

A STUDY OF SITE AMPLIFICATION EFFECTS IN SANTIAGO BASED ON EARTHQUAKE RECORDS OBTAINED FROM THE SMASCH ARRAY

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SUMMARY

The SMASCH array for the observation of strong ground motion has been operating in the Santiago area since 1989. One of the objectives of this instrumentation project is to study the influence of local site conditions on earthquake ground motions. The array consists of seven free-field sites located on different soil conditions ranging from a reference rock outcrop site to a site located on soft silty ground.

Using data from low to medium intensity events which occurred between 1989 and 1995, a preliminary evaluation of site amplification effects has been carried out. Fourier Amplitude spectra of the accelerograms for each site, for several different events, were computed. For this purpose only a limited portion of the record was used: that containing predominantly S waves. The spectral shapes were smoothed by simple averaging of the spectral ordinates over overlapping windows of 0.78 Hz and amplitude ratios with respect to the rock site were calculated. For each site the averages of the amplification ratios were computed grouping the events in three different sets: all events, events in two different magnitude ranges (4 to 5 and 5 to 6), and events having different epicenter location (NW azimuth and NE azimuth). From these results it is apparent that there is a noticeable influence of the site soil conditions on the amplification value and also that this amplification can be quite different depending on the period range considered. The influence of magnitude is not very large, but noticeable for several sites. The influence of azimuth is clear at some sites and not noticeable at others

INTRODUCTION

The overall purpose of the instrumentation program is the study of earthquake motion in Santiago as a basis for improving the specification of earthquake design requirements for buildings and other structures. A specific objective towards this general goal is to obtain a thorough knowledge of ground motion in sites with various soil conditions.

The SMASCH array consists of seven stations, and nine instruments as listed in Table 1. The location of the sites in the Valley of Santiago is shown in Figure 1. The sites are located on a range of soils and cover most of the city of Santiago, with spacing of 5 to 10 km. SMACMD digital accelerographs, manufactured by Akashi Seisakusho, Japan, are installed at five sites; since this instrument has an A/D converter with resolution of 16 bits, it can record not only strong motion but also weak motion with high accuracy. At two sites there are SSA-1 instruments, manufactured by Kinemetrics, USA, with characteristics similar to the SMAC-MD, although with only 12 bits resolution in the A/D converter. The array is completed with two RFT250 analog accelerographs (photographic film recording) manufactured by Teledyne-Geotech, USA.

To record free-field earthquake ground motions, small instrument shelters were constructed at all sites except CSL. The CSL site is a rock cave in the Santa Lucía hill in downtown Santiago; the instruments are installed

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directly on a concrete floor in the cave. A detailed description of the instruments and of the shelters characteristics can be found in [Midorikawa et al., 1990].

GEOLOGICAL CONDITIONS IN SANTIAGO AND AT ACCELEROGRAPH STATIONS

Santiago is situated in a narrow valley between the Andes and the coastal mountains. The altitude of the city is about 600 m above sea level. The valley originated from the depression of an area between two major faults, which are parallel to the two mountain chains. The depression was caused by tectonic movements in the Tertiary.

Most of the sediments which cover the valley were transported from the Andes mountains, mainly by streams. Some deposits are believed to be the result of volcanic mud flows or glaciers. The formation of the sediments is different in each area of the city. The surface geology of the city can be divided into several types, as shown in Figure 1 [Valenzuela, 1978]. In the central and southern parts of the city, sediments consist of very dense coarse gravel with cobbles. In the northwest part of the city, recent alluvial deposits, consisting of loose silty soils, cover the area. Between these two areas a transition zone exists. At the foot of the mountains, in the eastern part of the city, the ground surface is covered by colluvial deposits from the mountains. Stiff pumice of volcanic origin, which is called Pomacite, is found in the western part of the city. Outcrops of basement rock are found in the mountains and outliers form the hills which exist in the plain.

To investigate soil conditions at the sites, bore hole tests were carried out at PTP and PCQ and small pits were excavated at UC1 and UC2. Below is a brief description of the soil conditions at the sites based on these explorations and previous investigations compiled in [Valenzuela, 1978].

Site 1, CSL (Cerro Santa Lucía): Igneous rock surrounded by the alluvial deposits of the Mapocho river. The Santa Lucía hill rises about 60 m above the surrounding alluvial plain. The cave housing the instrument is about 20 m above the plain. Significant topographic effects from the hill are not expected in records at this site.

Site 2, UC1 (Universidad Católica, Casa Central): Alluvial deposits of the Mapocho river. Dense to very dense gravel is found at a depth of 2.4 m. An S wave velocity for the gravel deposits of approximately 700 m/s was measured. The superficial layers consist of artificial fills, silts and clay deposits. The depth to water table is approximately 50 m and the depth to rock is approximately 100 m. This site is about 300 m away from CSL.

Site 3, UC2 (Universidad Católica, Campus San Joaquín): Alluvial deposits. The soil conditions are similar to those of site 2, but dense gravel is found at a depth of 0.9 m. A thin clayey layer overlies the gravel deposits. The depth to water table is 80 m and the depth to rock is approximately 400 m.

Site 4, PTP (Planta Toyota, Rotonda Pudahuel): "Pomacite" deposits formed of volcanic pumice and ash. Standard penetration test (SPT) N value is 50-75. The fine content is between 6 and 32%. Pomacite overlies the gravel layer which is the typical soil in the city. The thickness of the layer of Pomacite is 40 m or less. S wave velocities of 300 m/s in the upper 6 m and 550 m/s at depths of 6 to 16 m were measured. The water table is deeper than 20 m and the depth to rock is approximately 300 m.

Site 5, PCQ (Planta Cervecera Santiago, Quilicura): Alternating layers of low to medium plasticity silts and clays, interbedded with gravel layers. From the surface to about 9 m depth the deposits have a soft consistency, low relative density and SPT N value of 2 to 4. The S wave velocity is around 200 m/s from the surface to a depth of 10 m. Below about 9 m the strata have a firm to hard consistency and medium to very high relative density and the SPT N value is 35. The depth to water table is about 2 m, the depth to rock about 100 m.

Site 6, ESM (Escuela Militar): Alluvial deposits of the Mapocho river. Dense to very dense gravel and unsaturated soil. The depth to water table is 25 m and the depth to rock is 100 to 200m.

Site 7, AES (Aeródromo Eulogio Sánchez, Tobalaba): Colluvial deposits. Inorganic silt of medium plasticity, firm, interbedded with 5 to 10 cm layers of dense silty gravel. Unsaturated soil. Estimated thickness of the stratum is more than 20 m. The depth to water table is about 90 m and the depth to rock is about 100 m. No data on S wave velocity is available for this site.

LOCAL SITE EFFECTS ON OBSERVED GROUND MOTIONS

Only events that have triggered three or more stations have been considered for this study (Table 2). The peak accelerations of the records vary between 1 and 113 cm/s². Three components are recorded at each site: two horizontal components aligned with the East-West (X) and North-South (Y) directions and a vertical component (Z). The epicenter locations for the events considered are shown in Figure 2, and in Figure 3 the foci locations are shown in terms of Longitude and Depth. Each event is identified with the label used in Table 2 that includes the year in which it occurred and the sequence number in the SMASCH Report of that year [Cruz et al., 1998].

It is clear that the observed ground motion is a consequence of source, path, and site effects. Only the amplitude ratio of the motion on soil ground to that on rock is representative of site effects, because the site effects can be ignored for a base rock site. A section of S waves in the record is used to calculate the spectral amplitude ratio, because the main portion of strong ground motion is mainly due to S waves. On each of the records and sites considered this is done for all the recorded components.

For each event the Fourier Amplitude Spectrum was computed for the selected portion of each record and the spectrum was smoothed using a simple average of the amplitudes over overlapping windows of 0.78 Hz. Then the ratio of the spectrum for each soil site to that of the reference rock site (CSL) was calculated.

Amplitude-ratio spectra for the various records available for each site were obtained. The ratios from different records are similar at each site, indicating that each site has particular properties regarding spectral amplification of ground motions. Simple statistics were performed for each site considering the full set of records available for the site, and plotted as shown in Figures 4 and 5 for sites 3 and 5.

These figures show that the soil conditions at the different sites have a significant influence in the amplification ratios. Some trends can be observed, and even though the difference between the average curves (solid lines) and the average plus one standard deviation curves (dashed lines) are rather large at some period ranges, the results are considered adequate for identifying the major trends in the behavior of the amplitude ratios over the period range considered.

Some of the trends observed can be summarized as follows:

- a) At UC1 (Site 2) and UC2 (Site 3) on gravel, the amplification of ground motion was generally small. At UC1, however, a large amplification was found in the period range 0.05 to 0.1 seconds. This peak is probably due to the artificial fill which exists locally at the site. When the effects of the artificial fill are ignored, the amplification is found to be around 2.5 in the period range 0.1 to 2 seconds for UC1, and 1.5 between 0.05 and 2 seconds for UC2. A measure of the rather large scatter of the data is given by difference of the two curves shown (solid and dashed) over the period range (Figure 4).
- b) At PTP (Site 4) the amplification was very small for periods shorter than 0.2 s and became larger in the longer period range. At a period of around 0.8 seconds, the ratio shows its maximum. The amplification on this site is about 1.5 for periods shorter than 0.2 seconds, and about 2.5 for periods larger than 0.4 seconds.
- c) At PCQ (Site 5) a large amplification was obtained over a wide period range. A peak was found at periods of about 1.0 second. The amplification on the silty soil site varies between 2 and 5 for periods longer than 0.1 second, with an average of about 3 (Figure 5).
- d) At AES (Site 7) rather small amplification was found for periods in the range 0.15 to 0.30 seconds with an average value of 2.5. For shorter periods the average amplification went up to about 6 and for longer periods it increased to about 4 or 5, except for the vertical component where values of the order of 10 were obtained.

EFFECT OF MAGNITUDE AND OF EPICENTER LOCATION

The second part of this investigation deals with the identification of the effects on the amplitude ratios of two parameters: the magnitude of the event, and the epicenter location relative to the site (azimuth). For this purpose the events at each site were divided into two sets: magnitude between 4 and 5, and between 5 and 6 for the study of the effect of magnitude; and North-West azimuth and North-East azimuth for the study of the effect of epicenter location. The statistics for the results (amplitude ratios) for these groups were then computed and typical results are shown in Figures 6 through 9 for site 5. Although the number of events considered in these groups is smaller than in the previous results they still provide some significant insight in the effect of the parameters considered.

The results need to be analyzed further, but preliminary analysis of them shows that the effect of azimuth can be significant, especially for Sites 4 and 7. The effect of magnitude is not very significant in most of the sites, except may be in Site 7, but this may change if the magnitude ranges increase as larger magnitude events are likely to induce nonlinear effects in the soil, especially at the softer soil sites. More definitive conclusions will be obtained only when several strong earthquake records with higher acceleration levels are available.

5. RESULTS OBTAINED FROM MICROTREMOR MEASUREMENTS

In order to have a procedure that can be extended to other sites, and thus allowing to establish a microzonation of the region based on actual measurements of ground motions, the ratios of the amplitude spectra computed in a similar fashion as those for the earthquake records, were obtained for several different sites where microtremor measurements were performed. Several campaigns of microtremor observation have been carried out, especially in the softer soils areas. The results from these observations are expressed in terms of horizontal to vertical velocity amplitude spectral ratios and sample results are shown in figures 10 and 11 for microtremor measurements performed at site3 and site 5 respectively.

SUMMARY AND CONCLUSIONS

Data from a recently installed strong ground motion monitoring array in Santiago, Chile (SMASCH array) has been used to study local site effects on ground motion. The spectral amplitude ratios of the observed earthquake motions at soil sites with respect to a reference rock site were calculated to examine the local site effects. The spectral amplitude ratios from different records are similar at each site, and the spectral amplification of ground motion is unique at each site. The effects of event magnitude and event epicenter location with respect to site location on the amplitude ratios are studied and show some influence on the shape and the value of the amplification ratios observed.

The results are complemented with others obtained from microtremor measurements that have shown that the amplitude ratios have some correlation to the thickness of the geological (Pleistocene) deposits, and also to the existence of soft subsurface soils.

ACKNOWLEDGMENTS

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TABLE 1. List of Strong-Motion Sites of the SMASCH Array

Site Name	Site Code	Site No.	Soil Condition	Coordinates	Instrument Type	Installation Date
Cerro Santa Lucía	CSL	1	Rock	33°26'25"S 70°38'32"W	SMAC-MD RFT-250	13/07/1989 24/01/1990
Universidad Católica, Casa Central	UC1	2	Dense Gravel	33°26'29"S 70°38'19"W	SMAC-MD	12/07/1989
	UC1B	6	(2nd Basement of 10 story Bldg.)	33°26'30"S 70°38'26"W	SSA-1	31/01/1990
Universidad Católica, Campus San Joaquín	UC2	3	Dense Gravel	33°29'59"S 70°36'49"W	SMAC-MD	11/07/1989
Planta Toyota, Rotonda Pudahuel	PTP	4	Stiff Fine Volcanic Sediment	33°27'01"S 70°46'34"W	SMAC-MD	14/07/1989
Planta Cervecera Santiago, Quilicura	PCQ	5	Alluvial Sediments	33°21'52"S 70°42'08"W	SMAC-MD	14/07/1989
Aeródromo Eulogio Sánchez, Tobalaba	AES	7	Colluvial Deposits	33°27'31"S 70°32'54"W	SSA-1	31/01/1990
Escuela Militar	ESM	8	Dense Gravel	33°24'43"S 70°34'55"W	RFT-250	00/03/1988

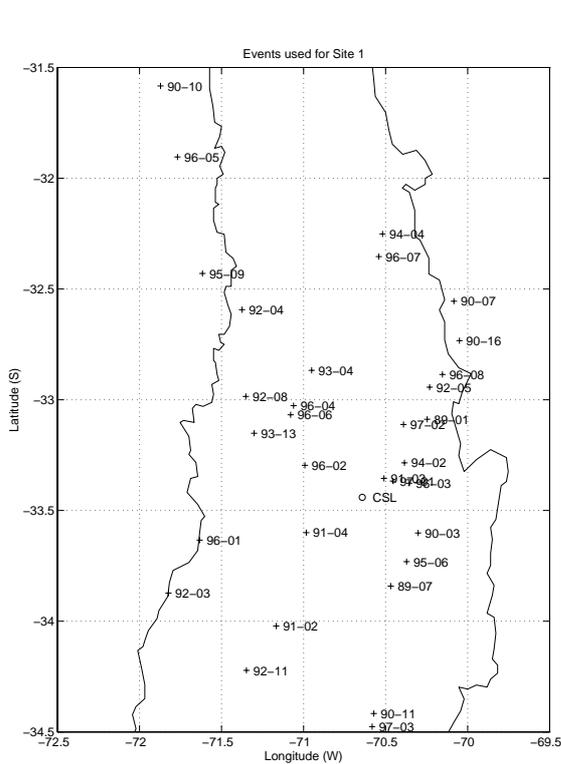


Figure 2. Epicenter Location for Events Used (approximate coast line and Chile-Argentina border are shown for reference).

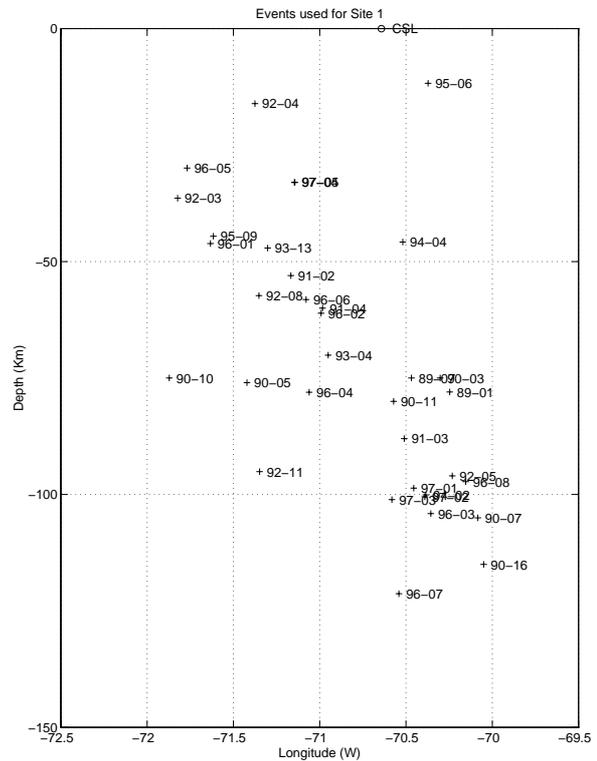


Figure 3. Hypocenter Locations for Events Used.

TABLE 2. Listing of events used for this study, and their characteristics (2 pages).

Event Label	Date	Time (GMT-4)	Epicenter Location	Depth (km)	Mag	Com	Uncorrected Peak Ground Acceleration (cm/s ²)						
							CSL	UC1	UC2	PTP	PCQ	AES	
97-01	Jan 12	12:00:42	33°22'01''S 70°27'18''W	98.63	3.87	E-W	3	12		2			
							S-N	4	9		1		
							U-D	3	3		3		
97-02	Feb 02	00:05:14	33°06'43''S 70°23'28''W	100.5	4.00	E-W	3	9		5			
							S-N	3	11		4		
							U-D	2	3		4		
97-03	Feb 05	19:17:35	34°28'34''S 70°34'55''W	101.1	4.55	E-W	6	20		6	15		
							S-N	7	32		7	11	
							U-D	5	9		6	4	
97-04	Mar 09	08:43:43	29°48'54''S 71°08'49''W	33.00	5.50	E-W	2	3		3	9		
							S-N	2	4		4	11	
							U-D	1	2		2	4	
97-05	Mar 10	00:53:00	29°40'52''S 71°08'38''W	33.00	5.20	E-W	2			3	6		
							S-N	2			3	6	
							U-D	1			1	3	
96-01	Feb 22	10:40:56	33°38'02''S 71°37'59''W	46.13	5.69	E-W	31	93	39	56	53		
							S-N	28	113	47	48	66	
							U-D	30	31	20	34	36	
96-02	Mar 02	14:26:52	33°17'46''S 70°59'31''W	61.08	4.53	E-W	8	21	13	13	14		
							S-N	6	24	13	15	13	
							U-D	5	9	8	19	19	
96-03	May 10	14:22:50	33°22'37''S 70°21'22''W	104.1	4.55	E-W	10	48	9	6	19		
							S-N	10	35	7	8	21	
							U-D	9	16	4	8	16	
96-04	Jul 24	00:21:17	33°01'37''S 71°03'40''W	78.06	4.68	E-W	12	30	8	7	26		
							S-N	12	37	8	9	45	
							U-D	8	12	6	12	21	
96-05	Sep 08	21:20:39	31°54'14''S 71°46'05''W	29.92		E-W	8	30	7	7	24		
							S-N	9	26	8	11	26	
							U-D	6	10	7	6	21	
96-06	Aug 24	23:28:21	33°04'05''S 71°04'44''W	58.16	4.04	E-W	3	8			4		
							S-N	3	8			5	
							U-D	3	3			5	
96-07	Oct 18	10:44:20	32°21'14''S 70°32'28''W	121.3	4.98	E-W	6	13		6	21		
							S-N	5	15		5	25	
							U-D	4	5		4	11	
96-08	Dec 13	22:11:10	32°53'10''S 70°09'14''W	97.24		E-W	5	10		3	14		
							S-N	8	11		3	10	
							U-D	5	4		2	9	
95-06	Jun 12	13:47:17	33°43'52''S 70°22'19''W	11.73	4.8	E-W	7	59	12	5			
							S-N	14	61	17	5		
							U-D	7	15	7	10		
95-09	Oct 9	05:47:31	32°25'48''S 71°36'58''W	44.56	5.0	E-W	7	29	7	8			
							S-N	6	26	8	7		
							U-D	4	9	5	6		
94-02	May 4	08:03:41	33°17'05''S 70°23'06''W	100.1	4.2	E-W	5	23	4	3	5	5	
							S-N	6	25	4	3	6	5
							U-D	4	7	3	5	4	3
94-04	Oct 11	01:37:23	32°15'05''S 71°31'06''W	45.8	5.4	E-W	7	37	9	9	33	22	
							S-N	9	28	11	9	27	13
							U-D	5	11	7	9	18	9
94-06	Oct 28	20:59:29	33°14'03''S 70°28'04''W	76.5	4.9	E-W	11	33	15	5	20	28	
						S-N	12	51	9	6	12	31	

						U-D	7	9	6	9	9	10
93-04	Feb 12	16:51:41	32°52'02''S 70°57'03''W	70.1	4.5	E-W	6	15	5	3	22	11
						S-N	5	16	4	4	12	12
						U-D	5	5	4	5	13	5
93-13	Oct 25	17:30:15	33°09'04''S 71°18'04''W	47.1	4.4	E-W	7	19	6	7	7	3
						S-N	7	19	6	6	9	3
						U-D	4	7	4	7	8	2
92-03	Apr 10	05:33:10	33°52'24''S 71°49'24''W	36.4	4.8	E-W	7	11	8	19	13	
						S-N	5	15	9	16	12	
						U-D	5	5	4	9	8	
92-04	May 2	23:40:40	32°35'36''S 70°13'54''W	16.1	5.0	E-W	7	38	9	6	22	
						S-N	7	28	7	7	19	
						U-D	6	9	6	8	13	
92-05	May 17	15:47:30	32°56'36''S 70°13'54''W	96.0	4.7	E-W	7	18	9	4	21	
						S-N	7	23	7	4	21	
						U-D	6	6	5	3	12	
92-08	Jul 23	09 :58 :20	32°53'42''S 71°21'06''W	57.3	5.0	E-W	10	34	12	11	22	
						S-N	8	30	11	9	18	
						U-D	7	10	9	12	19	
92-11	Aug 21	00:52:50	34°13'18''S 71°20'54''W	95.1	4.7	E-W	8	39	12	11	13	
						S-N	7	37	20	11	11	
						U-D	7	18	9	8	10	
91-02	Feb 23	16:20:02	34°01'18''S 71°10'00''W	53.0	4.6	E-W	7	16	6	10	11	5
						S-N	6	13	8	14	11	5
						U-D	5	9	4	9	9	4
91-03	May 21	00:24:17	33°21'18''S 70°30'36''W	88.0	4.6	E-W	10	44	12	9	19	
						S-N	12	31	13	11	16	
						U-D	8	11	6	11	11	
91-04	Jun 29	14:32:07	33°36'00''S 70°59'00''W	60.0	4.5	E-W	11	58	77		16	
						S-N	16	79	98		13	
						U-D	15	22	28		10	
90-03	Mar 6	22:13:35	33°36'06''S 70°18'06''W	75.0		E-W	9	12	3		13	5
						S-N	5	10	4		12	4
						U-D	7	6	2		5	8
90-05	May 14	17:34:04	35°53'18''S 71°25'18''W	76.0	5.4	E-W	8	19	9	7	17	8
						S-N	6	23	8	8	15	10
						U-D	6	8	5	7	11	6
90-07	Jul 16	10:51:36	32°33'16''S 70°05'00''W	105.0	5.4	E-W	28	35	22	23	99	30
						S-N	34	53	18	18	85	26
						U-D	15	17	14	11	45	18
90-10	Aug 2	01:24:07	31°35'00''S 71°52'18''W	75.0	5.5	E-W	2	3	2	3	7	6
						S-N	2	4	2	3	9	5
						U-D	1	1	1	2	6	3
90-11	Aug 26	22:44:20	34°25'00''S 70°34'18''W	80.0	4.6	E-W	3	6	3	3	6	2
						S-N	2	13	3	3	5	3
						U-D	3	3	2	2	3	2
90-16	Dec 21	14:31:46	32°44'00''S 70°03'00''W	115.0	5.0	E-W	5	18	6	4	25	8
						S-N	7	18	6	5	21	9
						U-D	4	6	4	5	11	6
89-01	Jul 22	23:23:00	33°05'18''S 70°14'48''W	78.0	4.7	E-W	8	20	11		14	
						S-N	9	24	11		12	
						U-D	6	10	6		10	
89-07	Nov 9	05:07:00	33°50'30''S 70°28'06''W	75.0	4.8	E-W	14	85	20	12	25	
						S-N	14	82	20	10	15	
						U-D	26	24	15	18	16	

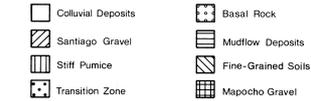
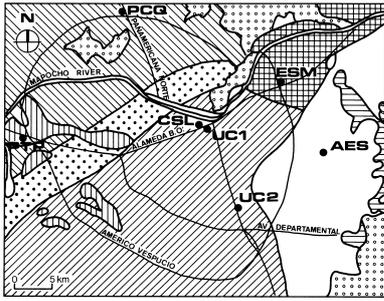


Figure 1. Geological map of Santiago and location of the stations of the SMASCH Array

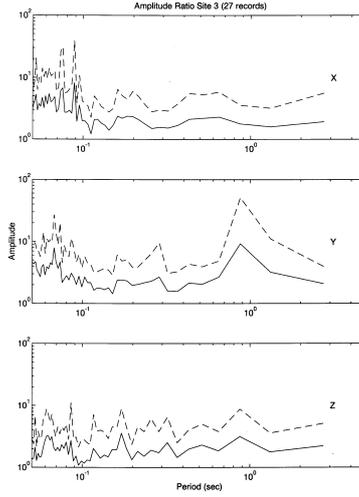


Figure 4. Amplitude Ratio Spectra for Site 3

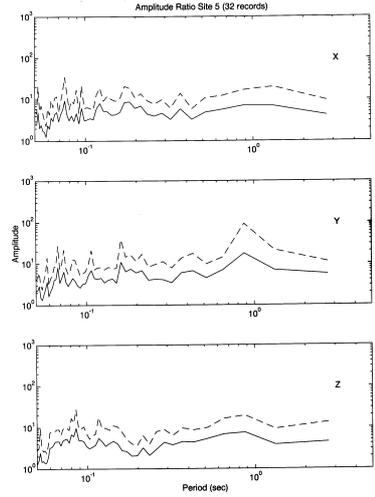


Figure 5. Amplitude Ratio Spectra for Site 5.

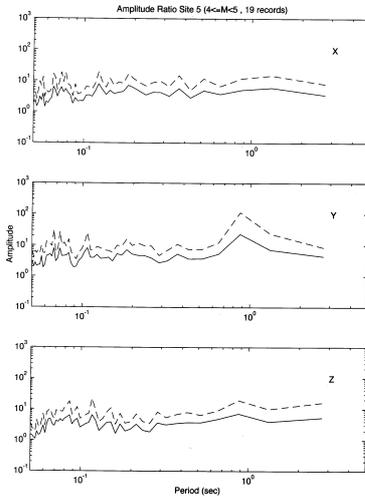


Figure 6. Amplitude Ratio Spectra for Site 5, 4<M<=5.

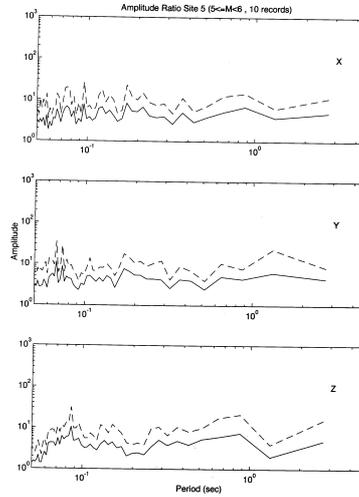


Figure 7. Amplitude Ratio Spectra for Site 5, 5<M<=6.

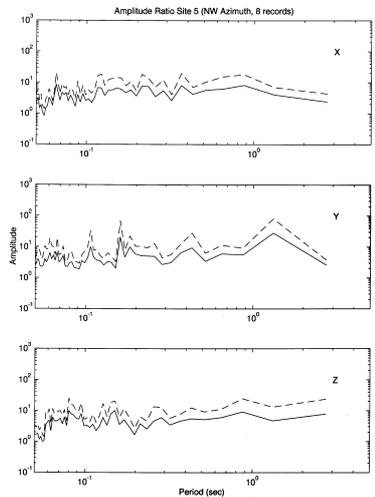


Figure 8. Amplitude Ratio Spectra for Site 5, NW Azimuth.

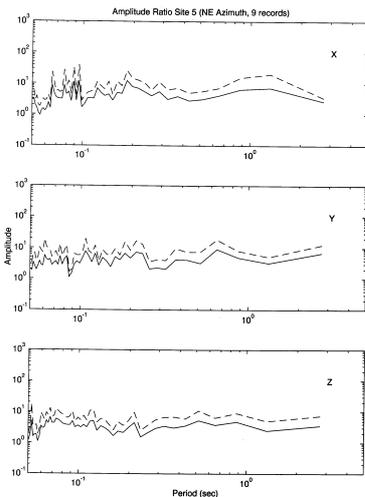


Figure 9. Amplitude Ratio Spectra for Site 5, NE Azimuth

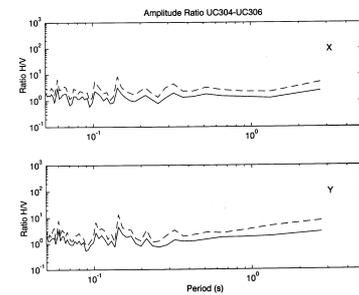


Figure 10. Amplitude Ratio Spectra for Site 3, Microtremors

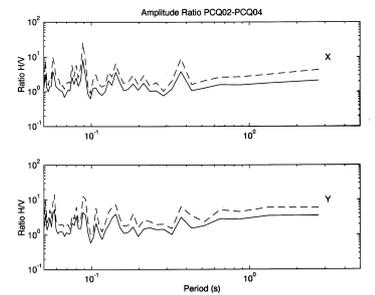


Figure 11. Amplitude Ratio Spectra for Site 5, Microtremors.