THE USE OF SHORE-BASED SEISMOMETERS FOR WAVE ENERGY RESOURCE ASSESSMENT IN NEW ZEALAND

by

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Abstract

The underwater pressure field and the seismic field in the seabed are known to be more wind dependent at frequencies below 5 Hz than in other parts of the spectrum. Nonlinear interactions in the ocean-wave field have been identified as the source of both the infrasonic component of the ocean-noise field and the wave-induced microseisms. The character of this source, its dependence on sea state and windspeed and the nature of the relevant transfer functions are now becoming well enough understood for the source to be exploited in geophysical investigations. This paper examines its application in the measurement of a near-shore ocean wave field with a land-based seismic sensor.

1. Introduction

In the absence of transient seismic signals such as earthquakes, the Earth is still found to be subject to minute tremors. These continuous motions at periods less than 10 seconds (frequencies greater than 0.1 Hz) are traditionally called microseisms and define a noise threshold against which all other seismic signals must be detected. Microseismic activity is all pervasive, being observed on land and on the deep-ocean floor. Although microseisms have been observed for over 100 years a clear understanding of their properties has been slow to appear.

Because of the sensitivity and passband limitations of the instrumentation early observations were generally restricted to high-amplitude activity. It was nevertheless quickly recognised that a close relationship existed between microseism activity and disturbances in the marine environment and the action of surf on steep coasts was suggested as a prime source. However other possible mechanisms such as atmospheric pressure fluctuations kept the issue in doubt.

Understanding developed when Longuet-Higgins [1] recognised the significance of a theoretical study by Miche [2]. Miche had evaluated the hydrodynamical equations governing standing waves in a fluid to second order and identified a pressure term which was proportional to the square of both the amplitude and frequency of the interacting progressive surface waves, had twice their frequency and, most importantly, was unattenuated with depth below the surface. Longuet-Higgins proposed this pressure term was responsible for the generation of microseisms. These ideas were developed by Hasslemann [3]. However over the next decade reservations persisted as to mechanisms by which the necessary standing waves could be generated at sea.

In the 1960's improved instrumentation brought renewed interest in the subject and in this period both the primary frequency (PF) and double frequency (DF) seismic components arising from an active swell were identified [4-6]. In this period also, the first reliable microseism measurements at the sea-floor were made following the development of the ocean-bottom seismometer (OBS) [7]. However inspite of the intense research into microseisms and related phenomena at this time, many characteristics still required clarification in the early 1980's. While the theories of Longuet-Higgins [1] and Hasslemann [3] appeared to provide an explanation of the effects observed, no comprehensive experimental program which resolved the many issues involved had been reported.

Clarification was to come from parallel studies in ocean acoustics and marine seismology, prompted by the growing defence interest in sound propagation in the sea at very low frequencies (< 5 Hz). Of particular interest to acousticians and geophysicists alike was the character of the ambient-noise spectrum and the reasons for its marked wind dependence in this range. From these programs evidence was built up to demonstrate that nonlinear wave-wave interactions in the ocean-wave field are the dominant source of both short-period microseisms and the high levels of the infrasonic noise spectrum in the sea [8-11]. Moreover the complex interplay between the wind and the ocean-wave field, between the developing sea and the pressure field generated in the ocean by nonlinear interactions among its components, and the induced pressure field and the seismic response in the seabed is now sufficiently well understood for this phenomenon to be an important tool for marine geophysical studies.

Of particular interest to this meeting is the possibility of using wave-induced microseisms observed on-shore to measure the properties of the ocean-wave field off-shore with sufficient accuracy for many geophysical and engineering purposes.

The cost advantage over conventional wave-measurement systems is obvious. The DF ocean wave-seismic relationship has been used to measure incident swell on the Oregon Coast for some years [12], but the basic physics involved has only been poorly understood until recently. It is the purpose of this paper to review some New Zealand studies which have improved our understanding of the processes involved to the point where a measurement of the total off-shore wave field can be made with sufficient accuracy for many purposes using an on-shore sensor.

2. The Maui Experiment

2.1 Background

For a number of years the University of Auckland was engaged in an environmental study in connection with the development of an off-shore gas field. A major element of this study involved an investigation of the wave climate of the Cook Strait region [13] - see **Fig 1**. The weather of this region is complex but because of the influence of a mountain chain the area experiences well defined changes in the wind field, with the wind vector often swinging rapidly through 180° from northwest to southeast. The region therefore provides an ideal environment for the study of ocean-wave phenomena.

On engineering grounds the general wave-climate study had of necessity to involve long term recording of the ocean-wave field and related environmental parameters. This fact, coupled with the unique orographic properties of the region, provided an opportunity to extend the basic study and include investigations of other wave related processes. In particular plans were made to examine wave-induced microseisms.

Reliable wave data were provided by a Datawell Waverider buoy moored in approximately 110 m of water close to the Maui-A platform, which provided the base for the relevant meteorological instrumentation. It was not feasible to deploy a hydrophone or

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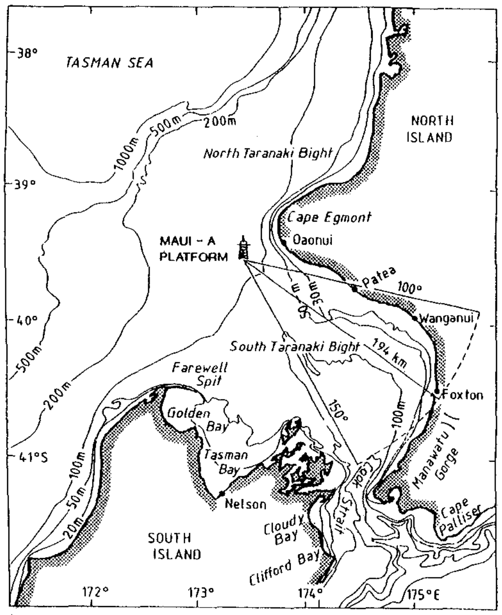


Fig. 1
Localities and bathymetry of Cook Strait and the Maui environment. The Waverider buoy was installed close to the Maui platform and the receiving instrumentation ashore at Oaonui.

ocean bottom seismometer for the microseism study, and as a compromise a long period seismometer was installed ashore at Oaonui - see **Fig 1**.

Recordings of wave and seismic signals of 20 minute duration were initiated automatically every four hours. Wave and seismic spectra were produced from the analogue records and various presentations of the data developed as required. Details of the instrumentation and analysis procedures used are available elsewhere [8, 13].

2.2 Microseism Generation - General Observations

Sea-wave/microseism correlations gave unequivocal evidence for the marine generation of microseisms in the frequency range 0.05 - 1.0 Hz. A comparison of any sea spectrum with its seismic equivalent would identify activity in the microseism spectrum, at or close to twice the frequency of that in the wave spectrum. **Fig 2** of **Ref** [8] provides good examples of the development of a local sea and the associated seismic response.

2.3 Generation Mechanism

The joint behaviour of the ocean-wave and seismic spectra could be interpreted in terms of wave-wave interactions. The quality of the data, moreover, allowed confirmation of most of the theoretical predictions of the Longuet-Higgins formalism. It was demonstrated clearly however that coastal reflection was not the dominant mechanism by which opposing wave trains were generated, seismic activity being just as energetic for off-shore as for onshore winds. The most energetic seismic activity was identified with two opposing seas, although high levels were also observed when only a single sea was active [8].

3. Wind-dependent Spectra

By careful selection of spectral pairs from a two-year data base it was possible to establish the wind-dependent spectra (in 2.5 ms^{-1} intervals) shown in **Fig 2**. These spectra are associated with south-easterly winds only and strict criteria were imposed in their selection [13]. The characteristic growth of the wave peak and its migration to lower frequencies with increasing wind speed is mirrored in the seismic spectra. A notable feature at low wind speeds is a non-wind dependent contribution, associated with a persistent SW swell, which originates in the Southern Ocean.

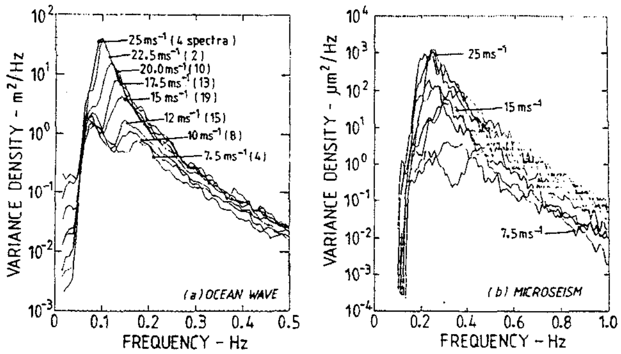


Fig. 2
Ocean wave and associated seismic spectra as a function of wind speed.

With data of this quality it is a simple matter to establish a transfer function for each wind regime from which the off-shore wave field can subsequently be derived from the on-shore seismic measurements. It is however only in exceptional circumstances that the environmental data, required to establish for a particular site the type of relationship shown in **Fig 2**, would be available. Furthermore a requirement to record for a two year period to establish such a transfer function defeats the objective of an on-shore monitoring system. What is clearly required is a better physical understanding of the transfer processes. This is now becoming available.

4. Theoretical Considerations

4.1 The Source-Pressure Field arising from Wave-Wave Interactions

For a given geoacoustic model involving a water layer of constant depth, H, overlying an elastic half space, the theoretical spectrum of the source pressure field, induced by the nonlinear interactions between components of the ocean-wave field and acting at the mean surface of the sea, has the traditional form (see for example Eq (1) of [14]).

$$F_P(f) = \frac{32\pi^4 \rho_1^2 g^2 f_w^3}{\alpha_1^2} Fa^2(f_w)\ I(f) \qquad (1)$$

where $f_w = f/2$ denotes the frequency of the interacting ocean waves; f is the frequency of the induced source pressure field and its seismic equivalent; $\omega = 2\pi f$; ρ_1 is the density of sea-water and α_1 its sound velocity; and $Fa(f_w)$ is the surface-wave spectral function describing the ocean wave field.

The spectra of the corresponding underwater noise (pressure) field, $F_N(f)$, and the microseism field (the displacement of the seabed), $F_M(f)$, are then given by

$$F_N(f) = F_P(f)\, T_{PN}(f) \qquad (2)$$

and

$$F_M(f) = F_P(f)\, T_{PM}(f) \qquad (3)$$

where $T_{PN}(f)$ and $T_{PM}(f)$ are the transfer functions relating the source-pressure field at the sea surface (arising from the wave interactions) to the pressure field in the water column and the seismic field in the seabed. They are complex functions involving the geoacoustic properties of the seabed. The term I is an integral of the spreading function describing the angular distribution of the surface-wave field (see [14, 15]).

To establish the acoustic pressure field from Eq (1) it is helpful to calculate an analytical form of the ocean-wave spectrum. Discounting the persistent swell from the southwest, the JONSWAP function, with parameters appropriate to the Maui

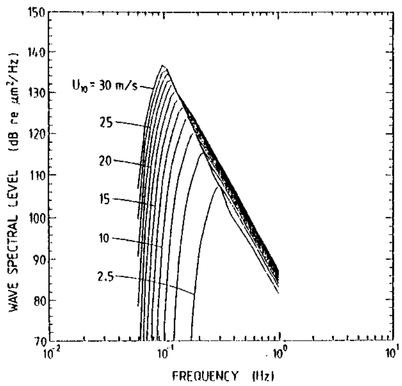


Fig. 3
(a) Analytical form of the Maui wave spectrum as a function of wind speed.

region, has been found to describe the MAUI spectrum very well. The JONSWAP function is traditionally calculated in terms of the peak frequency, but for our purposes a representation in terms of wind speed is more helpful [14]. The resulting one-dimensional MAUI spectra for wind speeds between 2.5 and 30 ms^{-1} are shown in **Fig 3a**.

With Fa (f_w) defined in terms of wind speed, and an accepted form of the spreading function used to calculate the integral I [14], we can derive the set of theoretical spectra for the source-pressure field of a single sea shown in **Fig 3b**. This is the acoustic pressure field that would be observed in an ocean of infinite depth.

4.2 The Acoustic Pressure Field Derived from the Seismic Spectra

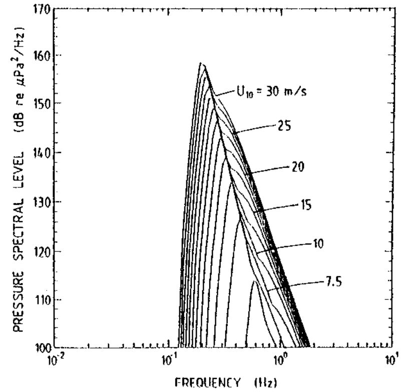
By using a simple approximation of the actual transfer function, T_{PM}, a set of experimental wind-dependent pressure spectra were derived from the seismic spectra of **Fig 2**, for comparison with the theoretical spectra shown in **Fig 3b** [8]. These are shown in **Fig 4**. A comparison of the two spectral sets shows that while there is reasonable agreement in peak spectral levels and shape, the large low-frequency component apparent in the experimental data at low wind speeds is not present in the theoretical spectra.

As was mentioned earlier, this low frequency component is associated with the southwesterly swell which is always present in the region - see **Fig 2a**. The JONSWAP form of the Maui spectra presented in **Fig 3a** deliberately omitted this swell in the interests of simplicity and the theoretical pressure spectra presented in **Fig 3b** represent the result of interactions within a single sea. It was thus of interest to examine the effects resulting from the combined interactions of the southwesterly swell, the decaying northwesterly sea and the developing sea from the southeast.

4.3 Nonlinear Interactions between Multiple Seas

Using certain reasonable assumptions regarding the directivity and spectral form of the interacting wave regimes, a set of theoretical pressure spectra were calculated for various wind speeds - see **Fig 5** - and compared in **Fig 6** with the experimental spectra derived from the seismic spectra of **Fig 2**, but using a slightly more sophisticated transfer function [14]. It is clear that the overall match in spectral levels is better than in the case of the single sea and in particular that the character in the experimental spectra related to the southwesterly swell, is mirrored in the theoretical spectra reasonably well.

While this agreement was gratifying its real significance had to remain in doubt until (i) certain aspects of the wave interaction process were clarified and (ii) the transfer function, T_{PM}, was established for a more realistic geoacoustical model of the Cook Strait region and (iii) the effect of placing the sensor on shore, outside the active wave region, was examined in more detail.



(b) Source pressure field arising from wave interactions, based on the wave spectra of Fig. 3a.

5. Recent Developments

5.1 The Full Standing Wave Solution of the Wave Interaction Mechanism

An analysis has recently been completed which provides a more complete description of the nonlinear interaction process between ocean-surface waves [16]. Its relevance to the present problem is that it incorporates the inhomogeneous component of the induced pressure field and establishes the relative importance of this component compared with the homogeneous component described by Eq (1), to which attention was confined in earlier theoretical treatments. It is sufficient here to note that the inhomogeneous component cannot be ignored, as was done in the analysis just described, when considering the interaction of the wave-induced pressure field with the ocean floor in continental shelf situations. In the Maui case for instance the pressure field (and its seismic response) on the shelf can be much greater (30 - 40 dB) than suggested by **Fig 3a**, which refers to the homogeneous field only. This implies that, either the evidence for the nonlinear interaction process being the source of the microseism peak is thrown into question, or that our understanding of the transfer function T_{PM} (and T_{WM}, linking the wave and microseism fields) is deficient.

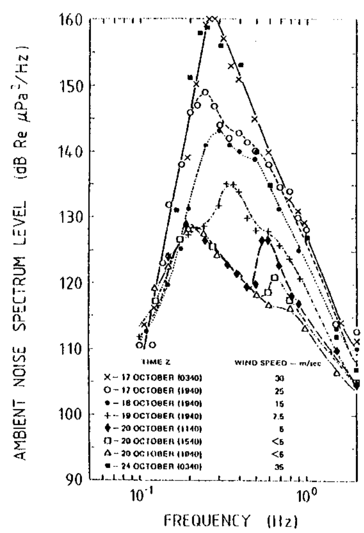


Fig. 4
Ambient noise pressure levels derived from seismic spectra as a function of wind speed.

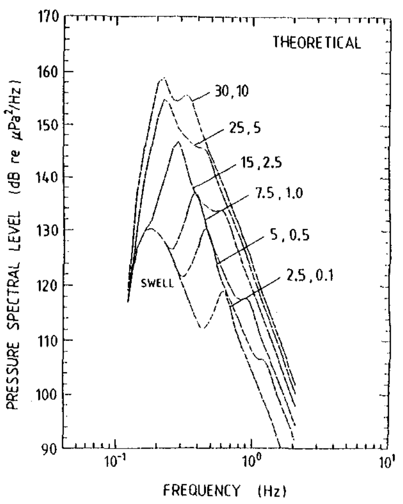


Fig. 5
Theoretical pressure spectra based on the interaction of multiple seas.

5.2 The Transfer Function

The answer proves to lie in the behaviour of these transfer functions, as the sensor is moved on-shore. An OBS (or hydrophone) deployed off-shore in shallow water and inside the active region would record the combined effects of the homogeneous and inhomogeneous components of the induced pressure field. It transpires, however, that the seismic response decays rapidly as the sensor is moved outside the active region onto shore. In the Maui environment the contribution of the inhomogeneous component becomes insignificant at the on-shore site, and the seismic response on shore is due primarily to the homogeneous component of the pressure field. It is because of this that the inversion based on the simple transfer function properly predicts pressure spectral levels appropriate to that component. With this behaviour understood seismic signals recorded on shore can be related to the off-shore wave activity with confidence. The details of this analysis will be presented shortly [17].

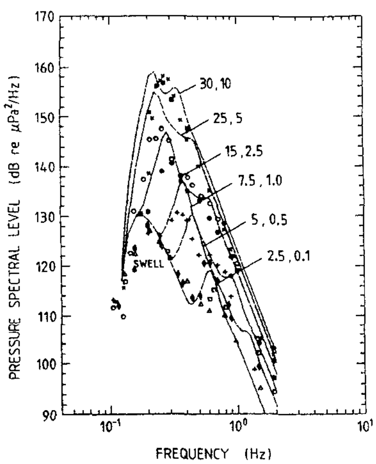


Fig. 6
Comparison of the theoretical pressure spectra with the experimental spectra derived from the seismic data, when bottom reflectivity and shear wave excitation are included.

6. The Southland Wave-Power Study

New Zealand is exposed to some of the most energetic seas in the world and Electricorp Production, which is the body responsible for electrical power generation in New Zealand, has been mindful for some time of the potential of wave power for that purpose. As part of its long term planning it has been anxious to establish some long term statistics on the wave field on the southern coast of the South Island and being aware of the wave/seismic measurements in Cook Strait sought to establish whether a shore-based installation could adequately provide the required data in the Southland environment.

Preliminary trials identified a suitable site for the on-shore sensor and confirmed strong wave related seismic activity. As the geophysical structure off the southern coast is not well known it was decided that the transfer function T_{MW} ($= T_{WM}^{-1}$) should be established experimentally. Accordingly parallel recordings of the off-shore wave-field and on-shore microseisms were made for a two month period. This proved long enough to experience a wide range of wave activity and test the reliability of the remote recording instrumentation specially developed for the station.

Good correlation between the wave and seismic spectra was obtained at all times. From the parallel recording available experimental transfer functions were established on the basis of both a deep water (100 m) and shallow water (20 m) waverider. A theoretical transfer function was also calculated, based on the limited geophysical data available. Typical time histories of $H_{1/3}$, as derived from the waverider and seismometer, are shown in **Fig 7**. These clearly track well. Although in this case the absolute levels established from the seismometer have been increased by a fixed 1.7 dB to achieve the agreement shown, the similarity in the two records gives confidence in our understanding of the processes involved. Most of the detail in the waverider record is reflected in the seismic record although the latter usually shows more stationarity and smaller deviations from the mean value. This characteristic is not due to the transfer function and is attributed to the fact that whereas the waverider measures the wavefields at a single point the seismometer signal is an average response to the whole off-shore region. This can lead on occasions to significant differences (up to 3 dB) in individual spectra but longer term statistics are more consistent.

On the basis of the results of this trial a decision was made to establish a semi-permanent facility capable of long-term recording. A more sophisticated long-period seismometer (Teledyne Model BB-13) was selected because the station would be effectively unmanned. Three units, one sensing the vertical ground displacement (V) and the other two the east-west (EW) and north-south (NS) components were installed in an underground chamber to provide a thermally stable environment. The EW and NS sensors were added in an attempt to also provide a measure of the spread and arrival angle of the incoming wave energy. Power and signal cables connect the sensors to the instrumentation package above ground. Here a rack contains the power supplies, terminal amplifiers, data logger for data acquisition, a lap-top computer for system control and data storage, and a modem link to permit the whole system to be monitored, interrogated and reformatted from Auckland [18].

Preliminary results confirm that the system is reliable and will provide the wave-power data to the accuracy required. The present indication is also that a reliable picture of the angular distribution of the incoming wave field will also be obtained.

An interesting contrast between the Maui and Southland sites is that the southeasterly seas at Maui are largely fetch-limited and best described by the JONSWAP form of the wave field. The long fetches of the Southern Ocean on the other hand produce a sea on the Southland coast better described by the PM spectrum. This difference must be recognised in any theoretical calculations based on Eq (1).

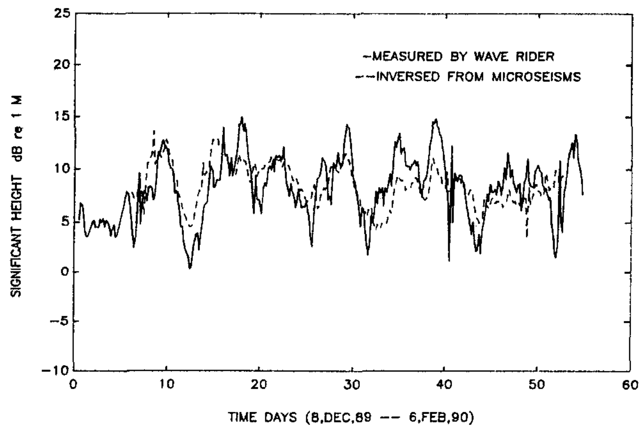


Fig. 7
Time histories of the significant wave height based on the theoretical transfer function.

7. Conclusions

Long term programs in New Zealand have shown that a reliable measure of the total wave climate can be obtained from a land based sensor, with sufficient accuracy for many purposes. Parallel theoretical developments have provided a better understanding of the physics involved. Indeed if the geological structure of a given area is known sufficiently well, the transfer function relating the off-shore wave field to the seismic response measured on shore can theoretically be calculated and established without recourse to a calibration measurement. In most cases however it will be preferable to carry out a short term calibration experiment to provide the necessary information.

The cost of a landbased system of the type described is bound to be much less than one involving the deployment of wave-riders, particularly if long term operation is planned. If the present directional measurements prove to be effective and are adequate and meaningful for the application envisaged, the costs involved will be an order of magnitude lower than those involving a marine system providing similar information.

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