Auckland *Regional* Council

Assessment for Amplification of Earthquake Shaking by Soft Soils in South Auckland

August 1997

Auckland Regional Council Technical Publication No.87

ASSESSMENT FOR AMPLIFICATION OF EARTHQUAKE SHAKING BY SOFT SOILS IN SOUTH AUCKLAND

Prepared for

AUCKLAND REGIONAL COUNCIL

by

W Stephenson, T Townsend & A Hull

Institute of Geological & Nuclear Sciences Ltd

August 1997

Auckland Regional Council Technical Publication No. 87

ISSN 1172 6415

CONTENTS

SUMMARY

A recommendation from the 1995 earthquake hazard assessment of the Auckland region (Hull et al, 1995) was to quantify more accurately the nature of each of the five preliminary ground shaking hazard zones. This study of 25 representative sites within mapped ground shaking hazard zones in South Auckland was undertaken to better quantify the likely response to future moderate to strong earthquake shaking in the Auckland region.

Sites in South Auckland show a good correlation between estimates of likely earthquake shaking response based on surficial geology and those based upon the Nakamura method of microtremor response:

- All sites measured within preliminary ground shaking hazard Class A show site resonance or possible resonance of microtremors.
- All sites measured within preliminary ground shaking hazard Class B show no site resonance or possible resonance at low frequencies.
- All sites measured within preliminary ground shaking hazard Classes B1 – D show no site resonance of microtremors.

Soft-soil amplification of earthquake motion in South Auckland is important in a few easily identified locations, where shaking is expected to be stronger during both low and moderate intensity earthquakes. In the less likely event of strong shaking, the nonlinear effects of liquefaction and of ground failure will limit such amplifications.

We recommend that the Nakamura method of microtremor analysis should be applied to other areas of Auckland. Future seismic hazard assessment work in the Auckland region should be directed to extending microtremor measurements to sites where preliminary mapping shows possible site-related amplification, and where there is a large investment in structures which would be damaged in the event of amplified shaking.

1.0 INTRODUCTION

In 1995, the Auckland Regional Council (ARC) commissioned the Institute of Geological and Nuclear Sciences (IGNS) to undertake a preliminary earthquake hazard assessment of the Auckland region.

One of the principal recommendations of the earthquake hazard assessment (Hull et al. 1995) was the need to quantify the nature of each of the five preliminary ground shaking hazard zones mapped for the Auckland region. They recognised that each zone was based on surficial geology only, and that their zonation needed testing by more quantitative methods. Following discussions with ARC, it was agreed that the most cost-effective means to test the likely seismic amplification in the Auckland region was to undertake a microtremor survey for each of the mapped ground shaking hazard zones.

In quantifying the seismic amplification at a soft soil site, the most important information required is a knowledge of the shear wave velocity in the top soil layers. Shear wave velocities down to several tens of metres depth are generally best for this purpose. In the absence of direct measurements, velocity profiles are usually assessed from existing drillhole logs and geotechnical data. These assessments, however, can be highly inaccurate. Numerous scientific advances have recently been made in assessing site-related amplification of earthquake-induced ground motion. In particular, it has been discovered that some sites covered with a significant depth of soft soil have not shown the usually expected high amplifications. This has been shown to have been caused both by the gradual nature of the change from soft surface soils to stiff basement rocks, and by the scattering of the arriving earthquake waves in the inhomogeneous Tertiary-age strata underlying the soft surface materials. By way of contrast, Wainuiomata near Lower Hutt, where surface peats and organic silts change abruptly to homogeneous stiff greywacke at a shallow depth, has high measured amplifications.

Nakamura's "Quasi-Transfer Spectrum" technique has recently been used to evaluate a selection of sites in New Zealand. This technique has been found to always identify sites with high resonant amplifications, in agreement with recently reported overseas work. The technique gives an accurate value for the natural period of a resonant site, and while it gives a less reliable value for the amplification factor, it is comparable with other techniques.

Using Nakamura's technique our study of ground shaking amplification in the Auckland region was established with the following objectives:

- To calculate quasi-spectral-ratio functions for a representative spread of sites within the preliminary ground shaking hazard zones identified by Hull et al. (1995).

- To provide comment on the meaning of the quasi-spectral-ratio graphs in terms of expected amplification of ground shaking in future earthquakes in these ground shaking hazard zones.

In accordance with these objectives we have undertaken the following work:

- Gathered existing drill hole and geotechnical information from the Auckland Regional Council database areas near Takanini and Manukau City Centre in the southern part of the region. Based on these data, 26 sites were selected for field measurement from all five preliminary ground shaking hazard zones.

- Collected measurements of ambient vibrations along 3 axes at each of the selected sites.

- Processed the collected vibration data using the Nakamura technique, providing quasi-spectral-ratio graphs for each of the selected sites.

- Prepared the technical report below that specifies the purpose of the study, definition of terminology and the assumptions and limitations of the data and interpretations presented.

This project was commissioned and funded by the Auckland Regional Council, and undertaken by staff of the Institute of Geological and Nuclear Sciences Ltd.

The microtremor data collection was completed by Mr D. Baguley, with Dr A. Hull and Miss T. Townsend compiling drill hole and geotechnical data. Mr W. Stephenson analysed and interpreted the microtremor data. The report was reviewed by Dr W. Cousins and R. Van Dissen from the Institute.

2.0 GEOLOGICAL ANALYSIS

This section identifies the geological setting of the Auckland region with respect to the preliminary ground shaking hazard zones, and outlines the methods of data collection and analysis.

2.1 Geological Setting

Hull et al. (1995) outlined the geological setting of the Auckland region in detail. The distribution of geological materials within the Auckland region can generally be characterised by a zone of volcanic debris in the west, greywacke terrain in the east, and marine sedimentation in the centre of the region overlain, in part, with basaltic volcanoes. A brief summary of each of the main ground shaking hazard classes that have been studied for this report is given below:

CLASS A Very soft to stiff deposits, usually less than 10,000 years old; sand, silt, mud, shell, and peat deposits mainly on coastal areas, having been (and still being) deposited in estuaries, swamps, low-lying alluvial plains and lakes. Also included is artificial fill.

CLASS B Loose to dense alluvium and sand, fossiliferous and pumiceous deposits, silt, mud, lignite, and clay make up this class of sediments; primarily deposited by marine processes during the last 3 million years.

CLASS B1 "Floating Volcanoes"; this class incorporates the thin (<30m thick) volcanic deposits overlying stiff Pleistocene sediments. Quaternary (1.6–0 million years) in age.

CLASS C Very weak to moderately strong sandstone, siltstone, mudstone, limestone and conglomerate. Deposits being derived from volcanic sources, 0 to 65 million years ago, are also included in this Tertiary-aged class of sediments. Basal coal measures are overlain by non-calcareous deposits, that are in turn overlain by calcareous, fossiliferous sediments including limestone deposited in shallow marine to estuarine and fluviatile environments.

CLASS D Moderately strong to very strong basement and old sedimentary rocks, Mesozoic in age (235 to 65 million years). This class contains greywacke, argillite, conglomerate, fossiliferous and tuff beds, deposited by marine processes.

2.2 Data Collection and Analysis

Existing drill hole and geotechnical information was collected, where available, for areas near Takanini and Manukau City Centre. Drill hole data were supplied by Auckland Regional Council from their digital database of drill hole logs. Based on these drill hole data and our preliminary ground shaking hazard map, 22 sites were selected for microtremor analysis. Ambient vibrations on three axes were measured at these 22 sites, plus an additional four sites selected because of extra available time and to increase the density of measurements in areas found to have resonant vibrations. These 26 sites were located on the five preliminary ground shaking hazard zones. Table 1 below lists the sites selected, their locations, preliminary ground shaking classes and closest correlating bore holes with descriptions of deposits underlying the ground surface, where available.

Table 1: Site Location and Corresponding Bore Hole Data

Site No.	Map Sheet (NZMS 260)	Grid Ref.	Ground Shaking Class (Hull et al. 1995)	Correlating Bore Hole No. (ARC Records)	Description (where available)
1	R11	769 660	B	21	
2	R11	768 651	B	19	
3	R11	763 665	B	8	Gravel 0-1.5m Sand & Rock Fragments 1.5-3m Sand 3-3.25m Peat 3.25-3.75m Sand 3.75-5.75m Silt 5.75-6m
4	R11	754 645	B	4	Gravel 0-2m Rock & Gravel 2-8m Rock (Basalt) 8-11m Waitemata Group 11-11.1
4a	R11	756 640	B	7	
5	R11	822 608	A	-	
6	R11	820 611	A	-	
7	R11	818 617	A	-	
8	R11	813 613	A	-	
9	R11	835 601	A	99	
10	R12	839 591	C	-	
11	R12	836 581	A	-	

Site No.	Map Sheet (NZMS 260)	Grid Ref.	Ground Shaking Class (Hull et al. 1995)	Correlating Bore Hole No. (ARC Records)	Description (where available)
12	R12	841 586	A	101	Fill 0-0.8m Silt 0.8-2.3m Sand 2.3-2.6m Peat 2.6-5m
13	R11	865 623	A	56	Peat & Timber 0-15m Sands & Silt 15-19.5m Pumice Silts 19.5-22m Silt/Clay 22-35m Mudstone 35-38m Waitemata Group 38-91m
14	R12	861 599	C	106	Clay 0-4m Silt 4-16m Mudstone & Gravels 16-30m Sandstone & Gravels 30-48m Limestone 48-52.5m Sandstone 52.5-56m Greywacke 56-102m
15	R11	862 608	B	53	Topsoil & Clay 0-5m Mudstone 5-15m Mudstone & Sandstone 15-31m Sandstone 31-46.7m
16	R11	846 607	B	41	Clay 0-1m Organics 1-2m Organics & Timber 2-20m Silt 20-43m Peat 43-59m Silt 59-72m Mudstone 72-84m
17	R11	825 639	C	37	
18	R11	838 635	B	40	
19	R11	816 644	C	36	
20	R11	869 650	D	51	
21	R11	883 632	A	69	
A	R11	796 621	C	–	
B	R11	790 626	C	–	
C	R11	785 634	B	–	
D	R11	782 616	B	–	

3.0 MICROTREMOR ANALYSIS

3.1 Introduction

Microtremors are the continuous microscopic vibrations of the ground which a seismograph records in the absence of earthquakes. They result from the ever-present surface waves generated by such sources as traffic, wind and surf.

The use of microtremors to characterise soft soils has a long history, commencing with the work of Omori in Japan in 1908, pursued vigorously by Kanai in the 1950's and finally brought to apparent fruition by Nakamura in 1989. The use of microtremors found little favour in New Zealand until Nakamura's work became available, largely because microtremor amplitudes:

1. were found to vary greatly with time;

2. had unrealistically large amplitude differences between different soil types; and

3. did not always indicate site periods in their spectra amplitude.

3.2 The Nakamura Method

In his original work, Nakamura (1989) considered a situation where bulk waves become trapped within an infinitely-extended, sharply-defined surface layer. He acknowledged that one component of microtremors was a manifestation of passing Rayleigh waves but gave reasons why these had only a small perturbing effect. Reasoning from this, he used the ratio of the amplitude spectrum of horizontal microtremor motion, to the amplitude spectrum of vertical microtremor motion, to represent the site transfer function. The site transfer function describes the way in which a layer of soil modifies the arriving rock-borne earthquake waves.

Later workers, e.g. Lermo and Chávez-García (1994) have acknowledged that microtremors are mainly the particle motions of passing Rayleigh waves, and have shown that, subject to the assumption that Rayleigh waves have equal vertical and horizontal components at the base of the surface layer, Nakamura's method gives valid results for a soft layer on top of a stiff basement.

In brief, Nakamura's method considers waves trapped in a uniform surface layer. Multiple reflections of these waves between the top and bottom of the layer give rise to resonances. Vertical resonant motion at the surface is due to trapped-p waves, while horizontal resonant motion at the surface is due to trapped-s waves. Because p-waves travel much faster than s-waves in recent sediments they will not be resonantly amplified at the s-wave natural frequency of a layer, and can be taken as a proxy for non-amplified s-waves. It follows that the ratio of the s-wave spectrum to the p-wave spectrum will have a character that shows the natural frequency and amplification factor of the site, and that the ratio of the spectrum of horizontal motion to the spectrum of vertical motion will behave in the same way. This latter ratio has been named the quasi-spectral ratio.

The Nakamura method has also been applied to recordings of earthquakes, but in this paper it and the term "quasi-spectral ratio" will be used only in the context of microtremors. The term HVSR is also used, denoting "horizontal-to-vertical spectral ratio".

Because the method relies on assumptions, it has been tested both by field measurements in known situations, and by computer modelling. The outcome of this testing is that there is now a general belief that, for microtremor motions, the method will give an accurate value of the dominant period of motion, and a rough estimate of the amplification factor applicable to low-moderate strength seismic input, provided site conditions are simple.

3.3 Microtremor studies by the Institute of Geological and Nuclear Sciences using the Nakamura Method

The Institute of Geological and Nuclear Sciences has used Nakamura's method to evaluate three sites (Timberlea, Miramar and Parkway) in the Wellington area, in order to select a resonant basin for intensive investigation. We have also retrospectively applied the method to a basin at Alfredton which was initially thought to be resonant, but which showed little amplification when actual earthquakes were recorded by a dense array of seismographs.

In addition we have recorded and analysed microtremors on the Porirua reclamation, at the top of the Hutt Valley Polytechnic tower block, and on the ground adjacent to that tower block. These measurements formed part of an evaluation of the Nakamura method, and were performed earlier than originally planned in order to give a better background to studies such as the present one.

Our experience with the applicability of the Nakamura Method agrees with those of other investigators. In the case of Alfredton the microtremor-derived quasi-spectral-ratio indicated moderate broad-band amplification; stronger than was seen in recordings of earthquakes (Appendix 1). In the cases of Timberlea and Miramar complex multiple resonances were indicated, and in Parkway (Wainuiomata) moderate resonant amplification was expected on the basis of microtremors analysed by Nakamura's method, but high amplifications were observed during earthquakes. This was in contrast with the main Wainuiomata valley where the quasi spectral ratio correctly predicted the extremely high amplifications which were observed (Appendix 1). It appears that the results from the Wainuiomata main valley were accurate because it approximates an extended soft layer over rock, whereas the Parkway gully is narrow and depth-varying. In the latter case the Nakamura ratio may reflect a very local geometry whereas earthquakes would excite the basin as a whole, resulting in a different resonant character.

The Porirua result (Appendix 1) emphasises the care which should be taken when considering quasi-spectral-ratios which are unsupported by other data. On the basis of Nakamura's method by itself, because the quasi spectral ratio for Porirua is much the same as for Alfredton, the earthquake responses of the two sites would be expected to be similar. Both these sites have been examined in great detail, and their soil-to-rock spectral ratios in small earthquakes are well known, as are the shear wave velocity profiles below both sites. The Porirua site in fact has much the same small earthquake amplification as Wainuiomata, albeit at a different frequency, and the Porirua amplification factor and frequency were both accurately predicted beforehand by Stephenson et al (1990) on the basis of geotechnical measurements.

Structures other than basins can be expected to resonate with a natural frequency for horizontal motion which is quite different from the natural frequency for vertical motion. Examples are buildings, ridges and embankments. In such cases the quasi-spectral-transfer ratio should reveal the resonant character of the relevant object, though the identity and extent of the object may not be obvious. Furthermore such a resonant object could radiate seismic waves which in turn could have a dominant horizontal component so that the resonant character of a building for instance, could emerge in microtremor records made close to it.

We agree with Lermo and Chávez-García that the Nakamura method will give a good estimate of the natural frequency of a resonant site, and a rough estimate of the amplification, provided that the local geology is simple. We can add, however, that we are confident that the method will locate the highly resonant areas where a widespread uniform soft layer has an abrupt interface with firmer material. Once a resonance has been detected **it is imperative that other methods be used to thoroughly characterise it.**

The case of a shear wave velocity profile which increases gradually with depth has apparently not been treated by any theorist. However, the microtremors recorded at Alfredton, where there is such a shear wave profile, yield a very broad-band quasi-spectral ratio. This does not mean that amplification is not expected. As energy propagates from the stiffer to the less stiff material the wave amplitude should increase, and such an increase occurs in Alfredton as shown by the slightly greater amplitudes of motion seen on soil compared with rock during earthquakes. Further work should show whether broad band resonances are associated with velocities steadily increasing with depth.

3.4 Data Collection

Microtremors (ambient ground vibrations) were recorded at 26 locations in South Auckland, for a minimum of ten minutes at each location. In this process seismometers (Kinemetrics model L4C-3D) sensed the ground velocity along each of three axes, producing voltages which were recorded by EARSS seismographs (Gledhill 1991) at a rate of 100 samples per second. Each seismometer had a nominal natural frequency of 1 Hz, and a nominal damping of 67% of critical.

The measurement locations were chosen by staff of the Institute of Geological and Nuclear Sciences principally on the basis of existing surface geological maps, but incorporating known geomorphology and stratigraphy so that a rough idea of the depth of soft soils was known. Measurement locations were specified as a street address, a street intersection, or a distance along a street from an intersection. This allowed all measurement locations to be fixed accurately.

At each location the seismometer was oriented north so that any future analysis could incorporate direction dependence, although this study treats the horizontal vibrations as azimuth-independent.

Data collection was undertaken from 30 October to 1 November 1996. It was possible to make a preliminary examination of the records each evening, and as a result six sites were re-occupied to see if unexpected results were duplicated.

The seismometer was generally placed on a concrete or tar-sealed surface, but in cases where only grass or soft soil was available a concrete pad 30 cm in diameter was used as a foundation to remove any resonance involving the seismometer and the ground.

In the case of site A (Cedar Park Motor Lodge), a long duration of recording took place so that variations of the quasi spectral ratio with time could be investigated. Five separate spectral ratios were computed for this site.

3.5 Data Analysis

The EARSS system records ground vibration in a series of "buffers", with each buffer being 27.28 seconds in length, and with each buffer having a time and date stamp derived from a crystal clock. By noting the time and day at each site we knew which buffers were associated with each site, and ultimate traceability was achieved by photographing each site with a camera which put a time and date stamp on each negative.

The data collected was periodically downloaded from the EARSS recorder and stored as a file on a portable computer. Five files were written in three days, an extra one being required for a 60 minute long recording made at the Cedar Park Motor Lodge. It was intended that this long period of data acquisition would give an opportunity to illustrate the stability of the quasi-spectral ratios with time.

Back in the office a utility computer program was run in order to list the commencement time of each of the 1220 buffers recorded. A note was made of the serial number of a suitable start buffer for each site, and a batch file prepared to control operations on each of the five data files. By archiving the batch files we have maintained an audit trail which ultimately links each site to the name of a file containing spectral ratio data.

The ten minutes of data specified for each site was operated on in the following manner:

1. The data, which the EARSS recorder stores in a non-standard format, was extracted into 45 ASCII files each of length 40 seconds. These comprised 15 files for each of the three directions of recording (two horizontal and one vertical). Each file was filtered in the time domain by enforcing an 8 second half-sinusoid run-in and run-out characteristic at its beginning and end, with the central 24 seconds remaining unaltered. This procedure removes the spurious spectral peaks which would originate from the implicit rectangular window applied to the continuous raw data. Each file then had a series of zeroes appended in order both to avoid wrap-around effects and to provide a series length of an integral power of two, for correct use of a fast Fourier transform algorithm at the next stage.

2. Each of the 45 files had its Fourier transform computed, thus moving all data into the frequency domain.

3. All spectral data was summed separately for the horizontal, and then for the vertical, data. This summation was performed in a conventional root-mean-square method by squaring the real and imaginary parts and summing, for each frequency, independently, the two vertical and four horizontal spectral coefficients. The square root was extracted for vertical and for horizontal motion at each frequency.

4. The ratio of horizontal to vertical motion was calculated at each frequency.

5. The spectral data was smoothed, by passing a nine-point binomial filter over the data twice. The filter weights were 1, 8, 28, 56, 70, 56, 28, 8 and 1. The resultant quasi spectral transfer ratio data was written to a file RATIOXX.DAT for each site, with XX being the serial number of each site. This is the data which is presented in each of the accompanying graphs.

Each seismometer has a natural frequency of 1 Hz. Consequently its output falls off greatly below this frequency, a fact that appears at first sight not to be of concern as the analytical procedure applied to the data involves taking ratios. However at low frequencies, differences in natural periods and dampings between seismometers can lead to errors, and we have chosen to truncate all spectral ratio results below 0.3 Hz. This corresponds to a 3 second period, which would be characteristic of a 30 storey building, justifying our truncation of the spectra. It is not known whether such low resonant frequencies are expected for the area, but it would be possible to explore this possibility by deploying a long-period seismometer and carrying out a similar analysis. The recording and analysis times required for such an investigation would be longer and more costly than required for this study. Another method would be to use a strong-motion recorder of the appropriate sensitivity at a greatly reduced cost and with greatly simplified procedures.

3.6 Results

The results of this study are essentially the quasi spectral ratios plotted in appendix 2 of this report. To put these ratios in perspective it is helpful to give some attention to the quasi-spectral ratios in Appendix 1. An examination of these quasi spectral ratio plots shows that it is possible within limits to distinguish sites which will resonantly amplify earthquake motions. Resonant sites are characterised by a narrow resonant peaks, and by quasi-spectral ratios which fall to values much less than one, at frequencies above the resonant peak. In some of the cases shown in appendix 2 a duplicate set of quasi-spectral ratios is shown by a dotted line. In each case the duplicate quasi-spectral ratio is derived from a separate set of microtremor data recorded on another day.

When assessing sites by the Nakamura method it is important to avoid over-interpreting spectral ratio plots. In particular the heights of resonant peaks should not be taken as indicating site amplifications, and a narrow peak with low ratio values at high frequencies should be the main criterion for assessing amplification.

3.6.1 Resonant Sites

Several South Auckland sites, chosen because they were expected to show resonant amplification on the basis of geological mapping, should clearly be described as resonant sites according to the criteria outlined above.

These are sites 5, 6, 8, 11, 12 and 13 (Table 2). In each case the spectrum has a resonant peak, and the amplitude falls off at low frequencies above the peak.

3.6.2 Possible Resonant Sites

Sites 7, 9, 10 and 21 produced spectra which have some features consistent with resonance (Table 2). These spectra were, however, derived from dubious data (described as "impulsive" in table 2). For microtremor recordings, and for repeat recordings, each of these sites was dominated by the infrequent passage of heavy traffic. This in effect makes the sampling time small which potentially gives rise to errors. These sites could be better evaluated by repeating the analysis of the data using digital automatic-gain-control, as described in Section 3.7 of this report, or by repeating the measurements at a quiet time, such as 2 am.

Sites 1, 15 and 16 have some of the character of resonant sites, but their quasi-spectral-ratios are derived from inadequate data. From a scientific viewpoint it would be prudent to investigate these sites further with some other technique. Any resonance at sites 15 or 16 would be of low frequency, and this possibility could be checked by repeating the Nakamura analysis with a long-period seismometer.

However, our comments on possible repeat measurements and analysis are made only from the perspective of resolving uncertainties, and not from the overall aim of understanding earthquake shaking hazard. Further investigations may be better concentrated on other parts of Auckland where potential losses are greater.

3.6.3 *Non Resonant Sites*

Sites 2, 3, 4, 4a, 14, 17, 18, 19, 20, A, B, C, and D have spectra which indicate non-resonant response (Table 2). It is difficult to comment on these sites without further investigation other than to remark that the method strictly applies only to sites where Rayleigh waves or mixtures of s-waves and p-waves propagate in a soft layer lying on a stiff layer.

No significance should be attached to the sizes of the quasi-spectral ratios obtained from these sites.

3.7 Limitations

We have identified five major limitations to this study. The first is the universal one of sampling. The quasi spectral ratio is only known at discrete locations, and it is possible that small unsampled areas might have high amplifications. Equally we do not know the extent of the amplifying areas identified at sites 5, 6, 8, 11, 12 and 13.

The second limitation identified is the small-strain nature of the microtremors measured. The stress-strain character of soils is nonlinear, such that in strong shaking both the amplification and the resonant frequency will fall. The strength of shaking at which nonlinear effects become important depends upon the soil material, and generally rises for more plastic materials. In the case of South Auckland, with its predominance of clays (which have high plasticity), it is assumed that nonlinear effects will only become important for high strains. This means that amplifications that occur for small shaking are assumed to remain important during damaging earthquakes.

The third limitation relates to the interpretation of soil-to-rock spectral ratios at other sites. These ratios were determined for low magnitude earthquakes, which generate only small amounts of surface waves. However, damaging earthquakes are generally shallow, with faults that break the surface. These events generate a higher proportion of surface waves, and it is conceivable that a site such as Alfredton, which had low amplifications in small earthquakes, could behave differently for larger magnitude events. This is significant because parts of South Auckland could be similar to Alfredton and thus show this same character of different responses to large and small earthquakes.

The fourth limitation concerns the unusual nature of microtremors measured at some sites in South Auckland. The Nakamura method has been shown to work irrespective of the nature of the source of microtremors, so that passing traffic is just as adequate as the action of the wind in trees at generating them. We have taken advantage of this in all our microtremor studies to date, by locating all of our sites at the roadside or in other public places accessible by vehicle. This reduces the time demands both of negotiating sites, and of carrying equipment to the sites. Usually there is a constant stream of traffic, and averaging the spectra of successive time periods gives a stable result.

Table 2: Sites With Locations and Microtremor Analysis Comments

Site No.	Map Sheet (NZMS 260)	Grid Ref. (NZMS 260)	Ground Shaking Class	Comments
1	R11	769 660	B	Possible resonance
2	R11	768 651	B	Non resonant
3	R11	763 665	B	Non resonant
4	R11	754 645	B	Non resonant
4a	R11	756 640	B	Non resonant
5	R11	822 608	A	Resonant
6	R11	820 611	A	Resonant
7	R11	818 617	A	Possibly resonant - impulsive data
8	R11	813 613	A	Resonant
9	R11	835 601	A	Possibly resonant - impulsive data
10	R12	839 591	C	Possibly resonant - impulsive data
11	R12	836 581	A	Resonant
12	R12	841 586	A	Resonant
13	R11	865 623	A	Resonant
14	R12	861 599	C	Non resonant
15	R11	862 608	B	Possible low frequency resonance
16	R11	846 607	B	Possible low frequency resonance
17	R11	825 639	C	Non resonant
18	R11	838 635	B	Non resonant
19	R11	816 644	C	Non resonant
20	R11	869 650	D	Non resonant
21	R11	883 632	A	Possibly resonant - impulsive data
A	R11	796 621	C	Non resonant
B	R11	790 626	C	Non resonant
C	R11	785 634	B	Non resonant
D	R11	782 616	B	Non resonant

However at some sites in South Auckland the traffic is made up of only occasional heavy vehicles travelling fast, with the result that they dominate the result. Effectively therefore, the sampling time is small, and the advantages of averaging are not seen. There was not enough total recording time at these sites to enable sufficient traffic-free intervals to be chosen (this is a time-consuming process that would make analysis no longer cost-effective). An alternative approach would be to incorporate digital automatic-gain-control, but that would require the development of new software.

The final limitation is the inability of this or any other method to predict amplifications for all earthquakes. On average we expect the method to give good results, but due to the varying depth, magnitude, fault plane orientation and rupture mechanism it is expected that amplification effects will vary from earthquake to earthquake. This especially applies to such effects as random reinforcement of waves to give abnormally high or low intensities, to topographic enhancements, and to boundary effects where soft soil meets stiffer material.

3.8 Significance

This study has shown a good correspondence between sites determined from surficial geology to be of highest earthquake shaking amplification and site resonance as measured by microtremor analysis. All sites classified by Hull et al. (1995) as having the greatest likely earthquake shaking response are shown to be resonant or possibly resonant. All sites selected within the next highest earthquake shaking response class — Class B — are either non-resonant or possibly resonant at low frequency. All other classes show a microtremor response of non-resonance. These results confirm that in the South Auckland area, unconsolidated Holocene-age sediments are likely to amplify earthquake shaking, while other sites may also amplify earthquake shaking, but to a lesser degree than the sites classified by Hull et al. (1995) as Class A.

The earthquake shaking amplification predicted by the results of this study could increase observed earthquake shaking intensity by up to three units on the Modified Mercalli (MM) scale. Such a result is of great economic significance because it increases the expected cost of repairing damage after an earthquake. The increase in cost can be roughly assessed by taking the relationship given by Dowrick (1991) between MM intensity and damage ratio for houses damaged by the 1987 Edgecumbe earthquake, or the similar one given by O'Rourke *et al* (1991) for pipelines damaged by the 1989 Loma Prieta earthquake.

Dowrick's Edgecumbe results imply that the cost per building, of repairing damage in some parts of South Auckland, will be greater than the costs in other parts by a factor of 40. The Loma Prieta results imply that the costs of repairing pipeline damage in these places will be increased by a factor of 1000.

In arriving at this result it is assumed that there will be no damage due to liquefaction. This assumption should be checked, but it is reasonable because liquefaction, while undoubtedly dramatic, is relatively uncommon. From recent earthquakes, only the 1960 Anchorage earthquake and the 1964 Niigata earthquake, have caused economically important liquefaction damage. Holzer (1964) points out that only 1% of the damage costs of the 1989 Loma Prieta earthquake were attributable to liquefaction. However, it is important to confirm that the soils that underlie South Auckland have low liquefaction potential.

4.0 CONCLUSIONS

1. This study of 25 sites within a small region of South Auckland shows a good correlation between estimates of likely earthquake shaking response based on surficial geology and those based upon the Nakamura Method of microtremor response.

2. All sites measured within preliminary ground shaking hazard Class A show site resonance or possible resonance of microtremors.

3. All sites measured within preliminary ground shaking hazard Class B show no site resonance or possible resonance at low frequencies.

4. All sites measured within preliminary ground shaking hazard Classes B1 – D show no site resonance of microtremors.

5. As assessed by Nakamura's microtremor quasi-spectral ratio technique, soft-soil amplification of earthquake motion in South Auckland is important in a few easily identified locations, where shaking is expected to be amplified during both low and moderate intensity earthquakes. In the less likely event of strong shaking, the nonlinear effects of liquefaction and of ground failure will limit such amplifications.

5.0 RECOMMENDATIONS

The completion of this initial study of earthquake shaking amplification using the Nakamura Method has identified a need to undertake further studies of earthquake shaking site response in two principal areas: (1) studies to determine the technical uncertainties related to the 25 sites measured in this study, and (2) studies related to determining likely earthquake response in other parts of the Auckland region.

While it would be valid to resolve the uncertainties described in Section 3.6.2 of this report, the sites concerned lie in zones where the subsurface layering is known, and these zones include sites where the Nakamura method gave good results. These sites do not have a potential for high financial loss in the event of strong shaking. We do not, therefore, believe that revisiting any of these sites would significantly increase the understanding of site response for the benefit of the Auckland Regional Council's hazard planning objectives.

We believe that the Nakamura method of microtremor analysis should be applied to other areas of Auckland. We recommend that future seismic hazard assessment work in the Auckland region should be directed to extending microtremor measurements to where preliminary mapping shows possible site-related amplification, and where there is a large investment in structures which would be damaged in the event of amplified shaking. Examples of suitable and high cost-benefit study sites include Auckland International Airport, Ports of Auckland facilities and major buildings in the Auckland CBD.

The greatest deficiency in the Auckland region data from a seismic microzoning point of view is the lack of either shear modulus data, or shear wave velocity data, as functions of depth. The way in which shear wave velocity changes with depth controls earthquake shaking amplification, and it would be valuable to know both the Nakamura ratio and the shear wave velocity at some major control points. Such a characterisation of shear wave velocities could be conveniently achieved by applying a Seismic Cone Penetration Test (SCPT) at sites where significant amplification is expected.

The SCPT work recommended above is of lower priority than making further microtremor measurements in the wider Auckland region.

6.0 REFERENCES

Dowrick, D.J, (1991) Damage Costs for Houses and Farms as a Function of Intensity in the 1987 Edgecumbe Earthquake, *Earthquake Engineering and Structural Dynamics*, 20(5) 455-469.

Gledhill, K.R. (1991) EARSS Users' Manual, *Technical Report No 109, Geophysics Division, DSIR.*

Hull, A.G.; Mansergh, G.D; Townsend, T.D.; Stagpoole, V. 1995: Earthquake Hazards in the Auckland Region. *Institute of Geological & Nuclear Sciences Ltd Client Report 33494D.10.*

Holzer, T.L. (1994) Loma Prieta damage largely attributed to enhanced ground shaking. *Eos.* 75(26):299-301.

Lermo, J. and Chávez-García, F.J. (1994) Are microtremors useful in site response evaluation? *Bulletin of the Seismological Society of America*, 84(5) 1350-1364, October 1994.

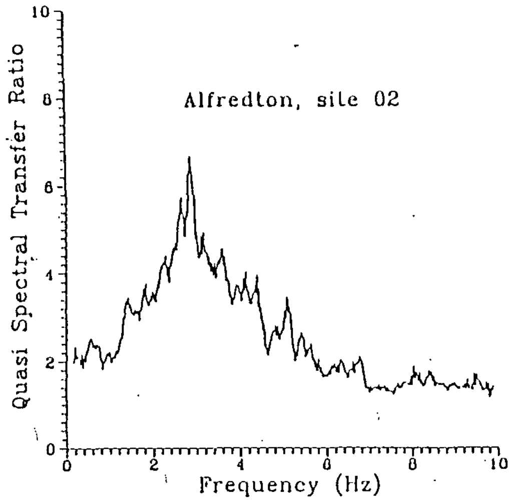
Nakamura, Y. (1989) A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, *Quarterly Report of Railways Technical Research Institute*, 30(1), February 1989.

O'Rourke, T.D.; Gowdy, T.E.; Stewart, H.E.; Pease, J.W. 1991: Lifeline and geotechnical aspects of the 1989 Loma Prieta earthquake. 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, University of Missouri, USA. Vol. 2: 1601.

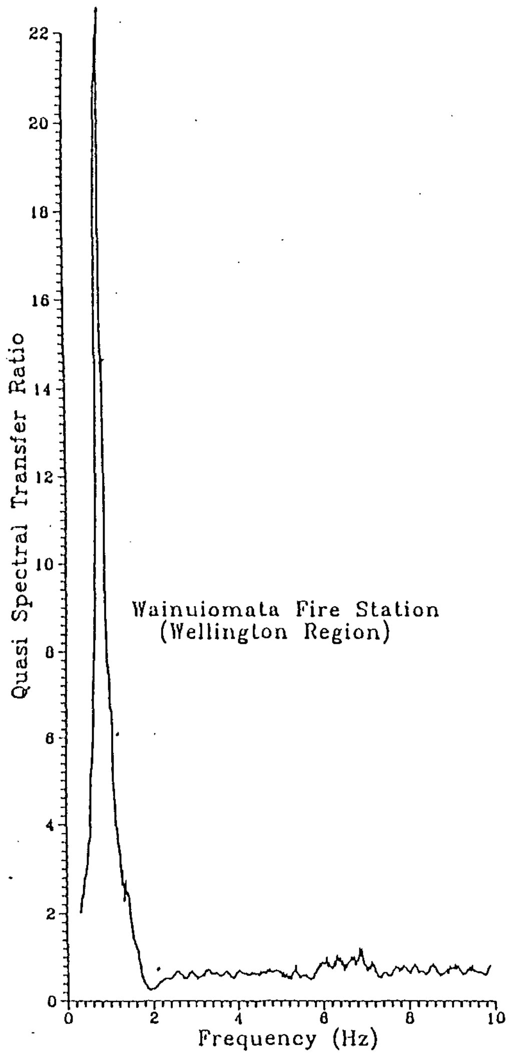
Stephenson, W.R., Barker, P.R. and Mew, G. (1990) Report on Resonant Alluvium Conditions for Part of Porirua Basin, *Contract 9A9101 between DSIR Division of Land and Soil Sciences and Wellington Regional Council.*

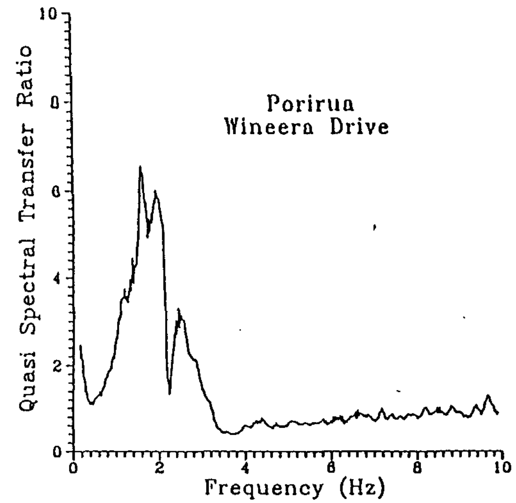
APPENDIX 1

Quasi Spectral Ratios of Microtremors at Well Characterised Sites



Example of broad-band, non-resonant behaviour





Two examples of resonant sites with similar observed amplifications

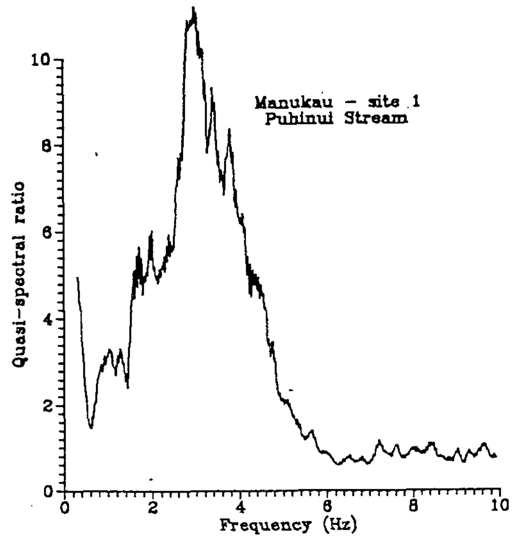
APPENDIX 2

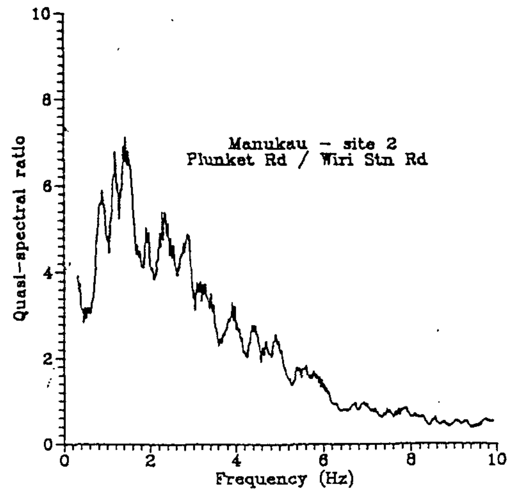
Quasi Spectral Ratios of Microtremors at Auckland Sites

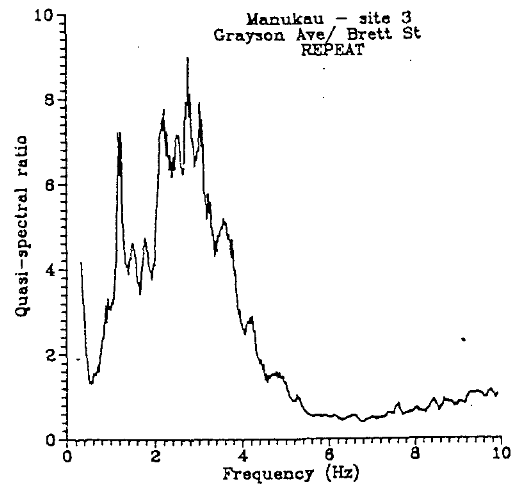
Notes:

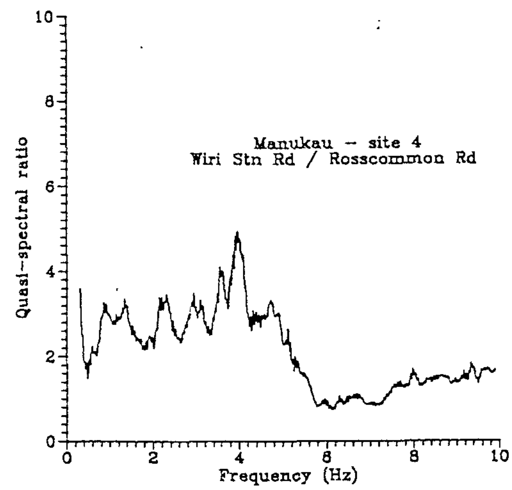
(1) Dotted traces indicate duplicate observations.

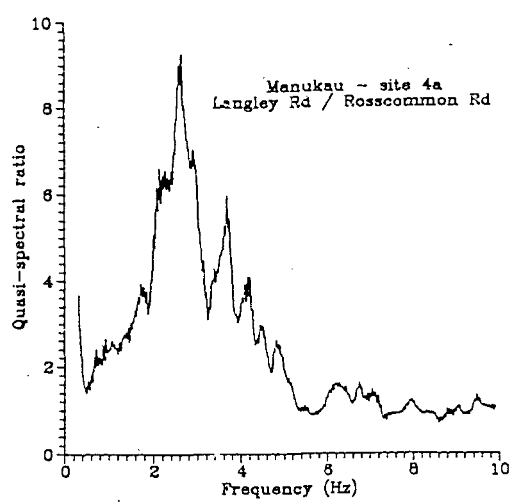
(2) Data for Manakau Site A are derived from observations for about one hour and the multiple ratios are superimposed. The meaning of the large ratios at high frequency is unknown.

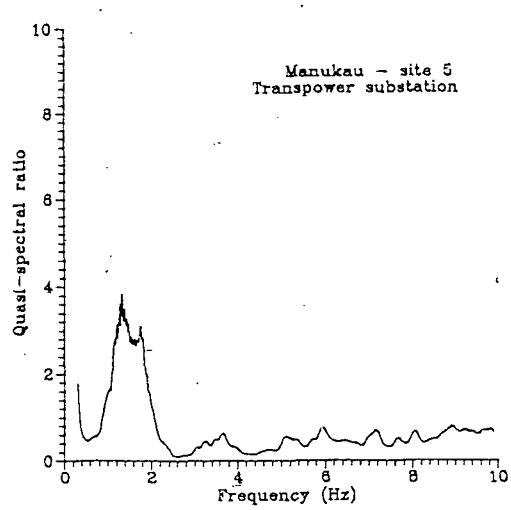

Manukau - site 1
Puhinui Stream
Quasi-spectral ratio
Frequency (Hz)

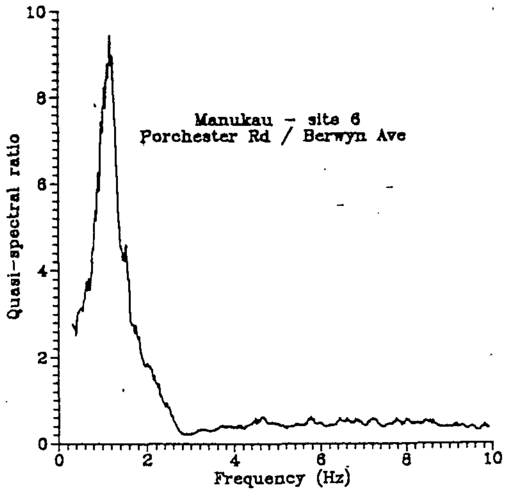

Manukau - site 2
Plunket Rd / Wiri Stn Rd
Quasi-spectral ratio
Frequency (Hz)

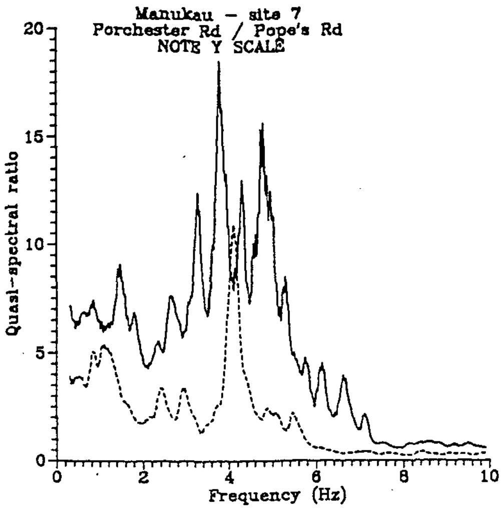

Manukau - site 3
Grayson Ave/ Brett St
REPEAT
Quasi-spectral ratio
Frequency (Hz)

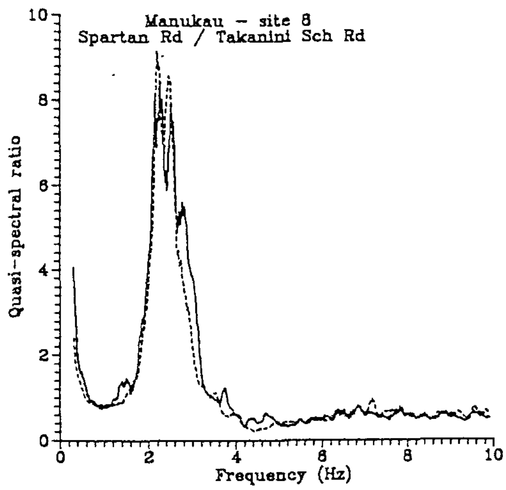

Manukau - site 4
Wiri Stn Rd / Rosscommon Rd
Quasi-spectral ratio
Frequency (Hz)

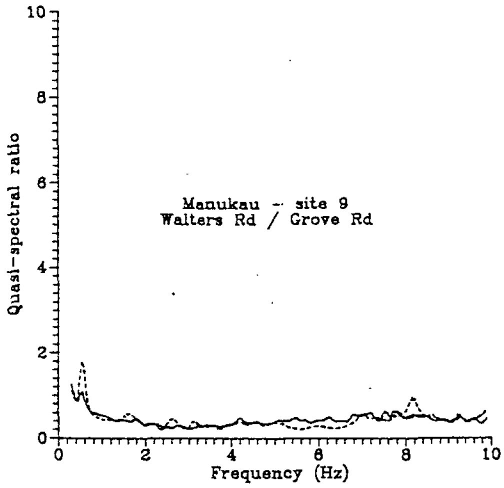

Manukau - site 4a
Langley Rd / Rosscommon Rd
Quasi-spectral ratio
Frequency (Hz)

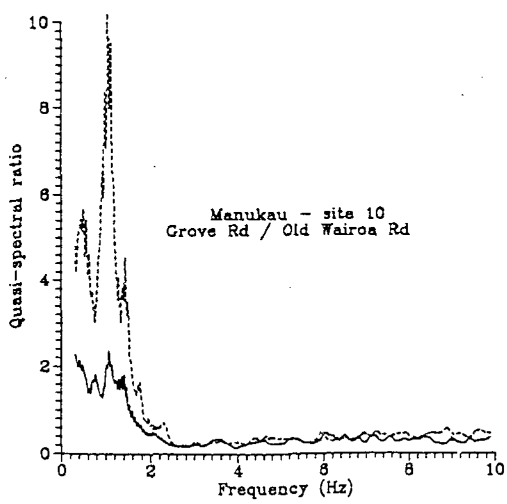

Manukau - site 5
Transpower substation
Quasi-spectral ratio
Frequency (Hz)

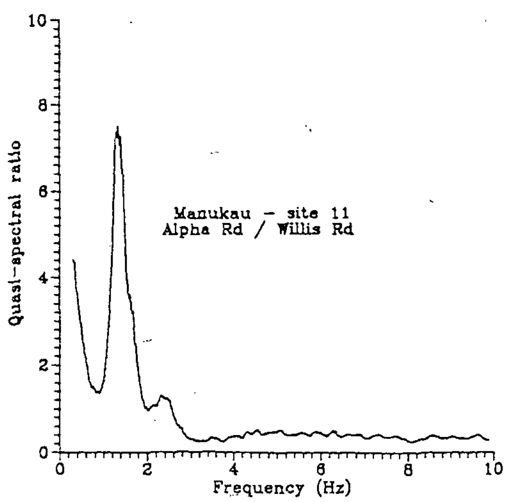

Manukau - site 6
Porchester Rd / Berwyn Ave
Quasi-spectral ratio
Frequency (Hz)

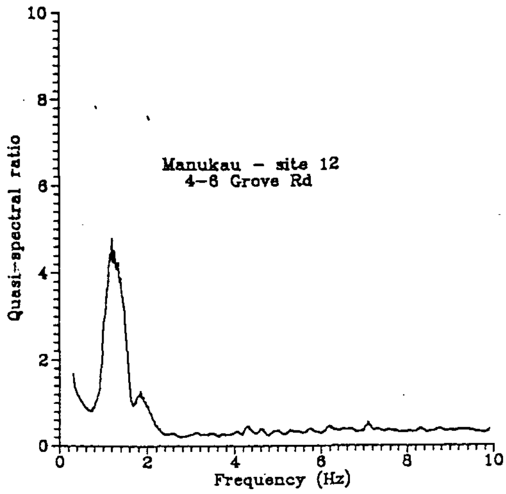

Manukau - site 7
Porchester Rd / Pope's Rd
NOTE Y SCALE
Quasi-spectral ratio
Frequency (Hz)

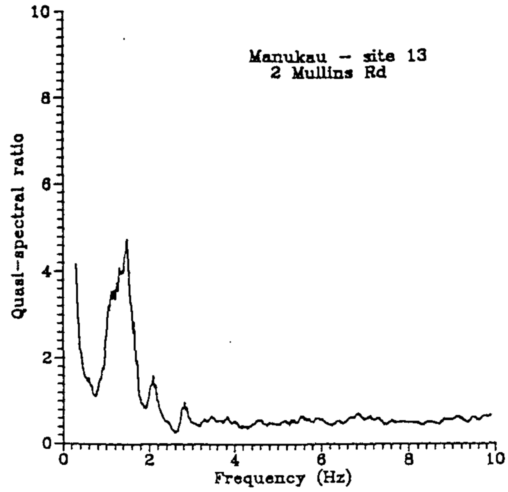

Manukau - site 8
Spartan Rd / Takanini Sch Rd
Quasi-spectral ratio
Frequency (Hz)

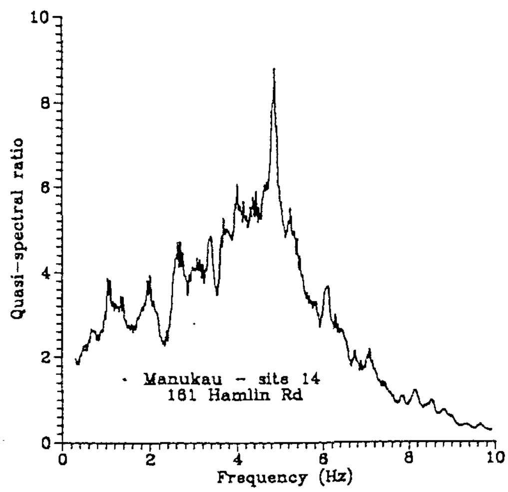

Manukau - site 9
Walters Rd / Grove Rd
Quasi-spectral ratio
Frequency (Hz)

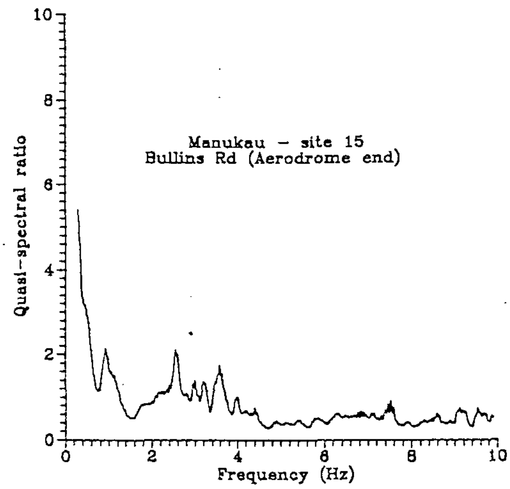

Manukau - site 10
Grove Rd / Old Wairoa Rd
Quasi-spectral ratio
Frequency (Hz)

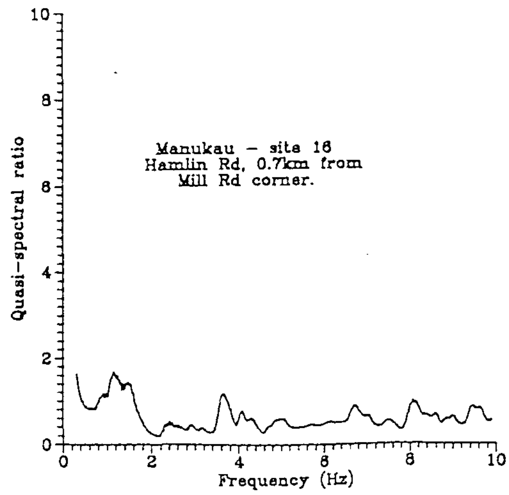

Manukau - site 11
Alpha Rd / Willis Rd
Quasi-spectral ratio
Frequency (Hz)

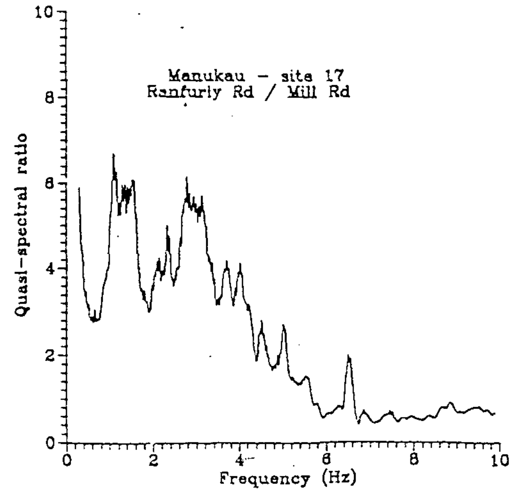

Manukau - site 12
4-6 Grove Rd
Quasi-spectral ratio
Frequency (Hz)

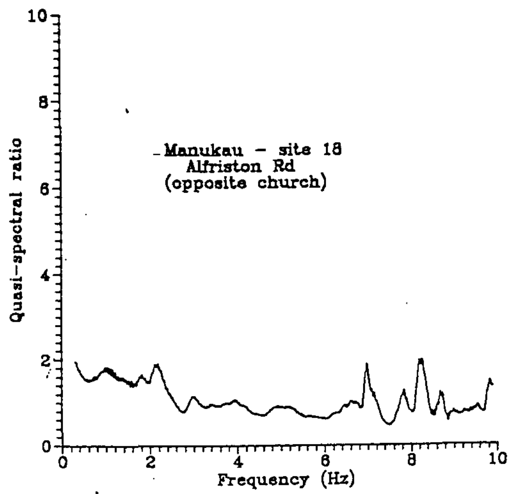

Manukau - site 13
2 Mullins Rd
Quasi-spectral ratio
Frequency (Hz)

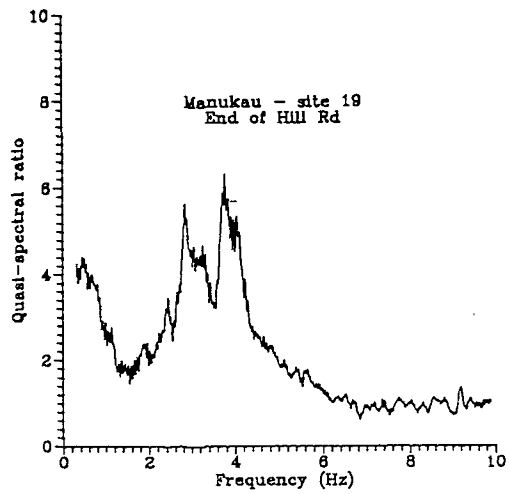

Manukau - site 14
161 Hamlin Rd
Quasi-spectral ratio
Frequency (Hz)

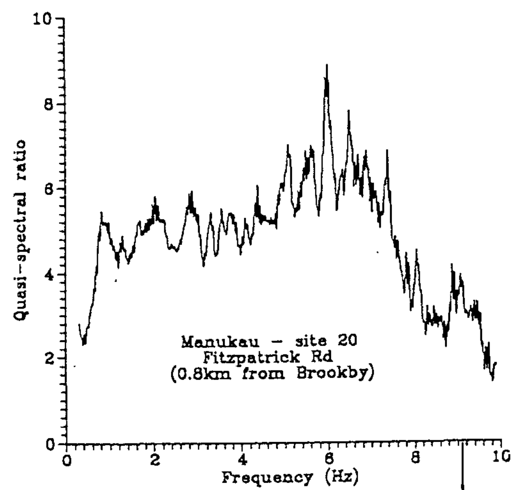

Manukau - site 15
Bullins Rd (Aerodrome end)
Quasi-spectral ratio
Frequency (Hz)

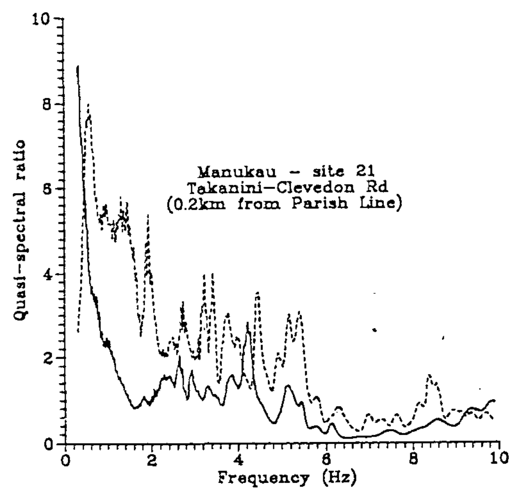

Manukau - site 16
Hamlin Rd, 0.7km from
Mill Rd corner.
Quasi-spectral ratio
Frequency (Hz)

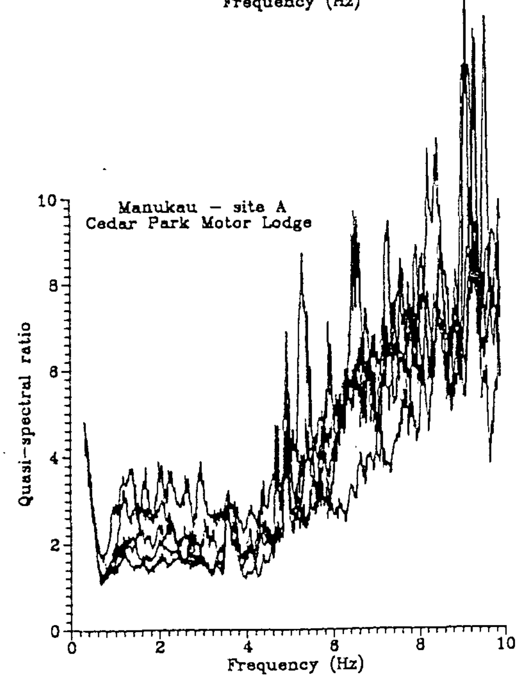

Manukau - site 17
Ranfurly Rd / Mill Rd
Quasi-spectral ratio
Frequency (Hz)

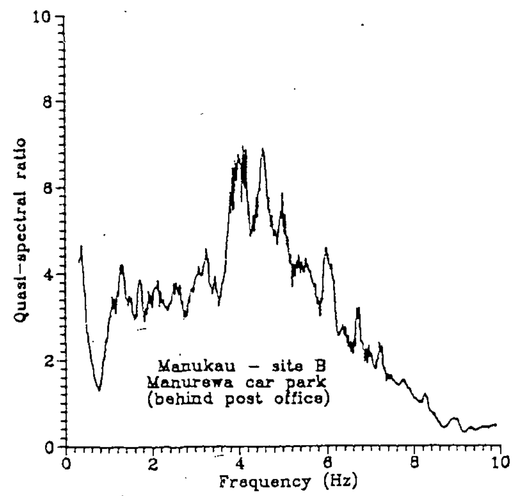

Manukau - site 18
Alfriston Rd
(opposite church)
Quasi-spectral ratio
Frequency (Hz)

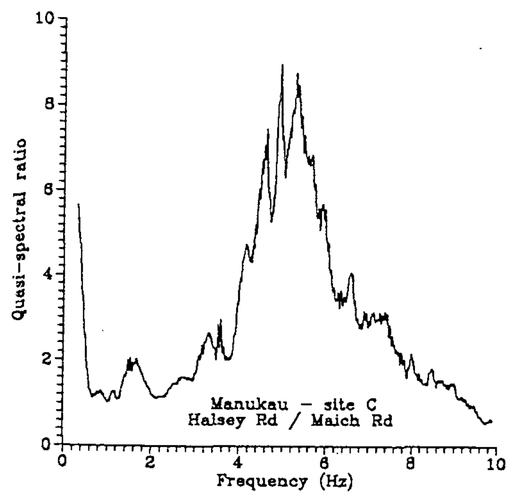

Manukau - site 19
End of Hill Rd
Quasi-spectral ratio
Frequency (Hz)

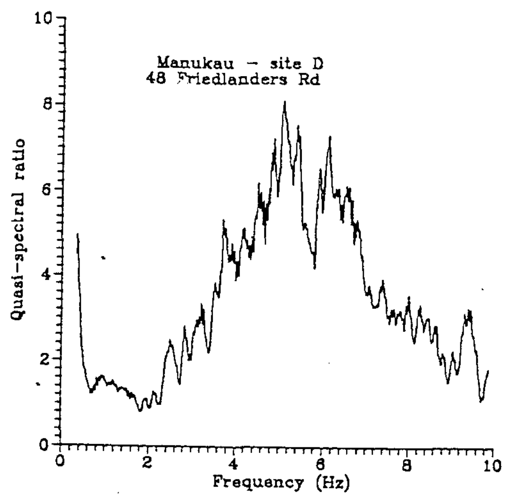

Manukau - site 20
Fitzpatrick Rd
(0.8km from Brookby)
Quasi-spectral ratio
Frequency (Hz)


Manukau - site 21
Takanini-Clevedon Rd
(0.2km from Parish Line)
Quasi-spectral ratio
Frequency (Hz)


Manukau - site A
Cedar Park Motor Lodge
Quasi-spectral ratio
Frequency (Hz)


Manukau - site B
Manurewa car park
(behind post office)
Quasi-spectral ratio
Frequency (Hz)


Manukau – site C
Halsey Rd / Maich Rd
Quasi-spectral ratio
Frequency (Hz)


Manukau – site D
48 Friedlanders Rd
Quasi-spectral ratio
Frequency (Hz)