SITE EFFECTS FROM SEISMIC SHAKING:

A COMPARISON OF STRONG AND WEAK GROUND-MOTION

IN WELLINGTON CITY AND THE HUTT VALLEY

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Contents

Summary

Weak- and strong-motion records have been compared at six sites in Lower Hutt and ten sites in Wellington city. The comparisons have been made in terms of Fourier spectral ratios of ground velocity and 5% damped response spectral ratios of ground acceleration. The peak accelerations for the strong-motion data range from 0.5% g to 10% g while the weak-motion range is 0.005% g to 0.4% g.

Non-linear behaviour does not appear to be significant over this ground motion range. In general the strong-motion ratios lie within one standard deviation of the weak-motion ratios at most frequencies, though the strong-motion ratios tend to lie below the mean of the weak-motion ratios. Only one site common to the weak- and strong-motion recorders was located on more than 10 m of soft soil. At this site, the lower strong-motion ratios might be due to non-linear behaviour. One site on about 70 m of alluvial gravels also had lower strong-motion ratios. One site on alluvium and thick gravel to a total depth of 275 m in the Hutt Valley had a greater strong-motion response in the longer period range. A site near the edge of the valley on alluvium had its peak at a shorter period in the weak-motion ratios.

1. Introduction

The importance of localised variations in earthquake ground motions has become widely recognised in the past few years, particularly after the amplifications seen in Mexico city in 1985 and San Francisco in 1989. Many New Zealand cities are built in sediment filled valleys or on recent fill and thus a similar amplification potential exists here. Ideally one would measure strong ground motion directly at a variety of sites to determine the relative levels of shaking, but sufficiently large events are too infrequent to provide enough information. Alternatively, in regions similar to New Zealand where damaging earthquakes are expected, but infrequent, the ground response due to microearthquakes has been successfully used to identify areas which subsequently experienced damaging shaking in a large earthquake (Borcherdt, 1991). Recent microzoning studies in the Wellington region (Taber and Smith, 1992) have shown there is a wide of range of weak-motion amplifications here (Figure 1). The question remains just how well these weak-motion amplifications can be used to predict strong motions, and particularly, how dependent is the non-linearity on the geologic properties of the soil.

The purpose of this study is to make a first attempt to compare weak-motion recordings in the Wellington region to the limited strong-motion data. The ultimate goal is to determine the relationship between amplification in weak and strong ground motions, including the level of shaking where non-linear effects become important. It is hoped to use the comparisons between weak- and strong-motion amplifications observed in the Wellington region study to extrapolate the results to weak-motion surveys which may be carried out in other parts of New Zealand where there are no strong-motion data. While the data have been interpreted to some extent, the primary results of the project are the presentation of the strong and weak motions processed in the same way on the same plots. The "strong-motion"

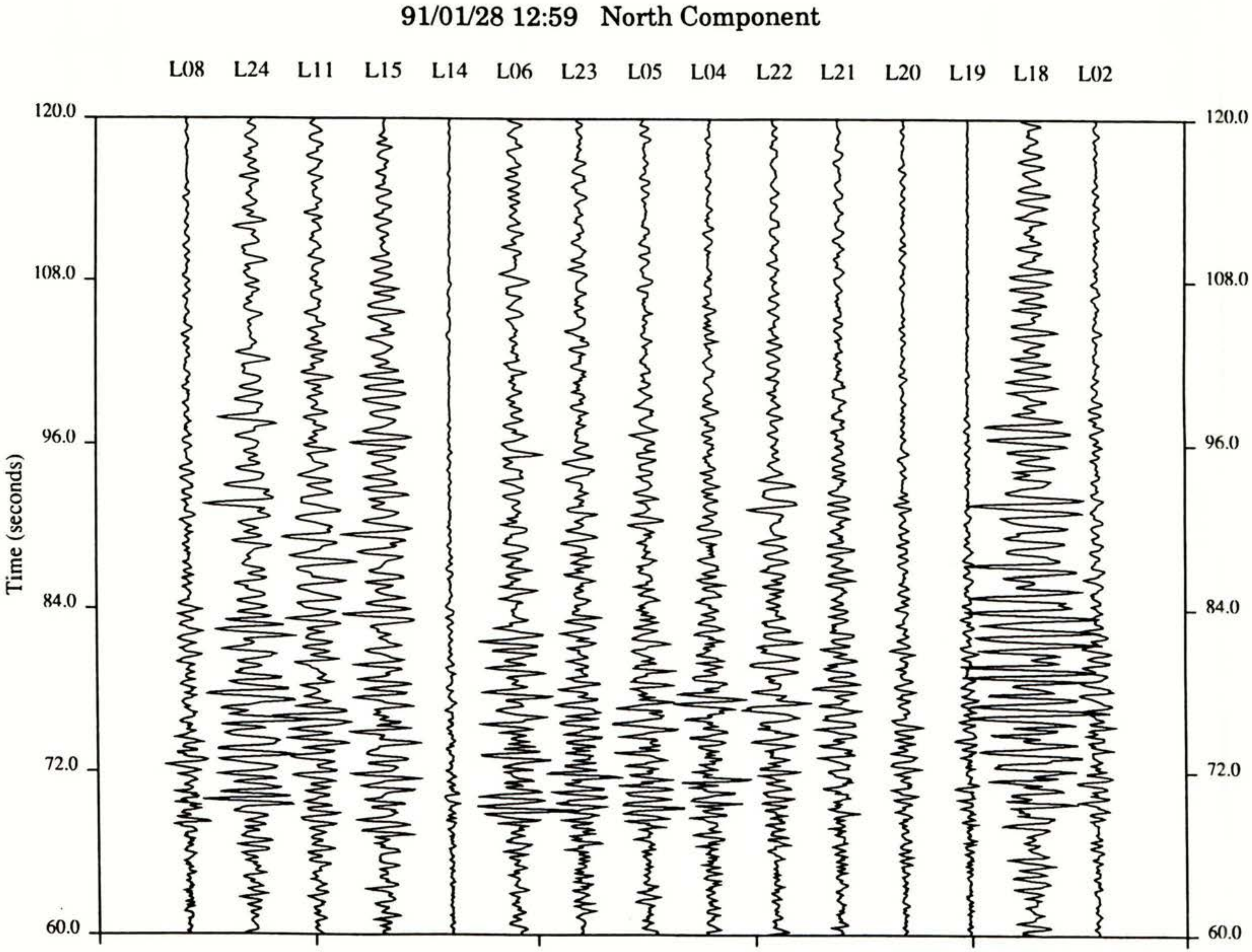


Figure 1. Seismograms displayed approximately along the length of the Hutt Valley. The firm, valley edge sites are L08, L14, and L19. There is a general decrease in amplitude when going up-valley from Petone (L24) to L02. Note the high amplitude at L18, which is located over a drained and filled swamp in Naenae. The maximum velocity at site L18 is 4.5 mm/s.

data collected to date in the Wellington region extends only to about 10% g, so that significant non-linear effects were not expected. However this study does provide the comparison of data ranging from .005% g to 10% g. Almost all of the strong-motion recorders are still operating so when a large earthquake occurs in the future, it will be possible to compare the weak motions from the current study to larger motions.

Up to 30 weak-motion recordings have been collected at each site whereas often only one or two strong-motion records exist. The weak-motion recordings show a wide variation of amplifications at the same site for different earthquakes (Taber and Smith, 1992). Therefore the approach in this study has been to show the range and mean of the weak-motion amplifications and to overlay these ranges with the strong-motion data. Effects due to individual earthquakes have not been considered in this report. For a detailed study of the strong-motion records of the 1973, 1977, and 1990 earthquakes, see Sritharan and McVerry (1992). The basic information about these earthquakes is listed in Table 1.

2. Data Collection and Site Specification

The data used in this study come from three different sources. The strong-motion data have been produced by the IGNS strong-motion network. We have limited our analysis to the largest earthquakes recorded before 1991. The two largest earthquakes are the events in 1973 and 1977 (Table 1). These two events were rather different in frequency content. The 1973 earthquake had a strong long-period response while the 1977 earthquake was richer in high frequencies (Sritharan and McVerry, 1990). Two smaller earthquakes that occurred in 1990 were included in the analysis because the 1973 and 1977 earthquakes were not recorded at one of the strong-motion sites.

Table 1. Earthquakes used in strong-motion analysis.

Date	Time	Lat	Lon	Depth (km)	Mag	MM Intensity In Wellington and Lower Hutt	Epicentral Distance from Site L14
05/01/77	13:54	39.13S	175.18E	173	7.0	V	235
18/01/77	05:42	41.84S	174.58E	33	6.0	V	73
19/02/90	05:34	40.47S	176.44E	34	5.9	-	154
04/10/90	23:48	41.64S	175.51E	23	4.9	-	67

Table 2. Earthquakes used in weak-motion analysis (locations from DSIR Seismological Observatory)

Wellington Array

Year	Month	Day	Hrmn	Sec	Lat	Lon	Depth (km)	Mag	Distance from site COT
1991	OCT	13	1642	17.24	41.80S	174.55E	30.5	2.9	60
1991	OCT	23	1438	45.27	37.00S	177.26E	216.3	5.8	523
1991	OCT	25	2106	5.49	38.02S	176.19E	213.3	5.6	383
1991	OCT	27	1142	16.78	41.37S	174.36E	33.7	2.8	35
1991	OCT	28	0304	28.68	41.51S	174.19E	42.8	3.2	54
1991	OCT	29	2019	21.87	41.43S	175.01E	28.3	3.2	25
1991	OCT	31	1422	10.31	41.82S	173.98E	44.4	4.8	88
1991	NOV	05	2016	41.97	41.42S	174.62E	30.8	2.9	19
1991	NOV	07	1647	51.75	40.60S	173.65E	96.7	3.7	121
1991	NOV	09	1836	50.71	40.47S	173.30E	158.0	4.3	153
1991	NOV	12	1403	8.27	41.04S	174.51E	54.3	3.7	35
1991	NOV	13	0602	37.32	41.24S	172.53E	229.0	4.4	187
1991	NOV	14	1154	58.17	40.22S	173.61E	152.1	4.0	154
1991	NOV	16	0035	39.95	37.11S	176.90E	263.2	6.1	500
1991	NOV	26	0943	39.54	39.71S	174.84E	114.5	4.6	176
1991	NOV	26	1514	29.90	41.06S	174.75E	31.2	2.5	26
1991	NOV	28	1544	8.80	41.43S	173.91E	42.8	3.5	73
1991	NOV	29	1340	56.69	39.94S	175.10E	27.4	3.4	152
1991	DEC	03	0943	7.28	41.08S	174.48E	35.8	3.4	33
1991	DEC	08	0423	29.68	41.25S	175.35E	30.5	4.2	49
1991	DEC	08	0615	37.42	41.24S	175.35E	29.9	3.7	49
1991	DEC	08	1007	24.37	41.25S	175.34E	28.5	3.1	48
1991	DEC	08	1010	42.82	41.24S	175.34E	27.2	2.9	48
1991	DEC	12	1411	57.05	41.23S	175.34E	27.2	3.1	48
1991	DEC	16	0446	28.55	41.27S	173.89E	61.8	3.8	73
1991	DEC	18	0818	10.04	40.68S	175.48E	10.4	3.6	90
1991	DEC	31	0459	28.16	41.25S	174.87E	28.4	2.9	10

1991	DEC	31	1028	59.48	41.50S	174.50E	19.8	3.0	32
1992	JAN	02	1445	23.69	41.04S	174.47E	16.3	2.8	37
1992	JAN	05	1004	42.27	41.30S	172.76E	154.2	4.5	168

Lower Hutt Array

Year	Mon	Day	Hrmn	Sec	Lat	Lon	Depth (km)	Mag	Distance from site L14
1990	NOV	27	1529	5.18	40.41S	174.46E	7.0	3.6	99
1990	NOV	29	2305	0.60	40.69S	174.66E	58.9	4.5	64
1990	NOV	30	1738	37.08	40.73S	174.95E	16.1	4.0	56
1990	DEC	9	0742	13.34	40.64S	175.39E	40.9	3.2	77
1990	DEC	12	0702	26.81	41.62S	175.37E	25.0	3.5	57
1990	DEC	16	1454	48.78	41.14S	175.16E	33.0	3.2	23
1990	DEC	16	1608	32.24	41.59S	173.64E	58.9	3.7	114
1990	DEC	20	1558	57.86	40.95S	174.65E	65.6	3.5	39
1990	DEC	23	2008	16.30	41.02S	174.59E	42.0	3.6	37
1990	DEC	26	1120	28.66	39.05S	175.26E	139.8	4.7	244
1990	DEC	29	1049	51.16	41.31S	174.11E	48.6	3.7	68
1991	JAN	9	1550	14.91	41.06S	174.73E	59.9	3.6	25
1991	JAN	11	1645	3.28	40.77S	176.32E	25.2	4.1	128
1991	JAN	15	1045	31.46	40.41S	174.47E	13.1	3.3	99
1991	JAN	17	1712	54.52	38.56S	175.62E	193.2	4.6	303
1991	JAN	22	1443	59.72	41.65S	175.40E	23.6	3.1	61
1991	JAN	24	1714	53.04	40.73S	175.38E	33.8	3.4	68
1991	JAN	26	1133	18.11	41.59S	174.48E	10.9	2.8	54
1991	JAN	28	1258	47.50	41.89S	171.61E	8.3	5.7	285
1991	JAN	28	1800	54.52	41.90S	171.73E	17.3	5.8	276
1991	FEB	1	1742	14.24	41.64S	175.49E	23.8	3.2	65
1991	FEB	2	1506	1.43	40.43S	176.40E	34.2	3.9	153

The weak-motion data come from separate short term surveys conducted in Lower Hutt and Wellington. There are strong- and weak-motion data from the same site at six locations in Lower Hutt and 10 locations in Wellington City (Table 3, Figures 2 and 3). The peak accelerations for the strong-motion data vary from 0.5% g to 10% g while the weak-motion range is 0.005% g to 0.4%g.

The Lower Hutt weak-motion data were collected between November 1990 and February 1991 as part of a microzoning survey for Wellington Regional Council (WRC) (Taber and Smith, 1992). A total of 24 sites were occupied during the survey, with six of the sites being locations were strong-motion data have been recorded by IGNS. Between 2 and 33 earthquakes were recorded at each site during that survey. Records from 22 of the earthquakes were used for the present study (Table 2).

The Wellington weak-motion data were collected specifically for this study in addition to being part of the microzoning study for WRC. The data were collected between October 1991 and January 1992. A total of 27 sites were occupied, 10 where strong-motion data have been collected. Between 5 and 30 earthquakes were recorded at each site (Table 2).

The weak-motion data were collected using 1 Hz natural period seismometers (Kinemetrics L4-3D) operated with EARSS digital seismographs at sampling rate of 100 Hz (see Gledhill *et al.* (1991) for a description of the EARSS seismograph). The recorders were sited primarily in the basement or ground floors of public buildings. In most cases the seismometer was placed within a few meters of the accelerometer. There were two sites where one of the instruments were inside a building and one was outside. One seismometer, at site W13, was located in the basement of the Vogel building whereas the accelerometer was located at a free-field site just outside the building. The weak-motion reference site for Lower Hutt, L14, was located on weathered bedrock 40 m outside of the IGNS building where the accelerometer was

Table 3.

Wellington Recording Sites

Weak Motion Sta #	Strong Motion Sta #	Location	Seismic Hazard Zone	Strong Motion Events	Weak Motion Events per Station	Lat	Lon
W03	916	ANZ bank, Cuba St.	2	77	5	-41.2957	174.7753
W07	911	Old Central Library, Harris St.	3-4	73,77	9	-41.2899	174.7772
W09	913	MED Substation, 215 The Terrace (Church St.)	1	73,77	8	-41.2893	174.7727
W10	904	Dalmuir House, The Terrace	1	73,77	8	-41.2849	174.7742
W11	905	Central Post Office, Waterloo Quay	3-4	73,77	9	-41.2822	174.7791
W12	906	Reserve Bank, The Terrace	2	73,77	11	-41.2806	174.7744
W13	902	Vogel Building, Aitken St.	2	73,77	11	-41.2789	174.7788
W19	914	Grey and Elliot building, 167 Vivian St.	2	77	6	-41.2962	174.7730
W20	910	Charles Fergusson Building, Bowen St.	2	77	11	-41.2793	174.7748
W21	918	DSIR Kelburn, Seismic Observatory	1	73	11	-41.2859	174.7680
COT		Victoria University, Cotton Building	1		30	-41.2916	174.7686

Lower Hutt Recording Sites

L05	935	IGNS, Knights Rd, LH (NZGS)	5	90a,90b	10	-41.2123	174.9042
L09	601	IBM, The Esplanade, Petone (GMT)	5	73,77	2	-41.2277	174.8710
L12	604	Elizabeth St. Pumping Station (ELS)	3-4	73,77	13	-41.2322	174.9087
L13	642	IGNS, Gracefield (PEL)	2	73,77	8	-41.2360	174.9175
L14	606	IGNS, Nuclear Sci. (INS)	1	73,77	22	-41.2350	174.9205
L19	605	Naenae reservoir (NAE)	1	77	10	-41.2095	174.9402

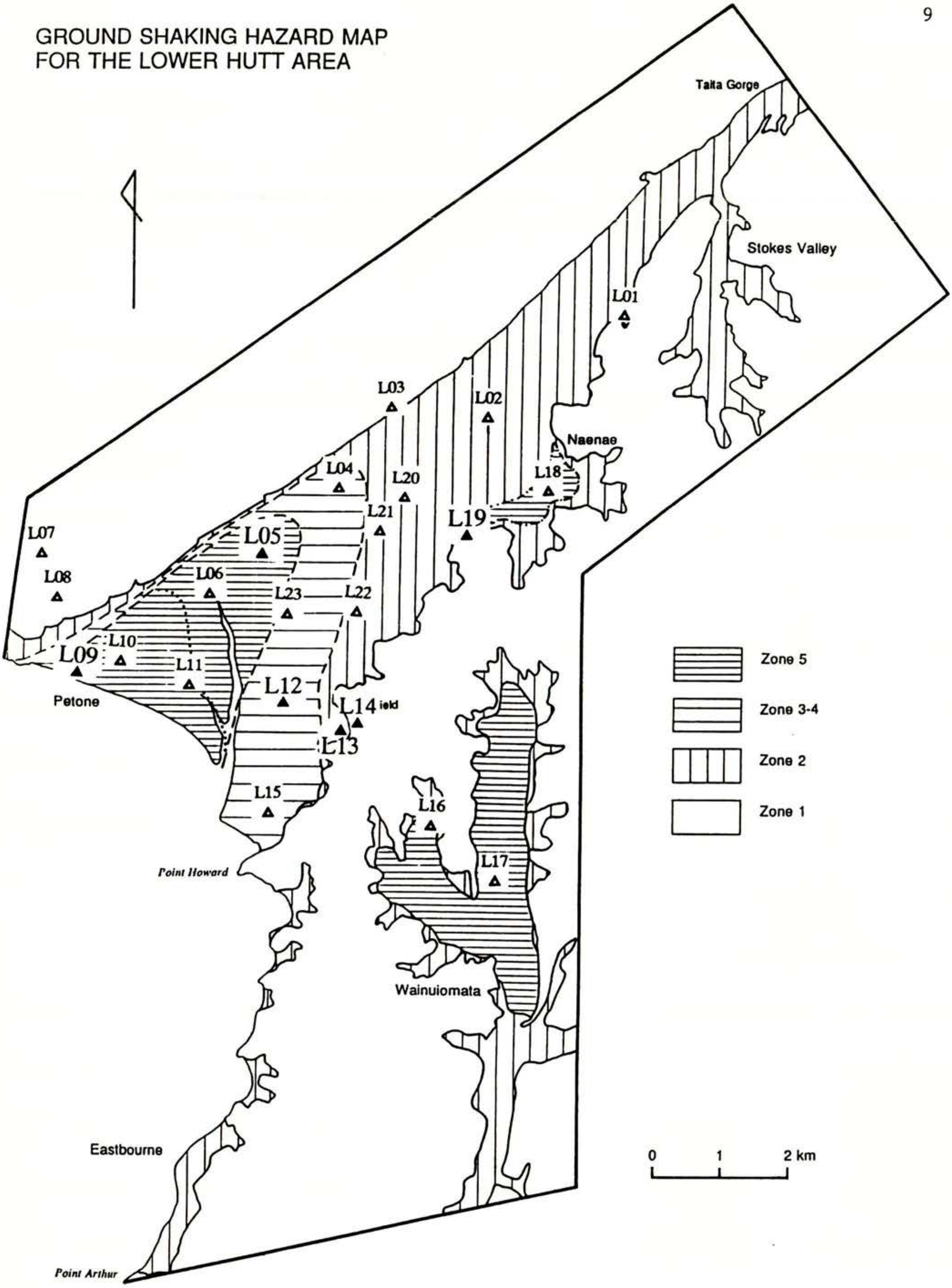


Figure 2. Locations of strong- and weak-motion recording sites in Lower Hutt plotted on the ground shaking hazard map of Van Dissen et al (1992a). Weak-motion recorders that are not co-located with strong-motion recorders are marked with open triangles. Strong-motion sites where data has been collected since 1990 are not shown.

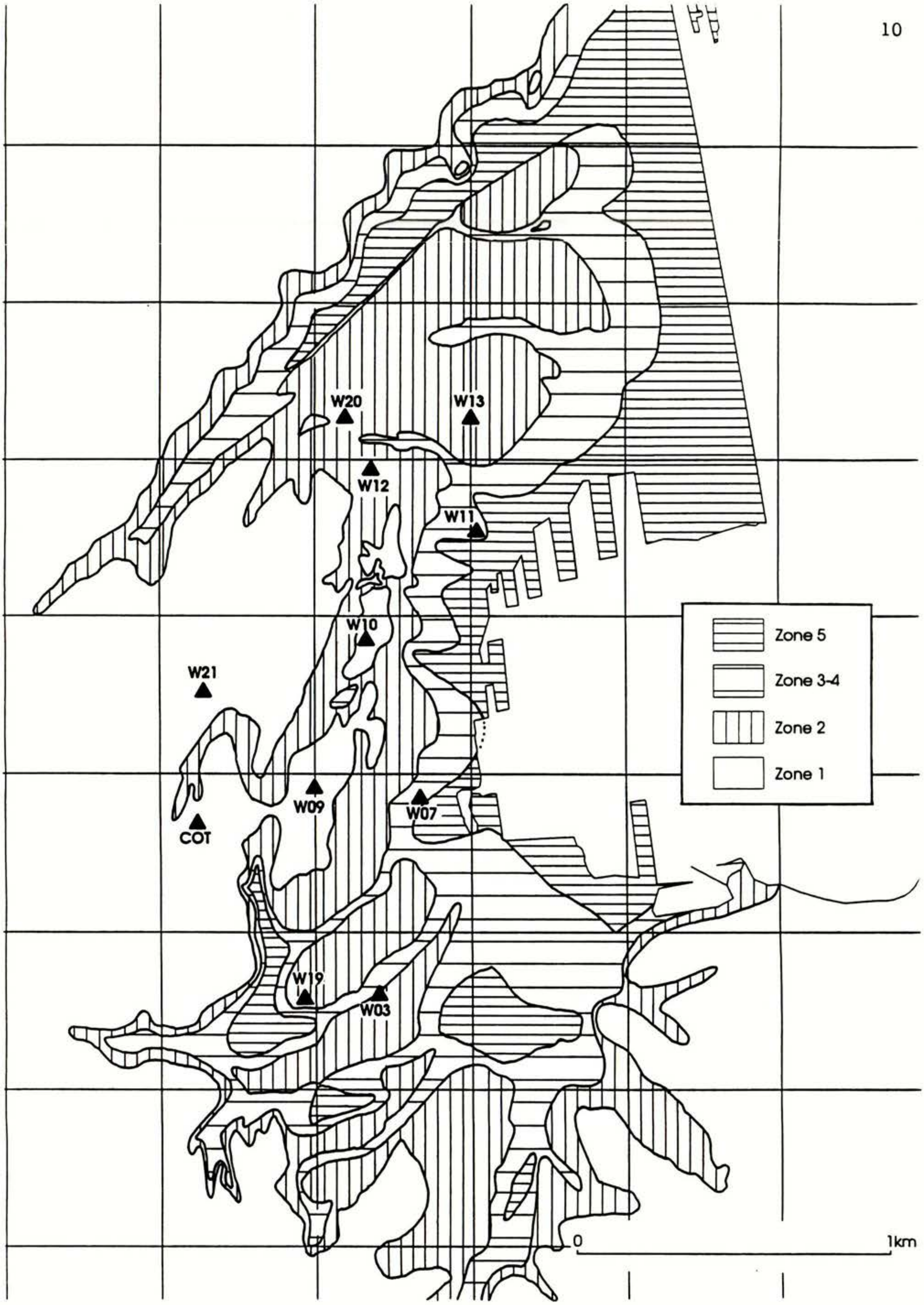


Figure 3. Location of joint strong- and weak-motion recording sites in Wellington plotted on the ground shaking hazard map of Van Dissen et al (1992b). Also plotted is the weak-motion reference site COT.

located.

The seismometers were installed with the horizontal components oriented north and east while the accelerometer axes were generally oriented parallel to the axes of the building. Since there were considerably more weak-motion data than strong-motion data, it was decided to rotate the strong-motion data into a north-south, east-west coordinate system. This means that the direction of greatest motion at individual sites has not been considered. It is known for example, that in the Hutt Valley some sites have very different along valley and across valley responses (Sritharan and McVerry, 1992). However the comparison of strong and weak motions should not be greatly dependent on the direction chosen for the comparison, so long as they are the same.

The responses of the seismometer and accelerometer were compared by recording a signal simultaneously on the two instruments. The source was a 25 tonne weight dropped from a height of 24 meters. The weight drops were part of the soil densification project for the new National Museum site. The instrument response was removed from the seismometer data and the resulting ground displacement was converted to acceleration. This acceleration waveform was then compared to the accelerogram recorded by the IGNS instrument. Excellent agreement was found between the waveforms. The Fourier spectra of the two recordings was also compared. The ratio of the Fourier spectra was near unity over the range of frequencies for which there was a sufficient signal to noise ratio.

The site conditions range from bedrock to thick flexible sediments, with a greater range of site conditions in the Lower Hutt sites than the Wellington sites (Appendix A). A description of the Lower Hutt subsurface geology can be found in Dellow et al (1992), while the Wellington subsurface geology is discussed in Perrin and Campbell (1992). The sites will be discussed in terms of their classification within the seismic hazard microzoning of Van Dissen et al (1992a,b). The classification of each site is listed in Table 3. Both Wellington and Lower Hutt were divided into 4 zones based on the potential ground shaking hazard. The zones were determined based on the geology and measured response to strong and weak seismic shaking. Zone 1 areas are underlain by bedrock or weathered bedrock, Zone 2 areas are typically underlain by compact alluvial and fan gravel, Zone 3-4 is underlain to a depth of 20 m by interfingered layers of flexible sediment and compact gravel and sand, and Zone 5 is generally underlain by more than 10 m of flexible sediment of low shear-wave velocity. The estimated amplification of the ground motions range from none for the rock sites (Zone 1) to increases in the peak ground acceleration (pga) of factors of 3 to 4 for Zone 5 for a large, shallow, distant earthquake (Van Dissen et al, 1992a,b). Zones 1, 2, and 3-4 are well represented in the strong-motion sites, but prior to the weak-motion study there were no strong-motion sites in Zone 5 in Wellington, and only two in Lower Hutt.

3. Data Analysis and Results

The acceleration traces allow a visual comparison of site response in terms of peak amplitude, approximate duration of shaking, and a very approximate indication of frequency content (Figure 4). To quantify the comparison of weak and strong motions, two different techniques were used. The first was to calculate Fourier spectra of each of the seismograms for each of the sites and then to compare the sites using spectral ratios. The second technique involved the calculation of damped acceleration response spectra from the same seismograms and then site comparisons via response spectral ratios. The two techniques provide different parameterisations of the data and thus it is possible for sites with similar weak- and strong-motion Fourier spectra to have different response spectra. Fourier spectra are used by the seismological community because they are a complete representation of the ground

Strong Motion

Weak Motion

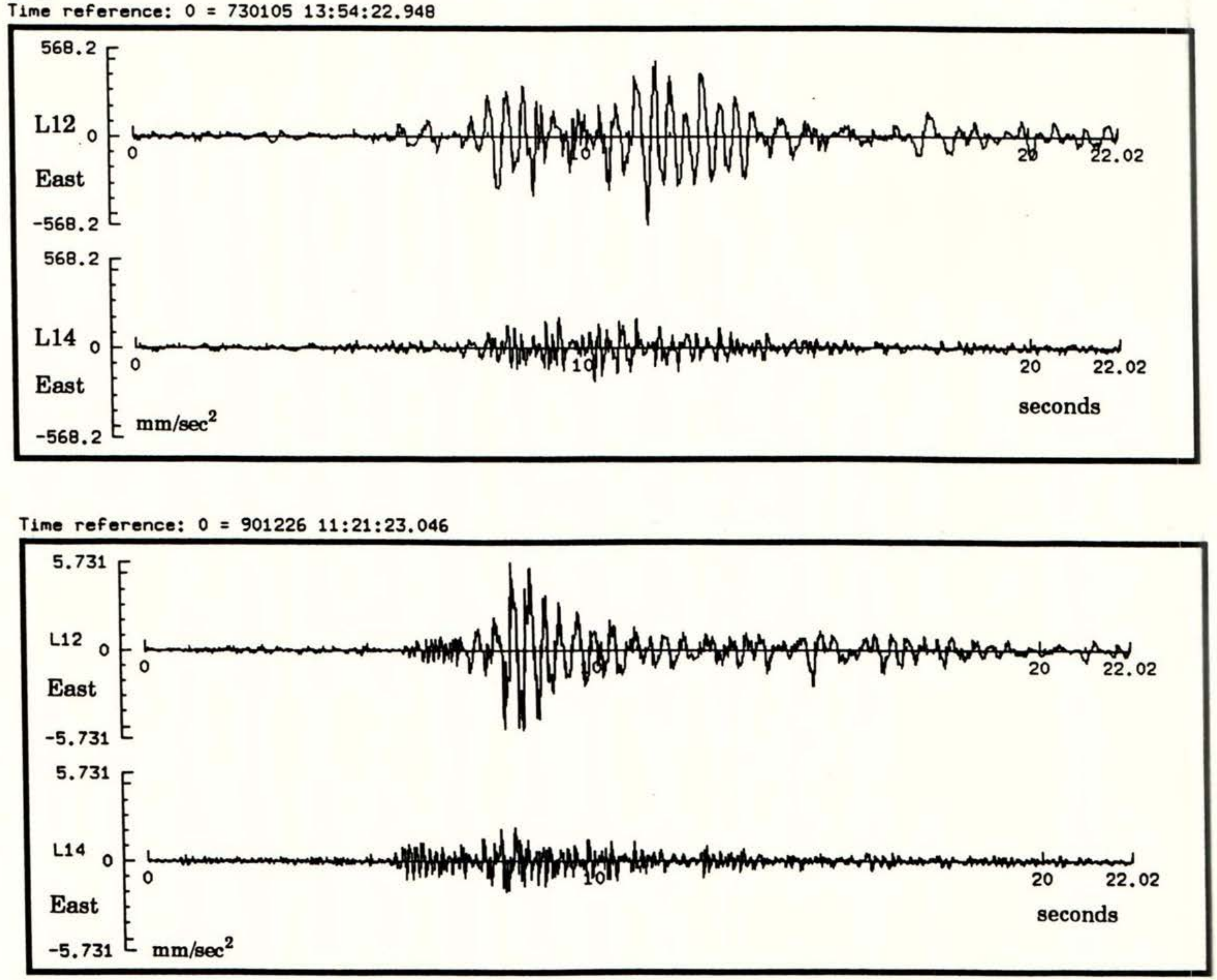


Figure 4. Comparison of strong- and weak-motion acceleration traces from two sites in Lower Hutt, on 200 m deep sediments and gravels (L12) and rock (L14).

motion (when phase is included). Response spectra are preferred by the engineering community because they provide better information about the response of buildings to the ground motion.

The variation of ratios at each site is presented differently for the two types of spectra. For the Fourier spectra, all the weak-motion ratios are plotted, along with the mean of the ratios. The strong-motion ratios are then plotted on top of the cluster of weak-motion ratios. This allows the comparison of the frequency response of individual earthquakes. Typically, peaks at the frequency of the dominate peaks in the strong-motion spectra exist for at least one weak-motion record, though there may not be a peak in the mean weak-motion spectra. For the response spectral ratios, standard deviations were calculated for the weak motions, and only the mean and +/- one standard deviation were plotted. This allows an easier comparison of the range of the weak-motion ratios to the ratios of the strong motions. In cases where there are only one or two weak-motion events the ratios of the events themselves are plotted instead of the standard deviation bounds.

3.1 Fourier Spectral Ratios

Fourier spectral ratios (FSR) for each of the sites were calculated for the weak-motion data in conjunction with a microzoning project for the WRC (Taber, 1991; Taber and Smith, 1992; Taber and Richardson, 1992). The same technique was then applied to the strong-motion data.

The amplification effect is primarily in the horizontal plane; hence a ten second window, starting 0.5 second before the S wave arrival, was selected from the horizontal components of each seismogram. A 4% Hanning taper was applied to the window before the Fourier amplitude spectra were calculated. The resulting spectra were then smoothed with a 1 Hz triangular moving window. This approach may omit some long period motion late in the record, and thus the long period ratios may be underestimated at some sites.

Spectral ratios were then calculated by dividing each spectrum by the spectrum for the reference site for that event. The reference site in Lower Hutt was site L14 (INS). In Wellington, site W10 (Dalmuir House) was used for the strong- and weak-motion response spectral ratios (RSR) and the strong-motion FSR while site COT (Victoria University) was used for the weak-motion FSR. A different reference site was used for the weak-motion FSR because many more earthquakes were recorded there. The response of the two sites is very similar up to 4-5 Hz (Figure 5). Above this frequency, site COT has a lower amplitude response. Thus above 5 Hz, the weak-motion ratios can be expected to be higher than the strong-motion ratios.

In Wellington, the north-south and east-west spectra were first combined into an average horizontal amplitude spectrum (Taber and Richardson, 1992) whereas in Lower Hutt the north-south and east-west components were analysed separately.

The weak-motion seismograms were not corrected for instrument response before the calculation of the ratios whereas the strong-motion records were corrected for instrument response, high pass filtered to eliminate those frequency components with low signal-to-noise ratios, and then integrated to obtain ground velocity (Cousins et al, 1988). The calculation of ratios removes effects due to instrument response so long as the characteristics of the instrument at the site of interest and at the reference site are the same. Effects due to the earthquake source or variations in the path between the source and the receiver are also reduced through the use of spectral ratios.

It is necessary to determine the frequency limits outside which the spectral ratios are not meaningful. At both high and low frequencies the amplitude spectrum of the signal approaches the spectral level of the background noise. The ratio values

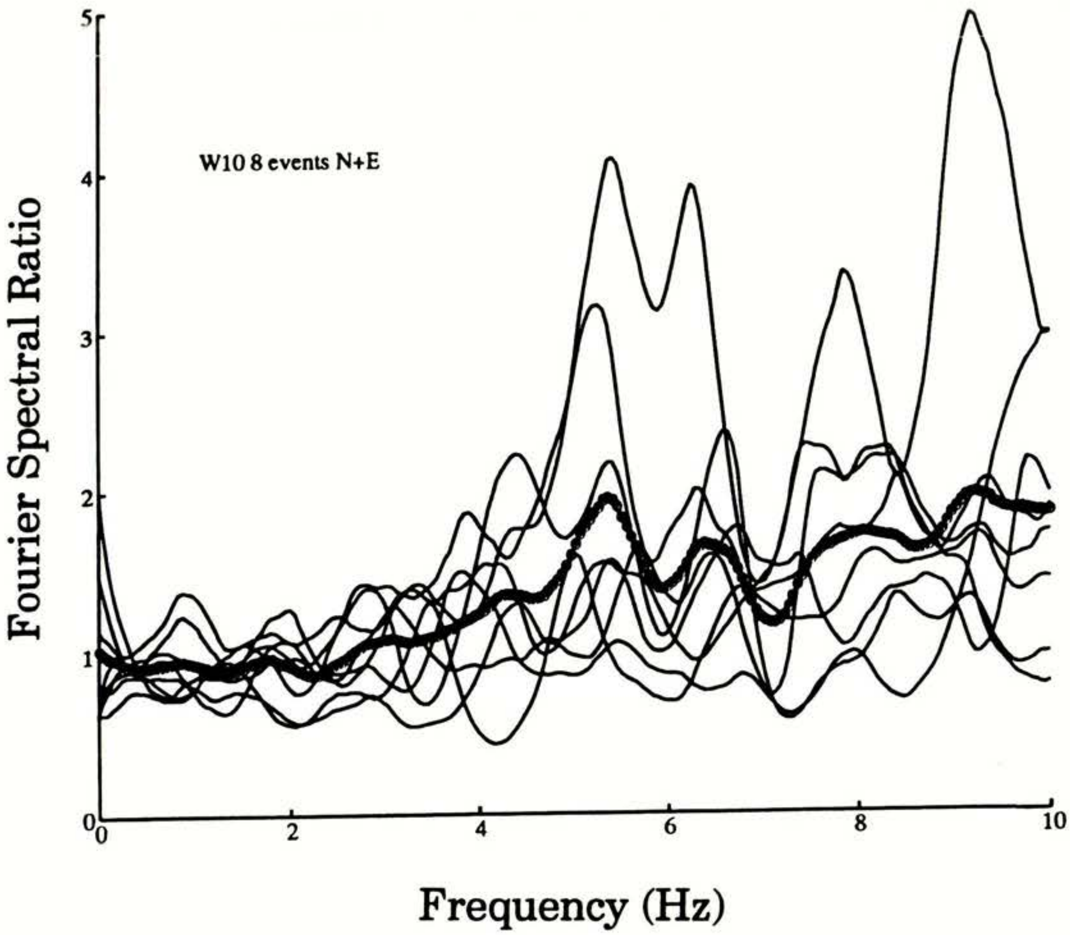


Figure 5. Weak-motion Fourier spectral ratios for the Wellington rock site W10 with respect to the reference site COT, for the combined north-south and east-west components. The dark line is the mean of the spectral ratios. Site W10 was used as the reference site for the strong-motion ratios, and for the weak-motion response spectral ratios.

below about 0.5 Hz are not meaningful here because of the limited response of the seismometers at low frequencies and the smoothing that has been applied to the spectra. At the high frequency end, the signal-to-noise ratio for several of the sites was found to drop below 4 near 12 Hz so 10 Hz was chosen as the maximum frequency on the plots. Note that high ratios at high frequencies do not necessarily mean large signal amplitudes; they can instead be due simply to a low level in the reference spectrum. In general, ratio peaks at frequencies above 6 Hz are not important, unless they are much higher than the rest of the spectrum.

The spectral ratio can not be directly correlated with peak acceleration or velocity since the spectral ratio is strongly influenced by the duration of the shaking. In general, the spectral ratio is higher than the ratio of peak velocity or acceleration, particularly for resonant sites. For example, for one event at one site, the peak spectral ratio was 11 whereas the ratio of peak ground velocity was only 3.8. Many cycles of moderate motion (as shown in the seismic traces in Figure 1) may excite resonances in buildings with the same natural period. Thus a high spectral ratio may be more important than a small increase in peak acceleration.

The response spectrum is more affected by the amplitude than the duration. A site with a long duration but low amplitude at a particular frequency can have a high Fourier spectral ratio but a much lower response spectral ratio. Thus strongly resonant sites are likely to have higher FSR than RSR.

3.1.1 Lower Hutt Fourier Spectral Ratios

Strong- and weak-motion ratios with respect to the reference site L14 (INS) have been compared at five sites in Lower Hutt. Figure 6 shows the north and east components of the rock site L19 (Naenae Reservoir). Only one strong-motion event (1977) was recorded at the site. The strong-motion ratio is less than the weak-

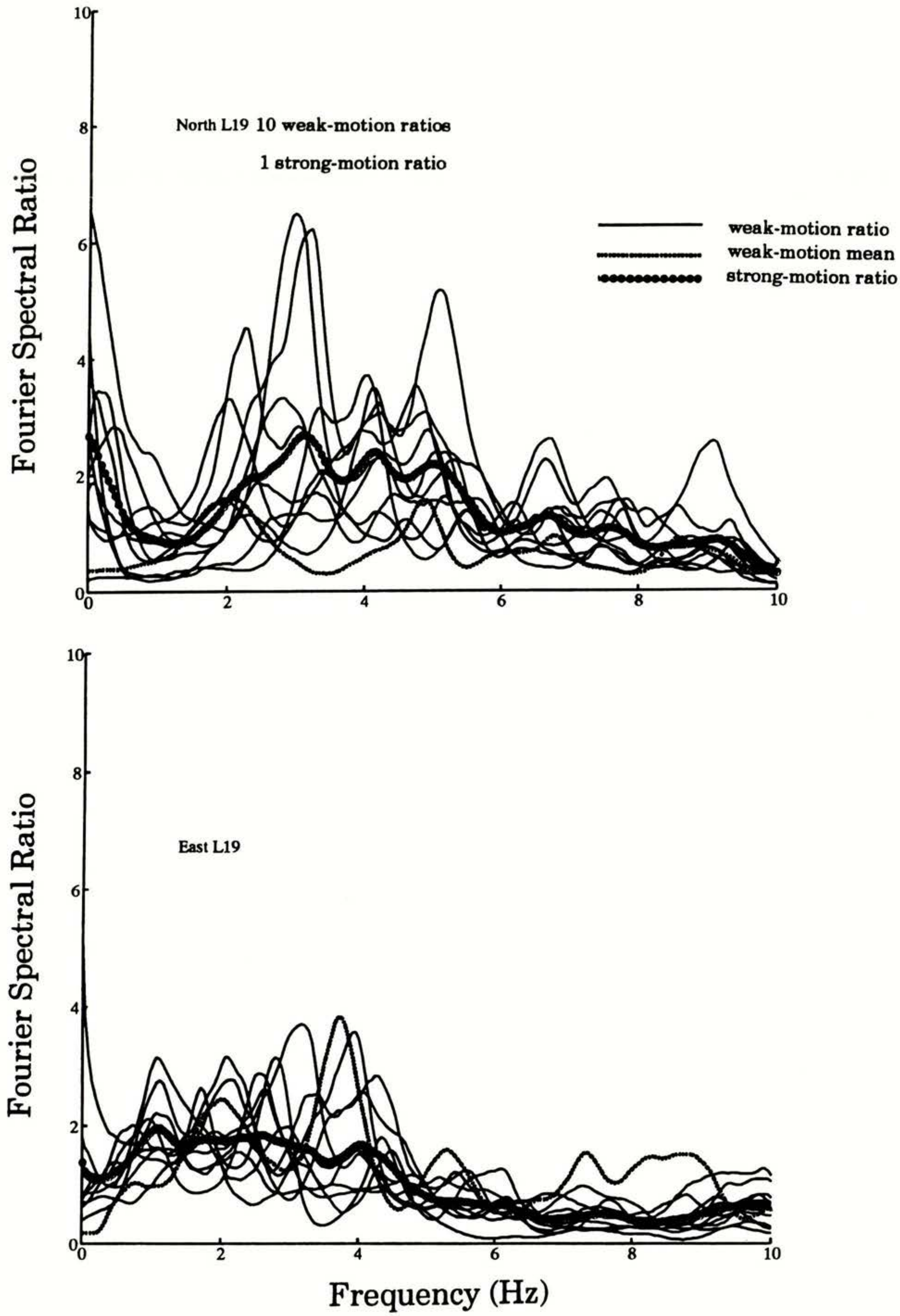


Figure 6. Top: Weak- and strong-motion Fourier spectral ratios for the north-south component at Lower Hutt site rock site L19 with respect to reference site L14. Solid lines are the weak-motion ratios for ten different earthquakes. The dark line is the mean of the weak-motion ratios. The dashed line is the strong-motion ratio.
Bottom: East-west component for site L19.

motion ratio at most frequencies on the north component, whereas the strong-motion ratio straddles the mean in the east direction. In general it appears that if the strong-motion ratio is well below the weak-motion ratio in one direction, it is equal to or above the mean in the other direction.

Site L13 (IGNS, Gracefield)(Figure 7) is in hazard Zone 2, less than 200 m from the reference site. Once again the strong-motion ratios are generally below the weak-motion mean on the north component whereas the ratios are more similar on the east component. The frequencies are similar on both components. Site L12 (Elizabeth St.)(Figure 8) is on softer sediment in Zone 3-4, and while the amplification is higher than at the firmer sites, the comparison of strong and weak motions is about the same as the Zone 1 and Zone 2 sites. Site L05 (Figure 9)(IGNS, Knights, Road) is in Zone 5 but its weak-motion characteristics and the comparison of strong and weak motions are similar to site L12. Site L05 is a "long-period" site, with strong amplifications at periods of 1-2 seconds or longer. For periods less than one second its amplitude may be no more than Zone 3-4 sites like L12. The longer period amplification at site L05 is more apparent in the larger magnitude events. Note that the "strong-motion" records used for site L05 are from earthquakes in 1990 that only generated a peak ground acceleration of 0.013 g at site L05, whereas the largest weak motion at L05 reached 0.002 g.

Only at the site with the highest weak-motion amplification (L09, IBM building, Figure 10), is there a significant difference between the strong and weak motions. The strong-motion records show a lower frequency response than the weak-motion ratios, and little energy at the peak of the weak-motion ratios. The strong-motion records showed unusual characteristics of no amplification above 2 Hz with a very sharp cutoff. Such strong attenuation of high frequency response is one manifestation of non-linearity. Unfortunately, only 2 earthquakes were recorded

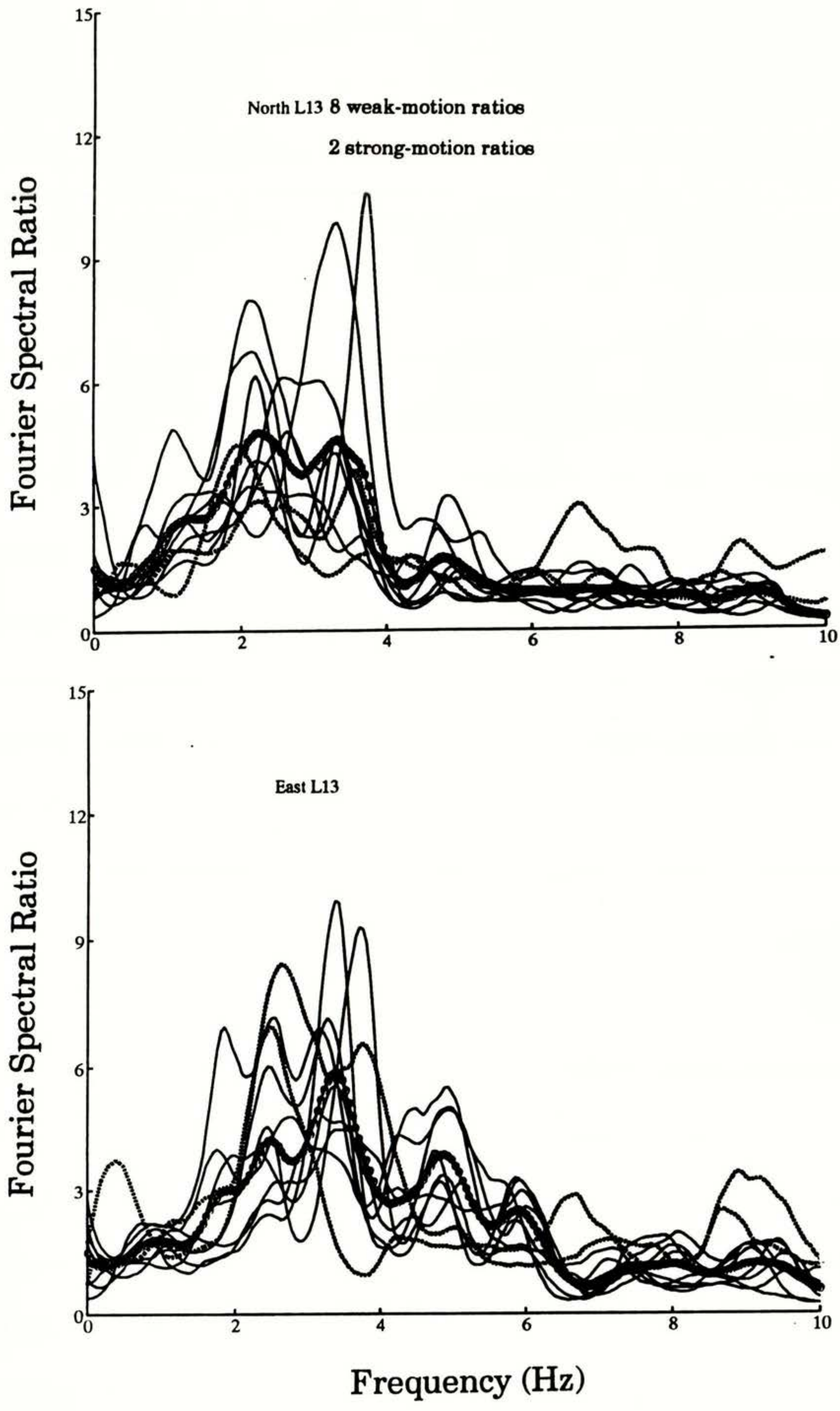


Figure 7. Top: Weak- and strong-motion Fourier spectral ratios for the north-south component at Lower Hutt site L13 on 20 m of gravels near the edge of the valley.
Bottom: East-west component for site L13. Symbols as in previous figure.

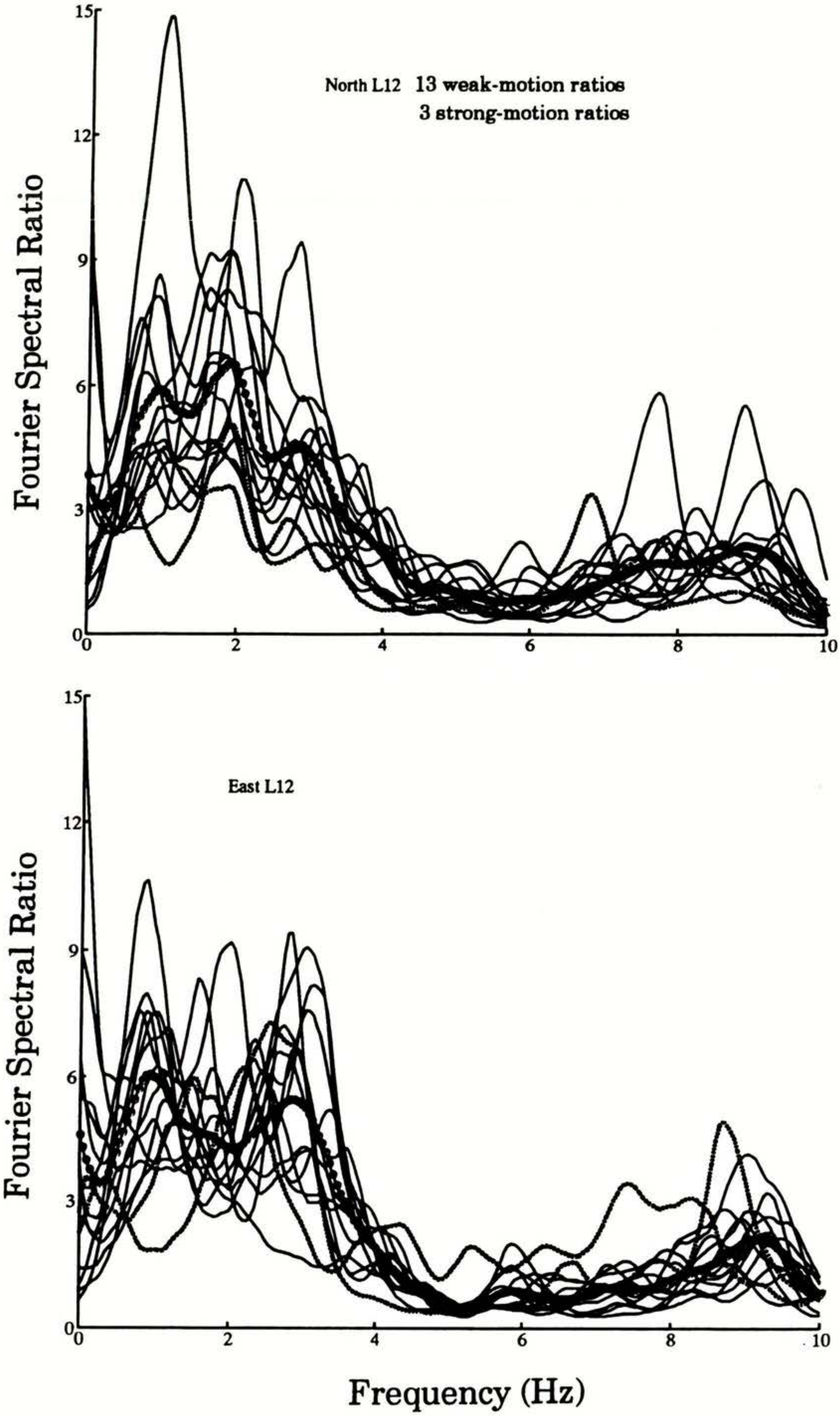


Figure 8. Top: Weak- and strong-motion Fourier spectral ratios for the north-south component at Lower Hutt site L12, with 20 m of soft material in a total depth to bedrock of 200 m. Bottom: East-west component for site L12.

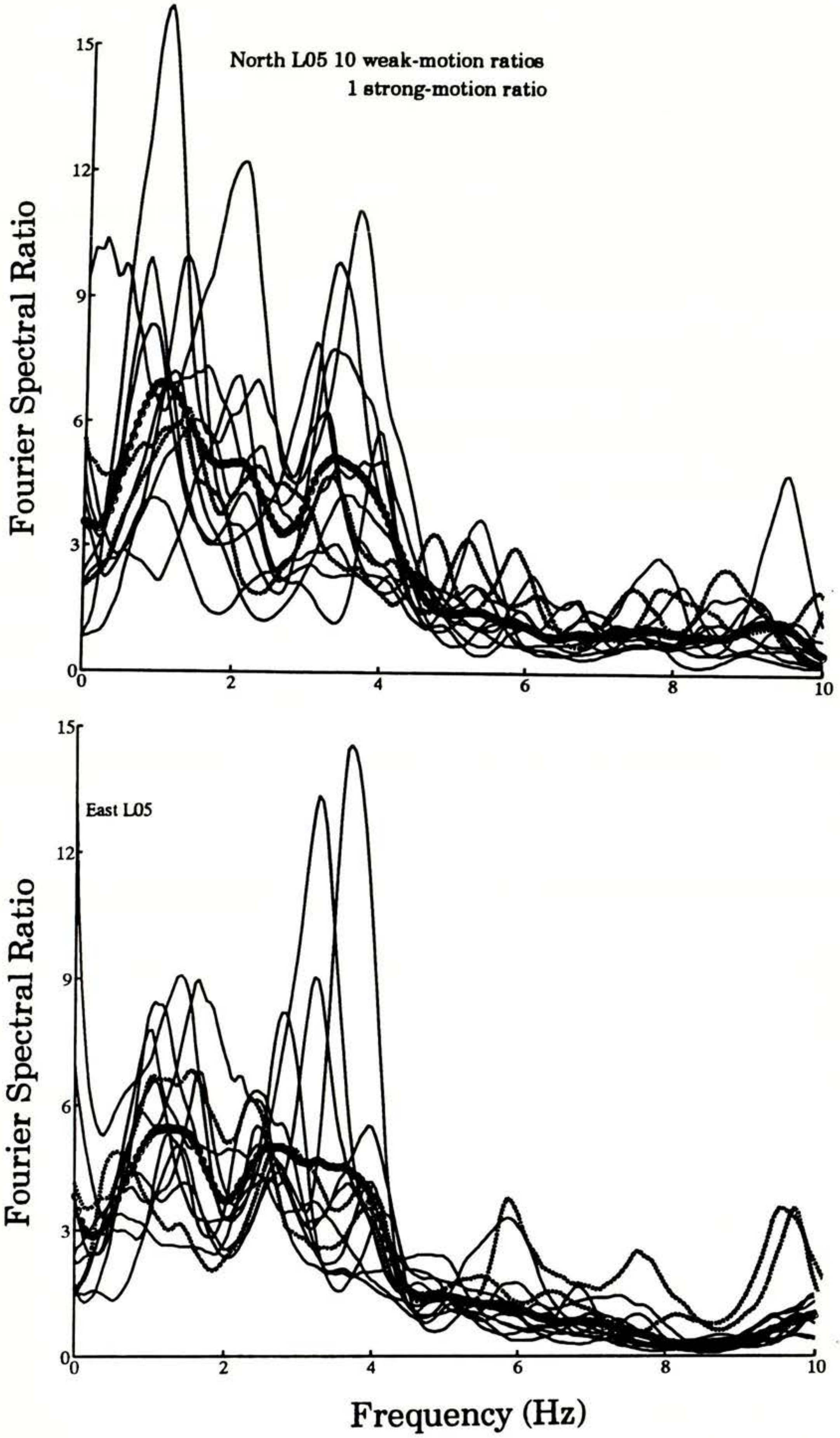


Figure 9. Top: Weak- and strong-motion Fourier spectral ratios for the north-south component at Lower Hutt site L05 in Zone 5 with 275 m of material to bedrock but with less than 10 m of soft surface soils.
Bottom: East-west component for site L05.

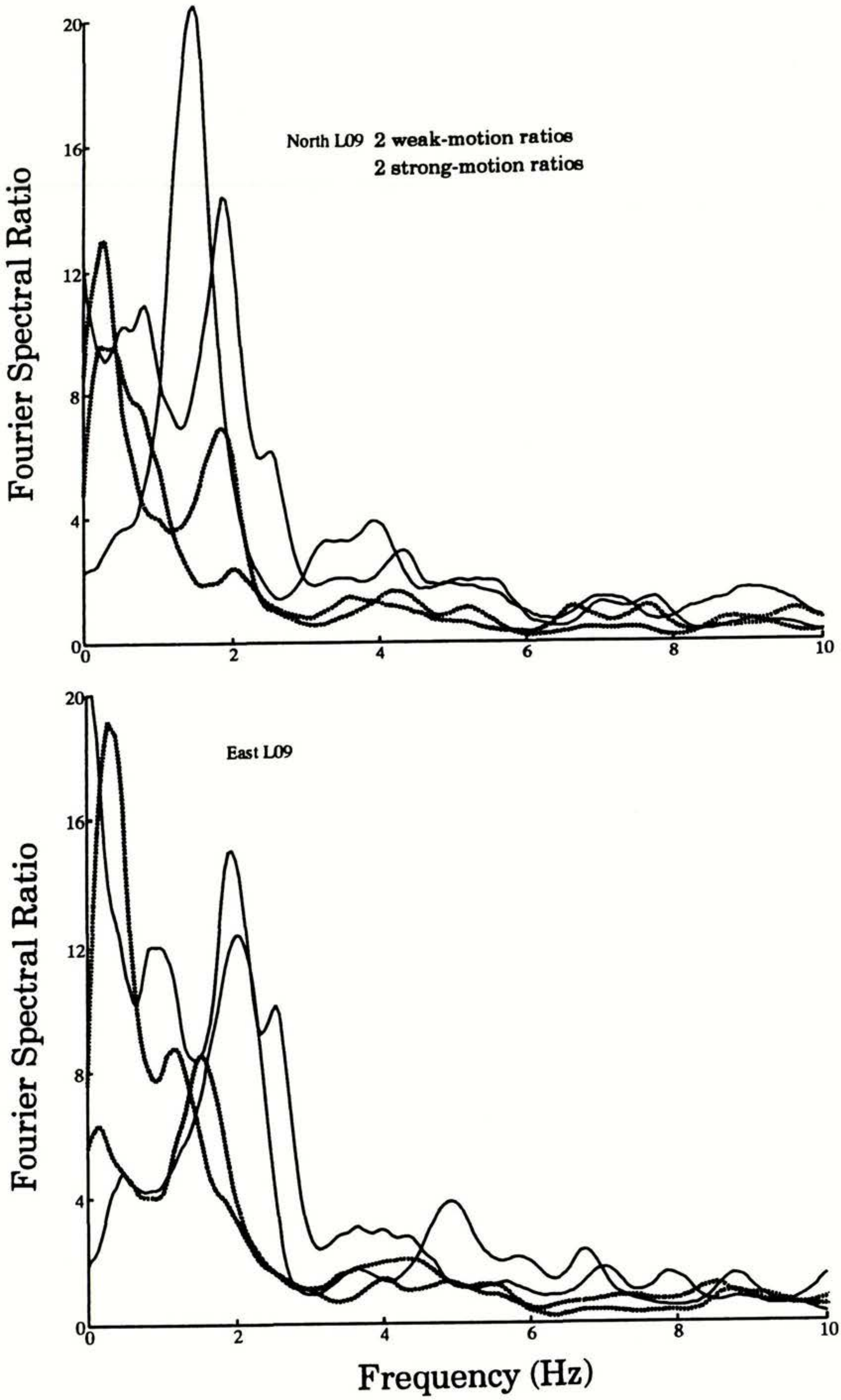


Figure 10. Top: Weak- and strong-motion Fourier spectral ratios for the north-south component at Lower Hutt site L09, with 30 m of soft surface soils in a total depth to basement of 300 m. There are only two weak-motion events so no mean was calculated.
Bottom: East-west component for site L09.

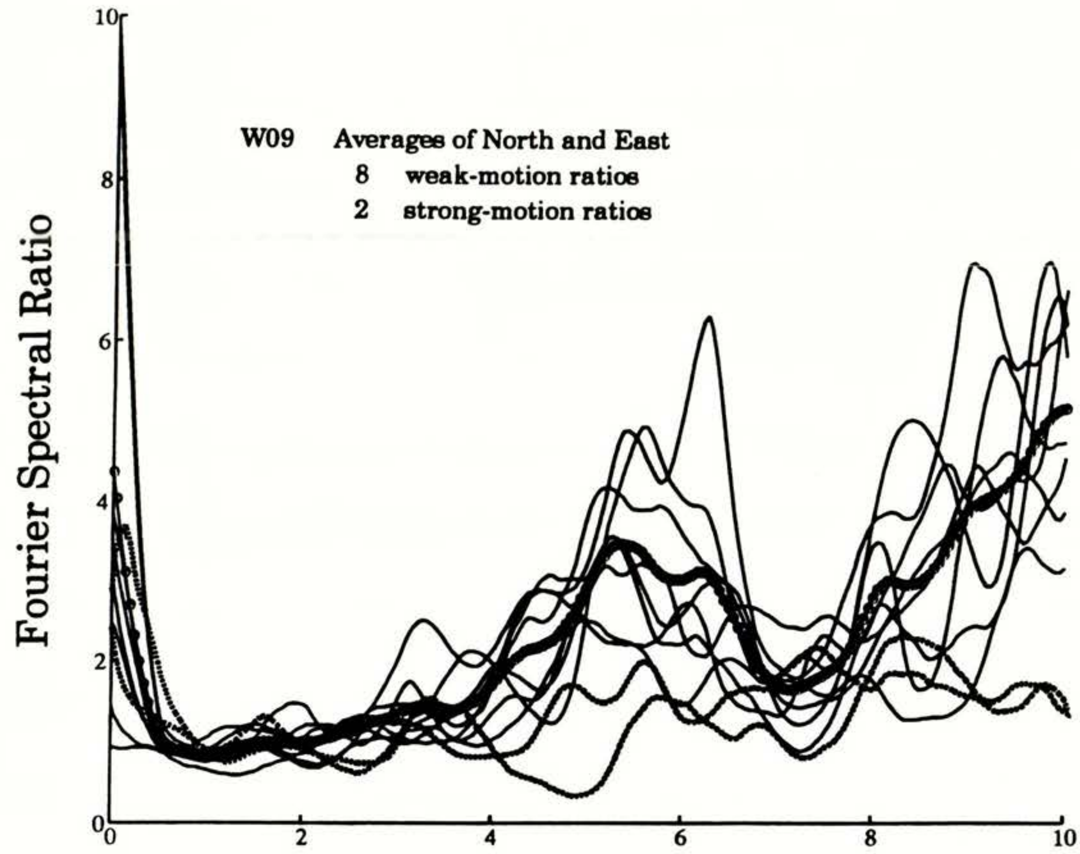
during the weak-motion survey, so the average weak-motion response is not well known. Some of the difference in the site characteristics could also be due to changes in the site itself. The accelerometer was located in the old Gear Meat Works while the seismometer was placed in the new IBM building. An attempt was made to find the point in the IBM building that was closest to the old site, but the new building with its different foundation could affect the measured response.

3.1.2 Wellington Fourier Spectral Ratios

The north and east components were averaged together for the Wellington sites to get a better idea of the average site response. Figure 11 shows the spectral ratios of the rock sites (W09 and W21) with respect to the reference site COT. The weak- and strong-motion ratios are fairly similar, with individual peaks varying between events.

There are five sites in Zone 2 in Wellington (W03, W12, W13, W19, and W20)(Figures 12-14). The strong- and weak-motion averages are similar at most of the sites, except for W03, where the one strong-motion ratio is lower than the weak-motion average at almost all frequencies. This may be partly due to the use of different reference sites for the strong and weak motion, but the same pattern is seen in the RSR (see below). At many of the sites, the weak-motion ratio is higher than the strong-motion ratio at high frequencies due to the difference in the frequency response of the reference sites mentioned earlier.

The two Zone 3-4 sites (W07 and W11) are shown in Figure 15. There are individual strong-motion ratio peaks that do not match weak-motion ratio peaks for any of the events. At sites where the amplification occurs over a broad frequency range, it appears that there can be peaks in the ratio at almost any frequency in the amplified frequency band. The comparison of strong and weak motions of the Zone 3-4



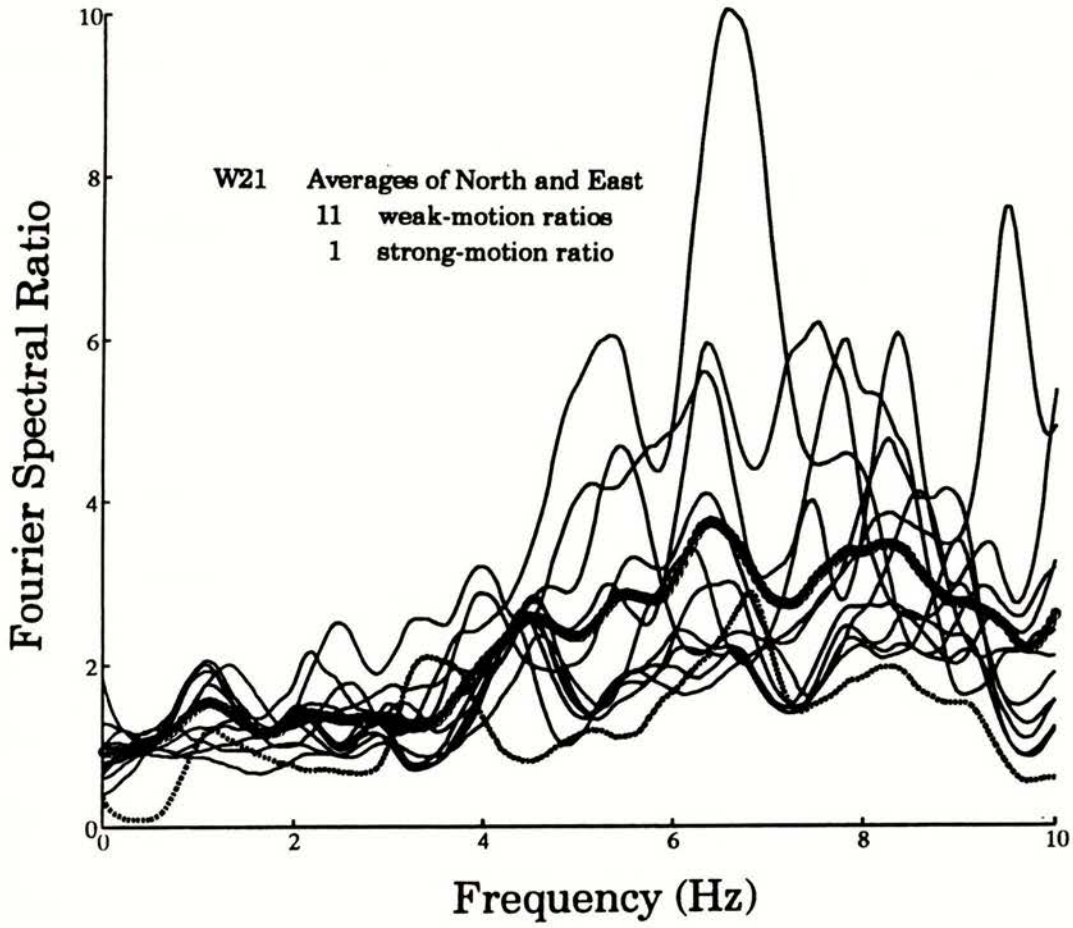


Figure 11. Top: Weak- and strong-motion Fourier spectral ratios for the combined north-south and east-west components at Wellington rock site W09.
Bottom: Weak- and strong-motion Fourier spectral ratios for the combined north-south and east-west components at Wellington rock site W21.

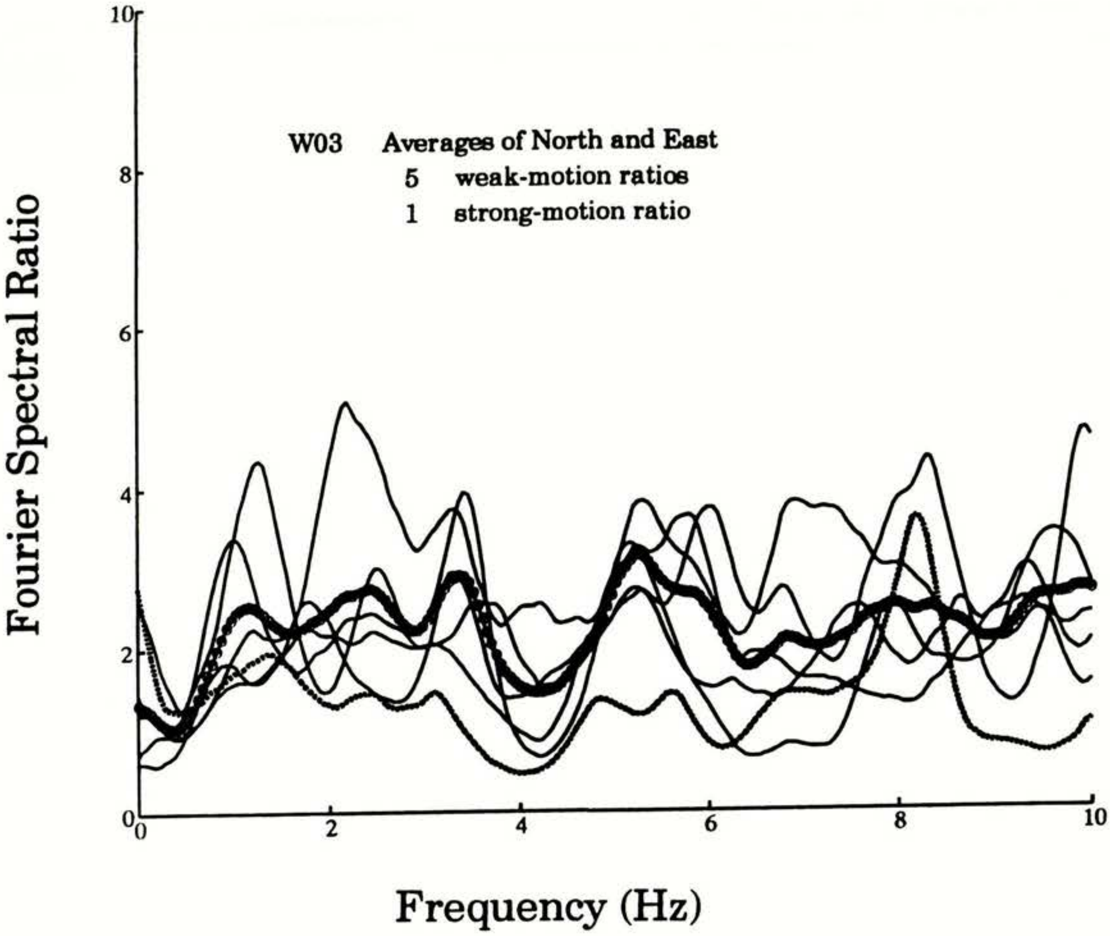


Figure 12. Weak- and strong-motion Fourier spectral ratios for the combined north-south and east-west components at Wellington gravel site W03 (Zone 2).

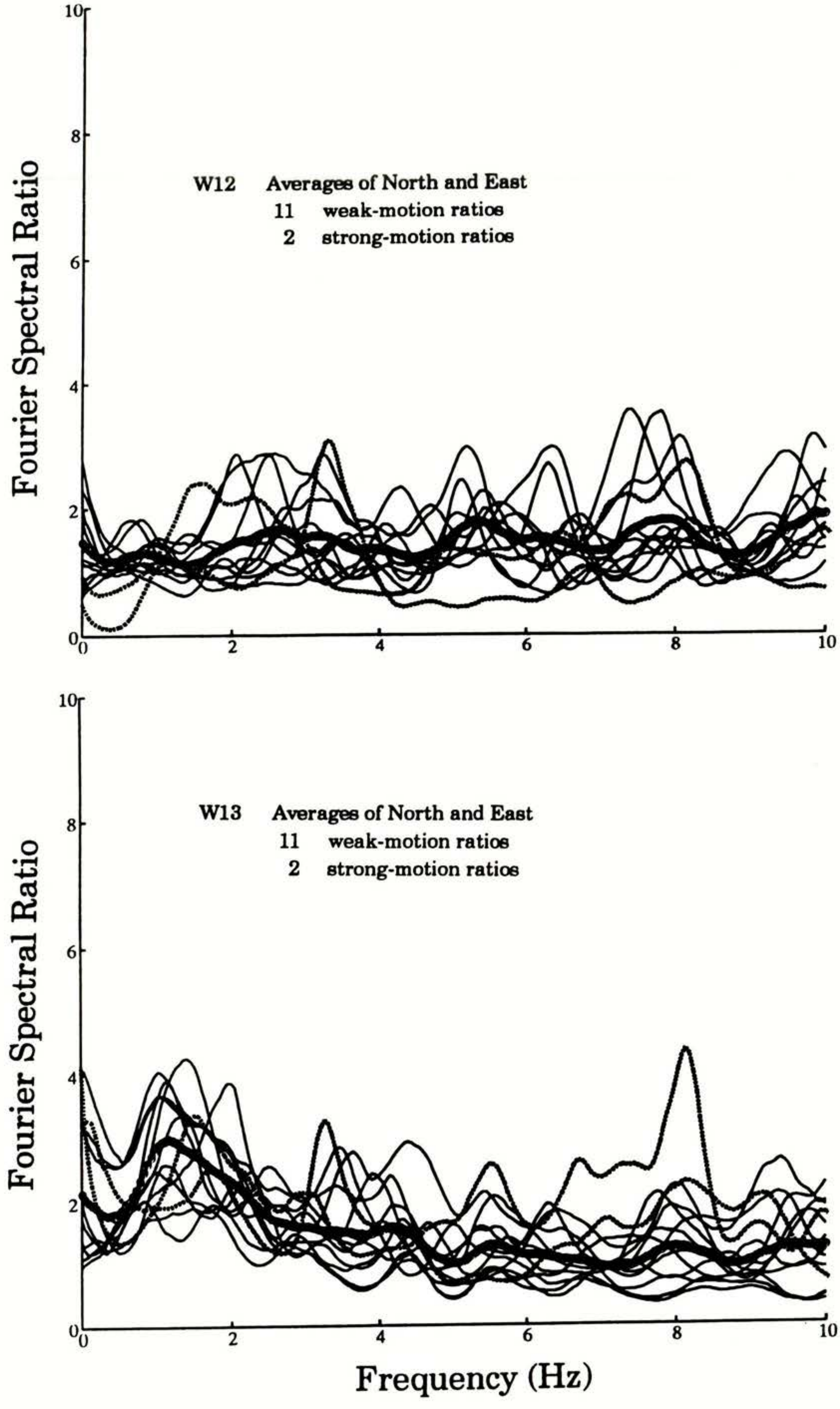
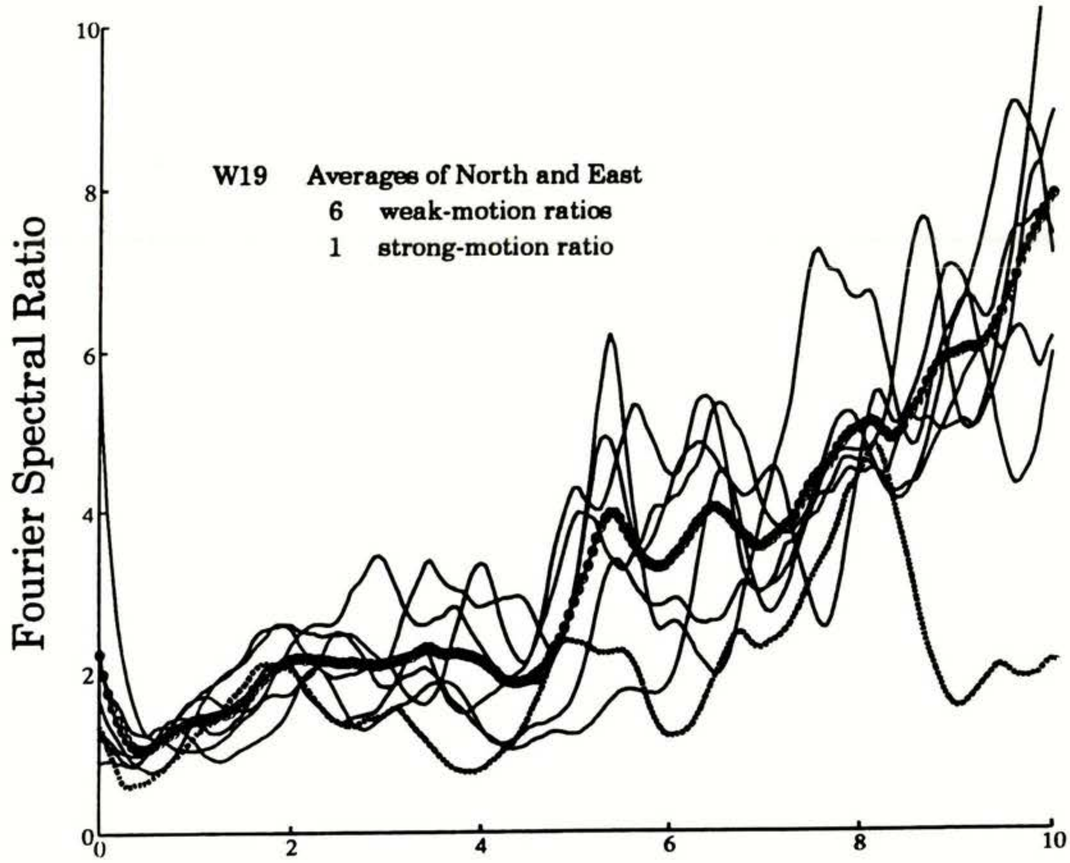


Figure 13. Top: Weak- and strong-motion Fourier spectral ratios for the combined north-south and east-west components at Wellington gravel site W12 (Zone 2).
Bottom: Weak- and strong-motion Fourier spectral ratios for the combined north-south and east-west components at Wellington deep weathered gravel site W13 (Zone 2).



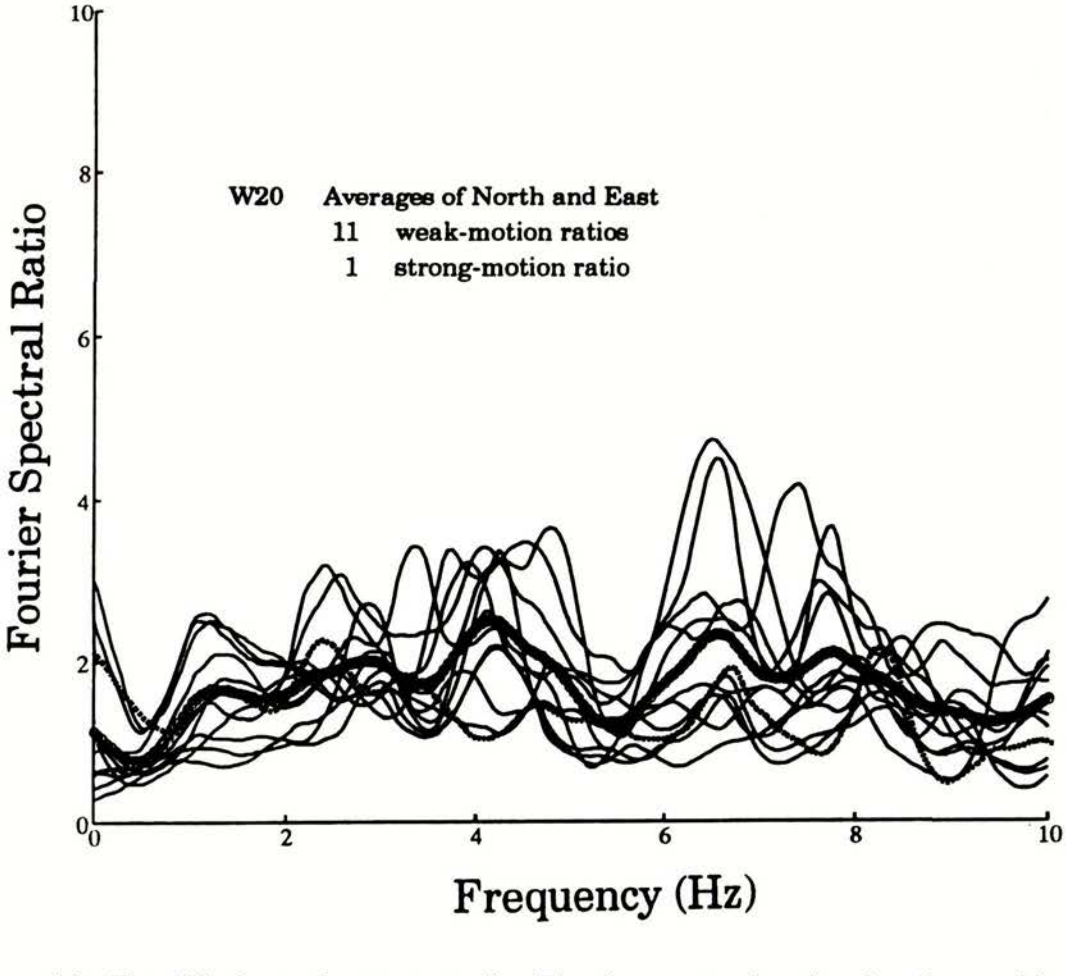
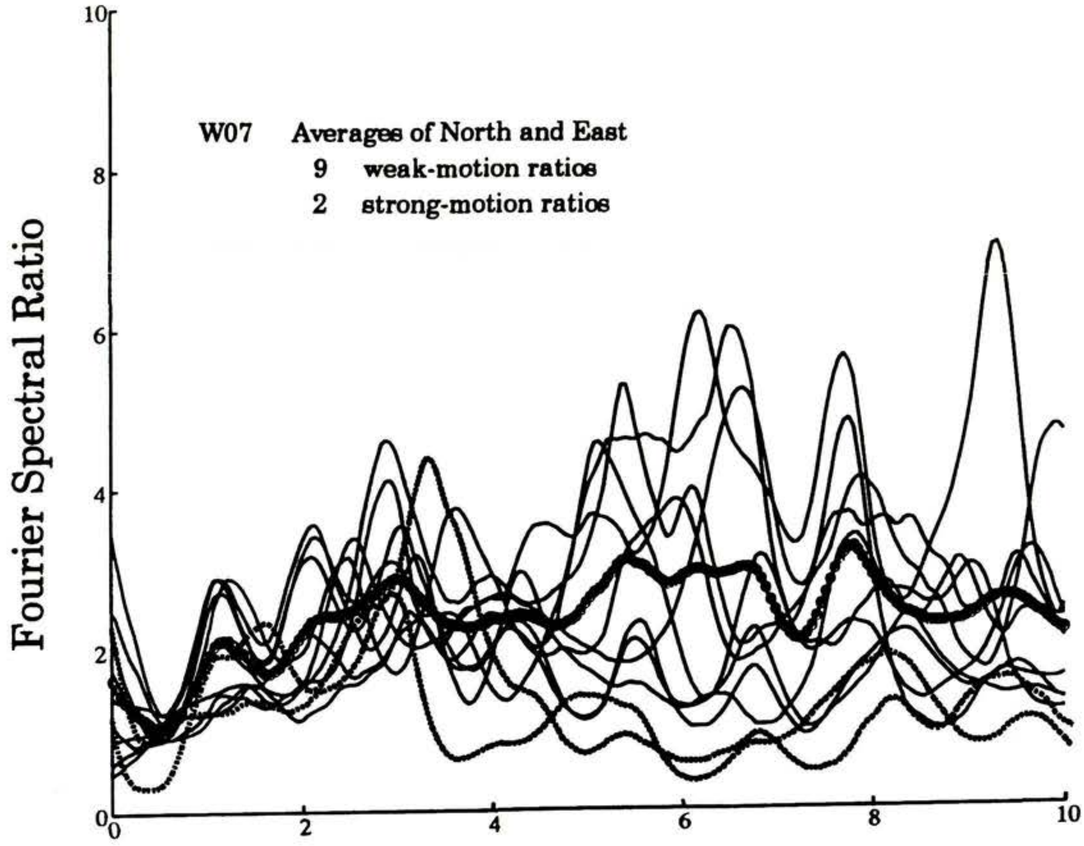


Figure 14. Top: Weak- and strong-motion Fourier spectral ratios for the combined north-south and east-west components at Wellington weathered gravel site W19 (Zone 2).
Bottom: Weak- and strong-motion Fourier spectral ratios for the combined north-south and east-west components at Wellington weathered gravel site W20 (Zone 2).



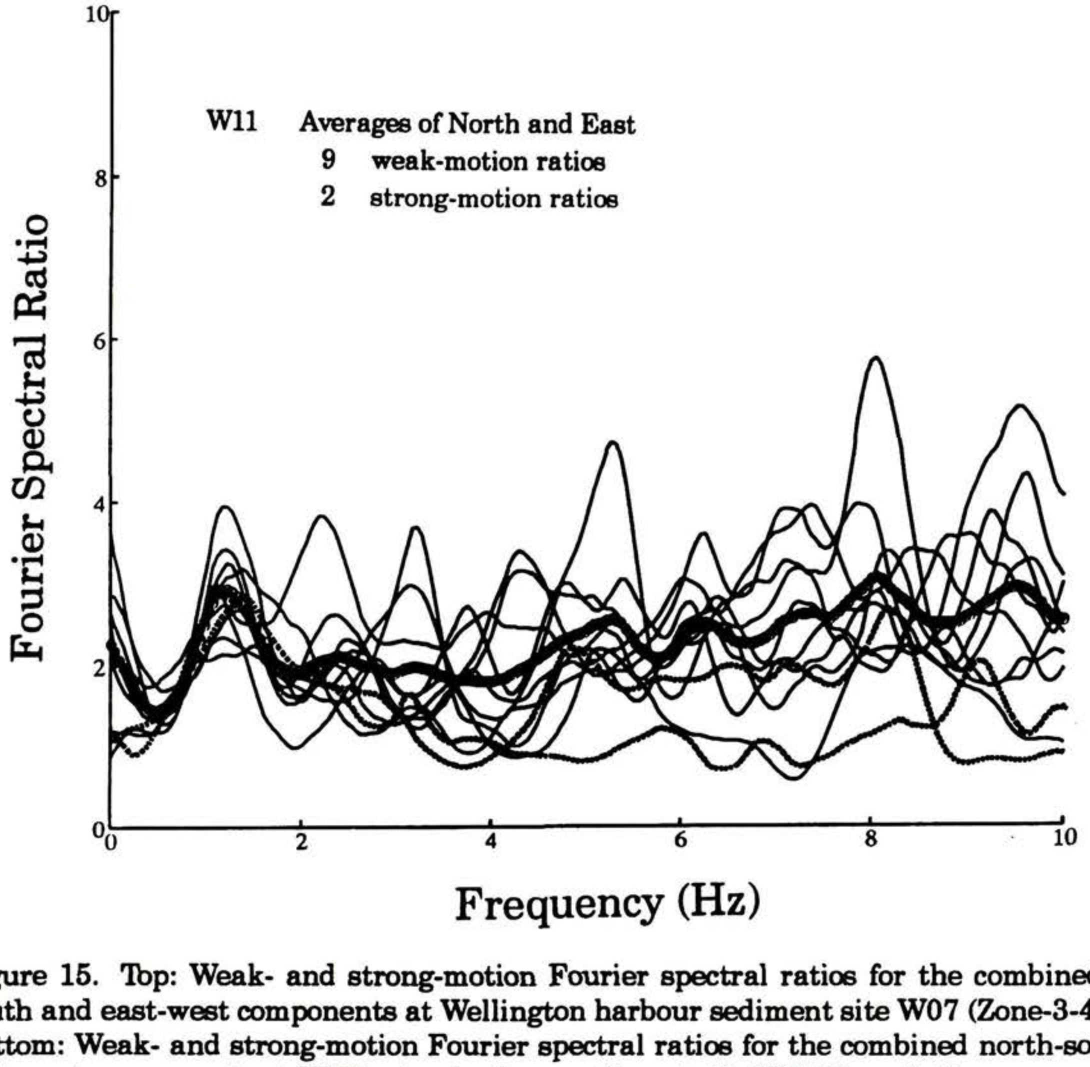


Figure 15. Top: Weak- and strong-motion Fourier spectral ratios for the combined north-south and east-west components at Wellington harbour sediment site W07 (Zone-3-4).
Bottom: Weak- and strong-motion Fourier spectral ratios for the combined north-south and east-west components at Wellington harbour sediment site W11 (Zone 3-4).

sites is similar to the other zones and thus there does not appear to be a systematic difference between the weak and strong motion when going from rock to moderately flexible soil sites in Wellington city.

3.2 Response Spectral Ratios

A similar approach to the data processing was taken in the preparation of the data for the calculation of response spectral ratios. For the weak-motion data the instrument response was first removed from the signal and then the resulting ground displacement was converted to acceleration, after appropriate filtering and tapering of the signal. Two different signal lengths were examined in the calculation of the 5% damped response spectra. The response spectra were first calculated for the same 10 second window that was used in calculation of FSR. Then the same calculation was performed on the longest S wave sample that could be extracted from all the sites for a particular event. Thus each response spectral ratio was calculated from two equal length accelerograms, but the length of accelerograms could be different for different events. The length ranged from 15 to 35 seconds. It was found that there were only minor differences between the ratios calculated from the short and long accelerograms. All of the plots in this report use the longest available length of the S wave. A more detailed discussion of the response spectra for the strong-motion events can be found in Sritharan and McVerry (1991, 1992) for Lower Hutt, and Sritharan and McVerry (1990) for Wellington. They note that the 1973 earthquake had a strong long-period response while the 1977 earthquake was richer in high frequencies.

3.2.1 Lower Hutt Response Spectral Ratios

The overall comparison of weak and strong motions is similar for the RSR though the differences at longer period are clearer than in the FSR. The response spectra are more sensitive to peak acceleration while the Fourier spectra are more sensitive to duration. The north and east spectral ratios are presented together on the Lower Hutt plots because the north strong-motion ratio tends to lie below the average weak-motion ratio while the east strong-motion ratio tends to lie above the weak-motion ratio. The weak-motion standard deviation is calculated from the combination of north and east component ratios. For the Wellington sites, only the north component is shown, as the north and east components are similar.

The ratios for the five Lower Hutt sites are shown in Figures 16-18. At site L19 (Zone 1) the frequency characteristics of the strong and weak motions are similar, though the strong-motion average is below the weak-motion average. The comparison of strong- and weak-motion ratios is similar at site L12 (Zone 3-4). For site L13 (Zone 2) near the edge of the valley, the strong-motion ratio peaks for the two east components are at a longer period than for the weak-motion average (Figure 16). The peaks for these two components are also at a slightly longer period than the average strong-motion response determined by Sritharan and McVerry (1991), but the peak of the weak-motion average is still lower than this average. Note that the peaks of the east component of the two strong-motion ratios exceed the mean ratio plus standard deviation from the weak-motion studies. Sritharan and McVerry (1992) showed that the response of this site near the edge of the valley was highly directional, so the mean of the weak-motion ratio in both directions is less than the mean in the east direction.

The strong-motion ratios are higher than the weak-motion ratios at long period for site L05 (Zone 5), where there is a depth to bedrock of 275 m. Sritharan and McVerry (1992) have suggested this may occur because the larger earthquakes, with greater long period energy, can excite low frequency modes in the deeper layers and perhaps the total width of the valley.

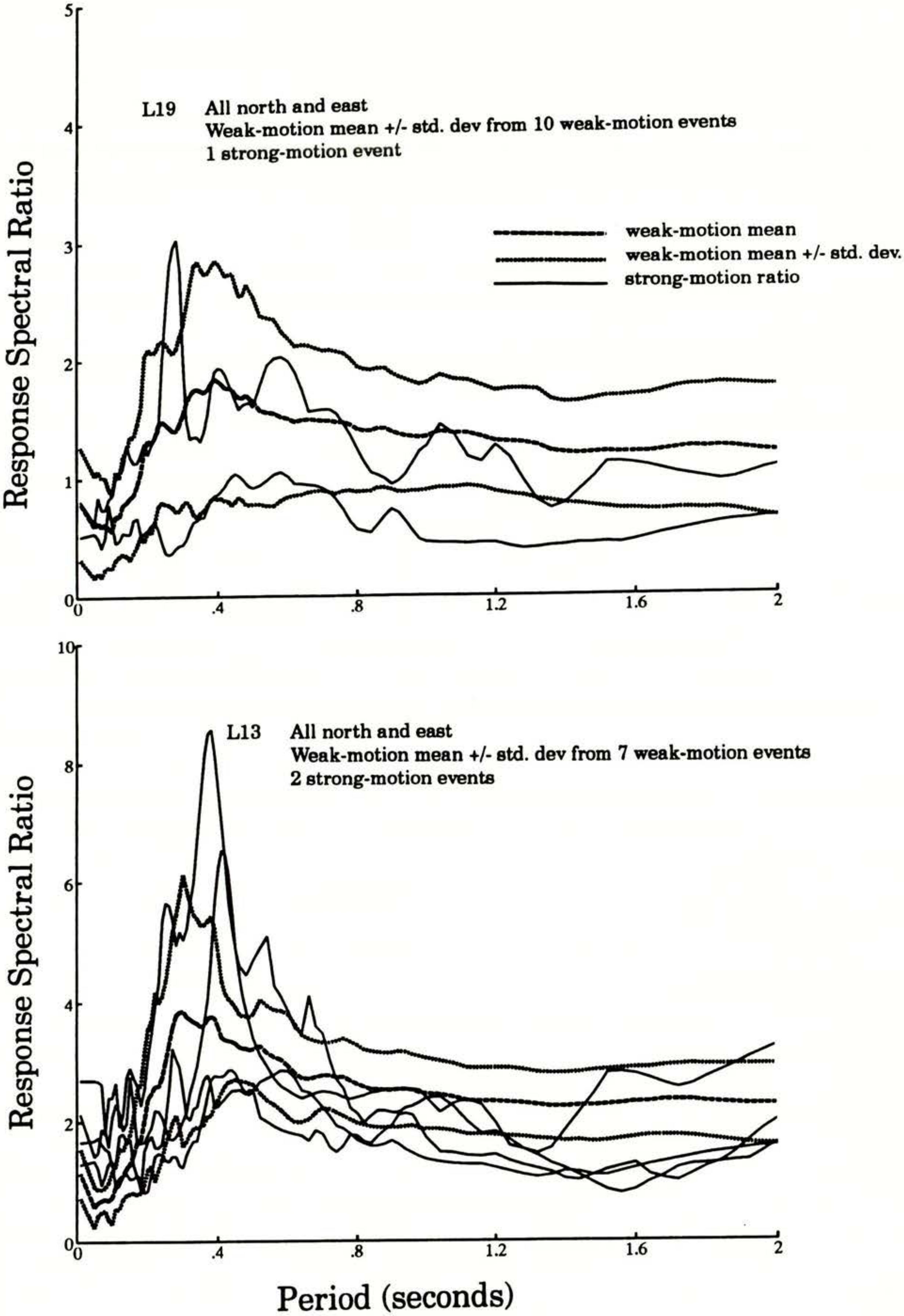


Figure 16. Top: Ratios of the 5% damped acceleration response spectral ratios for strong and weak motions at Lower Hutt rock site L19. The dashed line is the weak-motion mean of the north-south and east-west components while the dotted lines are +/- one standard deviation from the mean. The solid lines are the north-south and east-west strong-motion ratios for the 1977 earthquake. Bottom: North-south and east-west response spectral ratios for Lower Hutt site L13 (Zone 2).

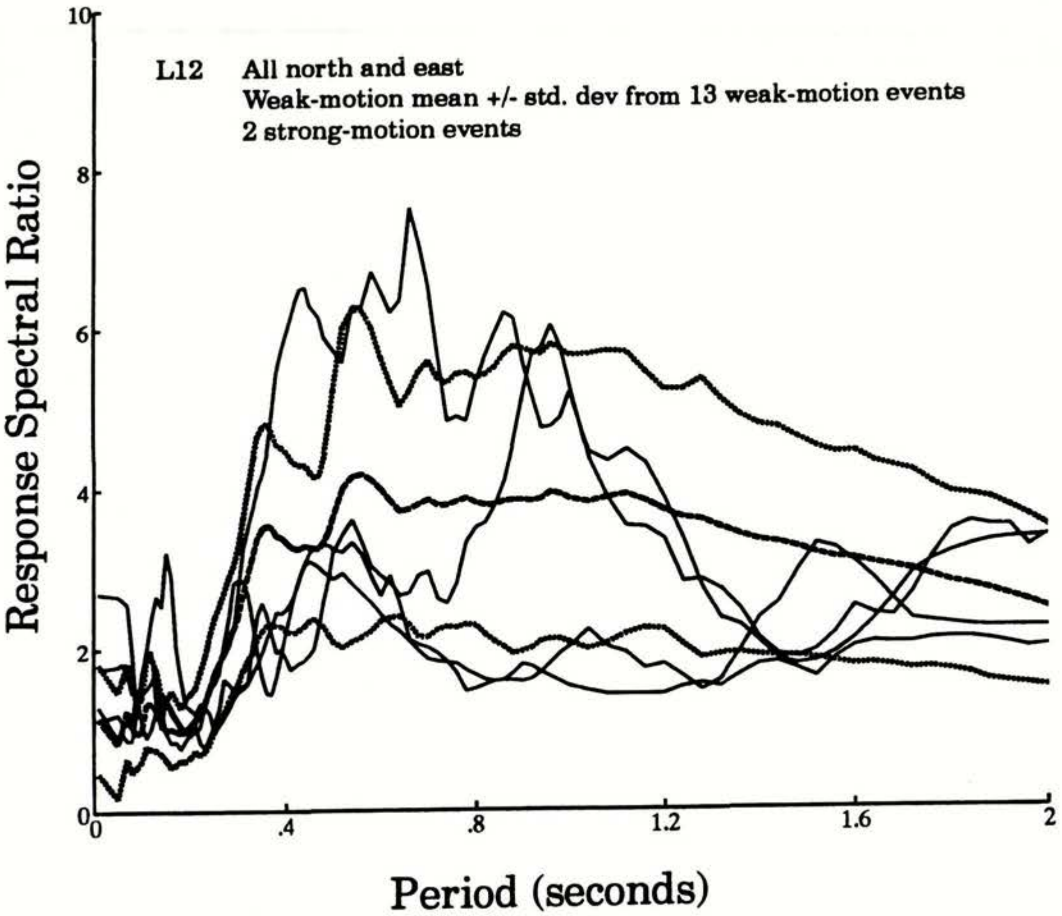
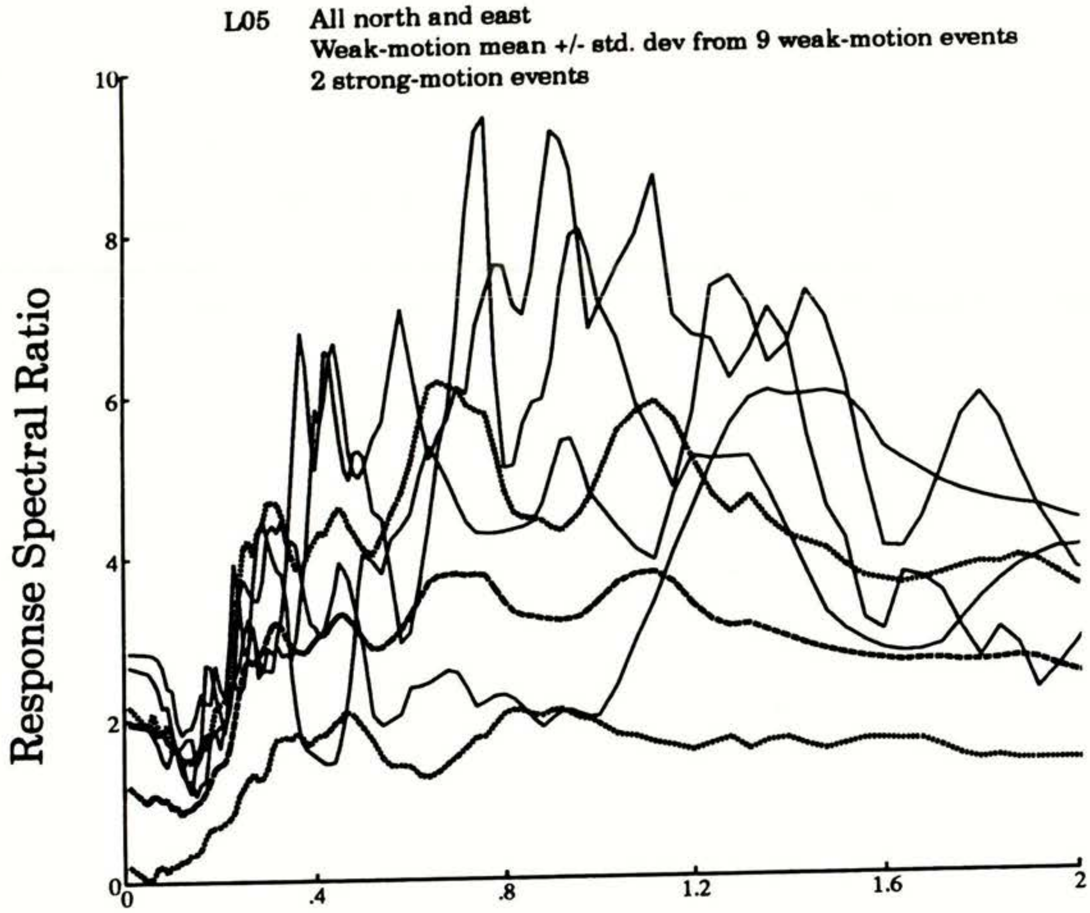


Figure 17. North-south and east-west response spectral ratios for Lower Hutt site L12 (Zone 3-4). Symbols as in previous figure.



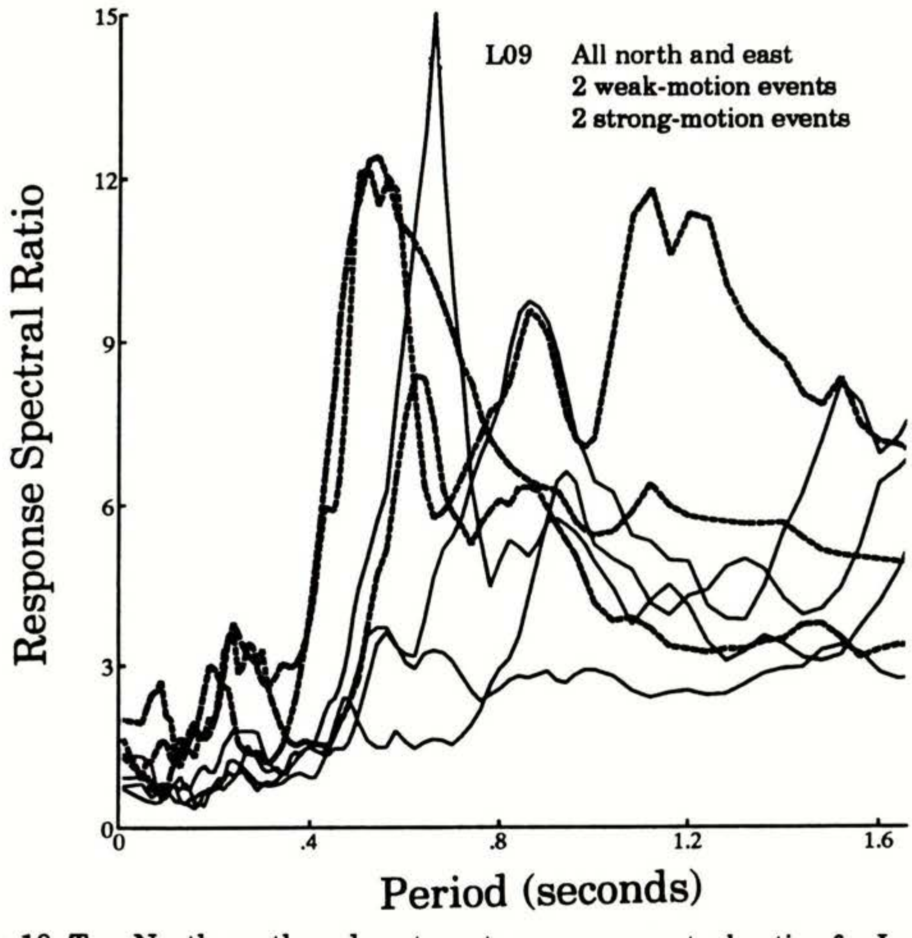


Figure 18. Top: North-south and east-west response spectral ratios for Lower Hutt site L05. Bottom: North-south and east-west response spectral ratios for Lower Hutt soft soil site L09. No mean and standard deviation is shown, the dashed lines are the weak-motion ratios. Strong longer period (>1.5 seconds) amplifications are visible in the strong-motion response spectra of L09 but are not shown here as the reference spectra were near noise in this period range.

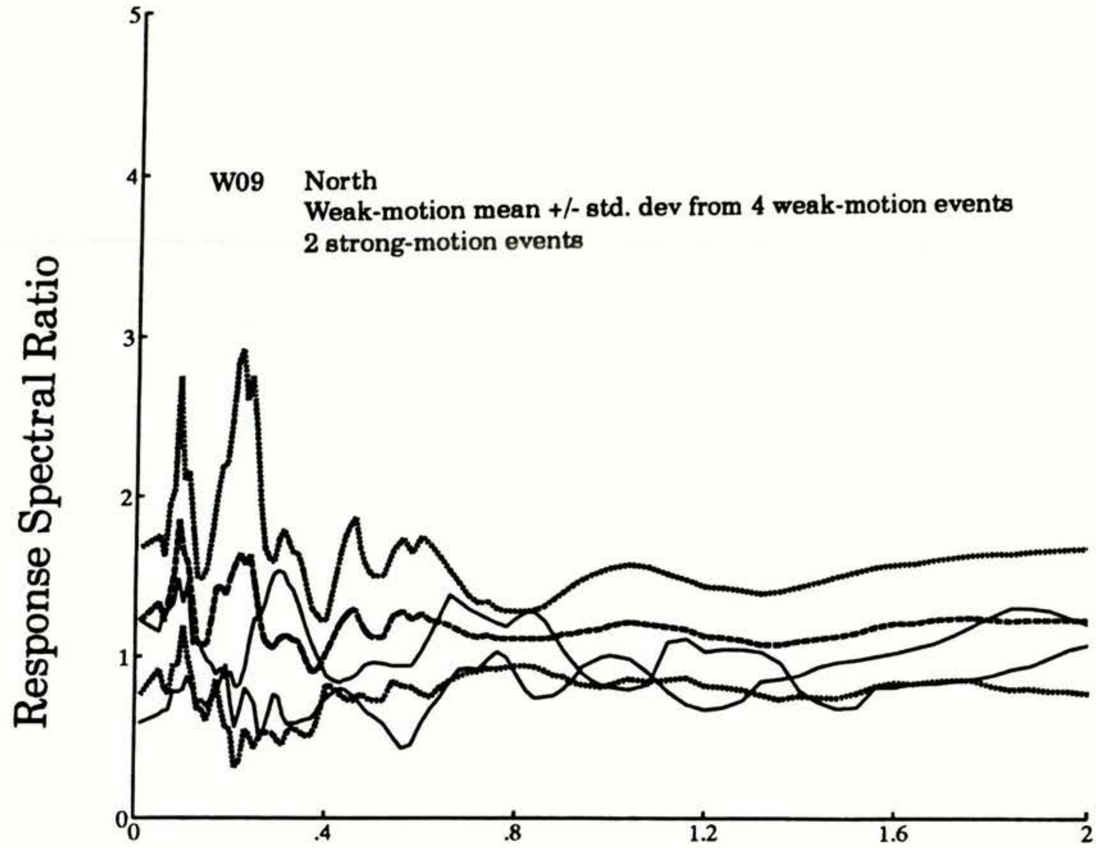
The weak and strong RSR are not very similar for site L09 (Zone 5). This site has 20 m of soft soils, underlain by 280 m of gravels. The strong-motion ratios are generally lower at short periods and equal or higher at long periods. The sharp strong-motion peak at 0.6 seconds is due to directional effects at that period. A peak in the response spectra of the east component of L09 corresponds to a low point on the L14 east spectra, yielding a high ratio. The opposite is true for the north component, yielding a very low ratio. The average of the two components might give a better estimate of the response at that period.

3.2.2 Wellington Response Spectral Ratios

Fewer events were used in the weak-motion response spectral averages because the reference site used (W10) did not record as many small earthquakes as did the other reference sites. The response spectral ratios for the two Wellington rock sites are shown in Figure 19. At site W21, the strong-motion ratio is much lower at long period, but otherwise the ratios are comparable. Three of the five Zone 2 sites (W13, W19, and W20) have similar weak and strong-motion ratios (Figures 20 and 21). One of the strong-motion ratios is much lower at long period for site W12 (Figure 22). As noted for the Fourier spectral ratios, the strong-motion RSR for W03 is less than the weak-motion ratios. For the two Zone 3-4 sites, W11 had very similar strong and weak-motion ratios while the strong-motion ratios for site W07 were near one standard deviation below the mean (Figure 23).

4. Discussion

There were four sites for which the strong- and weak-motion ratios (either Fourier or response spectra) differed significantly. For the other sites, the strong-motion ratio fell within the generally large scatter of the weak-motion ratios, which made the detection of systematic amplitude dependent effects difficult. For the



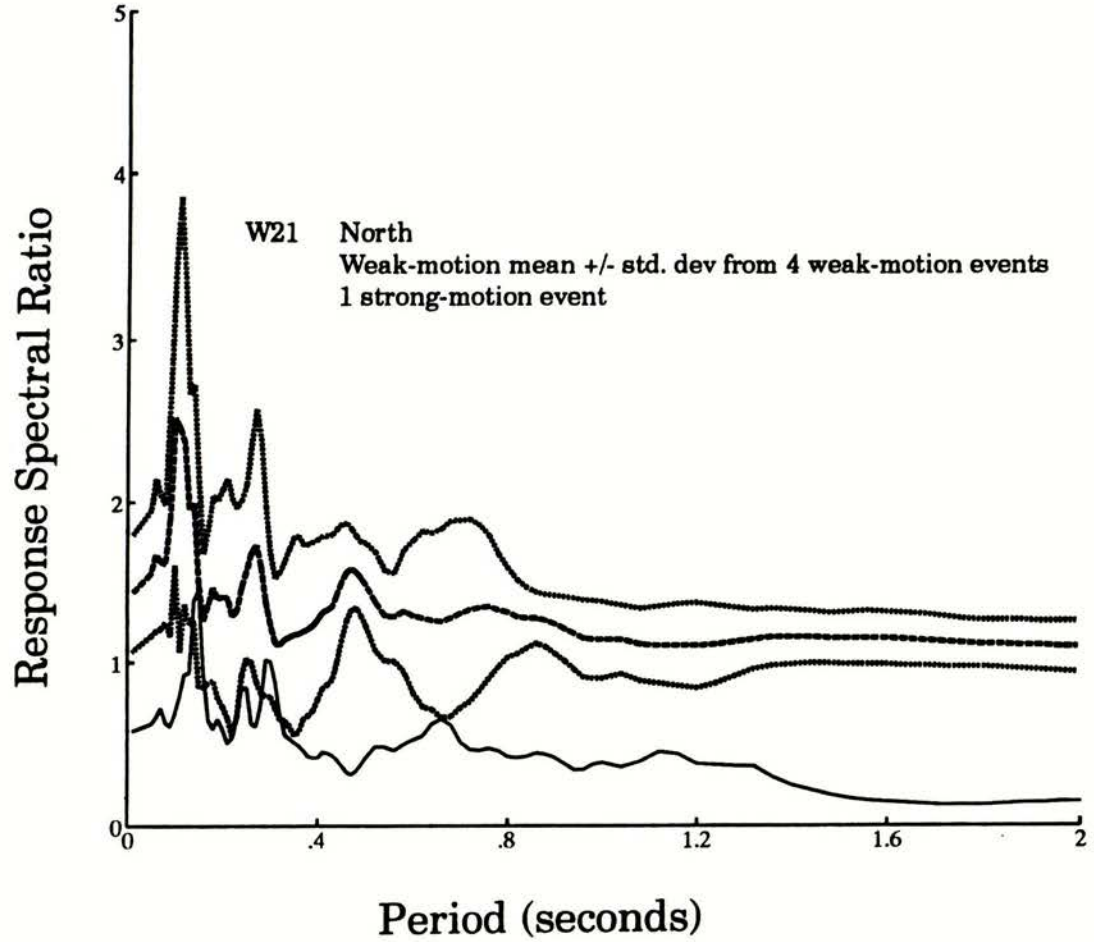
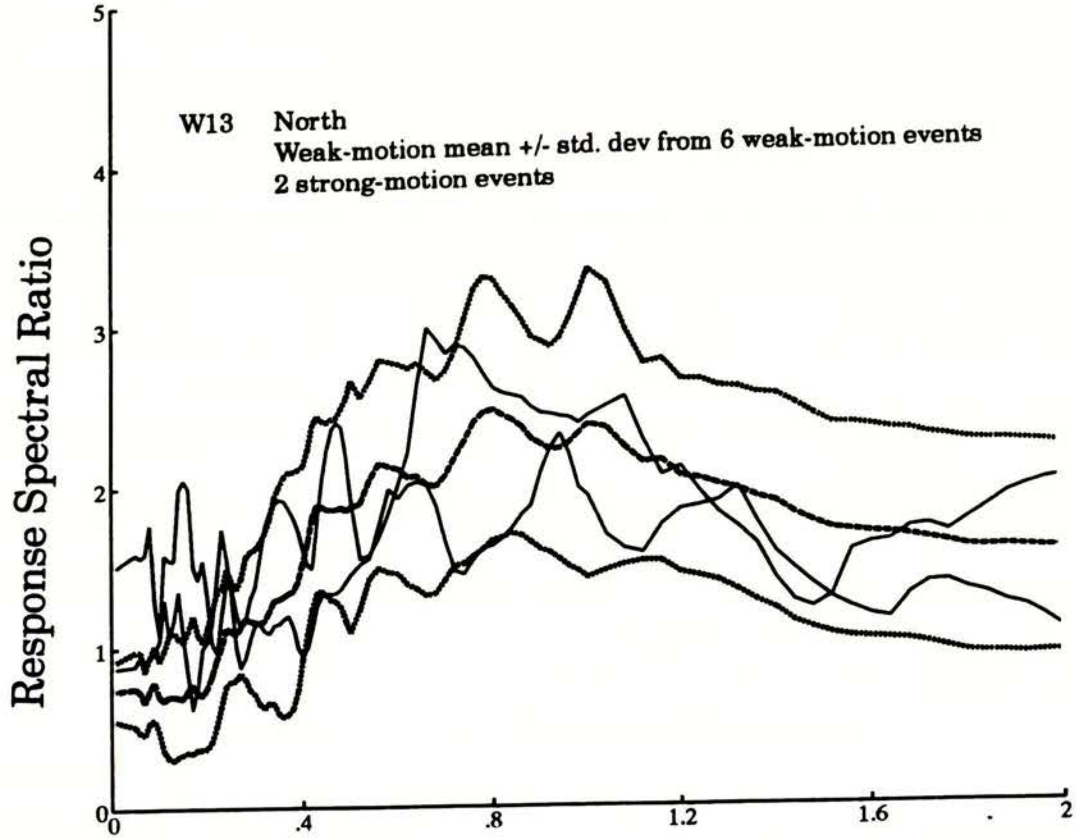


Figure 19. Top: North-south response spectral ratios for Wellington rock site W09. Bottom: North-south response spectral ratios for Wellington rock site W21.



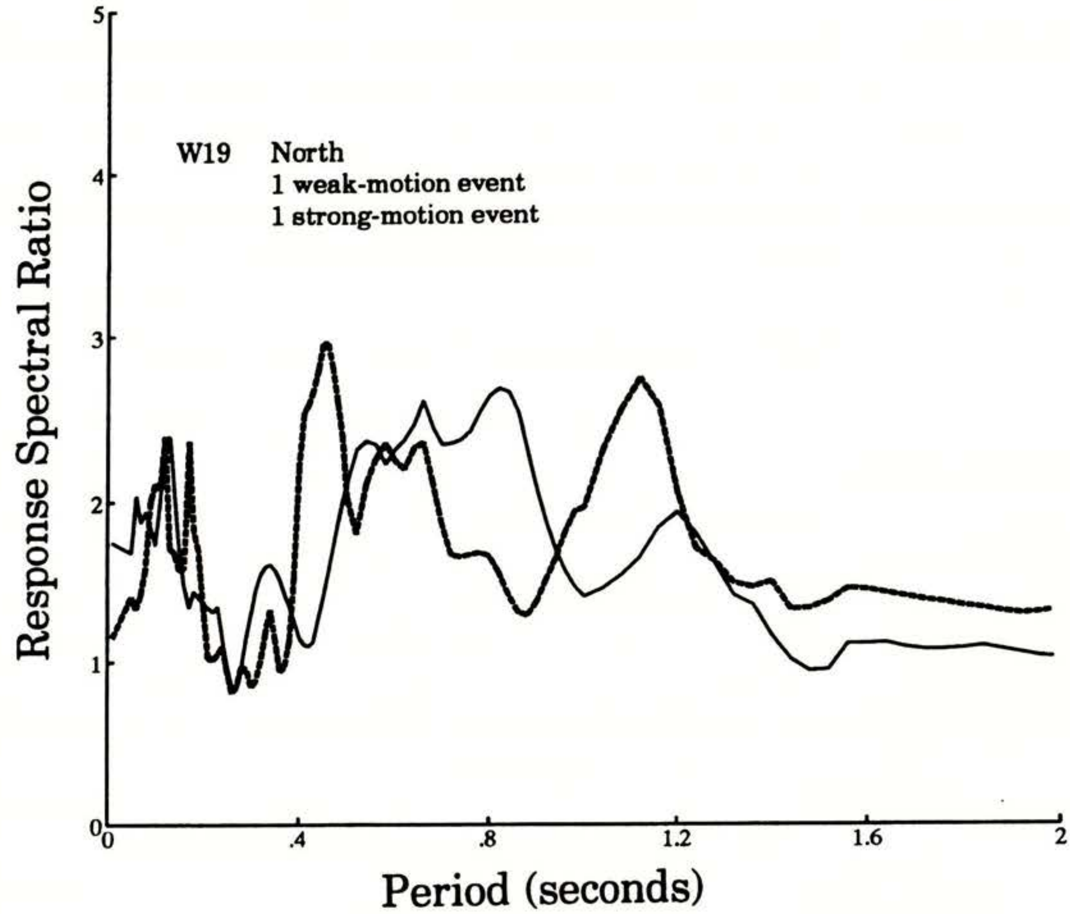


Figure 20. Top: North-south response spectral ratios for Wellington site W13 (Zone 2). Bottom: North-south response spectral ratios for Wellington site W19 (Zone 2). No mean and standard deviation is shown, the dashed lines are the weak-motion ratios.

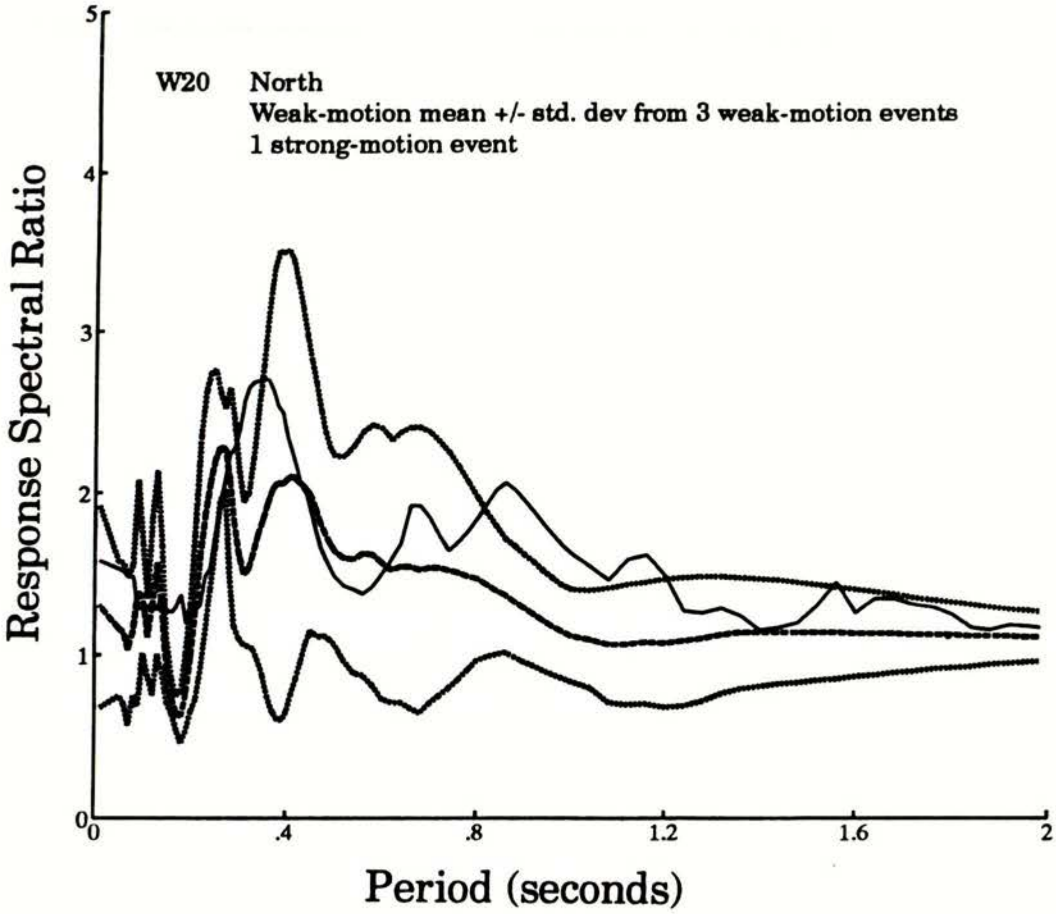
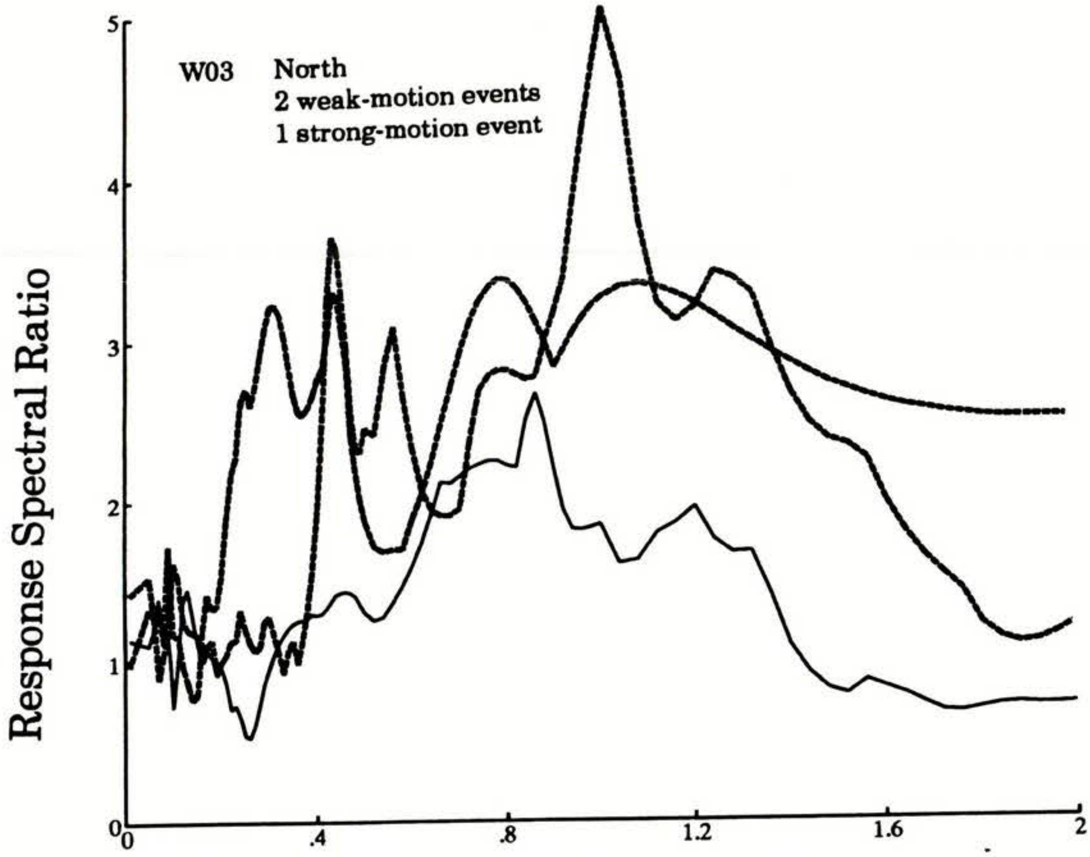


Figure 21. North-south response spectral ratios for Wellington site W20 (Zone 2).



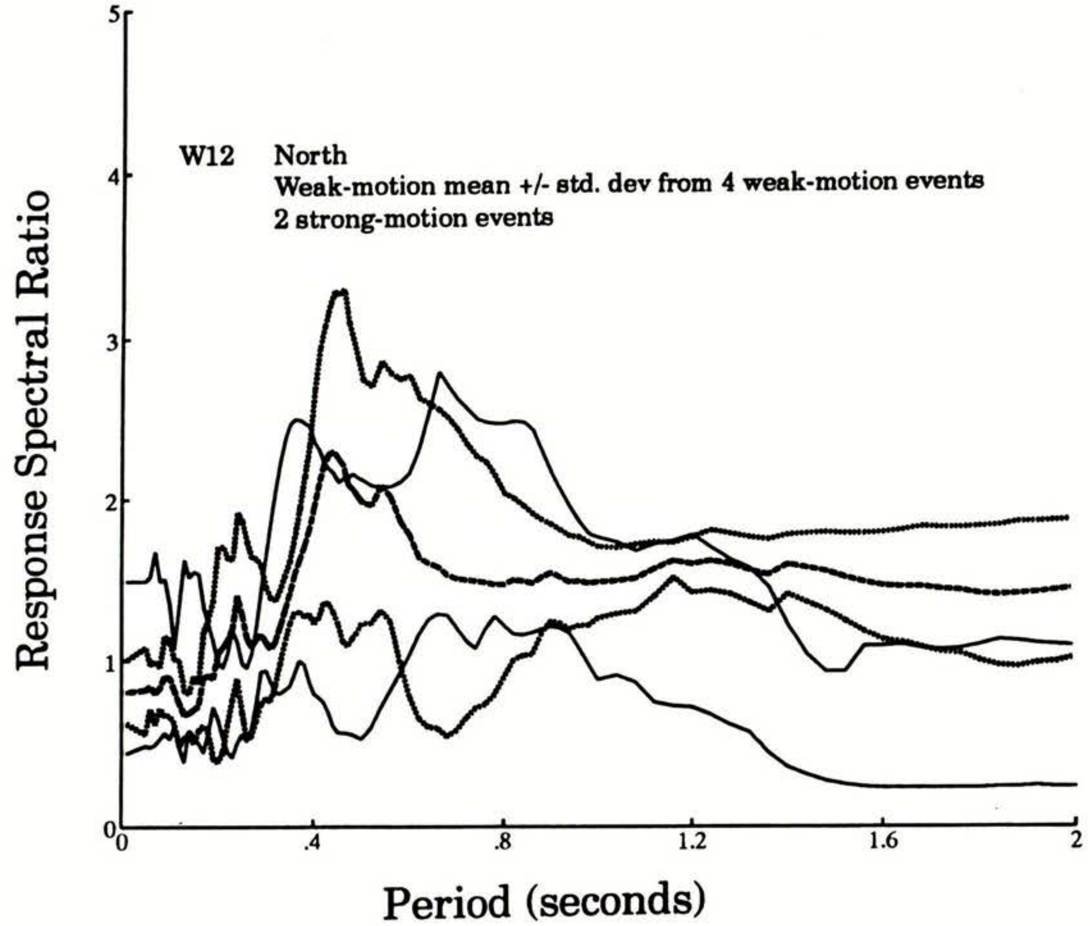


Figure 22. Top: North-south response spectral ratios for Wellington site W03 (Zone 2). No mean and standard deviation is shown, the dashed lines are the weak-motion ratios. Bottom: North-south response spectral ratios for Wellington site W12 (Zone 2).

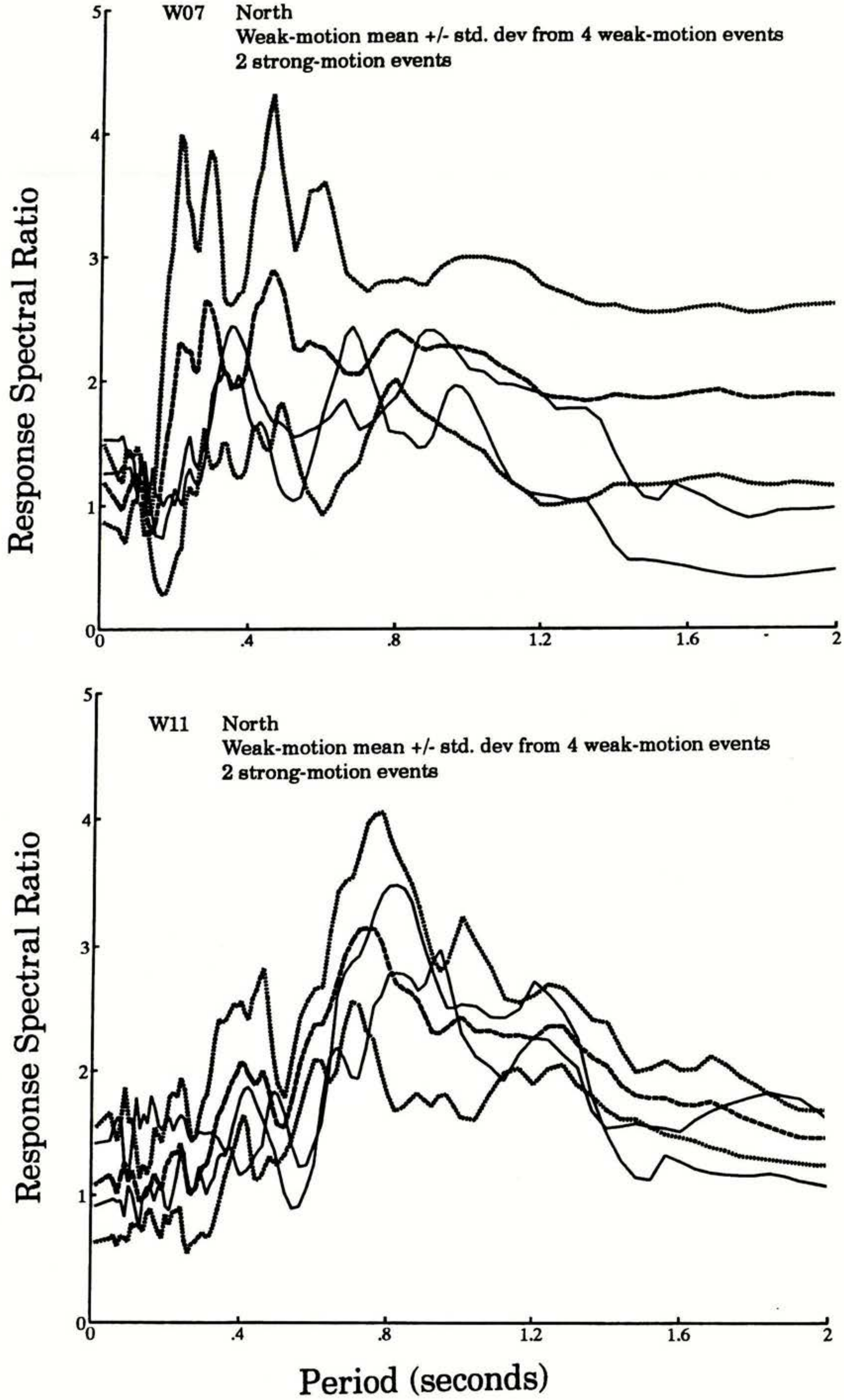


Figure 23. Top: North-south response spectral ratios for Wellington site W07 (Zone 3-4). Bottom: North-south response spectral ratios for Wellington site W11 (Zone 3-4).

range of motions available to this study, only one of the sites (L09) shows what could be interpreted as strongly non-linear behaviour. This is the site with the softest soil profile. However the removal of the original building and the construction of a new building at the site may have affected the results. If not, then it appears that at most short periods the weak-motion ratios exceed the strong-motion ratios whereas at long periods, the strong-motion ratios are higher.

However the weak motion ratios shown in Figures 10 and 18 are probably an overestimate of the average weak motion amplification. The ratios calculated for the other sites for the two events recorded at L09 were examined in detail. At each site, the ratios for those events exceeded the mean for that site in the 1-3 Hz frequency range. Thus if a greater number of the earthquakes used in this study had been recorded at site L09, the mean value in the 1-3 Hz frequency range would have been lower.

Site L05, in the center of the Hutt Valley with 275 m of deposits above bedrock, also showed a greater long-period response in the strong-motion records. In both cases the larger earthquakes recorded by the strong-motion instruments, which are richer in long-period energy, may be exciting longer period modes in the deeper layers of the valley (Sritharan and McVerry, 1992).

The lower strong-motion ratios at site W03, which is on weathered gravels in Zone 2, is unexplained. It is possible that the relatively small number of weak-motion events and the single strong-motion event are not representative of the site.

A difference in the peak frequency response between the strong and weak motions at site L13 is noticeable on the RSR plot (Figure 16). It is seen on the FSR plots (Figure 7) that the peak strong-motion frequencies do lie within the range of weak-motion peak frequencies. However the strong-motion peak frequencies are different than the weak-motion mean peak frequencies.

5. Recommendations for Further Work

This study has been the first step in the comparison of strong and weak motions in the Wellington area. There is additional analysis to conduct on the data already collected as well as the opportunity to collect additional data. One of the limitations of the current study is the lack of strong-motion data at the sites where there is the greatest weak-motion shaking. To address this problem, IGNS has installed accelerographs at several locations near where the greatest weak-motion shaking has been observed. Some records have been obtained at three of these newly instrumented soft sites, namely Naenae and Wainuiomata in the Lower Hutt area (Sritharan and McVerry, 1992) and Taranaki St. Wharf in Wellington. The maximum acceleration recorded thus far has been 0.06 g. Some data has also been recently recorded on two accelerographs that were operating at the time of the weak-motion study but had not yet triggered on any earthquakes. Thus felt earthquakes in the future will allow the comparison of existing weak motions to newly recorded strong motions at a greater number of sites than were compared in the current study.

The comparisons in this study could be improved by a more detailed analysis of the weak-motion earthquakes, to examine some of the causes of the variations between earthquakes.

The weak- and strong-motion ratios for earthquakes in similar locations should be examined in detail.

The comparison of strong and weak motions for site L13 could be redone in the along and across valley directions used by Sritharan and McVerry (1992) in their analysis of the strong-motion data in Lower Hutt. Analysis of the records from the strong-motion accelerographs has shown that the motion at this site is strongly directional, aligned in the along valley direction.

6. Conclusions

Comparisons of strong and weak ground motions in Wellington city and the Hutt Valley show that non-linear effects are minimal at most sites up to 0.1 g, the highest recorded shaking for the survey. At most sites, the strong-motion average ratio is similar or slightly lower than the weak-motion average ratio. The response spectral ratios show a greater tendency for the strong-motion ratio to be lower than do the Fourier spectral ratios. Four sites showed a significant departure from this trend. The only site common to both the strong- and weak-motion studies that had greater than 10 m of soft soil, had lower strong-motion ratios at most frequencies. One site on alluvial gravels also had lower strong-motion ratios. One site on alluvium and thick gravel to a depth of 275 m in the Hutt Valley had a greater strong-motion response in he long period range. A site near the edge of the valley on alluvium showed a shorter period frequency response in the weak-motion ratios.

7. Acknowledgements

The authors would like to thank numerous people who were involved in the collection and processing of the data use for this report. Jim Cousins, Dick Hefford, Shirley O'Kane and David Baguley participated in the recording, digitizing, and processing of the strong-motion records. Mark Chadwick, John Haines, Allister Gorman, and Jenny Rollo assisted in a variety of ways with the collection and processing of the weak-motion data.

Much of the weak-motion data was collected during two ground shaking hazard surveys conducted for, and funded by, the Wellington Regional Council, and the authors thank the WRC for their permission to use the data.

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Appendix A
Description of ground conditions at the joint weak- and strong-motion sites

The ground conditions at the accelerograph sites were produced by N. Perrin of IGNS, based on the geological information and borehole data currently available (see also Dellow et al, 1992; Perrin et al, 1992).

W03 ANZ Bank

Weathered gravel (completely weathered) under about 4.5 m of fill (Te Aro Stream course appears to cross this site). Bedrock 60 to 90 m. Add 15 m for effective bedrock.

W07 Old Central Library

Fill 3.5 m over beach and harbour sediments, deep weathered gravel and bedrock at considerable depth. Probably about 40 m. Add 15 m for effective bedrock.

W09 MED Substation (Church Street)

Site is near the north portal of the Terrace Tunnel. Should be on weathered rock near surface, but possibly on or near crush zone of Terrace Fault. On or near bedrock. Effective bedrock about 15 m, hard unweathered to slightly weathered about 30 m.

W10 Dalmuir House

Should be on weathered bedrock near surface, possibly on or near crush zone of Terrace Fault. On or near bedrock. Effective bedrock 10 to 15 m unweathered to slightly weathered bedrock 20 to 30 m.

W11 Central Post Office

Fill 4 to 5.5 m, over harbour sediments and deep bedrock, 60 to 90 m. Probably add 15 m for effective bedrock. Note harbour sediments probably less consolidated than completely weathered gravel, so seismic velocity etc will be lower as well.

W12 Reserve Bank

Completely weathered bedrock surface with a NE dip, with deepening completely weathered gravels overlying it in that direction. Bedrock around 20 m. Add 15 m for effective bedrock.

W13 Vogel Building

Completely weathered terrace gravels. Bedrock deep, 114 m. Add 15 m for effective bedrock.

W19 Gray and Elliot

As for WO3 above, but bedrock closer. Probably 61 m. Add 15 m for effective bedrock. This site is on the side of the former course of the Te Aro stream, but little or no fill on this spot.

W20 Charles Fergusson Old stream filled in, peat, clay etc (weathered terrace gravels), bedrock deep, dipping NE. Bedrock about 30 m. Add 15 m for effective bedrock. Note rock surface probably dips at about 30 degrees, as it does across the street at Reserve Bank site.

W21 Seismological Observatory

Top of hill in completely weathered bedrock, 15 m to effective bedrock.

L05 IGNS - Knights Road, (NZGS)

Very strong greywacke bedrock at 275 m in borehole. The soil types from the surface are 10 m firm to stiff Taita alluvium, 40 m compact to dense Waiwhetu artesian gravel, and 225 m dense(?) Moera gravel. Low seismic velocity materials present in the near-surface probably in the form of peat lenses within top 10 m.

L09 IBM Building (GMT)

Very strong greywacke bedrock at 297 m in borehole. The soil types from the surface are 10 m loose/soft Taita alluvium, 5 - 15 soft to stiff Petone marine, 60 m compact Waiwhetu gravel, 20 m stiff Wilford marine and 200 m dense Moera gravel.

L12 Elizabeth Street Pumping Station (ELS)

May expect a 30 degree westwards dip on surface of weathered very strong bedrock. Depth of alluvium is about 200 m. The soil types from the surface are respectively 10 m loose/soft Taita alluvium, 10 m soft to firm Petone marine, 30 m compact Waiwhetu gravel, 15-20 m stiff Wilford marine and about 130 m dense Moera gravel.

L13 IGNS, Gracefield (PEL)

Alluvium deepens westwards with a probable dip of about 30 degrees on bedrock surface under the site. The soil types from the surface are 2 m soft to firm loose Taita alluvium, 4 m to loose to medium dense Petone marine, 4 m to soft to firm Marine silt, less than 1 m to soft beach deposits and about 8 m medium dense(?) marine/alluvial. Bedrock weathered, but still effective bedrock at 20 m.

L14 IGNS, Nuclear Sciences (INS)

Weathered, but effective bedrock. Becoming hard within several metres of surface.

L19 Naenae Reservoir (NAE)

Weathered, but effective greywacke, becoming hard within several metres of surface.