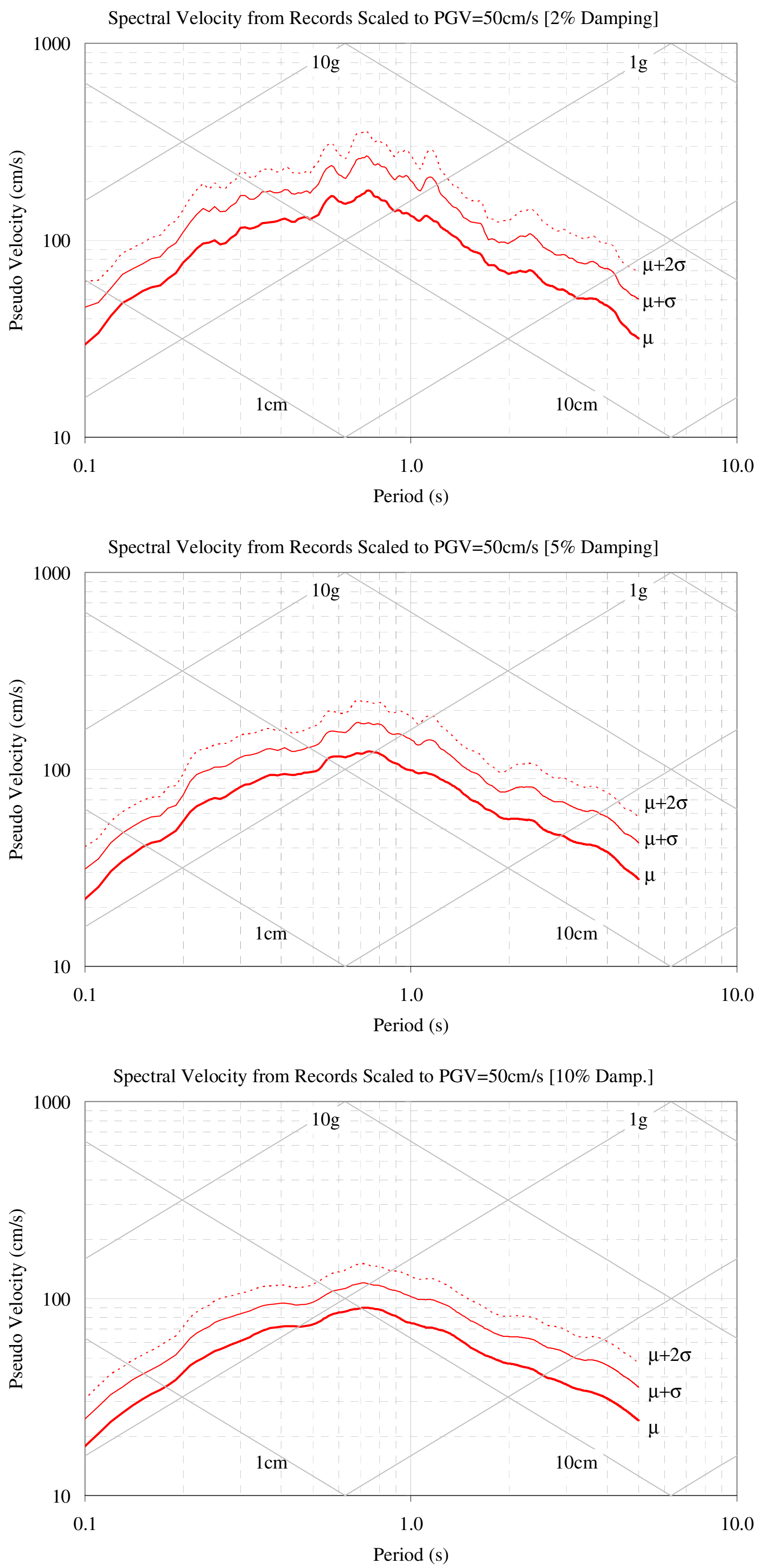


Figure 10. Pseudo velocity response, records normalized with respect to PGV

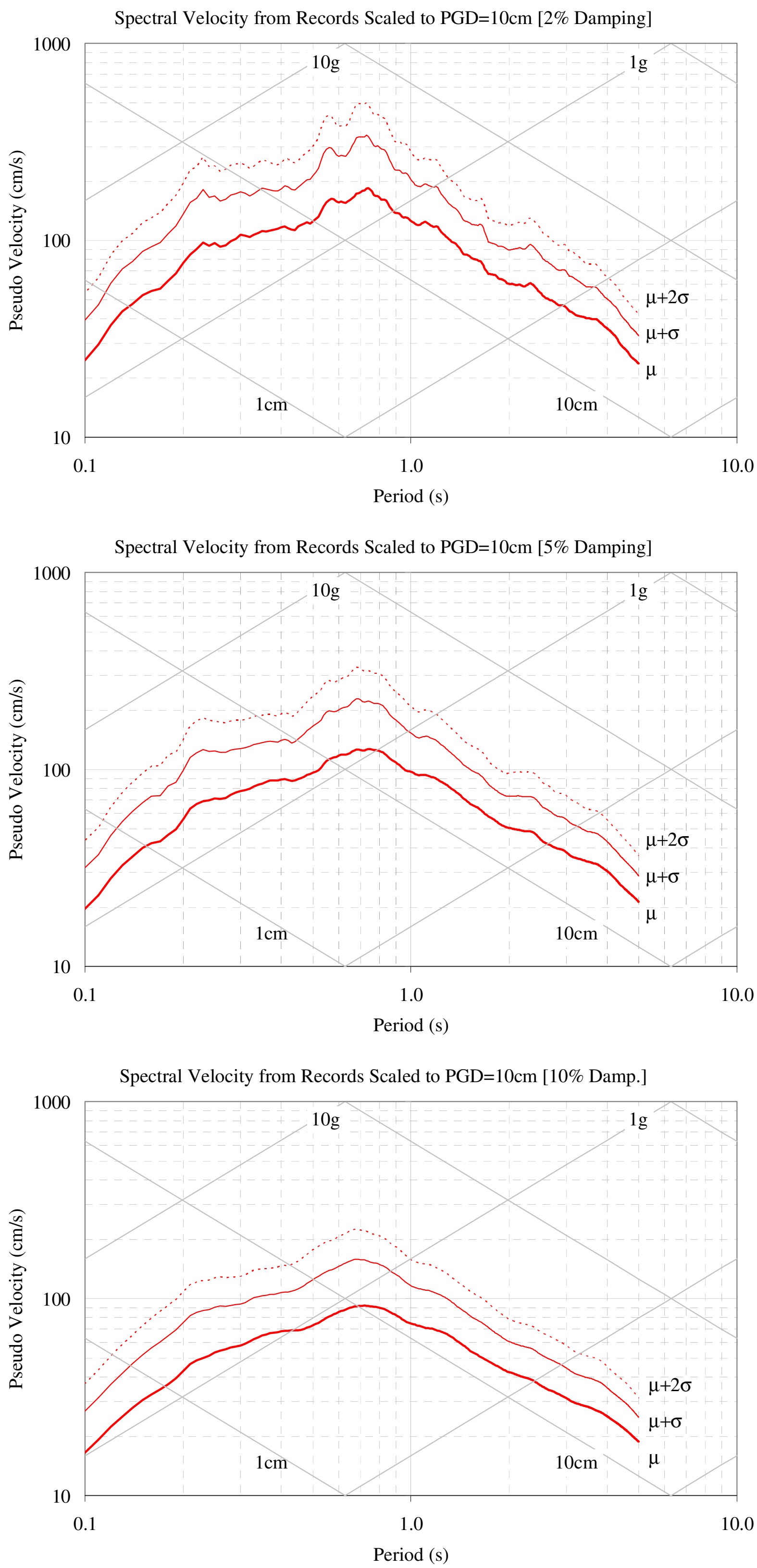
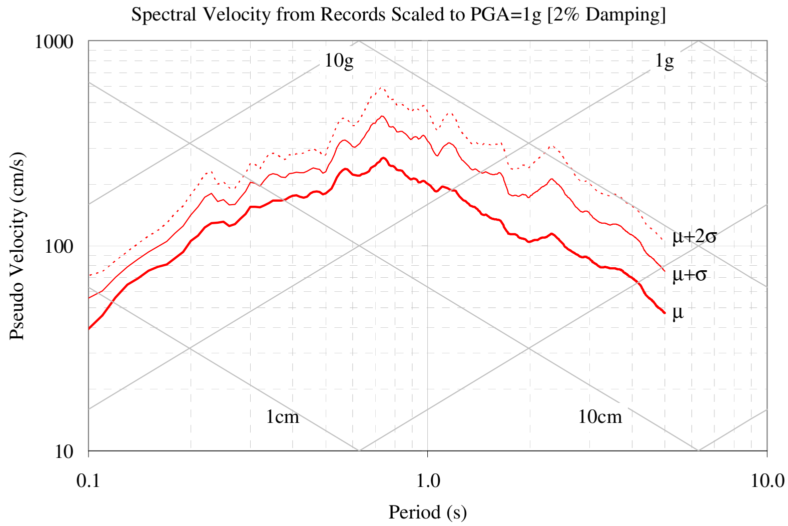
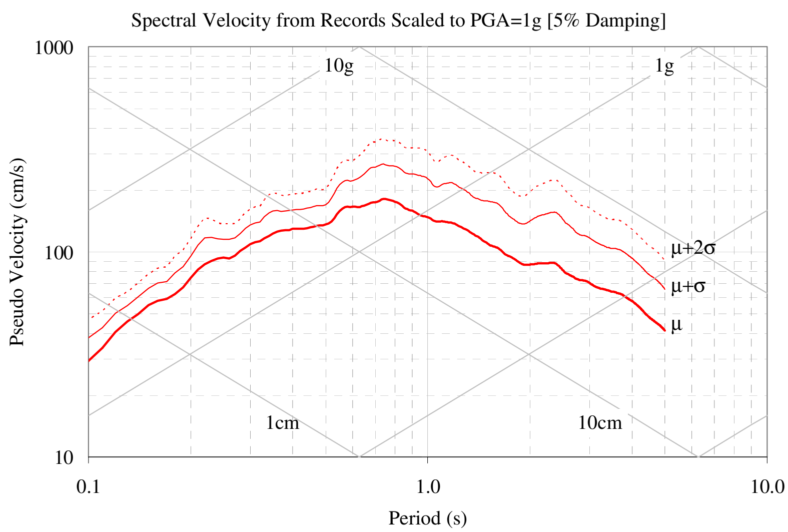


Figure 11. Pseudo velocity response, records normalized with respect to PGD





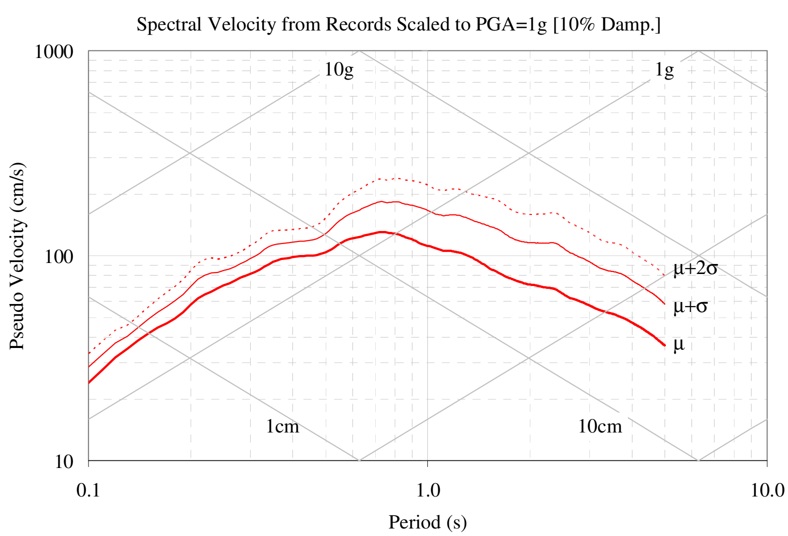


Figure 12. Pseudo velocity response, records normalized with respect to PGA

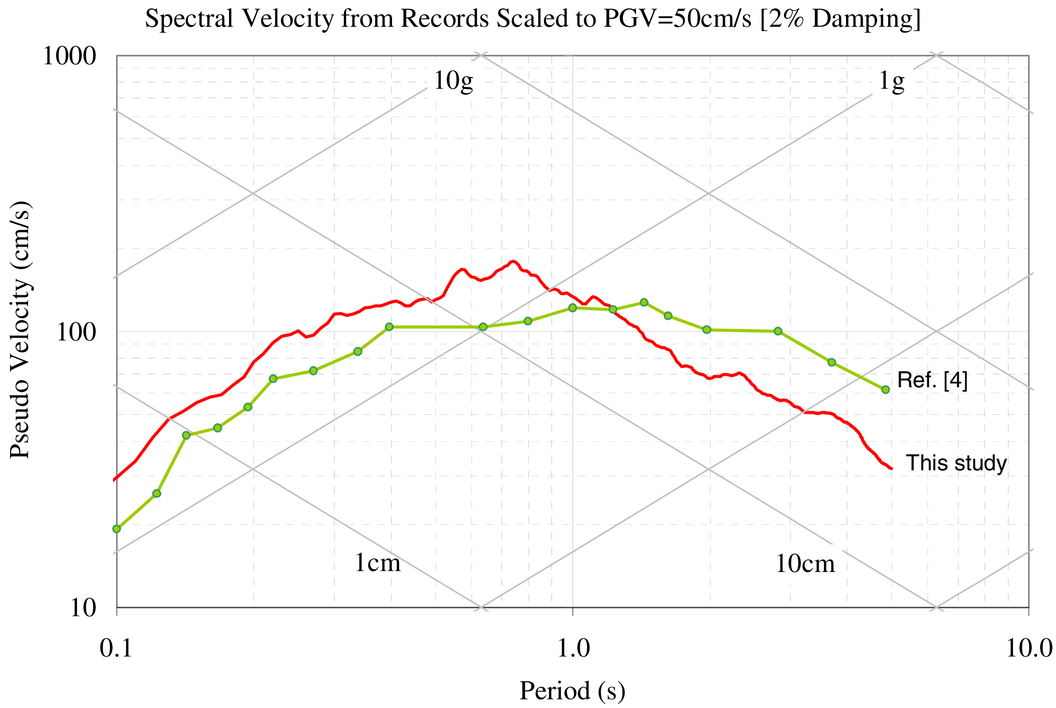


Figure 13. Average response spectrum, comparison with values reported by Mohraz et al. [4]