11 WCEE
*Paper No. 299. (quote when citing this article)*
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

# JOINT TIME-FREQUENCY-AZIMUTH DECOMPOSITION OF EARTHQUAKE-INDUCED RESONANT GROUND MOTION

W.R. STEPHENSON

Institute of Geological and Nuclear Sciences Ltd.,
P.O. Box 30 368, Lower Hutt, New Zealand.

## ABSTRACT

Records of strong-motion soft-soil acceleration can sometimes be decomposed into monochromatic components with independent linear polarisations. Techniques for achieving such decompositions are discussed, and applied to two records which have sharp resonant peaks, and which were obtained on rigid basins containing soft soils. In both cases the envelope histories of the components show late-arriving motions which may be either the result of propagating waves, or resonances excited by propagating waves.

## KEYWORDS

Michoacán; Edgecumbe; Mexico City; CDAO; Soft soil; Resonance; Decomposition.

## INTRODUCTION

It is quite common for much of the damage caused by earthquakes to be associated with soft soils. On the most dramatic of these occasions, for example when the complete collapse of a building on soft ground is contrasted with the survival of like buildings on nearby firm ground, there appear to be some common factors; i.e. the earthquake is large, distant and shallow, and the site resonant. An associated factor is the as yet unexplained, occasional long durations of the resonant motion. A good example occurred at the CDAO site in Mexico City during the 1985 September 19 Michoacán earthquake. It is therefore important to make a detailed study of prolonged resonant motion at soft sites during large, distant, shallow earthquakes.

The association of large distances with shallow sources suggests a possible role for crustal guided phases, and it would not be surprising to find that a particular class of basin resonant modes had large participation factors for one or more particular crustal guided phases. Invoking high participation factors of such modes when excited by crustal guided phases could explain the excitation of resonance when nearby rock motion has relatively little input energy at the resonant frequency of the soft site. An alternative view, foreshadowed by the work of Chávez-García *et al* (1995) in Mexico City, the work of Phillips *et al* (1993) in Fuchu, and the work of Hatayama *et al* (1995) in Osaka, is that waves arriving at the basin edge are converted into surface waves propagating within the basin. Chávez-García *et al* postulate arriving surface waves being converted into other surface waves, while Phillips *et al* and Hatayama *et al* identify surface waves which have been converted from body waves.

Any of these mechanisms (excitation of normal modes by crustal guided phases, conversion of crustal guided phases to surface waves, or conversion of body waves to surface waves) will result in trains of nearly monochromatic waves that arrive tens of seconds after the p and s waves. Whatever mechanism operates, it is important to separate the complicated resonant particle motions seen on basins into simple, but physically meaningful, linearly polarised components, in order to establish the origins of the motions.

## METHOD OF ANALYSIS

If the process of decomposing resonant records is seen from a wave propagation point of view then the decomposition is relatively simple. All that needs to be done is to examine pairs of strong motion records, each pair comprising one made on soft soil and one made on nearby hard rock. Occurrences of monochromatic energy late on in the soil record, when the rock motion possesses little energy at the observed response frequency of the soil, would be analysed by determining their polarisation, and coherence techniques would be used to establish a slowness vector for any propagating wave (assuming at least three ground motion records).

However the situation is more complex when seen from a normal mode point of view, and there are several factors that make the previous simple approach ineffective. These factors become clear when the probable nature of the resonant motion is considered. On the one hand a layer of soft soil will possess families of resonant modes, with resonant frequencies clustered just above the fundamental infinite layer quarter-wave frequency. On the other hand, in general each mode can be expected to have a unique polarisation and to be optimally excited by some other unique polarisation of rock motion. Stephenson (1989) gives experimental evidence to support the latter point. Thus a better approach is to attempt to separate the individual resonant motions of the modes, and to concentrate on any mode which has a late excitation. Such an approach breaks new ground, and there is no established practice to follow.

A simple-minded procedure is to examine the spectrum of the motions, and to apply a bandpass filter at each spectral peak. This has major disadvantages; the shape of the chosen spectral window influences the filtered motion in the time domain, it is not always easy to see where to centre a filter because the frequency of a peak can be a function of the azimuth of observation, and there is a possibility that the sidebands of various components will overlap, making simple filtering inapplicable. In fact the interactions of adjacent peaks and their sidebands can give rise to the apparent peak-shifts.

These difficulties may be illustrated by considering an artificial earthquake record constructed by summing several motions, each simulating the response to noise, of a resonator which has its motion along a specific azimuth, and with the resonant frequencies being closely spaced. All of the difficulties of decomposing a real resonant record are present, but the act of constructing the artificial record provides an assurance that the simple polarised resonant components are present.

The example waveforms of Fig. 1 have been constructed by summing three sine waves, each with its own frequency and polarisation. Each sine wave carrier was amplitude modulated by a separate arbitrary waveform, constructed by taking random Fourier coefficients up to a frequency of 0.07 Hz. Each final wavetrain was then filtered through a half sine wave window of 200 sec period. The fundamental waveforms were of 0.96 Hz acting along 15°, 1.0 Hz acting along 75°, and 1.04 Hz acting along 135°.

This arrangement simulates the random excitation of three directional resonators (or equally, the passage of three monochromatic wavetrains of different types, propagating in different directions). The relevance of this simulation is that it illustrates the way in which separate simple physical mechanisms can combine to show complicated behaviour. It is also quite common to obtain records resembling those in Fig 1a, 1b, 1c, 1d and 1e on resonant basins during earthquakes.

The challenge is, given a set of ground motions and spectra such as in Fig 1a, 1b, 1c, 1d and 1e, to reconstruct the generating waveforms as in Fig 1f, 1g and 1h. Such a decomposition can sometimes be achieved but it cannot be guaranteed unique. With multiple solutions potentially available it is necessary to appeal to physical reasoning in order to choose a meaningful decomposition, accepting that nearly-

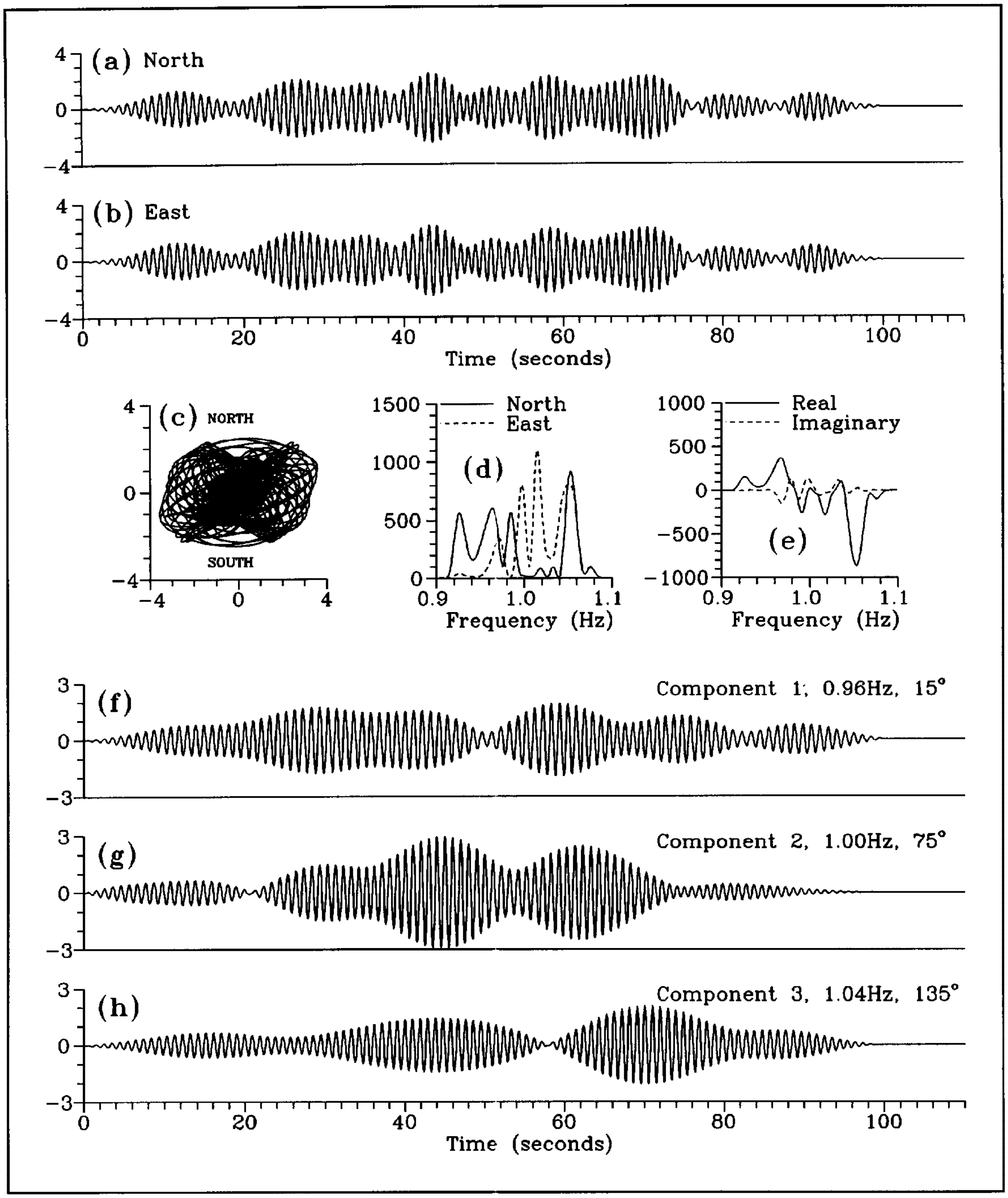


Fig. 1. An artificial resonant ground record. (a) North component. (b) East component. (c) Polar plot of ground motion. (d) Power spectra of North and East components. (e) Cross power spectra between North and East components. (f),(g),(h). The original three, monochromatic, linearly polarised components.

monochromatic, linearly polarised motion is consistent with a single, potentially identifiable, physical process.

General guidelines as to how to attempt decompositions can be stated, but it is clear that in the end the problem is an inverse one, and that any technique which provides a suitable set of waveforms is adequate. Each component of a suitable set must be linearly polarised and must completely account for a region of the original spectrum. The sum of the components (and an optional non-resonant noise component) must equal the original signal.

This paper will largely ignore the details of the process of decomposition, apart from stating general guidelines now.

## Guidelines

The cardinal principle of decomposition is to identify a directed resonance, to resolve the motion along the direction of resonance, to apply a bandpass filter centred at the resonant frequency, and then to subtract the filtered waveform from the original data. This process is iterated until all components have been isolated.

It may not always be physically reasonable to attach a direction and a waveform to each peak of a spectrum. For example, a triplet of one peak and two satellites, all having motion with the same polarisation, with the satellites being above and below the main peak in frequency, is most reasonably interpreted as the excitation of a single directed resonance, with the satellites being sidebands of the main peak. Conversely a motion whose polar plot has elliptical loops may betoken two unresolved resonant peaks that deserve further separation.

Two practical points concerning filtering, and determining directions, deserve elaboration.

## Filtering

The usual tradeoff between response in time and response in frequency can be avoided to some extent by employing a technique equivalent to filtering with an adaptive filter. In practice this involves fitting a sine wave to successive windows of the waveform, thus avoiding an output at times when the waveform is quiescent. In all the cases treated in this paper a sliding time window of error function shape was applied to both the target waveform and to the fitted sine wave and cosine wave at the resonance frequency.

## Directions

If a record contains a single directional resonance, or several directional resonances whose sidebands do not overlap, the situation is simple, and has been described by Stephenson (1975). In essence, the direction of a resonance is given by a function of three power spectra - the north and east autopower spectra, and the real part of the cross power spectrum between the north and east components (in this simple case the imaginary part of the cross power spectrum between the north and east components is zero).

In general not all resonant peaks will be isolated sufficiently in frequency to be rotated and filtered by this route. It is not uncommon for two components to be so close in frequency that their spectra overlap, and simple filtering is then insufficient. In such cases, a polar plot of the motion around the two resonant frequencies will often reveal two dominant directions. Then the motion orthogonal to each direction will contain only motion due to the other resonance. Suitable filtering and scaling will yield a pair of separated wave forms, one along each direction.

On other occasions a resonant peak which is clearly due to linearly polarised motion will appear in the spectrum, but its peak width will be much narrower than is suggested by the envelope of the original motion. This would be interpreted as being a sideband, with other spectral components of the resonant motion being contaminated by adjacent peaks, as shown by a non-zero imaginary cross spectral component. Nevertheless it would be a valid indicator of direction, applying to some other motions near the resonant frequency. The direction should therefore be incorporated into the decomposition procedure.

CASE STUDIES

The idea that the motion at resonant sites can be decomposed into linearly polarised components with closely spaced frequencies is a new one, and the cases treated so far reflect a learning process. It may be possible to revisit some records with the benefit of hindsight, either further decomposing components, or combining components with the recognition that they are physically associated. However there are already valuable lessons to be learned from the limited decompositions already achieved.

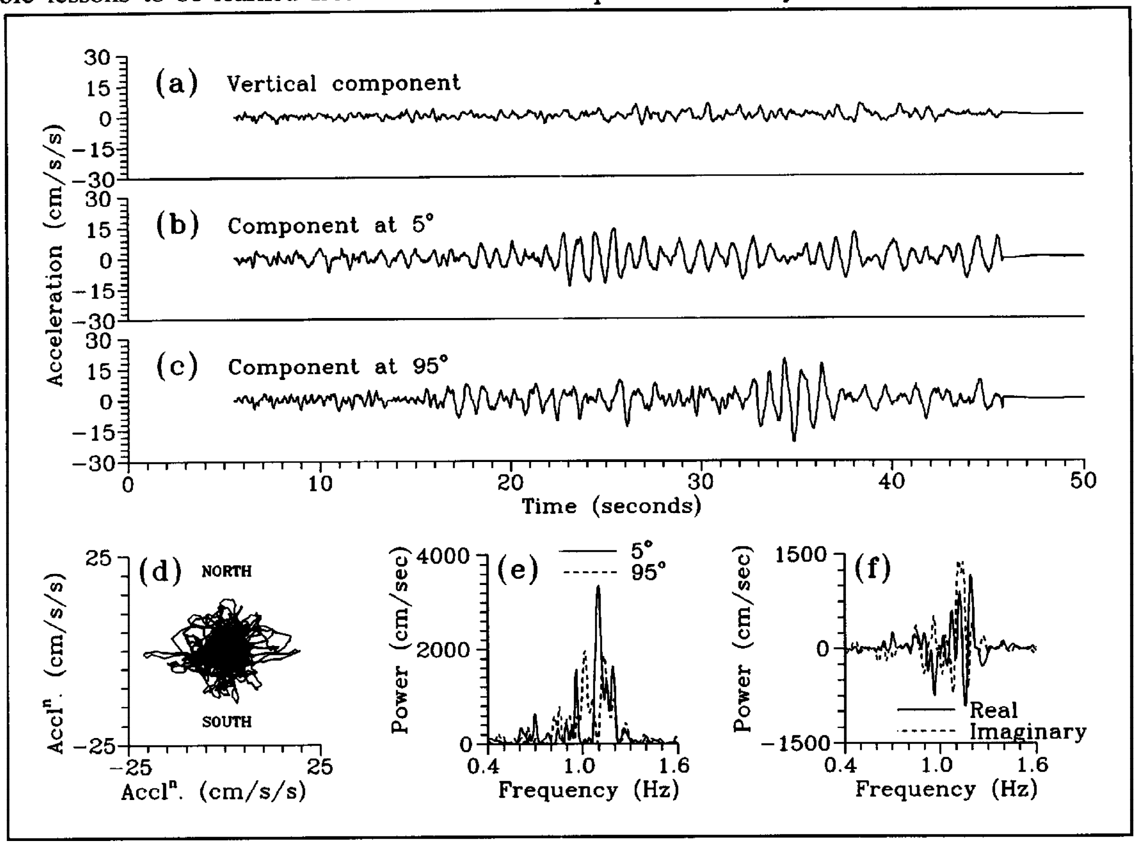


Fig. 2. (a), (b), (c); Recorded ground surface accelerations of the 1987 Edgecumbe earthquake, recorded on soft soil at Wairoa, 136km distant. (d) Polar plot of (b) and (c). (e) Power spectra of (b) and (c). (f) Real and imaginary parts of the cross-power spectrum between (b) and (c).

Wairoa, New Zealand; 1987 March 02 0142 UTC

The 1987 Edgecumbe earthquake is described by Staff of New Zealand Department of Scientific and Industrial Research (1987) and by Anderson and Webb (1989). It had a local magnitude of 6.3, its moment release was concentrated in the top 8km of the crust, and its normal faulting was associated with surface fault breaks.

The strong motion recording site at Wairoa (136km from the epicentre) is described by Barker (1994) as being underlain by at least 31m of soft sediments with a shear wave velocity of 130m/s at the surface, increasing gradually to 247m/s below 22m. On the basis of this profile, and assuming a one-dimensional geometry, a site frequency of about 1Hz is expected. The Wairoa strong motion record published by Cousins *et al* (1988) is reproduced in Fig. 2. It shows that the maximum acceleration of 0.021g occurred late in the recording, and in a roughly east-west direction. The power spectra of the horizontal components shown in Fig. 2(e) and (f) suggest that the region from 0.96Hz to 1.10Hz will be easily decomposed with simple techniques, but that in the region from 1.10Hz to 1.15Hz more advanced techniques will be needed.

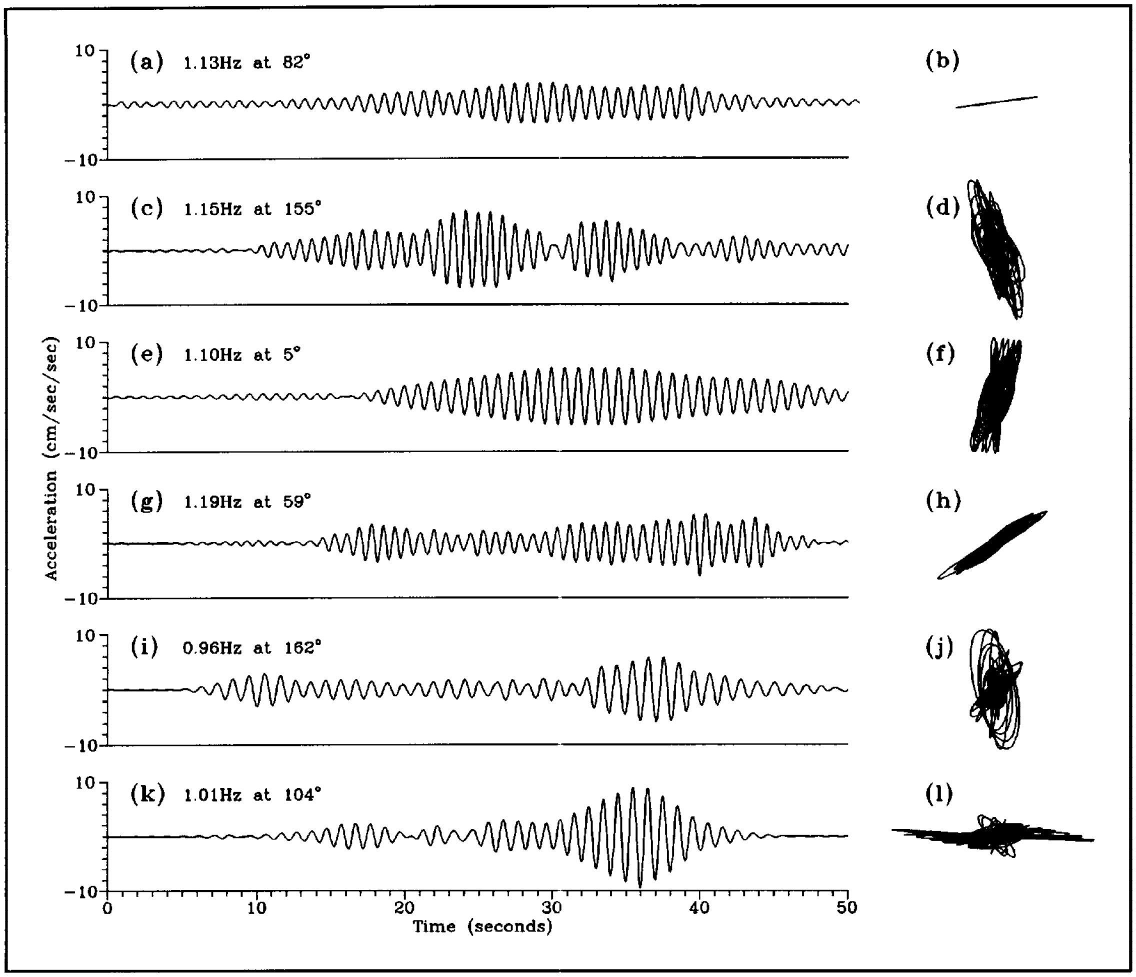


Fig. 3. The decomposed Wairoa record. (a), (c), (e), (g), (i), (k) - histories. (b), (d), (f), (h), (j), (l) - polar plots. *Note: Acceleration scale for polar plots is doubled.*

The eventual decomposition of resonant motion is shown in Fig. 3. For five of the components energy was present in a direction at right angles to the dominant direction. These minor components were also extracted by filtering and their contributions are seen in the polar plots. They could be artifacts of sidebands of nearby peaks. When the six resonant components are subtracted from the original record, there remains only a relatively small noise residue. It is noteworthy that a major contribution is made by the 1.01Hz, 104° component at 30 to 40 seconds, and that this is echoed by similar behaviour for the 0.96Hz, 162° component. On its own, either one of these could be interpreted as the passage of a particular propagating wave, but their occurrence at the same time is more suggestive of a single propagating wave exciting two local resonances.

It is not easy to assess the absolute time of excitation of these two components because absolute time was not available from the recorder. The lack of absolute time makes it impossible to determine the phase responsible for exciting the site resonances.

CDAO, Mexico; 19 September 1985

This earthquake, which was large ($M_s$ 8.1) and shallow (16km deep with 9° dip) , and centred 384km away from Mexico City, is noted for the high intensities observed in Mexico City, associated with a high casualty rate and extensive damage. Although the CDAO record was not made in the area of high damage

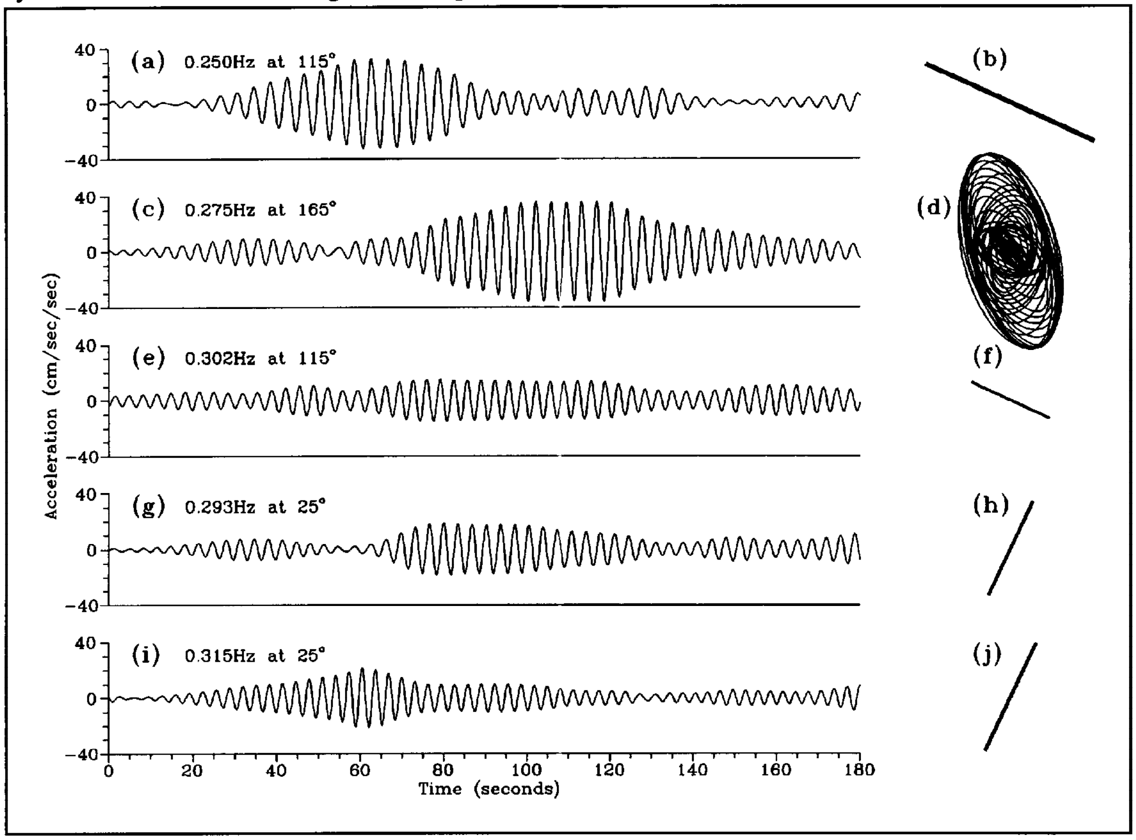


Fig. 4. The decomposed CDAO record. (a), (c), (e), (g), (i) - histories. (b), (d), (f), (h), (j) - polar plots. *Note: Acceleration scale for polar plots is doubled.*

it has attracted great interest because of its anomalously long duration of resonant motion.

The route followed in decomposing this record started with a filtering of the horizontal motion into three bands, at 0.250Hz, 0.276Hz, and 0.306Hz. Polar plots of these motions were the basis of selecting directions for further analysis.

The components of the resonant motion are shown in Fig. 4. It is noteworthy that the late resonant motion has two major components - a linearly polarised motion at 0.293Hz, and an elliptically polarised motion at 0.275Hz. The minor axis of the ellipse is oriented along 255°, whereas the direction to the epicentre is 250.7°, so the dominant part of the elliptical motion is suggestive of a Love wave propagating from the epicentre. However the linear component at 0.293Hz bears no obvious relation to the epicentre. The occurrence of two late resonant phases at much the same time is more likely due to two site resonances excited by a single late arriving wave than due to two such waves arriving from different directions at the same time.

## OTHER ANALYSES

Three other strong motion accelerograms each generated by the action of a distant large earthquake on a soft-soil site have been analysed by the techniques described here. In each case a late-arriving phase with a distinct polarisation has been identified. These accelerograms are TLHB and TLHD as recorded during the 1985 Michoacán earthquake, and that from St. Kilda, New Zealand, as recorded during the 1994 June 18 Arthur's Pass earthquake.

## CONCLUSIONS

Many of the complex spectral and temporal features of earthquake-induced ground motion recorded at resonant sites can be explained in a simple but satisfactory manner by seeking a restricted number of linearly polarized, nearly monochromatic motions, the sum of which closely approximates the resonant part of the recorded motion.

It is found that the resonant responses at closely spaced frequencies are often quite distinct in their timing and direction, suggesting that different resonant modes are being excited independently by different arriving earthquake phases.

The strong ground-motion recorded at the CDAO station in Mexico City on September 19th 1985, is shown to be the sum of early and late responses at slightly different frequencies, acting along different directions. This observation supports the proposition that the abnormally long duration of shaking in this record is a consequence of the excitation of a resonance by unrecorded rock motion rather than a consequence of lateral p-wave resonance or sub-basin resonance.

## ACKNOWLEDGEMENTS

This work was supported by the New Zealand Foundation for Science, Research and Technology, under contract C05319.

## REFERENCES

Anderson, H. and T. Webb. (1989). The rupture process of the Edgecumbe earthquake, New Zealand. *N.Z. J. Geol. and Geophys.*, **32(1)**, 43-52.

Barker, P.R., (1994). *A Report on Cone Penetrometer and Seismic Cone Penetrometer Testing at selected sites in lower North Island.* Barker Consulting, Wellington, New Zealand.

Chávez-García, F.J., J. Ramos-Martínez and E. Romero-Jiménez, (1995). Surface-Wave Dispersion in Mexico City. *Bull. Seis. Soc. Am.*, **85(4)**, 1116-1126.

Cousins, W.J., R.T. Hefford, G.H. McVerry, S.M. O'Kane, (1988). *Computer Analyses of New Zealand Earthquake Accelerograms, 3,* DSIR Physics and Engineering Laboratory, Lower Hutt, New Zealand.

Hatayama, K., K. Matsunami, T. Iwata, and I. Irikura, (1995). Basin-Induced Love Waves in the Eastern Part of the Osaka Basin. *J. Phys. Earth*, **43**, 131-155.

Phillips, W.S., S. Kinoshita, and H. Fujiwara, (1993). Basin-Induced Love Waves Observed Using the Strong-Motion Array at Fuchu, Japan. *Bull. Seis. Soc. Am.*, **83:1**, 64-84.

Staff of New Zealand Department of Scientific and Industrial Research. (1987). The 1987 March 2 earthquake near Edgecumbe, North Island, New Zealand. *EOS transactions of the American Geophysical Union*, **68(44)**, 1162-1171.

Stephenson, W.R. (1975). Cellular normal modes of Alluvium Response. *Bull. N.Z. Nat. Soc. Eq. Eng.*, **8(4)**, 245-254.

Stephenson, W.R. (1989). Observation of a Directed Resonance in Soil Driven by Transverse Rock Motion. *Bull. N.Z. Nat. Soc. Eq. Eng.*, **22(2)**, 81-89.