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SEISMIC ANALYSIS OF PIPELINES WITH INTERFERENCE RESPONSE SPECTRA

By

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Lifeline structures (bridges, tunnels, highways, and pipelines) that extend over long horizontal distances are affected by the non-coherent components of ground shaking. The response of interest is the relative displacement of adjacent points on the structure, instead of displacement relative to the ground. For this reason, the seismic analysis of lifelines requires techniques which are different from those used in the analysis of buildings. In this paper, the concept of the Interference Response Spectrum (IR Spectrum) is discussed. The IR Spectrum presents quantitatively and in a unified form the effects of the non-coherent free field on the dynamic response of lifeline structures. Derivations, properties and examples of IR spectra are given. Further investigations for using IR Spectrum in seismic analysis are suggested.

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PREFACE

This report is one of a series, summarizing the work started under Grant No. ENV P76-9838 of the National Science Foundation (RANN - Program Manager: Dr. S.C. Liu) on the project: "Underground Lifelines in a Seismic Environment." The work was continued under Grant No. PFR 78-15049. The objective of the research is to develop information needed for the formulation of guidelines for the design, evaluation and risk analysis of underground lifeline systems and components, located in areas which may be subjected to earthquakes. The results will be useful to public utilities, regulatory bodies, manufacturers, planners and civil engineers.

The research work is conducted by Weidlinger Associates and Columbia University (Department of Civil Engineering & Engineering Mechanics) with the following participants:

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

Lifeline structures extending over long horizontal distances are affected by the non-coherent components of ground shaking. The response of interest is the relative displacement of adjacent points on the structure, instead of displacement relative to the ground. For this reason, the seismic analysis of lifelines requires techniques which are distinct from those used in the analysis of buildings.

In this paper, the concept of the Interference Response Spectrum (IR Spectrum) is discussed. The IR Spectrum presents quantitatively and in a unified form the effects of the non-coherent free field on the dynamic response of lifeline structures. Derivations, properties and examples of IR spectra are given.

I. INTRODUCTION. Highways, bridges, tunnels and pipelines are called lifelines. A characteristic that distinquishes a lifeline from other structures is that it extends (essentially parallel to the ground surface) over a distance which is long compared to its other dimensions. The foundations, therefore, are either at widely separated points (e.g., bridges) or they extend continuously over long distances (pipes, tunnels). For this reason, in considering the effects of ground shaking, we cannot assume a priori that the motion at all points of ground contact is identical(*)(i.e., that the ground motion is coherent). When the motion is not coherent, the relative displacement of the points of contact produces stresses in the structure, whereas identical (i.e., coherent) excitation at continuous or closely spaced foundation points may result in primarily rigid body displacement, with no significant strain.

The analysis and design of lifelines subjected to earthquake is, therefore, different from that of buildings, where we customarily (and a priori) assume that the ground motion over the entire foundation plane is coherent and that the relevant response is displacement relative to the ground.

These two types of ground excitations and their consequences determine the essential difference between the analysis of buildings and lifelines, as summarized in the table below:

(*) The significance of this is recognized by researchers concerned with lifelines, Cf. Newmark in Ref. 11 p. 16, Christian (3) and Matsushima (9).

TABLE 1

		Buildings	Lifelines
1.	Ground motion:	coherent	non-coherent
2.	Relevant response:	relative to ground surface	relative to adjacent points in structure

The first line in Table 1 above is mostly a subject for seismological research (i.e., acquisition and analysis of records and extension of the knowledge of the free-field phenomena). The second item concerns itself with problems of dynamic analysis and methods of calculation. This investigation is addressed primarily to the latter but contributions to the clarification of non-coherent ground motion are offered by investigating appropriate forms of input for the analysis.

Consider a segment of a lifeline, as shown schematically in Figure 1. The structure is supported on the ground at points A and B, separated by an interval ℓ. The ground motions at these points are $z_A(t)$ and $z_B(t)$, and we call it coherent if

$$z_A = z_B \tag{1}$$

and non-coherent if

$$z_A \neq z_B \tag{2}$$

In the latter case, it is convenient to decompose the ground excitation into its coherent component:

$$z_c = \tfrac{1}{2}(z_A + z_B) \qquad (3)$$

and its incoherent component:

$$\Delta z = \pm\ (z_A - z_B) \qquad (4)$$

and we may note that if the structure itself is symmetrical, with respect to A and B, its response to the two components will be in symmetrical and antisymmetrical modes respectively. In the analysis of buildings (as mentioned previously) the assumption is either that

$$\Delta z = 0 \qquad (5)$$

or that its effects are negligible because of the dynamic characteristics of the structure or because the ground-structure interaction filters out incoherence.

In the analysis of lifelines, the coherent component should not be a priori neglected, but if it turns out to be significant, the procedures and methods are identical to those, used in the analysis of buildings. This investigation, therefore, concerns itself with the incoherent component of the ground motion.

Generally, if the time histories $z_A(t)$ and $z_B(t)$ are known (or can be synthetized), integration of the equations of motion provides the entire response without separation of the input into coherent and incoherent components. If we operate in the frequency domain, the modal contributions give a clear indication of the significance of each component. Whenever the significant response is contributed by coherent excitation, analysis by standard response spectrum techniques is the method of choice at the present. This procedure is very attractive because of the computational convenience it offers. Equally important is the free-field information contained implicitly in the response spectrum itself, as reflected by its modification due to variations of the resonant frequency of soil layers above the base rock. The spectrum also clarifies and quantifies the effect of structural damping and of non-linear elastoplastic response (12). By presenting these essential facts in a concise form, response spectra are useful tools for the definition of design earthquakes, and permit the codification of the design input and analytical procedure.

The purpose of this paper is to develop a similar technique (called Interference Response (IR) Spectrum) for incoherent ground excitation, applicable to lifeline analysis and design.

II. NON-COHERENT SEISMIC FREE-FIELD. The ground motion $z(x,t)$ is said to be coherent in the interval ℓ, if for purposes of analysis it is reasonable to assume that

$$z(x,t) \simeq z(t) \tag{6}$$

where x is a coordinate within ℓ. This assumption is used in the seismic analysis of buildings (as noted in the Introduction).

Consider now a straight branch of length L of a lifeline network consisting of links of length $\ell << L$. In this case, the approximation of Eq (6) is not valid, and the incoherent component of the ground motion, with respect to the (end points) of the interval ℓ is given by

$$\Delta z(x,t,\ell) = z(x+\ell/2,t) - z(x-\ell/2,t) \tag{7}$$

where x is a coordinate of the midpoint of the interval. In analysis of lifelines, it is usually permissible to use a first order approximation of the incoherent motion by setting

$$\Delta z(x,t,\ell) \simeq \Delta z(t,\ell) \tag{8}$$

for points in L, provided that the peak relative response of adjacent links, located at, or near the midpoint of L may be taken as representative of the performance of the entire segment. The approximation of the two types of ground motionsby Eq's (6) and (8) are assumed to be sufficiently accurate inputs for seismic analysis. The approximation is also justified by probabilistic considerations, in view of the limited resolution and the statistical nature of seismic records. In the discussions that follow, we will consider only first order incoherence as defined in Eq (8). Incoherent motion includes the following two special cases:

(a) If one of the end points of the interval is at rest at a time t, we have:

$$\Delta z(t,\ell) = z(t) \tag{9}$$

This will occur at all times if the separation interval ℓ is large, compared to the hypocentral distance.

(b) If all Fourier components of the motions of the two points of the interval are out of phase by an angle π, we have

$$\Delta z(t,\ell) = 2z(t) \tag{10}$$

and consequently, in general, the coherent and incoherent ground motion must satisfy the inequality:

$$\Delta z_{max} = \leq |2z_{max}| \tag{11}$$

which defines the upperbound of the incoherent motion (Newmark, op. cit. p. 14). Finally, incoherent motion leads to the definition of the mean strain, by

$$\bar{\varepsilon}(t,\ell) = \frac{\Delta z(t,\ell)}{\ell} \tag{12}$$

over the interval, and also to the strain at a point within the interval:

$$\varepsilon(t) = \lim_{\ell=o} \frac{\Delta z(t,\ell)}{\ell} \tag{13}$$

Such ground motion maxima and strains are important characteristics of the free field. If it can be assumed or shown, that the deformation of a lifeline structure conforms to that of the surrounding soil, these quantities are the design parameters of the system, otherwise, they are the input for further dynamic analysis.

To clarify the causes of incoherent ground motion,we consider a disturbance propagating from a symmetric point source in an infinite, homogenous isotropic, elastic space. One component of the motion of two spatially separate points will be coherent if, and only if, they are equidistant from the source. In all other cases, we will observe incoherence as manifested by phase shift and variations in amplitude. In seismic distrubances, non-coherent motion exists due to a variety of causes. The following is a list of some of the significant sources of non-coherent seismic ground motion.

TABLE 2

SOURCES OF NON-COHERENCE

1. Attenuation of amplitude as a function of hypocentral distance
2. Finite dimension and directionality of source (faults)
3. Phase delay due to finite propagation velocity
4. Observable and measurable geophysical and geological irregularities (inhomogeneity, layering, variation of soil properties, non-uniformity in layering)
5. Random variations
6. Man-made discontinuities

Cases 1 and 2 produce noncoherent ground motions in homogeneous soil, but changes in the wave form which are attributable to this cause are not significant if the epicentral distance $R >> \ell$. This restriction applies to most instances of practical interest and, therefore, these sources of non-coherence will not be considered.

Case 3 phase delay is the predominant source of non-coherent motion. In this case, the motion may be described by a single progressing wave equation, in the x direction

$$z(x,t) = f(x-ct) \tag{14}$$

where c is a constant velocity of propagation. (This formulation ignores variable phase velocity due to inhomogeneity and layering. Results obtained under this constant velocity assumption are expected to be modified, to some extent, by further research). By Eq's (7) and (14) we may now compute the incoherent ground motion by

$$\Delta z(t,\Delta t) = z(t) - z(t+\Delta t) \tag{15}$$

which is the interference of two waves and where

$$\Delta t = \ell/_c \tag{16}$$

is the phase delay when the direction of propagation is along the x coordinate. Examples of the use of Eq (15) with data obtained from integrated accelerometer records are shown on Figure 2. If the plane wave front is inclined at an angle α to the x axis the effective velocity to be used in Eq (16) is

$$c_e = c/\sin\alpha \tag{17}$$

and incoherent motion, in this case, vanishes whenever $\alpha = 0$ (i.e. $\Delta t=0$)

By substituting Eq's (15) and (16) into (13) the strain at point is

$$\varepsilon = \frac{1}{c} \lim_{\Delta t=o} \frac{\Delta z(t,\Delta t)}{\Delta t} = V/c \tag{18}$$

where

$$V = \frac{\partial z}{\partial t} \tag{19}$$

is the ground velocity. The maximum strain is

$$\varepsilon_{max} = \frac{V_{max}}{c} \tag{20}$$

where V_{max} is the maximum ground velocity.

The peak amplitude of the incoherent motion due to a phase delay is

$$\mathrm{MAX}|\Delta z(t,\Delta t)| = \Delta z_{\mathrm{max}}(\Delta t) = \Delta z(t_o,\Delta t) \tag{21}$$

where t_o is a root of

$$\frac{\partial z(t)}{\partial t} - \frac{\partial z(t+\Delta t)}{\partial t} = 0 \tag{22}$$

The peak amplitude of Δz is conveniently representated by a non-dimensional function

$$I(\Delta t) = \frac{\Delta z_{\mathrm{max}}(\Delta t)}{D_{\mathrm{max}}} \tag{23}$$

called the Incoherence function, where

$$D_{\mathrm{max}} = \mathrm{MAX}|z(t)| \tag{24}$$

The initial slope and the maximum value of this function are significant, and they are determined as follows:

It can be shown that

$$\left.\frac{d\Delta z_{\mathrm{max}}}{d\Delta t}\right|_{\Delta t=o} = \mathrm{MAX}\left.\frac{\partial\Delta z}{\partial\Delta t}\right|_{\Delta t=o} \tag{25}$$

and since

$$\lim_{\Delta t=o}\frac{\Delta z}{\Delta t} = \left.\frac{\partial z}{\partial t}\right|_{\Delta t=o} = V \tag{26}$$

we conclude that

$$\left.\frac{d\Delta z_{\mathrm{max}}}{d\Delta t}\right|_{\Delta t=o} = V_{\mathrm{max}} \tag{27}$$

and, therefore, by Eq's (23) and (27):

$$\left.\frac{dI}{d\Delta t}\right|_{\Delta t=o} = \frac{V_{\mathrm{max}}}{D_{\mathrm{max}}} \tag{28}$$

If the ground displacement z(t) exhibits a single dominant frequency ω the relation

$$\omega \simeq \frac{V_{max}}{D_{max}} \qquad (29)$$

follows and the maximum value of the incoherence, by Eq (11)

$$I(\Delta t)_{max} \leq 2 \qquad (30)$$

occurs when

$$\omega\Delta t = \pi \qquad (31)$$

Fig. 3 shows plots of incoherence I, (calculated from six accelerometer records) vs. the non-dimensional phase delay:

$$\tau = \frac{V_{max}}{D_{max}} \frac{\Delta t}{2} = \frac{\omega\Delta t}{2} \qquad (32)$$

where ω is given by Eq (29).

An upperbound approximation to these curves is the function

$$I(\tau) = MAX|\sin\omega t - \sin\omega(t-\Delta t)| = 2\sin\tau, \ \tau<\frac{\pi}{2} \qquad (33)$$

as shown by the solid line of Fig. 3. The numerical value for the frequency ω may be estimated by using the empirical relation given in Ref. 12.

$$\omega = \frac{Vmax}{D_{max}} = \frac{36}{48} = 0.75 \text{ rad/sec.} \qquad (34)$$

so that in this case

$$\tau = 0.375\ \Delta t \qquad (35)$$

The Incoherence function of Eq (33) may be used as the generic definition of the incoherent ground motion maximum as a function of phase delay. It is directly applicable as design input, and it is used in the IR Spectrum, as will be shown in the next section.

When incoherence is not attributable to phase delay phenomena, the following procedures for the other cases of Table 2 are suggested:

Cases 4 and 5 incoherent motions are calculated by Eq (7), where the ground motions $z(x \pm \ell/2)$ are synthetized in accordance with the subsurface conditions at the end points of the interval (4). The subsurface data (such as, resonant ground frequency, e.g.) are obtained either deterministically or by statistical methods (16, 17).

Case 6, occurs frequently in the lifeline networks at nodal or terminal points, where the lifeline is connected to a larger structure. If the coherent motion z(t) is known (or can be synthetized) we calculate the response time history R(t) of the nodal structure, and obtain

$$\Delta z(t) = z(t) - R(t) \tag{36}$$

provided that the presence of the nodal structure does not significantly affect the free field.

It is anticipated that further research will make it possible to deal with the above cases in a manner similar to that used in the case of phase delay. An illustration of the incoherent motion corresponding to Eq (36) is shown on Fig. 4, where both inputs, i.e., the free field z(t) and the function R(t) were available from accelerometer records. The instruments were placed at an interval of 160 ft at the Hollywood Storage basement and at the parking lot. The orientation of the interval is such that it is nearly perpendicular to the direction at which the epicenter is located, so that phase delay phenomena by Eq (17) do not contribute to the incoherent motion.

III. INTERFERENCE RESPONSE SPECTRUM (IR Spectrum).

1. Standard Frequency Response Spectrum. To develop the spectral technique of lifeline analysis, it is useful to recall the derivation of the single degree of freedom (SDF) response spectrum, which is used to represent the peak modal response of structures. The (relative) displacement spectrum (1) is defined by:

$$S_D(\omega, \zeta) \equiv \mathrm{MAX}|y(t)| \equiv y_{max} \qquad (37)$$

where y(t) is the solution to

$$\ddot{y} + 2\omega\zeta\dot{y} + \omega^2 y = -\ddot{z}(t) \qquad (38)$$

which is the response of a SDF oscillator (of undamped frequency ω and fraction of critical damping ζ), subject to the ground motion input z(t). The variable y(t) is the relative displacement of the mass point with respect to the ground displacement z(t), and y_{max} therefore is proportional to the peak force in the spring. The absolute displacement of the mass point is:

$$x = y + z \qquad (39)$$

and Eq (37) in absolute coordinates, is written as:

$$\ddot{x} + 2\omega\zeta\dot{x} + \omega^2 x = \omega^2 z(t) + 2\omega\zeta\dot{z}(t) \qquad (40)$$

and using "mixed" coordinates we find:

$$\ddot{x} + 2\omega\zeta\dot{y} + \omega^2 y = 0 \qquad (41)$$

from which, for an undamped oscillator, we obtain

$$\mathrm{MAX}|\ddot{x}(t)| = \mathrm{MAX}|\omega^2 y(t)| \qquad (42)$$

which is a good approximation for a damped system, provided that

$$\zeta << 1 \qquad (43)$$

By eq's (42) and (37) the spectral acceleration is defined as:

$$S_a(\omega,\zeta) \equiv \omega^2 S_D\ (\omega,\zeta) \qquad (44)$$

which is the approximate peak absolute acceleration of a lightly damped oscillator. By analogy,

$$S_V(\omega,\zeta) \equiv \omega S_D\ (\omega,\zeta) \qquad (45)$$

is called the spectral or pseudo velocity, which is taken as a measure of the kinetic energy of the system. It is the peak velocity response only when it occurs after ground motion has ceased, and is an approximation, provided that the peak response occurs after the strong motion phase. Eq's (44) and (45) permit the familiar tripartite logarithmic representation of the three spectral amplitudes in a single plot. An envelope obtained by statistical analysis of a large number of spectra is represented in the tripartite plot, consisting of three (or four) straight line segments, called a generic or design spectrum (12). It is used as an input for the seismic analysis of buildings and other structures.

2. Absolute Spectrum. In the standard response spectrum, discussed above, the spectral acceleration S_a is the peak absolute acceleration response, while the displacement spectrum S_D is in relative coordinates. The absolute displacement spectrum (2) is defined as

$$S_D^A\ (\omega,\zeta) \equiv \text{MAX}|x(t)| \qquad (46)$$

and the absolute velocity spectrum is defined as

$$S_V^A\ (\omega,\zeta) \equiv \text{MAX}|\dot{x}(t)| \qquad (47)$$

where $x(t)$ and $\dot{x}(t)$ are solutions of Eq (40).

In the high frequency range (i.e., ω = large), the oscilator is very stiff and the absolute response of the masspoint is not too different from the ground motion, so that the approximations

$$S_D^A \simeq D_{max} \tag{48}$$

and

$$S_V^A \simeq V_{max} \tag{49}$$

are good in the high frequency range (f>3Hz, approximately) and at high frequencies the spectral amplitudes are constant (i.e., horizontal) at the value of the ground motion maxima.

In the low frequency range, when the osscilator spring is "weak" (i.e., $\omega \simeq o$) we find

$$S_D^A \simeq S_V^A \simeq S_V \simeq 0 \tag{50}$$

but the displacement response relative to the ground motion is nearly that of the ground motion, so that

$$S_D \simeq D_{max} \tag{51}$$

Finally, in the mid and low frequency ranges, peak response to seismic excitations tend to occur after (or near the end) of the strong motion phase, and, therefore, in this regime the approximation

$$S_V^A \simeq S_V \tag{52}$$

is valid, but because of Eq (51), the approximation

$$S_D^A \simeq S_D \tag{53}$$

holds only in the mid frequency range. These observations are illustrated on Fig.'s 5(a) to (c) and Fig. 6(a) and (b) which compare pseudo velocity to absolute velocity and relative displacement to absolute displacement spectra calculated respectively from several accelerometer records. These comparisons suggest that absolute spectra may be constructed on a tripartite logarithmic plot from the pseudo velocity spectrum. This is shown on Fig. 7.

3. Interference Response (IR) Spectrum. We define the IR Spectrum by

$$S_I(\omega,\zeta,\ell) \equiv \mathrm{MAX}|\Delta x(t)| \equiv \Delta x_{\max} \tag{54}$$

as the solution to

$$\Delta\ddot{x} + 2\omega\zeta\Delta\dot{x} + \omega^2\Delta x = \omega^2\Delta z(t,\ell) + 2\omega\zeta\Delta\dot{z}(t,\ell) \tag{55}$$

where $\Delta z(t,\ell)$ is as in Eq (7), and the interference response

$$\Delta x = x_{i+1} - x_i \tag{56}$$

is the difference of the absolute displacements of two adjacent points i and i+1. Since the response is in absolute coordinates, the IR Spectrum may also be defined as an absolute displacement spectrum in which the ground motion input is as in Eq (9):

$$S_I(\omega,\zeta,\ell) \equiv S_D^A(\omega,\zeta)\Big|_{z=\Delta z} \tag{57}$$

The response of Eq (56) is interpreted as the distortion (separation or rotation) of a joint in a lifeline. It can be shown (23) that such response occurs in antisymmetric modes and it is excited only by the incoherent component of a multipoint ground input. If this component satisfies Eq (8), the response in the k-th (antisymmetric mode) is (23):

$$\Delta x_{k_{max}} = L_k S_I(\omega_k, \zeta, \ell) \tag{58}$$

where L_k is the modal participation factor. The contribution of n significant modes may be combined e.g., by:

$$\Delta x_{max} = \left[\sum_1^n (\Delta x_{k_{max}})^2 \right]^{\frac{1}{2}} \tag{59}$$

Eq (54) gives the IR spectrum as a family of curves parametric in ℓ (and ζ) which are computed from a set of two ground motion records, separated by various distances. This is done by solving Eq(55) for a set of inputs of the form of Eq (7). Only very few such record pairs are available at the present time from (closely spaced) instruments. Fig. 8 shows an IR spectrum computed from the input shown on Fig 4 corresponding to an interval ℓ = 160 ft (50 m).

If the interference response is excited by phase delay incoherence, the input (of the type shown on Fig. 2) is obtained from a single record by use of Eq. (15) and the spectrum is parametric in Δt, given in Eq. (16).

For small values of Δt, Taylor expansion of Eq. (15) yields

$$\Delta z(t, \Delta t) \approx \frac{dz}{dt} \Delta t \tag{60}$$

by neglecting higher order derivatives (11) and by using Eq. (60) as input into Eq (40) and using the equivalence of Eq (57) we obtain

$$S_I(\omega, \zeta, \Delta t) \approx \Delta t S_v^A (\omega, \zeta) \tag{61}$$

so that the parameter Δt is now a coefficient of the spectral amplitude. The approximation is good for the entire frequency range of interest for $\Delta t < 0.10$ sec., which for c = 1000 ft/sec (300 m/sec) represents intervals ℓ < 100 ft (30 m). This corresponds to the maximum spacing of joints as used in many pipelines.

In lifelines where the interval of interest is larger, the approximation

$$\Delta z(t,\Delta t) \approx I(\Delta t)\ z(t) \qquad (62)$$

may be used in the neighborhood of $\omega\Delta t < \pi$, where $I(\Delta t)$ is given in Eq's (23) or (33) and ω , in Eq (29). The approximation appears to be good for $0.5<\Delta t<2.5$ sec. When Eq (62) holds,

$$S_I(\omega,\zeta,\Delta t) \approx I(\Delta t)\ S_D^A(\omega,\zeta) \qquad (63)$$

where now the parameter appears through the incoherence function which is a coefficient of the spectral amplitude.

Eq (61) by Eq (26) leads to

$$\frac{S_I}{\Delta z_{max}} \approx \frac{S_V^A}{V_{max}} = \text{spectral amplitude} \qquad (64)$$

and Eq (63) by Eq (23) to:

$$\frac{S_I}{\Delta z_{max}} \approx \frac{S_D^A}{D_{max}} = \text{spectral amplitude} \qquad (65)$$

These relations are shown on Fig. 9(a) to (d), where IR spectra for various phase delays and the absolute spectra are calculated from four different records. These observations show that approximate IR spectra may be obtained from absolute velocity and displacement spectra, which in turn may be constructed from pseudo velocity spectra as shown on Fig. 7, so that, an IR spectrum approximation is obtainable, if a pseudo velocity spectrum is given.

IV. CONCLUSIONS. Examination of the curves of Fig. 9 show that the maximum spectral amplitude (i.e., dynamic amplification) of 2 to 4 occurs in the frequency band 0.1Hz<f<2.0Hz at a damping of 5.0% of critical. (Calculations show that the spectrum is essentially flat at an amplitude of unity when $\zeta > 0.25$). Because the failure or service limit of pipes subjected to seismic shaking, is most conveniently expressed by the separation or rotation of joints (7) the IR spectrum gives the peak relative displacement (or rotation) of adjacent points (i.e., links). Acceleration response can also be obtained from the spectral acceleration S_a calculated for the incoherent input.

For the IR spectrum technique to be applied for the analysis of lifeline networks, experimental (observational) and theoretical investigations in three major areas need to be completed:

1. The properties of the incoherent ground motion must be further explored and better understood. This should be accomplished by data acquisition from accelerometer arrays placed at close intervals and by the resolution of several theoretical problems regarding the properties of local velocity (20, 21) of propagation, free field strain and curvatures (22).

2. The work on static and dynamic failure and service limits of the various lifeline systems needs to be continued and expanded by experimental and analytical methods (5, 6, 15). Dynamic properties, such as typical response frequencies and damping characteristics of these systems must also be established (19).

3. The interaction of buried pipes with the surrounding soil must be better understood. The prevalent view in the current literature (7, 8) is that, usually, interaction is not significant. But, interaction with the incoherent

component of the motion has not been fully investigated, although general experimental (10, 18, 19) and theoretical (13, 14) work has been published. Ongoing research in this area indicates that there are ranges of dimensions, geometries and construction details where strong dynamic amplifications occur in significant frequency ranges. The assumption that buried pipes generally conform to the ground motion is almost certainly not correct in a number of instances of practical interest.

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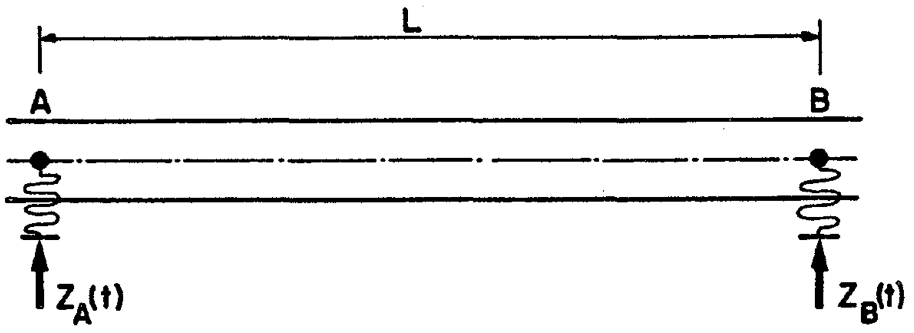
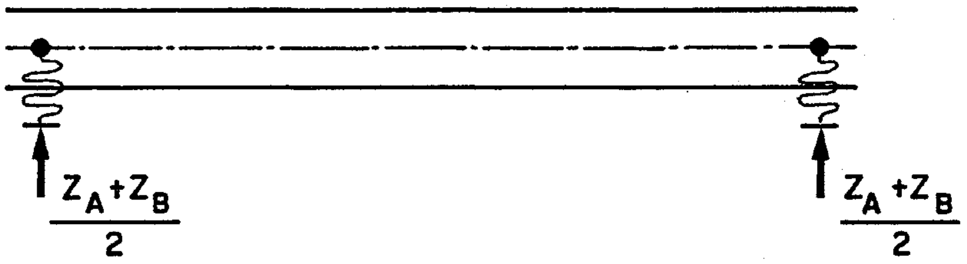
APPENDIX 2 - NOTATIONS

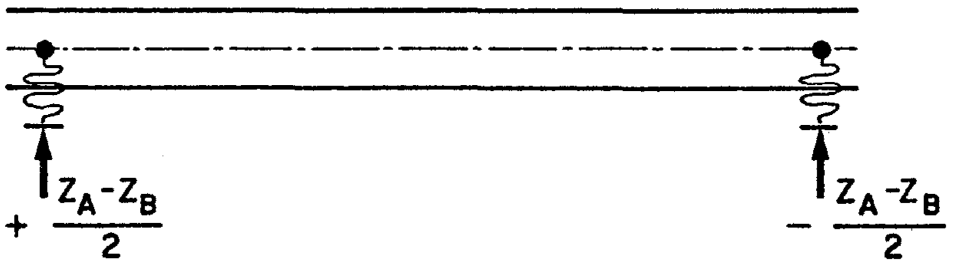
c = velocity of propagation
D_{max} = ground motion maximum
f = frequency
I = incoherence function
k = mode number
L_k = modal participation factor (k-th mode)
ℓ = interference interval
m = mass
$R(t)$ = response function
S_a = spectral acceleration - absolute
S_D = spectral displacement - relative
S_V = spectral velocity - pseudo velocity
S_D^A = spectral displacement - absolute
S_V^A = spectral velocity - absolute
S_I = interference response spectral displacement
t = time
T = period
V_{max} = ground velocity maximum
x = displacement - absolute
y = displacement - relative to ground
z = ground displacement
α = angle of incidence
Δt = phase delay time
Δx = displacement - relative to adjacent point
Δz = incoherent ground displacement component
ε = strain
ζ = fraction of critical damping
τ = nondimensional phase delay
ω = circular frequency



a) GROUND INPUT

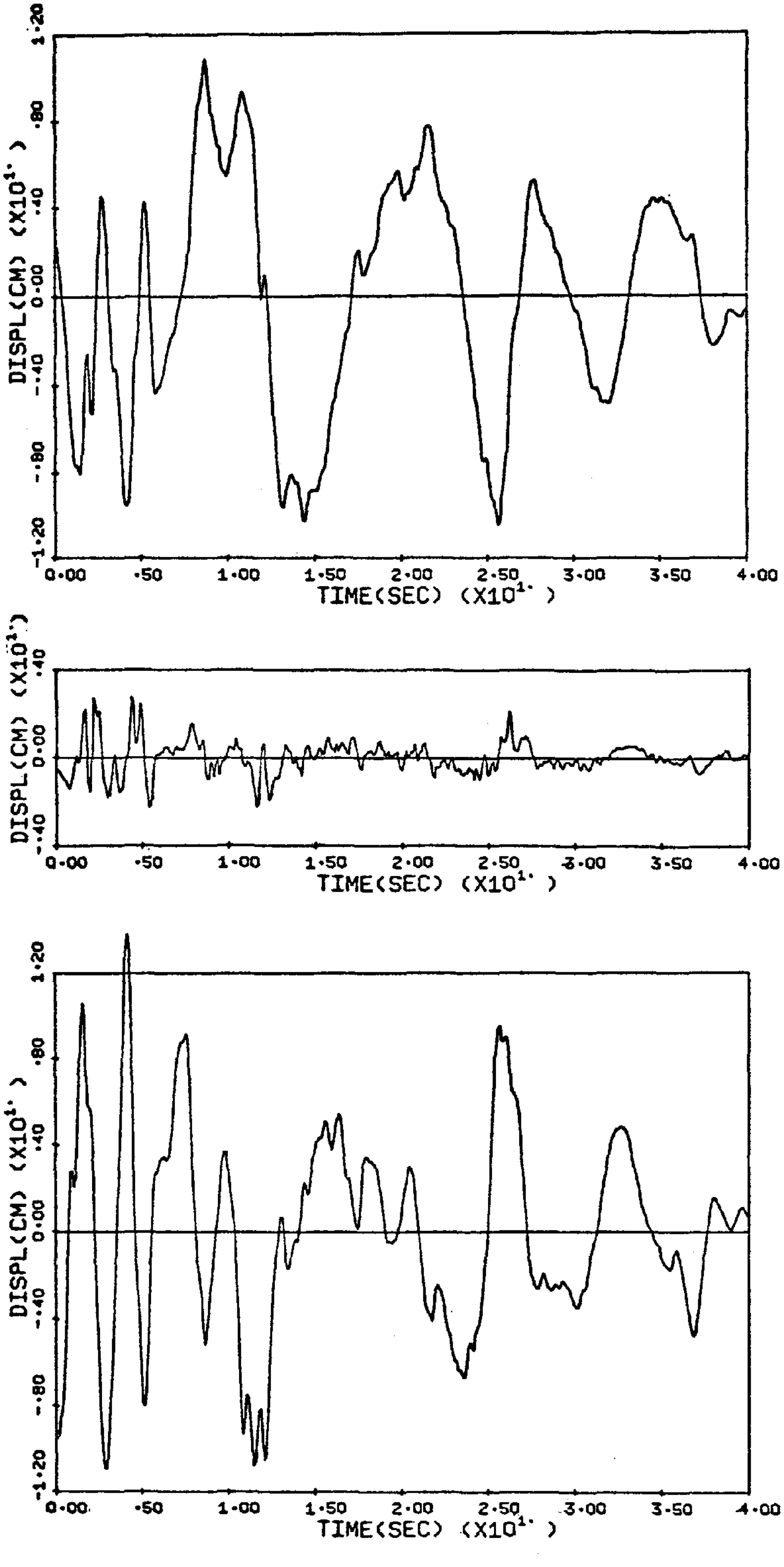


b) COHERENT COMPONENT



c) INCOHERENT COMPONENT

FIG. 1 COHERENT AND INCOHERENT COMPONENTS OF MULTIPOINT GROUND MOTION INPUT



A. ORIGINAL RECORD

B. INCOHERENT WAVE FORM Δt = 0.1 SEC.

C. INCOHERENT WAVE FORM Δt = 1.0 SEC.

FIG. 2 EXAMPLES OF INCOHERENT WAVE FORMS DUE TO PHASE DELAY (EL CENTRO, MAY 1940 COMP S 00 E)

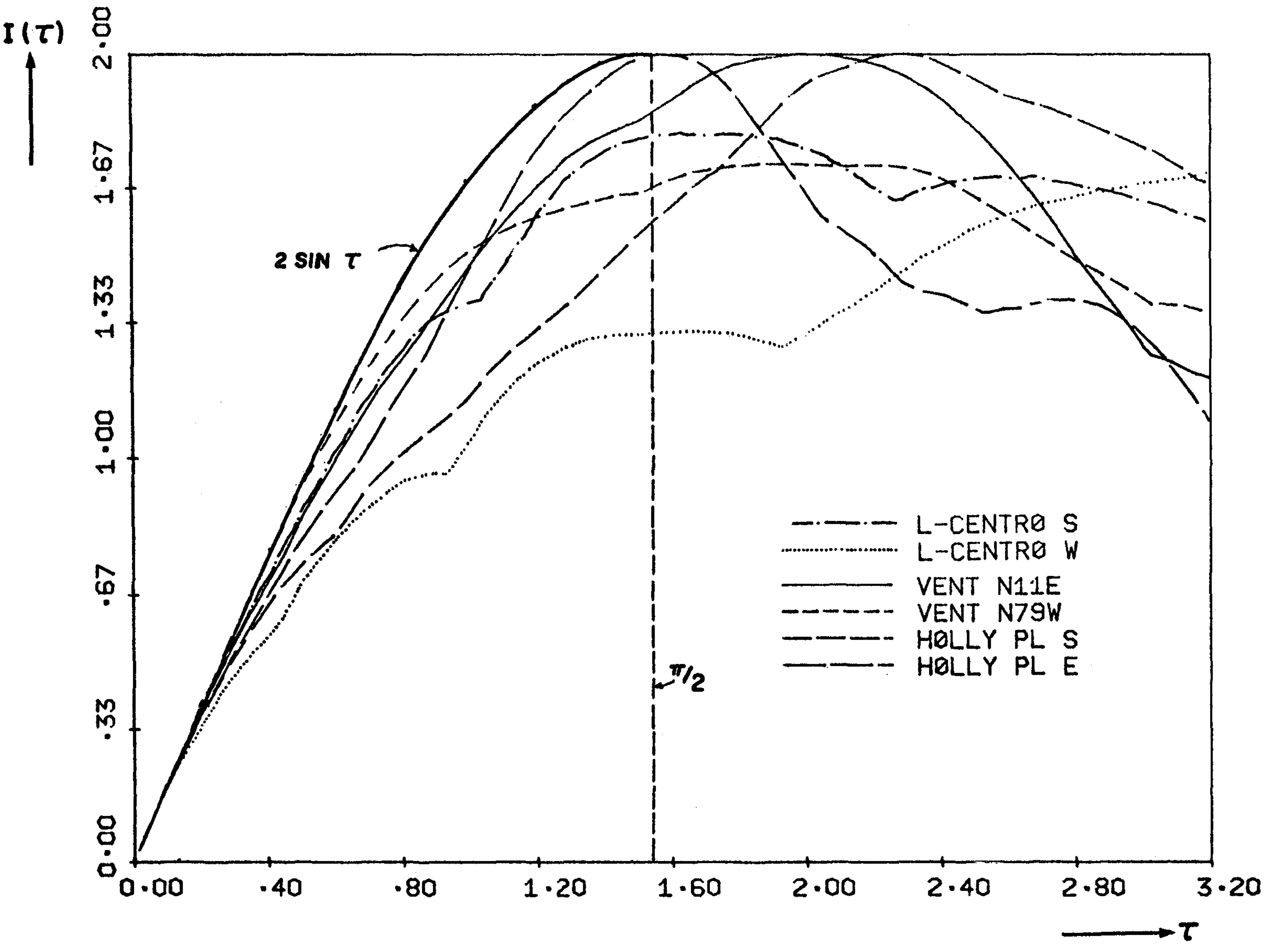
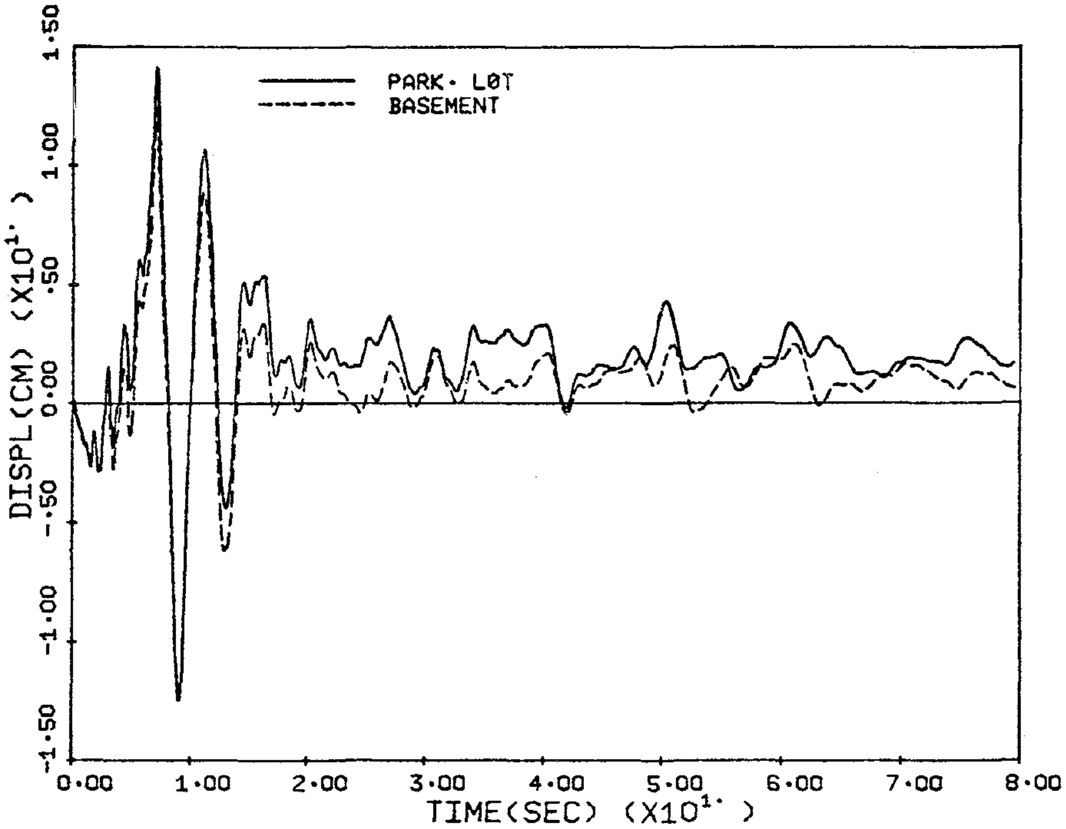
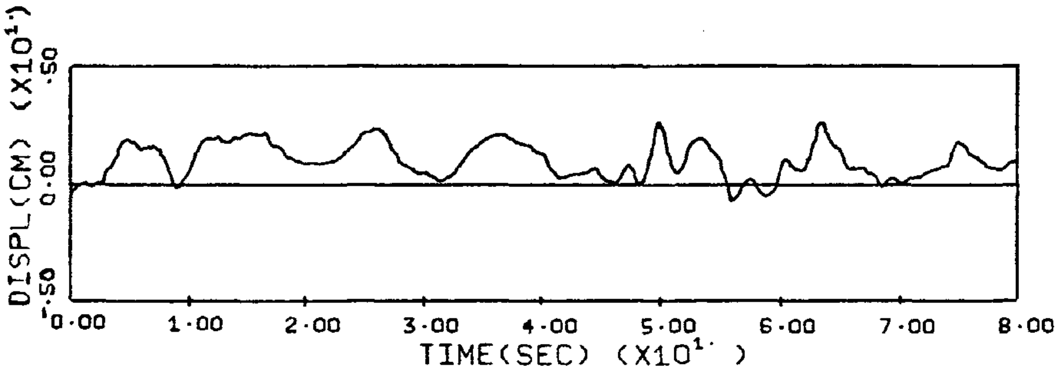


FIG. 3 INCOHERENT VS. NON-DIMENSIONAL PHASE DELAY



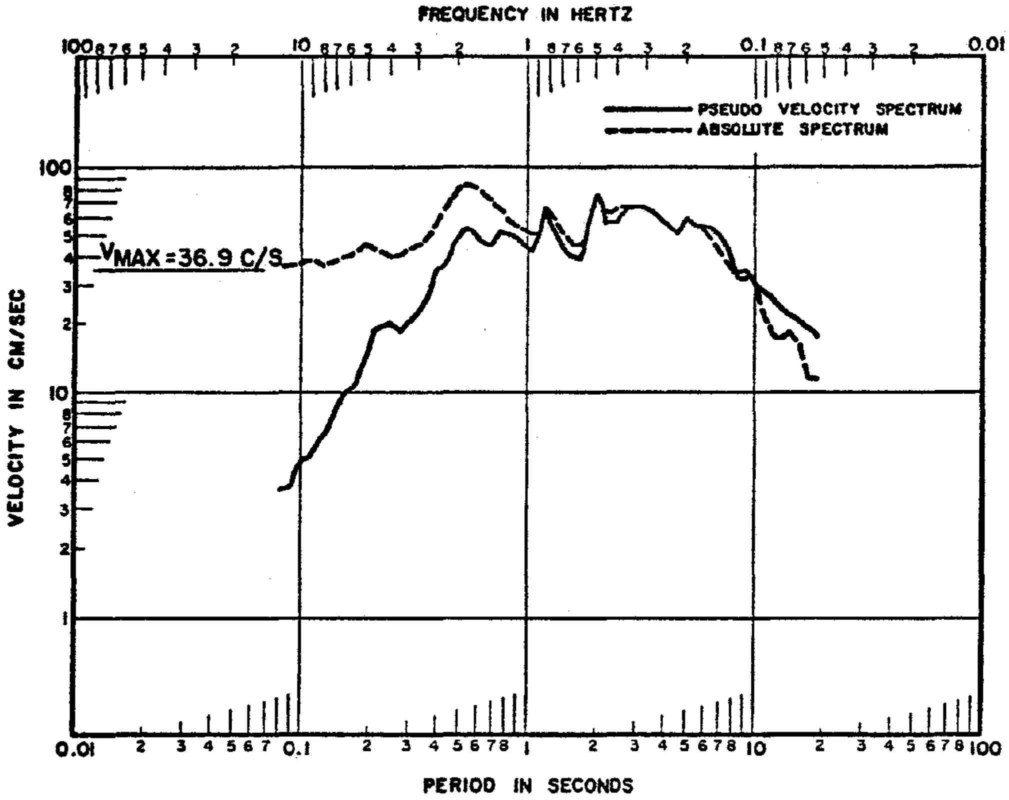
a. ORIGINAL RECORDS



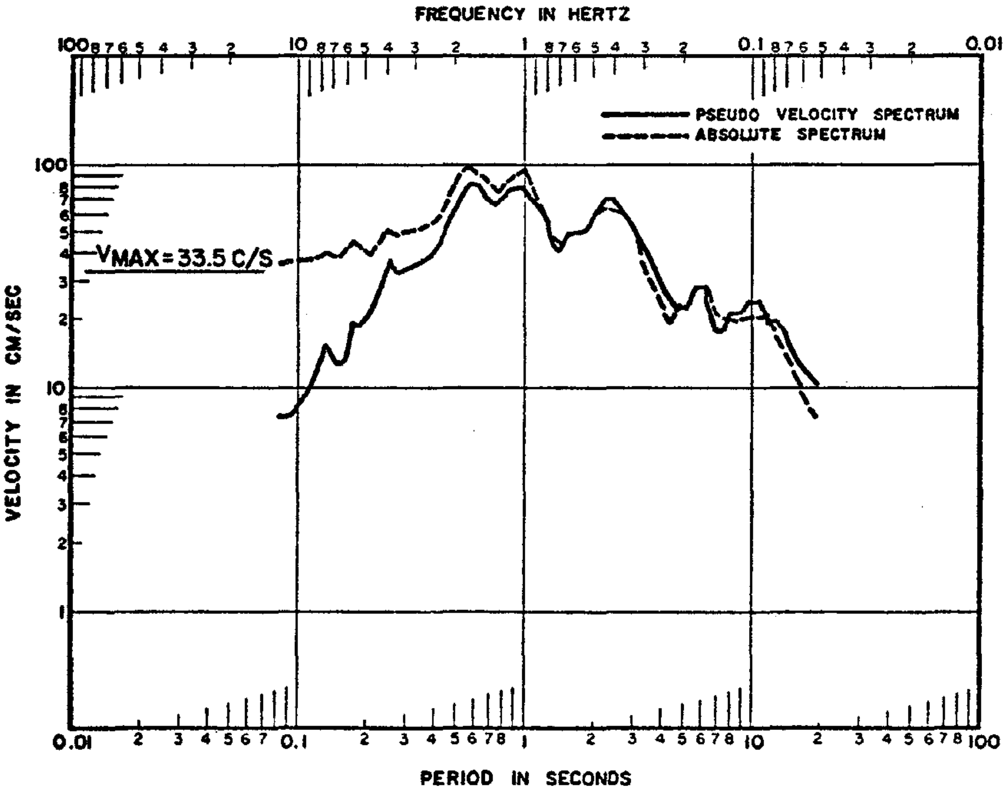
b. INCOHERENT WAVE FORM ℓ = 160 ft (50 m)
(PARKING LOT - BASEMENT)

NOTE: DISPLACEMENTS COMPUTED AS DOUBLE INTEGRALS OF ACCELERATION RECORDS

FIG. 4 EXAMPLE OF INCOHERENT WAVE FORM DUE TO DISCONTINUITY (SAN FERNANDO 1971, HOLLYWOOD STORAGE, COMP N 90 E)

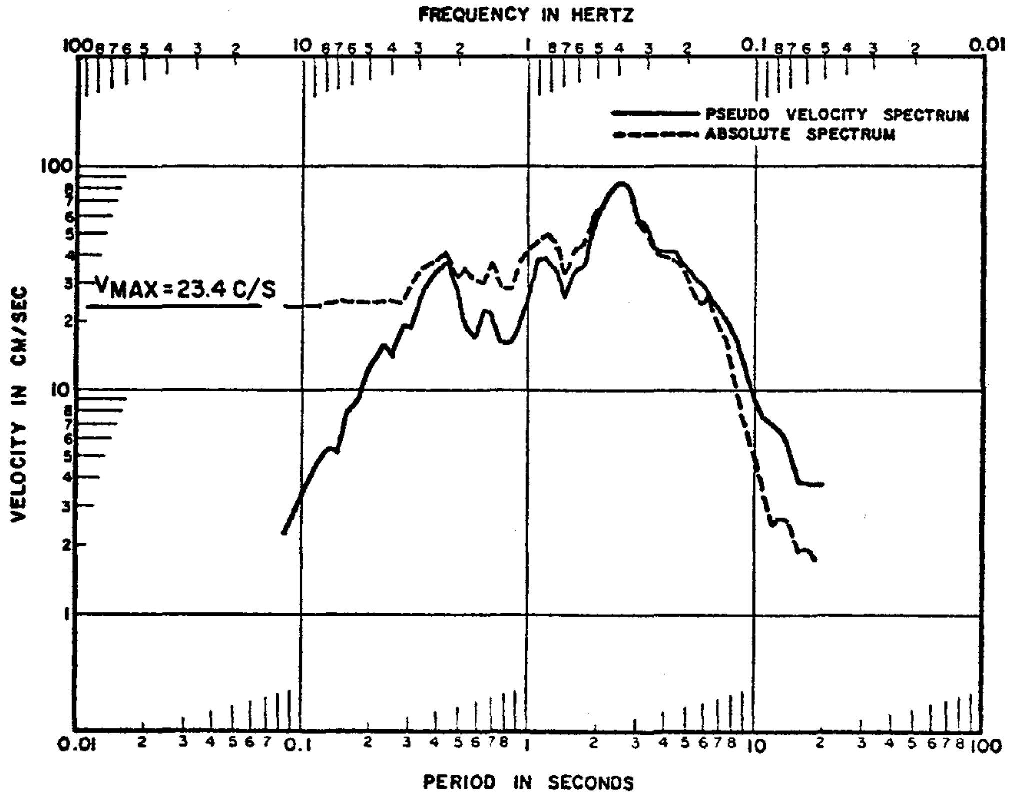


a. COMP S 90 W

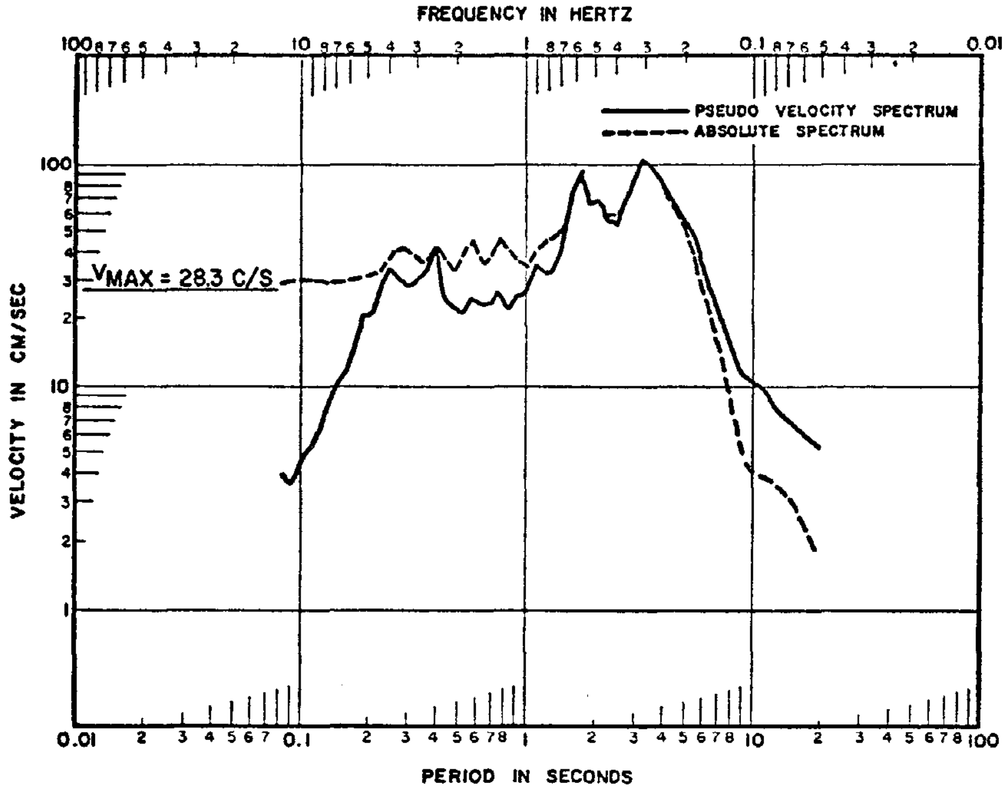


b. COMP S 00 E

FIG. 5 (a & b) COMPARISON OF PSEUDO VELOCITY (S_V) AND ABSOLUTE VELOCITY ($S_V{}^A$) SPECTRA ($\zeta = 0.05$) (IMPERIAL VALLEY, MAY 18, 1940 EL CENTRO SITE)

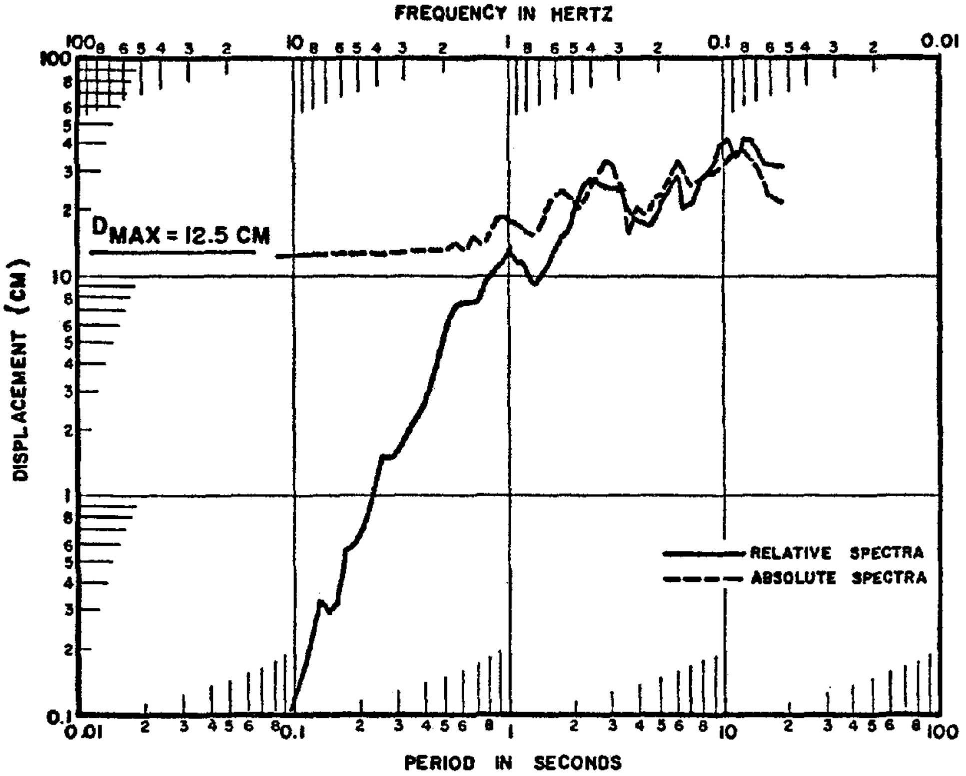


c. COMP N 79 W

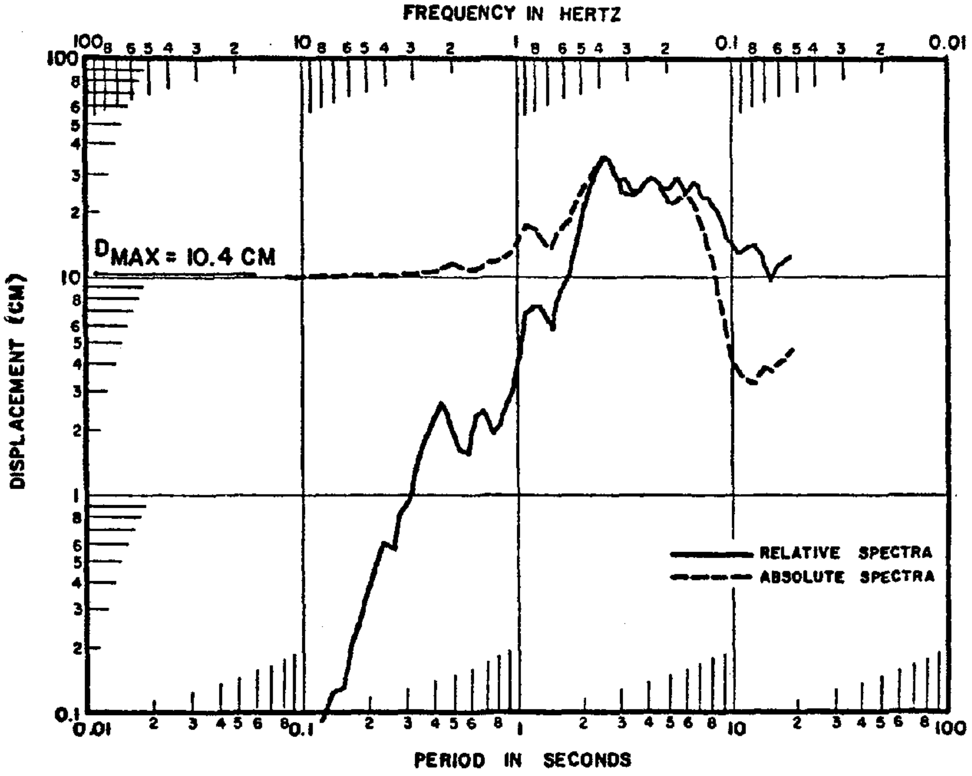


d. COMP N II E

FIG. 5 (c & d) COMPARISON OF PSEUDO VELOCITY (S_V) AND ABSOLUTE VELOCITY ($S_V{}^A$) SPECTRA (ζ=0.05) (SAN FERNANDO, FEB. 9, 1971, 15250 VENTURA BLVD)

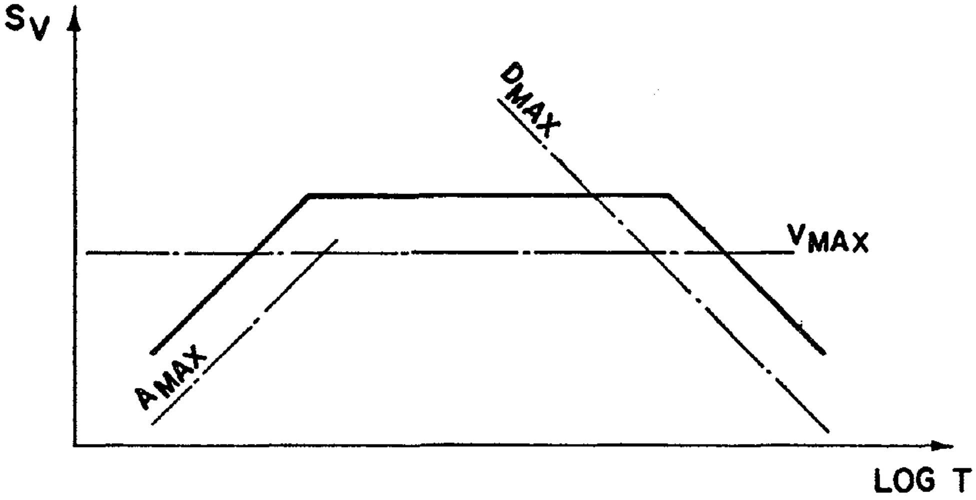


a. (IMPERIAL VALLEY, MAY 18, 1940 EL CENTRO SITE) COMP S 00 E

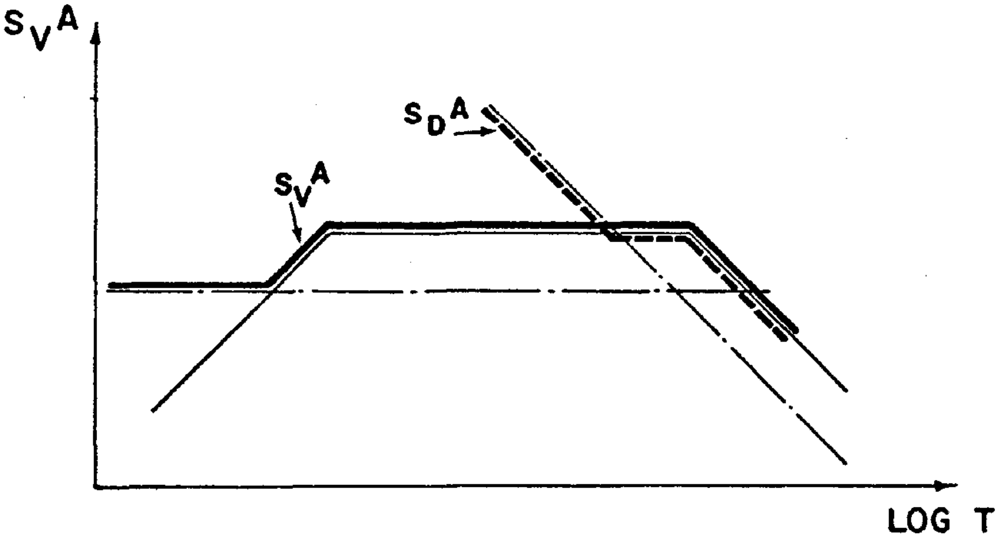


b. (SAN FERNANDO, FEB. 9, 1971, 15250 VENTURA BLVD) COMP N 79 W

FIG. 6 COMPARISON OF RELATIVE DISPLACEMENT (S_D) AND ABSOLUTE DISPLACEMENT (S_D^A) SPECTRA (ζ=0.05)



a. TRIPARTITE PSEUDO VELOCITY SPECTRUM



b. ABSOLUTE DISPLACEMENT ($S_D{}^A$) AND ABSOLUTE VELOCITY ($S_V{}^A$) SPECTRA

FIG. 7 CONSTRUCTION OF ABSOLUTE SPECTRA FROM PSEUDO VELOCITY SPECTRUM

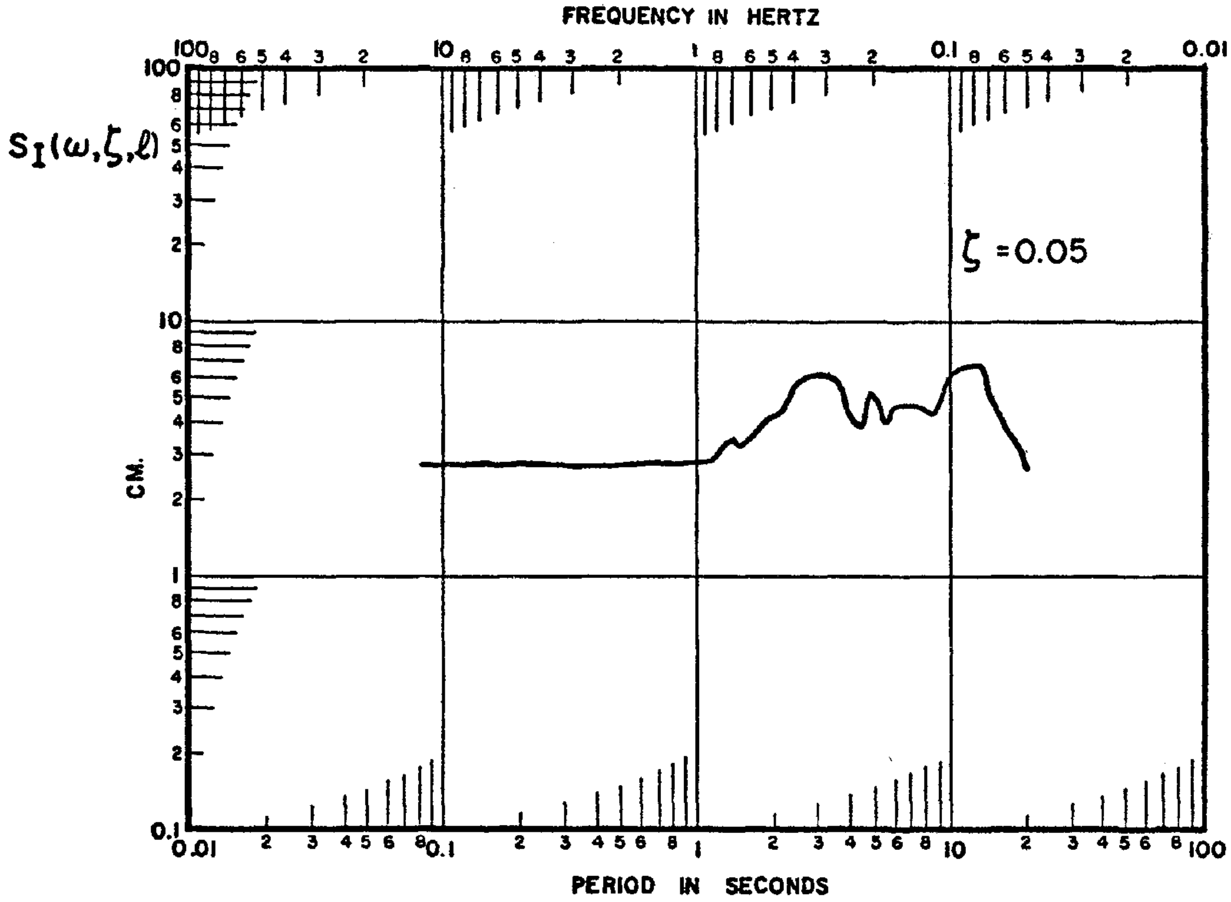
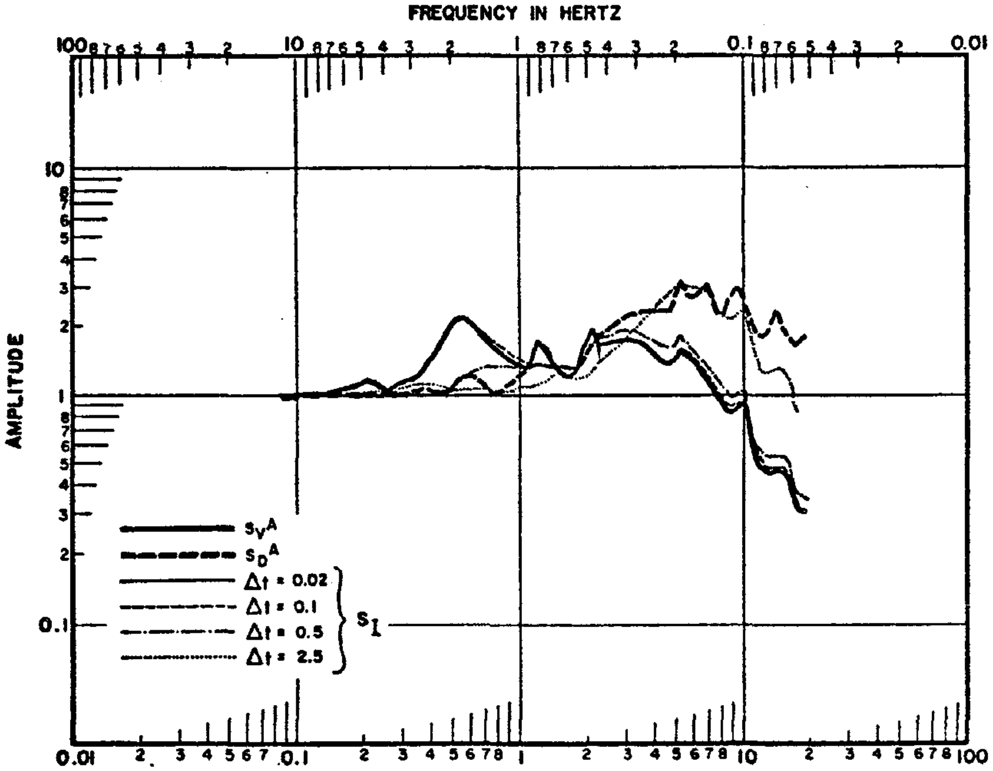
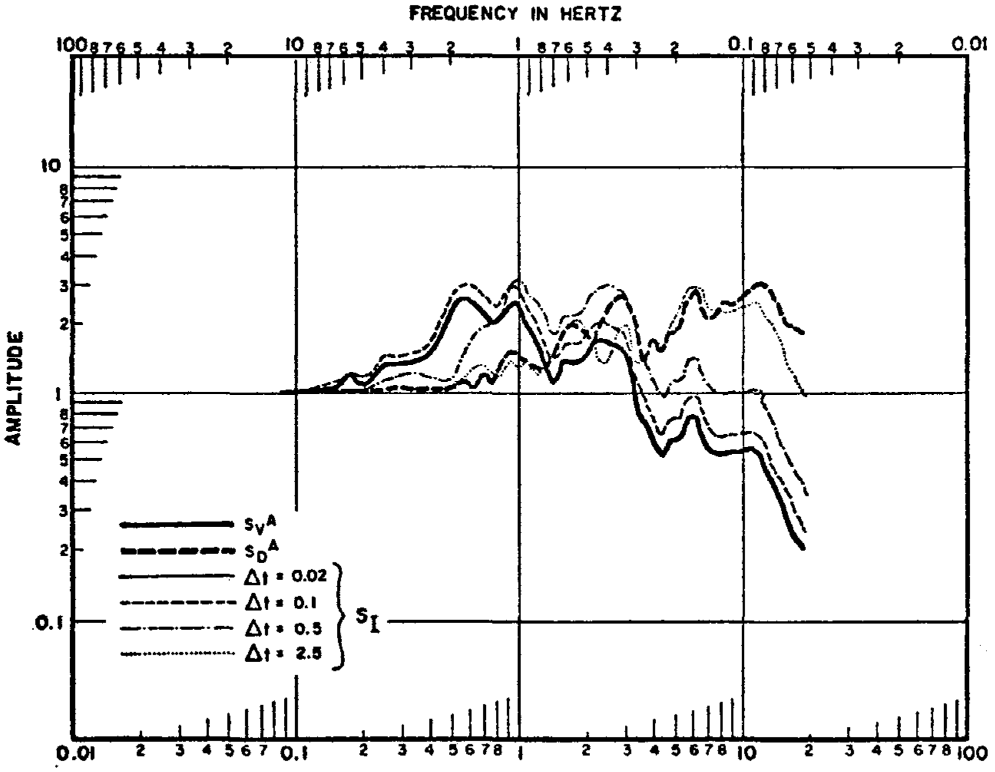


FIG. 8 IR SPECTRUM FROM A DISCONTINUITY ℓ = 160 ft (50m)
SAN FERNANDO, FEB. 9, 1971 HOLLYWOOD STORAGE
COMP N 90 E BASEMENT - PARKING LOT



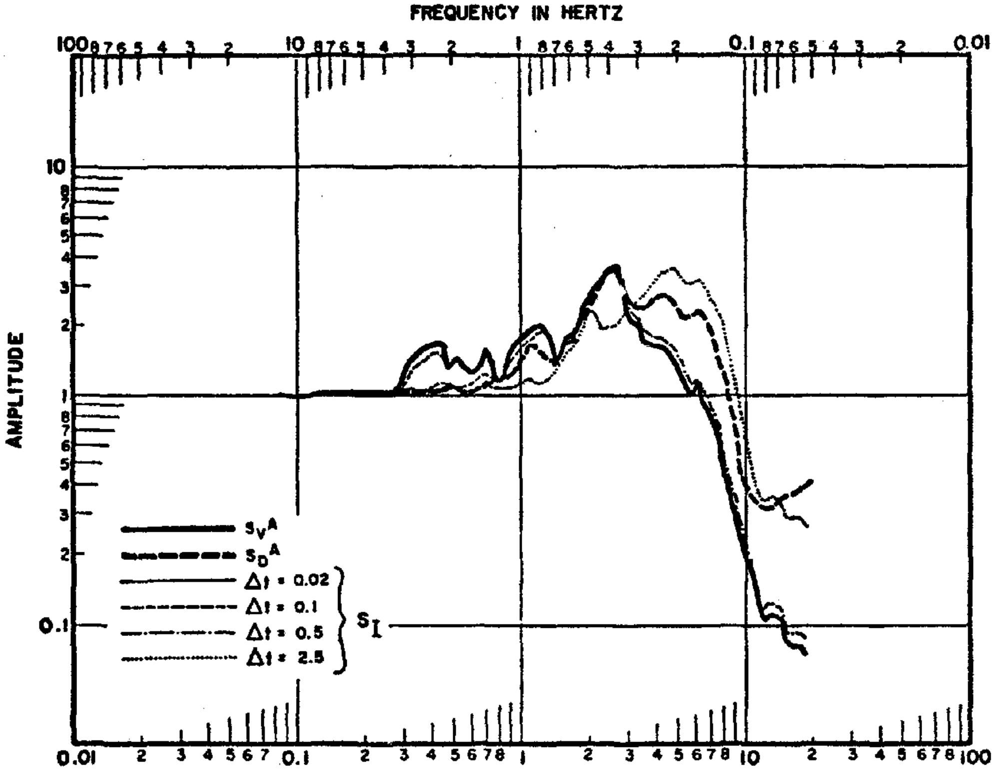
a. COMP S 90 W



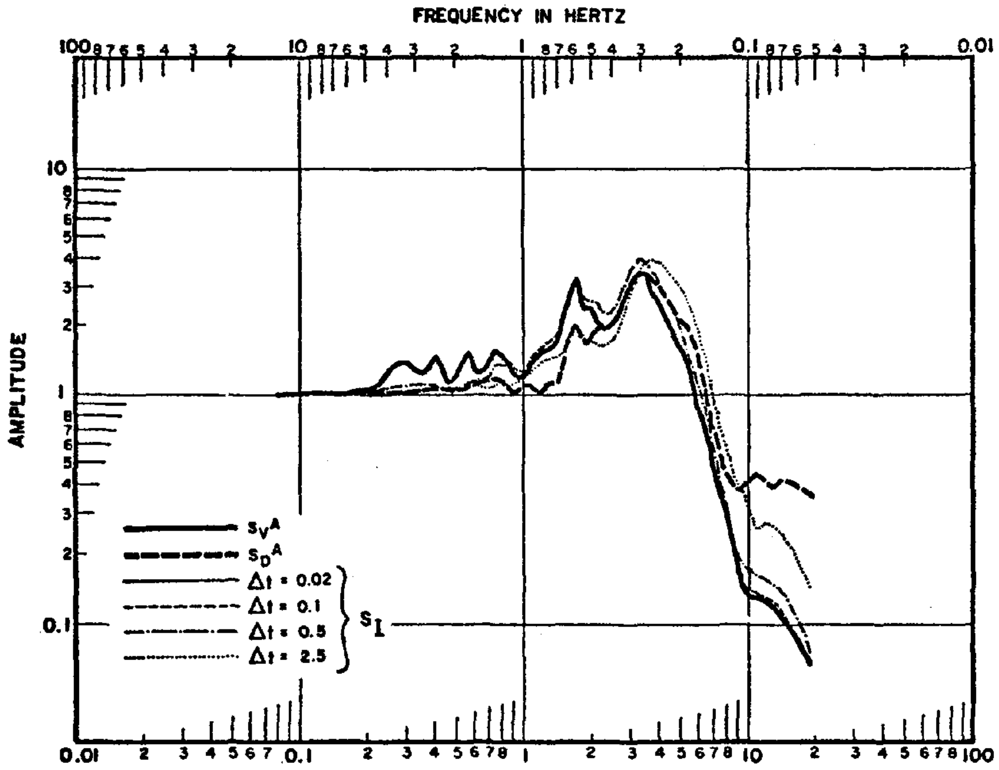
b. COMP S 00 E

FIG. 9 (a & b) COMPARISON OF ABSOLUTE DISPLACEMENT ($S_D{}^A$) AND ABSOLUTE VELOCITY ($S_V{}^A$) SPECTRA, WITH IR SPECTRA FOR SEVERAL VALUES OF PHASE DELAY TIME (ζ=0.05)

(IMPERIAL VALLEY, MAY 18, 1940 EL CENTRO SITE)



c. COMP N 79 W



d. COMP N 11 E

FIG 9 (c & d) COMPARISON OF ABSOLUTE DISPLACEMENT (S_D^A) AND ABSOLUTE VELOCITY (S_V^A) SPECTRA, WITH IR SPECTRA FOR SEVERAL VALUES OF PHASE DELAY TIME (ζ=0.05)

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