Auckland Regional Council

Assessment for Amplification of Earthquake Shaking by Soft Soils in Central Auckland - Stage 2

Prepared for Auckland Regional Council

by

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SUMMARY

An extension of the report by Stephenson *et al.* (1997) on the amplification of earthquake shaking by soft soils in South Auckland, to areas where preliminary mapping shows possible site-related resonant amplification, and where there is considerable investment in infrastructure, has revealed limitations in the preliminary zoning based only on surface geology. The conflicts between surface-geology based zoning and microtremor based zoning are thought to arise from two sources: the inappropriate lumping of geological classes into hazard zones, and the failure of surface mapping to recognise that their soft soil layers do not materially increase shaking hazard. Recognising that site-specific responses often differ from microzoning designations in the Auckland area, Auckland Regional Council commissioned the Institute of Geological & Nuclear Sciences to test numerous sites throughout the Central Auckland region to assess how well a relatively random selection of sites conforms to the hazard zoning.

The study used 47 sites in Central Auckland and shows only a rough correlation between estimates of likely earthquake shaking response based on surficial geology and those based upon the Nakamura method of microtremor response:

- 67% of the sites measured within preliminary ground shaking hazard zone 4 show site resonance or possible resonance based on microtremors.
- Three of the nine sites measured within preliminary ground shaking hazard zones 1 and 2 show no site resonance.
- Six of the nine sites measured within preliminary ground shaking hazard zones 1 and 2 show site resonance or possible resonance.

Based on our microtremor study, soft-soil amplification of earthquake motion in Auckland is important at many locations (as shown on the accompanying map), 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 collection of geological units which have been lumped together as zone 1, and the collection of geological units which have been lumped together as zone 2, should be investigated with a view to refining the definitions of which materials are appropriate to include in these groupings (McVerry *et al.*, 1997).

1.0 INTRODUCTION

Recognising that soft soils can cause a considerable increase in earthquake shaking hazard, the Auckland Regional Council commissioned a study of natural ground vibrations (microtremors) by the Institute of Geological & Nuclear Sciences, Limited. The resultant report by Stephenson *et al.* (1997) showed that for the South Auckland area the Nakamura method of microtremor analysis was able to predict shaking hazard in a manner that supported and partially quantified surface geological mapping. The report also recommended 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 investrment in structures which would be damaged in the event of amplified shaking".

Following this report and its recommendations, Auckland Regional Council commissioned a study of a further 47 sites which were chosen in consultation with Auckland Regional Council on the basis of the report by Stephenson *et al.* (1997) concentrating mainly on developed areas zoned A on the basis of surface geology. This resulted in a concentration of sites in the part of the Central Business District near the harbour foreshore.

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, at sites where there is a sudden change in stiffness there are often high amplifications, such as near and at Wainuiomata near Lower Hutt, where surface peats and organic silts change abruptly to homogeneous stiff greywacke at a shallow depth.

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 in Williams and Hull (1997).
- 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:

- Based on the 1997 map, 47 sites in central Auckland were selected for field measurement. Most sites were in ground shaking hazard zone 4, and a select few from zones 1 and 2.
- 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 this technical report that specifies the purpose of the study, definition of terminology, the assumptions and limitations of the data, and interpretation.

The microtremor data collection was completed by Mr D. Baguley. Mr W. Stephenson analysed and interpreted the microtremor data. The report was compiled and reviewed by Dr. Mike Kozuch. Dr. Graeme McVerry reviewed the final report.

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. The original recommendation to quantify the nature of the hazard zones is that by Hull *et al.* (1995). In that report they outlined 5 zones in the hazard classification scheme. A subsequent study led to a regrouping of the 5 zones into 4 (Williams and Hull, 1997), with the soil classification scheme as presented by McVerry *et al.* (1997) which is given below:

Hazard Zone 1. Residual Soil Overlying Rock. Residual and colluvial soils, ash and weathered tuff with up to (1) 30m overlying greywacke, or (2) 20m overlying interbedded sandstone and mudstone, conglomerate and basalt.

Hazard Zone 2. Firm to Stiff Sediment of Pleistocene age. May be either (1) alluvium or (2) basalt, ash and tuff overlying alluvium.

Hazard Zone 3. Coastal Deposits. May be either (1) beach and dune sands or (2) human-made fills overlying zone 1 or 2 deposits.

Hazard Zone 4. Estuarine Deposits of Holocene age. May be either (1) stream alluvium and swamp deposits, or (2) human-made fills overlying zone 3 or 4 deposits.

In addition, each of these zones may contain material subject to different grades of weathering including CW (completely weathered), HW (highly weathered), MW (moderately weathered or very weak rock), SW (slightly weathered), or UW (unweathered rock).

2.2 Data Collection and Analysis

Based on the preliminary ground shaking hazard map, 47 sites were selected for microtremor analysis. Ambient vibrations on three axes were measured at these 47 sites. All 47 sites were located on three of the four preliminary ground shaking hazard zones. Table 1 below lists the selected sites with their locations.

Table 1: Site Locations in Terms of NZMG Eastings and Northings of the 47 Auckland Nakamura Survey Sites

Site	E	N	Site	E	N
1	2666102	6489728	24	2668673	6480102
2	2668358	6488491	25	2668922	6479792
3	2669029	6488488	26	2670449	6480293
4	2671638	6484977	27	2670517	6479800
5	2671415	6484697	28	2674803	6481554
6	2670380	6484075	29	2675197	6478541
7	2665905	6483704	30	2665170	6477404
8	2666092	6483172	31	2666220	6475206
9	2666872	6482564	32	2670381	6477540
10	2667014	6482945	33	2674694	6476257
11	2667512	6482729	34	2668550	6473598
12	2667392	6481817	35	2669434	6472936
13	2668245	6482438	36	2669836	6473512
14	2668372	6482062	37	2669731	6472189
15	2668638	6482649	38	2672587	6474154
16	2669116	6482507	39	2673006	6474047
17	2669095	6482352	40	2673161	6473786
18	2669609	6482292	41	2675221	6474613
19	2668533	6481718	42	2668593	6469064
20	2667495	6481192	43	2667456	6463325
21	2663253	6481026	44	2669788	6464680
22	2665324	6480005	45	2670585	6464123
22a	2665341	6479957	46	2676534	6469420
23	2667833	6480076	47	2678273	6470994

2.2.1 Borehole Data

In the pilot South Auckland study (Stephenson *et al.*, 1997), client-provided borehole log data was tabulated even though it related to only 7 of the 25 sites. However, no analytical use was made of the borehole data because of its lack of information which could be converted into shear wave velocities.

In the context of microtremors analysed by the Nakamura method, borehole data is of very limited use. Because maps of surface geology reflect only the surface situation, it is possible for a region to be mapped as (for example) zone 4, when there is only a minimal depth of zone 4 material present. Thus a 1 m layer of peat, while contributing nothing to seismic hazard, can cause a zone to be mapped as 4. If however, a borehole were situated at that site, and it clearly showed that the surface geology consisted of a thin veneer of peat on rock, an apparently anomalous Nakamura classification would be explained. The converse does not usually apply - it is unusual for surface rock to be a thin layer over flexible material. The exception to this might be a lava flow resting on sediments.

Accordingly, the potential use of borehole log data is confined to resolving anomalies where a Nakamura classification of "resonant" or "possibly resonant" was made in zone 4. Even then, it is necessary that the borehole log be known to accurately reflect the situation at the microtremor recording site. But for this to occur in the Auckland situation, where zone 4 often occurs in very small patches, the borehole site and the microtremor site must be one and the same.

Given these tight constraints, the only comment that can be made is that there is every indication that for sites 25, 39, and 40 it is likely that the materials mapped as zone 4 are sufficiently thin that a non-resonant response would not be surprising.

3.0 Microtremor Analysis

3.1 Introduction

Microtremors are the continuous vibrations of the ground which a seismograph records in the absence of earthquakes. They often 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.

Microtremors primarily consist of the particle motions of passing Rayleigh waves. Assuming that Rayleigh waves have equal vertical and horizontal components at the base of the surface layer, Lermo and Chavez-Garcia (1994) showed that 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" (qsr) 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 & Nuclear Sciences Using the Nakamura Method

The Institute of Geological & 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 (qsr) indicated moderate broad-band amplification (Appendix 1); stronger than was seen in recordings of earthquakes. 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 (Appendix 1) correctly predicted the extremely high amplifications which were observed. 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 maximum quasi spectral ratio for Porirua is much the same as for Alfredton, the earthquake responses of the two sites might 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 maximum amplification as Wainuiomata, albeit at a different frequency, and the Porirua maximum amplification factor and frequency were both accurately predicted beforehand by Stephenson *et al.* (1990) on the basis of geotechnical measurements. The important difference in the qsr for these sites appear to be the high-frequency character. The Porirua qsr falls to less than one, while that at Alfredton does not show this character.

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 Chavez-Garcia 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 expected Nakamura ratio for 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 Advances in Knowledge Since Previous Report

Since the publication of the report on South Auckland by Stephenson *et al.* (1997), staff of the Institute of Geological & Nuclear Sciences have been involved in further microtremor analysis using the Nakamura method in studies of Suva and of Hawkes Bay. These studies have led to a better understanding of the relationship between surface geology and Nakamura ratios. In particular, the Hawke's Bay study, with its parallel investigations using penetrometry and recorded earthquakes at a range of sites, confirmed the ability of the Nakamura method to identify soft soil layers with a high impedance contrast between the basement and the soft layer. In addition the Suva study showed that in certain circumstances, mapped surface geology correlates only weakly with site amplification of earthquakes.

Application of the Nakamura technique to microtremors recorded at Pukehou, Hawke's Bay, showed that our equipment and techniques will identify resonant sites with natural frequencies down to 0.5 Hz.

A recent paper by Konno and Ohmachi (1998) which uses the Nakamura technique applied to microtremors recorded at 546 sites in Tokyo, uses our criterion of a trough at a frequency of twice the peak in a quasi-spectral ratio plot, to identify a resonant site.

3.5 Data Collection

Microtremors (ambient ground vibrations) were recorded at 47 locations in Auckland, for a minimum of ten minutes at each location. In this process, seismometers (Kinematrics 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 & Nuclear Sciences in consultation with Auckland Regional Council on the basis of existing surface geological maps. 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 directional dependence, although this study treats the horizontal vibrations as azimuth-independent.

Data collection were undertaken from 4 May to 7 May 1998. It was possible to make a preliminary examination of the records each evening, and as a result two sites were re-occupied to gather data which had been lost due to instrument malfunction.

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.

3.6 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.

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, were 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 were summed separately for the horizontal, and then for the vertical. 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 squared 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 were 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 were written to a file called sitexx.ratio for each site, with xx being the serial number of each site. These are the data which are 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 most spectral ratio results below 0.3 Hz. An exception has been made in the case of the 13 datasets which showed unusual low frequency peaks (section 3.7.5) in order that these peaks may be discussed. The usual cutoff frequency 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.

3.7 Results

The results of this study are the quasi-spectral ratios plotted in Appendix 2 of this report. The accompanying map depicts the locations of the sites on a zoning basemap. The symbols to the sites themselves have been coded to show whether they resonate, possibly resonate, do not resonate, or are in question. 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 one of the cases shown in Appendix 2 (site 22) a duplicate set of quasi-spectral ratios is shown by a dotted line. The duplicate quasi-spectral ratio is derived from a separate set of microtremor data recorded on another day, at a distance of 40m from the original site, but on the same material.

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. Narrow peaks with low ratio values at high frequencies should be the main criterion for assessing amplification. The criteria we use in identifying sites to be resonant, non-resonant or undetermined are outlined in Appendix 3.

3.7.1 Resonant Sites

Many 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 and in Appendix 3.

These are sites 2, 7, 10, 15, 16, 19, 20, 22, 27, 31, 34, 42, 44, and 46 (Table 2). In each case the spectrum has a resonant peak, and the amplitude falls off at frequencies above the peak.

3.7.2 Possible Resonant Sites

Sites 1, 3, 4, 6, 8, 9, 11, 12, 14, 17, 23, 24, 28, 41, 42, 43, 45 and 47 produced spectra which have some features consistent with resonance, but do not have the complete set of criteria which we deem necessary for a site to be unambiguously classified as resonant (Table 2). Examples are sites 8 and 9 where the quasi-spectral ratio eventually drops to a low value, but only at a relatively high frequency, and after a broader peak than is normally associated with resonance. A different example is at site 47, where the characteristic high-frequency fall-off is preceded by a very low, very broad peak.

3.7.3 Non Resonant Sites

Sites 5, 13, 18, 25, 30, 32, 35, 37, 38, 39 and 40 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.

3.7.4 Unclassified Sites

Sites 21, 26, 29, 33 and 36 gave rise to quasi-spectral ratio curves which do not fit within any established category - either the recorded vibrations were unsuitable for some reason, or the particular sites were of a type which we do not recognise from their quasi-spectral ratios.

3.7.5 Low Frequency Peaks

Unexpected peaks in the quasi-spectral ratio plots have been observed at 13 (about a quarter) of the sites. These peaks are at sites 2, 3, 4, 5, 6, 18, 19, 25, 29, 32, 37, 38, and 47, and have frequencies between 0.24 Hz and 0.44 Hz. The fact that each peak has a different frequency suggests that their cause is not instrument related, and the fact that the peaks are observed at some inland sites suggests that their cause is not surf. It is possible that the peaks arise from large scale topography or from a large scale deep geological layering.

If these peaks indicate a low frequency resonant response (and they may not), any resonant amplification will be at a frequency corresponding only to very tall structures. It is unusual for any except the very largest earthquakes to radiate significant amounts of energy at such low frequencies, so there will usually be little ground motion to be amplified. Furthermore, the low frequency resonators which are implied by the peaks will have an isolating effect at the higher frequencies at which structures usually respond to shaking.

Recent work by the Institute of Geological & Nuclear Sciences, funded by the Foundation for Science, Research and Technology, has compared Nakamura ratios computed for a known resonant site (Wainuiomata Fire Station) where the data was recorded both by the standard L4C3D seismometer (employed in this study) and by a Guralp long-period seismometer. The comparison (not yet published) suggests that use of the L4C3D sensor results in quasi-spectral ratios below 1 Hz which are progressively exaggerated as the frequency falls. The exaggeration amount to a few percent at 1 Hz, but a factor of 8 at 0.2 Hz. Thus, we believe that the low frequency peaks under discussion are probably exaggerated.

On the basis of all of the above, we consider that the low frequency peaks constitute an unimportant effect arising from an unknown cause.

3.7.6 Anomalous Results

In fourteen cases, the Nakamura results run counter to the hazard map based on geological mapping. In eight cases (sites 5, 18, 25, 30, 35, 37, 39 and 40) sites situated in zone 4 proved to lack a resonant character. There are three ways in which this could happen: (1) poor registration between the street map (used to locate sites) and the GIS based hazard map could cause site zones to be incorrectly assigned, (2) the correctly mapped surface geology could be a thin veneer, with the site response reflecting the geology a few metres below the surface (Steve Edbrooke, GNS, personal communciation), or (3) there is a velocity gradient as a function of depth rather than a sharp velocity contrast at the site.

In a further six cases (sites 2, 12, 14, 20, 46 and 47) sites situated in zones 1 and 2 proved to be resonant or possibly resonant. There are several reasons for this which may include: (1) poor registration between the street map (used to locate sites) and the GIS based hazard map could cause site zones to be incorrectly assigned; (2) there could be an inappropriate grouping of mapped materials into zones 1 and 2; (3) the wide range of materials and their properties in any particular hazard zone may yield exeptions to the zoning (McVerry *et al.*, 1997); and (4) the qsr would be demonstrating effects due to topography, which can also provide amplification, rather than geological materials. In particular, the Tauranga sequence materials which derive from Waitemata materials could have large amounts of clay, could incorporate pumice, and could have unusually high water content. If this were so, they would have low shear wave velocity, and would amplify earthquake shaking, perhaps resonantly (Steve Edbrooke, GNS, personal communication). It would be advantageous to determine whether or not the sites in zone 1 and 2 which were found to be resonant were situated over highly weathered material.

3.8 Limitations

We have identified five major limitations to this study which may have an impact on the overall interpretation or usage of results.

The first limitation is that of data 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 2, 7, 10, 15, 16, 19, 20, 22, 27, 31, 34, 44, and 46.

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. McVerry *et al.* (1997) included nonlinear behavior in their estimate of amplifications but did not take into account the high plasticity of clays. In the case of 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 (non-Auckland) 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 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 complex and rapidly varying geology in the Auckland area, with the shear wave velocities of typical materials quite unknown, except by correlation with materials of similar description elsewhere. In particular, a number of the Auckland soils are not included in the Borcherdt and NEHRP tables used to estimate amplification in Auckland (McVerry *et al.*, 1997).

Table 2: Sites With Locations and Microtremor Analysis Comments

This table shows the site name, site location, hazard zone in which the site is situated, the quasi-spectral ratio type (RES=resonant, NON=non-resonant, POSS=possibly resonant and ?=unknown) and an asterisk indicating a conflict between the zone and qsr. The exclamation remark denotes sites which were in a "good" zone, but which turned out "bad". This is significant because usually a "good" site is obvious, like hard rock, and will never be wrong, whereas a zone 4 site could be literally correct due to clay or peat which is only a metre thick, but which does little to modify shaking. An asterisk alone shows a conservative error, whereas an asterisk and exclamation mark together point to a dangerous situation - something which we said appears safe on the basis of zoning, is actually hazardous. It is important to note that the table of amplification factors for various zones pointed out that exceptions existed for every zone. NOTE: Use this table with the map that accompanies this report.

Site	Location	Zone	QSR	Conflict
Site 1	North Shore (Porana Rd / Goldfield)	4	POSS	
Site 2	North Shore (Byron Ave / Burns Ave)	2	RES	*!
Site 3	North Shore (Beach end of Park Ave)	4	POSS	
Site 4	North Shore (Beach end of Matai Rd)	4	POSS	
Site 5	North Shore (Cambridge Tce / Tui St)	4	NON	*
Site 6	North Shore (Garden Tce / Queens Pde)	4	POSS	
Site 7	Westhaven (Boat harbour - north mole)	4	RES	
Site 8	Westhaven (Boat harbour - south mole)	4	POSS	
Site 9	Auckland City (Fanshawe St / Daldy St)	4	POSS	
Site 10	Auckland City (Brigham St / Madden St)	4	RES	
Site 11	Auckland City (Market Pl / Customs St)	4	POSS	
Site 12	Auckland City (Cook St / Hobson St)	1	POSS	*!
Site 13	Auckland City (Gore St Ln / Fort St)	1	NON	
Site 14	Auckland City (Parliament St / Waterloo Qd)	1	POSS	*!
Site 15	Auckland City (Tinley St / Tooley St)	4	RES	
Site 16	Auckland City (Tooley St / Monash St)	4	RES	
Site 17	Auckland City (Quay St / Monash St)	4	POSS	
Site 18	Auckland City (Sunderland Rd - at bend)	4	NON	*
Site 19	Auckland City (Stanley St / Alten Rd)	4	RES	
Site 20	Auckland City (Queen St / Karangahape Rd)	2	RES	*!
Site 21	Pt Chevalier (Meola Rd 200m from Meola Ck)	4	?	
Site 22	Kingsland (end of School Rd)	4	RES	
Site 22a	Kingsland (Near end of School Rd)	4	RES	
Site 23	Mt Eden (Lauder Rd - Prison)	4	POSS	
Site 24	Newmarket (Khyber Pass Rd / Crowhurst St)	4	POSS	
Site 25	Newmarket (Remuera Rd / Broadway)	4	NON	*
Site 26	Remuera (Shore Rd, at Waitaramoa reserve)	4	?	
Site 27	Remuera (Portland Rd / Ingham Rd)	4	RES	
Site 28	Kohimarama (Melanesia Rd / Baddeley Ave)	4	POSS	
Site 29	St Johns (Merton Rd / Howard Hunter Ave)	4	?	
Site 30	Sandringham (Sandringham Rd / Kitchener Rd)	4	NON	*
Site 31	Mt Roskill (Frost Rd / Carr Rd)	4	RES	
Site 32	Green Lane (Green Lane / Marewa Rd)	1	NON	
Site 33	Mt Wellington (Mt Wellington Hwy / William Harvey Pl)	4	?	

Site	Location	Zone	QSR	Conflict
Site 34	Onehunga (Orpheus Drive at lagoon)	4	RES	
Site 35	Onehunga (Old Mangere Bridge, North end)	4	NON	*
Site 36	Onehunga (Neilson St / Victoria,Galway Sts)	4	?	
Site 37	Mangere Bridge (Crawford Ave / Waterfront Rd)	4	NON	*
Site 38	Southdown (Church St / O'Rorke Rd)	1	NON	
Site 39	Southdown (Industry Rd, 200m from Church St)	4	NON	*
Site 40	Southdown (Industry Rd / Southdown Lane)	4	NON	*
Site 41	Mt Wellington (Bowden Rd, at bend)	4	POSS	
Site 42	Mangere (Island Rd, 400m from Greenwood Rd)	4	POSS	
Site 43	Airport (Runway reclamation, west end)	4	POSS	
Site 44	Airport (George Bolt Dr / Andrew McKee Ave)	4	RES	
Site 45	Airport (south of Runway, Near east end)	4	POSS	
Site 46	Otara (Natalie Place, midway)	2	RES	*!
Site 47	East Tamaki (Kerwyn Ave / Andromeda Cres)	2	POSS	*!

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.

3.9 Significance

This study has shown a loose correspondence between sites determined from surficial geology to be of highest earthquake shaking amplification and site resonance as measured by microtremor analysis. Most sites classified by Williams and Hull (1997) [or Hull *et al.* (1995)] as having the greatest likely earthquake shaking response are shown to be resonant or possibly resonant. However, fully two thirds of the sites in zones 1 and 2, where little or no amplification was assigned to the zone as a whole, showed resonance or possible resonance. This may be a result of inappropriate lumping of geological units into hazard zones, and this merits additional investigation. Each zone contains material with amplifications characteristic of other zones. The current study did not endeavor to determine actual soil conditions at any of the sites where recordings were taken, so it is not possible to comment on whether any of the apparent conflicts between the mapped and actual amplification characteristics were due to the presence of materials lumped into an inappropriate zone.

This poor correspondence between mapped zones and Nakamura classifications is in marked contrast to the results of the South Auckland study by Stephenson *et al.* (1997). However, there is a crucial difference in the geological settings appropriate to the two areas. In the case of the South Auckland area, the distribution of the majority of the soft soils was controlled by the Drury fault, which by a process of continued vertical displacement acted to pond erosional material in a large basin to its western side. As a result, much of the soft material is deep and also extremely flexible. Accordingly, it is highly likely that in the South Auckland area any material zoned 4 will be unambiguously deep and flexible, while other materials will be much firmer.

By contrast, the materials from Takapuna through to Papatoetoe are of very mixed origin and vary rapidly over short distances. A common scenario for the origin of zone 4 material in this region involves erosional products of Tauranga group sediments being ponded very locally by volcanic material emerging through the Waitemata sandstones. Such a process gives rise to very small local deposits of clayey materials, with the ponded material often being shallow. As a result of this quite different process the likelihood is high that a material zoned 4 may be shallow and (as far as shaking amplification is concerned) act more in accordance with the underlying material. In addition, much of the material outside of zone 4 could have high flexibility despite its age and origin. This follows from the high clay content of the alluvial materials and the low density of the pumiceous materials, meaning that some zone 1 and zone 2 materials could have quite low shear wave velocities, making assignment into a higher zone more appropriate.

The earthquake shaking amplification predicted by the results of this study could increase observed earthquake shaking intensity by 1.5-2 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.

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 1964 Anchorage earthquake and the 1964 Niigata earthquake, have caused substantial economically liquefaction damage. Holzer (1994) 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

From this study we may conclude that:

1. Of 47 sites sampled in the greater central Auckland region, there is only a rough correlation between estimates of likely earthquake shaking response based on surficial geology and those based upon the Nakamura Method of microtremor response.

2. Most sites measured within preliminary ground shaking hazard zone 4 show site resonance or possible resonance of microtremors. The exceptions are likely to be where the correctly assessed surface geology is only superficial, with firmer material a very few metres below.

3. Few of the sites investigated in zones 1 and 2 showed the expected absence of resonant behaviour, presumably because of inappropriate lumping of geological classes into hazard zones or the larger scale of analysis in previous studies. The anomalies might also be due to the variability of material characteristics in each zone due to weathering.

4. As assessed by Nakamura's microtremor quasi-spectral ratio technique, soft-soil amplification of earthquake motion in Auckland is important in many 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 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 shear wave velocity characteristics of materials in the various geological units used to construct the zoning map, and (2) in areas zoned 4, where there is valuable infrastructure, and where it is suspected that the soft material may be shallow, to record and analyse microtremors (using the Nakamura method).

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.

6.0 ACKNOWLEDGMENTS

We are grateful to David Heron for producing the GIS hazard basemap for plotting the sites and to Steve Edbrooke who provided many useful comments on the geology. We also thank G. McVerry for his final review of the document.

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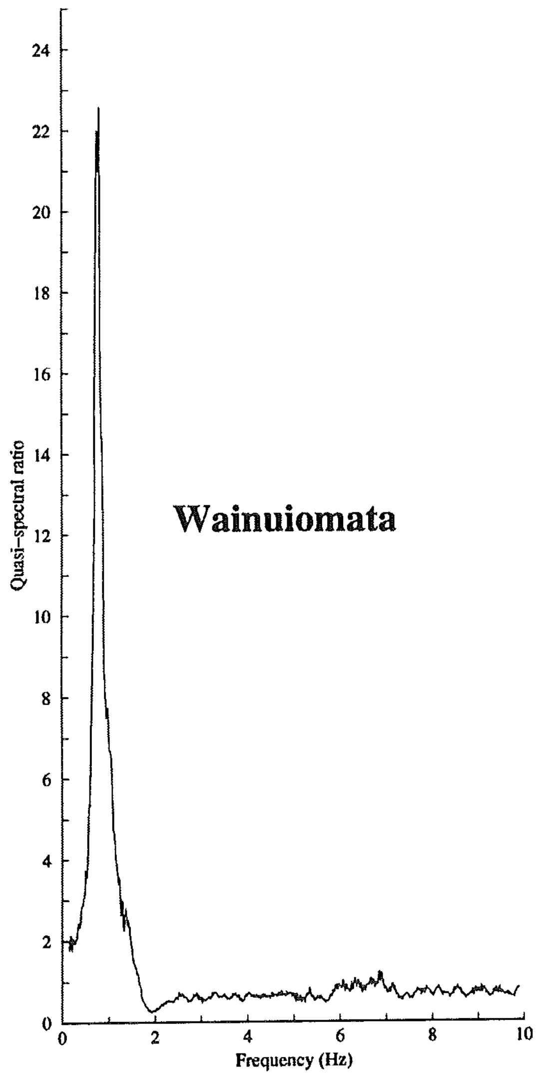
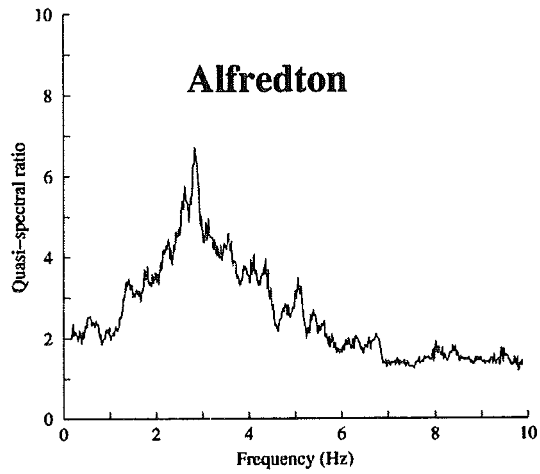
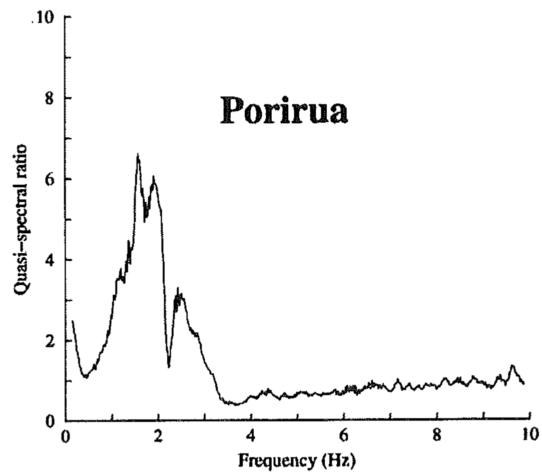
APPENDIX 1

Quasi Spectral Ratios of Microtremors at Known Sites


Wainuiomata
Quasi-spectral ratio
0
2
4
6
8
10
12
14
16
18
20
22
24
Frequency (Hz)
0
2
4
6
8
10


Alfredton
Quasi-spectral ratio
0
2
4
6
8
10
Frequency (Hz)
0
2
4
6
8
10


Porirua
Quasi-spectral ratio
0
2
4
6
8
.10
Frequency (Hz)
0
2
4
6
8
10

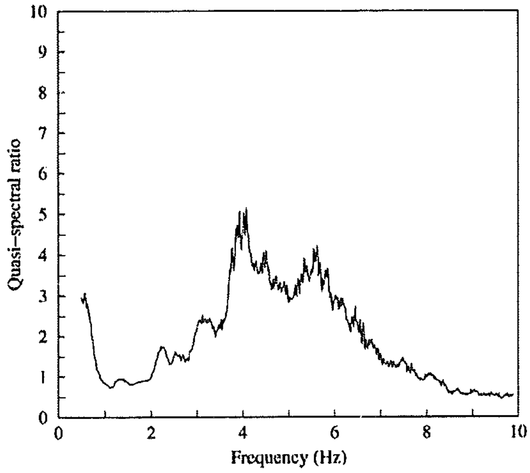
APPENDIX 2

Quasi Spectral Ratios of Microtremors at Auckland Sites

Auckland Quasi–Spectral Ratios

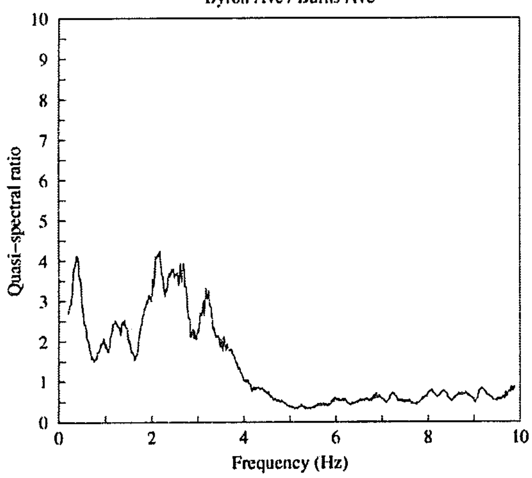
Site 1 – North Shore

Porana Rd / Goldfield



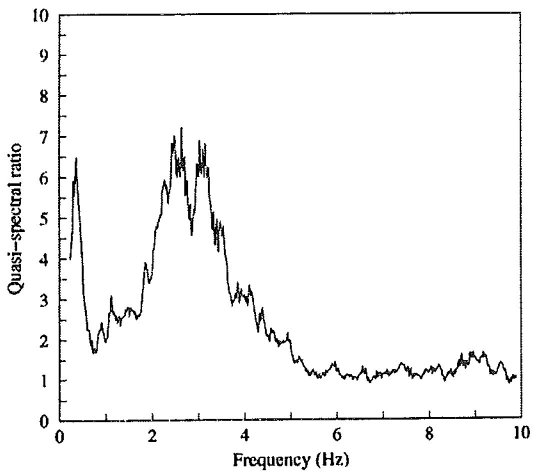
Site 2 – North Shore

Byron Ave / Burns Ave



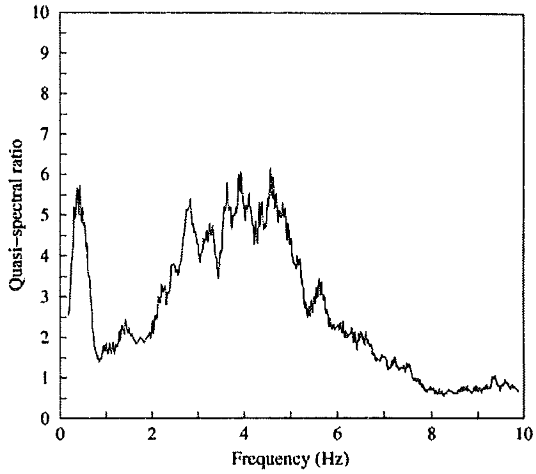
Site 3 – North Shore

Beach end of Park Ave



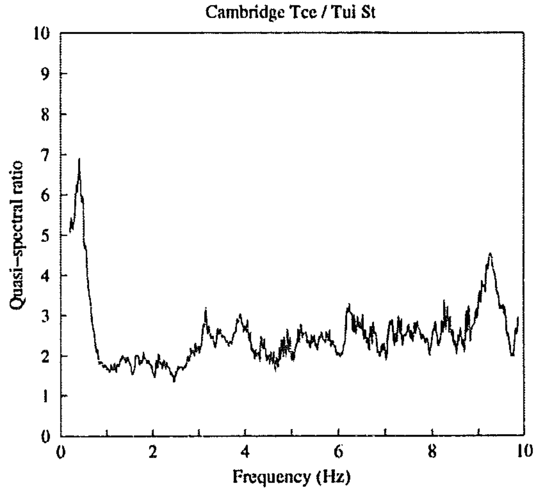
Site 4 – North Shore

Beach end of Matai Rd



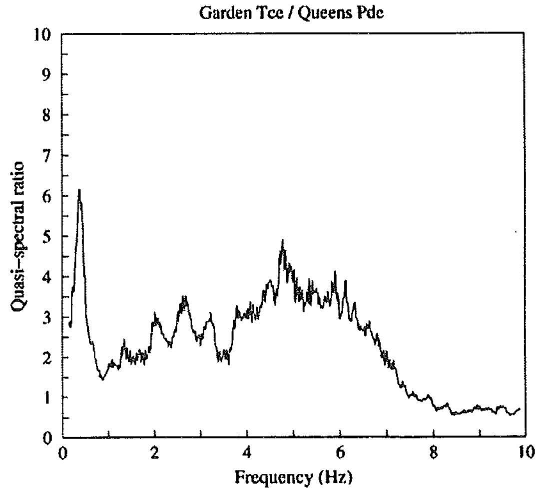
Site 5 – North Shore

Cambridge Tce / Tui St



Site 6 – North Shore

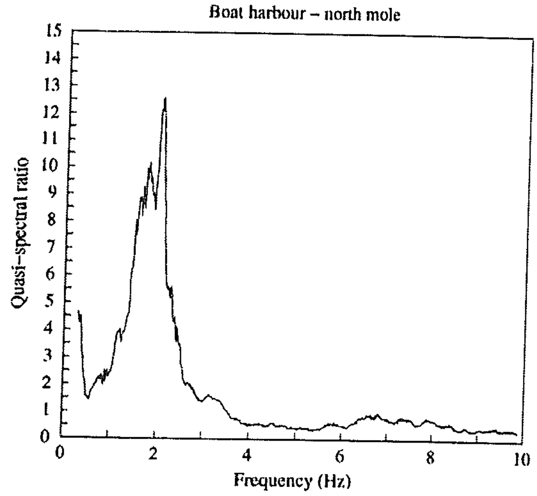
Garden Tce / Queens Pde



Auckland Quasi-Spectral Ratios

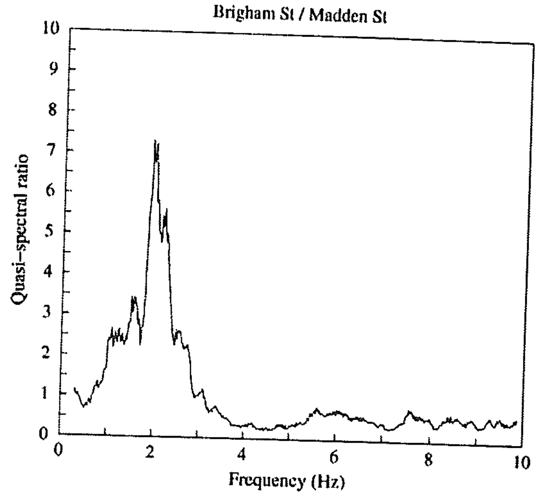
Site 7 – Westhaven

Boat harbour – north mole



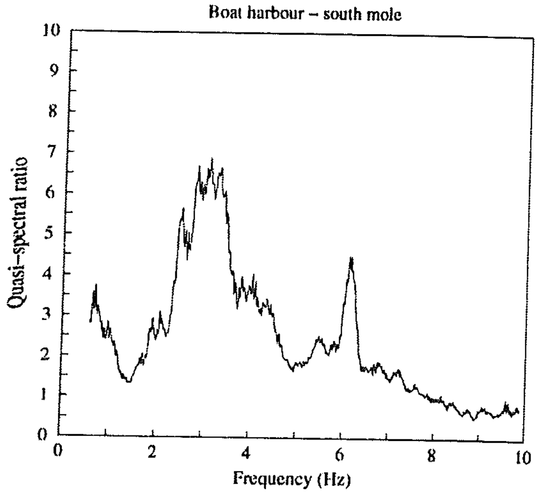
Site 10 – Auckland City

Brigham St / Madden St



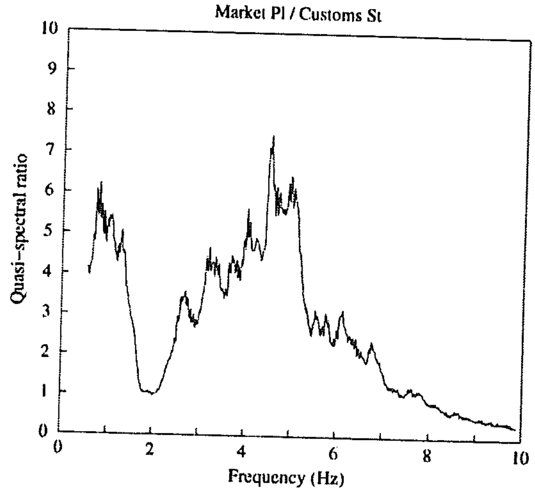
Site 8 – Westhaven

Boat harbour – south mole



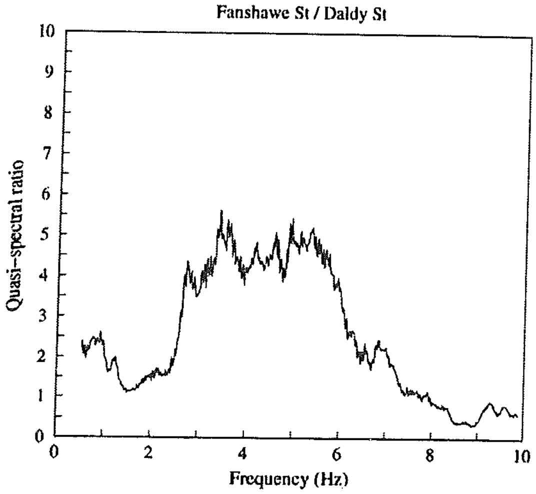
Site 11 – Auckland City

Market Pl / Customs St



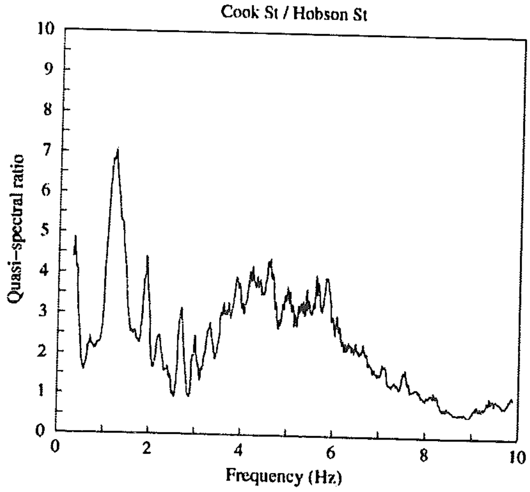
Site 9 – Auckland City

Fanshawe St / Daldy St



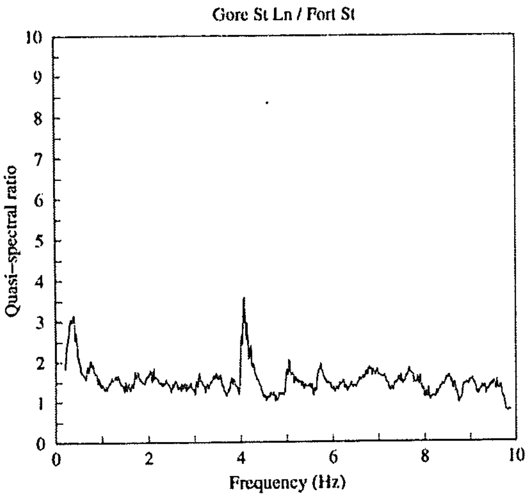
Site 12 – Auckland City

Cook St / Hobson St

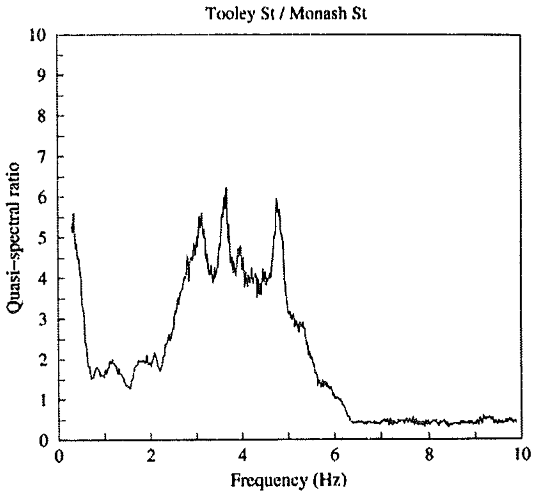


Auckland Quasi-Spectral Ratios

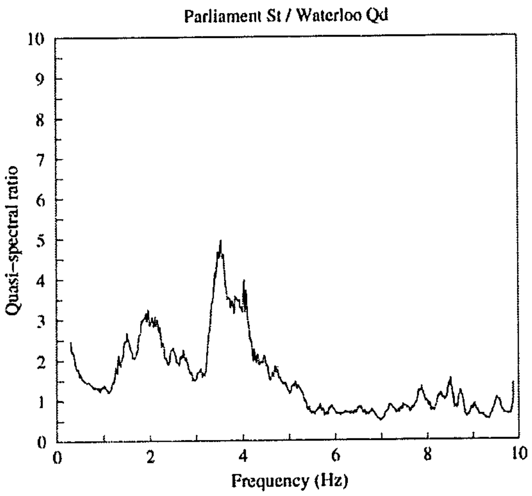
Site 13 – Auckland City



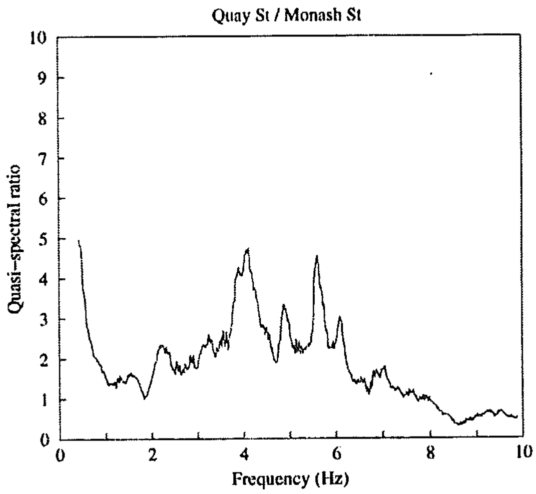
Site 16 – Auckland City



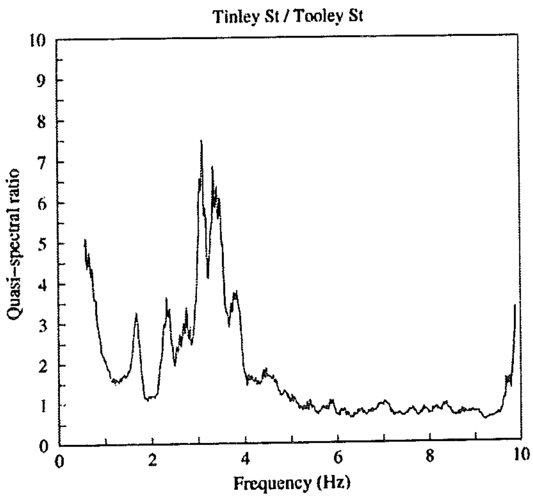
Site 14 – Auckland City



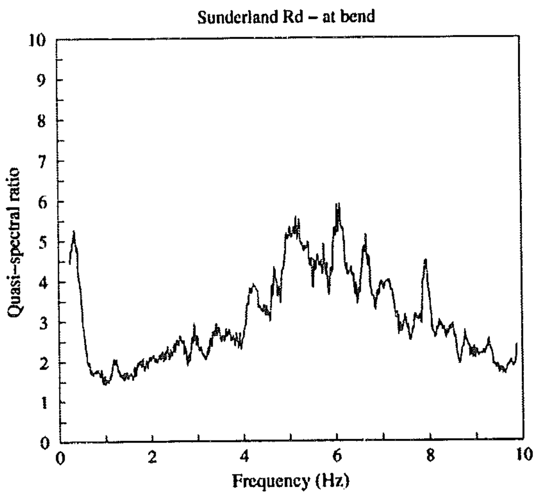
Site 17 – Auckland City



Site 15 – Auckland City



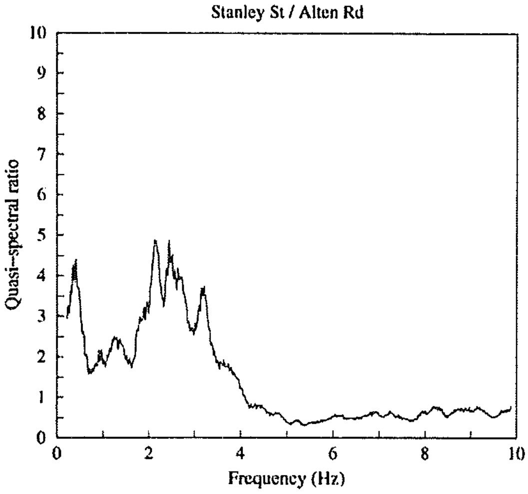
Site 18 – Auckland City



Auckland Quasi-Spectral Ratios

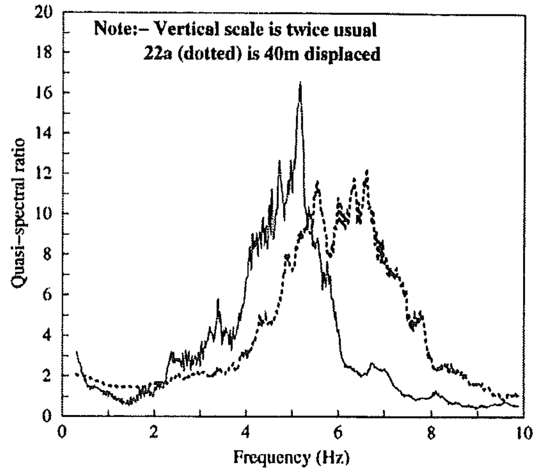
Site 19 – Auckland City

Stanley St / Alten Rd



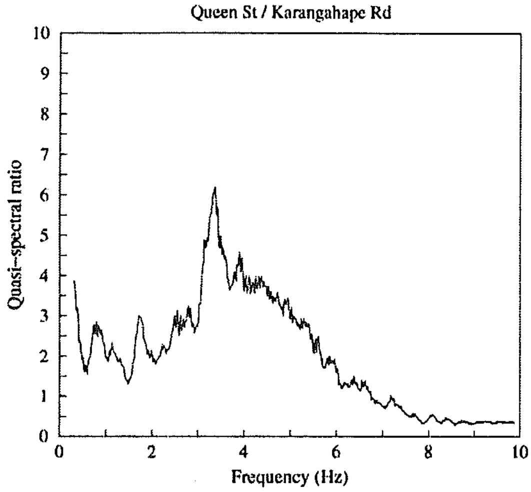
Site 22 – Kingsland

End of School Rd



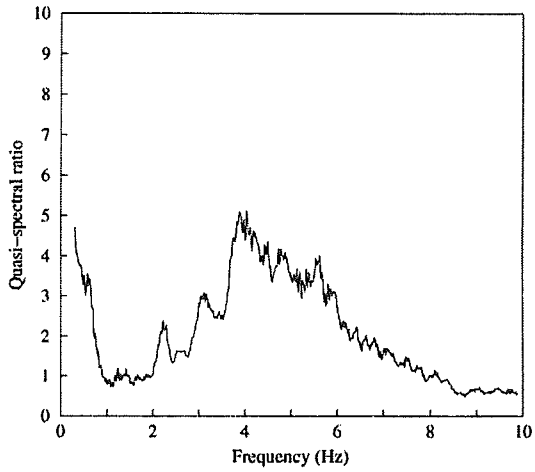
Site 20 – Auckland City

Queen St / Karangahape Rd



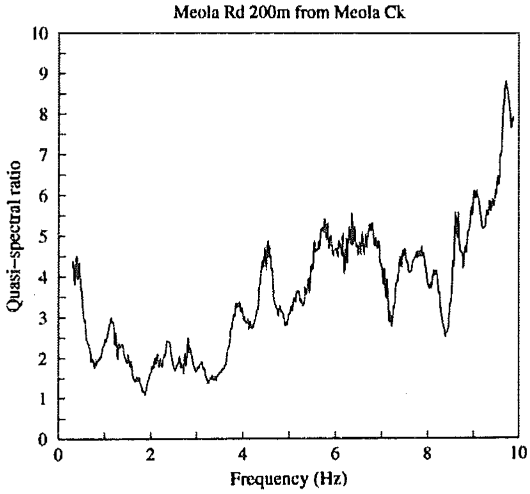
Site 23 – Mt Eden

Lauder Rd – Prison



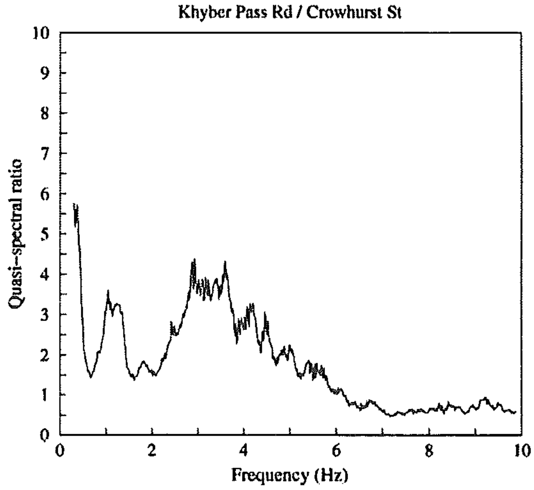
Site 21 – Pt Chevalier

Meola Rd 200m from Meola Ck



Site 24 – Newmarket

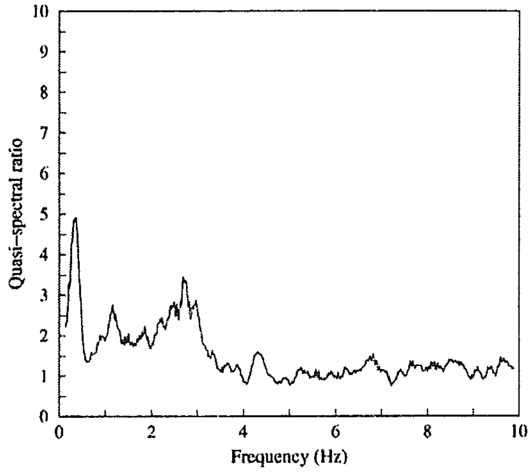
Khyber Pass Rd / Crowhurst St



Auckland Quasi–Spectral Ratios

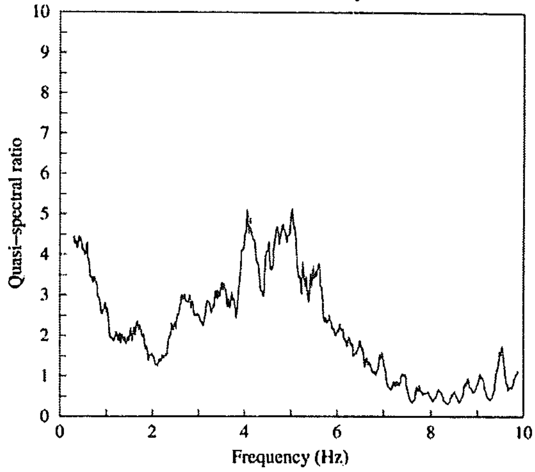
Site 25 – Newmarket

Remuera Rd / Broadway



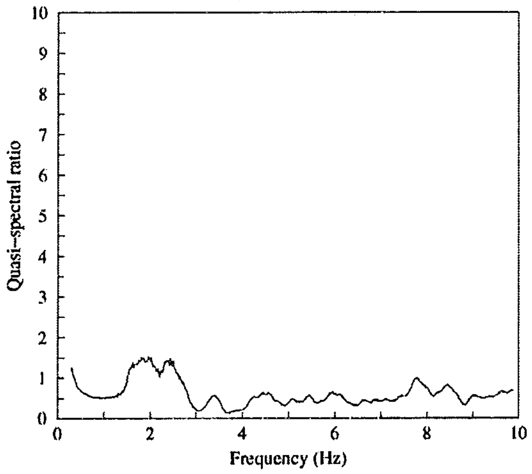
Site 28 – Kohimarama

Melanesia Rd / Baddeley Ave



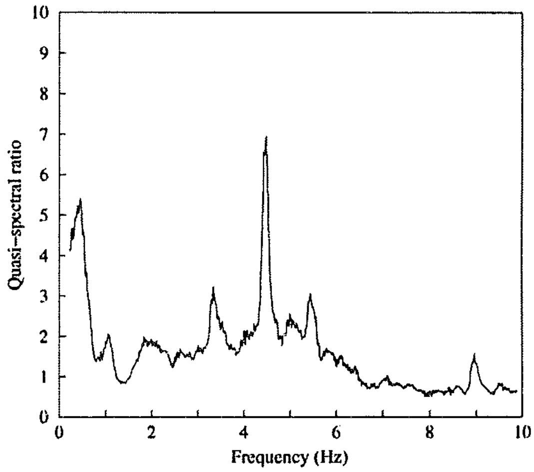
Site 26 – Remuera

Shore Rd, at Waitaramoa reserve



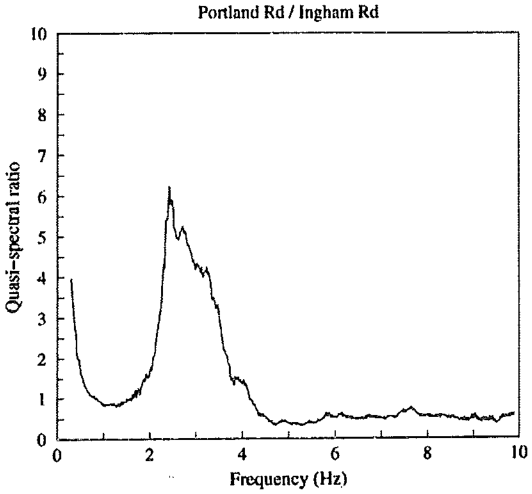
Site 29 – St Johns

Merton Rd / Howard Hunter Ave



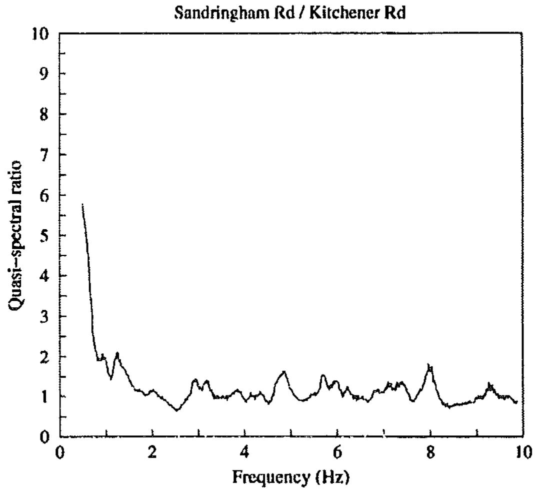
Site 27 – Remuera

Portland Rd / Ingham Rd



Site 30 – Sandringham

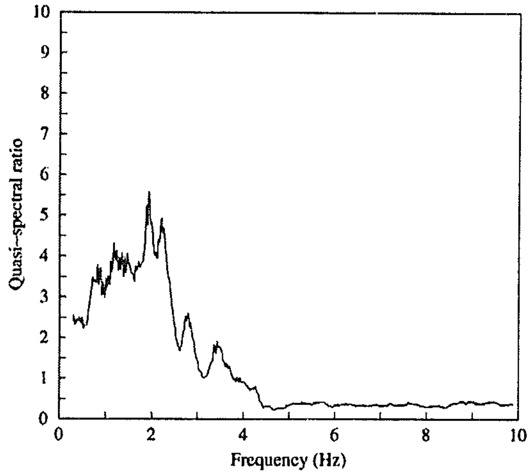
Sandringham Rd / Kitchener Rd



Auckland Quasi-Spectral Ratios

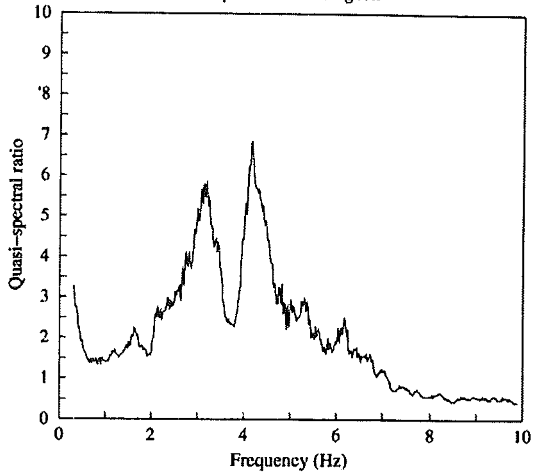
Site 31 – Mt Roskill

Frost Rd / Carr Rd



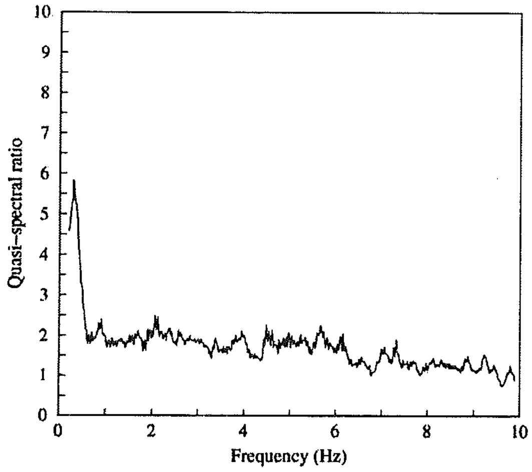
Site 34 – Onehunga

Orpheus Drive at lagoon



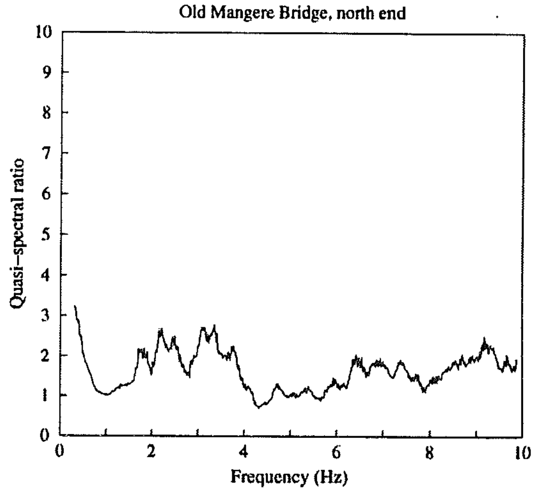
Site 32 – Green Lane

Green Lane / Marewa Rd



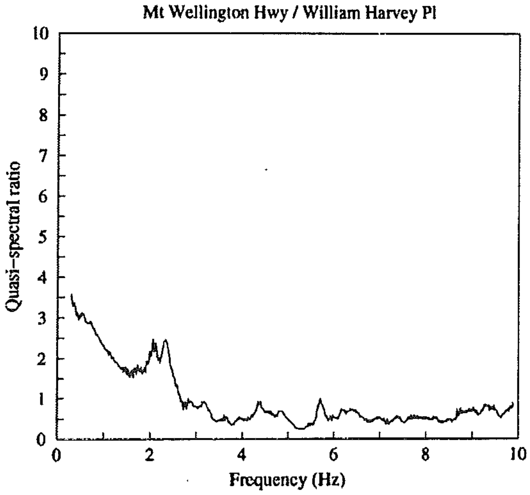
Site 35 – Onehunga

Old Mangere Bridge, north end



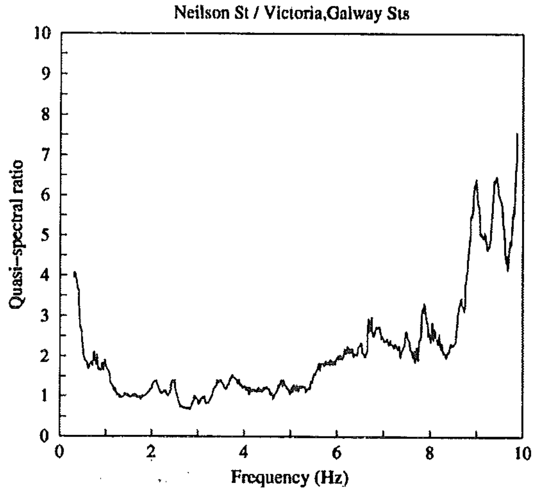
Site 33 – Mt Wellington

Mt Wellington Hwy / William Harvey Pl



Site 36 – Onehunga

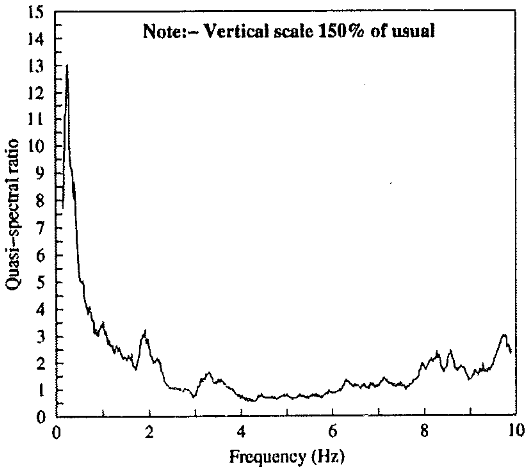
Neilson St / Victoria,Galway Sts



Auckland Quasi–Spectral Ratios

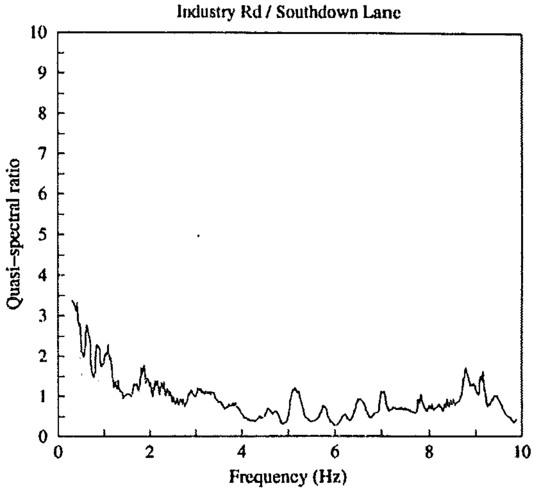
Site 37 – Mangere Bridge

Crawford Ave / Waterfront Rd



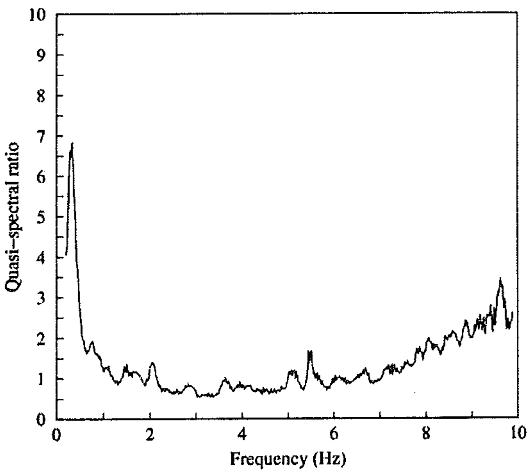
Site 40 – Southdown

Industry Rd / Southdown Lane



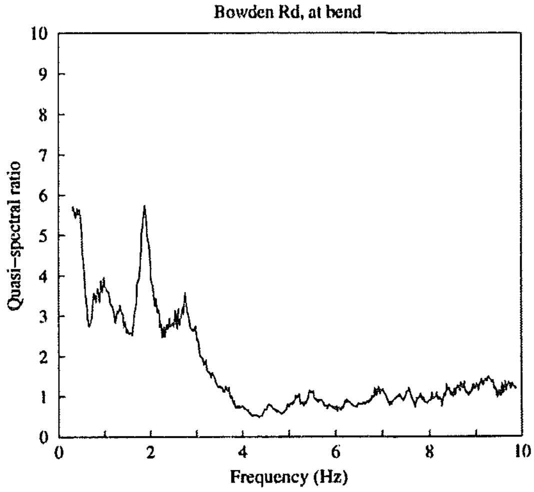
Site 38 – Southdown

Church St / O'Rorke Rd



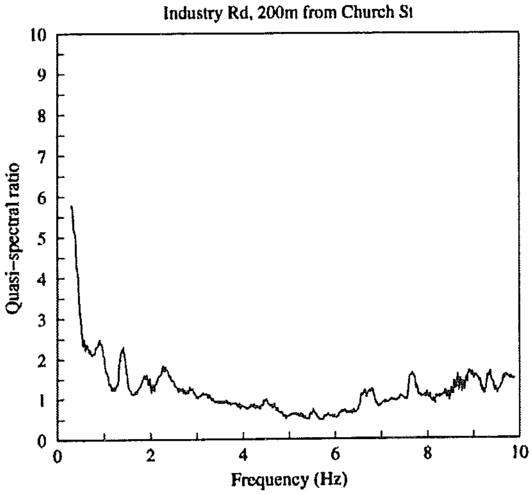
Site 41 – Mt Wellington

Bowden Rd, at bend



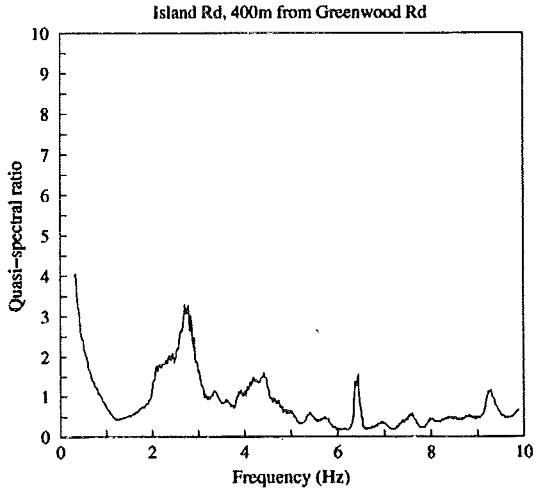
Site 39 – Southdown

Industry Rd, 200m from Church St



Site 42 – Mangere

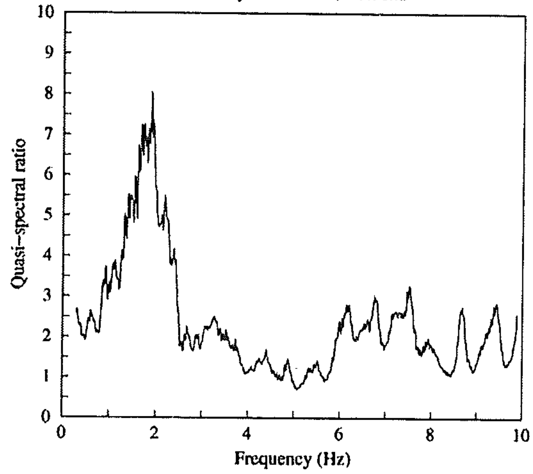
Island Rd, 400m from Greenwood Rd



Auckland Quasi-Spectral Ratios

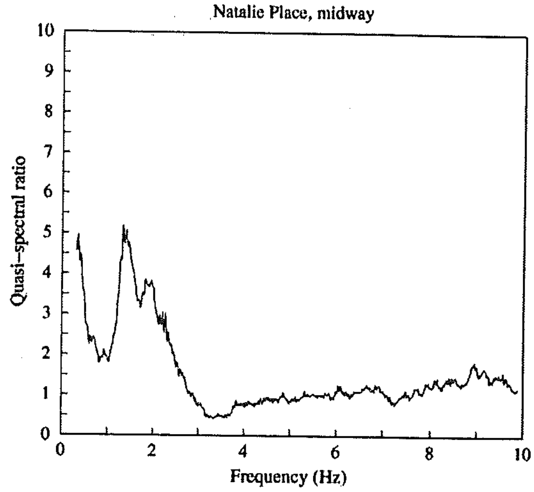
Site 43 – Airport

Runway reclamation, west end



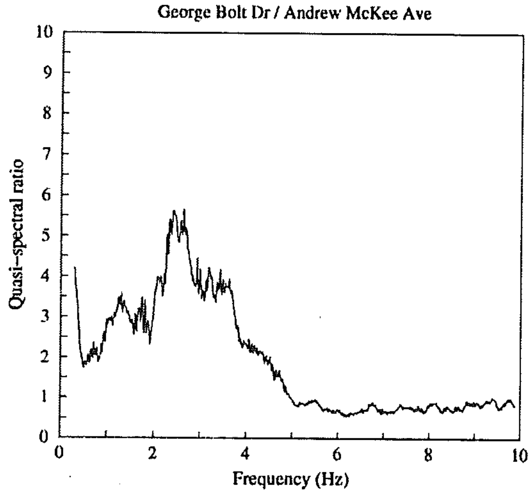
Site 46 – Otara

Natalie Place, midway



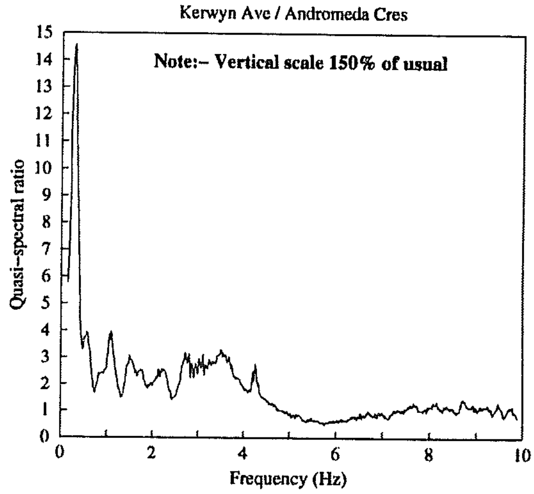
Site 44 – Airport

George Bolt Dr / Andrew McKee Ave



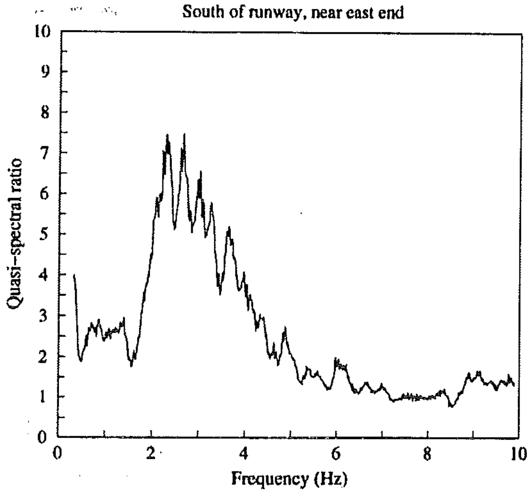
Site 47 – East Tamaki

Kerwyn Ave / Andromeda Cres



Site 45 – Airport

South of runway, near east end



APPENDIX 3

Criteria for Evaluating Quasi-Spectral Ratios

APPENDIX 3 - Criteria for Evaluating Quasi-Spectral Ratios

Theory suggests, and experience confirms, that the quasi-spectral ratio derived from a site where a soft soil layer overlies a harder material such as rock, will have the form of a sharp peak at a particular frequency, followed by a trough, which is in turn followed by a constant value which is substantially less than one (Konno and Ohmachi, 1998). For this type of site an idealised situation of a soil with a constant and low shear wave velocity, overlying a rock with a constant and high shear wave velocity, is assumed. The soft layer in this case traps incoming waves and resonates, so this form of quasi-spectral ratio curve characterises a resonant site.

On the other hand, a hard rock site is expected to have a quasi-spectral ratio with a constant value of one to two (because there are two contributions, north and east, for the horizontal motion). This is both a non-resonant and a non-amplifying situation.

In practice quasi-spectral ratio curves rarely have either of these two pure forms, and a judgement call must be made as to the character of a site. We consider the following criteria in assessing quasi-spectral ratio curves when classifying a site as *resonant* :

- One or more narrow peaks
- Low (less than one) qsr values at high frequencies
- A trough following the highest frequency peak

If all these features are present we classify the site as resonant.

The criterion for classifying a site as *non-resonant* is :

- a quasi spectral ratio value of between one and two.

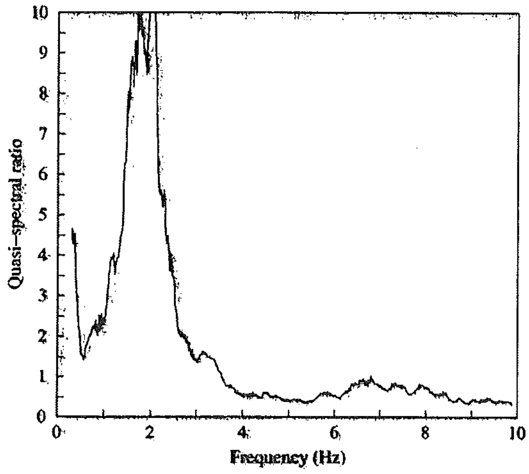
If a site has either of the first two resonance criteria, we classify it as possibly resonant on the basis that motion which does not excite Rayleigh waves may have occurred, and could obscure features normally associated with resonance. The boundary between resonant and possibly resonant becomes a matter of judgement, as for example the width of a peak increases, the frequency at which the qsr drops to a low value, increases, and the minimum value of qsr approaches unity. We have set no quantitative threshold values, because there is no firm basis to do so. As noted in section 3.7.5 of this report, an exception has been made in the case of sites 2, 3, 4, 5, 6, 18, 19, 25, 29, 32, 37, 38, and 47 where low frequency peaks (between 0.24 Hz and 0.44 Hz) were noted. If these peaks indicate a low frequency resonant response (and they may not), any resonant amplification will be at a frequency corresponding only to very tall structures. It is unusual for any except the very largest earthquakes to radiate significant amounts of energy at such low frequencies, so there will usually be little ground motion to be amplified. Furthermore, the low frequency resonators which are implied by the peaks will have an isolating effect at the higher frequencies at which structures usually respond to shaking. Finally, we are unable to identify any geological structure which may give rise to frequencies this low.

On the basis of the above, we consider that the low frequency peaks constitute an unimportant effect arising from an unknown cause.

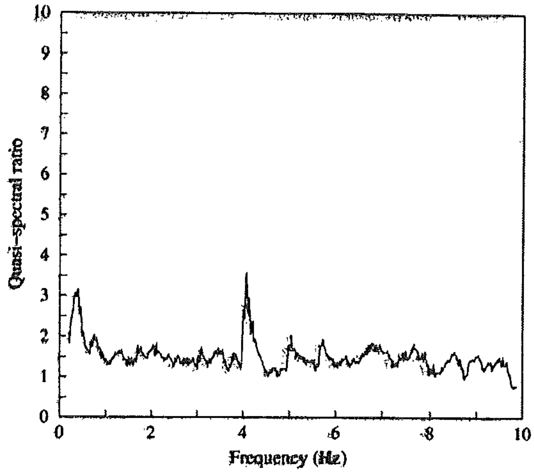
The example qsr plots of this appendix show typical examples of classification, together with the reasoning leading to the assignments.

Example Quasi-Spectral Ratios

Site 7
(Resonant)



Site 13
(Nonresonant)



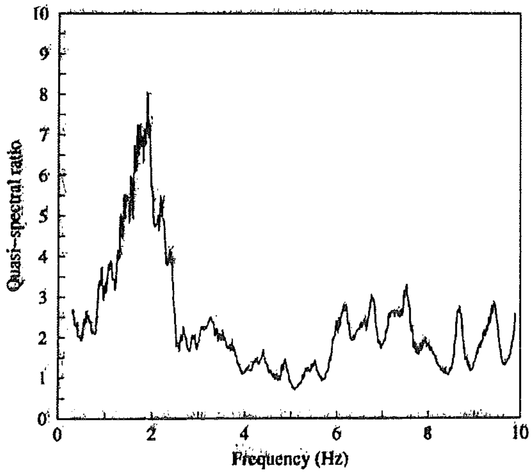
Above : Site judged resonant
* Sharp peak
* QSR < 1 over 3.5 Hz

Above : Site judged nonresonant
* No peak
* QSR between 1 and 2

Below : Site judged possibly resonant
* Sharp peak
* But high QSR at high frequencies

Below : Site judged possibly resonant
* Low QSR at high frequencies
* But no peak (other than the unexplained one at 0.27 Hz)

Site 43
(Possibly Resonant)



Site 47
(Possibly Resonant)