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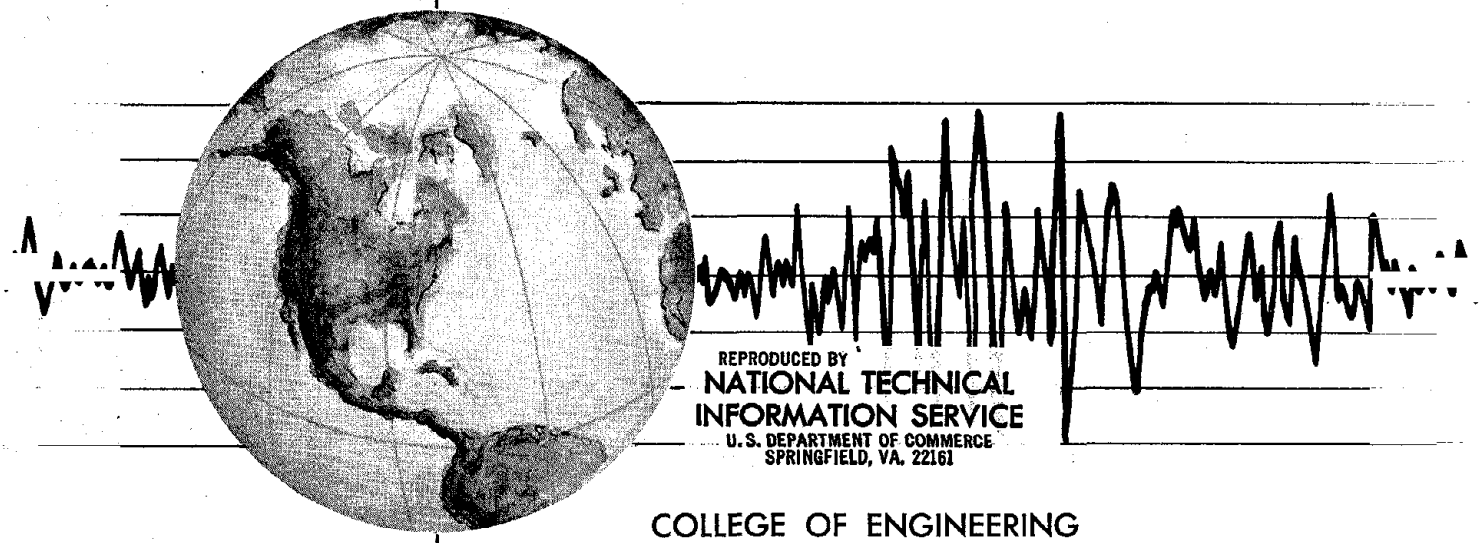
EARTHQUAKE ENGINEERING RESEARCH CENTER

SEISMIC STRAIN INDUCED IN THE GROUND DURING EARTHQUAKES

by
YOSHIHIRO SUGIMURA

Report to National Science Foundation



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The two earthquakes selected for this study have shallow focal depths and strong ground motions. For these earthquakes the parallel and normal directions to the causative fault line are shown to form a pair of orthogonal axes, along which the mean square intensities of the components of ground motion have maximum and minimum values.

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ABSTRACT

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INTRODUCTION

It is well-known that local soil conditions at sites subjected to seismic shaking considerably affect damage to structures at the site. Many analytical studies and laboratory tests have been performed to determine the dynamic characteristics of various types of soil deposits. In particular "strain dependence" of soils, i.e., nonlinearity of shear modulus and damping ratio with shear strain, has been clarified mainly by laboratory tests [1, 2, 3, 4, 5, 6].* A clue to the relationship between earthquake ground shaking and damage to structures may be found if strains induced in the ground during an earthquake are evaluated and then compared with results from laboratory tests.

An interesting question that also arises is as follows: "How large will the actual strain level in soil layers induced by seismic ground motion be, particularly in the case of a great destructive earthquake?" Strain data obtained directly from instruments in soil deposits would provide the answer. However, except for some geophysical and geotechnical surveys such as triangulation which are mostly in a static sense, no suitable instruments equivalent to strong-motion accelerographs for ground acceleration have been developed to measure local seismic strain waves.

This report develops a method of estimating seismic ground strain by using techniques for strong motion data and presents some computed results from these techniques. Although the depth of soils, especially soft soils, is a significant factor [7, 8] it is beyond the scope of this paper.

DETERMINATION OF STRAIN

First, consider a plane wave in an elastic homogeneous body. If the wave is a shear wave, particle motion in the body is transverse to the direction of propagation and if it is a compressional wave, particle motion

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*Numbers in square brackets refer to corresponding references.

is parallel to the direction of propagation (longitudinal). If the x and y axes are chosen in the longitudinal and transverse directions, respectively, and u and v are the corresponding particle displacements, then the fundamental wave propagation equations can be represented as follows:

For a longitudinal wave,

$$\frac{\partial^2 u}{\partial t^2} = c_1^2 \frac{\partial^2 u}{\partial x^2} \tag{1}$$

and for a transverse wave,

$$\frac{\partial^2 v}{\partial t^2} = c_2^2 \frac{\partial^2 v}{\partial x^2} \quad ; \tag{2}$$

where

$$c_1 = V_p = \left[\frac{E}{\rho} \frac{1-\nu}{(1+\nu)(1-2\nu)}\right]^{\frac{1}{2}} \tag{3}$$

and

$$c_2 = V_s = \left[\frac{G}{\rho}\right]^{\frac{1}{2}} \tag{4}$$

are the longitudinal (or compressional) wave velocity and transverse (or shear) wave velocity, respectively. E, G, and ν are Young's modulus, the shear modulus and Poisson's ratio of the elastic body, respectively. Equations (1) and (2) have similar solutions of the form

$$D = f(x-ct) + g(x+ct) \tag{5}$$

where D and c are either u and c_1 or v and c_2, respectively. The first term on the right hand side of eq. (5) represents a forward moving wave and the second term a backward moving wave. If the elastic body is infinite or if the effects of reflected waves from a boundary can be neglected, then it is only necessary to consider the forward wave to determine the behavior of an arbitrary point in the body, so that

$$D = f(x-ct) \ . \tag{6}$$

The particle velocity and strain at that location are obtained by differentiating eq. (6) with respect to t and x as shown below,

$$\dot{D} = \frac{dD}{dt} = -cf'(x-ct) \tag{7}$$

$$\varepsilon = \frac{dD}{dx} = f'(x-ct) \quad . \tag{8}$$

Hence

$$\varepsilon = -\frac{\dot{D}}{c} \quad . \tag{9}$$

Thus the strain can be simply expressed as the ratio of particle velocity to wave velocity. Therefore, axial and shear strains are shown, respectively, as follows:

$$\varepsilon_x = -\frac{\dot{u}}{c_1} \tag{10}$$

$$\gamma_{xy} = -\frac{\dot{v}}{c_2} \quad . \tag{11}$$

It is obvious, furthermore, that the maximum shear velocity $\dot{v}$ of a particle and the maximum shear strain γ_{xy} occur simultaneously when the solution v is expressed by the sinusoidal wave form.

In the case of seismic waves propagating through the earth, conditions are considerably different from the case of plane waves. The following difficulties must be considered.

(1) The energy source may move along a line or on a plane, i.e., an earthquake fault, so that the source is a function of time as well as space.

(2) A variety of properties might be contained within the waves themselves induced from the source. The structure is so complicated that in most cases it is not possible to represent the wave motion exactly by a physical model, therefore measurements of seismic waves will be considered as random quantities.

(3) There exist many soil layers and topographic boundaries in the actual ground at which reflection and refraction of seismic waves might occur.

(4) Parameters such as Young's modulus and the shear modulus of soils will not be constant during a destructive ground shaking since, in general, soils are not elastic.

If an observation station, however, is located far enough from the source, seismic records at that location can be decomposed into different wave components according to the different wave velocities c_1, c_2 and so on. Based on this possibility, decomposition technique has been used regularly in seismology to overcome to some extent the difficulties (1) and (2). Difficulties (3) and (4) are principally derived from local site conditions extremely near the surface of the earth so that they might not affect significantly arrival times of waves in earlier parts of seismic records. These effects cannot be neglected, however, if it is necessary to consider the amplitudes of recorded waves. It has been pointed out, for instance, that maximum values of ground response to seismic shaking scatter in a remarkably wide range under the influence of local soil conditions [1, 2]. In particular, because of the interdependence between elastic modulus and amplitude of the particle velocity, strains cannot be determined directly from seismic records.

In spite of all these difficulties and uncertainties, the application of the simple plane wave forms (eqs. (10) and (11)) to seismic records for an estimation of strain appears to be, at present, the best available first approximation for engineering use.

EARTHQUAKE WAVES USED AS EXAMPLES

Since the San Fernando earthquake in 1971 during which many seismic records were obtained in Southern California strong motion data from the Western states, including these records, have been processed at the Earthquake Engineering Research Laboratory, California Institute of Technology [9]. Some data processing techniques such as "baseline" correction and

high-frequency correction [10, 11] were applied to these data and, finally, the results were published as corrected accelerograms and integrated ground velocity and displacement curves [12]. The object of the base line correction was to prevent divergence of the resultant curves, which may occur if the original data are integrated simply and directly. The object of the high-frequency correction was to account for the fall-off of basic transducer response in the accelerographs [10, 11, 13].

These corrected data are suitable for the purpose of this work. Two earthquake records were selected from among them and used as shown in Table 1. Schematic maps of locations of the epicenters and recording stations for these earthquakes are shown in Figs. 1 and 2, respectively. Both earthquakes selected have strong ground motions and shallow focal depths as is generally the case in California and the Western states.

Geotechnical data from the sites of the stations are given by C. M. Duke and D. J. Leeds, 1962 [14]; W. R. Hansen et al., 1973 [15]; and the U.S. Department of the Interior, Geological Survey, 1976 [16]. Subsurface unit thickness and seismic data from Duke and Leeds are shown in Table 2, and will be used as basic in subsequent sections.

LONGITUDINAL AND TRANSVERSE COMPONENTS

Since earthquakes occur at random locations, the direction of each component of a seismogram at a station does not ordinarily coincide with the direction to the focus. Therefore, records are initially decomposed into longitudinal and transverse components. Let us consider u, v and w as vector components in the longitudinal, transverse and vertical directions, respectively, and u', v' and w' as former components. If a_i $(i = 1,2,3)$ are direction cosines, then

$$u = a_1u' + a_2v' + a_3w' \tag{12}$$

Similarly,

$$v = b_1u' + b_2v' + b_3w' \tag{13}$$

and

$$w = c_1 u' + c_2 v' + c_3 w' \tag{14}$$

in which $b_i (i = 1,2,3)$ and $c_i (i = 1,2,3)$ are direction cosines of v and w to u', v' and w', respectively.

If the depth of the focus can be neglected or is assumed not to affect the direction of wave propagation, direction cosines a_3, b_3, c_1 and c_2 are zero and $c_3 = 1$. Then, eqs. (12) to (14) reduce to the following simple forms.

$$u = a_1 u' + a_2 v' \tag{15}$$

$$v = b_1 u' + b_2 v' \tag{16}$$

$$w = w' \quad . \tag{17}$$

Furthermore, since the coordinate systems are Cartesian, eqs. (15) and (16) can be written as

$$\left.\begin{aligned} u &= u'\cos\theta + v'\sin\theta \\ V &= u'\sin\theta + v'\cos\theta \end{aligned}\right\} \quad (-90° < \theta < 90°) \quad . \tag{18}$$

We note that it does not necessarily follow that the positive direction of the longitudinal axis coincides with the direction from the station to the focus. For instance, for the Imperial Valley earthquake, the positive direction on the longitudinal axis coincides with the direction to the focus but vice versa for the Kern County earthquake, as shown in Figs. 4 and 5, respectively.

Acceleration and velocity curves in both cases generated by eq. (18) are shown in Figs. 6 to 9. Table 3 shows the maximum values and occurrence times for these curves compared with those of the original records. For the Taft record, there are only slight changes in the maximum values and wave shape, but no change in the occurrence time of the maximum values

since the direction cosines are nearly equal to zero or unity during the coordinate transformation; that is, the new longitudinal curves correspond to the original E-W component and the new transverse curves to the N-S components. On the other hand, in the case of the El Centro record after the coordinate transformation the new curves are different from those of the original records.

Figure 10 shows the particle orbit for the first six seconds based on both components of the transformed velocity curves at the Imperial Irrigation District station in El Centro. Similarly, the particle velocity orbit described for the first 4.8 seconds at Taft Lincoln School Tunnel station is shown in Fig. 11. Approximate directions along the fault lines observed on the ground surface during these earthquakes are also shown in these figures [17, 18]. The direction is shown by a single solid line at the El Centro site because the Imperial fault is running nearly straight (see Fig. 4). For the White Wolf fault in Kern County, the direction can be estimated as almost straight but slightly curved at the southern end near the epicenter (see Fig. 5). Thus two lines are shown in Fig. 11. The solid line shows the direction judged from the whole and the dashed line shows the direction estimated from the vicinity of the observed fault end. What is evident and interesting from these two figures is that large shaking components are induced along the direction of the fault line rather than along the longitudinal or transverse directions to the focus. Horizontal dislocation was predominant in the activity of both the Imperial fault and the White Wolf fault, thus causing strongest motions along their fault lines [19, 20, 21]. Distinctive characteristics of short or medium distance shocks should be considered for these earthquakes because the epicentral distances from the stations are about 7.3 miles (El Centro) and 25.6 miles (Taft), respectively. This fact suggests that for these earthquakes an important factor affecting the ground motion will be the direction of slip of the fault. Hence, it might be more informative to transform the coordinate system to the directions normal and parallel to the fault line. In any case, in order to confirm this suggestion, further research is necessary as well as improved methods of analyzing large quantities of data.

FOURIER ANALYSIS

Fourier analysis provides a powerful means of investigating the characteristics of a random wave in the frequency domain. Let us consider now the components in the frequency domain in the longitudinal and transverse directions. The Fourier amplitudes and phase angles for N discrete data samples X_m with time interval Δt, where N is even, are shown by

$$\left.\begin{aligned} X_k &= [A_k^2 + B_k^2]^{\frac{1}{2}} \\ \phi_k &= \tan^{-1}(-\frac{B_k}{A_k}) \end{aligned}\right\} , \quad k = 0,1,2,\ldots., \frac{N}{2} \tag{19}$$

where

$$\left.\begin{aligned} A_k &= \frac{2}{N} \sum_{m=0}^{N-1} X_m \cos\frac{2\pi km}{N} \\ B_k &= \frac{2}{N} \sum_{m=0}^{N-1} X_m \sin\frac{2\pi km}{N} \end{aligned}\right\} . \tag{20}$$

Then, the time history of each component of the Fourier transform wave is expressed by

$$X_k'(t) = X_k \cos(2\pi f_k t + \phi_k), \quad k = 0,1,2,\ldots, \frac{N}{2}, \tag{21}$$

where

$$f_k = \frac{k}{N\Delta t} \tag{22}$$

is the frequency of the k^{th} Fourier transform wave. Recalling the definition of

$$C_k = \frac{A_k - iB_k}{2} , \quad k = 0,1,2,\ldots, N-1 \tag{23}$$

then

$$A_k + iB_k = A_{N-k} - iB_{N-k}, \quad k = 0,1,2,\ldots, \frac{N}{2} \quad ; \tag{24}$$

so that eq. (21) can be expressed in terms of discrete complex Fourier coefficients given by the equation,

$$C_k = \frac{1}{N} \sum_{m=0}^{N-1} X_m \, e^{-i(2\ km/N)} \quad , \quad k = 0,1,2,\ldots, N-1 \quad . \tag{25}$$

The discrete Fourier coefficients A_k and B_k are shown as follows:

$$\left.\begin{aligned} A_k &= 2\mathrm{Re}(C_k) \\ B_k &= -2\mathrm{Im}(C_k) \end{aligned}\right\} \quad k = 0,1,2,\ldots, \frac{N}{2} \tag{26}$$

(This method is the fast Fourier transformation (FFT) [22].) Coefficients C_k were computed first by using a subroutine program of the FFT coded by Y. Ohsaki (see program list in Appendix), then the Fourier amplitudes and phase angles were obtained by eq. (19). These results are shown in Figs. 12 to 13c for the El Centro site, and in Figs. 14 to 15c for the Taft site.

Two approaches were attempted in this computation process: (1) The time duration during which the Fourier analysis is applied is divided into four different parts; viz., the total fifty seconds from the initial time; zero to ten seconds; ten to thirty seconds; and thirty to fifty seconds. The results from the latter three parts correspond to the so-called running Fourier spectrum. (2) Using the phase angle, a correction was made to the Fourier amplitude of the longitudinal component at each frequency so as to satisfy simultaneously the maximum value of the transverse component. The results of these calculations are tabulated in Table 4.

The purpose of these computations is to consider whether there exists a frequency at which either the longitudinal or transverse component shows a high peak and the other a low trough. If this were found in the figures, it could be used to distinguish the kind or type of wave which is the dominant component in the ground motion. For instance, if the transverse component is more dominant than the longitudinal, such a frequency component might be identified as a shear wave and so forth. This idea can also be applied by a statistical approach corresponding to the concept of "principal

axes of ground motion" presented by T. Kubo and J. Penzien [23], although in a slightly different sense.

Each shaded part in Figs. 12 to 15c shows the range where the transverse component becomes larger than the longitudinal. The selection of several peaks for the transverse component from this range was attempted. The results are summarized in Table 5 and Table 6. What is evident here is that the same or a very close frequency component for each peak in the total fifty seconds is clearly confirmed in each of the three intervals. The classification of the wave type, however, is fairly complicated because a low value of the longitudinal component does not always correspond to the peak of the transverse component.

NORMAL AND PARALLEL COMPONENTS TO THE FAULT LINE

In this section let us consider the normal and parallel waves to the fault line reproduced from the original records. The procedure is the same as that described in the preceding sections with the appropriate angle of transformation; i.e., $\theta = +54°.5$ for the El Centro site and $\theta = -40°.4$ for the Taft site, as shown in Table 7. Note that for the Taft site, the direction of the dashed line in Fig. 11 was assumed to be the direction of fault slip in the area nearest to the station.

Figures 16 and 17 show the acceleration and velocity waves for the Imperial Valley earthquake; those of the Kern County earthquake are shown in Figs. 18 and 19. Consider the parallel components of these waves and compare them schematically with the longitudinal and transverse curves shown before (Figs. 6, 7 for the El Centro site and Figs. 8, 9 for the Taft site) and the original north-south and east-west records. Initially we will call these waves SH (parallel), LO (longitudinal), TR (transverse), NS (original north-south) and EW (original east-west).

In the case of the Imperial Valley, if the sign is reversed the form of the SH wave is similar to that of LO even though the values of the amplitudes are different from each other. This tendency is particularly conspicuous in the velocity curves. Now LO was quite different from

either NS or EW, as mentioned before, hence SH bears no resemblance to either NS or EW.

In the case of the Kern County earthquake, it can be seen from Figs. 8 and 18, or Figs. 9 and 19 that SH is not like LO or TR. In particular, the amplitudes are different. Meanwhile LO resembles EW closely and TR resembles NS, as before. Therefore, it can be said that SH bears no resemblance to either NS or EW.

This result can be justified theoretically as follows: Assuming $u' = v' = 1$ and solving eq. (18) for u with $0° < \theta < 45°$, the result shown in Fig. 20 is obtained. The new component u or the ratio $r = u/u'$ (in which $u' = 1$) can be expressed by the length of the chord for values of θ and changes on the continuous curve described in this figure. The range of r is $r = 1$ at $\theta = 0°$ to $r = 2$ at $\theta = 45°$. Three pairs of components corresponding to the smallest rotation angle were selected from among the three coordinates of SH, LO-TR and NS-EW and each ratio was calculated. The results are summarized below.

<u>El Centro site</u>			
Case 1	SH to LO	18°.5	r = 1.266
Case 2	SH to NS	35°.5	r = 1.395
Case 3	LO to EW	36°.0	r = 1.397
<u>Taft site</u>			
Case 4	SH to LO	43°.0	r = 1.413
Case 5	SH to EW	40°.4	r = 1.409
Case 6	LO to EW	2°.6	r = 1.044

All the other combinations of components have larger ratios than these cases. It is clear from the above that the pairs of waves are similar to each other in Case 1 and especially in Case 6 because of their small ratios, but look quite different from each other in Cases 2, 3, 4 and 5.

Attention should also be paid to the fact that for $\theta = 45°$ one component becomes zero. This fact suggests that there may exist a set of directions of the predominant and minor ground motion that are principal axes. At the same time, it also suggests that it might not be reasonable to use directly the values measured by a seismograph as the ground motion at the site because only in rare cases do the directions of the seismograph agree with these principal axes.

The computed Fourier amplitudes of the parallel and normal velocity waves are shown in Figs. 21 to 22c for the El Centro site and in Figs. 23 to 24c for the Taft site. The computations are the same as before (Table 4); in particular, comparing Fig. 21 with Fig. 12 or Fig. 23 with Fig. 14, for these curves the shaded part is more clearly defined than before. The selection of peaks of the parallel components from among these figures was performed in the same manner as before. The results are summarized in Table 8 and Table 9 for the El Centro and Taft sites, respectively. The peak of the parallel component corresponds to the low trough of the normal component at almost all the frequencies so that the component waves can be identified as shear waves or, at least, waves of shear type. Hence, a coordinate transformation to the normal and parallel directions to the causative fault line rather than to the longitudinal and transverse directions to the epicenter seems to be more satisfactory for explaining the characteristics of ground motion at a station site.

ESTIMATION OF SEISMIC SHEAR STRAIN

From the preceding section, it seems reasonable to assume as a first approximation that each predominant frequency component in the parallel direction is a shear wave. In this section, an estimate of the seismic shear strain in the ground at each site is attempted by applying eq. (11). First the seismic data shown in Table 2 are simplified as follows: At each site some equivalent single soil layers are considered with an average shear wave velocity shown by,

$$\overline{V}_{si} = \frac{\Sigma V_{si} H_i}{\Sigma H_i} \tag{27}$$

in which i is the stratum number from the surface and V_{si} and H_i are the

shear wave velocity and the thickness of each stratum, respectively. Then the natural frequency of each equivalent layer is expressed by

$$\bar{f}_i = \frac{4\Sigma H_i}{V_{si}} \quad . \tag{28}$$

The average velocity and frequency calculated for each layer from eqs. (27) and (28), respectively, are summarized in Table 10 and Table 11. Five equivalent single layers exist at the El Centro site and four at the Taft site. Next, taking these frequencies as representative boundary values, peak frequency components shown in Table 8 and Table 9 are classified into several groups. Then, shear strains at each site are calculated by eq. (11) for each case using the value $\bar{V}_s$ of the adjacent lower frequency (lower limit of shear strain) and higher frequency (upper limit of shear strain). The results are summarized in Table 12 and Table 13, respectively. Finally, the average value of shear strain corresponding to each frequency will change within the range between these lower and upper limits. The order of these strain levels is estimated as about 10^{-3} (%) at the El Centro site and about 10^{-4} (%) at the Taft site.

The above approach provides a basis for the assumption that each peak seen in Fig. 21 or Fig. 23 corresponds to a single soil layer of some depth for which the first vibration mode corresponds to the particular peak frequency. As is generally known, the first mode of a soil layer is to some extent predominant in the ground motion at a site. Therefore, as a first approximation this assumption will be an effective method of investigating the ground motion. It should be kept in mind, however, that such a method (1) gives the average value through the whole soil deposit; (2) shows only the discrete Fourier amplitude corresponding to each frequency; and (3) gives no consideration to the higher modes of the ground. Hence, further studies such as improvement of the method and analysis of more data are necessary to clarify the real shear strain wave induced in the local part of the ground during earthquakes.

CONCLUSIONS

The conclusions achieved in this work can be divided into the following

two categories.

(1) The mean square intensity of a single orthogonal component of ground motion at a site depends on the direction of that component. There exists a pair of orthogonal axes (principal axes) along which the mean square intensities of the components of motion have maximum and minimum values. The parallel and normal directions to the causative fault line were shown to correspond to such a coordinate system for the two examples of earthquake and station, i.e., Imperial Valley earthquake (1940) recorded at El Centro site and Kern County earthquake (1952) recorded at Taft site. This is consistent with the characteristics of these causative faults, namely that they (a) slip mainly horizontally, and (b) are regarded as nearly straight lines. A more difficult situation will arise in the case of earthquakes caused by faults with more complicated characteristics.

(2) Provided that the velocity curves are transformed to the coordinate system mentioned above and that the predominant components in the parallel direction are assumed to be of shear wave type, it is possible to evaluate the seismic shear strain component at each frequency by applying Fourier analysis and the simple plane wave solution. The order of the average shear strain component at each frequency caused by ground shaking can be estimated at about 10^{-3}(%) at the El Centro site and about 10^{-4}(%) at the Taft site as a first approximation. It should be noted, however, that additional detailed study is necessary to determine the shear strain induced in the ground during an earthquake.

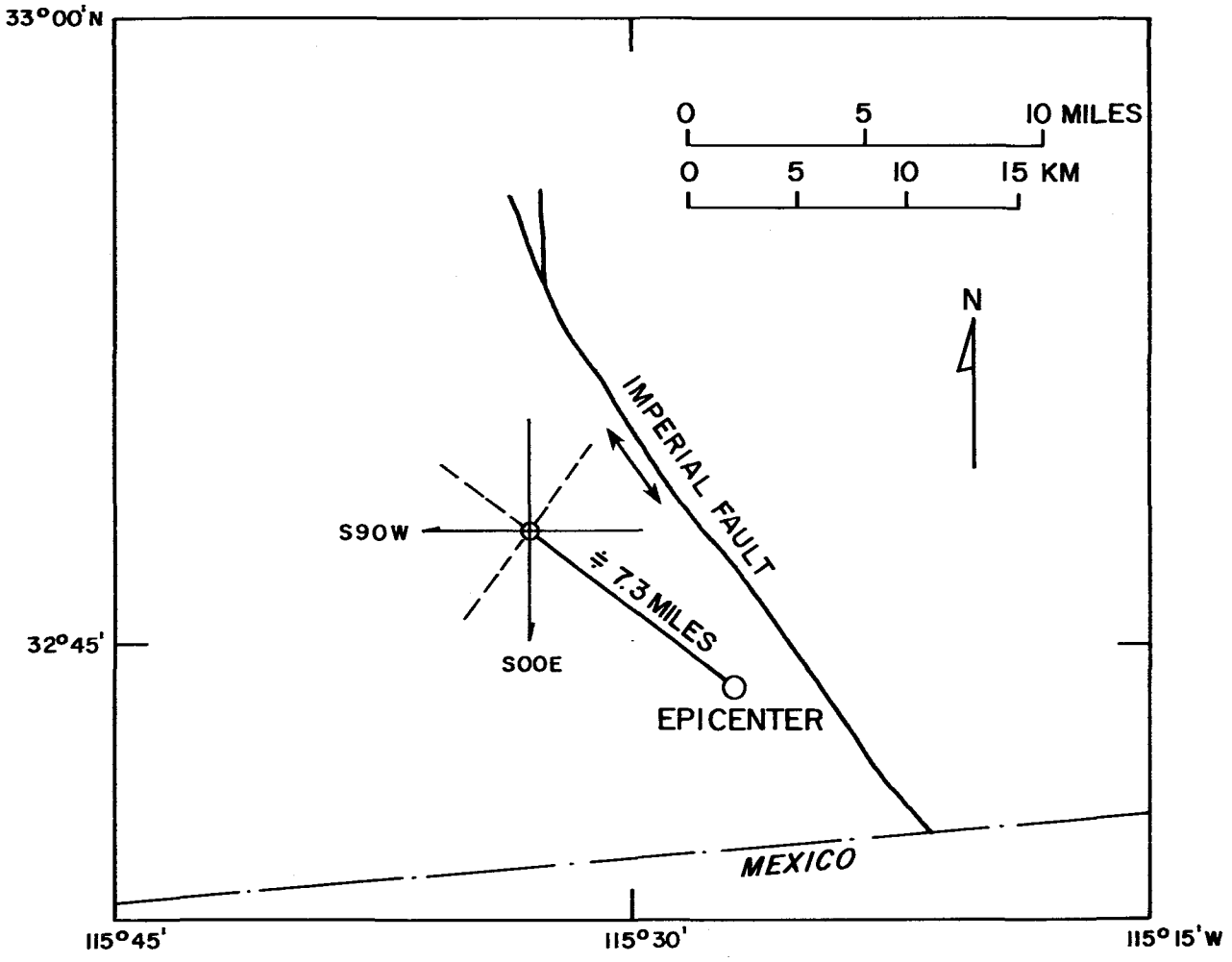

Fig. 1 Schematic location map of station, epicenter and causative fault (Imperial Valley Earthquake)

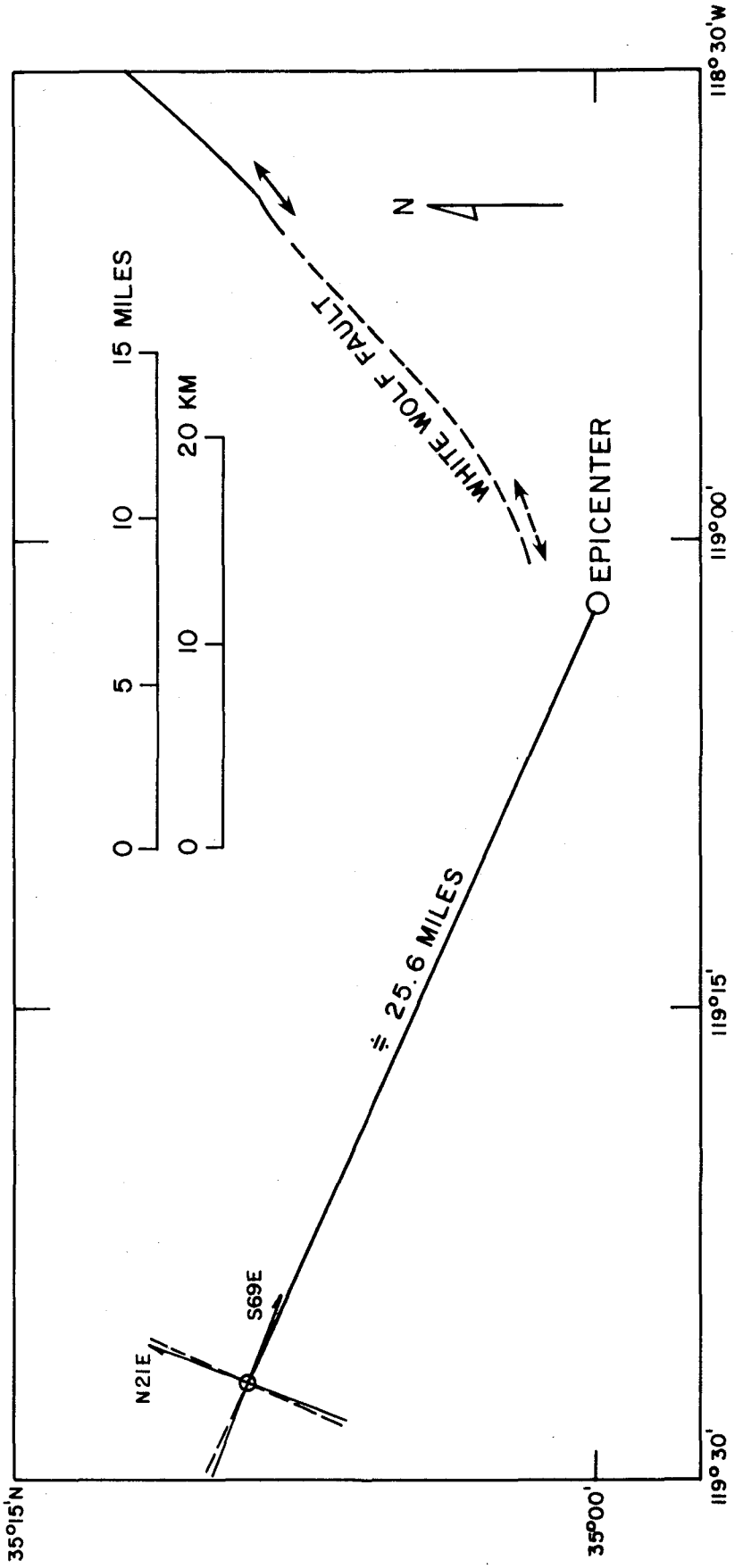

Fig. 2 Schematic location map of station, epicenter and causative fault (Kern County Earthquake)

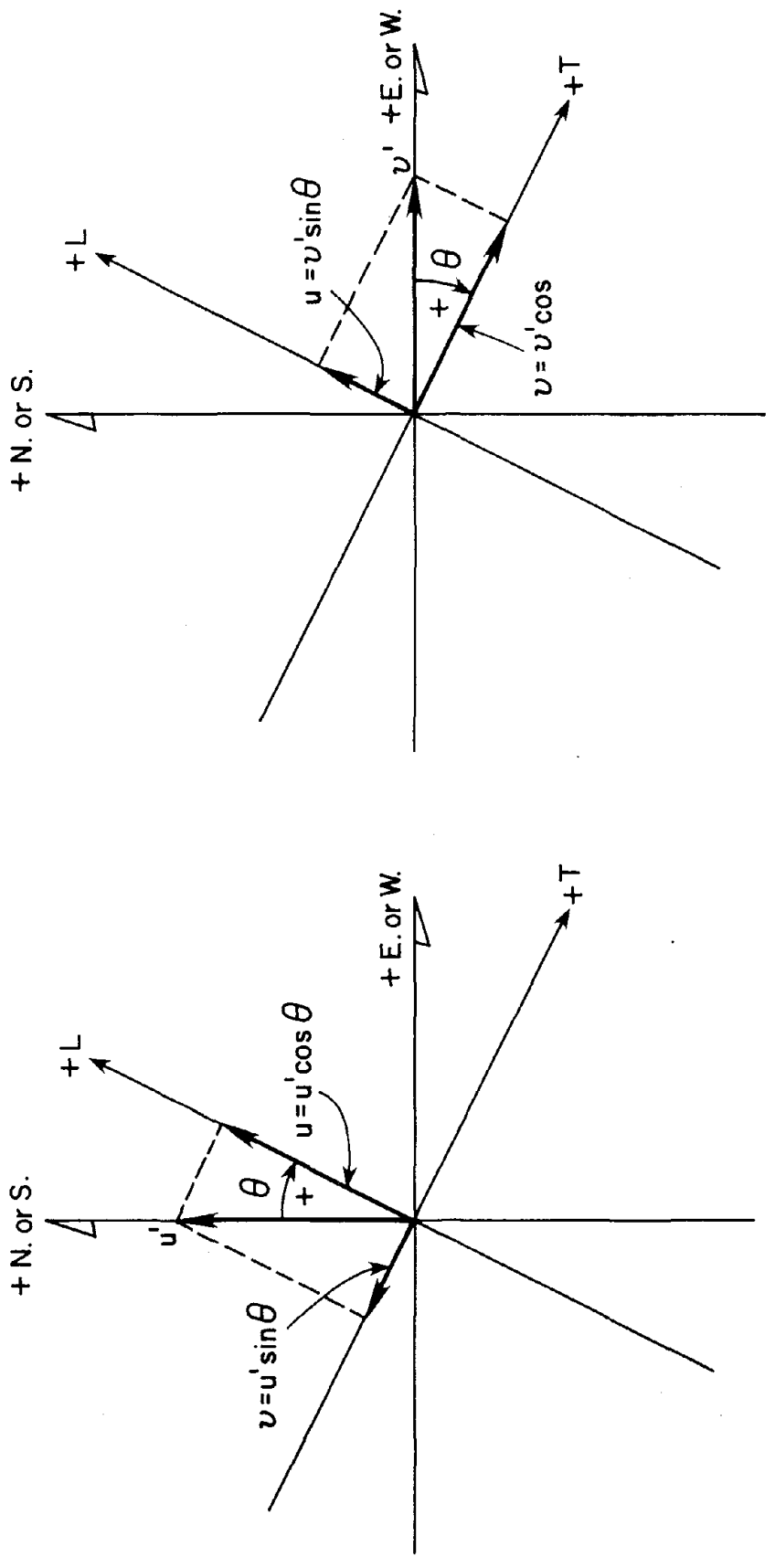

Fig. 3 Transformation of coordinates

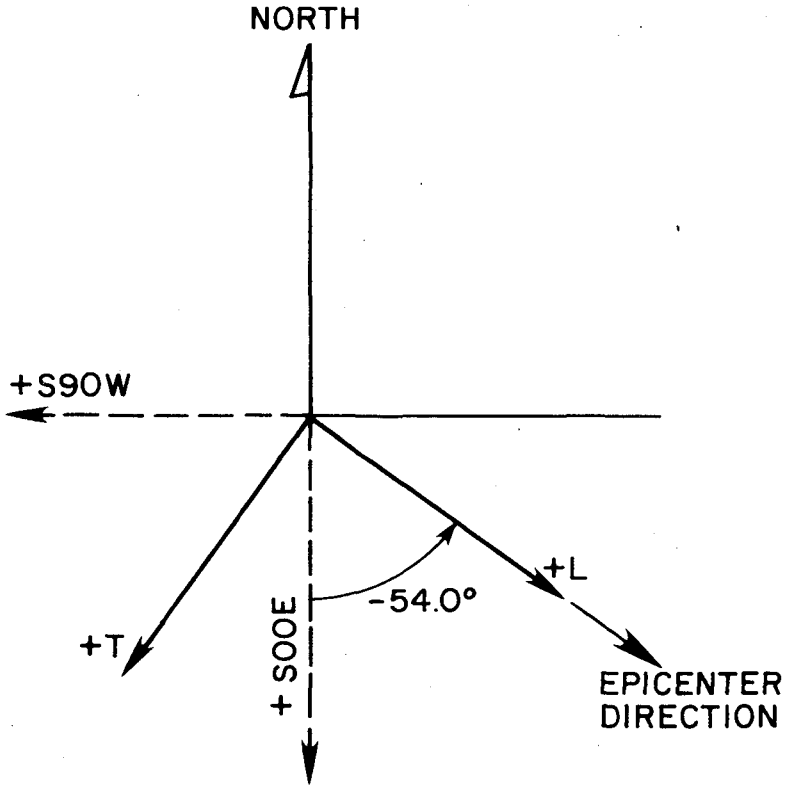

Fig. 4 Relation between components of seismograph and transformed coordinates (Imperial Valley Earthquake)

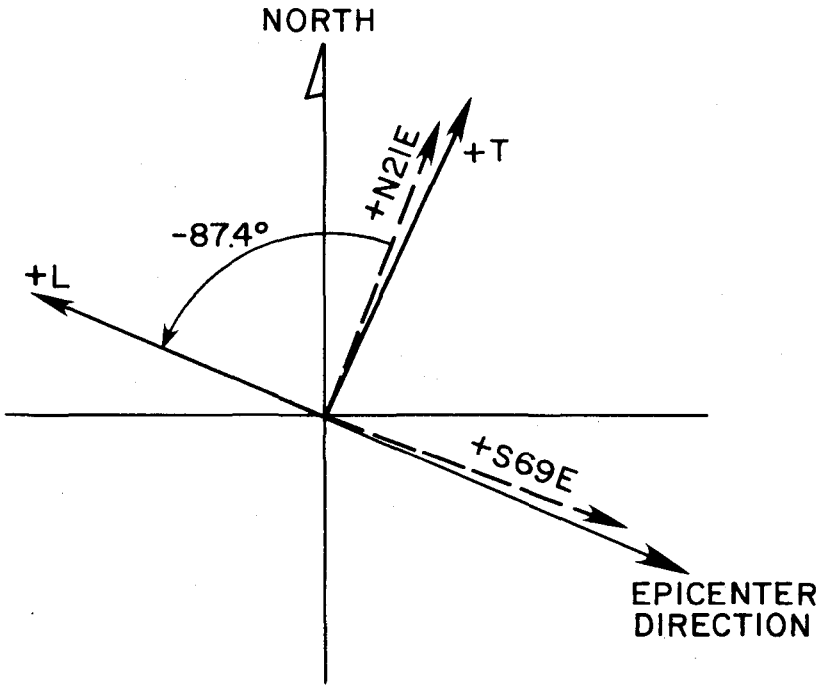

Fig. 5 Relation between components of seismograph and transformed coordinates (Kern County Earthquake)

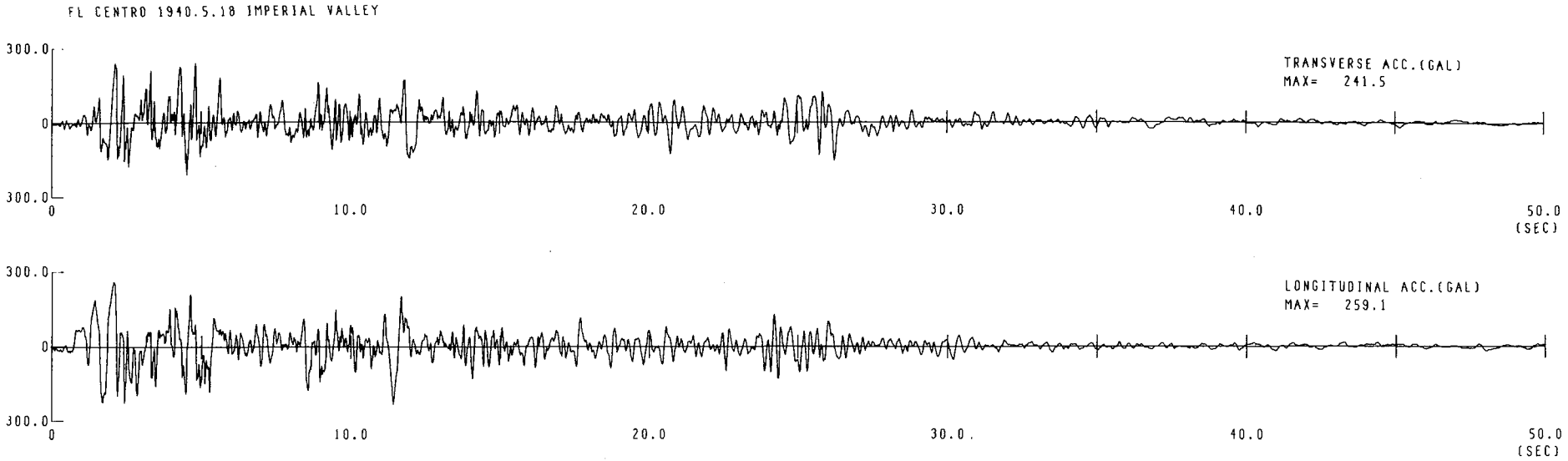

Fig. 6 Reproduced acceleration curves in longitudinal and transverse directions (Imperial Valley Earthquake)

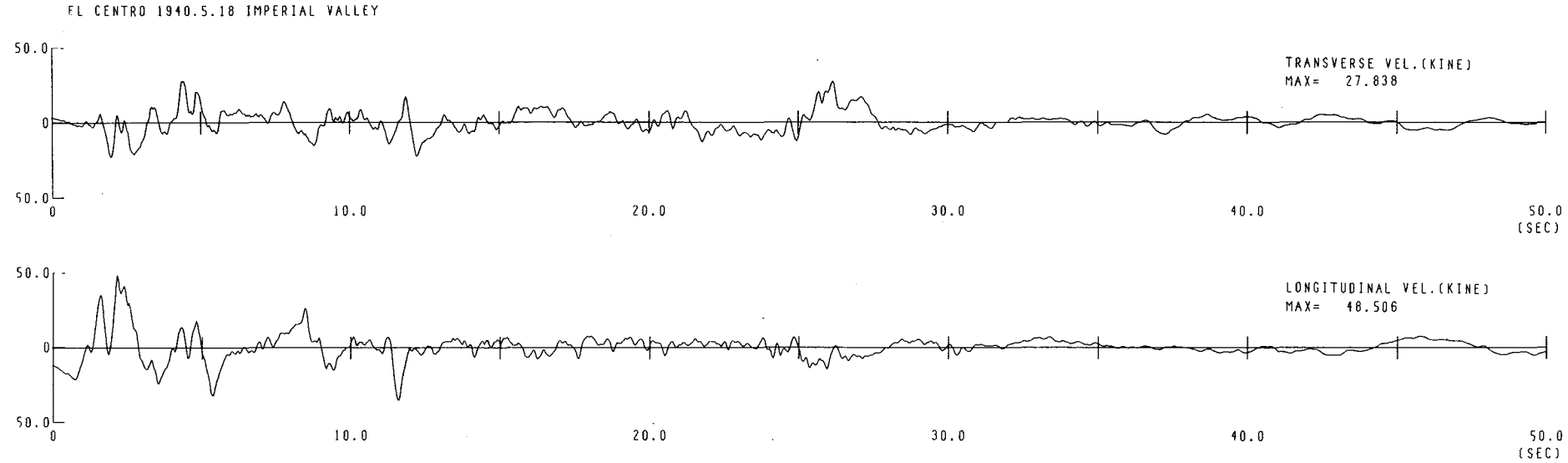

Fig. 7 Reproduced velocity curves in longitudinal and transverse directions (Imperial Valley Earthquake)

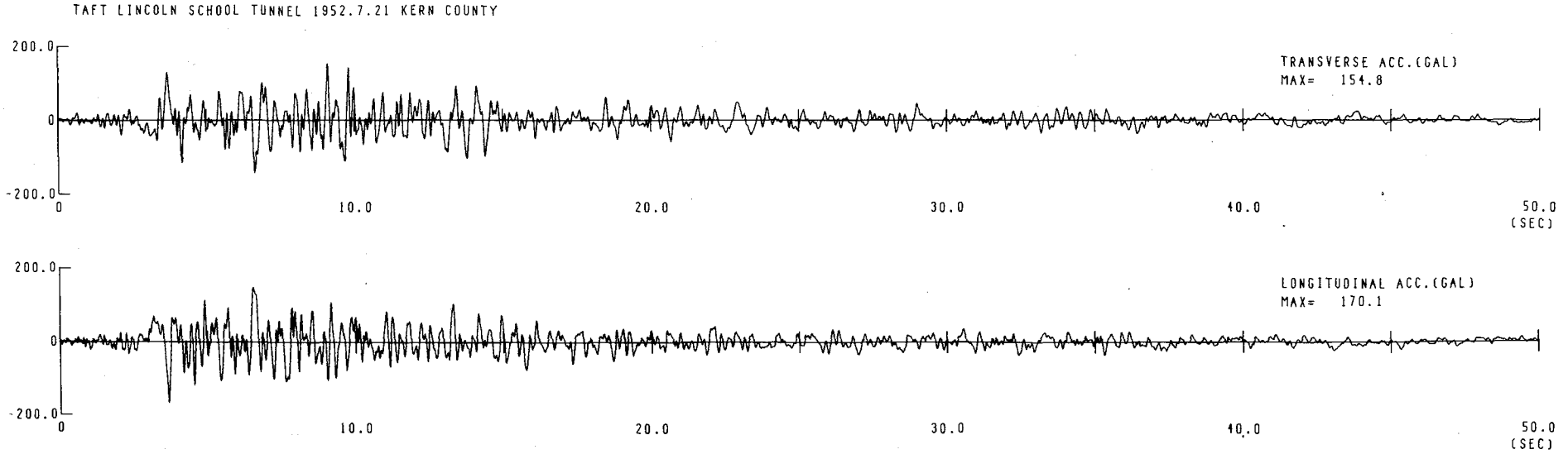

Fig. 8 Reproduced acceleration curves in longitudinal and transverse directions (Kern County Earthquake)

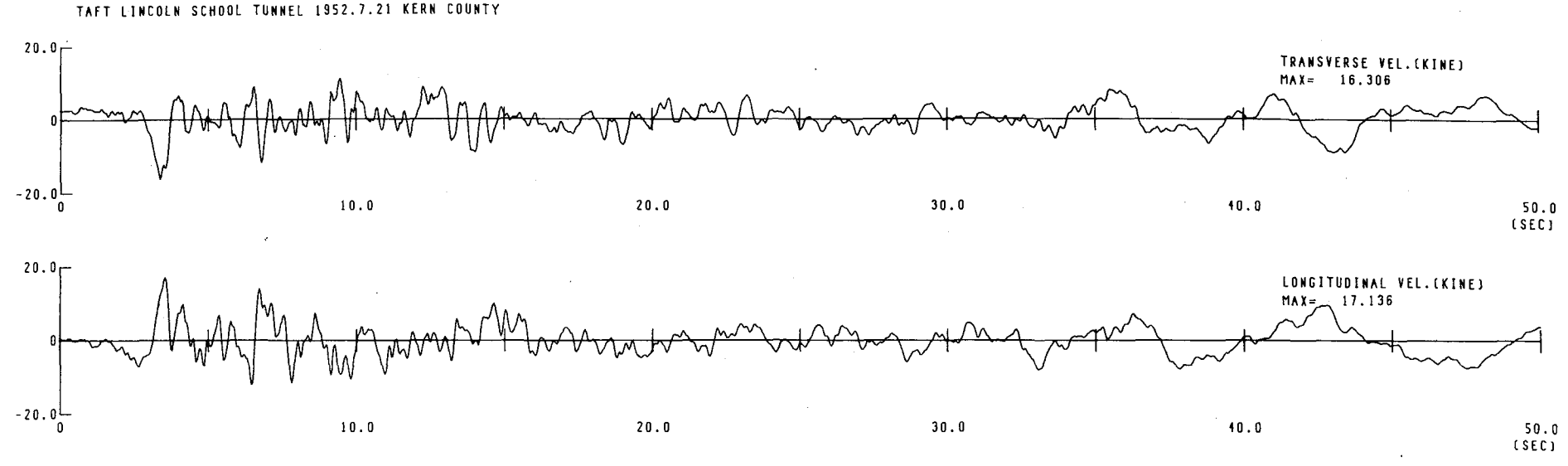

Fig. 9 Reproduced velocity curves in longitudinal and transverse directions (Kern County Earthquake)

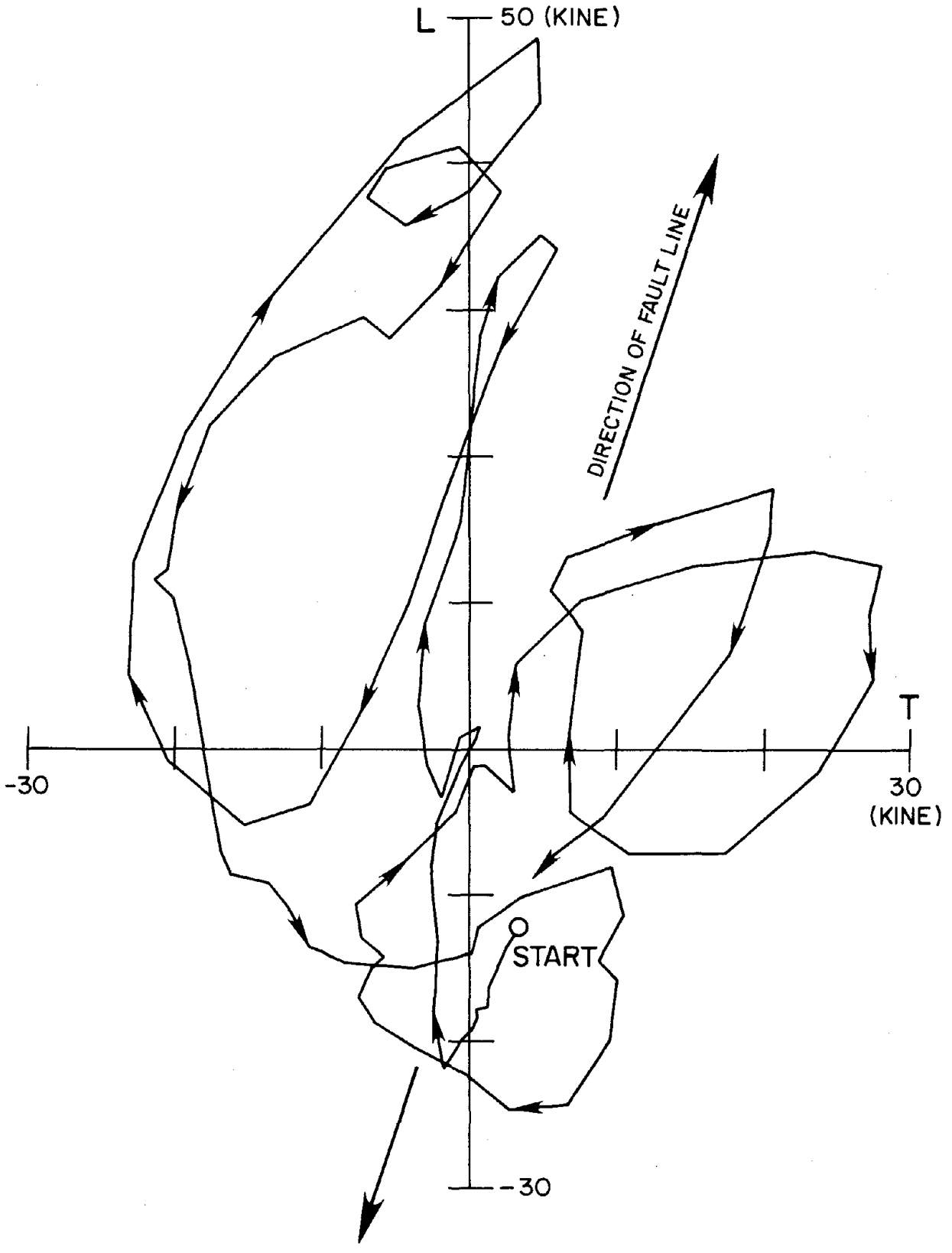

Fig. 10 Particle velocity orbit for first 6 seconds at Imperial Valley Irrigation District

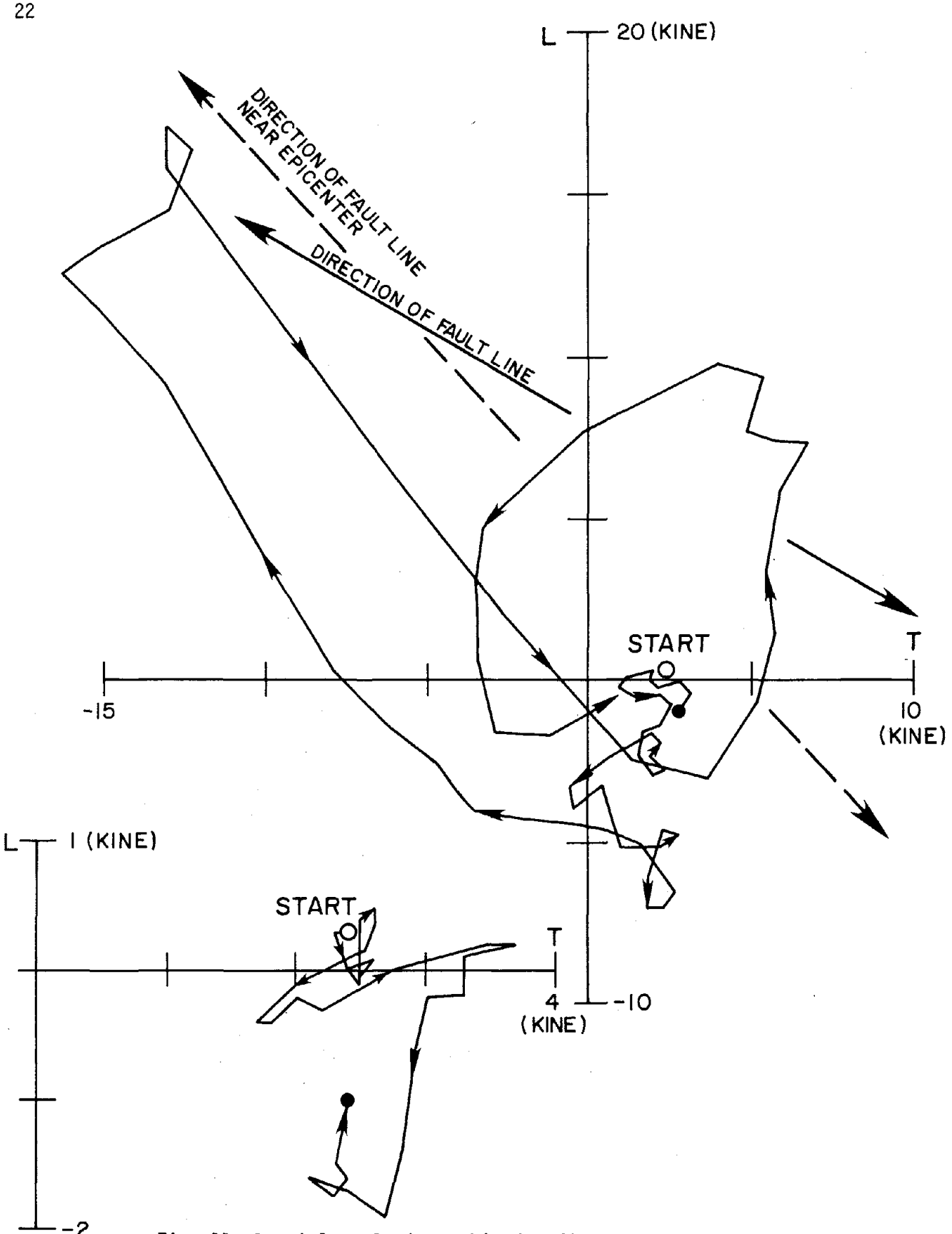

Fig. 11 Particle velocity orbit for first 4.8 seconds at Taft Lincoln School Tunnel

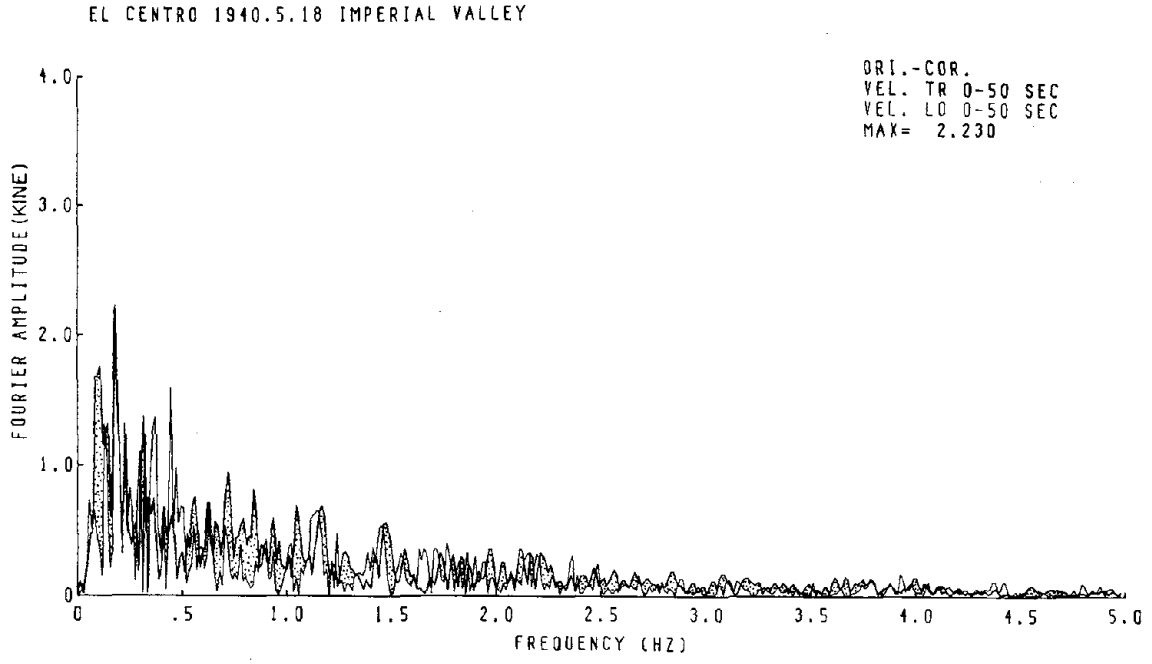

Fig. 12 Fourier amplitudes of longitudinal and transverse components relative to the direction from the epicenter - El Centro 0 - 50 sec.

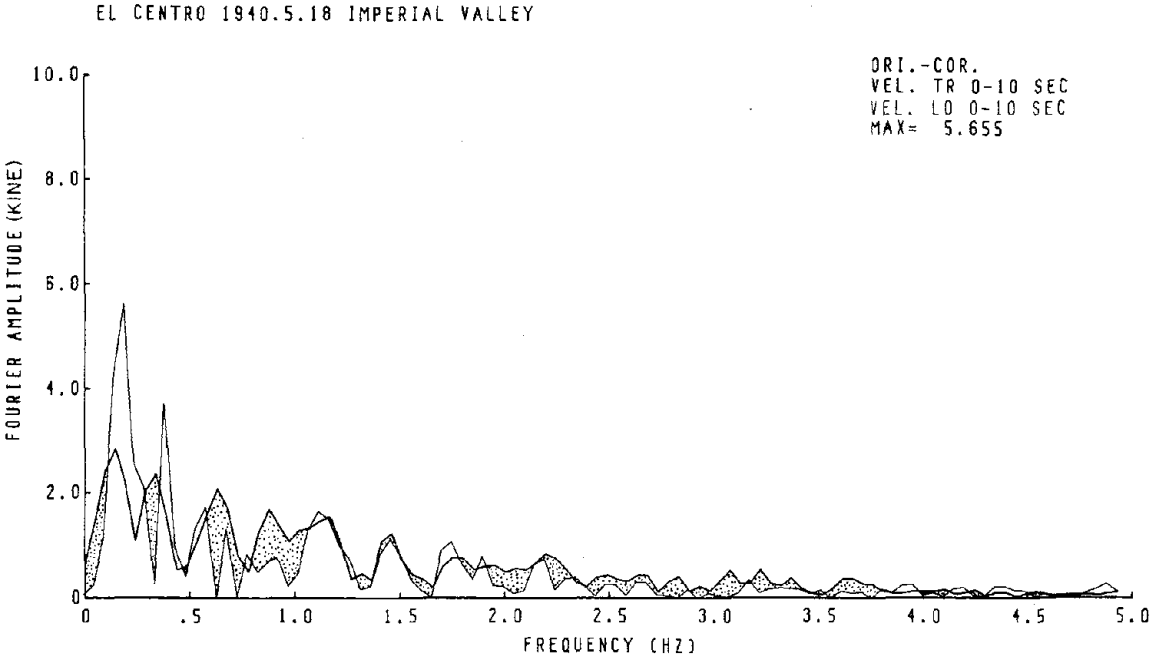

Fig. 13a Fourier amplitudes of longitudinal and transverse components relative to the direction from the epicenter - El Centro 0 - 10 sec.

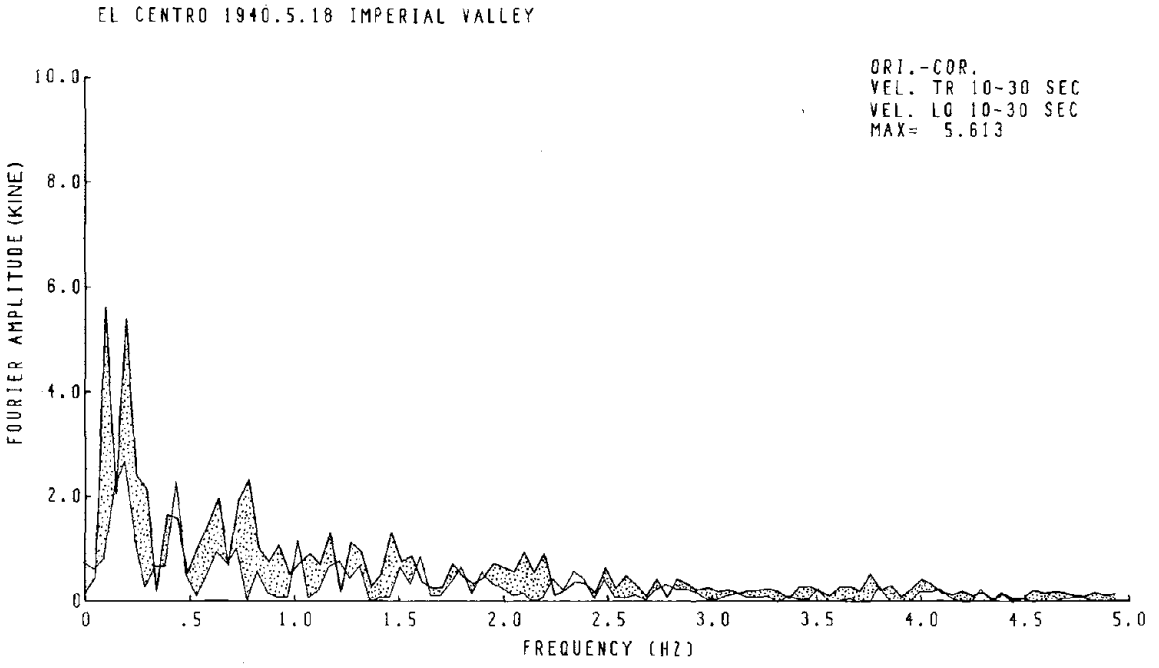

Fig. 13b Fourier amplitudes of longitudinal and transverse components relative to the direction from the epicenter - El Centro 10 - 30 sec.

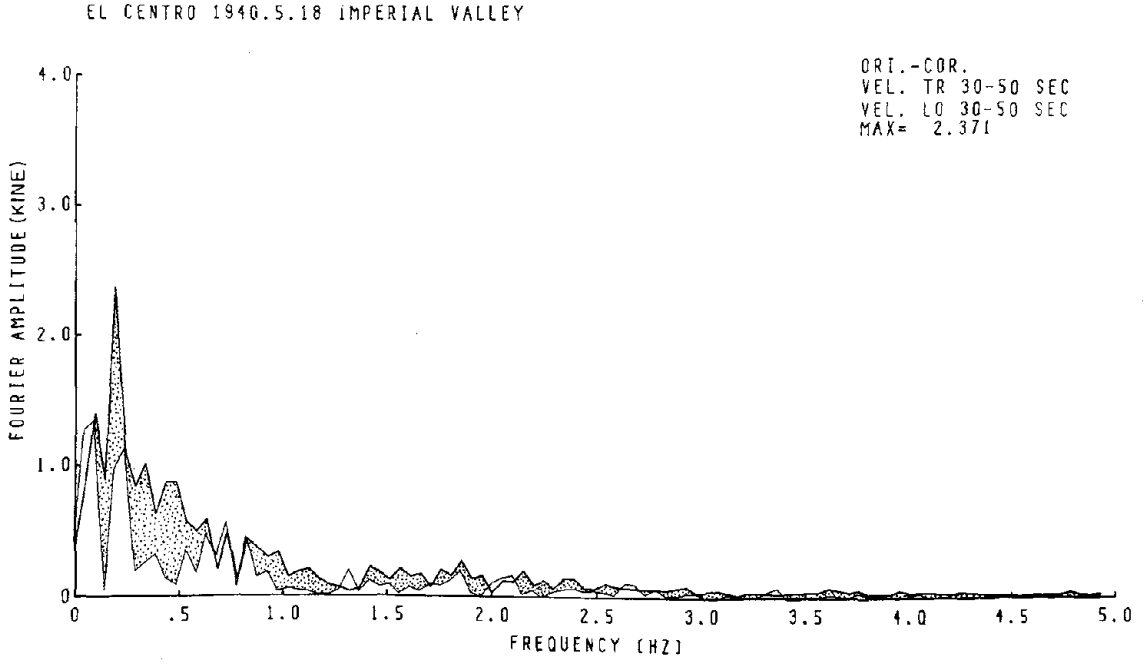

Fig. 13c Fourier amplitudes of longitudinal and transverse components relative to the direction from the epicenter - El Centro 30 - 50 sec.

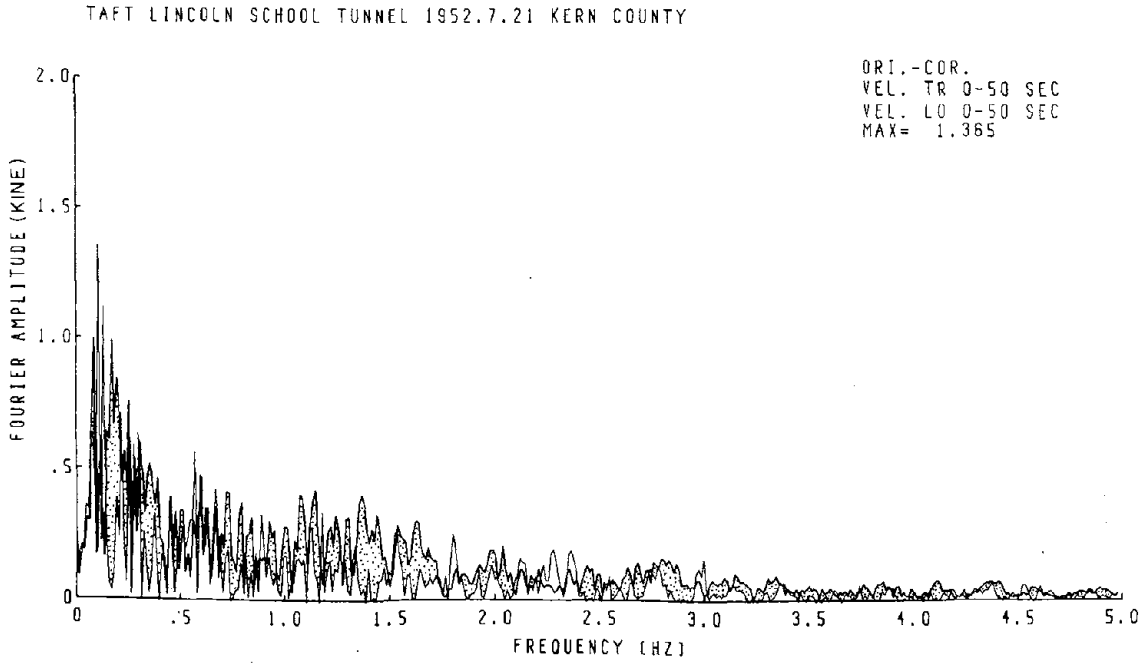

Fig. 14 Fourier amplitudes of transverse and corrected longitudinal components relative to the direction from the epicenter - Taft 0 - 50 sec.

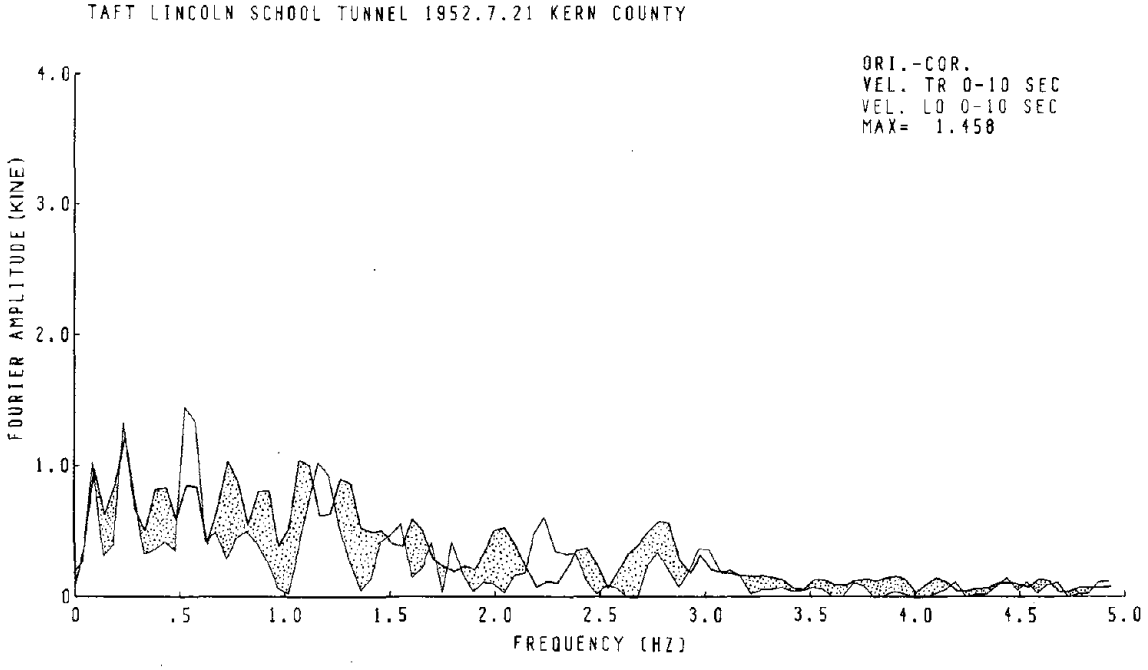

Fig. 15a Fourier amplitudes of transverse and corrected longitudinal components relative to the direction from the epicenter - Taft 0 - 10 sec.

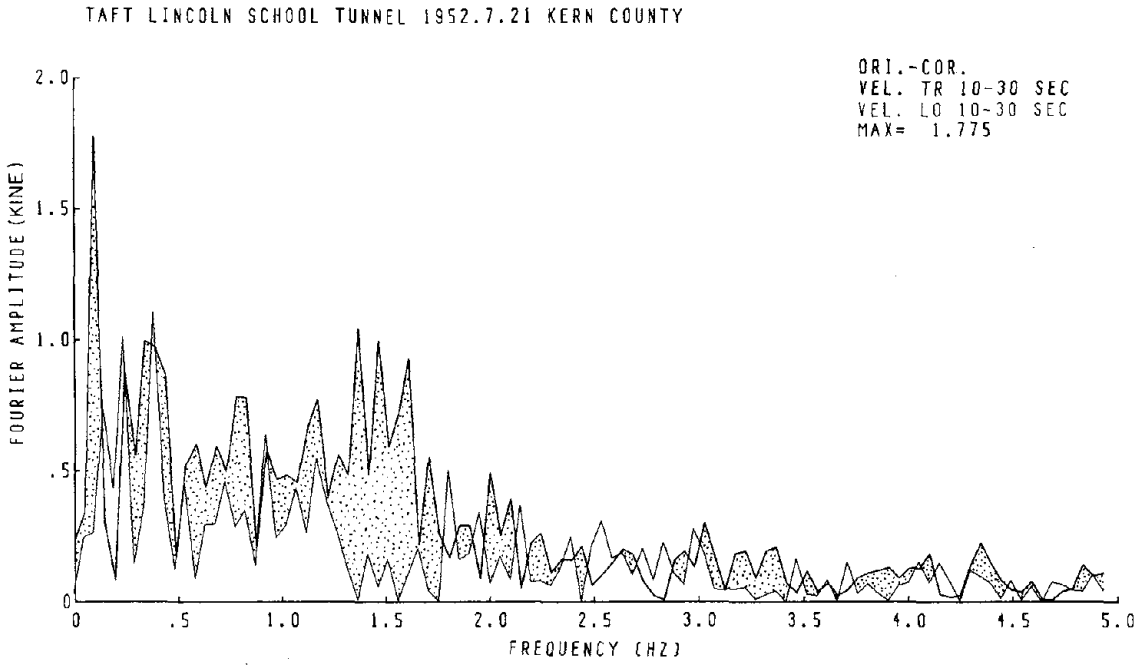

Fig. 15b Fourier amplitudes of transverse and corrected longitudinal components relative to the direction from the epicenter - Taft 10 - 30 sec.

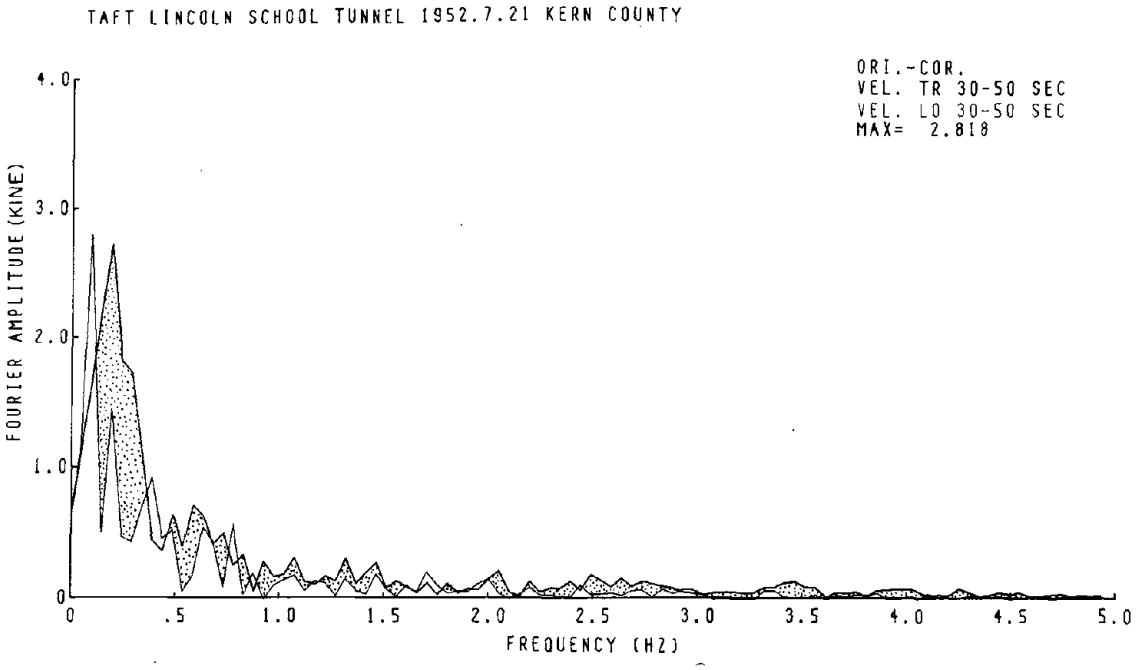

Fig. 15c Fourier amplitudes of transverse and corrected longitudinal components relative to the direction from the epicenter - Taft 30 - 50 sec.

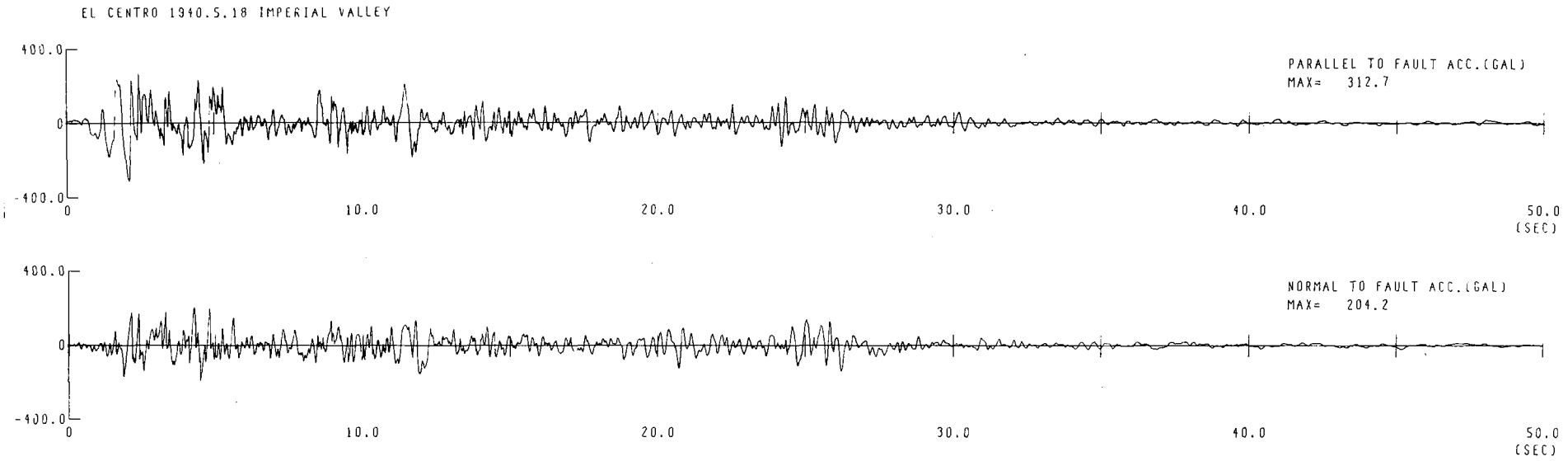

Fig. 16 Reproduced acceleration curves in normal and parallel directions (Imperial Valley Earthquake)

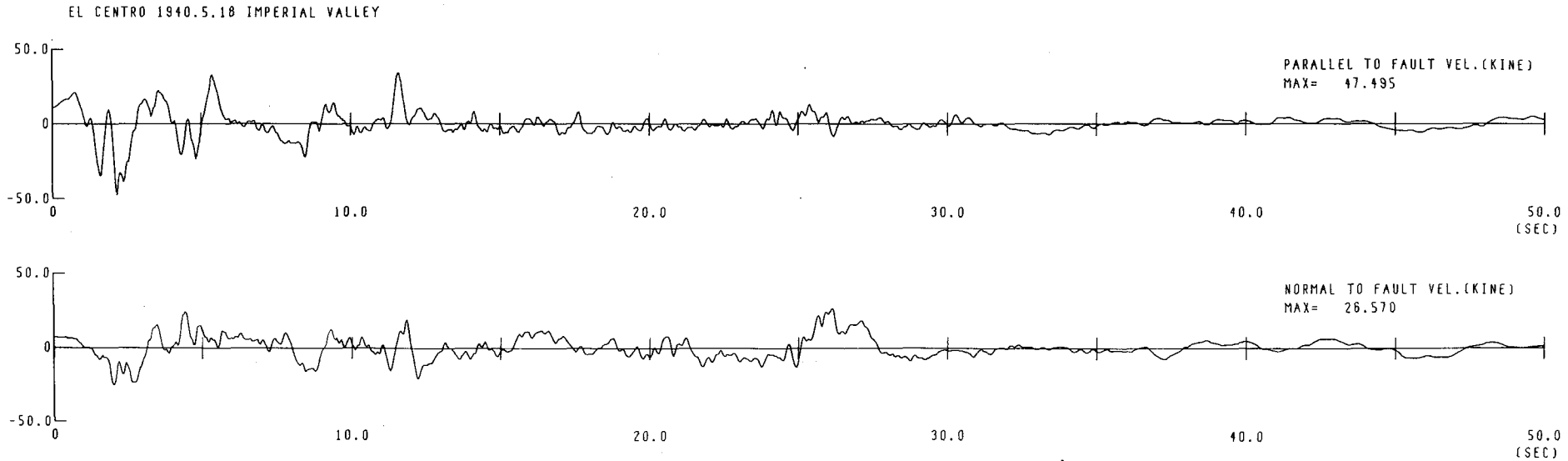

Fig. 17 Reproduced velocity curves in normal and parallel directions (Imperial Valley Earthquake)

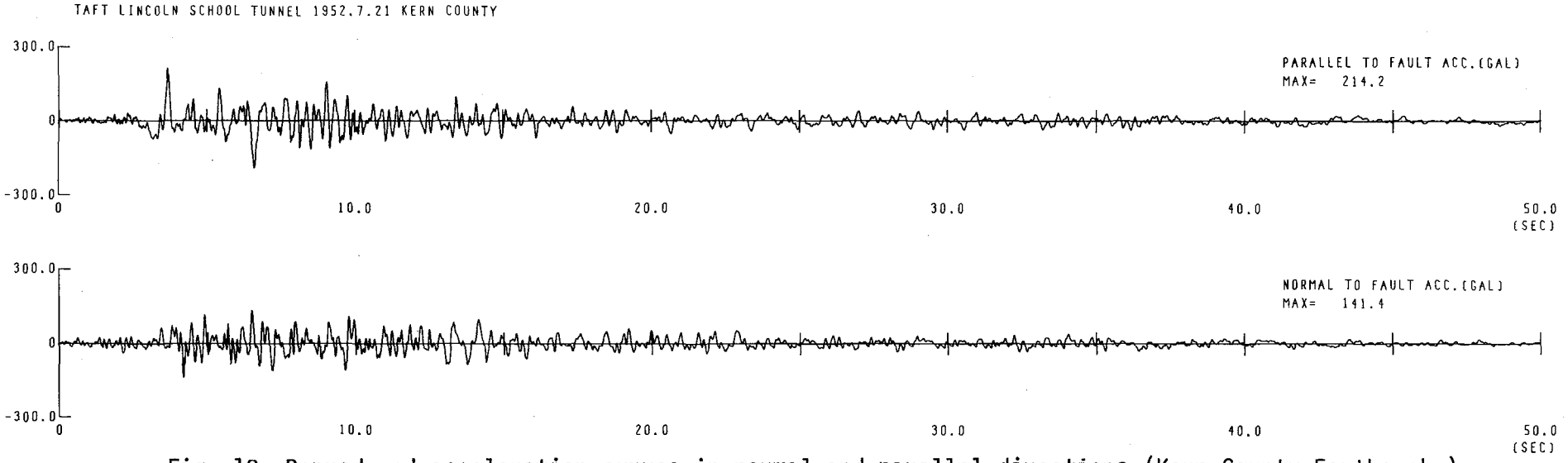

Fig. 18 Reproduced acceleration curves in normal and parallel directions (Kern County Earthquake)

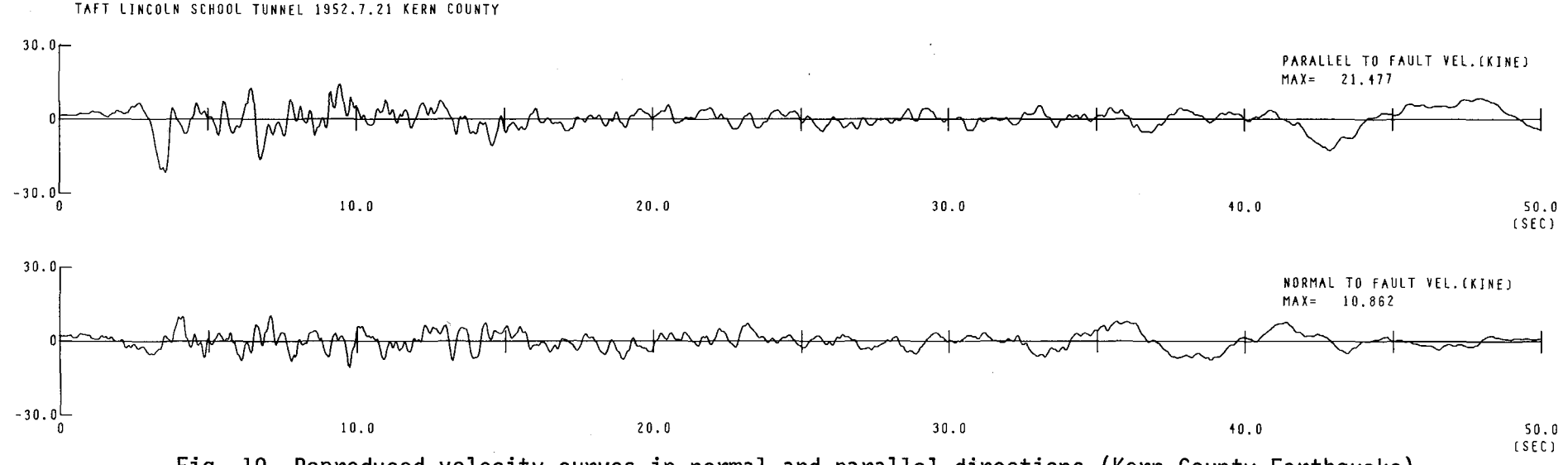

Fig. 19 Reproduced velocity curves in normal and parallel directions (Kern County Earthquake)

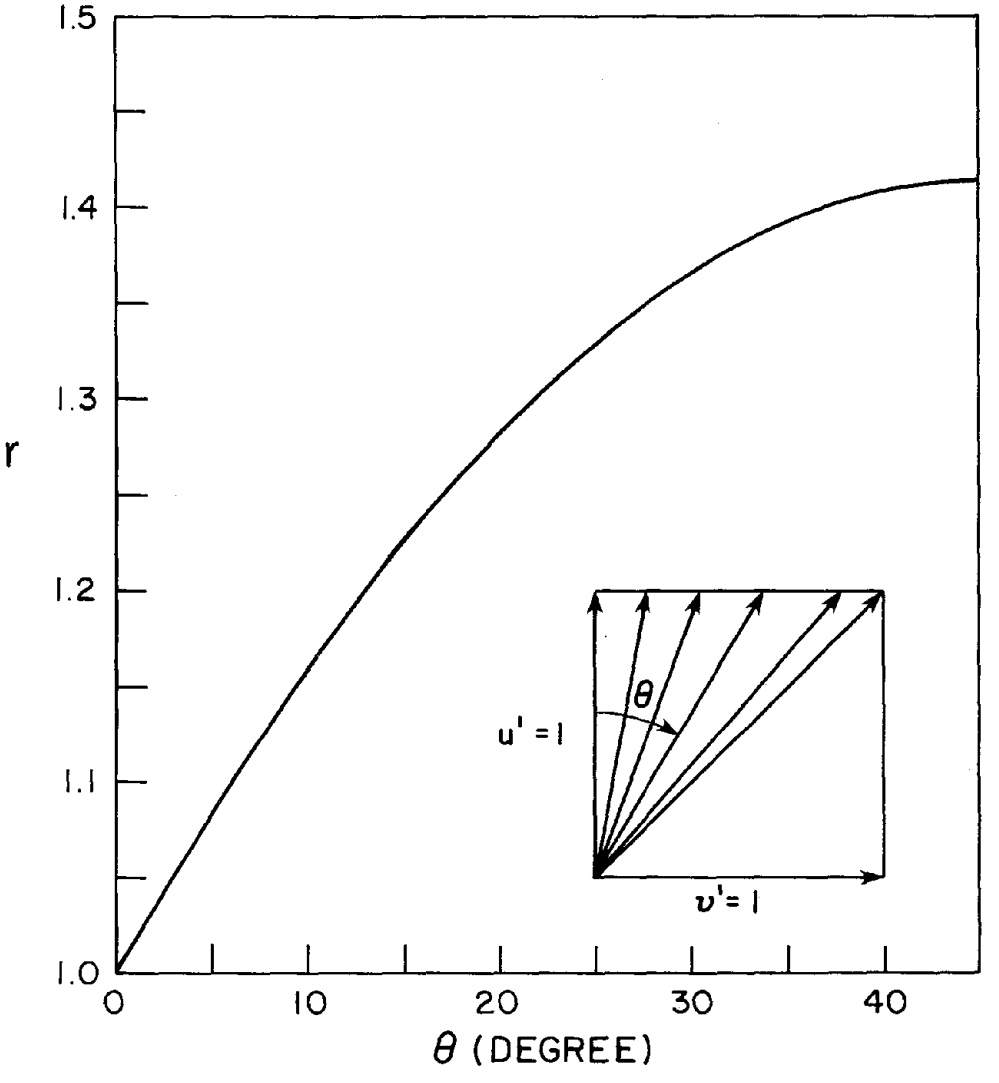

Fig. 20 Schematic explanation of coordinate transformation

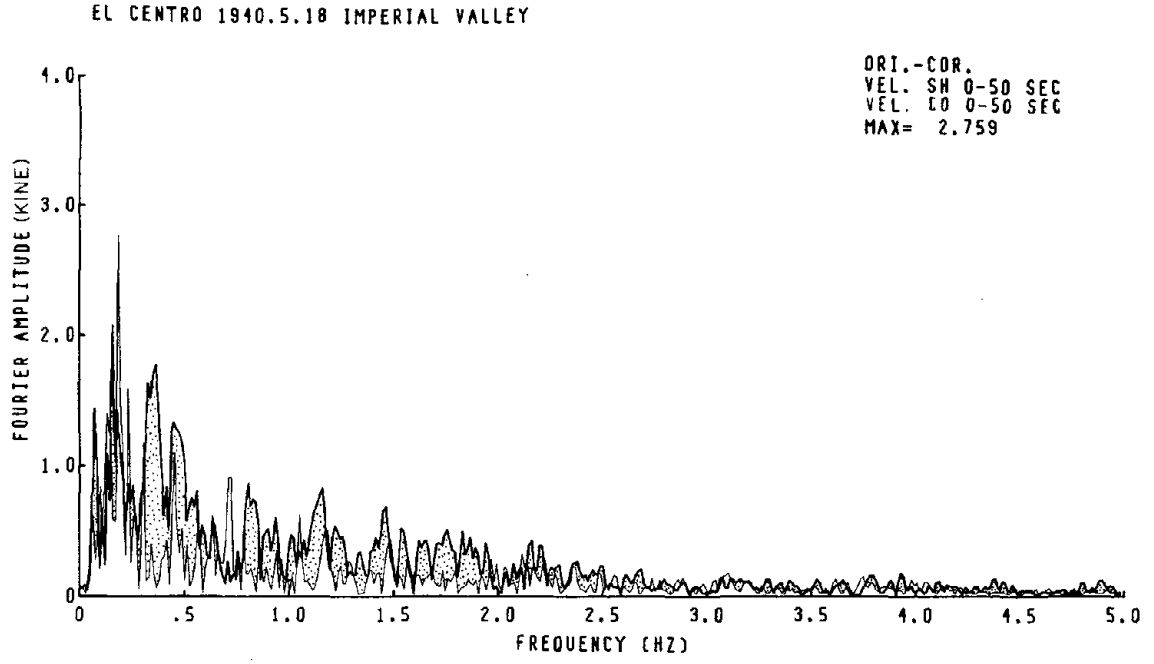

Fig. 21 Fourier amplitudes of parallel and corrected normal components in the direction of the fault line - El Centro 0 - 50 sec.

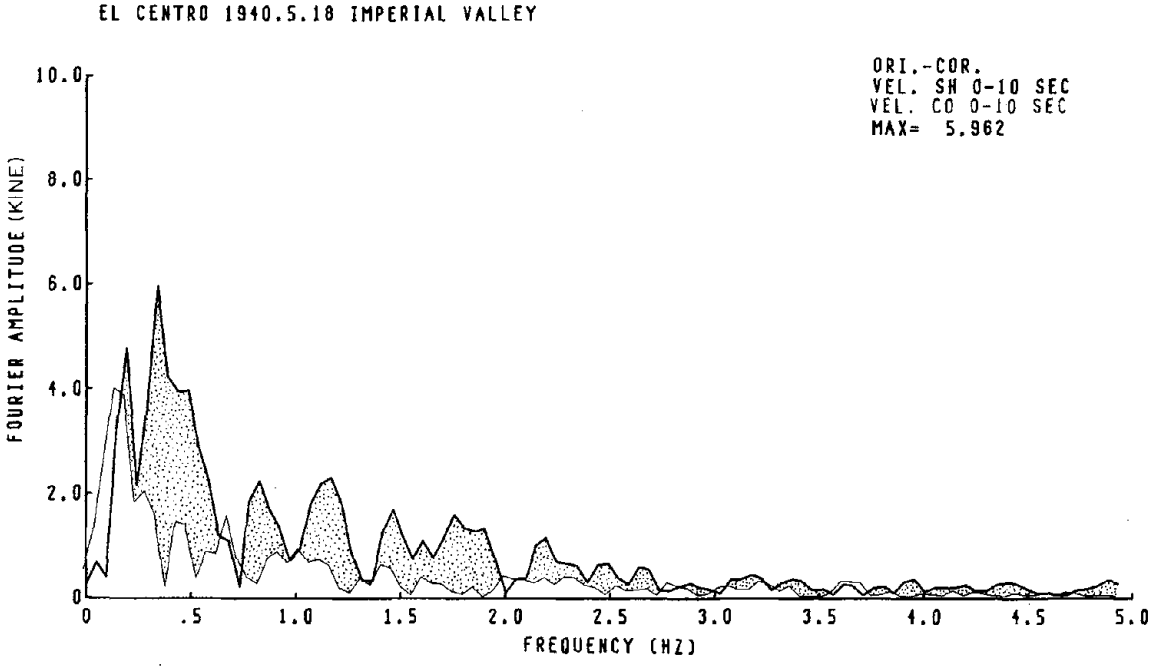

Fig. 22a Fourier amplitudes of parallel and corrected normal components in the direction of the fault line - El Centro 0 - 10 sec.

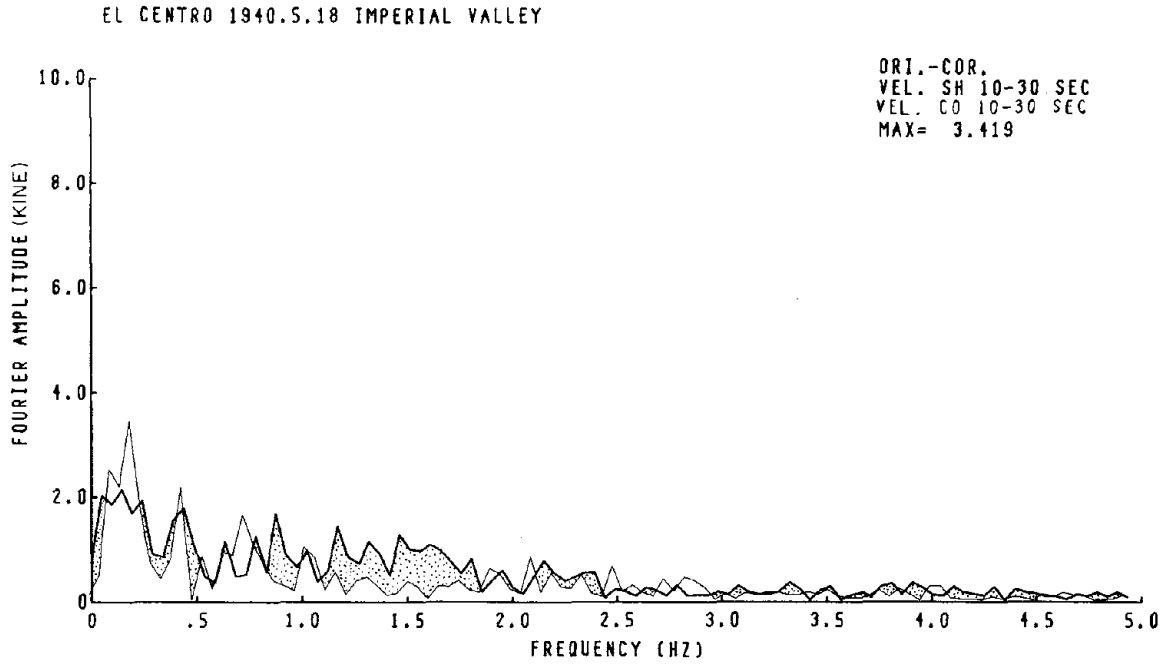

Fig. 22b Fourier amplitudes of parallel and corrected normal components in the direction of the fault line - El Centro 10 - 30 sec.

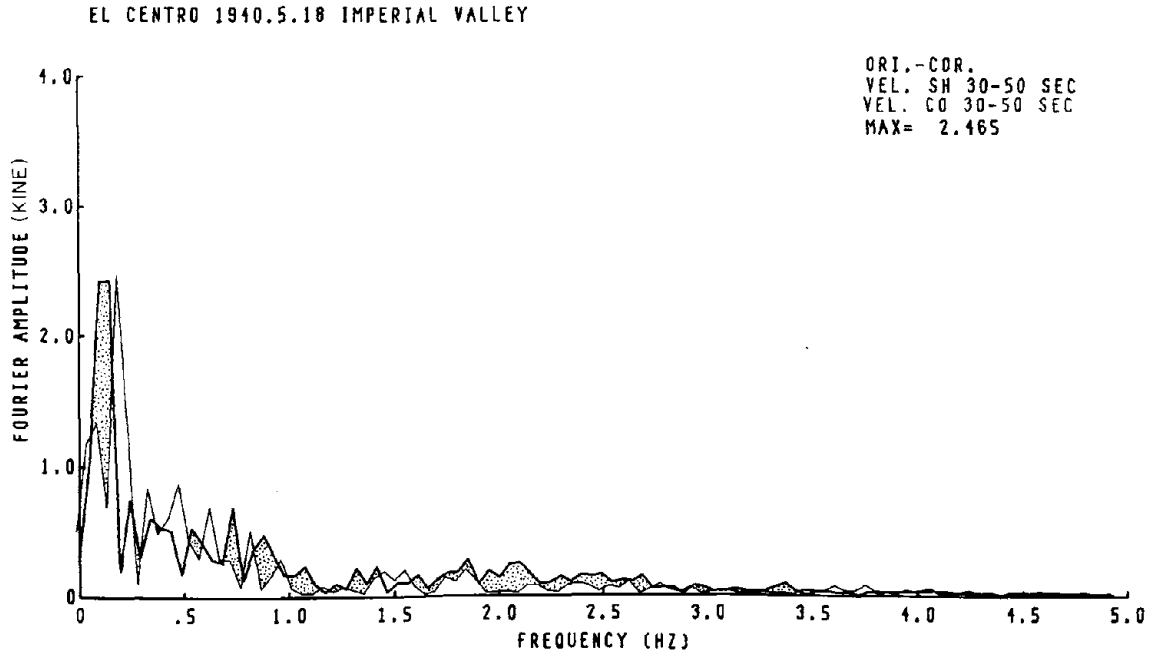

Fig. 22c Fourier amplitudes of parallel and corrected normal components in the direction of the fault line - El Centro 30 - 50 sec.

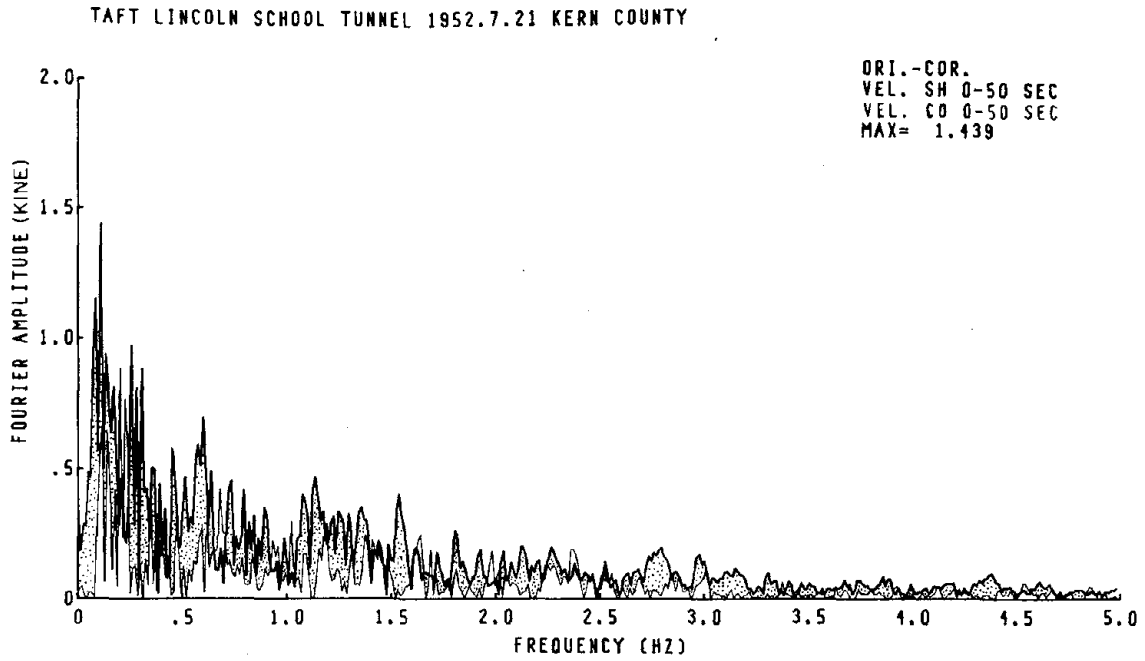

Fig. 23 Fourier amplitudes of parallel and corrected normal components in the direction of the fault line - Taft 0 - 50 sec.

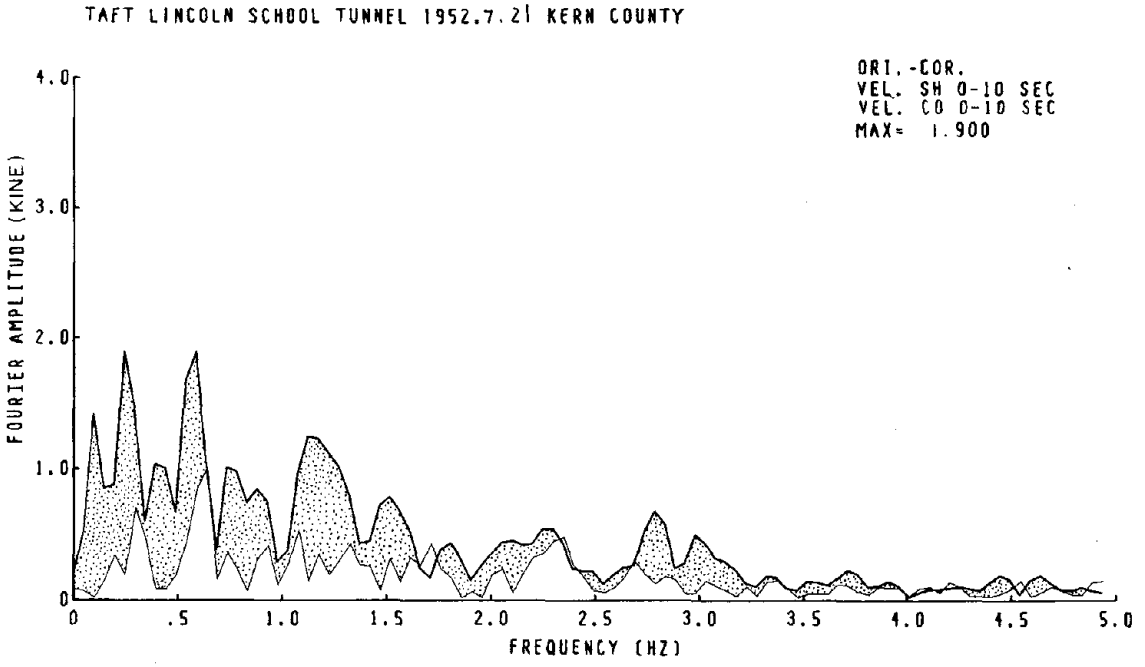

Fig. 24a Fourier amplitudes of parallel and corrected normal components in the direction of the fault line - Taft 0 - 10 sec.

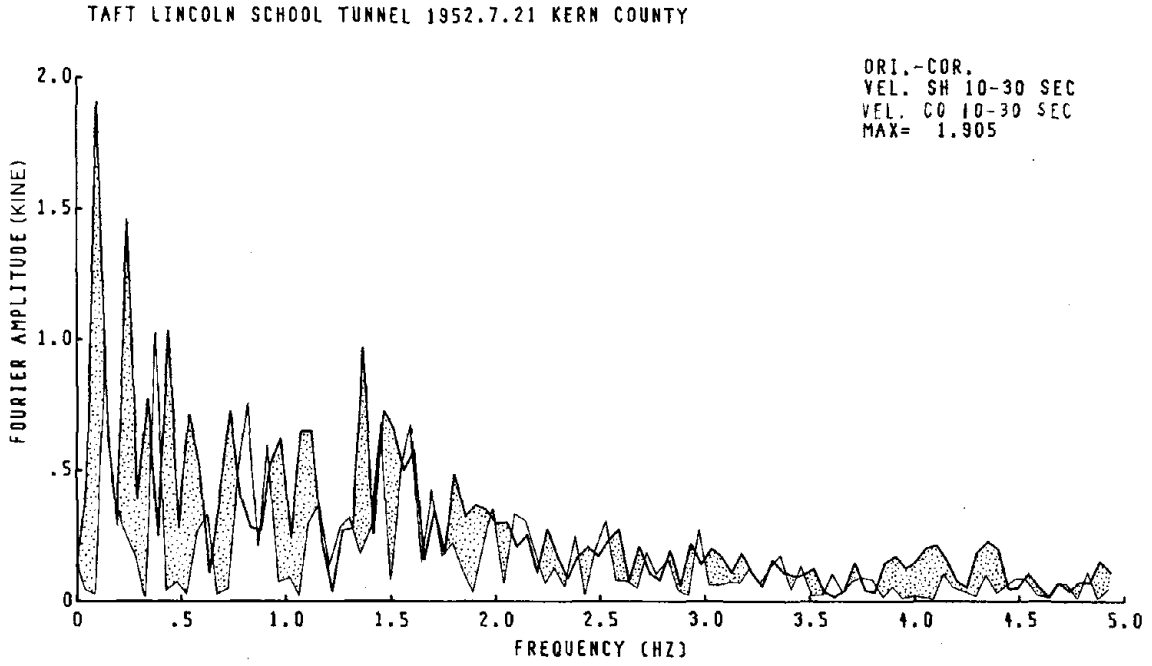

Fig. 24b Fourier amplitudes of parallel and corrected normal components in the direction of the fault line - Taft 10 - 30 sec.

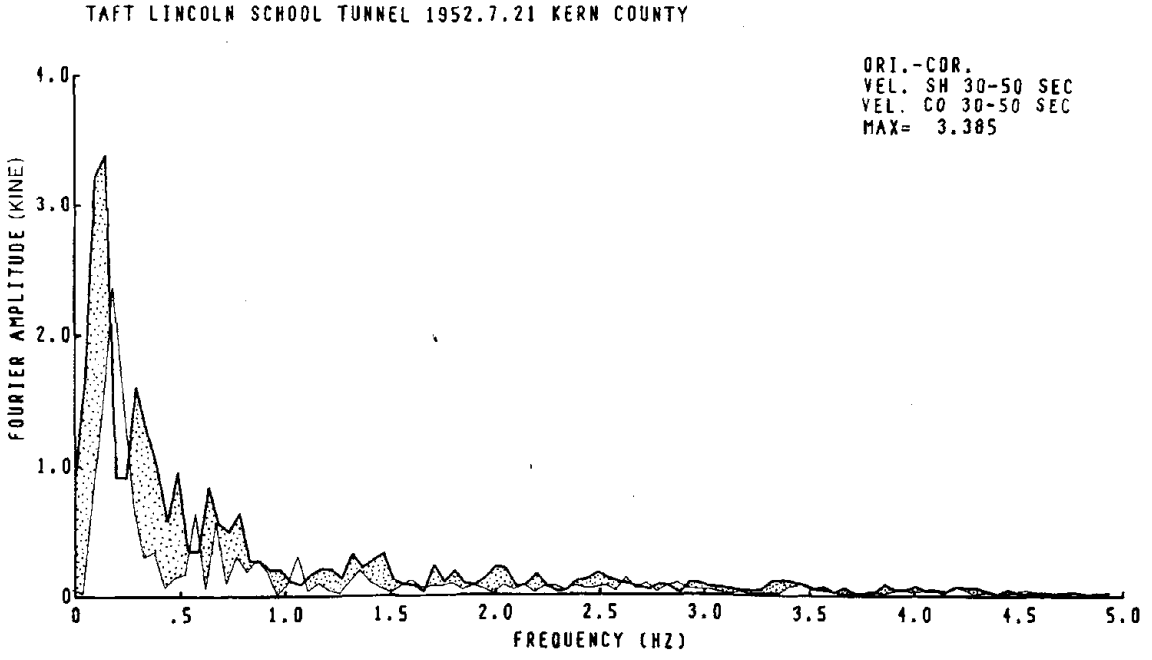

Fig. 24c Fourier amplitudes of parallel and corrected normal components in the direction of the fault line - Taft 30 - 50 sec.

Table 1 Properties of Earthquakes and Stations

	Example 1	Example 2
Name of earthquake	Imperial Valley, California	Kern County, California
Date and (local) time	May 18, 1940 20:37 PST	July 21, 1952 4:53 PDT
Epicenter location	32° 44' 00" N 115° 27' 00" W	35° 00' 00" N 119° 02' 00" W
Richter Magnitude	7.1	7.7
Approximate length of surface faulting (miles)	40 minimum	14
Number and name of station	117 El Centro, Imperial Valley Irrigation District	095 Taft, Lincoln School Tunnel
Station location	32° 47' 43" N 115° 32' 55" W	35° 09' 00" N 119° 27' 00" W
Site characteristics	Alluvium, more than 300 m	Alluvium
Structure type/size	2-story bldg.	1-story bldg.
Instrument location(s)	Ground level	Tunnel and roof
Components of instrument location	S00E S90E	N21E S69E
Modified Mercalli Intensity near station	VII to VIII	VII

Table 2 Subsurface Unit Thickness and Seismic Data at Each Station
(After Duke and Leeds, 1962)

Imperial Valley Irrigation District				
Thickness (feet)	V_p (fps)	Density (pcf)	$\frac{V_s}{V_p}$	V_s (fps)
100	522	128	1.0	522
1000	2810	139	1.0	2810
3000	3620	139	1.0	3620
3500	4050	147	1.0	4050
3500	7200	147	1.0	7200
	10000	172	1.0	10000

Taft Lincoln School				
Thickness (feet)	V_p (fps)	Density (pcf)	$\frac{V_s}{V_p}$	V_s (fps)
40	1190	140	0.45	535
160	5000	144	0.48	2399
500	6500	144	0.48	3119
3300	8000	148	0.48	3839
	15500	170	0.61	9454

Table 3 Maximum Value and Occurrence Time, Longitudinal and Transverse Components

Direction		Acceleration			Velocity		
			Max. Val (gal)	Occ. Time (sec)		Max. Val (kine)	Occ. Time (sec)
El Centro, Imperial Valley Irrigation District, May 18, 1940, Imperial Valley							
Longitudinal	S54E	$\ddot{u}$	259.1	2.08	$\dot{u}$	48.5	2.16
Transverse	S36W	$\ddot{v}$	241.5	2.12	$\dot{v}$	27.8	4.36
N-S	S00E	$\ddot{u}'$	341.7	2.12	$\dot{u}'$	33.4	2.18
E-W	S90W	$\ddot{v}'$	210.1	11.44	$\dot{v}'$	-36.9	2.14
Taft Lincoln School Tunnel, July 21, 1952, Kern County							
Longitudinal	N66.4W	$\ddot{u}$	-170.1	3.70	$\dot{u}$	17.1	3.56
Transverse	N23.6E	$\ddot{v}$	154.8	9.10	$\dot{v}$	-16.3	3.40
N-S	N21E	$\ddot{u}'$	152.7	9.10	$\dot{u}'$	-15.7	3.40
E-W	S69E	$\ddot{v}'$	175.9	3.70	$\dot{v}'$	-17.7	3.56

Table 4 Conditions of Computation and Corresponding Figure Number

Time (sec)	0 - 50	0 - 10	10 - 30	30 - 50
Number of data (n)	1251	251	501	501
Number used in FFT* (N)	2048	512	512	512
Frequency interval (Hz)	0.012	0.049	0.049	0.049
Nyquist frequency (Hz)	12.5	12.5	12.5	12.5
El Centro site	Fig. 12	Fig. 13a	Fig. 13b	Fig. 13c
Taft site	Fig. 14	Fig. 15a	Fig. 15b	Fig. 15c

*Remaining parts of data (N-n) are set to be equal to zero

Table 5 Peak Fourier Amplitude and
Frequency of Transverse Component at El Centro Site

0 - 50 sec.	0 - 10 sec.	10 - 30 sec.	30 - 50 sec.
0.11 (1.76)	----	0.10 (5.61)	0.10 (1.40)
0.18 (2.23)	0.15 (2.83)	1.20 (5.40)	0.20 (2.37)
0.32 (1.37)	0.34 (2.35)	----	0.34 (1.01)
0.72 (0.95)	----	----	0.73 (0.48)
0.84 (0.82)	0.88 (1.68)	----	0.83 (0.44)
1.17 (0.69)	1.17 (1.55)	1.17 (1.31)	----

Note: Numerals without parentheses are frequency (Hz) and those in parentheses are peak values of transverse components (kine)

Table 6 Peak Fourier Amplitude and
Frequency of Transverse Component at Taft Site

0 - 50 sec.	0 - 10 sec.	10 - 30 sec.	30 - 50 sec.
0.09 (1.00)	0.10 (0.97)	0.10 (1.78)	----
0.17 (0.99)	----	----	0.20 (2.72)
0.26 (0.76)	0.24 (1.22)	0.24 (0.88)	----
0.35 (0.52)	----	0.34 (1.00)	----
0.45 (0.39)	0.44 (0.83)	----	----
0.60 (0.47)	----	0.59 (0.60)	0.59 (0.71)
0.72 (0.41)	0.73 (1.03)	0.78 (0.78)	----
1.17 (0.42)	1.07 (1.04)	1.17 (0.77)	----
1.37 (0.40)	----	1.37 (1.04)	----

Note: Numerals without parentheses are frequency (Hz) and those in parentheses are peak values of transverse components (kine)

Table 7 Maximum Value and Occurrence Time, Normal and Parallel Components

Direction		Acceleration			Velocity		
			Max. Val (gal)	Occ. Time (sec)		Max. Val (kine)	Occ. Time (sec)
El Centro, Imperial Valley Irrigation District, May 18, 1940, Imperial Valley							
Normal to fault	S54.5W	$\ddot{u}$	204.2	4.30	$\dot{u}$	26.6	26.16
Parallel to fault	S35.5E	$\ddot{v}$	-312.7	2.12	$\dot{v}$	-47.5	2.16
N-S	S00E	$\ddot{u}'$	341.7	2.12	$\dot{u}'$	33.4	2.18
E-W	S90W	$\ddot{v}'$	210.1	11.44	$\dot{v}'$	-36.9	2.14
Taft Lincoln School Tunnel, July 21, 1952, Kern County							
Normal to fault	N19.4W	$\ddot{u}$	-141.4	4.20	$\dot{u}$	-10.9	9.76
Parallel to fault	N70.6E	$\ddot{v}$	214.2	3.70	$\dot{v}$	-21.5	3.56
N-S	N21E	$\ddot{u}'$	152.7	9.10	$\dot{u}'$	-15.7	3.40
E-W	S69E	$\ddot{v}'$	175.9	3.70	$\dot{v}'$	-17.7	3.56

Table 8 Peak Fourier Amplitude and Frequency of Parallel Component at El Centro Site

0 - 50 sec	0 - 10 sec.	10 - 30 sec.	30 - 50 sec.
0.07 (1.43)	----	----	0.10 (2.43)
0.18 (1.42)	0.20 (4.78)	0.24 (1.94)	0.24 (0.74)
0.37 (1.78)	0.34 (5.96)	----	0.34 (0.61)
0.45 (1.33)	0.49 (3.97)	0.44 (1.79)	----
0.81 (0.87)	0.83 (2.24)	0.88 (1.68)	0.88 (0.48)
1.16 (0.83)	1.17 (2.30)	1.17 (1.44)	----
1.47 (0.69)	1.47 (1.70)	1.47 (1.28)	----
1.54 (0.52)	1.61 (1.09)	1.61 (1.10)	----
1.76 (0.52)	1.76 (1.60)	----	----
1.83 (0.50)	1.90 (1.33)	1.81 (0.83)	----

Note: Numerals without parentheses are frequency (Hz) and those in parentheses are peak values of parallel components (kine)

Table 9 Peak Fourier Amplitude and Frequency of Parallel Component at Taft Site

0 - 50 sec.	0 - 10 sec.	10 - 30 sec.	30 - 50 sec.
0.11 (1.44)	0.10 (1.42)	0.10 (1.91)	0.15 (3.39)
0.26 (0.97)	0.24 (1.90)	0.24 (1.46)	----
0.31 (0.88)	----	----	0.29 (1.60)
0.45 (0.58)	0.39 (1.40)	0.44 (1.03)	0.49 (0.95)
0.60 (0.70)	0.59 (1.90)	----	0.64 (0.84)
0.73 (0.45)	0.73 (1.01)	0.73 (0.73)	0.78 (0.64)
1.14 (0.47)	1.12 (1.25)	1.07 (0.65)	----
1.54 (0.40)	1.51 (0.78)	----	----

Note: Numerals without parentheses are frequency (Hz) and those in parentheses are peak values of parallel components (kine)

Table 10 Simplified Seismic Data at El Centro Site

Case	Depth (ft)	$\bar{V}_s$ (fps)	$\bar{f}$ (Hz)
1	100	522	1.31
2	1100	2602	0.59
3	4100	3347	0.20
4	7600	3671	0.12
5	11100	4784	0.11

Table 11 Simplified Seismic Data at Taft Site

Case	Depth (ft)	$\bar{V}_s$ (fps)	$\bar{f}$ (Hz)
1	40	535	3.34
2	200	2026	2.53
3	700	2807	1.00
4	4000	3658	0.23

Table 12 Estimated Lower and Upper Limit of Shear Strain at El Centro Site

Fourier Amplitude		Shear Strain $\times 10^{-3}$ (%)			
f (Hz)	Amp (kine)	$\bar{f}$ (Hz)	Lower Limit	$\bar{f}$ (Hz)	Upper Limit
0.07	1.43	--	--	0.11	0.98
0.18	1.42	0.12	1.27	0.20	1.40
0.37	1.78	0.20	1.75	0.59	2.25
0.45	1.33	0.20	1.31	0.59	1.68
0.81	0.87	0.59	1.10	1.31	5.48
1.16	0.83	0.59	1.05	1.31	5.23
1.47	0.69	1.31	4.35	--	--
1.54	0.52	1.31	3.28	--	--
1.76	0.52	1.31	3.28	--	--
1.83	0.50	1.31	3.15	--	--

Table 13 Estimated Lower and Upper Limit of Shear Strain at Taft Site

Fourier Amplitude		Shear Strain $\times 10^{-4}$ (%)			
f (Hz)	Amp (kine)	$\bar{f}$ (Hz)	Lower Limit	$\bar{f}$ (Hz)	Upper Limit
0.11	1.44	--	--	0.23	12.95
0.26	0.97	0.23	8.72	1.00	11.37
0.31	0.88	0.23	7.91	1.00	10.31
0.45	0.58	0.23	5.22	1.00	6.80
0.60	0.70	0.23	6.29	1.00	8.20
0.73	0.45	0.23	4.05	1.00	5.27
1.14	0.47	1.00	5.51	2.53	7.63
1.54	0.40	1.00	4.69	2.53	6.49

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APPENDIX

Computer Program Listings

```
      PROGRAM CORIN(INPUT,OUTPUT,TAPE1,TAPE5=INPUT,TAPE6=OUTPUT,PUNCH)
      COMMON /DATAN/X(2501,2),XD(2500,2),XMAX(2,2)
      COMMON /N11/NAME(8)
C     CORRECTION OF ORIGINAL TWO HORIZONTAL DIRECTION DATA INTO
C     LONGITUDINAL AND TRANSEVERSE COMPONENTS TOWARD THE EPICENTER
C     INPUT DATA
C       NAME = NAME OF EARTHQUAKE
C       TT   = DURATION (SEC) AND TT.LE.50.0
C       TETA = ANGLE OF N TO L OR E TO T
C                +=CLOCKWISE, -=COUNTERCLOCKWISE
C       IND1 = NE.0 IF PRINT OUT DATA ARE NECESSARY
C       IND2 = NE.0 IF PUNCH OUT DATA ARE NECESSARY
C       IND3 = NE.0 IF PLOT  OUT DATA ARE NECESSARY
C     CAUTION - ORIGINAL DATA SHOULD BE AS A RIGHTHAND SYSTEM,I.E.,
C               IF N SIDE IS POSITIVE, E SIDE SHOULD BE POSITIVE.
C               IF S SIDE IS POSITIVE, W SIDE SHOULD BE POSITIVE.
      READ(5,40) NAME
      READ(5,100) TT
      READ(5,100) TETA
      READ(5,101) IND1,IND2,IND3
      NA=IFIX(TT/0.02)+1
      NV=NA/2+1
      CALL SETFXB(5LTAPE1,2500,100)
      CALL INPUT(NA)
      TETA =TETA *0.0174533
      XMAX1=0.0
      XMAX2=0.0
      X1=COS(TETA)
      X2=SIN(TETA)
      DO 901 K=1,NA
      XX=X(K,1)
      XY=X(K,2)
      XK1=XX*X1+XY*X2
      XK2=XY*X1-XX*X2
      XMAX1=AMAX1(XMAX1,ABS(XK1))
      XMAX2=AMAX1(XMAX2,ABS(XK2))
      X(K,1)=XK1
  901 X(K,2)=XK2
      XMAX(1,1)=XMAX1
      XMAX(1,2)=XMAX2
      XMAX1=0.0
      XMAX2=0.0
      DO 902 K=1,NV
      XXD=XD(K,1)
      XYD=XD(K,2)
      XK1=XXD*X1+XYD*X2
      XK2=XYD*X1-XXD*X2
      XMAX1=AMAX1(XMAX1,ABS(XK1))
      XMAX2=AMAX1(XMAX2,ABS(XK2))
      XD(K,1)=XK1
  902 XD(K,2)=XK2
      XMAX(2,1)=XMAX1
      XMAX(2,2)=XMAX2
      IF(IND1.EQ.0) GO TO 10
      CALL PRINP(TETA,NA,NV)
   10 IF(IND2.EQ.0) GO TO 20
      CALL PUINP(NA,NV)
   20 IF(IND3.EQ.0) GO TO 30
   30 CONTINUE
      STOP
   40 FORMAT(8A10)
  100 FORMAT(2F10.0)
  101 FORMAT(3I1)
      END
```

```
      SUBROUTINE INPUT(NA)
      DIMENSION CORTIL(250),ICOR(100),FCOR(100),IX(5000,2),
     1          XDD(1250,2)
      COMMON /DATAN/X(2501,2),XD(2500,2),XMAX(2,2)
      DO 900 II=1,2
  110 READ(1,50) CORTIL
      IF(EOF,1) 110,9
    9 READ(1,60) ICOR
      NDATA=ICOR(53)
      NDATV=ICOR(64)
      NDATD=ICOR(66)
      READ(1,70) FCOR
      READ(1,80) (IX(K,II),K=1,NDATA)
      READ(1,80) (XD(K,II),K=1,NDATV)
      READ(1,80) (XDD(K,II),K=1,NDATD)
      DO 800 K=1,NA
      X(K,II)=FLOAT(IX(K,II))*0.1
  800 CONTINUE
  900 CONTINUE
      RETURN
   50 FORMAT(10A10)
   60 FORMAT(10I10)
   70 FORMAT(10F10.5)
   80 FORMAT(10F10.3)
      END
```

```
      SUBROUTINE PRINP(TETA,NA,NV)
      COMMON /DATAN/X(2501,2),XD(2500,2),XMAX(2,2)
      COMMON /N11/NAME(8)
      DO 909 II=1,2
      WRITE(6,51) NAME
      GO TO(1,2),II
    1 WRITE(6,52)
      GO TO 3
    2 WRITE(6,53)
    3 WRITE(6,54) XMAX(1,II),TETA,NA
      WRITE(6,55) (X(K,II),K=1,NA)
      WRITE(6,51) NAME
      GO TO(4,5),II
    4 WRITE(6,52)
      GO TO 6
    5 WRITE(6,53)
    6 WRITE(6,56) XMAX(2,II),TETA,NV
      WRITE(6,57) (XD(K,II),K=1,NV)
  909 CONTINUE
      RETURN
   51 FORMAT(1H1,2X,8A10)
   52 FORMAT(1H ,2X,22HLONGITUDINAL COMPONENT)
   53 FORMAT(1H ,2X,20HTRANSVERSE COMPONENT)
   54 FORMAT(1H0,80X,9HACC. MAX=,F10.4/1H ,80X,5HTETA=,F14.4/
     1 1H ,80X,3HNA=,I16/1H ,80X,14HDT= 0.02 (SEC)/
     2 1H ,80X,14HFMT= (10F10.1)/)
   55 FORMAT(1H ,10F10.1)
   56 FORMAT(1H0,80X,9HVEL. MAX=,F10.4/1H ,80X,5HTETA=,F14.4/
     1 1H ,80X,3HNV=,I16/1H ,80X,14HDT= 0.04 (SEC)/
     2 1H ,80X,14HFMT= (10F10.3)/)
   57 FORMAT(1H ,10F10.3)
      END
```

```
      SUBROUTINE PUINP(NA,NV)
      COMMON /DATAN/X(2501,2),XD(2500,2),XMAX(2,2)
      COMMON /N11/NAME(8)
      DO 910 II=1,2
      PUNCH 71,NAME
      GO TO(1,2),II
    1 PUNCH 72
      GO TO 3
    2 PUNCH 73
    3 PUNCH 74,XMAX(1,II)
      PUNCH 77,NA
      PUNCH 75,(X(K,II),K=1,NA)
      PUNCH 71,NAME
      GO TO(4,5),II
    4 PUNCH 72
      GO TO 6
    5 PUNCH 73
    6 PUNCH 74,XMAX(2,II)
      PUNCH 78,NV
      PUNCH 75,(XD(K,II),K=1,NV)
  910 CONTINUE
      RETURN
   71 FORMAT(8A10)
   72 FORMAT(18HLONGITUDINAL COMP.)
   73 FORMAT(16HTRANSVERSE COMP.)
   74 FORMAT(F10.4)
   75 FORMAT(10F7.1)
   76 FORMAT(10F7.3)
   77 FORMAT(I5/4H0.02/8H(10F7.1))
   78 FORMAT(I5/4H0.04/8H(10F7.3))
      END
```

```
EL CENTRO 1940.5.18 IMPERIAL VALLEY
50.0
54.5
111
```

```
      PROGRAM RUNF1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,PUNCH)
C     INPUT DATA
C       NG     - NUMBER OF DIVIDED INTERVALS
C       NAMI   - NAME OF EACH INTERVAL
C       NII,NNI- STEP NUMBER OF START AND END OF EACH INTERVAL
C       NAME   - NAME OF STATION AND EARTHQUAKE
C       NE     - TOTAL NUMBER OF EARTHQUAKE DATA
C       DT     - TIME INTERVAL OF DATA (SEC)
C       FMT    - FORMAT OF DATA
C       XD     - EARTHQUAKE DATA
C     PUNCHED CARDS BY PROGRAM (CORIN) CAN BE USED AS NAME TO XD
C     DIRECTLY.
      DIMENSION NAME( 8),NAM(2),NAMI(2,5),NNI(5),NII(5)
      DIMENSION X(2501),XD(1251),XX(2501),XXX(2501)
      COMPLEX C(4096)
      READ(5,12) NG
   12 FORMAT(2I5)
      DO 21 I=1,NG
      READ(5,10) (NAMI(J,I),J=1,2)
      READ(5,12) NII(I),NNI(I)
   21 CONTINUE
      READ(5,10) NAME
   10 FORMAT(8A10)
      READ(5,11) NE,DT,FMT
   11 FORMAT(//I5/F10.0/A10)
      READ(5,FMT) (XD(K),K=1,NE)
      DO 1000 II=1,NG
      N1=NII(II)
      NN=NNI(II)-N1+1
      DO 22 J=1,2
   22 NAM(J)=NAMI(J,II)
      WRITE(6,31) NAME
   31 FORMAT(1H1,2X,8A10)
      WRITE(6,82) NAM,N1,NN,DT
   82 FORMAT(1H ,70X,2A10/1H0,20X,3HN1=,I5/1H ,20X,3HNN=,I5/
     1  1H ,80X,3HDT=,F5.2,6H (SEC)/)
      N=512
      IF(NN.GT.N) N=1024
      IF(NN.GT.N) N=2048
      IF(NN.GT.N) N=4096
      IF(NN.LE.N) GO TO 201
      DO 200 K=1,N
      J=N1+K-1
  200 C(K)=CMPLX(XD(J),0.0)
      GO TO 204
  201 DO 202 K=1,NN
      J=N1+K-1
  202 C(K)=CMPLX(XD(J),0.0)
      NE=NN+1
      DO 203 K=NE,N
  203 C(K)=CMPLX(0.0,0.0)
  204 CALL FAST(N,C,4096,-1)
      AN=FLOAT(N)
      DO 209 K=1,N
  209 C(K)=C(K)/AN
      N2=N/2
      DO 205 K=1,N2
      AC=C(K)
      PC=C(K)*(0.0,-1.0)
      XX(K)=CABS(C(K))*2.0
  205 XXX(K)=ATAN(PC/AC)
      WRITE(6,88) C(1),XX(1),XXX(1)
   88 FORMAT(7X,1HK,3X,5HF(HZ),2X,6HT(SEC),11X,4HC(K),8X,
     111HAMP(CM/SEC),1X,9HPHAI(RAD)/1H ,6X,
     21H1,3X,3H0.0,5X,3H---,4X,2F10.4,2X,2F10.4,E15.6,F11.5)
      DF=1./(DT*AN)
      F=0.0
      DO 206 K=2,N2
      F=F+DF
      TF=1./F
      WRITE(6,91) K,F,TF,C(K),XX(K),XXX(K)
   91 FORMAT(1H ,I7,2F8.3,2X,2F10.4,2X,2F10.4)
  206 CONTINUE
      PUNCH 300,NAME
  300 FORMAT(8A10)
      PUNCH 302,NAM
  302 FORMAT(2A10)
      PUNCH 301,(XX(K),K=1,N2)
  301 FORMAT(10F7.4)
      PUNCH 301,(XXX(K),K=1,N2)
      CALL SPAR(NAME,N2,XX,2501,DF,100.0,NAM)
 1000 CONTINUE
      STOP
      END
```

```
C  ****************************************
C     SUBROUTINE FOR FAST FOURIER TRANSFORM
C  ****************************************
      SUBROUTINE FAST(N,X,ND,IND)
C
C                                        CODED BY Y. OHSAKI
C
C     PURPOSE
C       TO PERFORM FAST FOURIER OR INVERSE FOURIER TRANSFORM FOR
C       A SERIES OF EQUI-SPACED DATA
C
C     USAGE
C       CALL FAST(N,X,ND,IND)
C
C     DESCRIPTION OF PARAMETERS
C       N      - TOTAL NUMBER OF COMPLEX DATA AND TRANSFORMED VALUES
C       X(ND)  - EQUI-SPACED COMPLEX DATA/TRANSFORMED VALUES AT
C                CALL/RETURN
C       ND     - DIMENSION OF X IN CALLING PROGRAM
C       IND    - IND=-1 FOR FOURIER TRANSFORM
C                    +1 FOR INVERSE FOURIER TRANSFORM
C
C     REMARKS
C       (1) N MUST BE EQUAL TO POWERS OF 2
C       (2) WHEN IND=-1, TRANSFORMED VALUES ARE MULTIPLIED BY N
C       (3) EXAMPLE OF CALLING
C                COMPLEX   A(1024)
C                DIMENSION DATA(1024)
C                DATA      NN/1024/
C                DO 1 M=1,NN
C                A(M)=CMPLX(DATA(M),0.0)
C              1 CONTINUE
C                CALL FAST(NN,A,1024,-1)
C
C     REFERENCE
C
C       N.M.BRENNER/ THREE FORTRAN PROGRAMS THAT PERFORM THE COOLEY
C      -TUKEY FOURIER TRANSFORM / MIT JULY 1967
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C       NONE
C
      COMPLEX X(ND),TEMP,THETA
C
      J=1
      DO 140 I=1,N
      IF(I.GE.J) GO TO 110
      TEMP=X(J)
      X(J)=X(I)
      X(I)=TEMP
  110 M=N/2
  120 IF(J.LE.M) GO TO 130
      J=J-M
      M=M/2
      IF(M.GE.2) GO TO 120
  130 J=J+M
  140 CONTINUE
      KMAX=1
  150 IF(KMAX.GE.N) RETURN
      ISTEP=KMAX*2
      DO 170 K=1,KMAX
      THETA=CMPLX(0.0,3.141593*FLOAT(IND*(K-1))/FLOAT(KMAX))
      DO 160 I=K,N,ISTEP
      J=I+KMAX
      TEMP=X(J)*CEXP(THETA)
      X(J)=X(I)-TEMP
      X(I)=X(I)+TEMP
  160 CONTINUE
  170 CONTINUE
      KMAX=ISTEP
      GO TO 150
      END
```

```
C  ********************************************************************
C     SUBROUTINE FOR PRINT OF SPECTRA AND AUTOCORRELATION
C  ********************************************************************
      SUBROUTINE SPAR(NAME,N,Y,ND,DX,IND,IAXIS,NAM)
C
C
C                                        CODED BY Y. OHSAKI
C
C     PURPOSE
C       TO PRINT ON LINE-PRINTER APPROXIMATE SHAPE OF FOURIER, POWER
C       SPECTRA OR AUTOCORRELATION
C
C     USAGE
C       CALL SPAR(NAME,N,Y,ND,DX,IND,IAXIS)
C
C     DESCRIPTION OF PARAMETERS
C       NAME( 8) - NAME OF DATA
C       N        - TOTAL NUMBER OF SPECTRAL VALUES OR AUTOCORRELATION
C                  COEFFICIENTS
C       Y(ND)    - SPECTRAL VALUES OR AUTOCORRELATION COEFFICIENTS
C       ND       - DIMENSION OF Y IN CALLING PROGRAM
C       DX       - FREQUENCY INCREMENT IN CYCLES/SEC IN FOURIER OR
C                  POWER SPECTRUM, OR LAG INCREMENT IN SEC IN AUTOCOR-
C                  RELATION
C       IND      - 100 FOR PRINT OF FOURIER SPECTRUM
C                  010 FOR PRINT OF POWER SPECTRUM
C                  001 FOR PRINT OF AUTOCORRELATION
C       IAXIS    - IF 0, VERTICAL SCALE IS NEWLY DEFINED
C                  IF 1, VERTICAL SCALE IN PREVIOUS CALL IS RETAINED
C
C     REMARKS
C       (1) AUTOCORRELATION MUST HAVE BEEN NORMALIZED IN TERMS OF MEAN
C           SQUARED VALUE OF DATA
C       (2) FOR IND=001(AUTOCORRELATION), IAXIS HAS NO MEANING
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C       NONE
C
      DIMENSION NAME( 8),Y(ND)
      DIMENSION NAM(2)
      DIMENSION L(101),SMAX(4),STEP(4),LSTEP(4),FMT(3),FMT3(6),NUM(9)
      DATA      SMAX/2..4..5..10./,STEP/.5,1.,1.,2./,LSTEP/10,10,8,8/
      DATA      FMT3/4H.1) ,4H.2) ,4H.3) ,4H.4) ,4H.5) ,4H.6) /
      DATA      NUM/1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9/
C
C     HEADING
C
      WRITE(6,601) NAME
      WRITE(6,701) NAM
      IF(IND.EQ.100) WRITE(6,602)
      IF(IND.EQ.010) WRITE(6,603)
      IF(IND.EQ.001) WRITE(6,604)
      IF(IND.EQ.001) GO TO 140
      YMAX=0.0
      DO 110 K=1,N
      YMAX=AMAX1(YMAX,Y(K))
  110 CONTINUE
      WRITE(6,605) YMAX
C
C     VERTICAL SCALE
C
      IF(IAXIS.EQ.1) GO TO 160
      M=IFIX(ALOG10(YMAX))
      IF(ALOG10(YMAX).LT.0.0) M=M-1
      DO 120 J=1,4
      IF(YMAX/10.0**M.LE.SMAX(J)) GO TO 130
  120 CONTINUE
  130 SMAXJ=SMAX(J)*10.0**M
      STEPJ=STEP(J)*10.0**M
      LSTEPJ=LSTEP(J)
      IF(M.GT.0) FMT(3)=4H.0)
      IF(M.LE.0) FMT(3)=FMT3(1-M)
      LINE0=41
      XMAX=10.0
      GO TO 150
  140 SMAXJ=1.0
      STEPJ=0.5
      LSTEPJ=10
      FMT(3)=4H.1)
      LINE0=21
      XMAX=5.0
  150 FMT(1)=4H(1H+
      FMT(2)=4H,F13
C
C     PRINT
C
  160 NSTEP=MAX1(XMAX/DX/100.0+0.0001,1.0)
      IF(IND.EQ.001) GO TO 180
      IF(IAXIS.EQ.0) COR=40.0/SMAXJ
      DO 170 K=1,N,NSTEP
      Y(K)=Y(K)*COR
  170 CONTINUE
      GO TO 200
  180 DO 190 K=1,N,NSTEP
      Y(K)=(Y(K)+1.0)*20.0
  190 CONTINUE
  200 SCALE=SMAXJ
      DO 250 LINE=1,41
      L(1)=1HI
      LI=1H
      IF(LINE.EQ.LINE0) LI=1H-
      DO 210 I=2,101
      L(I)=LI
  210 CONTINUE
      BU=FLOAT(41-LINE)+0.5
      BL=FLOAT(41-LINE)-0.5
      DO 220 K=1,N,NSTEP
      IF(FLOAT(K-1)*DX.GT.XMAX) GO TO 230
      IF(Y(K).GE.BU.OR.Y(K).LT.BL) GO TO 220
      LL=IFIX(FLOAT(K-1)*DX/XMAX*100.0+0.5)+1
      L(LL)=1H*
  220 CONTINUE
  230 WRITE(6,605)
      IF(MOD(LINE,LSTEPJ).NE.1) GO TO 240
      WRITE(6,FMT) SCALE
      SCALE=SCALE-STEPJ
  240 WRITE(6,607) L
  250 CONTINUE
C
C     HORIZONTAL SCALE
C
      L(1)=1H0
      DO 260 I=2,101
      L(I)=1H
  260 CONTINUE
      DO 270 I=1,9
      INUM=IFIX(100.0/XMAX)*I+1
      IF(INUM.GT.101) GO TO 280
      L(INUM)=NUM(I)
  270 CONTINUE
  280 WRITE(6,608) L
      IF(IND.NE.001) WRITE(6,609)
      IF(IND.EQ.001) WRITE(6,610)
      RETURN
C
C     FORMAT STATEMENTS
C
  601 FORMAT(1H1,10X,8A10)
  602 FORMAT(1H0,12X,22H-- FOURIER SPECTRUM --)
  603 FORMAT(1H0,12X,20H-- POWER SPECTRUM --)
  604 FORMAT(1H0,12X,21H-- AUTOCORRELATION --/1H0/)
  605 FORMAT(1H0,98X,4HMAX.,F13.5/)
  606 FORMAT(1H )
  607 FORMAT(1H+,14X,101A1)
  608 FORMAT(1H0,14X,101A1/)
  609 FORMAT(1H0,57X,15HFREQUENCY (CPS))
  610 FORMAT(1H0,58X,13HTIME LAG(SEC))
  701 FORMAT(1H+,80X,2A10)
C
      END
```

```
      PROGRAM CORFA(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE99)
C     INPUT DATA
C       DT       - TIME INTERVAL OF EARTHQUAKE DATA
C       FMAX     - MAXIMUM FREQUENCY ON FIGURE OF FOURIER SPECTRUM
C       NG       - NUMBER OF DIVIDED INTERVALS
C       NF       - NUMBER OF NP
C       NP       - 1-2 FOR NS-EW, LO-TR OR CO-SH
C                  2-3 FOR EW-COR, NS, TR-COR, LO OR SH-COR, CO
C                  1-4 FOR NS-COR, EW, LO-COR, TR OR CO-COR, SH
C       N        - NUMBER OF COMPLEX FOURIER FREQUENCIES
C       YMAL,DIVY- MAX, VALUE AND NUMBER OF EQUAL DIVISIONS ON ORDINATE
C       NAME     - NAME OF STATION AND EARTHQUAKE
C       NAM      - NAME OF EACH DIVIDED INTERVAL
C       AMP      - FOURIER AMPLITUDE
C       PHAI     - PHASE DIFFERENCE
C     FMAX CAN BE SELECTED ARBITRARILY.
C     PUNCHED CARDS BY PROGRAM (RUNF1) CAN BE USED AS NAME TO PHAI
C     DIRECTLY.
C       AMP(K,1) = ORIGINAL FOURIER AMPLITUDE NS OR LO
C       AMP(K,2) = ORIGINAL FOURIER AMPLITUDE EW OR TR
C       AMP(K,3) = CORRECTED FOURIER AMPLITUDE NS OR LO
C       AMP(K,4) = CORRECTED FOURIER AMPLITUDE EW OR TR
      DIMENSION NAME( 8,2),NAM(2,2),AMP(2048,4),PHAI(2048,4)
      DIMENSION NAM1( 8),NAM2(2)
      DIMENSION  X(2048),Y(2048),DIVY(5),YMAL(5),NP(2,3)
      DIMENSION SPECS(35)
      READ(5,102) DT
      READ(5,102) FMAX
      READ(5,100) NG
      READ(5,100) NF
      DO 1 I=1,NF
    1 READ(5,100) (NP(J,I),J=1,2)
  100 FORMAT(8I5)
      XFRM=1.5
      DO 999 II=1,NG
      READ(5,100) N
      READ(5,102) YMAL(II),DIVY(II)
      N2=N/2
      AN=FLOAT(N)
      DO 10 I=1,2
      READ(5,101) (NAME(J,I),J=1,8)
  101 FORMAT(8A10)
      READ(5,103) (NAM(J,I),J=1,2)
  103 FORMAT(2A10)
  102 FORMAT(10F7.0)
      READ(5,102) (AMP(K,I),K=1,N2)
      READ(5,102) (PHAI(K,I),K=1,N2)
   10 CONTINUE
      DO 20 K=1,N2
      AMP1=AMP(K,1)
      AMP2=AMP(K,2)
      PHAI1=PHAI(K,1)
      PHAI2=PHAI(K,2)
      P1=PHAI1-PHAI2
      P2=PHAI2-PHAI1
      AMP3=AMP1*COS(P1)
      AMP4=AMP2*COS(P2)
      PHAI(K,3)=AMP3/AMP1
      PHAI(K,4)=AMP4/AMP2
      AMP(K,3)=AMP3
      AMP(K,4)=AMP4
   20 CONTINUE
      XFRM=XFRM+44.0*FLOAT(II-1)
      DO 990 JJ=1,NF
      SPECS( 1)=XFRM
      SPECS( 2)=3.0
      SPECS( 7)=10.0
      SPECS( 8)=5.0
      SPECS( 9)=10.0
      SPECS(10)= DIVY(II)
      SPECS(11)=1.
      SPECS(12)=99.
      CALL AXLILI(SPECS)
      SPECS( 3)=FMAX
      SPECS( 4)=0.0
      SPECS(17)=0.12
      SPECS(18)=0.18
      SPECS(19)=0.0
      SPECS(21)=1.0
      SPECS(24)=0.0
      SPECS(25)=1.0
      CALL NODLIB(SPECS)
      SPECS( 5)=YMAL(II)
      SPECS( 6)=0.0
      SPECS(20)=0.0
      SPECS(26)=0.0
      CALL NODLIL(SPECS)
      CALL TITLEB(14HFREQUENCY (HZ),SPECS)
      CALL TITLEL(17HFOURIER AMPLITUDE,SPECS)
      DF=1./(DT*AN)
      F=0.0
      DO 30 K=1,N2
      X(K)=F
      F=F+DF
      IF(F.GT.FMAX) GO TO 31
   30 CONTINUE
   31 NEND=K-1
      SPECS(13)=FLOAT(NEND)
      YMAX=0.0
      DO 50 J=1,2
      NPJ=NP(J,JJ)
      DO 40 K=1,NEND
      YK=ABS(AMP(K,NPJ))
      YMAX=AMAX1(YMAX,YK)
   40 Y(K)=YK
      IF(J.EQ.2) SPECS(11)=2.
      SPECS(14)=1.0
      SPECS(15)=1.0
      CALL SLLILI(X,Y,SPECS)
   50 CONTINUE
      SPECS(11)=1.
      SPECS(22)= XFRM+0.1
      SPECS(23)= 8.5
      DO 51 J=1,7
   51 NAM1(J)=NAME(J,1)
      RULE=1.
      NAM1(8)=0
      CALL TITLEG(RULE,NAM1,SPECS)
      SPECS(22)=XFRM+7.5
      SPECS(23)=8.0
      NP2=NP(2,JJ)
      IF(NP2.GT.2) GO TO 41
      CALL TITLEG(RULE,9HORI.-OR1.,SPECS)
      GO TO 42
   41 CALL TITLEG(RULE,9HORI.-COR.,SPECS)
   42 CONTINUE
      DO 54 I=1,2
      INF=I
      JNF=2-I+1
      JF=MOD(NP(1,JJ),2)
      IF(JF.EQ.0) INF=JNF
      DO 52 J=1,2
   52 NAM2(J)=NAM(J,INF)
      SPECS(23)=7.8
      IF(I.NE.2) GO TO 53
      SPECS(23)=7.6
      SPECS(11)=2.
   53 CALL TITLEG(RULE,NAM2,SPECS)
   54 CONTINUE
      SPECS(11)=1.
      SPECS(23)=7.4
      CALL TITLEG(RULE,4HMAX=,SPECS)
      SPECS(22)=XFRM+8.2
      SPECS(28)=3.0
      CALL DECVAL(RULE,YMAX,SPECS)
      XFRM=XFRM+14.0
  990 CONTINUE
  999 CONTINUE
      CALL GDSEND(SPECS)
      STOP
      END
```

```
      PROGRAM PWAVE(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE99)
C     INPUT DATA
C       ILN         - =1 CASE OF COORDINATE TRANSFORMATION TO
C                        LONGITUDINAL AND TRANSVERSE DIRECTION TOWARD
C                        EPICENTER
C                     =2 CASE OF COORDINATE TRANSFORMATION TO
C                        NORMAL AND PARALLEL DIRECTION TO FAULT LINE
C       NAME      - NAME OF STATION AND EARTHQUAKE
C       XMAX(1,II)- MAXIMUM VALUE OF ACCELERATION (GAL)
C       NA        - TOTAL NUMBER OF X
C       X         - ACCELERATION DATA
C       XMAX(2,II)- MAXIMUM VALUE OF VELOCITY (KINE)
C       NV        - TOTAL NUMBER OF XD
C       XD        - VELOCITY DATA
C     PUNCHED CARDS BY PROGRAM (CORIN) CAN BE USED AS NAME TO XD
C     DIRECTLY.
C     II=1-LONGITUDINAL DATA, =2-TRANSVERSE DATA
C     III=1-ACC. DATA, =2-VEL. DATA
      DIMENSION XMAL(2),XSC(7)
      COMMON /DATAN/X(3000,2),XD(1500,2),XMAX(2,2)
      COMMON /N11/NAME(8)
      COMMON /ILONO/ILN
      DATA XSC/10.,20.,30.,40.,50.,60.,100./
      READ(5,1) ILN
      DO 10 II=1,2
      READ(5,100) NAME,XMAX(1,II),NA
      READ(5,101) (X(K,II),K=1,NA)
      READ(5,102) XMAX(2,II),NV
      READ(5,101) (XD(K,II),K=1,NV)
   10 CONTINUE
      XM=0.0
      DO 50 III=1,2
      DO 20 II=1,2
      XM=AMAX1(XM,XMAX(III,II))
   20 CONTINUE
      IF(III.EQ.1) XM=XM*0.1
      XMM=100.
      IF(XM.GE.XMM) GO TO 40
      XMM=10.
      IF(XM.LE.XMM) GO TO 40
      DO 30 KK=1,7
      IF(XM.GT.XSC(KK)) GO TO 30
      XMM=XSC(KK)
      GO TO 40
   30 CONTINUE
   40 IF(III.EQ.1) XMM=XMM*10.
      XMAL(III)=XMM
   50 CONTINUE
      CALL PLINP(NA,NV,XMAL)
      STOP
    1 FORMAT(I5)
  100 FORMAT(8A10//F10.4/I5//)
  101 FORMAT(10F7.0)
  102 FORMAT(//F10.4/I5//)
      END
```

```
      SUBROUTINE PLINP(NA,NV,XMAL)
C     III=1-PLOT OF ACC. DATA, =2-PLOT OF VEL. DATA
C     II =1-PLOT OF LONGITUDINAL DATA, =2-PLOT OF TRANSVERSE DATA
      DIMENSION T1(2501),Y(2501),S(35),GXS(4),XTI(3,2),YTI(3,2)
      DIMENSION XMAL(2)
      COMMON /DATAN/X(3000,2),XD(1500,2),XMAX(2,2)
      COMMON /N11/NAME(8)
      COMMON /ILONO/ILN
      XFRM=1.5
      DO 500 III=1,2
      T1(1)=0.0
      T11=0.02
      NAV=NA
      IF(III.EQ.1) GO TO 349
      T11=0.04
      NAV=NV
  349 DO 350 K=2,NAV
  350 T1(K)=T11*FLOAT(K-1)
      DO 400 II=1,2
      YFRM=3.*FLOAT(II-1)
      S( 1)=XFRM
      S( 2)=3.0+YFRM
      S( 3)=T1(NAV)
      S( 4)=0.
      S( 5)= XMAL(III)
      S( 6)= -S(5)
      S( 7)=20.
      S( 8)=2.
      S(11)=1.
      S(12)=99.
      GXS(1)=0.
      GXS(2)=0.
      GXS(3)=1.
      GXS(4)=1.
      XTI(1,1)=3.0
      XTI(2,1)=0.3
      XTI(3,1)=10.0
      YTI(1,1)=1.0
      YTI(2,1)=0.15
      YTI(3,1)=2.0
      CALL GXLILI(GXS,XTI,YTI,S)
      S( 9)=5.
      S(17)=0.12
      S(18)=0.18
      S(19)=0.0
      S(20)=0.0
      S(21)=1.
      S(24)=0.0
      S(28)=1.
      CALL NODL18(S)
      RULE=1.
      S(22)=XFRM+19.6
      S(23)=2.5+YFRM
      CALL TITLEG(RULE,5H(SEC),S)
      S(18)=2.
      S(26)=0.0
      CALL NODLIL(S)
      DO 380 K=1,NAV
      GO TO(378,379),III
  378 Y(K)=X(K,II)
      GO TO 380
  379 Y(K)=XD(K,II)
  380 CONTINUE
      S(13)=NAV
      S(14)=1.
      S(15)=1.
      CALL SLLILI(T1,Y,S)
      S(22)=XFRM+16.5
      S(23)=YFRM+4.7
      GO TO(392,492),ILN
  392 GO TO(393,396),II
  393 GO TO(394,395),III
  394 CALL TITLEG(RULE,22HLONGITUDINAL ACC.(GAL),S)
      GO TO 399
  395 CALL TITLEG(RULE,23HLONGITUDINAL VEL.(KINE),S)
      GO TO 399
  396 GO TO(397,398),III
  397 CALL TITLEG(RULE,20HTRANSVERSE ACC.(GAL),S)
      GO TO 399
  398 CALL TITLEG(RULE,21HTRANSVERSE VEL.(KINE),S)
      GO TO 399
  492 GO TO(493,496),II
  493 GO TO(494,495),III
  494 CALL TITLEG(RULE,25HNORMAL TO FAULT ACC.(GAL),S)
      GO TO 399
  495 CALL TITLEG(RULE,26HNORMAL TO FAULT VEL.(KINE),S)
      GO TO 399
  496 GO TO(497,498),III
  497 CALL TITLEG(RULE,27HPARALLEL TO FAULT ACC.(GAL),S)
      GO TO 399
  498 CALL TITLEG(RULE,26HPARALLEL TO FAULT VEL.(KINE),S)
  399 S(23)=S(23)-0.25
      CALL TITLEG(RULE,4HMAX=,S)
      S(22)=S(22)+0.8
      IF(III.EQ.2) S(28)=3.
      CALL DECVAL(RULE,XMAX(III,II),S)
  400 CONTINUE
      S(22)=S(1)+0.2
      S(23)=8.4
      NAME(8)=0
      CALL TITLEG(RULE,NAME,S)
      XFRM=XFRM+25.0
  500 CONTINUE
      CALL GDSEND(S)
      RETURN
      END
```

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EERC 73-24 Unassigned

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