# SITE AMPLIFICATION EFFECTS OBSERVED FROM MODERATE INTENSITY EARTHQUAKE RECORDS OBTAINED IN THE SMASCH ARRAY

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**Abstract:** 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 observed 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 2001, an 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 and amplitude ratios with respect to the rock site were calculated.

For each site the averages of the amplification ratios were computed after 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 relative to the array location). From the results obtained 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 in not very large, but is noticeable for several sites. The influence of azimuth is clear at some sites and not noticeable at others.

## 1. CONFIGURATION OF THE SMASCH ARRAY

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 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. SMAC-MD digital accelerographs, manufactured by Akashi Seisakusho Inc., 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 one site there is an SSA-1 instrument, manufactured by Kinemetrics Inc., USA, with characteristics similar to the SMAC-MD, although with only 12 bits resolution in the A/D converter. The instrument at site No.8 was originally an analog type instrument, that has been removed and is presently being replaced by a new instrument, that is not yet fully operational.

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; where the instrument is installed 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).

## 2. GEOLOGICAL CONDITIONS IN SANTIAGO AND AT INSTRUMENT SITES

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, PCQ, and AES 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 on 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 (U. Católica, Campus 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 base rock is approximately 100 m. This site is about 300 m away from CSL.

Site 3, UC2 (U. 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 base 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 40m 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, 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 base rock is 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 base rock is 100 to 200 m.

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. The S wave velocity profile was obtained using seismic refraction. It varies from 300 m/s at the top layer (considered to be 4m thick), to 480 m/s for the next layer (considered to be 6 m thick) with a final value of 1000 m/s for the infinite layer below that depth.

## 3. LOCAL SITE EFFECTS ON OBSERVED GROUND MOTIONS

Only events that have triggered three or more stations have been considered for this study. Detailed information regarding each event can be obtained from the report that is published every year with the corresponding data (see for example Cruz et al, 2001). Alternatively, the data can be obtained from the web page www.ing.puc.cl/~wwwice/sismologia, of the Strong Motion Seismology Laboratory. A summary of the events considered is presented in Table 2.

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 focii locations are shown in terms of Longitude and Depth, where the inclination (dip angle) of the subduction zone, the predominant source of earthquake events in the area is clearly observed. Each event is identified with a label that includes the year in which it occurred and the sequence number of the event in the SMASCH Report of that year (Cruz et al., 2001).

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 amplifications 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:

1. 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 effect is probably due to the artificial fill which exists locally at the site just below the instrument location. 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 the difference of the two curves shown (solid and dashed) over the period range (Figure 4).

2. At PTP (Site 4) on the Pomacite deposits site, the amplification was 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 2 for periods shorter than 0.2 seconds, and between 3 and 4 for periods larger than 0.4 seconds.
3. At PCQ (Site 5) on the silty soil site, a large amplification was obtained over a wide period range. The amplification tends to increase more or less linearly from 0.05 to about 0.1 seconds and then it remains fairly constant with an average value of about 6 (Figure 5).
4. At AES (Site 7) on the colluvial deposits site, limited amplification was found for periods in the range 0.10 to 0.25 seconds with an average value of about 3.5. For shorter periods the went up to about 7 at 0.05 seconds, and for longer periods it increased (more or less linearly) to about 9 or 10 at about 2 seconds, and then remains constant.

## 4. 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 micro-zoning 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 micro-tremor measurements were performed. Several campaigns of micro-tremor 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 micro-tremor measurements performed at site 3 and site 5 respectively.

The results obtained show rather large dispersion, but in general it is observed that the magnitudes of the amplitude ratios have some correlation to the thickness of the deposits at the different sites, and also to the existence of soft soil layers.

## 6. SUMMARY AND CONCLUSIONS

Data from a 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 amplification values observed can be quite large reaching values as high as 9 or 10 for some period ranges in the softer soil sites. The effects of event magnitude and event epicenter location with respect to site location on the amplitude ratios are studied and are found to have some influence on the shape and the value of the amplification ratios observed.

The results are complemented with others obtained from micro-tremor measurements that have shown that the magnitude of the amplitude ratios have some correlation to the thickness of the deposits, and also to the existence of soft soil layers.

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**References:**

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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 | 13/07/1989 |
| U. Católica, Campus Casa Central | UC1 | 2 | Dense Gravel | 33°26'29"S 70°38'19"W | SMAC-MD | 12/07/1989 |
| U. 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 | | |

Table 2. Summary of Earthquake Events Considered.

| Site No. | M ≤ 5 | M > 5 | Azimuth N-W | Azimuth N-E | Total |
|---|---|---|---|---|---|
| 1 | - | - | - | - | 80 |
| 2 | 50 | 16 | 16 | 20 | 66 |
| 3 | 43 | 14 | 15 | 14 | 57 |
| 4 | 54 | 17 | 17 | 18 | 71 |
| 5 | 53 | 17 | 16 | 19 | 70 |
| 7 | 24 | 9 | 5 | 8 | 33 |

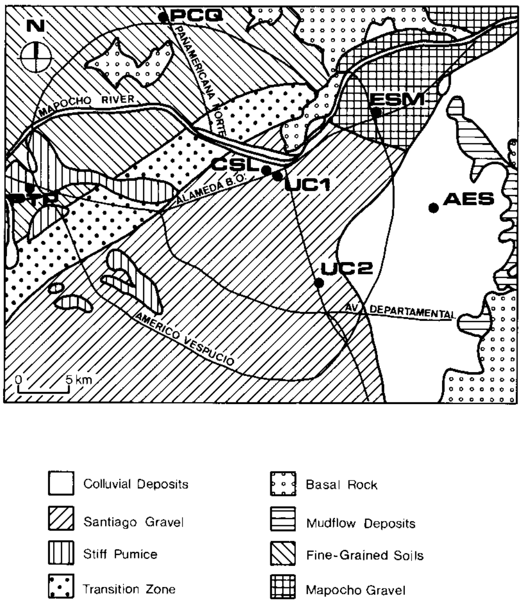


Figure 1. Geological map of Santiago and location of the stations of the SMASCH Array.

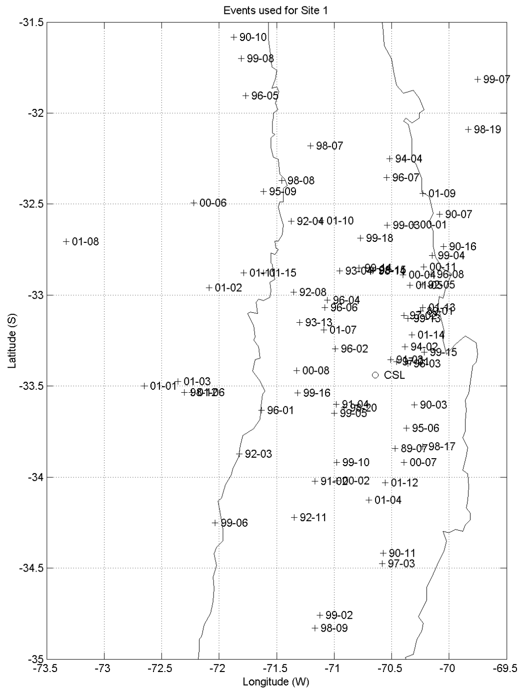


Figure 2. Epicenter Location for Events Used (Coast line and Chile-Argentina border are shown).

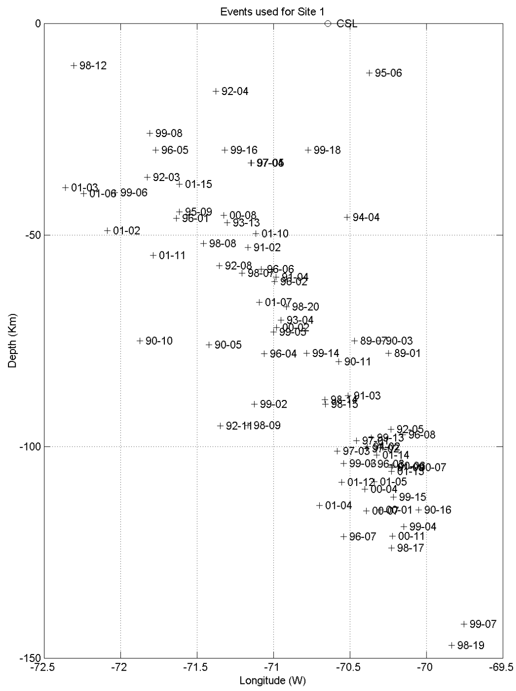


Figure 3. Hypocenter Locations for Events Used.

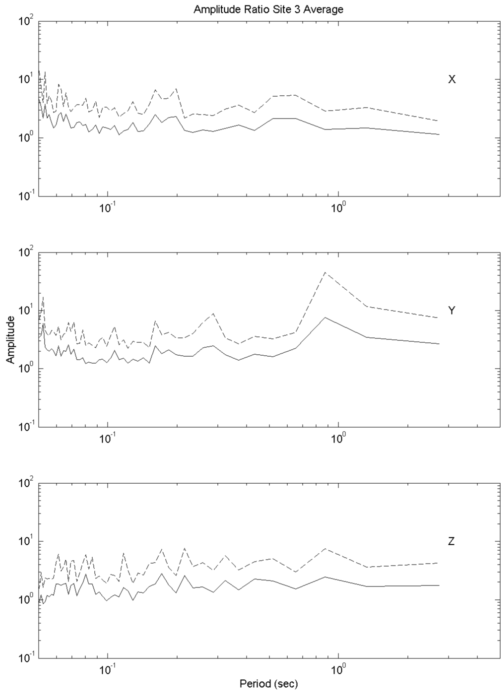


Figure 4. Amplitude Ratio Spectra for Site 3.

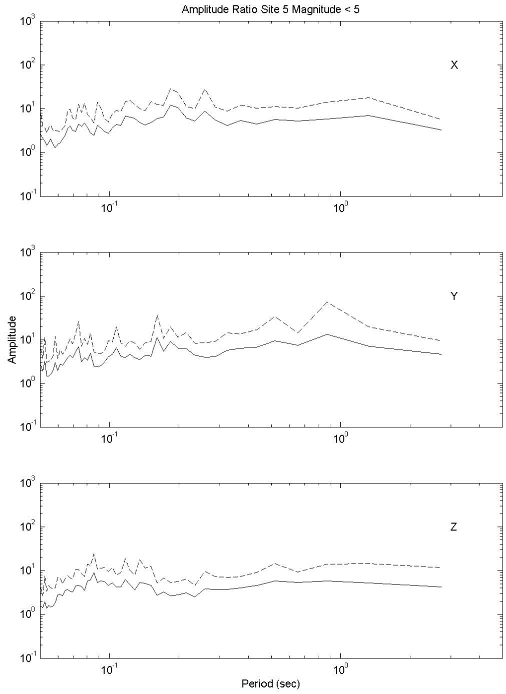


Figure 6. Amplitude Ratio Spectra for Site 5, $4 \leq$ Magnitude $\leq 5$.

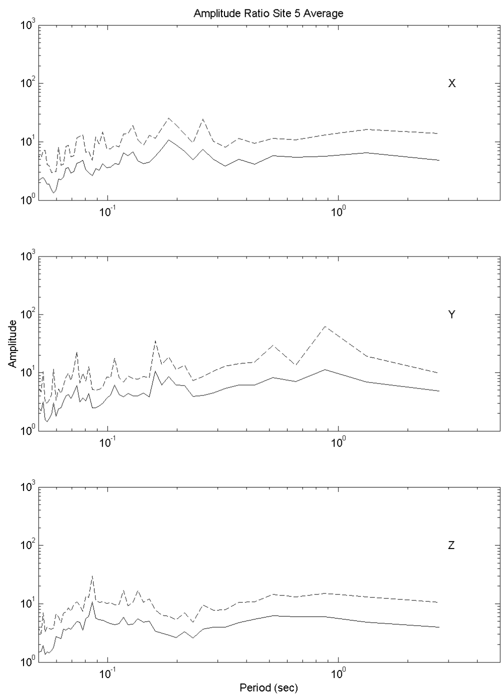


Figure 5. Amplitude Ratio Spectra for Site 5.

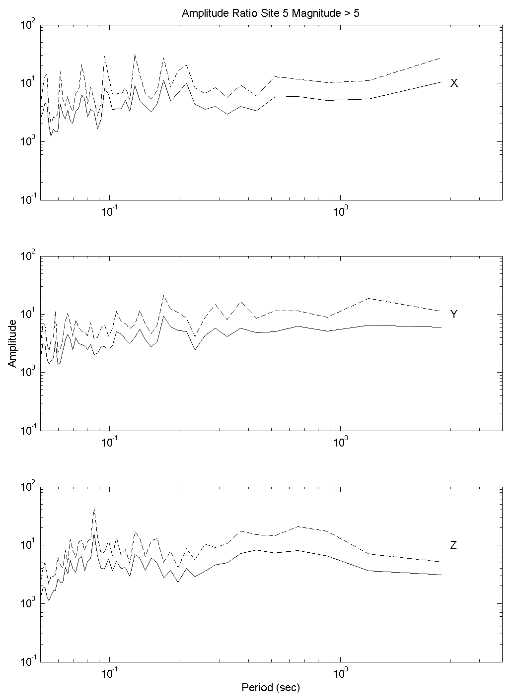


Figure 7. Amplitude Ratio Spectra for Site 5, $5 \leq$ Magnitude $\leq 6$.

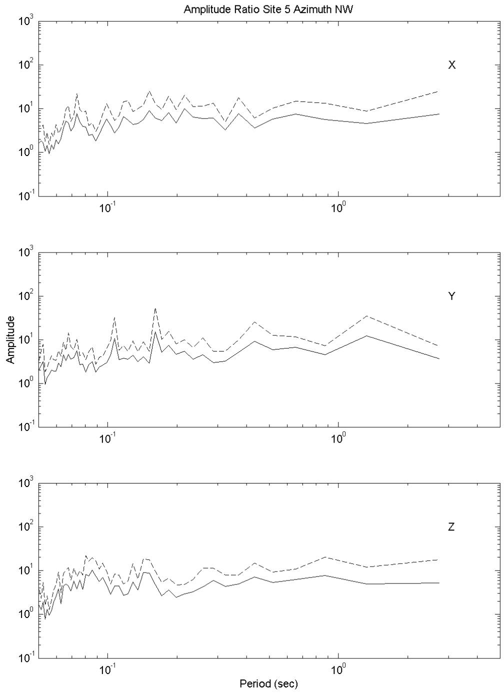


Figure 8. Amplitude Ratio Spectra for Site 5, NW Azimuth.

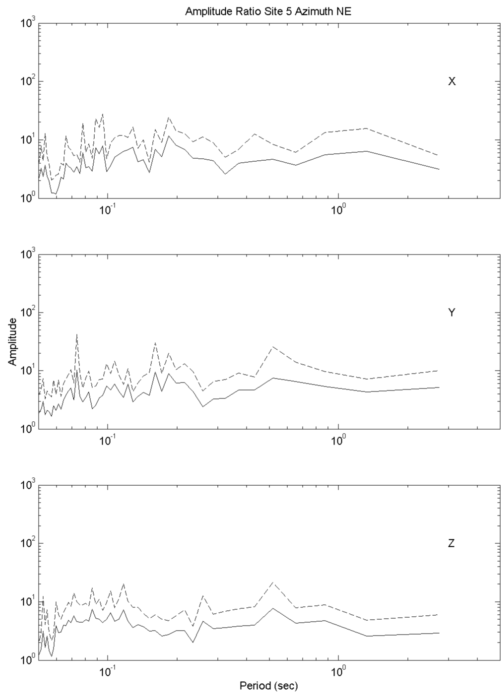


Figure 9. Amplitude Ratio Spectra for Site 5, NE Azimuth

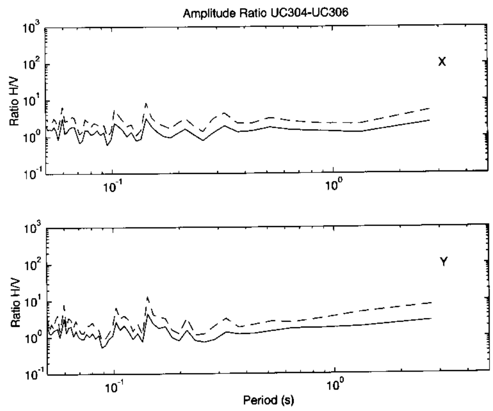


Figure 10. Amplitude Ratio Spectra for Site 3, Micro-tremors.

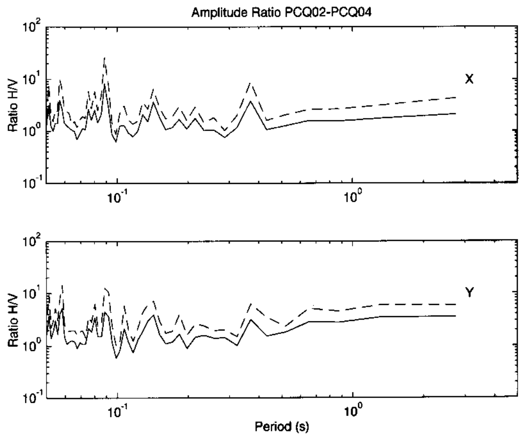


Figure 11. Amplitude Ratio Spectra for Site 5, Micro-tremors.