

ANALYSIS OF MICROTREMOR RECORDS

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INTRODUCTION

A previous paper⁽¹⁾ described two techniques developed at the University of Auckland, School of Engineering for recording microtremors. In this paper, various possible methods of analysing such records, with emphasis on the discernment of frequency content, are outlined. Those which were found most useful in microtremor analysis are described in more detail and examples of their use are given.

FREQUENCY ANALYSIS

When studying the frequency content of recorded ground motions, an examination of the record of signal amplitude versus time is usually not sufficient on its own. All the information required is contained in the record, but it is not usually in the most convenient form. Occasionally, dominant periods may be identified directly from the seismometer record, but generally the irregularities of such a record effectively mask a good deal of the information contained therein.

The method used to analyse any oscillatory record must depend upon the nature of the record. The simplest type of record (not usually found in earthquake engineering) is a periodic stationary function, of period T_1 . This may be analysed as a Fourier Series giving a number of discrete harmonic components which when summed exactly reproduce the record. This method has been applied to tidal records, for example.

Strong motion records of actual earthquakes are limited generally to half a minute or so in duration. They are non-stationary aperiodic or random-periodic functions of time and the Response Spectrum method has been used most frequently to determine the frequency content of such motions.

Microtremors may be recorded over a relatively long period of time and, if variations in artificial excitation do not occur, may be regarded as stationary aperiodic functions.

One of the earliest and simplest methods of analysing microtremors was developed in Japan, notably by Kanai⁽²⁾. From recordings of ground velocity, samples of two minutes duration were taken. Time intervals between successive points where the graph crossed the (zero-velocity) axis were measured. Each interval was taken to be the half-period for that cycle. The frequency of occurrence was plotted against period to give a period distribution curve. Originally the process was carried out manually, but optical

scanning and electronic tuning was later introduced.

For aperiodic functions, the Fourier spectrum provides a clearer indication of frequency content. Unlike the Fourier series, where a number of discrete components are evaluated, the Fourier spectrum gives the relative level over the whole range of frequencies.

More complicated methods than basic Fourier analysis have been devised because frequently signals are available only in short time stretches or they may contain a large random element making them unsuitable for analysis by more elementary means. The most commonly used of these more sophisticated methods is the Power Spectral Density method. This method has been applied both in communications engineering and earthquake engineering studies.

ANALYSIS OF MICROTREMORS

Two distinct methods of recording microtremor movements were described in the earlier paper⁽¹⁾.

The first, which was termed the 'Direct Recording Method' uses a low speed tape recorder to record low frequency (0.1 - 20 Hz) microtremor signals directly.

The second method, termed the 'Frequency Modulation Method' uses a constant frequency carrier wave which is modulated by the incoming microtremor signal. The modulated wave is recorded on an instrumentation quality direct-recording tape recorder.

DIRECT RECORDING METHOD - ANALOGUE ANALYSIS

The basic aim of this method is to provide a relatively simple recording and analysis method which uses readily available equipment. By replaying at normal speed a tape which has been recorded at low speed, not only is the signal level raised above amplifier noise level, but the microtremor frequencies are brought into the audio frequency range. Thus it is possible to use conventional audio analysis equipment to determine the energy distribution at each frequency. The apparatus is shown in the photograph, Figure 1.

A frequency spectrum analyser (General Radio type 1568-A) with constant percentage bandwidth and high harmonic rejection is used. Measured between the 3 db points on the filter characteristic, the filter bandwidth is 1 per cent of the selected centre frequency. The frequency range of the analyzer is 20 Hz to 20 KHz. Attenuation of the signal one octave

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away from the selected frequency is 75 db.

A special tape loop device has been constructed which can be attached to a conventional direct recording tape recorder. The recorded tape, up to 4 m long, is joined end to end to form a loop. Usually, about half an hour of recording time is included in the length of tape analysed. This loop is continuously recycled through the playback mechanism of a high quality portable instrumentation recorder (Nagra III, Type BH). At the normal playback tape speed, recorded frequencies are multiplied by the "speed-up ratio" and the output signal (now in the audio frequency range) is scanned by the analyser. This is equipped with automatic range switching which allows the analysis process to be set in motion and left to run unattended. The frequency scanner is driven by a small synchronous motor through a reduction gear box at a suitable sweep-rate. The apparatus is shown in the photograph, Figure 1.

An X-Y recorder is used to plot the output signal from the analyser. The d.c. output voltage, corresponding to the signal level at a particular frequency, controls the Y-axis of the plotter. A ten-turn potentiometer geared to the scanner drive and acting as a voltage divider provides a d.c. voltage for X-axis control of the plotter giving a logarithmic frequency scale. The indicated frequencies must, of course, be divided by the speedup ratio to obtain the actual microtremor frequencies.

This system provides excellent frequency discrimination. At 5 Hz for example, the bandwidth is 0.05 Hz, enabling closely-spaced peaks in the spectrum to be separately distinguished.

FREQUENCY MODULATION METHOD

Two digital analysis methods are used to analyse these tapes. The first method is the Response Spectrum technique which has been used by structural engineers for some years to determine the response of single degree of freedom systems to earthquake excitation. The second method is the Power Spectrum technique which has been used previously by communications engineers to determine the frequency content of input signals. In recent years the power spectrum method has been used increasingly in earthquake engineering studies.

Before any digital method is applied, the continuously-varying analogue signal must be digitized at uniform time intervals, for transfer to the computer. The digitization interval must be short enough that no significant information is lost.

The record from the F.M. tape is low-pass filtered to remove the 5 kHz carrier frequency, then digitized (at 0.01 second intervals) and punched, in binary form, on 8-channel paper tape. The data is then transferred to computer storage using a paper tape reader.

Response Spectrum Technique

This was devised by Benioff in 1934 and has been used extensively by Biot, Hudson, Housner and others in earthquake studies. Basically, a linear, single degree of freedom oscillator, with viscous damping, is subjected to the

recorded accelerations. This record may be that of a strong motion earthquake. The mass and stiffness determine the undamped natural natural period of the system, whilst the damping determines the 'sharpness' of the system response. By varying the stiffness of the system over a suitable range, maximum response values of acceleration, relative velocity and displacement for each corresponding natural period may be obtained. A plot of maximum response value versus natural period is termed a 'Response Spectrum'.

From the definition of a response spectrum it can be seen intuitively that the presence of strongly periodic components in the input record will cause resonance effects in single degree of freedom oscillators that have natural periods near the predominant periods in the input. Response spectra will highlight differences in frequency content of ground motions and show up changes in amplitude of the basic motion.

Power Spectrum Technique

The power spectrum method is based on Fourier analysis. That is, a given signal may be considered as resulting from the superposition of a large number of sine waves of differing amplitude, frequency and phase. Power spectrum analysis aims to produce a measure of the contribution of each sine wave (expressed in terms of its 'power', the square of its amplitude) as a function of frequency.

In most cases noises and signals may be represented or approximated by random, stationary processes with zero mean values. Under these conditions all of their relevant statistical properties will be expressed in terms of the autocovariance function or the power spectrum. The mathematical derivation and expression of the form of these functions is complex and will not be reproduced here.

The autocovariance function gives an average measure of the dependence of a point in the data on another ordinate at a specified time from it (in terms of a time series). The measure of dependence is a function of the time interval between the points. This time is called the lag (τ). Generally the autocovariance is defined as:

$$C(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{+\frac{T}{2}} \ddot{u}(t) \ddot{u}(t+\tau) dt \quad (1)$$

for a stationary process $\ddot{u}(t)$ with zero mean and of duration T .

The power spectral density function at a frequency f , represents the contribution to the autocovariance from frequencies in the equivalent bandwidth of the process. Inverting this function it is possible to express the power spectrum as the Fourier transform of the autocovariance function, thus

$$P(f) = 2 \int_0^{\infty} C(\tau) \cos 2\pi f \tau d\tau$$

The computation process used consists of determining the autocovariance and transforming it to determine the spectral density. Corrections are

made for the effect of record length and aliasing but will not be discussed here.

A more complete description of analysis techniques used in earthquake engineering and their mathematical derivations has been presented by Parton⁽³⁾.

EXAMPLES OF ANALYSED MICROTREMOR RECORDS

The wide variety of soil conditions encountered in the Auckland area make it an ideal location for microtremor investigations. The underlying sedimentary deposits consist largely of Miocene Waitemata sandstone. The sandstone has weathered near the surface to firm clays and sandy silts but beyond depths of about 10 m the strength of the unweathered material increases rapidly.

In many places the Waitemata sandstone has been ruptured by outbreaks of volcanic activity. The landscape is characterized by the number of small scoria cones protruding from the generally flat non-volcanic area. Weathering and other natural geological processes have produced clays which make up extensive Pleistocene and Pliocene deposits. Thus sites which are typical of 'hard' and 'soft' subsoil conditions are readily accessible.

Three sites were considered for microtremor recording and analysis. The object of the study was to apply the recording and analysis methods described in this and the preceding paper and produce a basic comparison of microtremors recorded at a few different sites.

Meadowbank Site

A subdivision site at Meadowbank was selected as the 'hard' site. Extensive landscaping of the area had resulted in the weathered surface material being stripped from the higher ground to expose firm relatively unweathered Waitemata sandstone. The site was free from any major industrial disturbance. Buildings in the area were limited to one or two storey residential structures. Roads and a railway line about 500 m away were the main sources of traffic disturbance.

Takanini Site

This was selected as a soft site. The area lies in the Papakura - Drury Graben fault and consists of very soft peat underlain by sand and firmer Pliocene and Pleistocene clays. Borelogs, from a site investigation carried out adjacent to the recording location, were available down to 26 m. The area is semi-rural. Buildings adjacent to the site were limited to single storey structures. The Southern motorway, Great South Road and main trunk railway line about 1 km away provided background excitation. Traffic moving in the immediate vicinity provided greater excitation.

Tamaki Site

This was selected as an additional soft site. An extensive site investigation had been undertaken to obtain information for the design and construction of a new road bridge. Dynamic testing had been carried out on undisturbed samples recovered from the site. Response analyses had also been computed to aid the consultants in their design (Ref. 4). Borelogs show the site to consist of 20 m of

silts and soft clay overlying hard Waitemata sandstone.

The Pakuranga highway, 100 m away provided a constant source of traffic excitation. Adjacent buildings were limited to single storey structures.

Site Recordings

At each site recordings were made in the N-S and E-W directions using both 'Direct Recording' and the 'Frequency Modulated' methods. The equipment was housed in a small van and shielded cables run out to the seismometer. Recorded tapes were analysed using the techniques outlined above.

Computed spectra from each site are presented in Figures 2 - 10. It will be noted that, while velocity response spectra are plotted against period, the results of analogue analysis and power spectral densities are plotted against frequency. The Meadowbank spectra (Figures 2, 3, 4) all show a pronounced peak in the period range 0.10 - 0.14 seconds. There is a good agreement between N-S and E-W spectra. Additionally, all analysis methods show good correlation. The maximum amplitude, integrated from the recorded velocity record, was found to be 0.36 micrometres (μm).

The Takanini spectra (Figures 5, 6, 7) show predominant periods in the range 0.2 to 0.5 seconds. Maximum amplitude recorded at this site was 2.62 μm , that is about 8 times that at Meadowbank.

The Tamaki spectra (Figures 8, 9, 10) show a single predominant period of 0.2 seconds. There is excellent correlation between N-S and E-W spectra. Maximum recorded amplitude was 3.6 μm , or about 10 times that at Meadowbank.

DISCUSSION

Each site studied appears to possess a particular predominant period. As has been observed elsewhere, the "softer" the site the longer the predominant period. That is, the Meadowbank site, which may be considered to be unweathered sandstone, exhibits an average predominant period of 0.12 seconds whilst the Tamaki site exhibits a natural period of 0.5 seconds.

Inspection of computed spectra for the Takanini site reveals that two periods are dominant. Correlation of observed periods with traffic activity confirmed that the two periods were associated with different wave mechanisms. When there was little apparent human activity in the vicinity of the site, the monitoring oscilloscope showed a low frequency periodic signal. However, when a vehicle passed along adjoining roads the signal frequency increased noticeably.

These findings are in agreement with Wilson⁽⁵⁾ who recorded microtremors generated by moving vehicles. He found that close to the source body waves spread out uniformly. However, with increasing distance from the source, surface waves tend to predominate. As the recording sessions were not concurrent, and the area was semi-rural with quiet periods not uncommon, it is felt that the different wave mechanisms recorded account for the

difference in spectra.

CONCLUSIONS

Spectra presented in the preceding pages show that recorded microtremor motions exhibit a predominant period for each site. Generally the range of predominant periods exhibited in the spectra agree with those published by other investigators with regard to subsoil conditions. Normally, the dominant periods fall within the range 0.1 - 10 seconds.

Kanai and Tanaka⁽⁶⁾ believe that on very soft sites, or where a depth of subsoil greater than 30 metres exists, the microtremor spectra will not exhibit predominant periods. The Tamaki and Takanini spectra both show resonance type peaks, and it is the contention of the authors that every soft site, regardless of subsoil properties will exhibit a natural period.

Recorded amplitudes of motion are consistent with Kanai's published data. Amplitudes are nominally within the range 0.1 to 10 μ m. Amplitudes on soft ground appear to be greater than those on hard ground by a factor of 10.

The application of microtremor measurements to the design of earthquake-resistant structures will be critically examined in the final paper of this series, to be presented in a future issue of this Bulletin.

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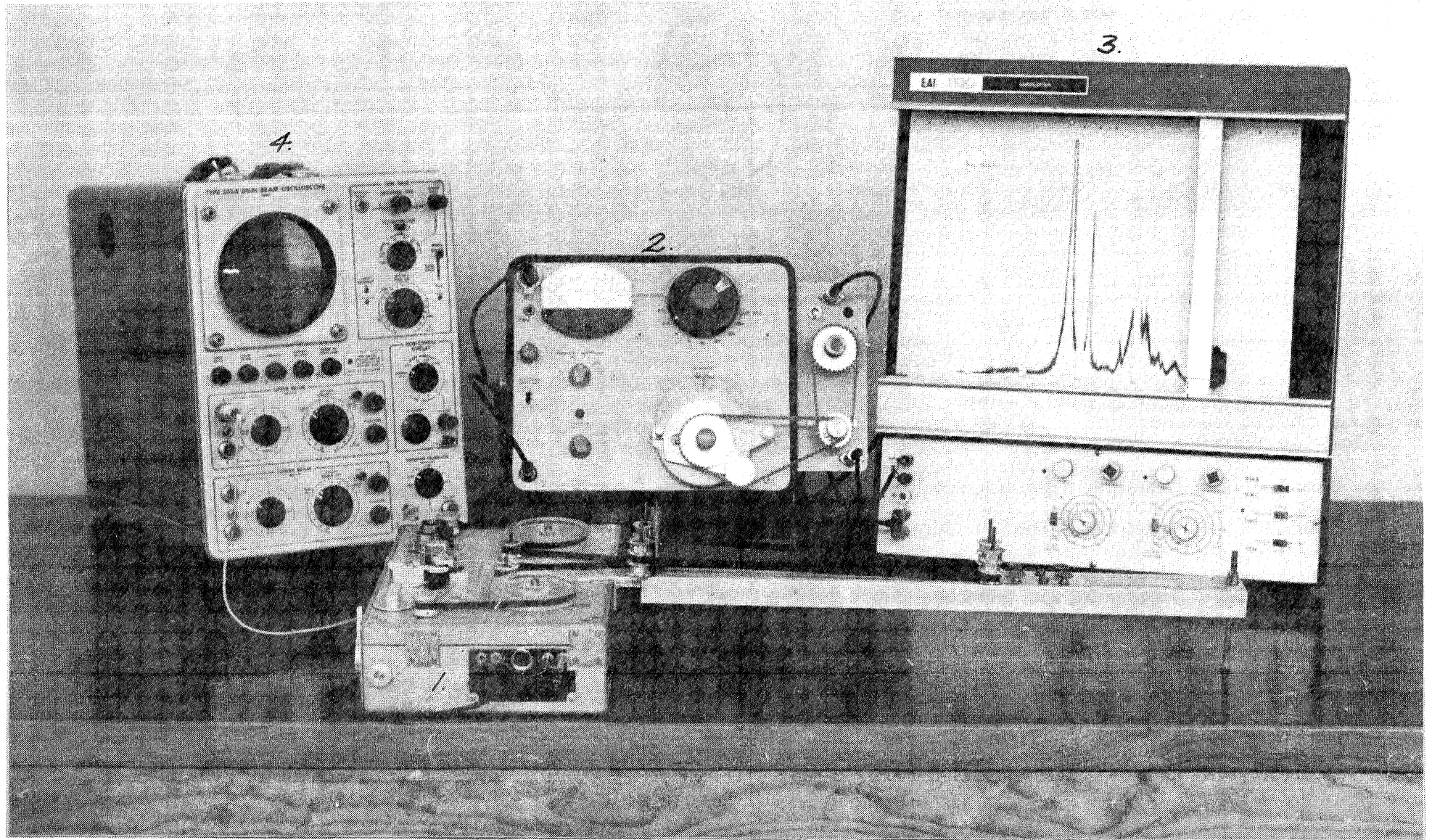
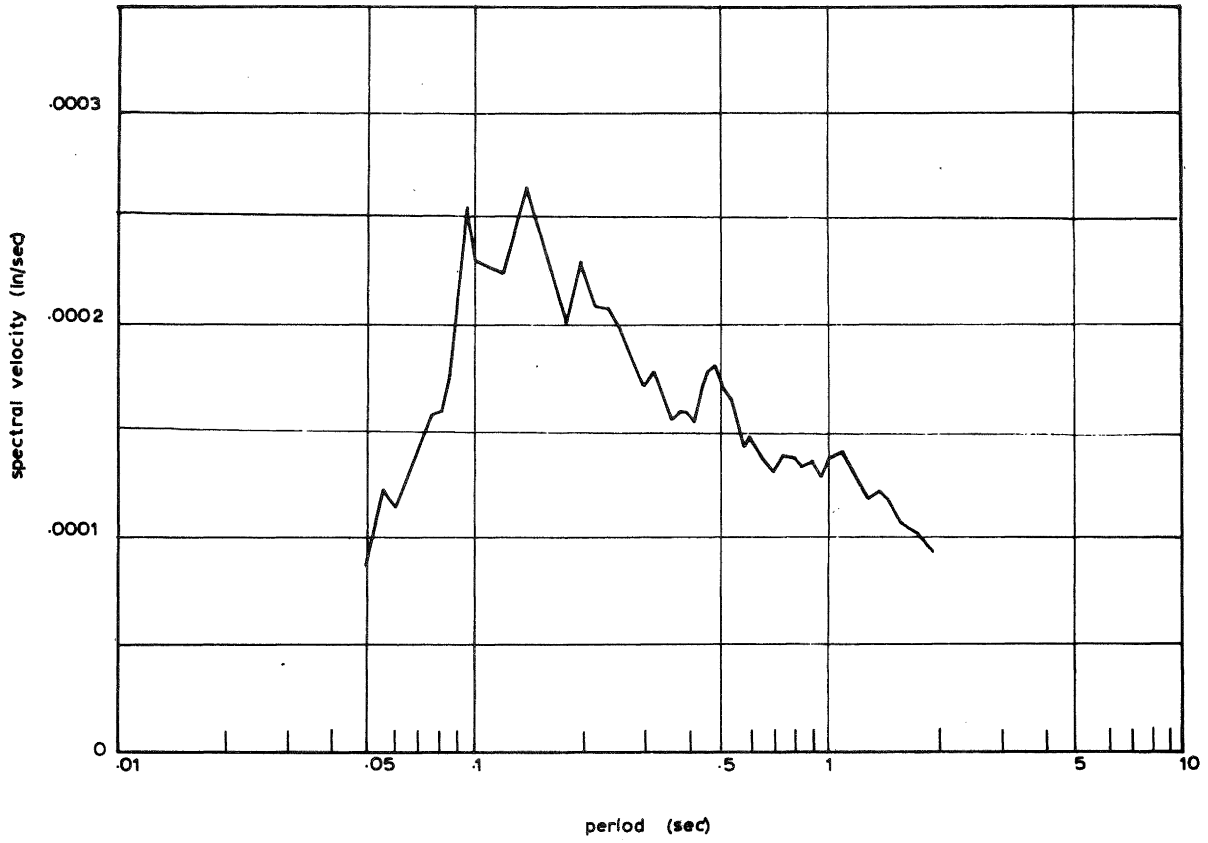
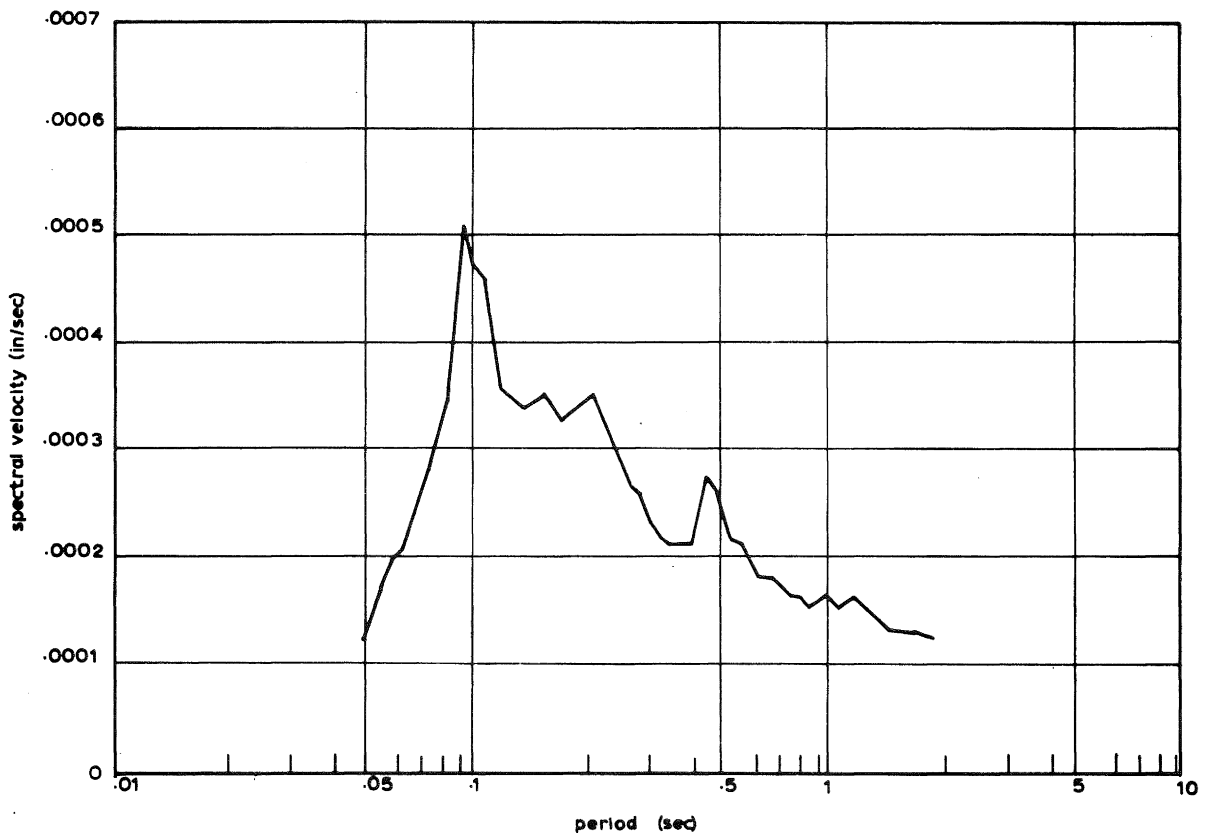


Figure 1 FREQUENCY ANALYSIS – DIRECT RECORDING METHOD

1. Tape playback machine with tape loop attachment
2. Frequency Analyser
3. X-Y recorder
4. Oscilloscope, to monitor signal level.



**FIG 2a Meadowbank Microtremor Analysis N-S
Response Spectrum , 5% damping**



**FIG 2b Meadowbank Microtremor Analysis E-W
Response Spectrum , 5% damping**

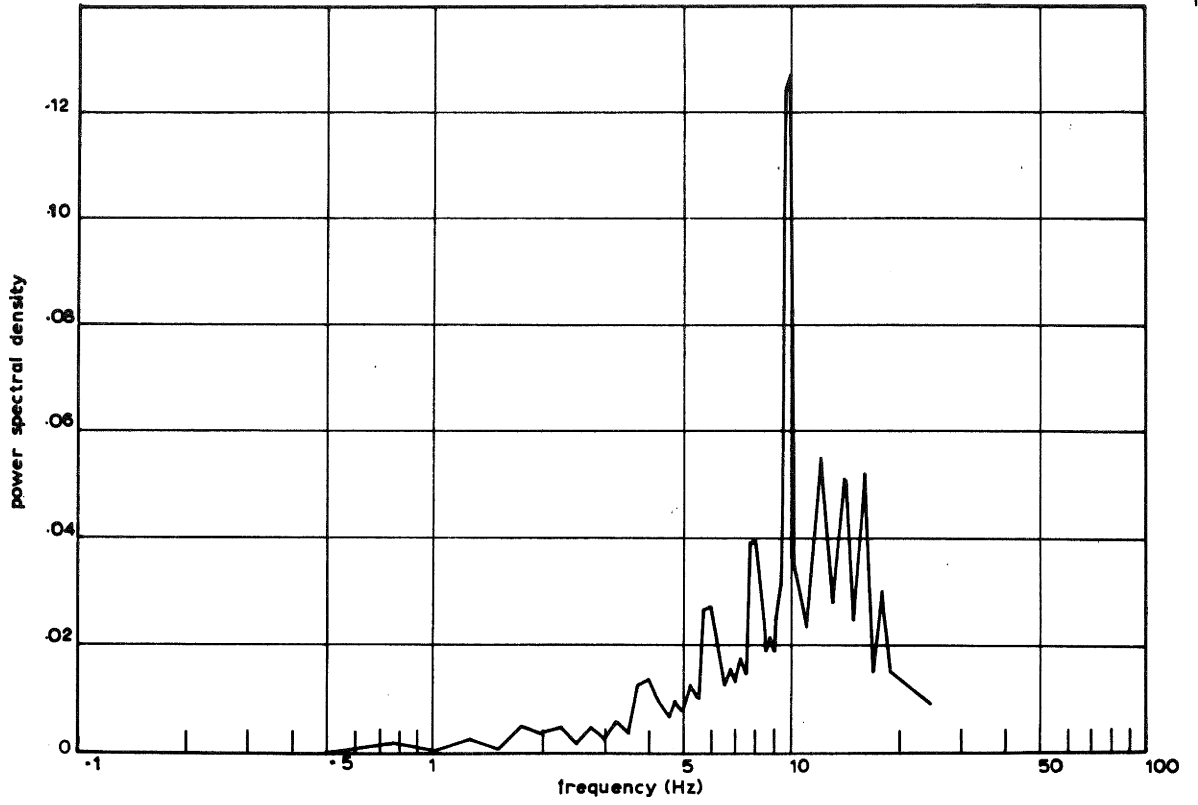


FIG 3b Meadowbank Microtremor Analysis N-S
Power Spectrum

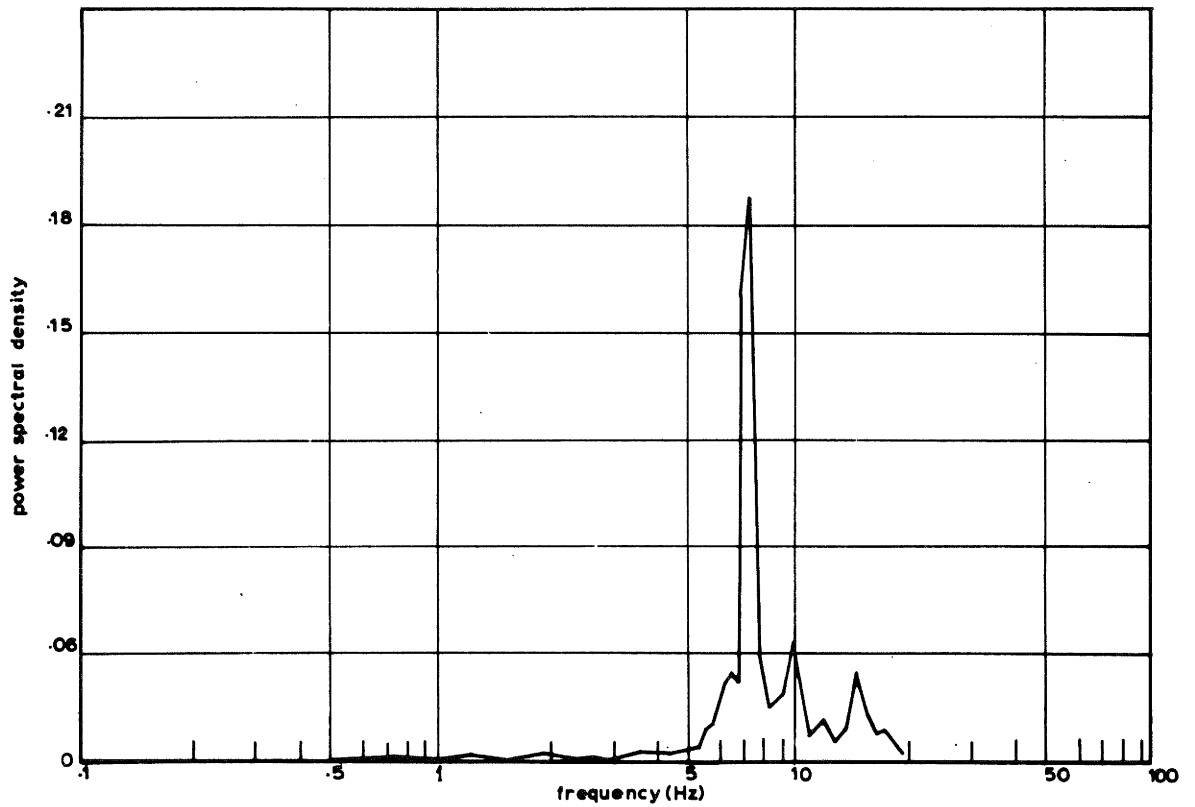


FIG 3a Meadowbank Microtremor Analysis E-W
Power Spectrum

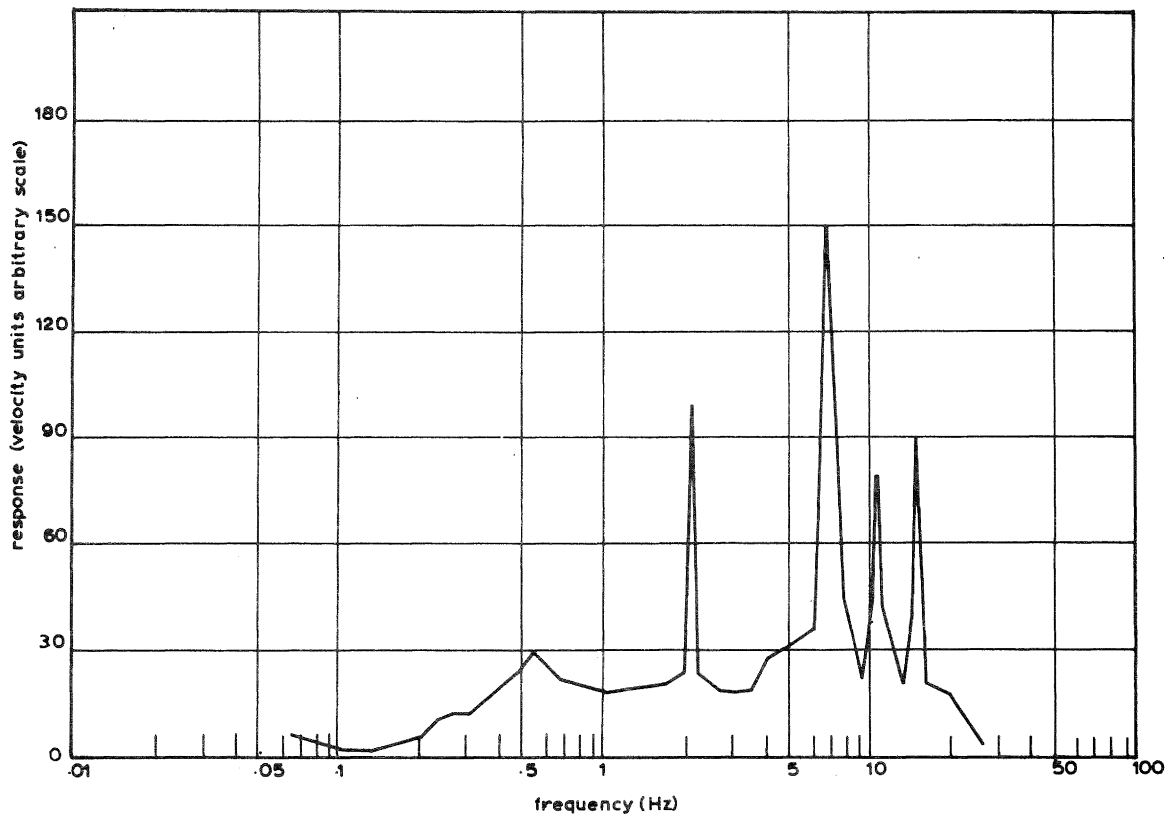


FIG 4a Meadowbank Microtremor Analysis N - S
Analogue Analysis

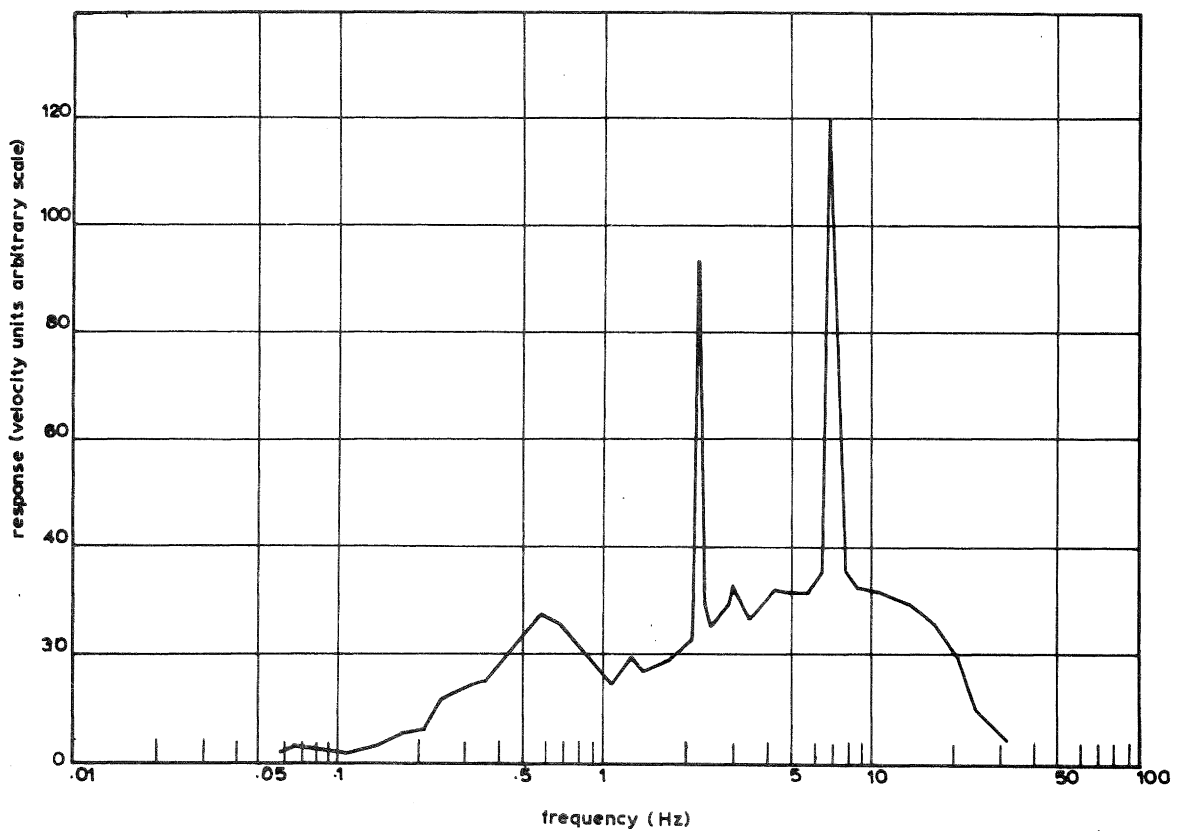


FIG 4b Meadowbank Microtremor Analysis E - W
Analogue Analysis

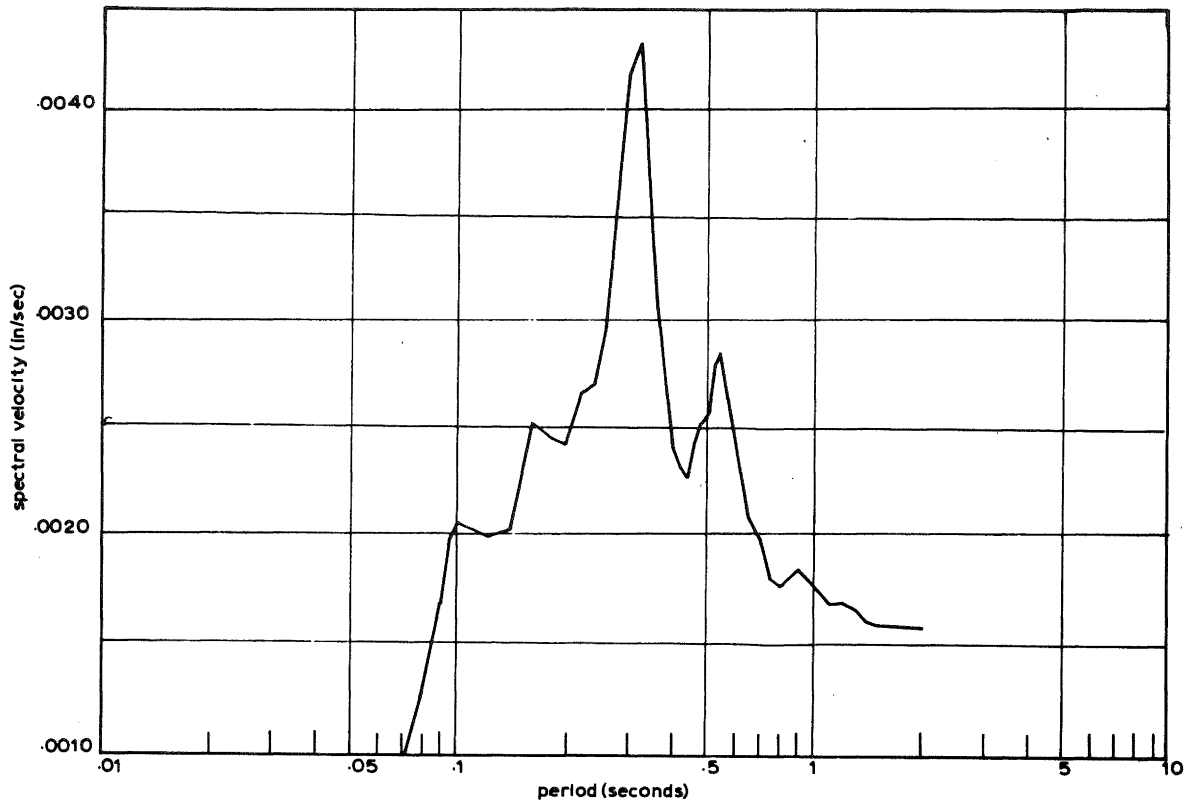


FIG 5a **Takanini Microtremor Analysis N-S**
Response Spectrum , 5 % damping

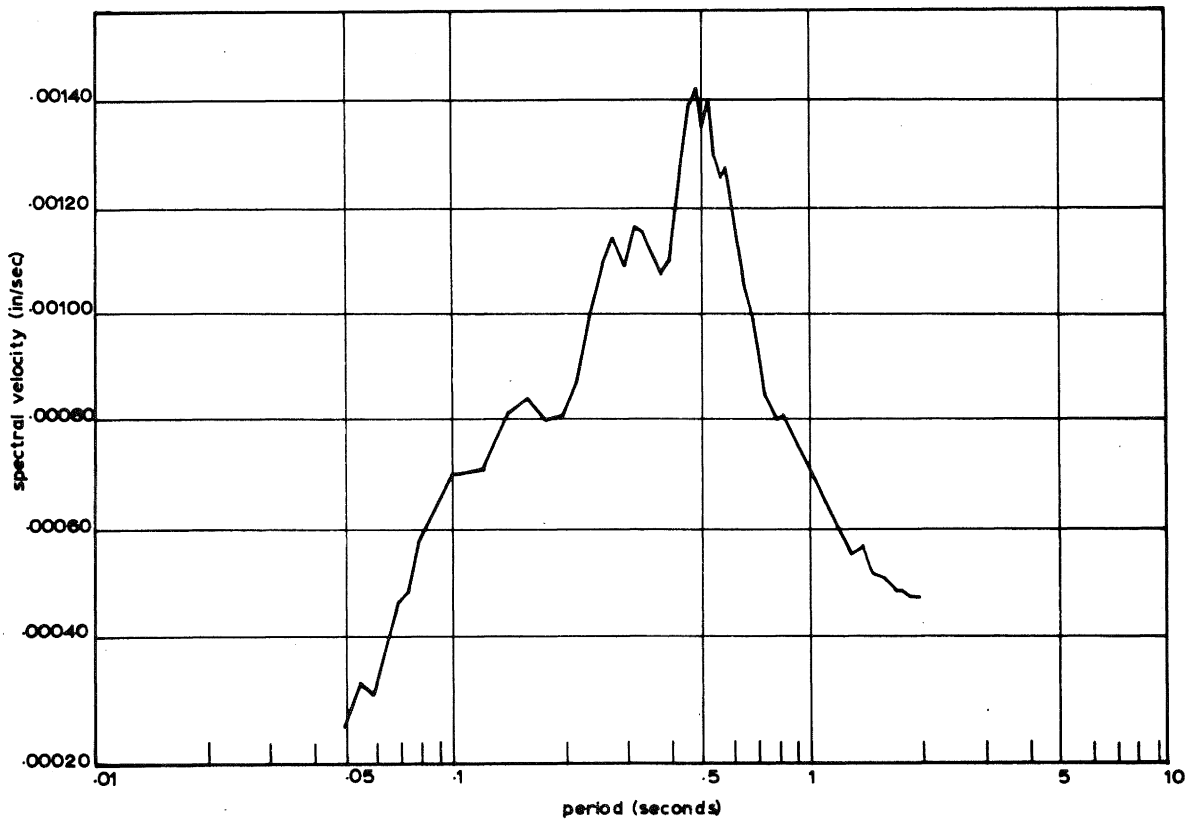


FIG 5b **Takanini Microtremor Analysis E-W**
Response Spectrum , 5 % damping

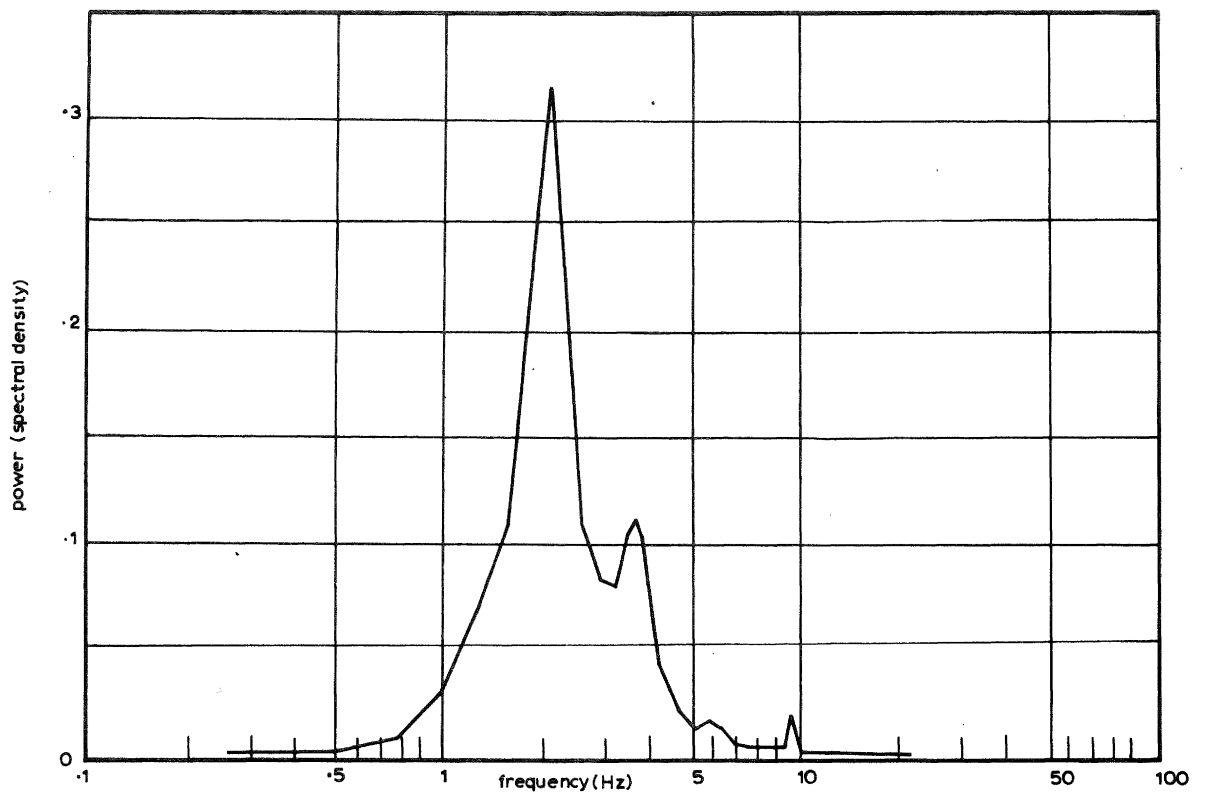


FIG 6a **Takanini Microtremor Analysis N - S**
Power Spectrum

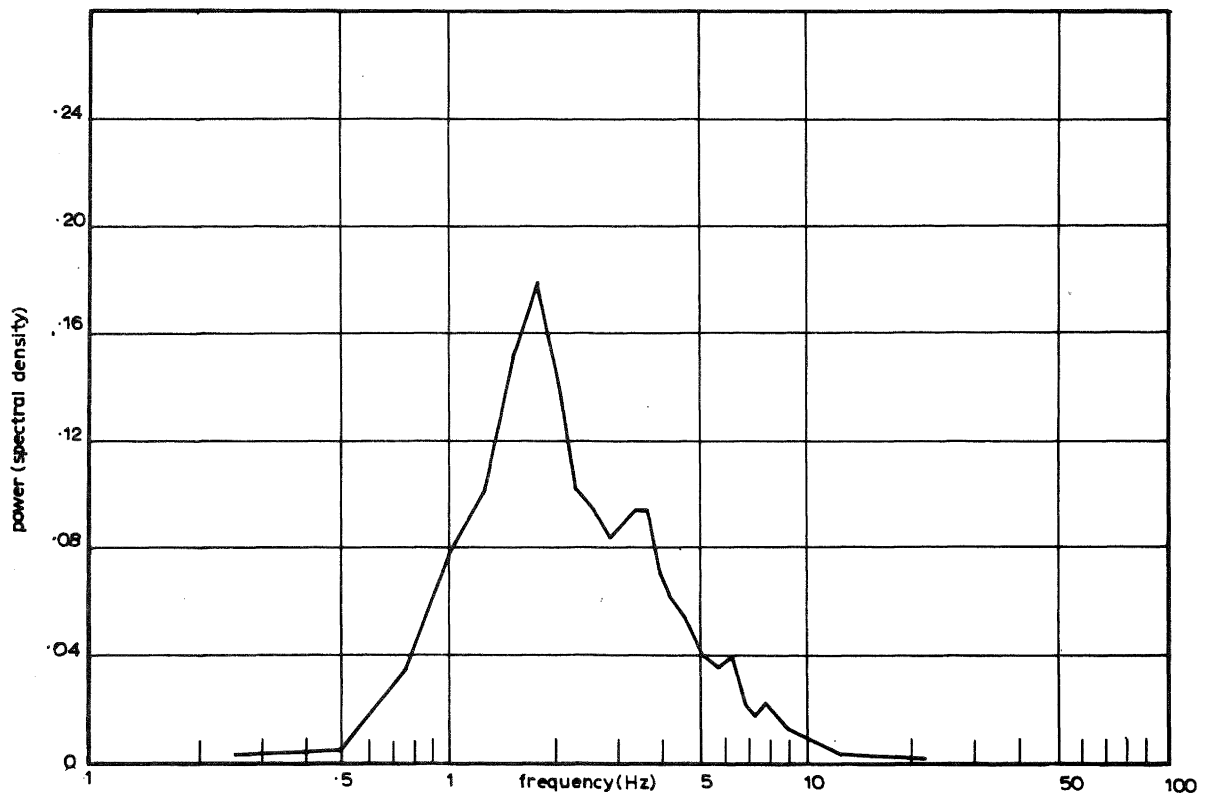


FIG 6b **Takanini Microtremor Analysis E - W**
Power Spectrum

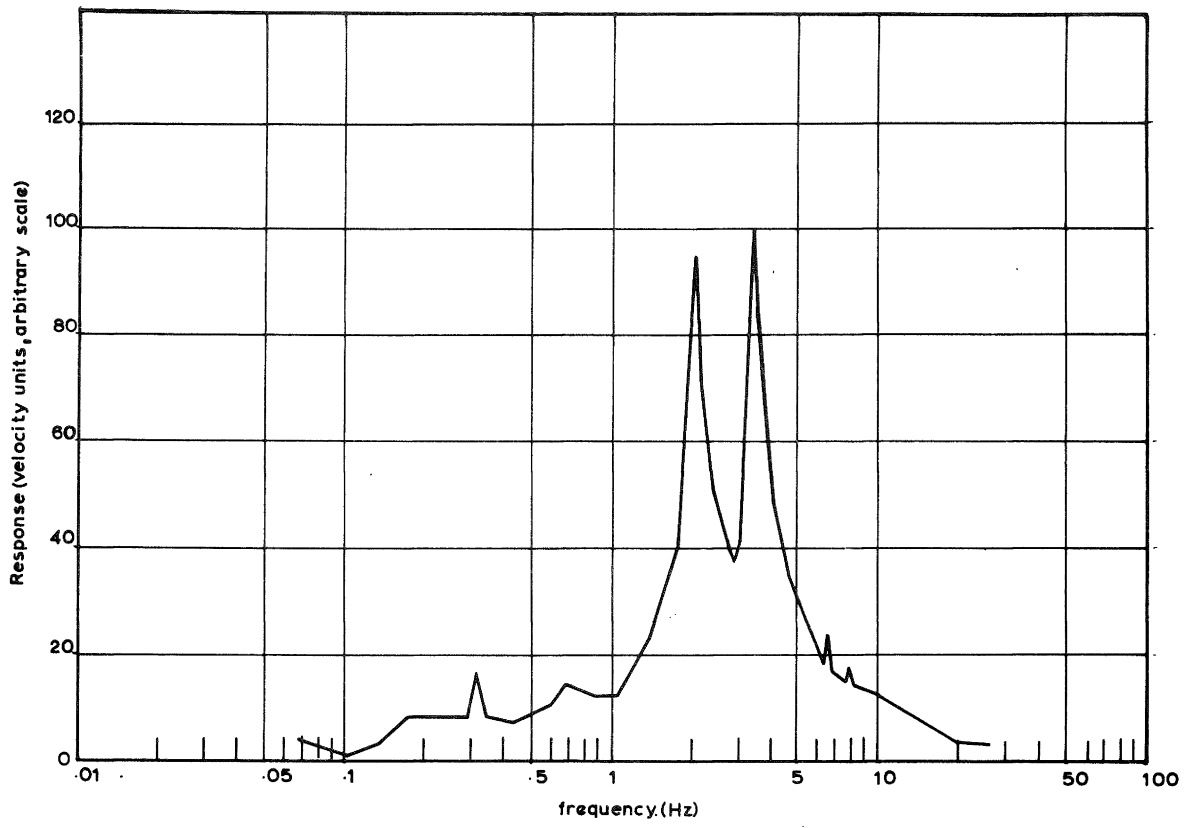


FIG 7a Takanini Microtremor Analysis N-S
Analogue Analysis

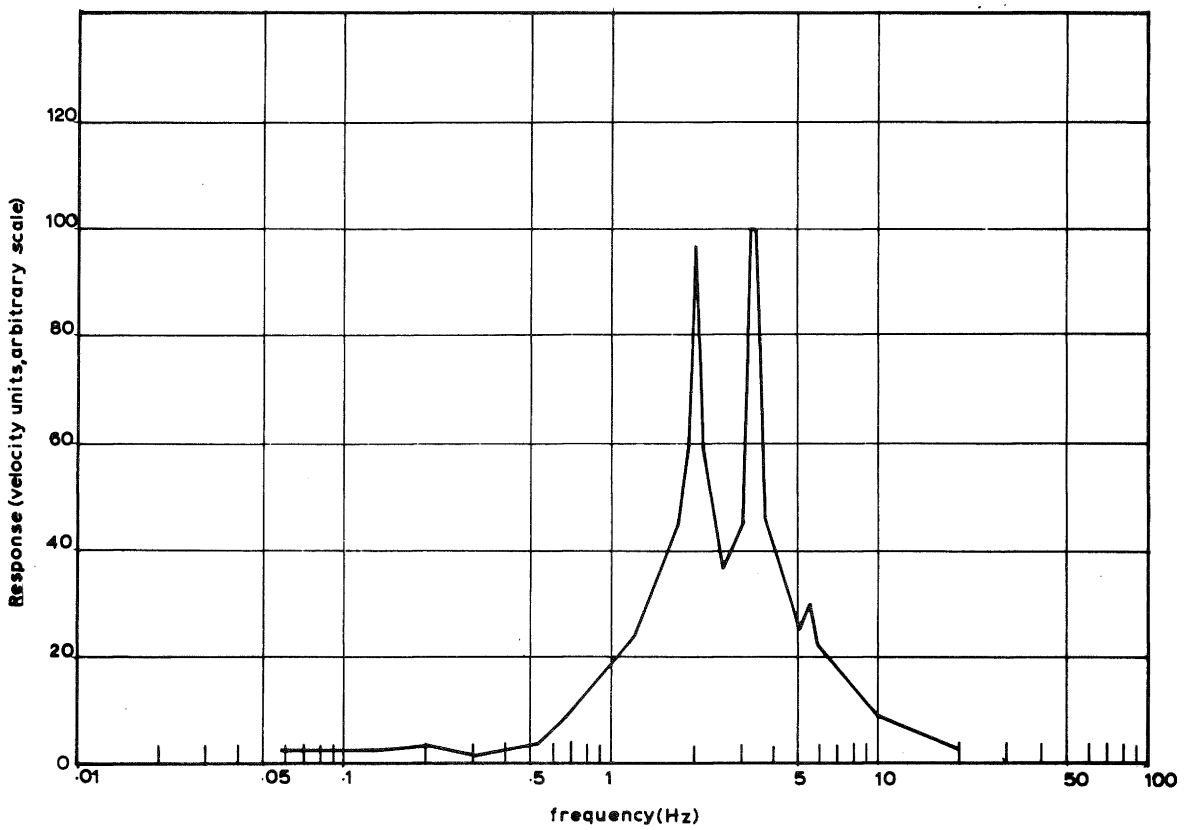


FIG 7b Takanini Microtremor Analysis E-W
Analogue Analysis

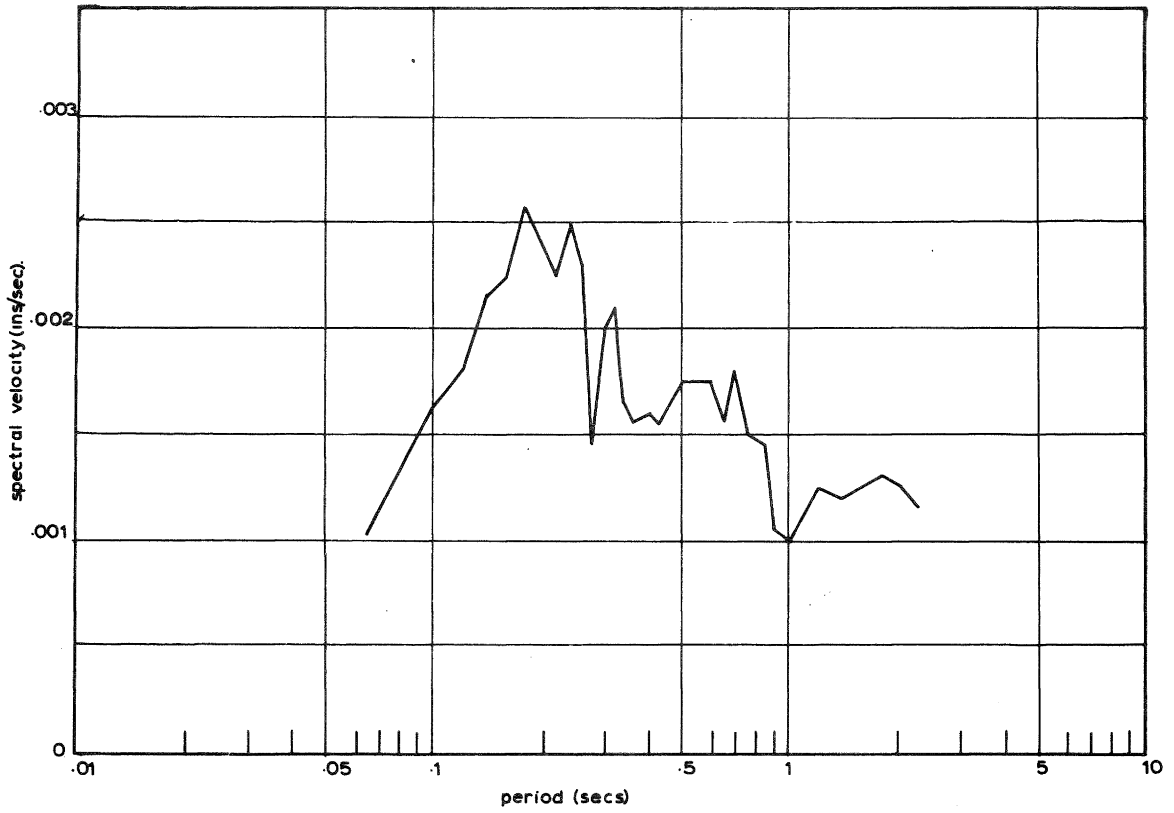


FIG 8a Tamaki River Microtremor Analysis E-W
Response Spectrum , 5% damping

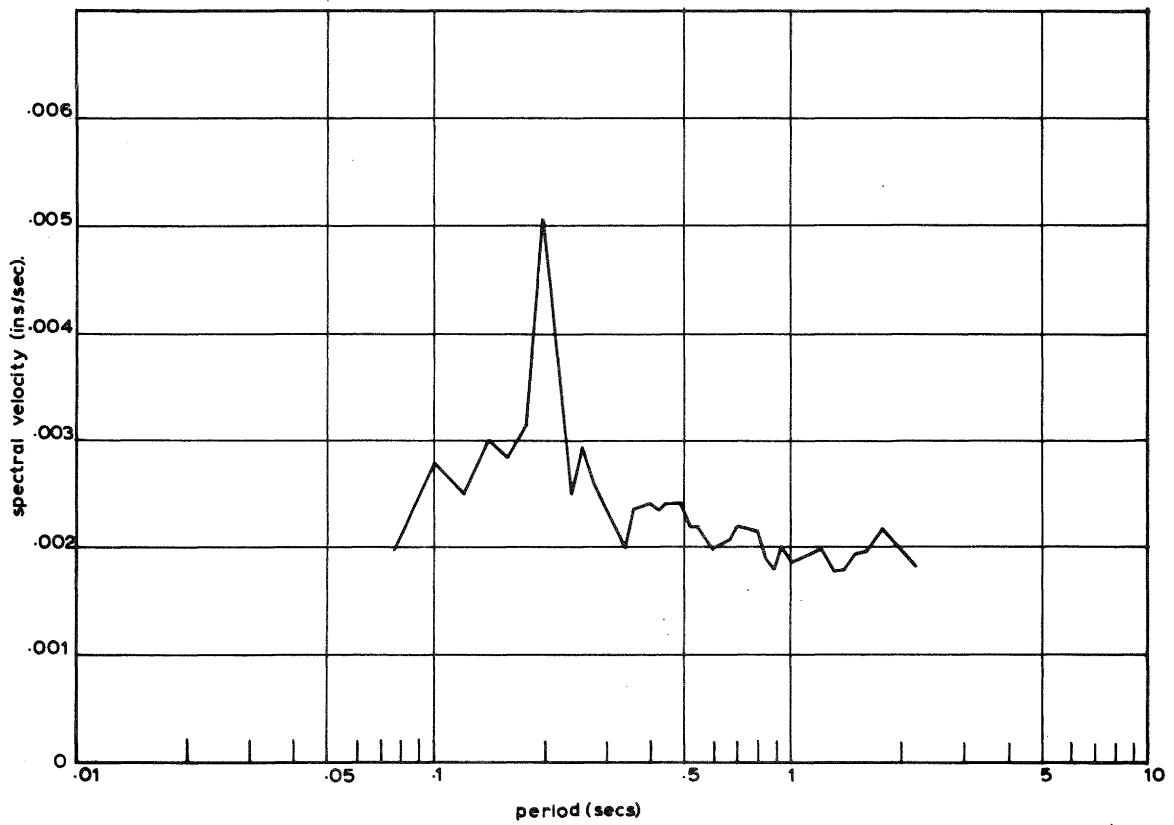


FIG 8b Tamaki River Microtremor Analysis N-S
Response Spectrum , 5% damping

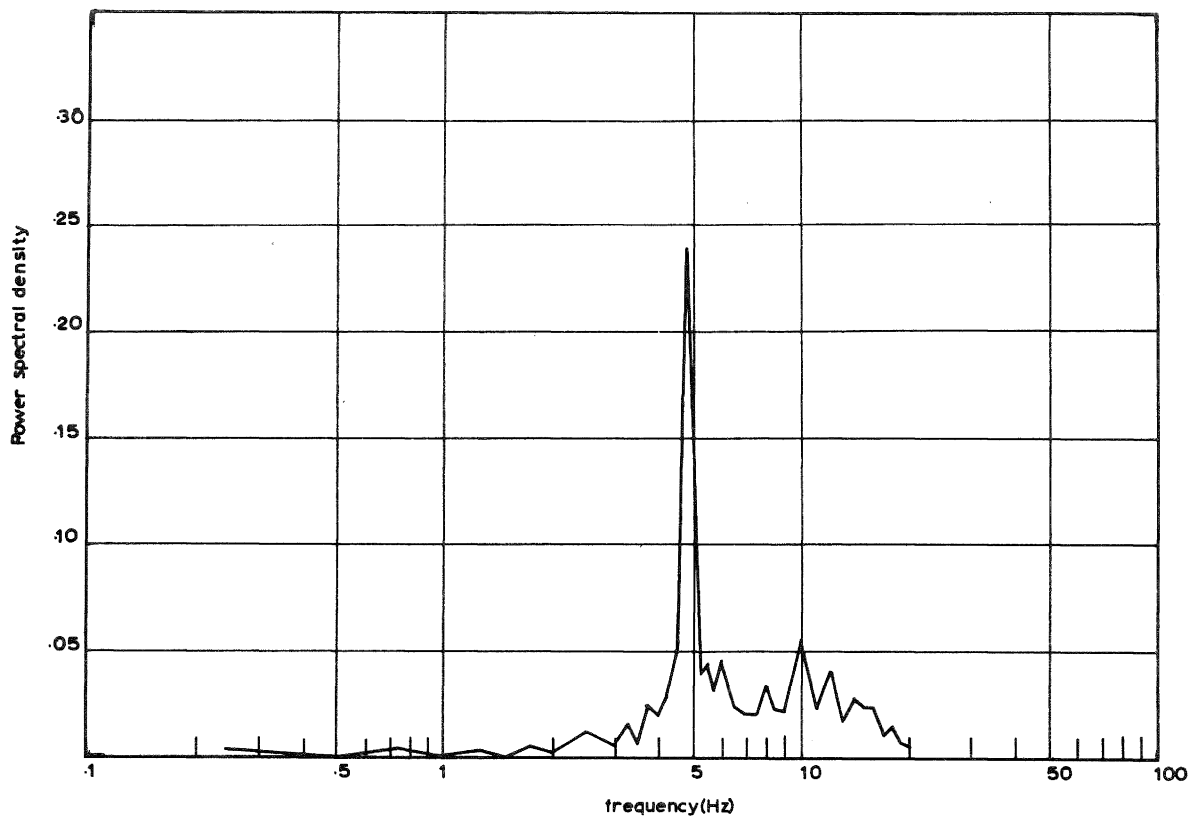


FIG 9a Tamaki River Microtremor Analysis N - S
Power Spectrum

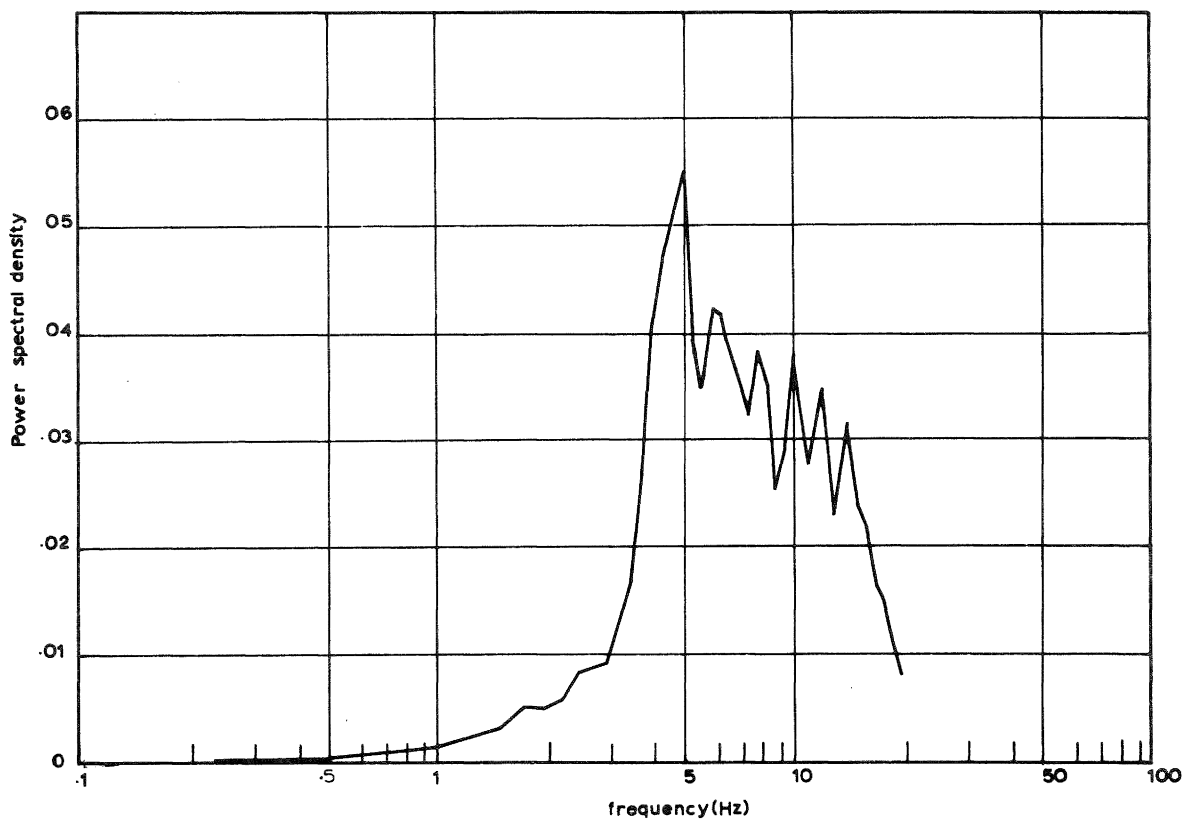


FIG 9b Tamaki River Microtremor Analysis E - W
Power Spectrum

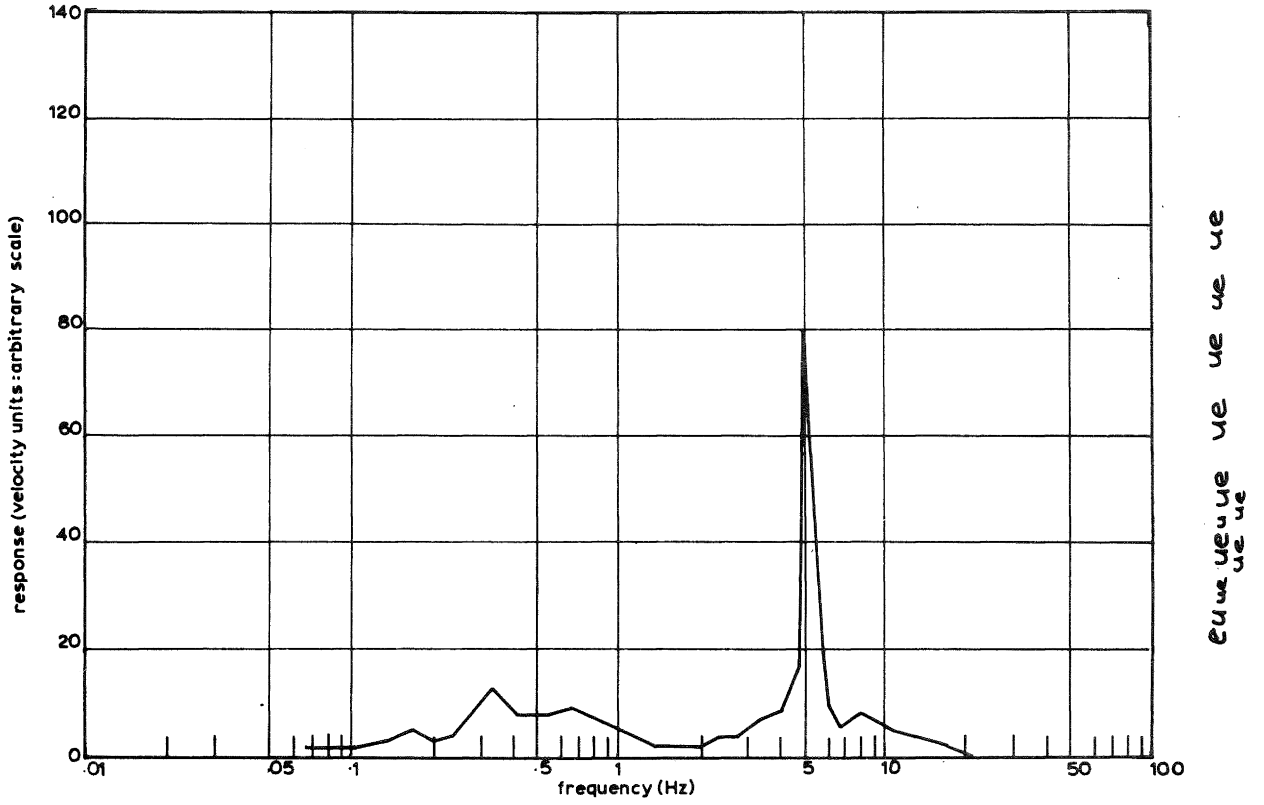


FIG 10a ^{10a} Tamaki River Microtremor Analysis N-S
Analogue Analysis

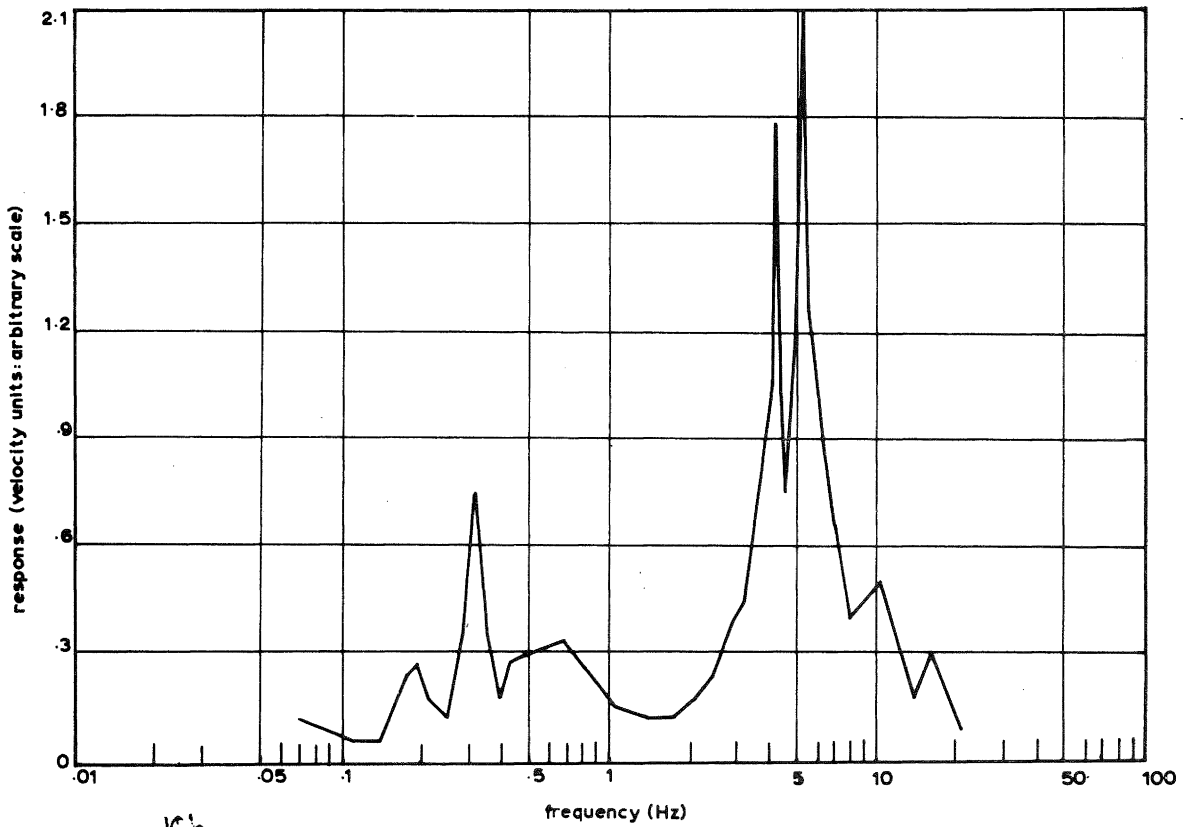


FIG 10b ^{10b} Tamaki River Microtremor Analysis E-W
Analogue Analysis