CALIFORNIA INSTITUTE OF TECHNOLOGY

EARTHQUAKE ENGINEERING RESEARCH LABORATORY

RESPONSE ENVELOPE SPECTRUM AND INTERPRETATION OF STRONG EARTHQUAKE GROUND MOTION

BY

MIHAILO D. TRIFUNAC

EERL 70-06

A REPORT ON RESEARCH CONDUCTED UNDER A GRANT FROM THE NATIONAL SCIENCE FOUNDATION

PASADENA, CALIFORNIA

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ABSTRACT

A multiple filter technique is developed using a single degree of freedom lightly damped oscillator as a narrow band-pass filter. It provides for a physically simple approach to the analysis of accelerograph records from the point of view of structural engineering.

The analysis of several typical accelerograph records indicates that a significant portion of strong earthquake ground motion consists of surface waves. It is concluded that the duration of intense shaking will be determined predominantly by the dispersion properties of the ground.

INTRODUCTION

An understanding of the phenomena associated with strong earthquake motion is important for many areas of research and application. This motion of destructive intensity endangers the safety of all man-made structures and has, on several occasions, led to complete or partial devastation of whole cities. The recording and interpreting of strong motion data is also essential for various studies of earthquake mechanism, for high resolution of the patterns of earthquake energy release and in general for better understanding of the close field of earthquake ground motion.

The basic information related to this phenomenon comes from strong-motion accelerographs. The first instruments of this kind were installed in the field some forty years ago and the first strong motion record was obtained during the 1933 Long Beach, California earthquake. Since that time several hundred earthquakes have been recorded, predominantly in California and Japan.

Although the history of modern recording of teleseismic earthquake waves is not much older than the measurements of strong, near field, ground motion, the nature of teleseismic waves and the great number of recorded shocks resulted in early interpretations of the different wave forms displayed in those records. This was not the case with the strong motion records.

The inhomogeneities and discontinuities in the earth's crust lead to a wide variety of wave velocities. For distant recordings different frequency wave components are dispersed and cause natural separation of various wave types. This separation, which helps in the record interpretation, is further enhanced by the great distances and hence the long travel times which allow dispersion effects to take place.

Strong earthquake ground motion close to the source of energy release is less obvious to interpret. In principle it is composed of essentially the same types of waves, but often they are not clearly separated in time because of the source proximity. In addition, high frequency motions, whose amplitudes decay rapidly with distance and so cannot be observed on most teleseismic records, are also present. Also source size, relative to the distance to the recording station, and the spatial and temporal distribution of energy release, become important. All of these complexities are probably the reason why, so far, no notable attempts have been made to determine the detailed character of strong earthquake ground motion.

Because the collection of recorded strong motion accelerograms for engineering applications is still far from complete, many research workers have made valuable attempts to generate artificial accelerograms. Some of these are based on white noise (Housner, 1947; Rosenblueth, 1956; Rosenblueth et al., 1962; Bycroft, 1960), Stationary Gaussian process (Tajimi, 1960; Housner and Jennings, 1964; Barstein, 1960) and various nonstationary processes (Bolotin, 1960; Bogdanoff et al., 1961; Cornell, 1964; Amin and Ang, 1966; Shinozuka and Sato, 1967; Jennings et al., 1968). Although these approaches represent a significant step forward in the engineering use of accelerograms, they are often based on simplified interpretations of the properties of strong motion. Usually only the simplest features of the recorded accelerograms are employed to model the "rapid build-up" of the motion, the "central portion of strong shaking" and the "decaying tail." The nonstationary time dependence of the intensity and frequency content of strong-motion are usually neglected in such models. The reasons for these simplifications come partly from the mathematical complexity in generating these processes but are mainly the result of the lack of our knowledge of the actual character of strong-motion accelerograms.

The area of earthquake engineering research concerned with the effects of local geology on the amplitudes of strong-motion waves is also directly affected by the lack of detailed interpretation of strong-motion accelerograms. Most of these studies are based on models in which earthquake waves are assumed to propagate vertically up towards the set of horizontal surface layers, irrespective of the question of whether such motions are predominant or not. However, the simple qualitative analysis of the parameters which govern the properties of strong-motion waves leads to the conclusion that a predominant part of the near field ground shaking may be composed of surface waves associated with energy propagating horizontally through soft surface layers as a wave guide (Trifunac, 1969). The following analysis of some typical strong-motion records supports such an interpretation.

RESPONSE ENVELOPE SPECTRUM (RES)

The need for improved methods of assessment of information from seismograms stimulated the development of the moving window Fourier analysis and multiple filter techniques. Alexander (1963) used frequency and velocity windows to extract information on wave modes. Archambeau, Flinn and Lambert (1966) studied the dispersion of body wave arrivals by using digital filters. Landisman, Dziewonski and Sato (1969) developed a process called "moving window analysis" to display the amplitudes and phases of transient seismic signals as functions of period and group velocity. Dziewonski, Bloch and Landisman (1969) reported on the "multiple filter technique" as an efficient method for analyzing multiple dispersed signals. These approaches based on different numerical methods are aimed at the same objective, which is to extract a maximum of information present in the seismograms. This information typically consists of the dispersion as indicated by arrival times of different frequency components in the seismic surface waves. It further consists of the phase data, elipticity of the surface particle motion, and other features from which the character of energy release at the source can be determined. Trifunac and Brune (1970), for example, used a simple form of moving window Fourier analysis to study the extended time behavior of seismic energy release.

In engineering seismology and in particular in the analysis of strong-motion accelerograms similar information is needed. The knowledge of the time dependent amplitudes and the frequency content of strong-motion records is required for predicting the vibration behavior of engineering structures.

Small motion of a single degree of freedom viscously damped linear oscillator is described by the well known differential equation

$$\ddot{x} + 2\omega_n \zeta \dot{x} + \omega_n^2 x = -a(t) \tag{1}$$

where

x = relative motion of the mass

ζ = fraction of critical viscous damping

ω_n = natural frequency of vibration

$a(t)$ = absolute acceleration of the ground

The vibration of several types of structures such as elevated water tanks and small buildings can be described by the single degree of freedom oscillator. For tall buildings, chimneys and towers, when contribution of the higher modes of vibration cannot be neglected, each mode of vibration may be represented by the equation of the same form as (1). Then, by combining the response from all higher modes, the resulting response of the multi-degree of freedom system can be determined (Merchant and Hudson, 1962). Hence, from the engineering point of view the most valuable information about the structural vibrations during earthquake motion will be obtained by studying the response of the system described by equation (1). Similar ideas led to the introduction of the concept of the response spectrum by Benioff (1934) and Biot (1941) further developed and applied by Housner, Martel and Alford (1953), Hudson (1956) and others.

In order to find a physically simple method for analyzing accelerograph records from the point of view of structural engineering we consider again equation (1). It is well known that if for a(t) is substituted $-A\omega^2 \sin \omega t$ and if it is assumed that the vibration will go on for a long time, so that transient vibrations generated by the initial conditions have decayed, the steady state part of the relative response x(t) is determined by the following expression:

$$x(t) = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\frac{\omega}{\omega_n}\zeta\right)^2}} \cdot A \cdot \sin(\omega t - \Phi) \qquad (2)$$

where

$$\Phi = \tan^{-1}\left(\frac{2\omega_n \omega \zeta}{\omega_n^2 - \omega^2}\right) \qquad (3)$$

The factor $\frac{1}{\sqrt{\cdot}}$ in equation (2) represents a dynamic amplication factor and gives the ratio between the dynamic and static deflections. It is easily seen that for small ζ this factor is maximum when $\omega = \omega_n$ and equals $1/2\zeta$. For most engineering structures ζ the equivalent viscous damping is in the range between 1% and 5% of critical. For structures oscillating in the nonlinear and plastic range the equivalent ζ increases to about 10% and more. Also when $\omega = \omega_n$ from equation (3) it follows that the phase shift Φ is equal to $\pi/2$. Thus we see that a typical lightly damped single degree of freedom system acts like a narrow band filter which amplifies the input frequencies, centered around ω_n, by $\frac{1}{2\zeta}$ times and follows the input wave form with $\pi/2$ delay. When $A = A(t)$ is a slowly changing function of time, the response $x(t)$ will also have a slowly varying amplitude. The envelope of the response of the single degree of freesom oscillator is thus approximately $A(t)/2\zeta$.

The physical appropriateness of the single degree of freedom system as a narrow band filter suggests that the response of a series of such systems can be used to infer the character of the input acceleration. This is of course the basic idea behind the Response Spectrum and the following analysis is simply a means of introducing more detail into the use of such spectra. Computing the response envelopes for many filters for equally spaced frequencies will enable one to construct a three-dimensional diagram which indicates the time and frequency dependence of the instantaneous envelope $A(t, \omega)$ of the harmonic component of ground motion with frequency ω at time t. We will call $A(t, \omega)$ the Response Envelope Spectrum (RES) of the ground displacement. Likewise we will call $\omega A(t, \omega)$ the RES of the ground velocity and $\omega^2 A(t, \omega)$ the RES of the ground acceleration.

The relationship between the RES and the response spectrum is obvious. A point on the relative displacement spectrum for the frequency ω corresponds to the maximum of $A(t, \omega)$ during the time of excitation. Thus RES contains all the information required to construct the relative response spectrum (i.e. relative displacement, and approximately velocity or acceleration spectrum), and in addition retains information about the time at which various responses occur.

The RES technique is closely related to the "multiple filter technique" or the "moving window analysis." It is, in fact, simply a multiple filter technique with filter properties specified by the single degree of freedom viscously damped oscillator. Therefore the RES can be used as a tool to study dispersion properties of seismic waves and complicated multiple arrivals. Like multiple filter techniques or moving window analysis, it enables one to determine group velocity curves for these cases for which the signal to noise ratio is so small, that the peak and the trough method cannot be applied.

The RES in Figures 3 to 6 were computed in the following way. Recorded ground acceleration, shown on the side of each figure is substituted in equation (1) as $a(t)$. The $a(t)$ for computation was in the form of equally spaced data points with $\Delta t = 0.02$ seconds, interpolated from the original unequally spaced data. Equation (1) was then integrated by the Adams-Moulton method, for each frequency ω and damping $\zeta = 0.10$ of critical. The envelope of the relative response $x(t)$ was approximated by connecting the successive peaks in $x(t)$ by a straight line. This is illustrated in Figure 1, where the response and the envelope are computed for the NS component of the El Centro 1940 accelerogram for an oscillator with $\omega_n = 10$ radians/second and $\zeta = 0.10$. The computations were repeated

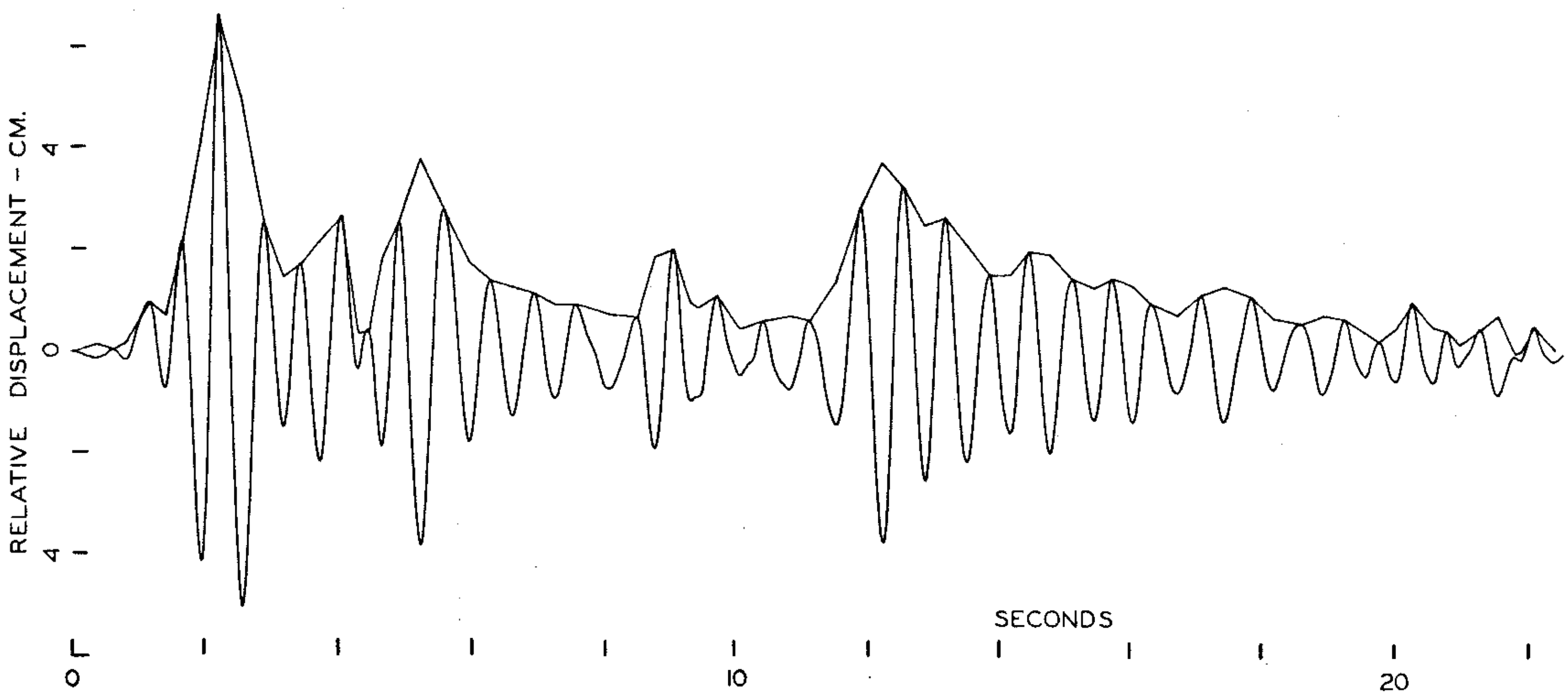

Figure 1

The relative displacement and its envelope for an oscillator with natural frequency ω_n = 10 rad/sec and fraction of critical damping ζ = 0.10, for the NS component of the El Centro, 1940, strong motion accelerogram (Fig. 5).

for 100 oscillators with frequencies equally spaced at $\Delta\omega_n = 0.166$ radians/second and ranging from 0.166 radians/second to 16.66 radians/second. All these envelopes together define $\omega^2 A(t, \omega)$. The RES for $\omega^2 A(t, \omega)$ was chosen for this work because, as will be seen later, our main interest in this paper is concerned with studying the properties of accelerograms in which higher frequencies are emphasized. To form a rectangular mesh for Figures 3 to 6 it is necessary to interpolate equally spaced envelope amplitudes along the time coordinates. This was done by interpolating amplitudes every 0.25 seconds. For simplicity of visual presentation all the amplitudes were normalized so that the peak equals 5. Intermediate amplitudes were determined in the following way. When the normalized amplitude A_n was $k \le A_n < k + \frac{1}{2}$, for $k = 0, 1, 2, 3, 4, 5$, A_n was rounded off to k and that value was printed in the corresponding slot. When $k + \frac{1}{2} \le A_n < k + 1$, A_n was substituted by a blank and nothing was printed on the output paper. In this way elevation contours of $\omega^2 A(t, \omega)$ became clear and easy to interpret. Because of the photographic reduction of the original scale all the contours of $\omega^2 A(t, \omega)$ in Figures 3 to 6 are also traced by hand. The actual amplitudes of the RES may be obtained by multiplying normalized amplitude values by the "peak value" which is given for each figure.

ANALYSIS OF ACCELEROGRAMS FOR THE IMPERIAL VALLEY MAY 18, 1940, CALIFORNIA, EARTHQUAKE

Several typical accelerograms from the El Centro accelerograph record of May 18, 1940, were chosen as the optimal samples for this analysis for the following reasons. The dispersion of the surface waves can be theoretically estimated, provided the layer thicknesses and velocities of wave propagation are well known in the area between the station and the source. Detailed studies of the local travel times and layer thickness in the Imperial Valley were made by Biehler (1964). Trifunac and Brune (1970) used the data from the Westmoreland seismic profile (Biehler, 1964) to compute the group velocity curves for several Love and Rayleigh modes (Figure 2). These dispersion curves are based on the five layer model. Layer properties were taken as follows (Trifunac and Brune, 1970):

Layer	Thickness(km)	α(km/sec)	β(km/sec)	ζ(gr/cm^3)
1	0.18	1.70	0.98	1.28
2	0.55	1.96	1.13	1.36
3	0.98	2.71	1.57	1.59
4	1.19	3.76	2.17	1.91
5	2.68	4.69	2.71	2.19
6	∞	6.40	3.70	2.71

The flat character of the fundamental mode group velocity indicates that most of the energy in the short period range (shorter than about 5 seconds) will travel with a velocity of about 1 km/sec. In the same paper, approximate distances and tentative locations for all shocks recorded on the El Centro strong-motion accelerograph were

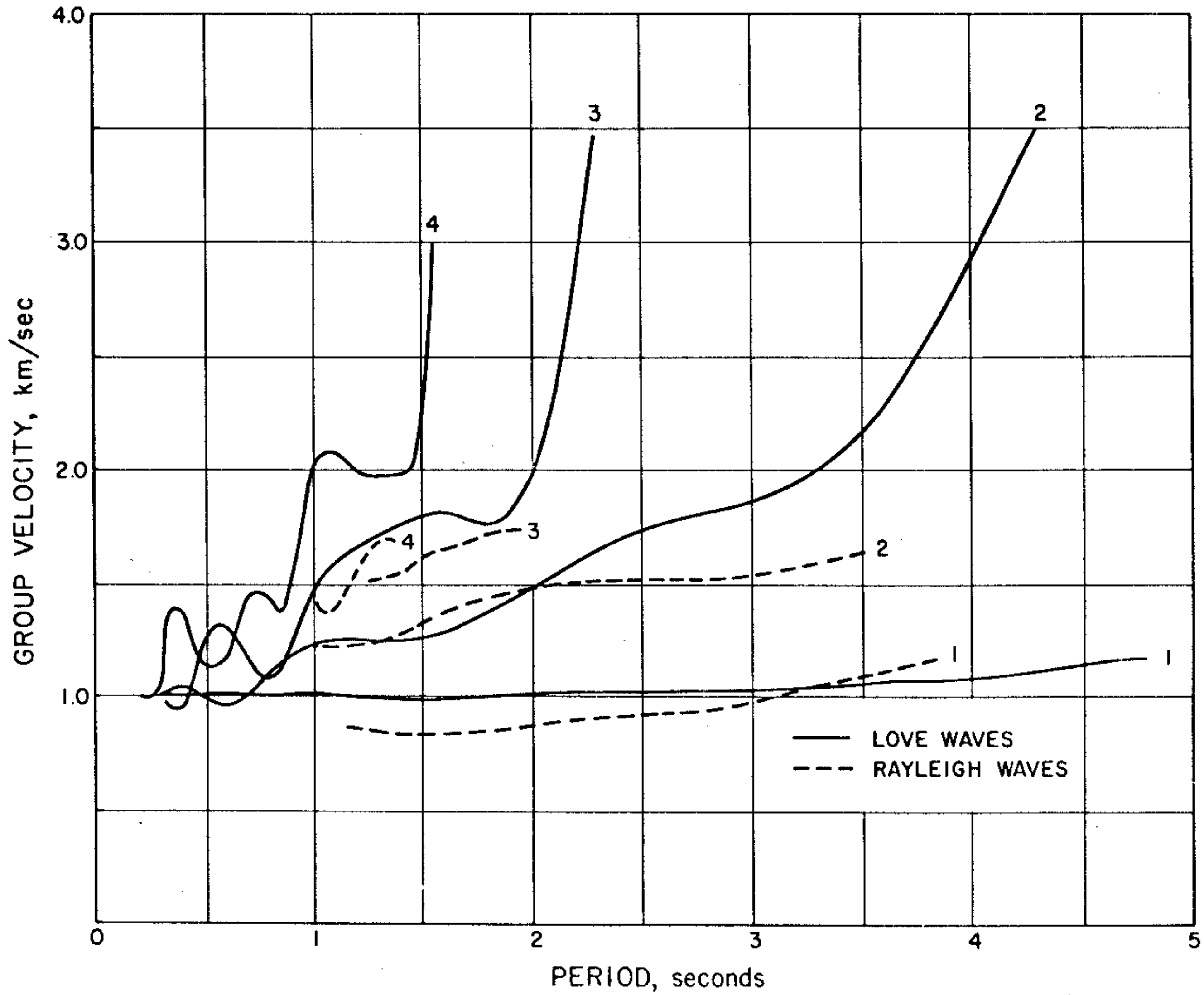

Figure 2

Love and Rayleigh wave dispersion curves for the structure corresponding to the Westmoreland profile (Biehler, 1964) in the Imperial Valley.

determined. Trifunac and Brune (1970) also interpreted all obvious (P and S) phases for all recorded events. Therefore these accelerograms permit a comparison of an interpretation based on RES with that carried out in the previous study.

We first analyze an aftershock referred to as Event 9 (Trifunac and Brune, 1970). Figure 3 shows the trace and RES of the NS acceleration component and Figure 4 shows the same for the EW acceleration component. Epicentral distance for this event was estimated (Trifunac and Brune, 1970) to be about 13 - 19 km from El Centro. If it is assumed that the actual distance was about 19 km, it is possible to calculate the expected arrival times for all surface phases for which theoretical dispersion curves were calculated (Figure 2). It should be pointed out that our interpretation here is only qualitative since we have estimated only the theoretical group velocities in the absence of actual measurements. Nevertheless, when the expected arrivals for the surface phases are superimposed on RES one can easily associate various bursts of arriving energy in the accelerogram with the estimated arrivals. In this way we interpret the RES high amplitudes between 17 and 22 seconds (Figure 3) to be associated with the fundamental Love and Rayleigh waves. Likewise, waves arriving during the time interval from about 6 to 16 seconds are interpreted to be the higher surface wave modes, as may be seen in the same Figures 3 and 4.

It may be difficult and perhaps useless to draw a clear line in the RES separating surface waves from body waves. This is clear from the Figures 3 and 4 where it may be seen that some surface wave phases (in RES from 6 to 10 seconds and for frequency $\omega \lesssim 8$ rad/sec, Figures 3 and 4) do arrive simultaneously with the higher frequency energy (in RES

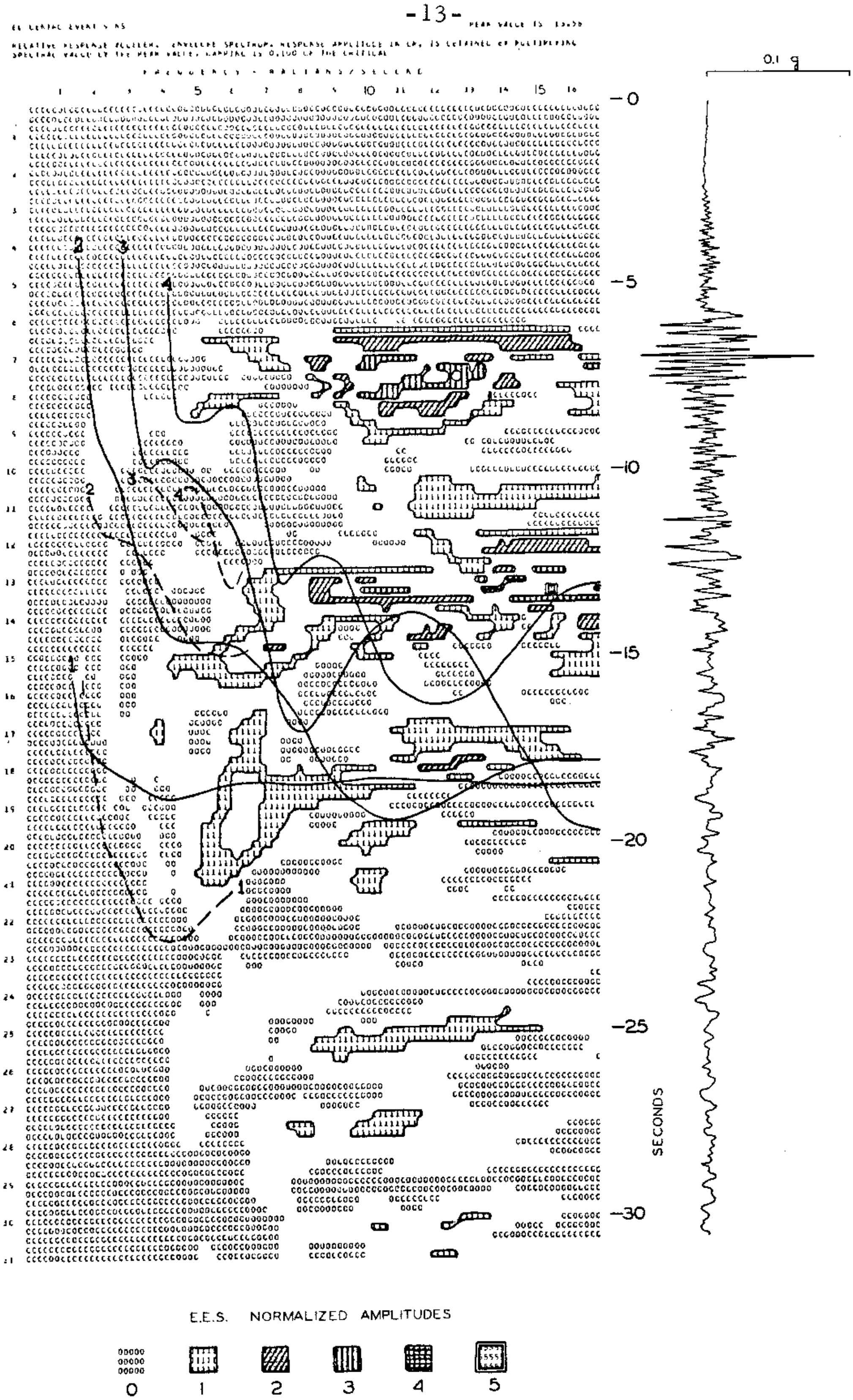

Fig. 3 The $\omega^2 A(t, \omega)$ Response Envelope Spectrum (RES) for Event 9, NS component, recorded during the Imperial Valley, California, earthquake, 1940 (Trifunac and Brune, 1970). The actual amplitude of $\omega^2 A(t, \omega)$ in cm/sec^2 is obtained by multiplying the normalized amplitudes (0 to 5) by the peak amplitude $\omega^2 A$ peak = 13.58 cm/sec^2. Frequency scale for RES is in radians per second and the time scale is in seconds. Arrivals of the surface wave groups were computed using the theoretical dispersion curves (Fig. 2) and the epicentral distance Δ = 19 km. Damping ζ = 0.1 of critical.

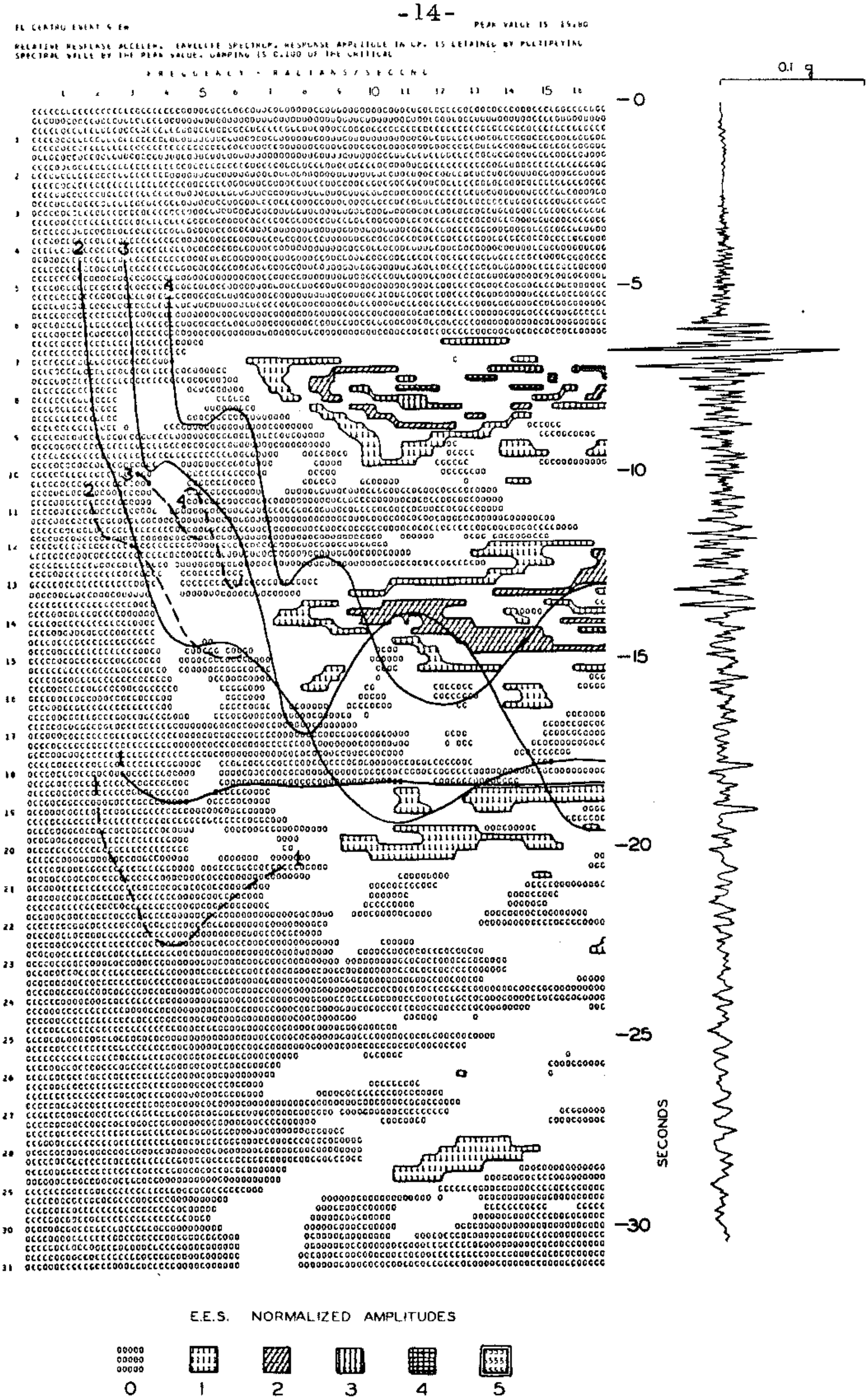

Fig. 4 The $\omega^2 A(t, \omega)$ Response Envelope Spectrum (RES) for Event 9, EW component, recorded during the Imperial Valley, California, earthquake, 1940 (Trifunac and Brune, 1970). The actual amplitude of $\omega^2 A(t, \omega)$ in cm/sec^2 is obtained by multiplying the normalized amplitudes (0 to 5) by the peak amplitude $\omega^2 A$ peak = 19.80 cm/sec^2. Frequency scale for RES is in radians per second and the time scale is in seconds. Arrivals of the surface wave groups were computed using the theoretical dispersion curves (Fig. 2) and the epicentral distance Δ = 19 km. Damping ζ = 0.1 of critical.

from 6 to about 10 seconds and for $\omega \gtrsim 8$ rad/sec, Figures 3 and 4) which we may call S wave. The arrivals after 22 seconds (Figures 3 and 4) cannot be interpreted in a simple way and probably represent reflections which traveled along the indirect paths and hence arrived later at the recording station.

In the light of these interpretations, based on the calculated arrivals of surface waves, we can conclude that except for the high frequency arrivals from about 6 to 8 seconds (Figures 3 and 4) all other motions recorded during Event 9 are represented by surface waves. The first burst of higher frequencies which we may call the S wave arrival is the prominent feature of an accelerogram in almost every case. However from the RES one can find that, from the point of view of the vibration amplitudes of the wide class of simple oscillators, surface waves may be more significant. During surface wave accelerations, structures may experience the longest and biggest oscillations. In Figure 3, for example, the response spectrum peak would occur for a frequency 15.3 cps at a time t=13.25 sec which is definitely in the region of surface wave excitation.

The duration of strong earthquake ground motion is one of the most important parameters governing destruction of man-made structures. In terms of duration, the body, P and S, waves are recorded on most accelerograms in the form of relatively higher frequency bursts of energy, arriving at the station for several seconds. The surface waves, on the other hand, usually composed of somewhat longer period waves, arrive during considerably longer time intervals. This extended arrival of the energy in the form of the surface waves is the consequence of the dispersion through the horizontal wave guides which are usually characterized by the low velocity of wave propagation. Dispersion curves in

Figure 2 can serve as one example of this. The surface wave motions characterized by such a dispersion will thus last for

$$\Delta\left(\frac{1}{V\,\mathrm{min}} - \frac{1}{V\,\mathrm{max}}\right)$$

time units, where Δ is the epicentral distance and V is the group velocity.

The main part of the energy release during the Imperial Valley, 1940 earthquake was recorded on the accelerograph at El Centro for about twenty-five seconds (Figures 5 and 6). The approximate analysis of this record (Trifunac and Brune, 1970) indicates that at least four distinct shocks may be associated with individual bursts of S wave arrivals on the NS and EW accelerograph records at about 2, 8, 13 and 23.5 seconds. Corresponding P wave arrivals for each of these events cannot be unequivocally identified because of the high level of short period vibrations produced by the previous events. For this reason the estimated distances based on the S-P times may be in error. In this study we interpret RES for these events in an attempt to find the best fit of the observed and expected arrivals of surface wave energy. The results of this fit are shown in Figures 5 and 6 which indicate that our previous estimates (Trifunac and Brune, 1970) for the events 1A and 1C were probably within the correct range. The tentative interpretation based on the surface wave arrivals indicates that Event 1B could have occurred within a smaller epicentral distance than estimated previously. Surface wave arrivals for Event 2 are not interpreted here separately. The epicentral distance for this event is probably 35-44 km which places it at the southern-most end of the observed surface fault. For this distance, fundamental Love and Rayleigh modes would arrive more than 50 seconds after the strong

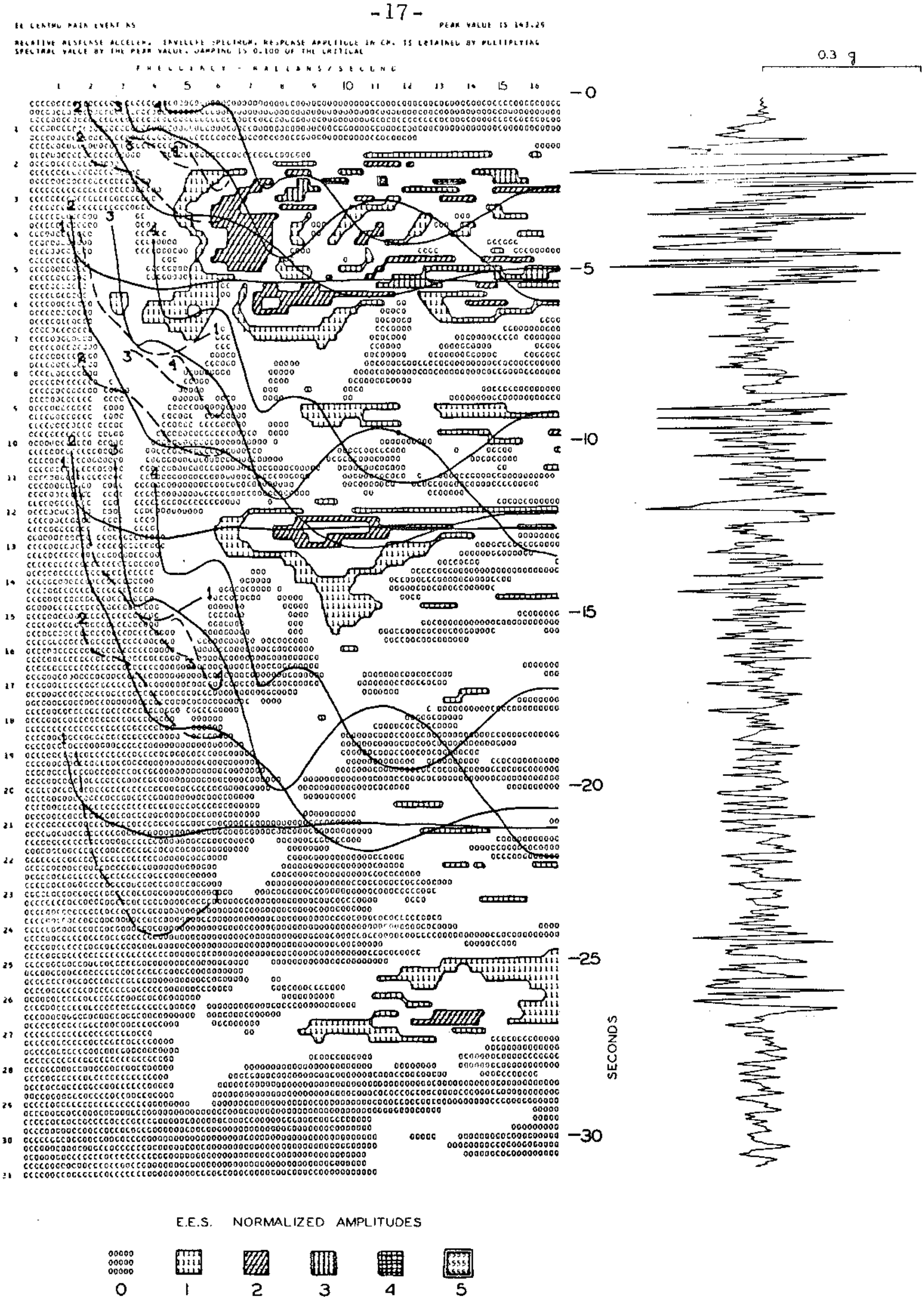

Fig. 5 The $\omega^2 A(t, \omega)$ Response Envelope Spectrum (RES) for Events 1A, 1B and 1C, NS component, recorded during the Imperial Valley, California, earthquake, 1940 (Trifunac and Brune, 1970). The actual amplitude of $\omega^2 A(t, \omega)$ in cm/sec^2 is obtained by multiplying the normalized amplitudes (0 to 5) by the peak amplitude $\omega^2 A$ peak = 143.29 cm/sec^2. Frequency scale for RES is in radians per second and the time scale is in seconds. Arrivals of the surface wave groups were computed using the theoretical dispersion curves (Fig. 2) and the epicentral distances Δ_{1A} = 10 km, Δ_{1B} = 12.5 km and Δ_{1C} = 15 km. Damping $\zeta = 0.1$ of critical.

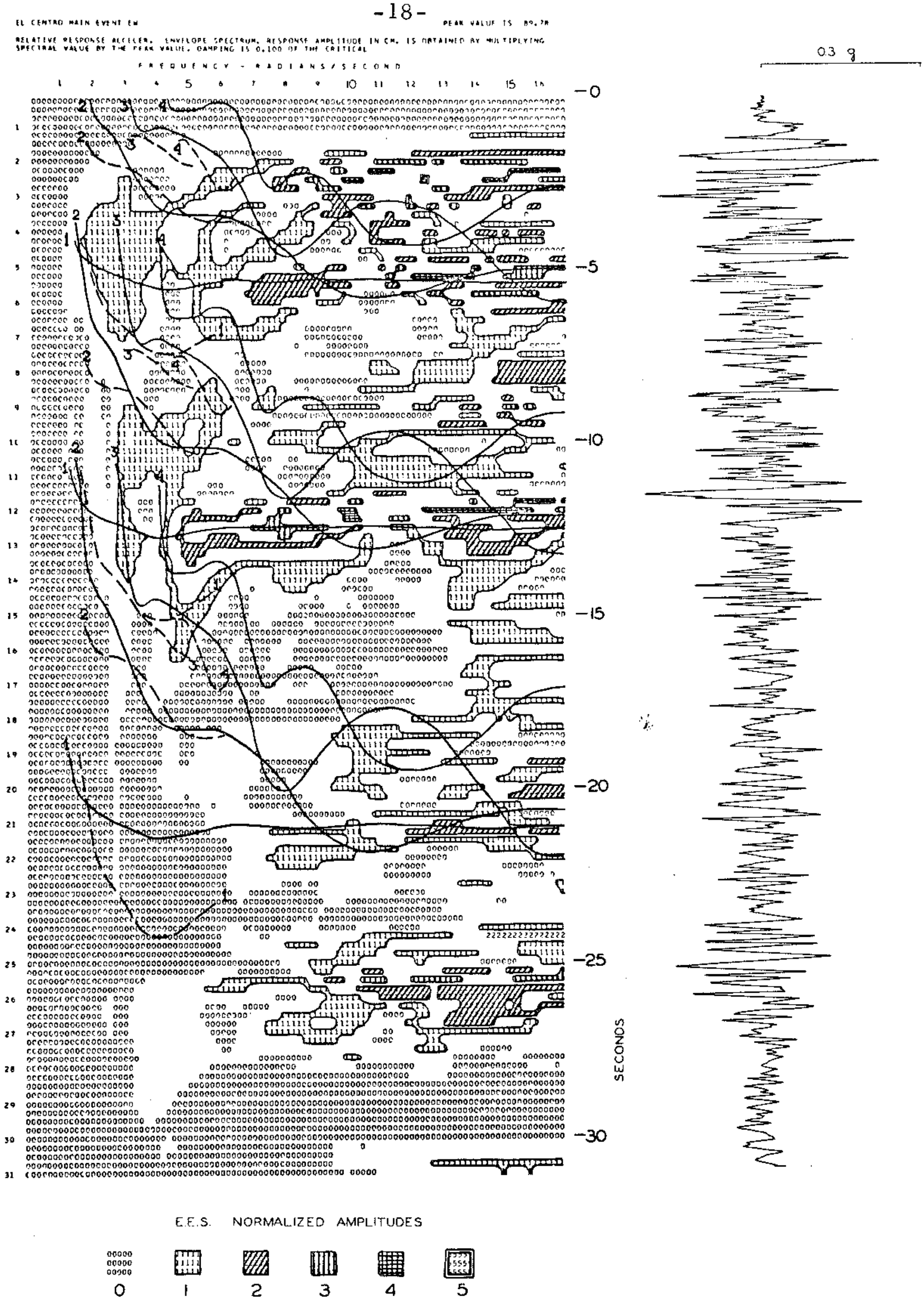

Fig. 6 The $\omega^2 A(t, \omega)$ Response Envelope Spectrum (RES) for Events 1A, 1B and 1C, EW component, recorded during the Imperial Valley, California, earthquake, 1940 (Trifunac and Brune 1970). The actual amplitude of $\omega^2 A(t, \omega)$ in cm/sec^2 is obtained by multiplying the normalized amplitudes (0 to 5) by the peak amplitude $\omega^2 A$ peak = 89.78 cm/sec^2. Frequency scale for RES is in radians per second and the time scale is in seconds. Arrivals of the surface wave groups were computed using the theoretical dispersion curves (Fig. 2) and the epicentral distances Δ_{1A} = 10 km, Δ_{1B} = 12.5 km and Δ_{1C} = 15 km. Damping ζ = 0.1 of critical.

motion was triggered, and would be mixed with the arrivals from Event 3. If we assume the epicentral distances for events 1A, 1B and 1C to be about 10, 12.5 and 15 km, then the expected surface wave arrivals are as indicated in Figures 5 and 6.

Although the accuracy in the above interpretations depends on a knowledge of the correct epicentral distances, the applicability of our theoretical dispersion curves, and on the properties of the RES, the most important tentative conclusion of this work seems well established. This conclusion is, as already mentioned, that the predominant part of strong earthquake ground motion consists of surface waves. The form of these waves is considerably more complicated than for teleseismic surface waves because of the proximity and size of the source of the seismic energy release and the frequency domain considered. In our interpretation these waves are surface waves in the sense that their arrivals are governed by the travel-time-distance relationships based on a simplified model for surface wave dispersion.

CONCLUSIONS

The main results of this study can be summarized as follows.

The Response Envelope Spectrum (RES), a multiple filter technique, represents a physically simple and informative tool for the analysis of strong earthquake ground motion accelerograph records. It contains all the information necessary to determine the relative response spectra, and is a logical extension of response spectrum techniques. The most important property of this method is that it displays the time dependence of the amplitude and frequency changes in the accelerograph record. It is particularly useful in detecting arrivals of different wave forms and may be used as a tool in dispersion analysis.

The analysis of several strong motion accelerograph records using the RES indicates that the predominant part of the strong earthquake ground motion, generated by a near shallow earthquake energy release is represented by surface waves. This is important from the point of view of destructiveness and also from the point of view of the establishment of the correct simplified wave-propagation models for studying the effects of local geology. The analysis indicates that the duration of the intense shaking will be mainly governed by the dispersion properties of the ground.

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