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SUPERCONDUCTING SUPER COLLIDER

ENVIRONMENTAL GROUND VIBRATION STUDY

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1. INTRODUCTION

Methods are provided for characterizing the local ground vibration exposure of the proposed Superconducting Super Collider (SSC). Three tools are provided. The first is a compendium of ground vibration data collected for several types of sources at a variety of geographic locations. The second tool is a simple method for estimating subsurface ground vibration amplitudes from vibration data collected at the ground surface. These data may include the data presented here, or data collected during the course of a vibration survey. To this end, practical procedures are recommended as the third tool of this work for performing site vibration surveys.

A primary feature of the methods and data discussed here is the use of 1/3 octave band spectral representations rather than narrow band constant bandwidth FFT analyses. The emphasis is on developing data which may be easily handled, interpreted, and compared with other data or criteria. The 1/3 octave band spectra provides a broad picture of the vibration spectrum, yet has a sufficiently narrow bandwidth to provide respectable estimates of power spectral densities. The 1/3 octave spectrum plotted with respect to the logarithm of frequency provides a practical display of constant percentage bandwidth data on a log frequency scale.

Most of the data presented here are in terms of vibration velocity or vibration velocity levels in dB. This is primarily because of industry practice and the fact that the tolerance of sensitive machines and optical apparatus is often best described in terms of vibration velocities. Even structural damage to buildings due to ground motion is most closely related to peak ground velocity. Furthermore, use of velocity spectra is often preferable to acceleration spectra or displacement spectra since the former de-emphasizes the low frequency components of vibration while the latter de-emphasizes the high frequency end of the spectrum. The use of velocity spectra often minimizes the display range required for presentation of data.

The simple model presented here is based on the problem of an oscillating point load acting normal to the surface of an elastic half space, using classical solutions developed in the literature. Attenuations due to dissipation and increasing soil stiffness are included in the simplest of terms. One should be aware, however, that the problem of predicting ground vibration has received considerable attention over the past 20 years, and no very reliable simple analytical methods have been developed and validated. The problem is complicated by unknown soil and rock conditions, uneven layering, and highly variable dissipation properties. Unless good soils data are available, only the simplest conservative models should be used.

The recommendations for performing site vibration surveys include measurement locations, procedures, instrumentation, and presentation of data. Although a simple model and data are presented for estimating vibration amplitudes at depth, the value of site vibrations surveys cannot be under estimated. If there is any doubt as to whether or not a measurement of ground vibration should be performed, then it should probably be performed. Identification of high levels of environmental ground vibration is critical to include appropriate vibration control provision early in the design phase of the project, thereby minimizing its eventual cost. Site vibration surveys may be done economically and efficiently.

2. VIBRATION DATA

Discussed in this section are representative samples of measured ground vibration data collected at a variety of locations about the United States. These data are not comprehensive - samples are not presented for every locale, soil type, or source type. The samples selected for presentation are good examples of what may be expected.

The samples of vibration are presented in the appendices, as follows:

Type of Vibration	Appendix
Train	A
Highway Truck and Auto	B
Street	C
Rail Transit Subsurface Vibration	D
Construction Equipment	E
Pile Driving, Rock Drilling	F

Blasting	G
Tunnel Boring Machine	H

Short discussions of each of these categories are presented below.

The spectral data presented in the appendices are given as 1/3 octave band rms velocity levels in dB re 1 micro-inch/sec or 1/3 octave band rms acceleration levels in dB re 1 micro-g. The 1/3 octave band spectrum is one of the most practical forms of spectral data presentation and is common in the fields of vibration (and noise) control engineering. The 1/3 octave spectrum is particularly useful for comparing spectral vibration data with criteria. Though not a rigorous statement, the 1/3 octave band level may often be compared directly with criteria written for sinusoidal vibration (discrete frequency vibration).

The level in dB is a logarithmic quantity, given as

$$L \text{ (dB re } a_o) = 20 \text{ Log } (a/a_o) \qquad 2.1$$

where: a = magnitude

a_o = reference quantity

One should be able to move freely between the absolute magnitude, a, and its dB equivalent. For instance, a level of 0 dB re 1 micron/sec is equivalent to 1 micron/sec, a level of 20 dB is equivalent to 10 microns/sec, and so on.

The 1/3 octave band vibration data given in the appendices may be converted to Power Spectral Densities (PSD). The PSD levels corresponding to a level L in dB relative to v_o at the 1/3 octave band center frequency, f_o, is simply

$$PSD = \frac{v_o^2 \; 10^{L(dBrev_o)/10}}{0.23 f_o} \qquad 2.2$$

That is, the 1/3 octave band "Power" is divided by the filter bandwidth to obtain the "Power Spectral Density" or PSD. To obtain the displacement PSD, the above quantity is again divided by $4\pi^2 f_o^2$.

For example, the velocity Power Spectral Density in $(in/sec)^2/Hz$ for a 10 Hz 1/3 octave band velocity level of 40 dB re 1 micro-inch/sec is

$$PSD_v = \frac{(10^{-6} \text{ in/sec})^2}{0.23 \times 10 \text{ Hz}} \times 10^{40/10} \qquad 2.3$$

The displacement PSD is

$$PSD_D = PSD_V / (4\pi^2 f_o^2) = 1.1 \text{ (micro-in)}^2 / \text{Hz} \qquad 2.4$$

This can further be expressed in microns as

$$PSD_D(\text{microns}^2/\text{Hz}) = PSD_D((\text{micro-in})^2/\text{Hz}) \times (0.0254 \text{ m/in})^2 \qquad 2.5$$
$$= 0.00071 \text{ microns}^2/\text{Hz}$$

One of the primary reasons for employing the level representation is that attenuation requirements are easily thought of in terms of dB. The velocity response of a harmonic oscillator to a sinusoidal force can be described as having a +6 dB/octave slope below resonance and a -6 dB/octave slope above resonance. When plotted against a logarithmic frequency scale, these slopes appear as straight lines. Levels in dB may be added and subtracted easily to represent attenuation, amplification, etc.

Although vibration velocity levels presented in the appendices are with a reference magnitude of 1 micro-inch/sec, the recommended reference magnitude for use by the international scientific community is 10^{-8}m/sec, the preferred reference velocity (ISO Draft Recommendation, 508E) (ANSI Standard S1.8, 1969) for vibration velocity levels. For displacement data, the preferred reference magnitude is 10^{-11}m. Thus, an rms vibration displacement of 1 micron will correspond to 100 dB re 10^{-11}m and an rms vibration displacement of 0.1 micron will correspond to 80 dB re 10^{-11}m.

The vibration velocity level in dB re 10^{-8}m/sec may be obtained by adding +20 log (2.54)= 8.1 dB to the velocity level expressed in dB re 1 micro-in/sec.

Constant displacement curves are presented in Figure 2.1 to facilitate converting the velocity data presented here as levels in dB re 1 micro-in/sec to displacement single amplitudes in microns. This figure can be reproduced on vellum paper to lay over the velocity level data presented here, matching the left hand scales for levels in dB re 1 micro-in/sec and the frequency scales along the bottom. The scale at the right hand edge of Figure 2.1 is the level in dB re 10^{-8}m/sec.

2.1 Train Vibration Data

Ground vibration data for railroad trains are presented in Appendix A. Figures A-1 through A-4 illustrate data collected in Atlanta, Georgia. A sample of what may be a ballast compactor is given in Figure A-1, indicated as "construction activity". At 235 ft from the track, the ballast compactor produced a vibration velocity of almost 3000 micro-inches per second or a vibration displacement of about 0.6 micron rms at 20 Hz. Note that the spectral peak in the railway wayside vibration data is in the neighborhood of 8 to 20 Hz. This peak depends strongly on train speed.

In Figures A-5 through A-6, data are presented for Southern Pacific freight trains operating at about 20 mph in Reno, Nevada. The spectral peaks shown for these data are in the range of 20 to 40 Hz, substantially different from the Atlanta data. Soil stiffness, damping, and propagation distances are primary factors determining the spectral character of these data. Displacement amplitudes are in the range of 1 to 3 microns rms at 10 feet from the track centerline.

Ground vibration collected in the Kamloops area of British Columbia are presented in Figures A-7 through A-9 for train speeds of 20, 30, and 40 mph, respectively. The tracks follow the edge of an alluvial valley of basically sandy soils. These data are particularly interesting since they exhibit very pronounced peaks at about 4, 6.3, and 10 Hz, for each of the respective speeds. These peaks correspond to vibration displacements of roughly 3-10 microns, 10-15 microns, and 10 microns, respectively. These peaks were traced to a perturbation in vertical rail head profile caused by the rail straightening machine.

Train data are presented in Figures A-10 through A-15 for trains passing through Carbondale, Illinois. These data clearly indicate high levels of vibration velocity, peaking in the 6 to 31.5 Hz 1/3 octave bands. Compare these data with that data shown for Kamloops, B.C. Except for the 25 foot data, most of the levels shown are under 1 micron displacement. At less than 250 ft, the vibration velocities are in excess of about 300 micro-in/sec.

In Figure A-16, 1/3 octave band ground vibration acceleration levels are given for 30 mph freight train operation on a 15 foot high berm in Marysville, California. The observation distance was 120 feet, located on a concrete floor slab inside a building. The vibration velocities corresponding to these data are all in excess of 1000 micro-in/sec. Although not known, the soils at this site are of alluvial type deposited by the Feather River, and are likely similar to soils found elsewhere in the low Central Valley of California.

2.2 Highway Ground Vibration

Highway ground vibration velocities measured along I-75 in the Atlanta area are presented in Figures B-1 and B-2. These data illustrate a peak in vibration at roughly 12 to 16 Hz, corresponding to suspension resonances of the vehicles.

Highway ground vibration data collected in Reno, Nevada along I-80 are presented in Figures B-3, B-4, and B-5 for an open cut, elevated berm, and at-grade section of I-80, respectively. Data collected along the open cut section are relatively low, and are also dominated by instrumentation noise at 3 to 4 Hz. The data shown for the at-grade location are most representative.

Data measured at about 220 to 340 feet from freeway traffic (Stevenson Expressway, Interstate 55) in Chicago, Illinois, are presented in Figure B-6. These data are presented as statistical exceedance levels, L_1, L_{10}, L_{50}, and L_{90}, where L_N is the level exceeded N% of the time. The L_{eq} is the energy averaged (rms) vibration velocity level for the measurement period, about 10 minutes. These data are based on an ensemble of about 600 1 second samples of rms 1/3 octave band velocity.

2.3 Street Traffic Vibration

Street traffic vibration data are presented in Appendix C for bus and automobile traffic. Two examples are given in Figures C-1 and C-2 of ground vibration at 12 feet and 25 feet from the curb of Piedmont Avenue in Atlanta, Georgia. Note that these data are described in terms of the rms level exceeded 1% and 10% of the time. Also shown are the maximum rms vibration levels measured within any 1-second period and the equivalent vibration level (rms average over the entire duration) L_{eq}. There is a substantial difference between the L_{max}, L_1, and L_{10} levels compared with the long term L_{eq}. For this reason, a statistical analyses such as presented in Appendix C is very desirable for describing highway or street ground vibration.

Examples of ground vibration caused by heavy buses at 4 locations along the proposed MUNI J-Line Corridor in San Francisco are presented in Figure C-3. Statistical analyses of rush hour traffic ground vibration measured at 20 feet from the centerline of the nearest lane of traffic are presented in Figure C-4. These data were collected along the proposed MUNI J-Line at the point designated as Location 4 in Figure C-3. The L_{90} spectrum is representative of background vibration, though still influenced by traffic at substantial distances. The traffic at this location would be considered heavy.

Finally, data characterizing street traffic vibration at several points and source/receiver distances along heavily traveled streets in San Jose are given in Figures C-5 through C-8. These data are presented as the 1/3 octave statistical exceedance levels L_1, L_{10}, L_{50}, L_{90}, and L_{99}. The data were collected in the downtown and northern San Jose areas. The soils in this area are primarily alluvial in nature, probably sandy, silty clays. San Francisco Bay is located to the north. Detailed soil surveys have been performed and data should be available as part of the preconstruction survey work along the corridor for the San Jose Light Rail Transit system.

2.4 Vibration vs. Depth

Downhole 1/3 octave vibration velocity data are presented for rail transit subway generated ground vibration at various borehole depths. Source/receiver distances are 110 and 125 feet for Figures D-1 and D-2, respectively. The data in Figure D-2 are for trains on the far track of a double-box subway structure. These data clearly indicate a substantial reduction of vibration below 20 Hz with increasing borehole depth. The major reduction is likely due to increasing soil stiffness. At this site, a weathered rock layer exists at 24'-33'. As the borehole depth approaches the rock layer, the amplitude of vibration decreases significantly at frequencies below 20 Hz. At frequencies above 20 Hz, reduction of vibration with increasing depth is less significant, or non-existent. This is typical for subway type sources and is related to conduction of high frequency vibration in the rock layer.

2.5 Construction Equipment

One-third octave band vibration due to construction equipment are presented in Figures E-1 and E-2. These data were selected as being very representative of construction related vibration. Wiss (1981) provides representative peak particle velocities for a variety of construction equipment, presented in Figure 2.2, as functions of source receiver distance. Although source receiver distances of less than 10 ft are indicated, these data should not be used for scaling measured vibration data at source distances less than perhaps 25 to 50 ft.

2.6 Pile Driving and Rock Drilling

One-third octave data for pile driving and rock drilling are presented in Appendix F. Impact pile driving data presented in Figure F-1 are for maximum rms vibration velocity levels measured over about 1 second. Peak particle velocities are substantially higher than indicated by the overall vibration velocity level of 80 to 85 dB re 1 micro-inch/sec. Peak particle velocities for pile driving at various scaled source/receiver distances are given in Figure 2.3. These data should be used for estimating ground vibration velocities due to pile driving.

One-third octave vibration velocity data are presented in Figures F-2 and F-3 for sonic or vibratory pile drivers. An immediate conclusion to be drawn from these data is that vibration displacements generated by a sonic pile driver are far lower than for an impact pile driver due to its operation at the relatively high frequency of 80 Hz to 100 Hz.

One-third octave data are presented in Figure F-4 for rock drilling machines. These data are for surface ground vibration due to subsurface drilling in rock. Data are not available for vibration at subsurface locations.

2.7 Surface Vibration due to Blasting

One-third octave ground surface vibration velocity data for tunnel blasting operations are presented in Figure G-1 of Appendix G. These data are important for illustration of the spectral characteristics of blast induced vibration. A one-second integration time was used to develop the "rms" velocity levels shown in Figure G-1.

Representative peak particle velocities as functions of scaled distance are provided in Figure 2.4, taken from the Blasters Handbook (1977). Numerous other references are included in the bibliography.

2.8 Tunnel Boring Machine

One-third octave vibration velocity levels measured at the ground surface for various distances from a tunnel boring machine are presented in Figures H-1 through H-3. These data are for a tunnel boring machine operating at 40 ft depth in Buffalo, New York. Soils data are unknown, but are likely to be a relatively soft soil layer over rock. The tunnel boring machine was excavating a tunnel for the Niagara Frontier Transportation Authority (NFTA) light rail subway. The diameter of the boring machine should be about 16-18 ft.

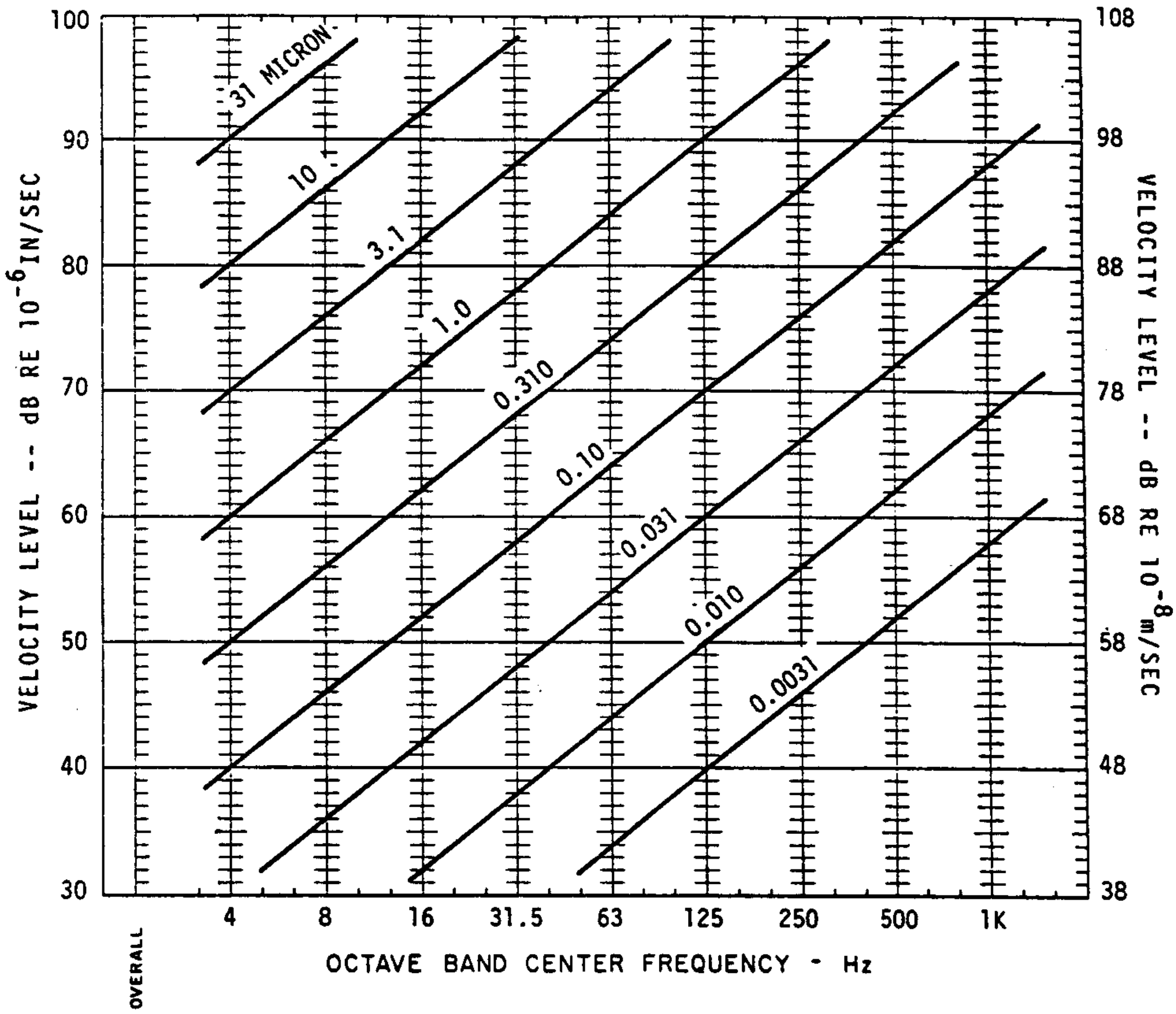

FIGURE 2.1 CONSTANT VIBRATION DISPLACEMENT CURVES

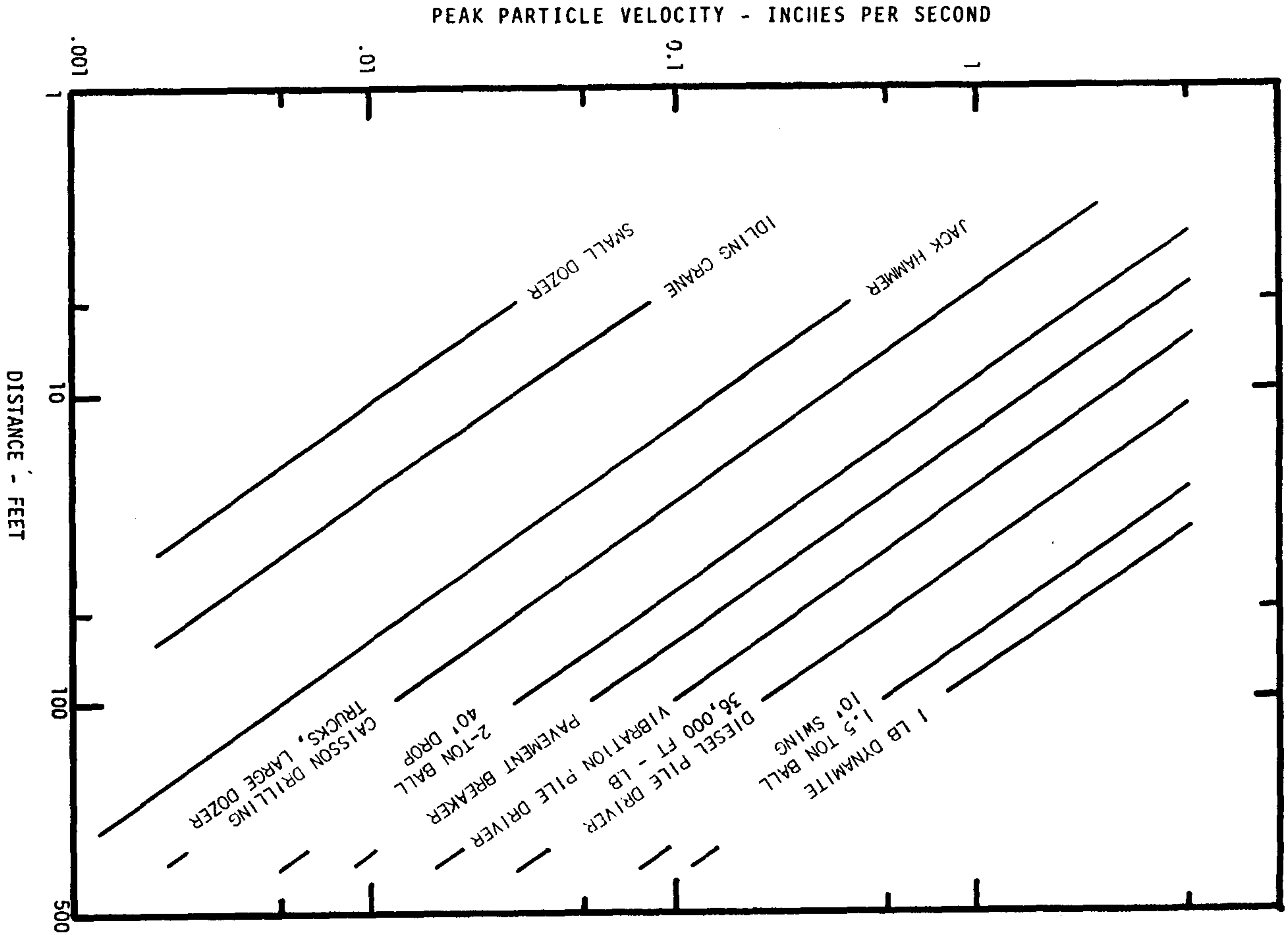

FIGURE 2.2 RELATIVE INTENSITIES OF CONSTRUCTION VIBRATION (FROM WISS, J.F., "CONSTRUCTION VIBRATION: STATE-OF-THE-ART," JOURNAL OF THE GEOTECHNICAL ENGINEERING DIVISION, FEBRUARY 1981)

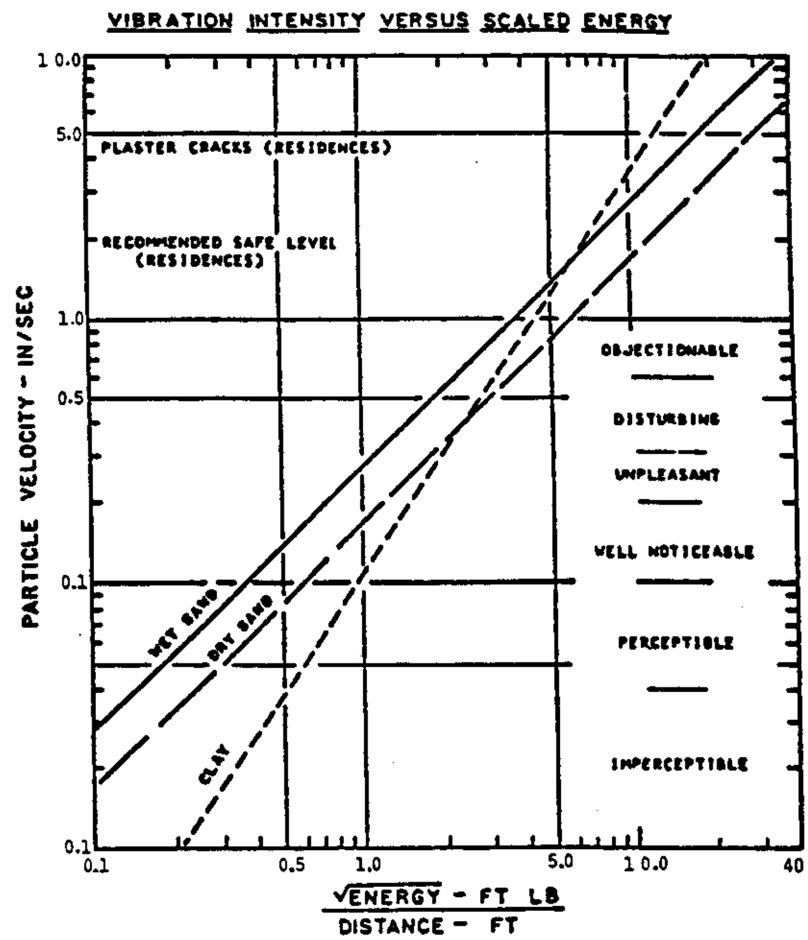

FIGURE 2.3 MAXIMUM VIBRATION INTENSITIES EXPECTED FROM PILE DRIVING ON WET SAND, DRY SAND, AND CLAY. (FROM WISS, J.F., "DAMAGE EFFECTS OF PILE DRIVING VIBRATION," HIGHWAY RESEARCH RECORD, NO. 155, 1967)

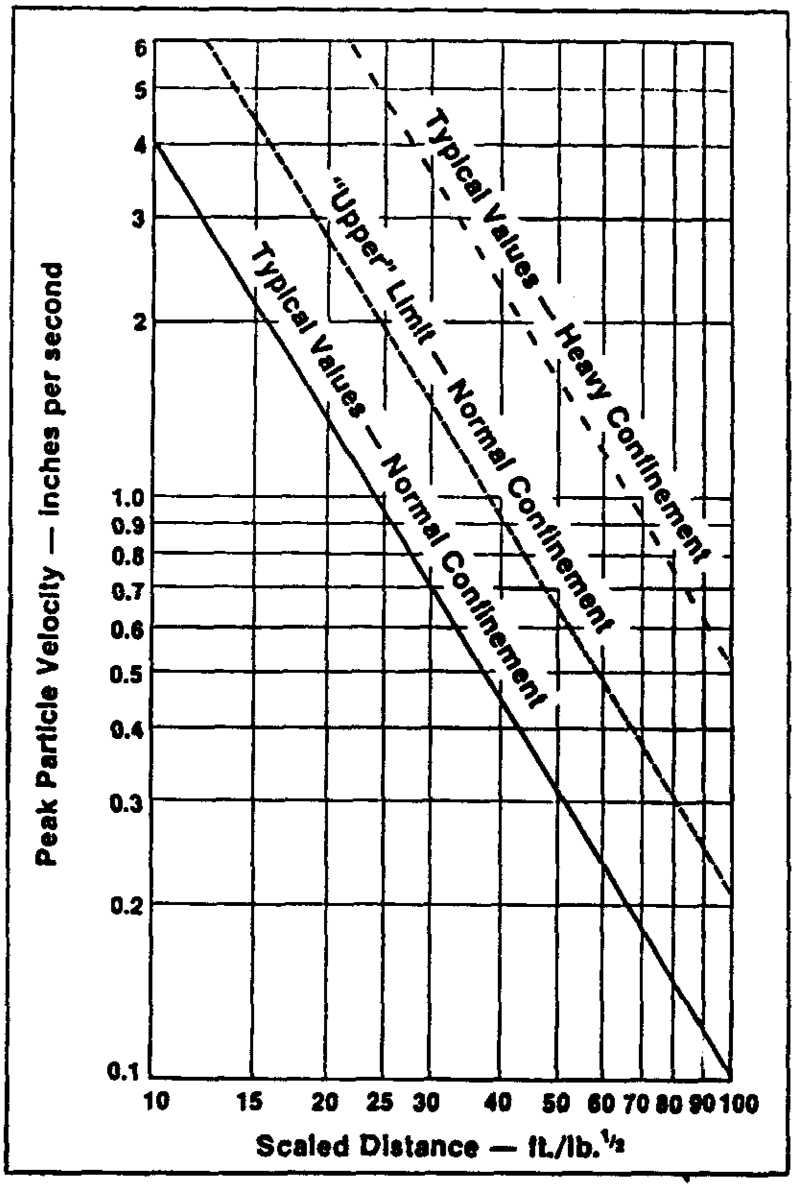

FIGURE 2.4 TYPICAL VALUES OF PEAK PARTICLE VELOCITY AS A FUNCTION OF SCALED DISTANCE FOR BLASTING TO A FREE FACE. CHARGE WEIGHT IS PER-DELAY-PERIOD OF EIGHT MILLISECONDS OR MORE. BLASTS MADE UNDER TIGHT CONFINEMENT SUCH AS THE OPENING OF HOLES IN HEADINGS OR IN PRESPLITTING MAY GIVE VALUES FIVE TIMES MORE THAN TYPICAL UNDER NORMAL CONFINEMENT. (FROM BLASTERS HANDBOOK BY DU PONT, 175TH ANNIVERSARY EDITION, 1977)

3. VIBRATION ATTENUATION

This section begins with a discussion of wave types which may be expected from surface sources, attenuation due to dissipation and to changes in soil and rock stiffness. This preliminary discussion is followed with presentation of a simple model based on elastic half-space theory to interpret surface ground vibration data and allow estimating wave amplitudes at depth. Since the SSC tunnel may be located at substantial depths, e.g. perhaps up to 100 meters below the ground surface, the prediction of the vibration environment of the SSC ring based on surface or shallow soils data will necessarily remain ambitious. The model should be described as qualitative, capable of identifying on the basis of soils and vibration data, those proposed sites which deserve either detailed site vibration measurements including borehole tests, detailed numerical analyses, or both. Efforts should be directed to check model performance at representative locations.

Ground vibration is very difficult to model, even with modern computer codes, simply because of the complexity of near surface geology. The factors which complicate the prediction process include:

- o anisotropy

- o complex layering

- o dissipation

- o lack of detailed subsurface soils data

In spite of these limitations, the model should be capable of providing a "first cut" estimate of subsurface body wave amplitudes from surface data dominated by Rayleigh surface waves, both in the near- and far-field.

3.1 Wave Types

There are two basic wave types which propagate in a homogeneous, isotropic, elastic medium. The first of these (and the one which arrives first,) is a compressional wave, or P-wave, propagating at the dilatational wave speed, c_p. The second of these wave types is a shear, or S-wave, propagating at speed, c_s. Representative values of dilatational and shear wave propagation velocities are given in Table 3.1, based on data given by Barkan (1965). For a semi-infinite, isotropic, homogenous, elastic medium, a third type of wave may exist in addition to the two body waves. The third type of wave is a surface wave, often referred to as a Rayleigh wave. Each of these waves are well described in standard texts by Fung (1965) and Graf (1975). In the case of an elastic layer over an elastic half-space, Love waves consisting of horizontally polarized shear waves may propagate as a trapped mode in the upper layer (Graf, pg. 382), provided that the upper layer exhibits a lower shear wave velocity than the underlying half space. Both Love and Rayleigh surface waves propagate with trace velocities along the surface which are less than the shear wave velocity of the semi-infinite medium. If this were not the case, these waves would couple with shear waves in the half-space and radiate energy away from the surface, thus destroying the surface wave character. Love waves will not be dealt with directly here, but their existence should be noted, especially in the case of horizontal excitations.

3.2 Source Type

For the purpose of discussion, the attenuation of vibration as a function of source-receiver distance is loosely described by the following relation

$$\frac{v_2}{v_1} = A\left(\frac{R_1}{R_2}\right)^n e^{-\alpha(R_2-R_1)} \qquad 3.1$$

where: v_i is the amplitude of vibration at the i^{th} receiver

R_i = Source/Receiver distance for the i^{th} receiver

n = A parameter describing geometrical spreading losses

α = Attenuation coefficient

A = A factor accounting for reflection/transmission across an interface, or transmission through a region of variable stiffness

Two primary sources to consider are point sources and line sources, the latter usually be being to be a distribution of incoherent point forces.

The parameter "n" in Equation 3.1 assumes the value 0, 1/2, or 1, according to the following matrix:

Wave Type	Point Source	Line Source
Body	1	1/2
Surface	1/2	0

In the above matrix a Line source may be coherent or incoherent, and the surface wave may be a Rayleigh surface wave, Love wave, or any type of wave which is non-radiating into the underlying strata.

Most of the discussion presented here will be for vertical forces, forces which do not create Love waves or other transverse horizontal wave motion. This approach is taken as a simplification motivated by the fact that most transportation and stationary vibration sources induce primarily vertical forces into the soil. This would not be the case, however, for a horizontal reciprocating compressor, since its dynamic foundation forces will be primarily horizontal.

3.3 Dissipation

The attenuation coefficient " " is used to describe the attenuation of vibration with distance due to dissipation. A good assemblage of literature on the subject is contained in a Geophysics Reprint Series titled "Seismic Wave Attenuation", edited by Toksoz and Johnston (1981). The attenuation coefficient is related to the Qualify Factor, Q, the frequency of excitation, f, and the velocity of propagation, c, as

$$\alpha = \frac{\pi f}{QC} \qquad 3.2$$

For most purposes, the factor Q may be assumed frequency independent, though this violates certain causal restrictions. The quality factor Q is not independent of frequency for most soils. In fact, Barkan (1965, pg. 346) provides data indicating that for soils the attenuation coefficient α is independent of frequency for frequencies between 10 Hz and 30 Hz, implying that Q is proportional to frequency.

Representative dissipation data are presented in Table 3.2 for a variety of soils and rocks. These data are derived from Barkan (1965) and Kudo and Shima. Where values are given for α, these values should be used directly without adjustment for frequency, velocity, etc. Where values are given for Q, values for α should be computed with the constant Q model, Equation 3.2. The shear wave velocity should be used for computation of α since shear waves carry substantially more energy than compressional waves for most conditions.

For propagation through soils and rocks where the attenuation coefficient varies appreciably over the propagation path, Equation 3.1 should be recast as

$$\frac{v_2}{v_1} = A\left(\frac{R_1}{R_2}\right)^n e^{-\int_{R_1}^{R_2}\alpha(s)ds} \qquad 3.3$$

where the integral runs over the path length. The integral can be easily approximated by a finite sum of no more than 2 or 3 terms, especially since sufficient soils data will not usually be available for very detailed approximation, and because the model itself is qualitative in nature.

3.4 Soil Stiffness Variation

As a wave propagates to underlying soil or rock layers, considerable variation in stiffness is encountered. Seismologists have been active for decades in computing synthetic seismograms for layered media, and the art is at a high state of development. Aki and Richards (1980) provide a detailed summary of techniques for computing synthetic seismograms, thus "solving" the problem. These solution procedures typically involve substantial computer time and programming ability, though relatively simple layer models could be programmed to provide a more accurate estimate of subsurface response than the methods presented here. Even so, these more accurate methods would involve Hankel transform inversion, an often difficult numerical inversion problem, or finite difference methods. Well developed computer models are being used by the Center for Computational Seismology at Lawrence Berkeley Laboratory (CCS/LBL) for modeling synthetic seismograms in layered half spaces.

A simple model for estimating the effect of increasing soil stiffness with increasing depth is presented here for hand calculation. Two cases are considered. One is reflection and transmission at a plane interface, well known in physics and engineering. The other is gradual amplitude reduction due to propagation through a medium with smoothly increasing stiffness.

The former of these, the transmission across a plane interface, is illustrated in Figure 3.1. In this example, a wave in medium 1 with characteristic impedance $\rho_1 c_1$, is incident at a plane boundary with medium 2 with characteristic impedance $\rho_2 c_2$. Here, ρ_1 and ρ_2 are the mass densities of the medium, c_1 and c_2 are the propagation velocities, usually assumed to be shear wave velocities.

Reflected and transmitted waves are produced at the boundary, the amplitudes of which depend on the angle of incidence. In an elastic medium, mode conversion may occur between shear and compression waves. That is, incident P-waves can produce reflected and transmitted S-waves and vice versa. The issue of angle of incidence and mode conversion shall be ignored, motivated by the fact that soil layering is rarely plane, and numerous inhomogeneities may exist in the ground which will frustrate more detailed analysis. Thus, the reflected wave amplitude is estimated as

$$v_{ref} = v_{inc} \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \qquad 3.4a$$

and the transmitted wave as

$$v_{trans} = v_{inc} \frac{2\rho_1 c_1}{\rho_1 c_1 + \rho_2 c_2} \qquad 3.4b$$

Consider only the transmitted wave, and assume that the incident wave amplitude is known. In this case, the effect of soil stiffness discontinuity is simply represented by the transmission coefficient. In particular, for transmission of shear waves from a soft soil to rock, the impedance ratio $\rho_2 c_2/\rho_1 c_1$ may be as much as 10 or more. In this case, the transmitted wave amplitude would be 2/11 that of the incident wave amplitude, and the resulting attenuation in dB would be about 15 dB. In practice, attenuations in excess of 20 dB are observed, illustrating the conservative nature of the estimate. The shear wave velocity should be used in estimating the transmission coefficient, since shear waves are usually dominant in ground vibration.

The second case, that of a smoothly increasing soil stiffness, is more difficult to consider. A simple approach, however, is to assume that the intensity of downgoing waves is constant with depth, and that there are no up-going waves. The intensity, I, is proportional to the square of the vibration velocity:

$$I \simeq \rho c v^2 \qquad 3.5$$

Thus, if $\rho_1 c_1$ and $\rho_2 c_2$ are the impedances at depth Z_1 and Z_2, respectively, and v_1, v_2 are the corresponding particle velocities, one obtains as a rough approximation:

$$\frac{v_2}{v_1} = \sqrt{\frac{\rho_1 c_1}{\rho_2 c_2}} \qquad 3.6$$

Again, one should use the shear wave velocity, c_s. Assuming a 10 to 1 impedance ratio, the attenuation will be about 10 dB, significantly less than that predicted for the reflection/transmission problem. For practical problems, the impedance ratio over a smoothly increasing stiffness will probably not be as large as 10 to 1. A factor of 2 to 1 may be more realistic. In this case, the attenuation would be about 3 dB. Thus, the correction for smoothly increasing soil or rock stiffness (impedance) should be viewed as relatively minor in comparison with the correction due to transmission across a discontinuity.

Attenuation due to reflection/transmission through multiple layers is discussed by Schoenberger and Levin (1974). Secondly, the methods discussed by Aki and Richards would yield substantially improved estimates.

3.5 Half Space Model

The response of an elastic half-space to point surface loading is critical to understanding and interpreting measured ground vibration data. Presented here is a simple model based on the problems of Boussinesq and Lamb (Fung, 1965, pg. 205, and pg. 214). These two problems concern vertical point loads acting normal to the plane surface of an elastic semi-infinite medium. Boussinesq's problem concerns a static load, while Lamb's problem concerns sinusoidal loads. Both of these problems are classics in the literature.

The problem is illustrated in Figure 3.2. The elastic half-space is homogeneous and isotropic, characterized by the mass density, ρ , and the Lame parameters λ , μ . These are related to Young's modulus, E, and Poisson ratio, ν , by

$$E = 2\mu(1+\nu)$$

$$\nu = \frac{\lambda}{2(\lambda+\mu)} \qquad 3.7$$

The shear modulus for the material is simply the Lame parameter, "μ ". For later reference, the propagation velocities for shear and compression waves are, respectively:

$$c_s = \sqrt{\frac{\mu}{\rho}} \qquad c_p = \sqrt{\frac{\lambda+2\mu}{\rho}} \qquad 3.8$$

Before proceeding, Graf (1975) provides a summary of the literature concerning solutions to this problem for a horizontal and torsional point loads in addition to the vertical load case considered here. See also Richart, Hall, and Woods (1970), Fung (1965), and Barkan (1962). As it turns out, there are no "exact" mathematical expressions for the vertical point load problem in the frequency domain, though elegant temporal solutions have been obtained via the Cagniard-de Hoop method, described by Graf (1975). See also the papers by Pekeris who provides exact temporal solutions for surface and buried sources.

3.5.1 Body Waves

Miller and Pursey (1955) have provided approximate solutions to Lamb's problem for radiated body waves, those spreading with an amplitude dependence of 1/r at large distance. These solutions are, with respect to Figure 3.2:

$$u_R(r,z,\omega) = \frac{P_o e^{i\omega t}}{2\pi\mu} \frac{e^{-k_p R}}{R} \Theta_R(\theta) \qquad 3.9$$

$$u_\theta(r,z,\omega) = \frac{iP_o e^{i\omega t}}{2\pi\mu} a^3 \frac{e^{-ik_s R}}{R} \Theta_\theta(\theta) \qquad 3.10$$

$$\Theta_R(\theta) = \frac{\cos\theta(a^2-2\sin^2\theta)}{F_o(\sin\theta)} \qquad 3.11$$

$$\Theta_\theta(\theta) = \frac{\sin 2\theta(a^2\sin^2\theta-1)^{1/2}}{F_o(a\sin\theta)} \qquad 3.12$$

$$F_o(\alpha) = (2\alpha^2-a^2)^2 - 4\alpha^2\sqrt{\alpha^2-a^2}\sqrt{\alpha^2-1} \qquad 3.13$$

$$k_p = \frac{\omega}{c_p} \qquad k_s = \frac{\omega}{c_s} \tag{3.14}$$

$$R = \sqrt{r^2 + z^2}$$

$$a = \frac{k_s}{k_p} = \frac{c_p}{c_s} \tag{3.15}$$

The displacements are u_R and u_θ corresponding to the longitudinally and transversely polarized particle displacements, as defined in Figure 3.2. The vertical and horizontal displacement components may be constructed as

$$u_z = u_R \cos\theta - u_\theta \sin\theta \tag{3.16}$$

$$u_r^B = u_R \sin\theta + u_\theta \cos\theta \tag{3.17}$$

A peculiar result of these solutions is that for an observer at the surface z = 0, the body wave response is identically zero. Also, for an observer directly beneath the source, the transverse shear wave, u_θ, is identically zero, leaving only the longitudinally polarized P-wave. The model tends to over-simply the case for vertical incidence. Secondly, most source-receiver angles are oblique, and the responses observed at oblique incidence will be representative of ground vibration magnitudes for most situations, especially for line sources or for a line receiver such as the SSC.

The above equations do not contain the near-field response, and are only accurate for values of $k_p r$, $k_s r$, >>1. In practice, they probably give reasonable estimates for values of $k_p r \geq 1$. For $k_p r < 1$, the near-field response must be included, which will be contained in the static solution, discussed below.

3.5.2 Rayleigh Surface Wave

Miller and Pursey (1955) also provide solutions to Lamb's problem for the surface wave. The vertical and horizontal displacements at arbitrary depth, due to the surface wave motion, are:

$$u_z^R = \frac{P_o e^{i\omega t}}{\pi\mu F_o'(p)} \sqrt{\frac{\pi k_p p(p^2-1)}{2r}}\; e^{-i(k_R + \pi/4)r} \left(2p^2 e_a(z) - (2p^2 - a^2)\, e_1(z)\right) \qquad 3.18$$

$$u_z^R = \frac{-P_o e^{i\omega t}}{\pi\mu F_o'(p)} \sqrt{\frac{\pi k_p p^3}{2r}}\, e^{-i(k_R - \pi/4)r} \left(2\sqrt{p^2-1}\,\sqrt{p^2-a^2}\, e_a(z) - (2p^2-a^2)\, e_1(z) \right) \qquad 3.19$$

In these equations, "p" is a root of the Rayleigh equation, Eq. 3.13, and $F_o'(p)$ is given by Miller and Pursey (1955) as

$$F_o'(p) = 8p\left[2p^2-a^2 - \frac{(2p^2-a^2)^2}{4p^2} - \frac{2p^4(p^2-a^2-1)}{(2p^2-a^2)^2}\right] \qquad 3.20$$

Finally, the Rayleigh wave number is

$$k_R = pk_p \qquad 3.21$$

The depth dependence is contained in the function $e_a(Z)$, $e_1(Z)$:

$$e_a(z) = e^{-\sqrt{k_R^2 - k_s^2}\, z}, \quad e_1(z) = e^{-\sqrt{k_R^2 - k_p^2}\, z} \qquad 3.22$$

Unfortunately, the above formulae for far-field surface waves due to vertical point loads are valid only for large argument, $k_R r$. No exact spectral solution has been obtained thus far for the near-field or intermediate field response. Barkan (1962) summarizes a near-field asymptotic solution as $k_R r \rightarrow 0$. In particular, the vertical asymptotic response is given by

$$u_z^R = \frac{P_o e^{i\omega t}}{\mu} k_s (f_1 + if_2) \qquad 3.23$$

For Poisson-ratio $\nu = 0.5$, and setting $\gamma = k_s r$

$$f_1 = 0.0796\frac{1}{\gamma} - 0.0598\gamma + 0.00607\gamma^3 - 0.000243\gamma^5 + 0.00000517\gamma^7 + \dots \qquad 3.24$$

$$f_2 = -0.0571\ J_0(1.047\gamma) - 0.0474 + 0.00647\gamma^2 - 0.000264\gamma^4 + 0.00000517\gamma^6 + \dots$$

For Poisson ratio $\nu = 0.25$

$$f_1 = 0.119\frac{1}{\gamma} - 0.0895\gamma + 0.0104\gamma^3 - 0.000466\gamma^5 + 0.0000109\gamma^7 + \dots \qquad 3.25$$

$$f_2 = -0.0998\ J_0(1.08777\gamma) - 0.0484 + 0.00595\gamma^2 - 0.000240\gamma^4 + 0.00000484\gamma^6 + \dots$$

Values for Poisson ratio $\nu = 0.0$ are also given by Barkan, but most soils have a Poisson ratio between 0.25 and 0.5.

For comparison, the static solution, $\omega = 0$, (this is Boussinesq's problem) is given by Fung (1965, pg. 205):

$$u_z^S = \frac{Po}{4\pi\mu R}\left[2(1-\nu) + \frac{z^2}{R^2}\right] \tag{3.26}$$

$$u_r^S = \frac{P_o}{4\pi\mu R}\left[\frac{rz}{R^2} - (1-2\nu)\frac{r}{z+R}\right] \tag{3.27}$$

where, as above, $R = \left(r^2 + z^2\right)^{1/2}$. For a Poisson ratio $\nu = 0.25$, and $z = 0$, the vertical static displacement is

$$u_z^S = \frac{3P_o}{8\pi\mu r} = 0.119\,\frac{P_o}{\mu r} \tag{3.28}$$

For a Poisson ratio of $\nu = 0.5$,

$$u_z^S = \frac{P_o}{4\pi\mu r} = 0.0796 \frac{P_o}{\mu r} \qquad 3.29$$

These static solutions are just exactly those given by the leading terms in the approximations for f_1.

In the limit of $\alpha = k_s r \to o$ the function f_2 remains finite, and is thus overcome by the singular character of f_1 at $\gamma = 0$. For $\alpha = k_s r = 1$, the absolute magnitude of the response given by 3.23 is closely represented by the static solution for the vertical. In fact, the agreement is within about 13% for $k_s r$ as high 3. This strongly suggests using the static solution for values of $k_s r \leq 3$ for both the vertical and radial displacement amplitudes. For $k_s r = 3$, the observer is at about 1/2 wavelength from the source.

To obtain a transition between near- and far-field responses Barkan suggests choosing a transition value for $k_s r$ such that the asymptotic solution for the far-field vertical response at the ground surface is approximately equal to that predicted by equation 3.23. Therefore, Barkan suggests using the near-field approximation (Eq. 3.23) for $k_s r \leq 1$ and the far-field approximation (Eqs. 3.18 and 3.19) for $k_s r > 1$. Such close agreement between the near- and far-field solutions is not clear since the far-field approximation appears to under predict Eq. 3.23 by a factor of 2. Some additional checking of solutions for $\nu = 0.5$ and 0.25 is warranted to determine the proper transition from near to far-field. A transition point of $k_s r = 3$ is recommended unless further analysis suggests otherwise.

3.5.3 Combined Point Load Solution

For assessing ground vibration, the solution for the Rayleigh surface wave should be superposed with the body wave solution. Thus, for $k_s r > 3$, the amplitude of vertical and horizontal ground motion is given by

$$u_z(r,z,\omega) = u_z^B(r,z,\omega) + u_z^R(r,z,\omega) \qquad 3.30$$

$$u_r(r,z,\omega) = u_r^B(r,z,\omega) + u_r^R(r,z,\omega) \qquad 3.31$$

For $k_s r < 3$, the static solution should be used, given by equations 3.26 and 3.27.

3.5.4 Line Sources

To account for trains or other line sources, the response at a given point should be considered as the sum of responses to a line of incoherent point sources. That is, the spectral response is

$$u_{line}(r,z,\omega) = \left[\int_{-L/2}^{L/2} | u(r',z,\omega) |^2 \, dy' \right]^{1/2} \qquad 3.32$$

$$r' = \sqrt{r^2 + y'^2}$$

This integration is perhaps best carried out numerically. Excess attenuation due to dissipation could be included for a more realistic estimate. The integration should extend only over the source length. The load used in calculating $u(r'_1 z_1)$ should be a force density in units of Force/$\sqrt{\text{Length}}$. This procedure has been performed with good success with experimentally determined point load responses.

TABLE 3.1 TYPICAL VELOCITIES AND DENSITIES (AFTER BARKAN) FOR SOILS, PG. 316

	Density - kg/m^3 -	Shear Wave Velocity - m/s -	Compression Wave Velocity - m/s -
Moist clay	1,760	150	1,500
Loess at natural moisture	1,640	260	800
Dense sand and gravel	1,670	250	480
Fine grained sand	1,620	110	300
Medium grained sand	1,620	160	550
Medium-sized gravel	1,760	180	750
Granite	2,700-3,000	2,000-3,000	5,000-6,000
Shale	2,000-2,500	2,100	1,400

TABLE 3.2 ATTENUATION DATA

Soil Description	Shear Wave Velocity -m/s-	Q	α $-m^{-1}-$	Ref
Diluvial sand	260	8	--	1
Alluvial silt	102	20	--	1
Tertiary mudstone	420	6.5	--	1
Kuanto loam	150	5	--	1
Yellow saturated fine grained sand	--	--	0.1	2
Yellow saturated frozen fine grained sand	--	--	0.06	2
Gray saturated sand with laminae of peat and organic silt	--	--	0.04	2
Clayey sands, above water table	--	--	0.04	2
Heavy saturated brown clay	--	--	0.04-0.12	2
Marley chalk	--	--	0.1	2
Loess and Loessial soil	--	--	0.1	2

1. Kudo, K. and Shima, S., "Attenuation of Shear Waves in Soil," Bulletin of the Earthquake Research Institute v. 48, pg. 145-158.

2. Barkan, D. D., "Dynamics of Bases and Foundations," pg. 347.

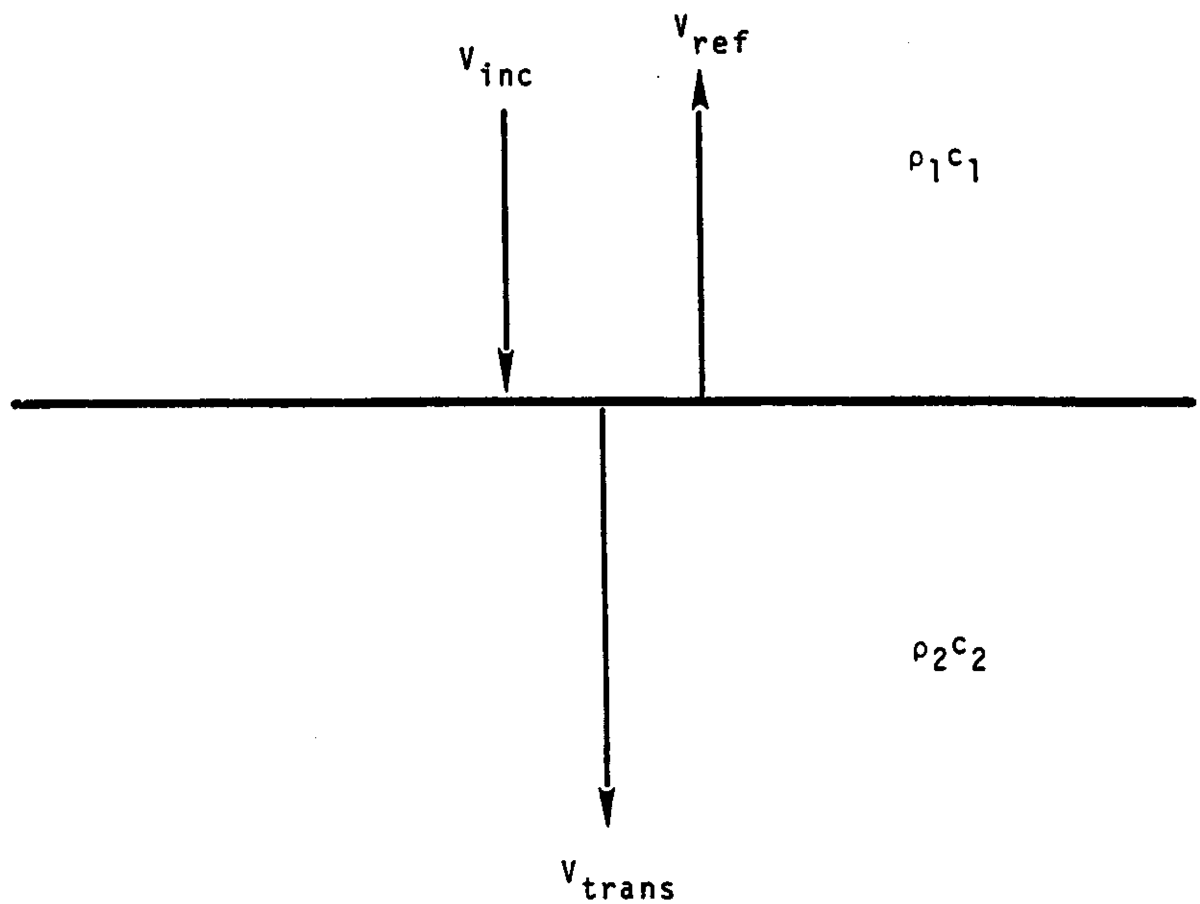

FIGURE 3.1 REFLECTIONS AND TRANSMISSION AT A PLANE INTERFACE

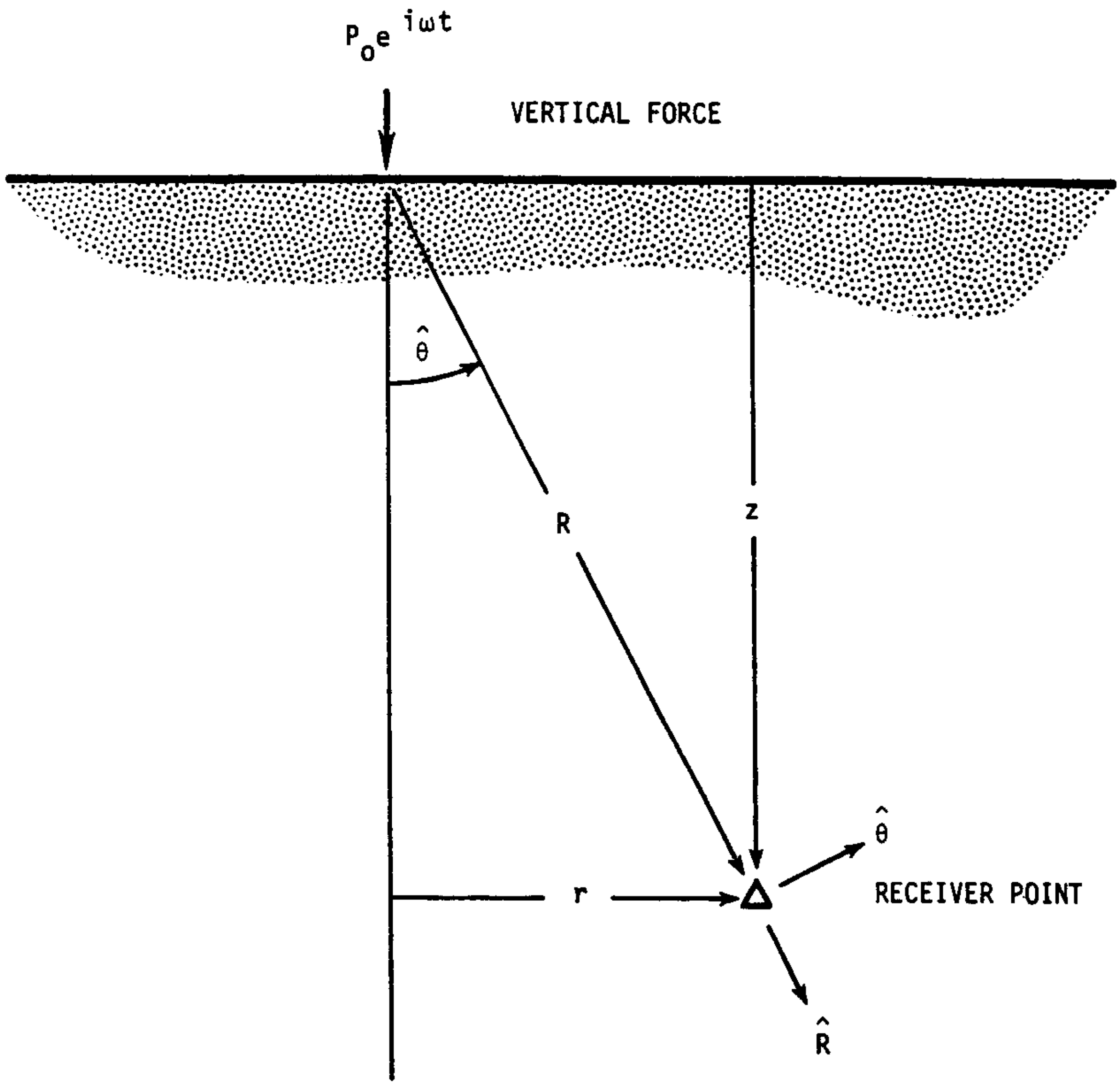

FIGURE 3.2 VERTICAL POINT LOAD ON SURFACE OF ELASTIC HALF-SPACE

4. SITE VIBRATION SURVEY

Recommended procedures for experimentally evaluating the vibration environment of proposed sites for the SSC are given below. The discussion includes field and laboratory procedures, data presentation, and instrumentation. Uniform test procedures and data presentation methods are recommended to simplify comparing data collected at different sites. Another feature is the use of procedures which are common to the vibration control industry. Moreover, 1/3 octave band spectral analysis techniques rather than narrow band constant bandwidth analyses (FFT-based) techniques are recommended. A uniform metric for spectral data should be adopted; namely, the vibration velocity in microns/sec or the vibration velocity level in dB re 10^{-8}m/sec. The choice of the metric system is based on the assumption that the scientific community will be the primary audience regarding site vibration data (despite the fact that virtually all of the data presented above are in dB re 1 micro-in/sec or in dB re 1 micro-g). To convert from velocity spectra in dB re 10^{-8}m/sec, see, for example, Figure 2.1 in which constant displacement curves are plotted against velocity levels in db re 10^{-8}m/sec, shown on the right hand scale.

The basic approach to performing a site vibration survey includes documenting the spectral and amplitude characteristics of vibration for both surface and sub-surface locations, the latter requiring down-hole measurements. Very critical detector sites should include triaxial data, while less critical areas may require measurement of only vertical vibration. Time domain data should be recorded continuously for laboratory analyses and archival storage. Laboratory analyses should include 1/3 octave band analysis and peak-detected velocity and/or displacement. Additional analyses may include narrow band constant bandwidth FFT-based spectral analyses. For non-stationary vibration, a statistical analysis of 1/3 octave vibration velocity and displacement levels, or possibly only the overall vibration velocity or displacement level, should be performed. Examples include vibration caused by highway and industrial sources. These latter techniques have been applied in site surveys on numerous occasions for the semi-conductor industry.

4.1 Measurement Locations

Measurement locations will depend on the type of vibration source and particular component of the SSC system. All locations should be directly over the alignment of the beam, since this is the most critical area, and obtaining data as representative as possible is important. Soil and rock layering geometry are rarely uniform and significant variation in propagation characteristics can be expected from point-to-point.

Down-hole measurements are recommended in addition to surface measurements as the only un-ambiguous way to determine vibration amplitudes at depth. Practical borehole measurements can be done using local drilling contractors. Often, cased holes will not be necessary (depending on depth), requiring only a 4" or 5" diameter hole. The risk with an uncased hole is loss of the transducer. The borehole measurements might be conducted at the same time as the soil pre-construction surveys, which involve the same drilling apparatus, thus reducing overall costs for downhole vibration surveys.

One can also contemplate performing downhole measurements at each pre-construction soil survey hole in the vicinity of vibration sources, though this is not specifically recommended. This procedure would provide substantial data at beam depths with possibly relatively small increases in cost, depending on coordination between test personnel.

Vibration due to trains will perhaps be the most severe of all. For this type of vibration, measurement points should be distributed along the ground surface directly over the proposed beam alignment at the following distances from the track centerline:

50 feet
100 feet
200 feet
400 feet
800 feet

An additional measurement at 1600 ft may be advisable if data collected at 800 ft indicate excessive vibration levels. The length of a typical railroad train may be long in comparison with the typical source-receiver distance. The train should be considered as a line of incoherent point sources, though partially coherent vibration radiation may be possible. For this reason, measurements at large distances are recommended. If the beam approaches the railroad track alignment, but does not pass beneath it, measurements should be performed at the point closest to the track, as well as at the more distant points given above.

Because of the possible severity of vibration due to trains, down-hole measurements at the projected depth of the SSC beam, and directly over the beam alignment, should be conducted at 50 ft and perhaps 200 ft from the track centerline using boreholes. Measurements should be conducted at mid-depth and at the surface for projecting vibration magnitudes, or levels, at other locations. These data will be valuable for checking the model given in Section 3 for estimating attenuation with depth. If the beam depth is less than 50 feet, the horizontal distance between borehole and track center should be equal to the beam depth.

Highway vibration is usually less severe than train vibration, primarily because of lower vehicle weights and the dispersed nature of the sources. However, trucks passing over a "washboard", "pothole", or other irregularity, may generate substantial transient vibration. Measurement points should be located at the ground surface directly over the beam alignment at the following distances from the nearest lane.

50 feet
100 feet
200 feet
400 feet

At least one borehole measurement at beam depth should be conducted, with additional measurements at mid-depth and surface for checking attenuation with depth. The distance of the bore hole from the nearest lane should be the lesser of the beam depth or 50 ft. In the case of a freeway, the bore hole might be located in the median.

Stationary sources of vibration, such as reciprocating pumps and compressors, usually produce lower levels of vibration than either trains or auto and truck traffic. On the other hand, vibration caused by a stamping machine or other large source can be very significant. In industrial areas through which the SSC beam may pass, a series of surface ground vibration measurements should be conducted along the beam alignment. Measurement locations should be limited to where the alignment passes close to industrial facilities or buildings. Source-receiver distances should be noted and used to estimate sub-surface vibration magnitudes from the measured surface data. The spacing between measurement points should be sufficient to characterize the area. Moreover, plant and equipment operators should be interviewed to determine specific sources of vibration. If projected sub-surface vibration levels are excessive, a down-hole test should be conducted to determine actual severity. The borehole test might be coordinated with preconstruction survey drilling, as discussed above.

The question of whether or not to perform ambient vibration measurements in remote areas for documenting seismic motion should be considered. Displacements in excess of one micron due to natural seismicity might occur at very low frequencies below 1 Hz. In addition to natural faulting activity, background seismicity is caused by barometric pressure fluctuations and the ocean waves along the coasts. Both of these effects are observed at mid-continent locations. To cover these effects, ambient seismic surveys could be conducted at each proposed target area. The survey should probably be performed at beam depth, requiring very specialized intermediate period seismographs (0.1 Hz to 1 Hz) for borehole applications. The cost for this may be excessive, however, and a surface measurement may be sufficient to "verify" that seismic motion is within criteria. A review of natural seismicity in the area of the proposed site for the SSC should be conducted before deciding whether or not to conduct an intermediate period seismic survey. If a survey is performed, it should probably be performed at a time when there is a large storm occurring along the nearest coast, or during periods with large barometric changes. Fischer (1985) provide a good discussion of ambient intermediate period seismisity.

4.2 Sample Times and Duration

For train vibration, the sample time is naturally determined by train scheduling. The railroad company should be contacted to determine schedules or approximate schedules of train operation to allow coordination of test personnel, drillers, etc.

The time period for collecting highway vibration should include the weekday period 10:00 a.m. to 4:00 p.m., during which time vehicle speeds are likely to be greatest, thus producing the highest levels of vibration. Vehicle speech during rush hours may be low, due to traffic jams and may thus not be representative. Interstate highways through rural areas may not have a well defined peak hour or rush hour period, in which case measurements at any time of day are appropriate. The main goal is to capture numerous representative samples of ground vibration due to trucks and other heavy vehicles as well as automobile traffic. Truck and auto traffic counts should be made for each measurement where feasible.

For stationary sources, such as pumps, compressors, stamping machines, etc., tests will have to be scheduled during the normal operating periods of these various equipment. Plant and equipment personnel must be contacted to determine when such equipment will be operated. Unscheduled operation of heavy equipment or machinery for ground vibration measurements is unlikely.

Sample duration will depend on the source or type of vibration. For railroad train vibration, the sample duration should be long enough to include the entire passby of the train, plus some extra time to obtain the rise and fall of vibration as the train approaches and recedes. Secondly, a background sample of ground vibration should be obtained immediately prior to or after the train passby.

Sample durations for highway vibration should be between 20 and 40 minutes, although 10 minutes will be adequate if sufficiently high volumes of traffic exist. Traffic vibration should be described in statistical terms because of the highly variable nature of vehicles, vehicle speeds, loading, etc. Thus, relatively long samples of vibration are required to allow statistical analyses to be performed. These analyses procedures are described below.

For stationary sources such as pumps, compressors, etc., representative samples must be obtained, but need not be long. Sample durations of 1 minute are usually adequate for most analyses, including narrowband FFT analyses.

4.3 Frequency Range

The spectral range of man-made vibration depends strongly on the nature of the source, rotation or reciprocation frequencies, passby rate, etc. A frequency range of 1.0 Hz to 100 Hz should be selected as a standard range for analysis. For recording purposes, this range should be extended to 0.5 Hz to 200 Hz, i.e., a full octave above and below the nominal analysis range. This should cover the entire range of man-made or cultural vibration which can be practically measured using seismic accelerometers and low noise instrumentation. Measurements in excess of this range, e.g. 0.3 Hz to 300 Hz are being performed for the aerospace industry for evaluation of vibration exposures of certain optical experiments. Extending the measurement range to 0.3 to 300 Hz can be done practically, but may impact the cost of vibration survey work substantially. Secondly, vibration below 0.5 to 1 Hz might be more effectively covered during the course of seismic surveys involving use of long or intermediate period seismometers.

4.4 Recording Procedures

All data collected should be recorded in time domain form using continuous frequency modulated carriers or digital techniques. Discrete "1024-Point" temporal data should not be employed except perhaps for measurements of discrete impulsive events such as blasts or "sonic booms". Continuous recordings provide maximum flexibility during data analyses. The tape recordings should be catalogued and stored for archival purposes should additional analyses be required for detailed design of vibration isolation systems or for modeling purposes. For maximum efficiency, Use of computer tapes for storage of temporal data should be avoided, especially since data can be stored and reproduced as conventional FM magnetic tape recordings quite easily. Results of frequency analyses could be digitized and stored for archival purposes.

To achieve the maximum dynamic range, data should be recorded as vibration velocity. If accelerometers are used, analog integration of accelerometer signals may be required to convert the analog acceleration data to analog velocity data prior to recording. Analog displacement is not recommended for recording because of the extreme de-emphasis of high frequency data. If geophones or seismometers are used, the data will already be in analog velocity form.

Announcements should be recorded on a separate channel or, if on a data channel, after a data sample. Announcements should include test object, location, time of day, gain settings, etc. A parallel set of written notes should be produced. Recording levels should be adjusted to utilize the maximum dynamic range of the recorder. Instrumentation gain should be adjusted in 10 dB steps to achieve optimum recording conditions. Clipping or overloading of data must not occur, so that gain settings should be under-estimated rather than over-estimated.

4.5 Analysis Procedures

Analysis procedures will depend on the character of vibration being studied. The primary spectral analysis technique should be 1/3 octave band analysis, supplemented by zero-to-peak overall vibration displacement and/or velocity measurements. The 1/3 octave band data provide information on the spectral character of vibration and the type of vibration isolation provisions which may be required. The peak displacement or velocity measurements provide a measure of the crest factor associated with the data.

One-third octave band analyses are performed with constant percentage bandwidth filters meeting ANSI Standards S1.11 specifications for Class III (high attenuation) filters. These filters are ideal for analyzing noise and vibration data and are standards in the industry. The typical approach is to measure the level in dB of the rms vibration velocity passed by these filters over an integration time which will vary from perhaps as little as a fraction of a second to as long a time period as may be desired. For ground vibration down to perhaps 1 Hz, a minimum of 1 second should be used. One-third octave filters have effective noise bandwidths of 23% of their nominal center frequencies. One-third octave band analyses of random vibration data may be converted to power spectral estimate by dividing the 1/3 octave band mean square velocity by the filter's effective noise bandwidth, a function of the filter's nominal center frequency. See Section 2 for a discussion of converting 1/3 octave data to PSD data.

A second approach to spectral analysis includes the use of a Fourier transform (FFT) analyzer to produce constant bandwidth spectral analyses. These data are ideal as input data to numerical models of experimental apparatus, but are difficult to compare and evaluate because of the tremendous detail provided by the spectral analysis. Secondly, constant bandwidth data have high relative resolution at high frequencies and poor relative resolution at low frequencies. For these reasons, 1/3 octave analysis is the recommended primary spectral analysis procedure for comparing vibration data collected at a number of different sites. FFT analyses are useful, however, and may be considered as an additional analysis technique to supplement the 1/3 octave band analyses. In particular, the root-sum-square function, obtained by

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integrating the displacement power spectral density with respect to frequency, is commonly used for evaluating vibration data and could be considered as a very useful addition to the spectral data.

Peak displacement or velocity measurements should be performed over a specified bandwidth. Often, the bandwidth is limited by natural source and transmission characteristics. For example, most ground vibration velocity data will peak in the 10 Hz to 60 Hz region, although vibration in rock may have substantial energy at higher frequencies. If necessary, an upper frequency limit of 100 Hz should be placed on peak vibration velocity measurements and be defined by a low pass simple RC or two-pole Butterworth filter. Intermediate upper frequency limits may be desirable - e.g. 10 Hz and 50 Hz, depending on the vibration sensitivity of the SSC beam apparatus. Higher order filters are not recommended due to possible ringing or poorly defined pass band characteristics. The low pass simple RC network or two-pole Butterworth filters have reasonably flat responses over most of the frequency range and are 3 dB down (x.707) at their nominal roll-off frequencies - e.g. 100 Hz. Above the roll-off frequency, the eventual attenuation rate is +6 dB or 12 dB per octave, respectively. Actual roll-off frequencies may be adjusted to conform with SSC design considerations.

Depending on the outcome of studies regarding vibration sensitivity of the SSC beam, a measurement of peak displacement may be most desirable. In this case, the low frequency roll-off should be defined at perhaps 0.5 Hz,and no upper frequency limit should be used other than that provided by the recording and transducer equipment. Peak-to-peak displacement is often used in the industry. However, the recommended quantity is the zero-to-peak displacement since zero is the assumed reference point. The unit for data presentation should be the micron or 10^{-6} meter. Alternatively, the vibration displacement level in dB re 10^{-11}m provides a convenient logarithmic scale. No data should be displayed on a strip chart record as the peak magnitude in microns or microns per second. The vertical scale should be logarithmic, 5 dB/centimeter, and the horizontal scale should be 1 second/mm. An example is given in Figure 4.2.

Quantifying peak displacements or displacements or velocities can be difficult and subject to interpretation. The usual procedure is to count and tabulate magnitudes of events which exhibit peak values in excess of some magnitude or criteria. In practice, significant ambiguities and a degree of arbitrariness exist in the process for non-stationary random vibration due to highway traffic. An alternative approach is to measure the statistical distribution, or histogram, of vibration displacement or velocity levels in 1 dB increments. This approach is fundamental to characterizing community and environmental noise, and a variety of instrumentation is available for performing such measurements. An extension of this process is to perform a 1/3 octave band statistical analysis, equivalent to the above but performed over each 1/3 octave band. This approach has been used for characterizing proposed sites for high resolution (sub-micron) semi-conductor wafer fabrication facilities. The statistical analysis should be developed from an ensemble of 1-second samples of rms 1/3 octave or overall vibration displacement or velocity levels. Contiguous samples are desirable but not strictly necessary. A histogram is formed to compute L_n, the level of vibration in dB exceeded n percent of the time. The parameter "N" may be 0 (L_{max}), 1, 10, 50, or any other desired percentage. The histogram can also be used to compute the equivalent vibration displacement or velocity level, L_{eq}. L_{eq} is the level in dB of continuous vibration equivalent in energy to the time varying velocity level. L_{eq} is also exactly equal to the level in dB of the rms vibration velocity determined for the sample duration.

Statistical analyses are usually performed over sample durations of 10 minutes or more, and may extend for 24 hours. An example of a vibration velocity level histogram is given in Figure 4.1.

4.5.1 Stationary Steady-State Sources

Steady-state vibration produced by stationary sources such as pumps, compressors, etc., should be analyzed in terms of 1/3 octave band rms velocity levels and peak vibration displacement or velocity levels. A 16-second to 32-second integration time should be used. A shorter time is required if the vibration is transient in nature, e.g., rising to a maximum level for a few seconds, then decaying. In this case, the maximum "rms" level should be obtained by analyzing only the plateau of the vibration. An FFT spectral analysis will provide useful information on discrete frequencies, thus aiding identification of sinusoidal sources.

4.5.2 Non-Stationary Random Vibration - Highways

Non-stationary random vibration such as produced by highway truck and auto traffic should be analyzed on a statistical basis. The recommended approach is 1/3 octave band statistical analysis as described above. At the very least, the overall vibration velocity or displacement should be subjected to statistical analysis, provided that 1/3 octave analyses of vibration produced by individual trucks and autos are presented. The 1/3 octave band statistical analysis is a practical means of representing vibration produced by a wide variety and number of vehicles. The overall velocity or displacement statistics may be plotted on probability paper or, alternatively L_1, L_{10}, L_{50}, and L_{eq} may be tabulated.

Peak vibration displacement or velocity analysis of road traffic vibration should be performed in addition to 1/3 octave band analysis. The purpose of peak vibration analysis is to capture transients caused by vehicles passing over potholes or other roadbed irregularities. Peak levels will not be captured reliably by the statistical analysis described above. Factors of 2 or more may be expected between peak magnitudes and the lower rms magnitudes.

4.5.3 Train Vibration

One-third octave band analyses should be performed during passage of locomotives and again during passage of the rail cars. In the former case, the integration or averaging time should be limited to the engine passby duration. In the latter case, the analysis should be extended to perhaps 30 seconds to 1 minute or more. Peak vibration velocity or displacement analysis should be performed over the entire train passby.

4.5.4 Sonic Booms, Blasting

Analysis of transient vibration such as blasting or sonic booms is complicated by the fact that the rms magnitude or level is not definable. An alternative to the above procedure is to analyze the entire transient vibration signature with a 1/3 octave band analyzer and normalize the result to 1 sec. That is, add 10 Log (T) to the measured velocity level in dB, where T is the averaging or integration time. The result will be an un-ambiguous measure of the 1/3 octave band "energy" associated with the event. A Fourier analysis of a transient event is of practical value also. In this case, the amplitude of the Fourier transform of the transient vibration signature may be measured using a conventional FFT analyzer with "rectangular" weighting. Regardless of the spectral analysis procedure, of prime importance is the peak velocity or displacement and the fundamental period of the event, given by the spectral analysis.

4.6 Instrumentation

Instrumentation capable of performing the measurements outlined above are described below. These instruments are common in the industry of vibration control engineering, though may involve considerable expense and some software development.

4.6.1 Transducers

The most practical transducer for measuring ground vibration in the range of 1 Hz to 300 Hz is a seismic accelerometer. A good commercial unit has the following specifications:

Sensitivity:	10 v/g
Noise Floor:	0.5 g broadband (0.1 to 500 Hz)
	0.05 g/Hz$^{1/2}$ @ 1 Hz
	0.002 g/Hz$^{1/2}$ @ 10 Hz
Frequency Range:	0.1 to 300 Hz ± 10%
Weight:	<1 kg

Accelerometers meeting these specifications will provide data capable of resolving displacements of less than .02 micron/Hz$^{1/2}$ at 1 Hz and can be used at frequencies as low as 0.3 Hz. These accelerometers are ideal for performing low level ground vibration studies, exhibiting very little phase shift over the frequency range of interest. Low phase shift is very desirable for peak amplitude analysis.

The seismic accelerometer can be effectively coupled to the ground surface using 12" to 16" aluminum spikes with an "x" cross-section to maximize the soil contact area. An alternative and less practical approach is to bury the accelerometer in a water tight housing to avoid surface noise pick-up. For asphalt or concrete surfaces, scientific wax makes a good temporary adhesive bond between accelerometer and test surface.

If an accelerometer is used, an analog integrator may be advisable to convert the analog acceleration signal to analog velocity to take maximum advantage of the limited dynamic range of instrumentation recorders. Often, much of the ground vibration energy is between 10 and 30 Hz, while data in the 1 Hz region is still of interest. This low-end data may be forced into the noise floor of the instrumentation recorder if recorded as acceleration data. The analog integrator improves the low frequency signal-to-noise ratio. Analog integration can be achieved with a "simple RC" resistor capacitor network with corner frequency of 1 Hz (3 dB down at 1 Hz). A good low noise high input impedance amplifier is required to amplify the integrated data. If practical, acceleration data should be recorded directly.

The 1 Hz geophone is an alternative to the seismic accelerometer, offering substantially improved resolution, or lower noise floor, at frequencies below perhaps 5 Hz to 10 Hz. Their primary limitation is bulkiness, higher mass, leveling requirements, and poor high frequency response. These transducers are velocity transducers with a frequency range usually limited to 1 Hz to 20 Hz. Above 20 Hz, they are subject to spurious resonances, and their high mass to base area contact ratio precludes good coupling at higher frequencies. These units are often supplied with adjustable legs for levelling, and these legs do not allow good coupling with soils at higher frequencies. Below 1 Hz, their sensitivity rolls off at 12 dB per octave frequency. They are, however, very respectable instruments and are ideal for measuring very low amplitudes of ground vibration velocity. Also, manufacturers can provide 1 Hz geophone packages for down-hole use.

4.6.2 Amplifiers

When performing a ground vibration survey, good quality, wide dynamic range, low noise FET input amplifiers are required to amplify analog vibration data to levels suitable for recording on an instrumentation recorder. The amplifier frequency response should be ± 1 dB from 1 Hz to at least 1 kHz and should have an equivalent input noise voltage of about 30 nano-volts/$Hz^{1/2}$ or less at 10 Hz. Substantially quieter amplifiers can be obtained. The FET input is required to maintain low input leakage currents, thereby maintaining low noise floors at very low frequencies in the presence of coupling or blocking capacitors. This is a critical consideration when amplifying low level data below 1 Hz.

4.6.3 Recording Instrumentation

The most practical approach for recording continuous time domain data is to use frequency-modulated carrier recording techniques (fm). Four-channel battery operated fm recorders are available for this purpose (e.g., B&K 7000 series). Several 8-channel line operated units are also available (Hewlett Packard, Racal), but require a portable generator or storage batteries at remote locations. A portable generator will contribute to the background noise in the ground and should be avoided.

4.6.4 Analysis Instrumentation

Commercial 1/3 octave band real time analyzers are available for analyzing analog vibration data. Historically, these analyzers could accommodate sample lengths of 0.1 to about 32 or 64 seconds. Recently, analyzers have become available for extended periods of analysis and, perhaps with some software modification, can be used for statistical analysis of 1/3 octave band data as described above, though this may best be performed with a computer interfaced to the analyzer for real time statistical data analysis. One-third octave band analyzers should feature constant percentage effective noise bandwidth (23%) filters meeting ANSI Standards S1.11 specifications for Class III filters.

One-third octave analyses can be synthesized from narrow band constant bandwidth analyses, e.g., Fast Fourier Transform spectral analyses. Several FFT analyzers are available which feature synthesized 1/3 octave bands. This approach is not recommended, however, since precise agreement between the two approaches at the low end of the frequency range is difficult to obtain, in spite of manufacturers' claims. Basically, 1/3 octave band filters should be used for 1/3 octave analyses, and FFT analyzers should be used for FFT constant bandwidth analyses. Use of the synthesized 1/3 octave approach should not be strictly prohibited, however, since there are occasions when such an approach may be the most practical.

Fast Fourier Transform (FFT) analysis of vibration data should be performed with an averaging FFT spectrum analyzer, of which several models are available (e.g., Spectral Dynamics, Bruel & Kjaer, Nicolet). These analyzers can perform spectral analyses in real time. They can be interfaced to plotters and/or computers for data display and/or further processing.

Use of computer based numerical FFT analysis is not recommended since it is usually far less efficient than use of FFT real time analyzers. This is because the FFT analyzer can digitize and process analog data automatically, while computer based approaches require that the data be digitized and stored on magnetic tape or other media. FFT analyzers can be used directly in the field provided that line power is available.

Peak detectors and analog strip chart recorders are available for performing peak velocity or displacement analyses. Examples include Bruel and Kjaer's Type 2607 Measuring Amplifier (lower frequency limit 2 Hz) and Type 2307 Level Recorder. The latter allows display of the level in dB of the d.c. analog of the peak detected signal obtained with the Bruel & Kjaer Type 2607. The frequency response of the Bruel & Kjaer 2607 Measuring Amplifier is not strictly appropriate for detecting data over the frequency range of 1 Hz to 100 Hz, due to its lower limit frequency of 2 Hz. The manufacturer should be consulted for alternatives. Secondly, very good custom peak detectors may be constructed with a few operational amplifiers, and rectifiers to generate a d.c. output signal proportional to the maximum positive or negative peak vibration amplitude.

Computers which may be interfaced to vibration analyzers to perform statistical analyses, average data, plot results, on any number of other operations, include the time-honored Digital Equipment Corporation (DEC) PDP-11 running the RT-11 or similar operating system, as well as modern desk-top IBM or HP computers. Manufacturers of 1/3 octave and FFT analyzers usually can recommend appropriate computer and software packages for performing a variety of post real time processing. The statistical level analysis discussed throughout this report may require development of custom software, though there are a number of vibration consulting firms which should be able to perform this type of analyses.

4.7 Data Presentation

Examples of 1/3 octave band analyses results are presented in the appendices. All 1/3 octave band data should be plotted using the industry standard vertical and horizontal scales of 2 cm per decade dB and 1.5 cm/octave, respectively. This allows overlaying individual charts to facilitate comparing data. The vertical scale legend should read as "1/3 Octave Band RMS Velocity Level - dB re 10^{-8}m/sec" or "1/3 Octave Band RMS Displacement - dB re 10^{-11} meter" as the case may be. The data should be accompanied with other information such as sample duration, source receiver distances, etc.

An example of 1/3 octave statistical analyses is presented in Figures C-5 through C-8. Shown are the 1/3 octave spectra corresponding to the statistical exceedance levels of L_1, L_{10}, L_{50}, etc. Also plotted is the L_{EQ}, the equivalent rms vibration spectrum for the sample period.

A histogram plot of overall rms vibration velocity levels in dB vs percentage exceedance is illustrated in Figure 4.1. The vertical scale is such that if the probability distribution of velocity level (not amplitude) is gaussian with a median value of L_{50} and a standard deviation of 10 dB, the histogram will be a straight line with slope of 45° passing through the point L_{50} and 50%. This plot is possibly the only quantitative method of presenting non-stationary random environmental vibration data. These data should be accompanied by the number of "micro" samples used to develop the histogram, and an indication of the integration time used to determine the rms level for each "micro" sample, (e.g., 1 sec) and the bandwidth of the overall velocity level (e.g., 1 Hz to 100 Hz).

An example of a strip chart record of a peak detected displacement is presented in Figure 4.2. Paper speed is 1 mm/sec and the vertical scale is 5 dB per cm. A writing speed of 100 mm/sec (100 dB/sec) was used. The vertical scale is 100 mm wide, representing a 50 dB range. The left hand scale is given in the absolute units of "microns", thus giving a convenient indication of peak magnitude.

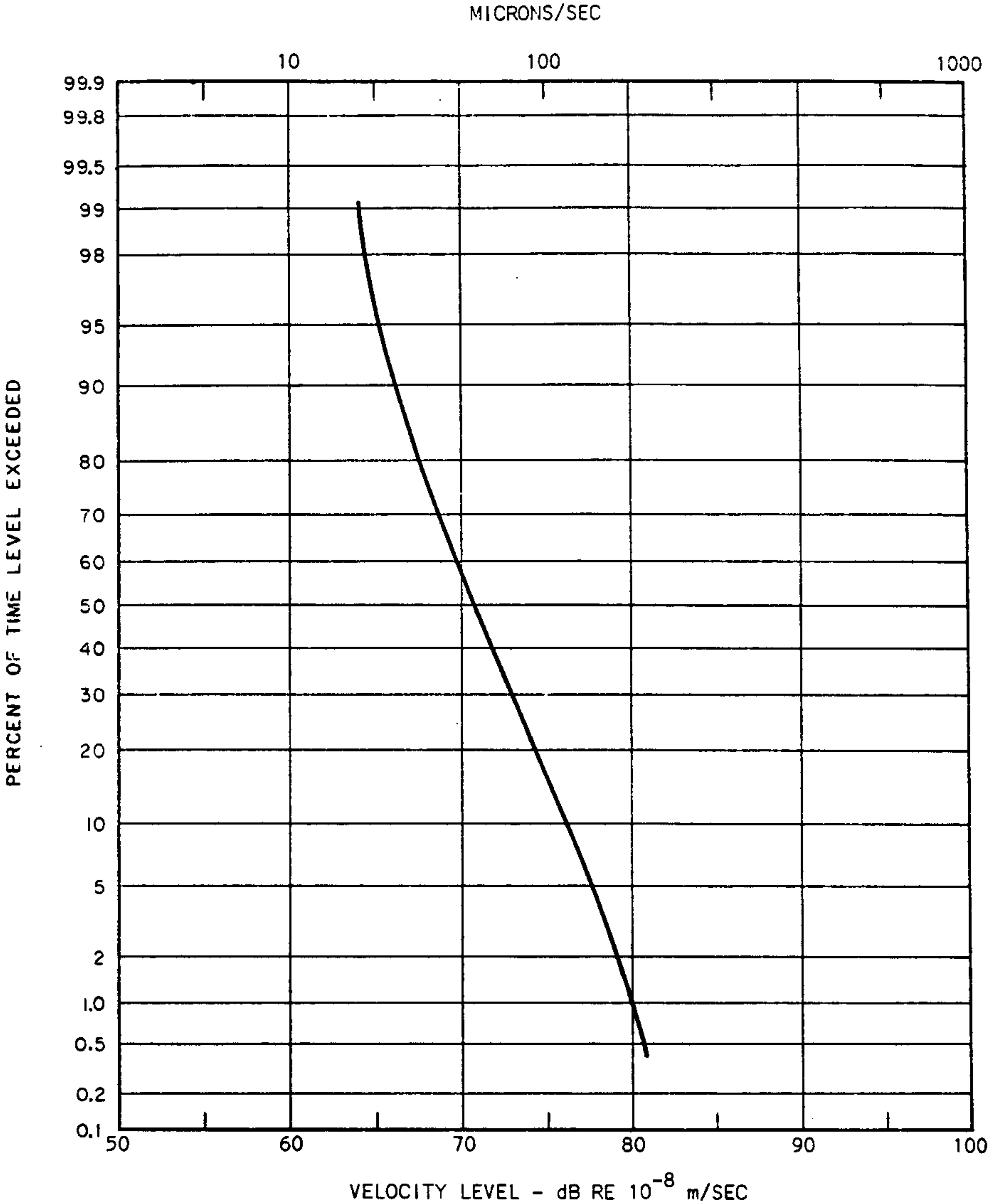

FIGURE 4.1 EXAMPLE OF STATISTICAL DISTRIBUTION OF NON-STATIONARY VIBRATION

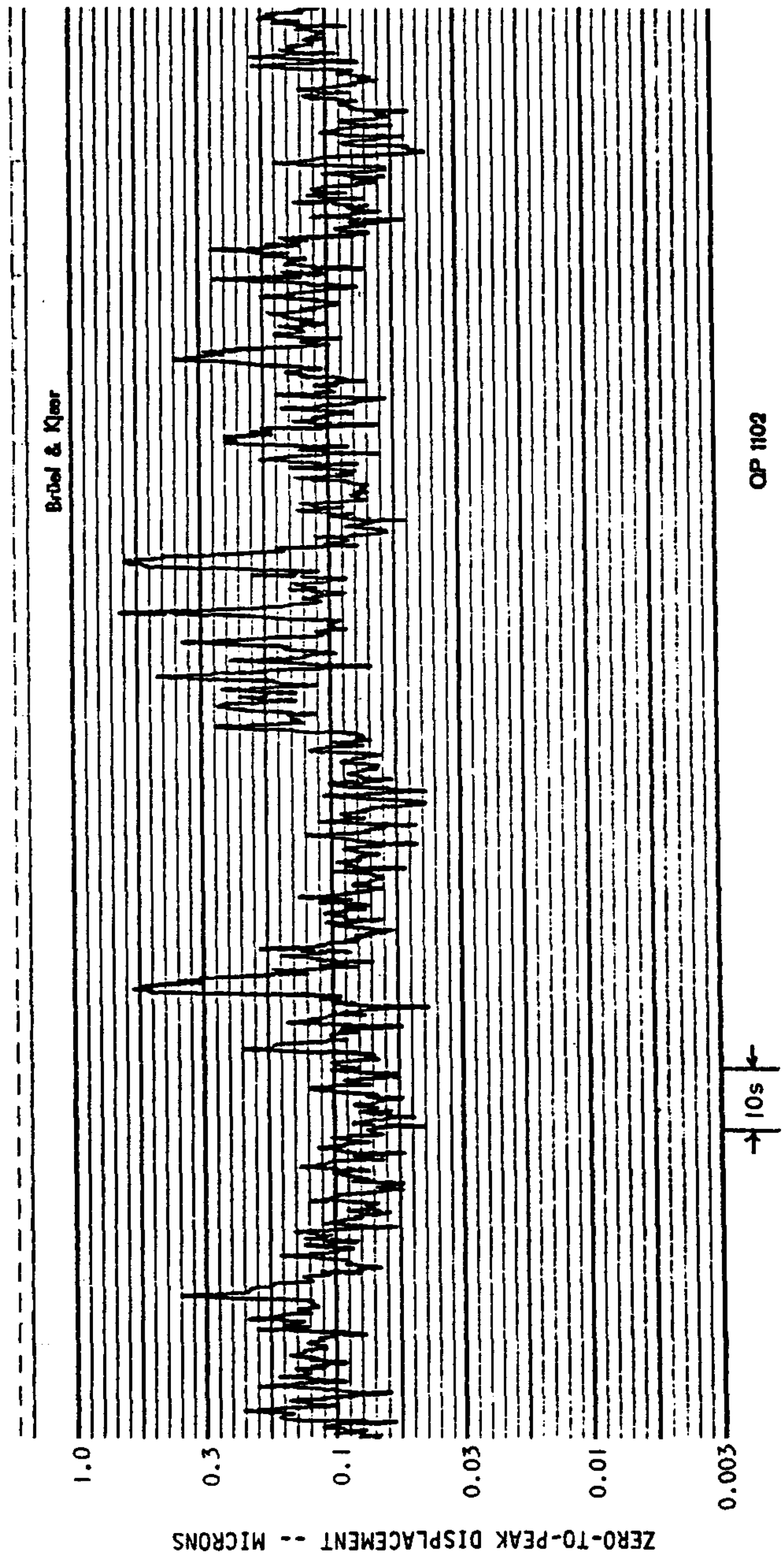

FIGURE 4.2 REPRESENTATIVE PEAK VERTICAL DISPLACEMENTS DUE TO TRAFFIC AT ABOUT 100 FEET

REFERENCES

1. "Control of Vibration and Blast Noise from Surface Coal Miners: Volumes I through IV," Wiss, Janney, Elstrom and Associates, Inc. for U. S. Department of Interior, Bureau of Mines, 1978.

2. "Seismic Wave Attenution," Edited by M. Nafi Toksoz and D. H. Johnston, Geophysics Reprint Series, Society of Exploration Geophsicists, 1981.

3. Achenbach, J.D., "Elastic Wave Propagation," North Holland, 1980.

4. Aki, K., and Richards, P.G., "Quantitative Seismology, Vol. 1: Theory and Methods," Freeman, San Francisco, CA., 1980.

5. Barkan, D. D., "Dynamics of Bases and Foundations," McGraw-Hill Book Company, New York, 1965.

6. Fischer, G. E., "Ground Motion and Its Effects in Accleration Design," SLAC-PUB - 3392 Rev., July 1985.

7. Fung, Y.C., "Foundation of Solid Mechanics," Prentice Hall, Inc., Englewood Cliffs, New Jersey, 1965.

8. Graf, K. F., "Wave Motion in Elastic Solids," Ohio State University Press (1975).

9. Kudo, K. and Shima, S., "Attenuation of Shear Waves in Soil," Bulletin of the Earthquake Research Institute, Vol. 48, PP. 145-158.

10. Miller, G. F. and Pursey, H., "On the Partition of Energy Between Elastic Waves in a Semi-Infinite Solid," Proceedings Royal Society, London, England, Vol. 233, PP. 55-69., 1955.

11. Pekeris, C. L., "The Seismic Buried Pulse," Proceedings of the National Academic of Sciences, Vol. 41, 1955, PP. 629-639.

12. Pekeris, C. L., "The Seismic Surface Pulse," Proceedings of the National Academy of Sciences, Vol. 41, PP. 469-480, 1955.

13. Pekeris, C. L. and Lifson, H., "Motion of the Surface of a Uniform Elastic Half-Space Produced by a Buried Pulse," Journal of the Acoustical Society of America, Vol. 29, No. 11, November 1957, PP. 1233-1238.

14. Richart, F. E., Hall, J. R., Jr. and Woods, R. D., "Vibrations of Soils and Foundations," Prentice-Hall (1970).

15. Schoenberger, M. and Levin, K. F., "Apparent Attenuation due to Intrabed Multiples," Geophysics, Vol. 39, PP. 278-291 (1979).

16. Siskind, D. E., Stagg, M.S., Kopp, J. W., and Dowdins, C. H., "Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting," U. S. Bureau of Mines Report of Investigation RI 8507, U. S. Department of Interior, 1980.

17. "Blasters' Handbook," Technical Service Section, Explosives Products Division, E. I. duPont de Nemours & Co. (Inc.), Wilmington, Delaware, 1977.

APPENDIX A

Ground Vibration from Railroad Operations

FIGURES A-1 THROUGH A-4

Type of Vibration:	Surface Railroad - Southern Railway
Location:	Atlanta, Georgia
Measurement Dates:	November and December 1984, October 1986
Soil Type:	Primarily loose to firm gray, white and tan silty fine to medium sand
Additional Details:	Measurements made to characterize ground vibration from railroad operations prior to relocation of tracks

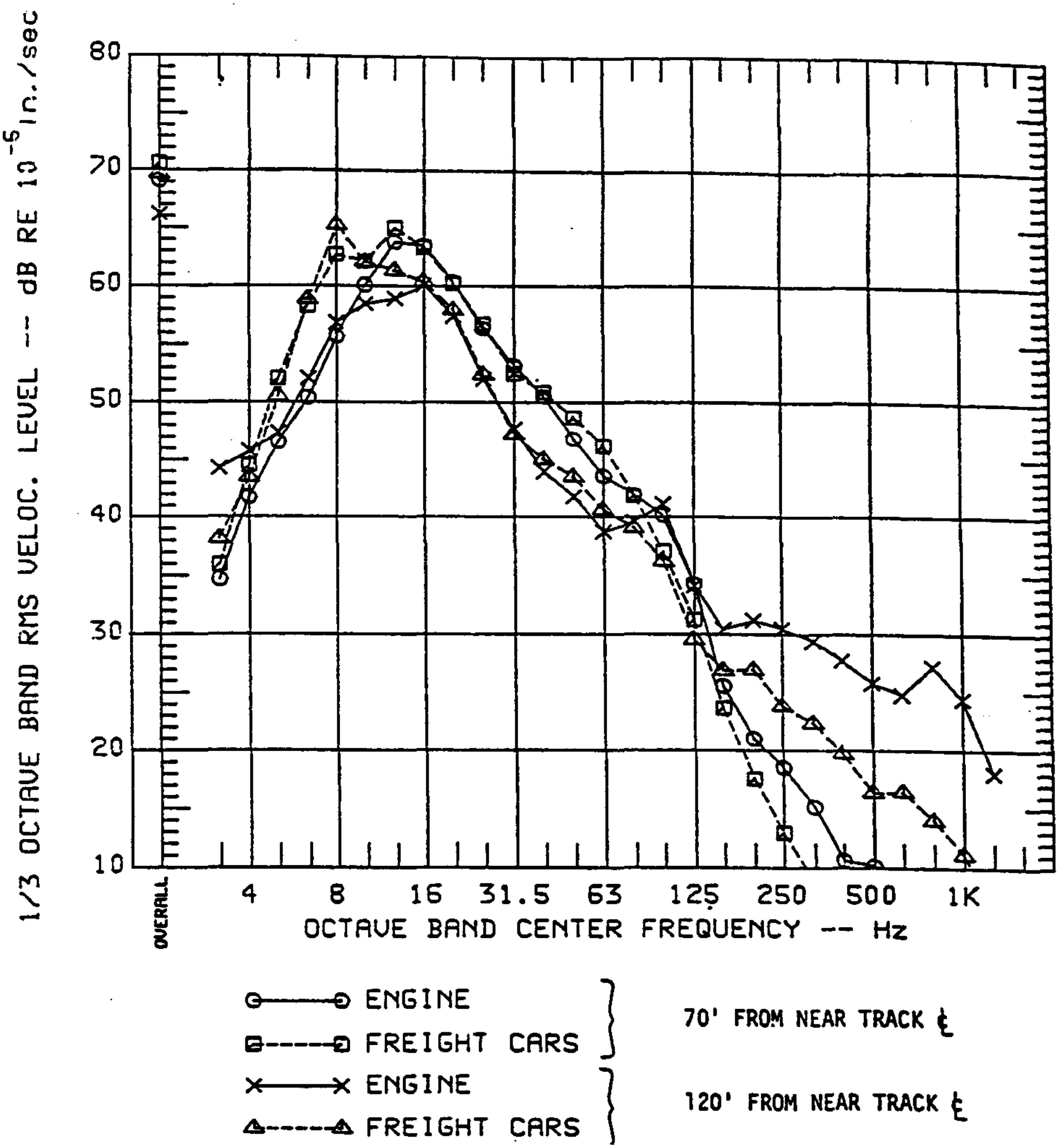

FIGURE A-1 GROUND VIBRATION FROM SOUTHERN RAILWAY FREIGHT TRAIN PASSBYS AT LOCATION 2, LOT N 339, NEAR STATION 548+00

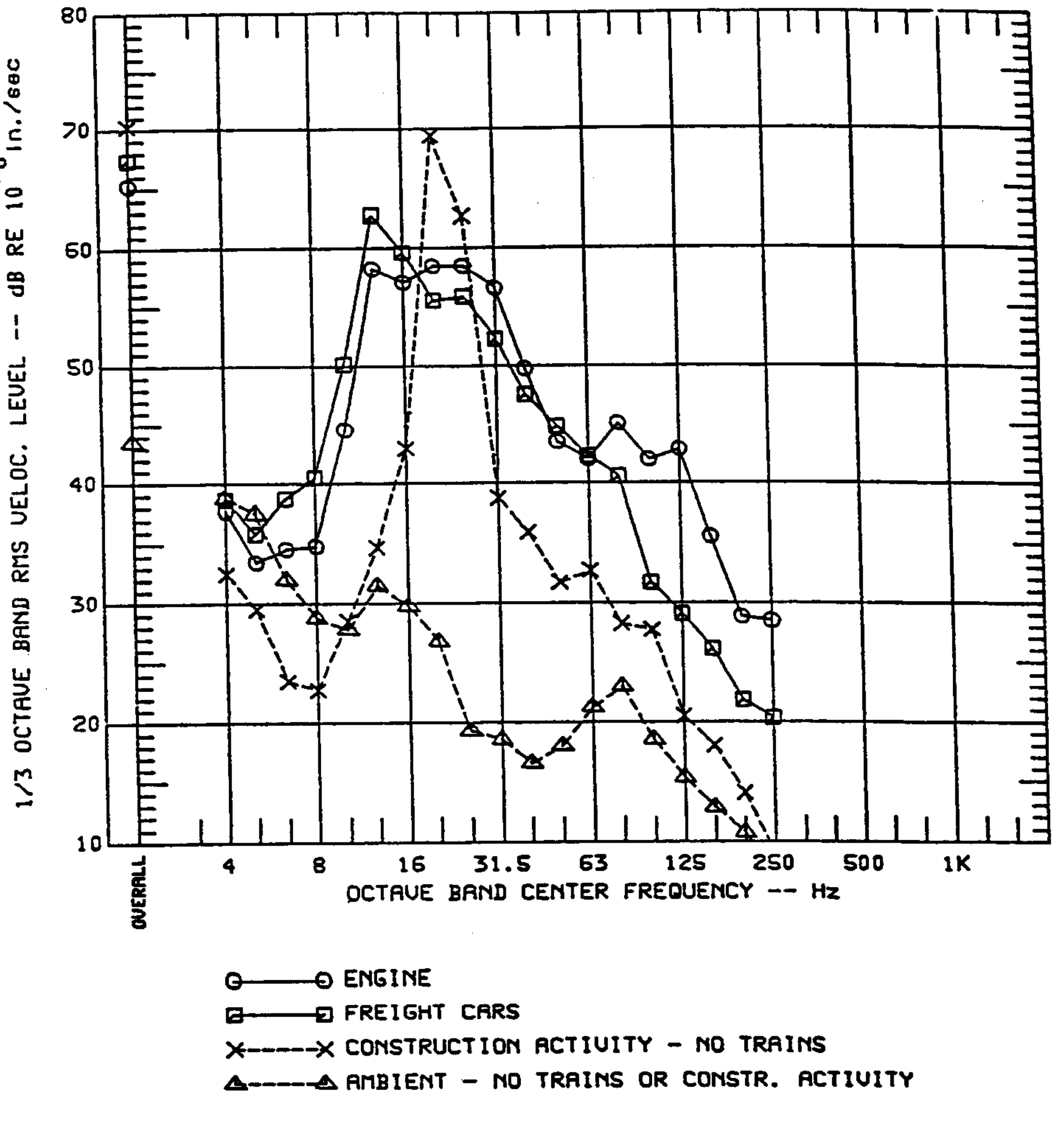

FIGURE A-2 GROUND VIBRATION FROM SOUTHERN RAILWAY FREIGHT TRAIN PASSBYS ON RELOCATED TRACK AT 2958 CALDWELL ROAD - 235 FT FROM NEAR TRACK CENTERLINE

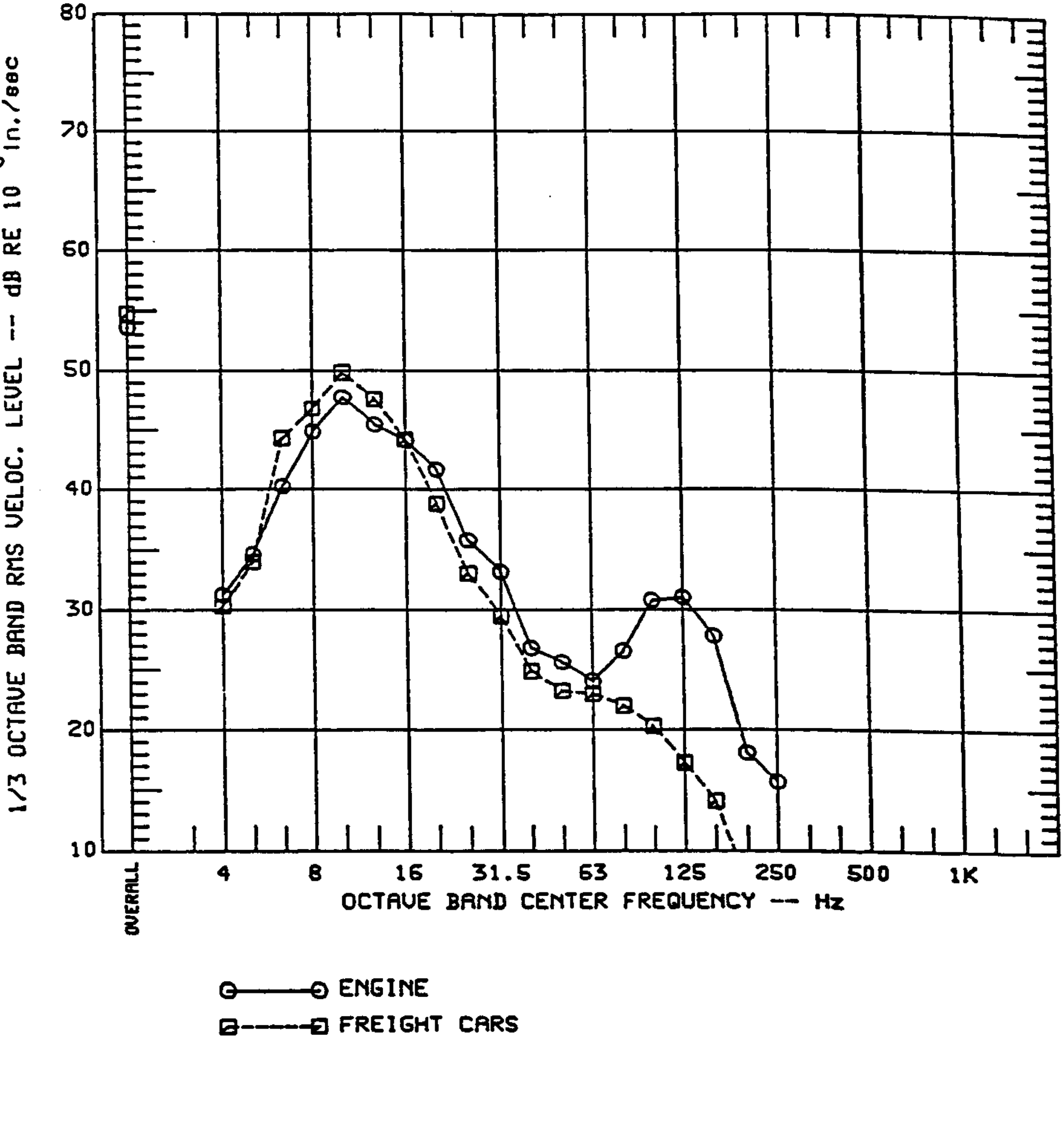

FIGURE A-3 GROUND VIBRATION FROM SOUTHERN RAILWAY FREIGHT TRAIN PASSBYS ON TRACK AT ORIGINAL LOCATION, 2984 CALDWELL ROAD, 360 FT FROM NEAR TRACK CENTERLINE

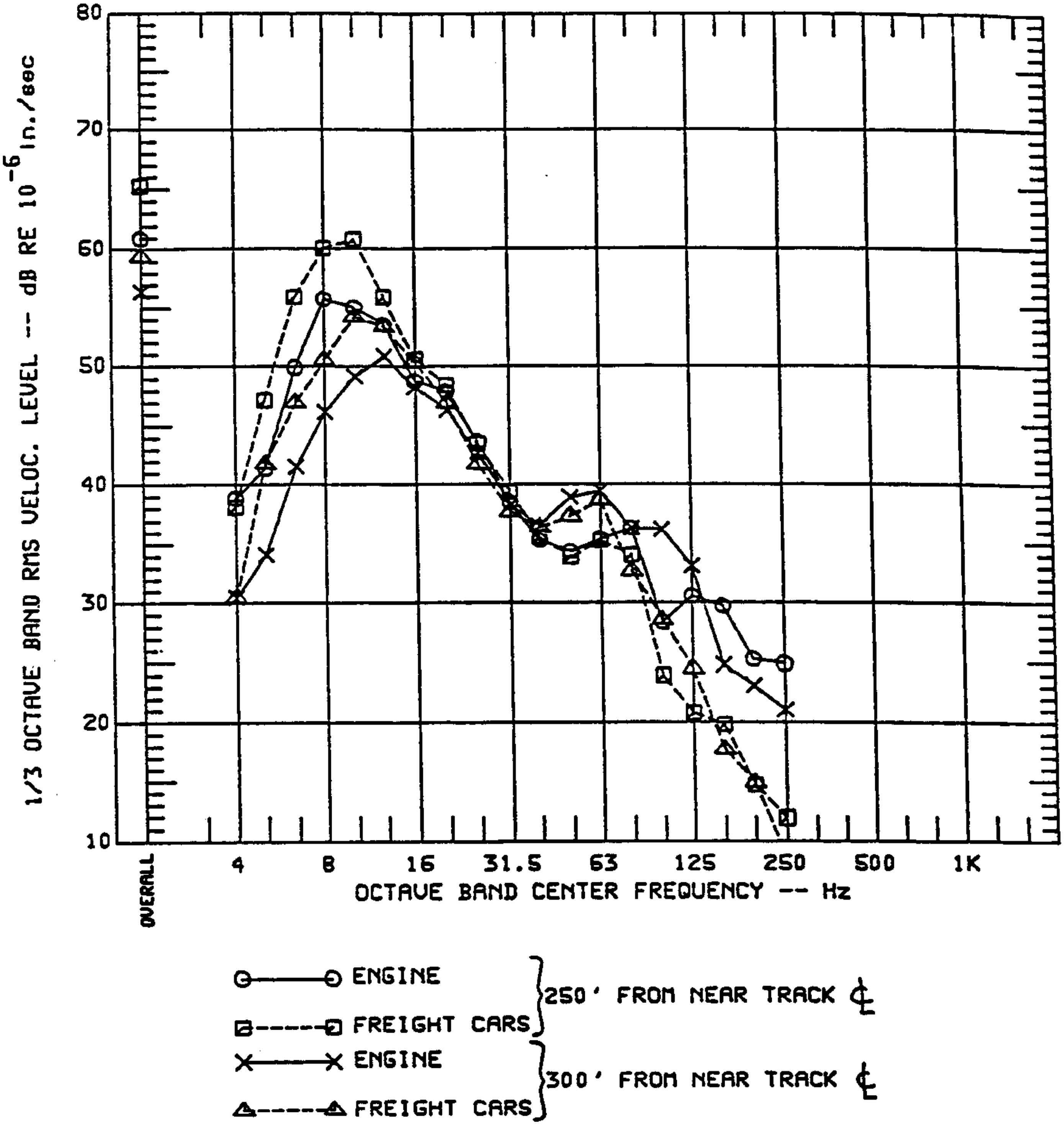

FIGURE A-4 GROUND VIBRATION FROM SOUTHERN RAILWAY FREIGHT TRAIN PASSBYS ON TRACK AT ORIGINAL LOCATION, LOT N 345, NEAR STATION 555+70

FIGURES A-5 THROUGH A-6

Type of Vibration:	Surface Vibration - Southern Pacific Railroad
Location:	Reno, Nevada
Measurement Date:	December 12, 1978
Soil Type:	Unkown
Additional Details:	Measurements made to characterize ground vibration from railroad operations prior to modification of railroad grade profile

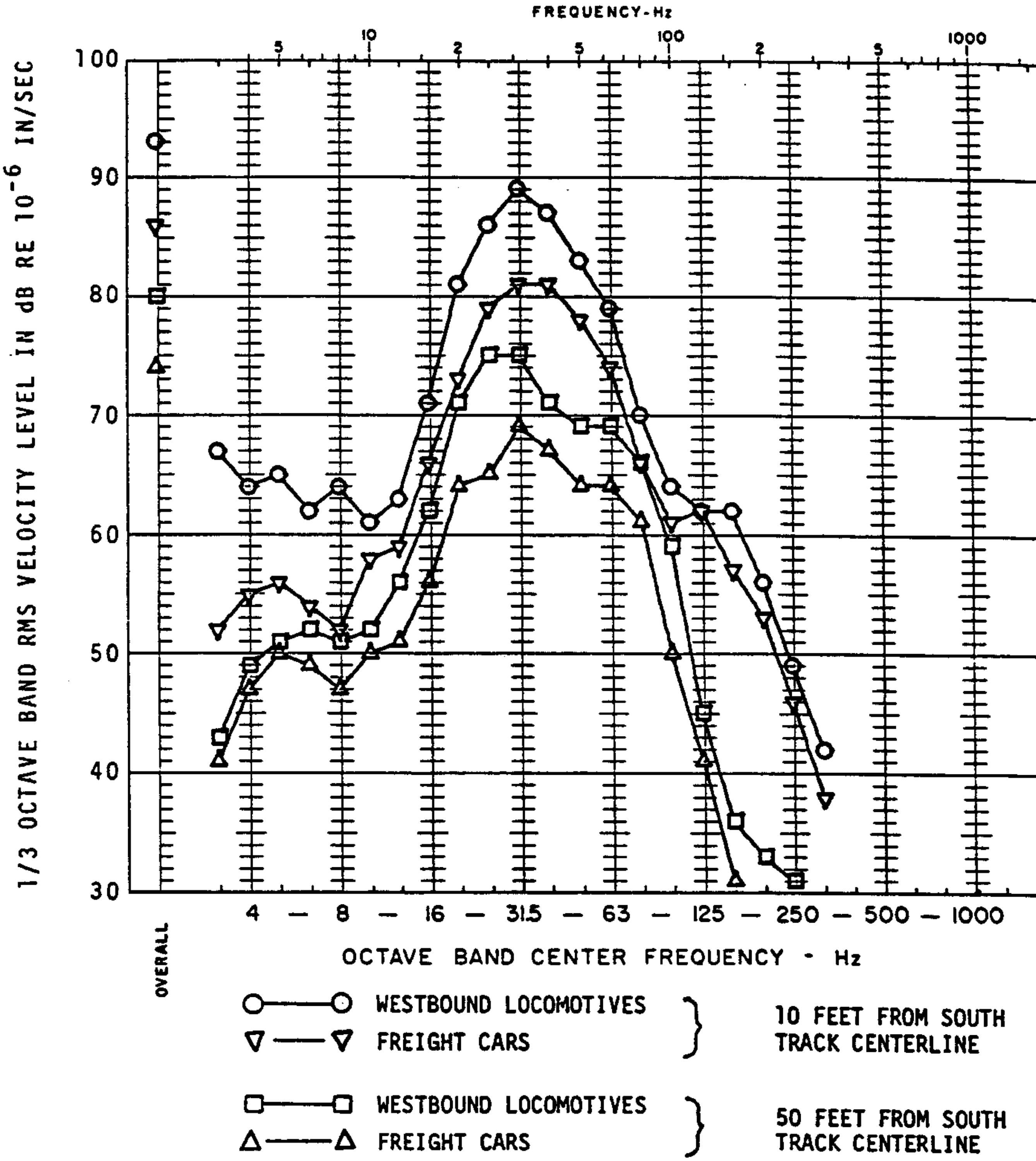

FIGURE A-5 GROUND-BORNE VIBRATION FROM SIMULTANEOUS WESTBOUND AND EASTBOUND SOUTHERN PACIFIC TRAINS ON AT-GRADE JOINTED RAIL ON BALLAST AND TIE - WESTBOUND TRAIN ON SOUTH TRACK

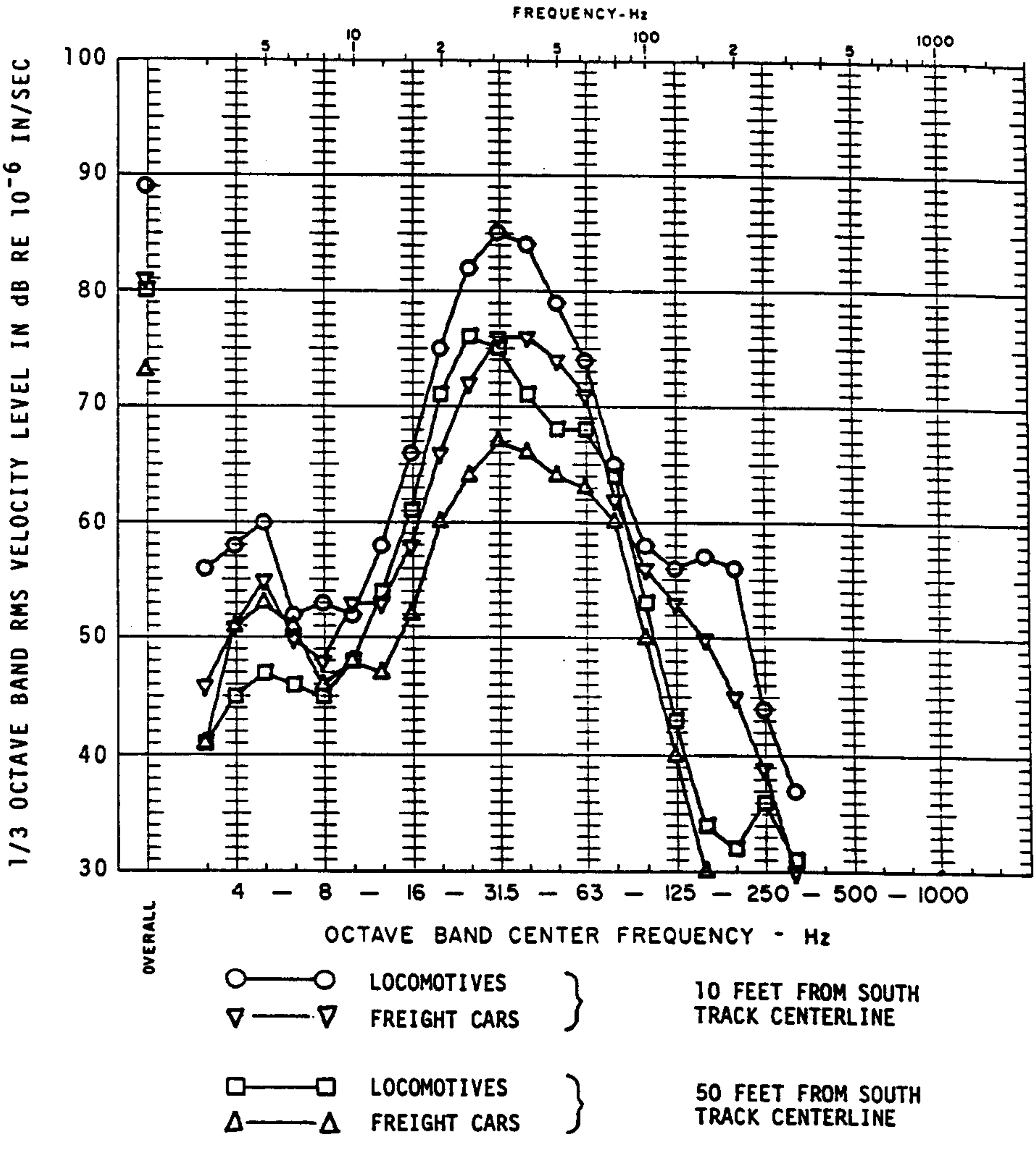

FIGURE A-6 GROUND-BORNE VIBRATION FROM WESTBOUND SOUTHERN PACIFIC TRAIN AT-GRADE JOINTED RAIL ON BALLAST AND TIE — WESTBOUND TRAIN ON SOUTH TRACK

FIGURES A-7 THROUGH A-9

Type of Vibration:	Surface Railroad - CN Rail
Location:	Kamloops, British Columbia, Canada
Measurement Dates:	October 7-11, 1985
Soil Type:	Generally sandy soil with some silty layers
Additional Details:	Measurements made to characterize ground vibration in order to determine why vibration from train operations on newly installed north track is greater than operations on existing south track

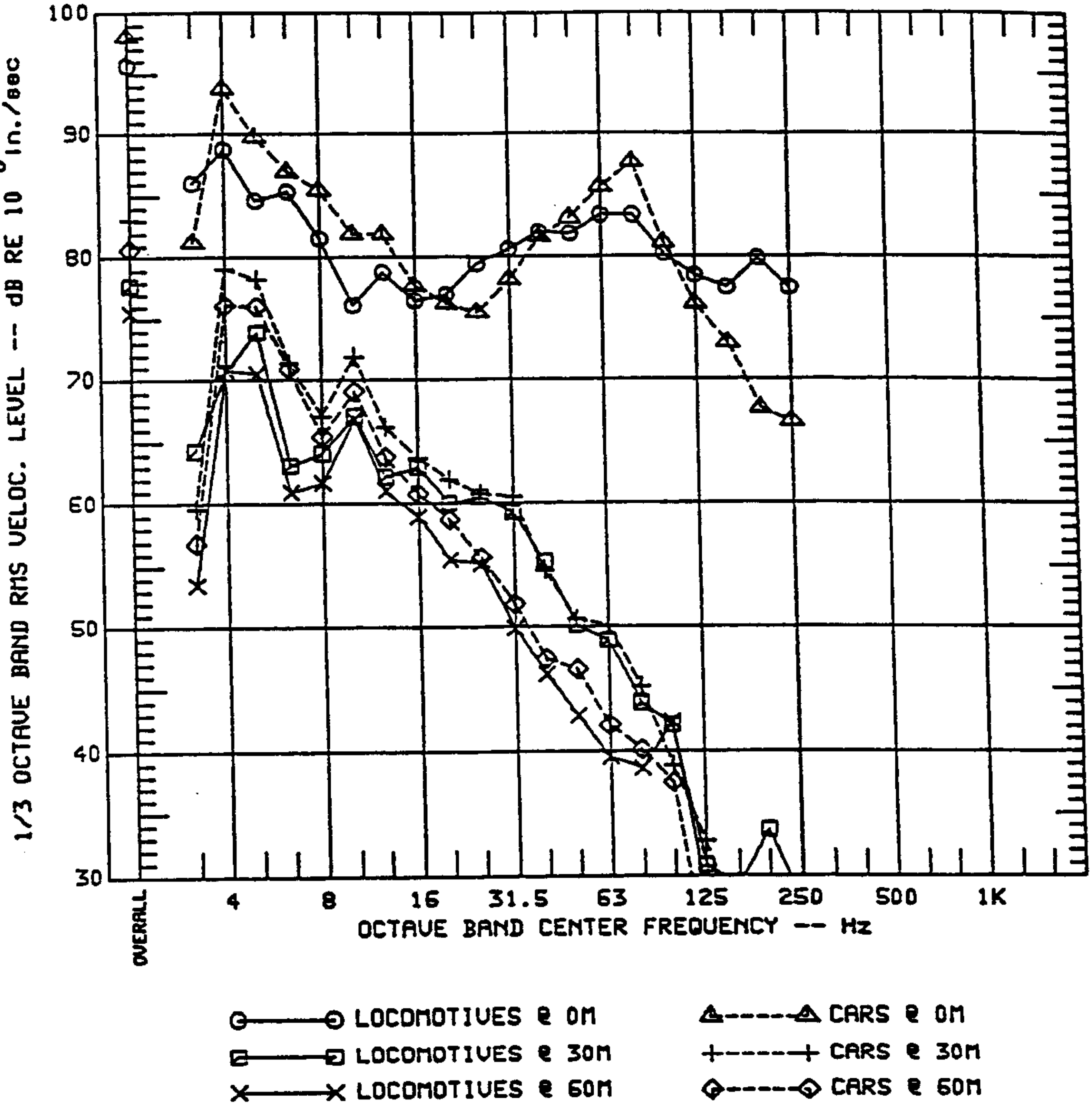

FIGURE A-7 AVG. GROUND VIBRATION - LOCOS.& CARS - N.TRK
AFTER COMPACTION
LOW SPEED TRAINS, APX. 20MPH
SITE 1

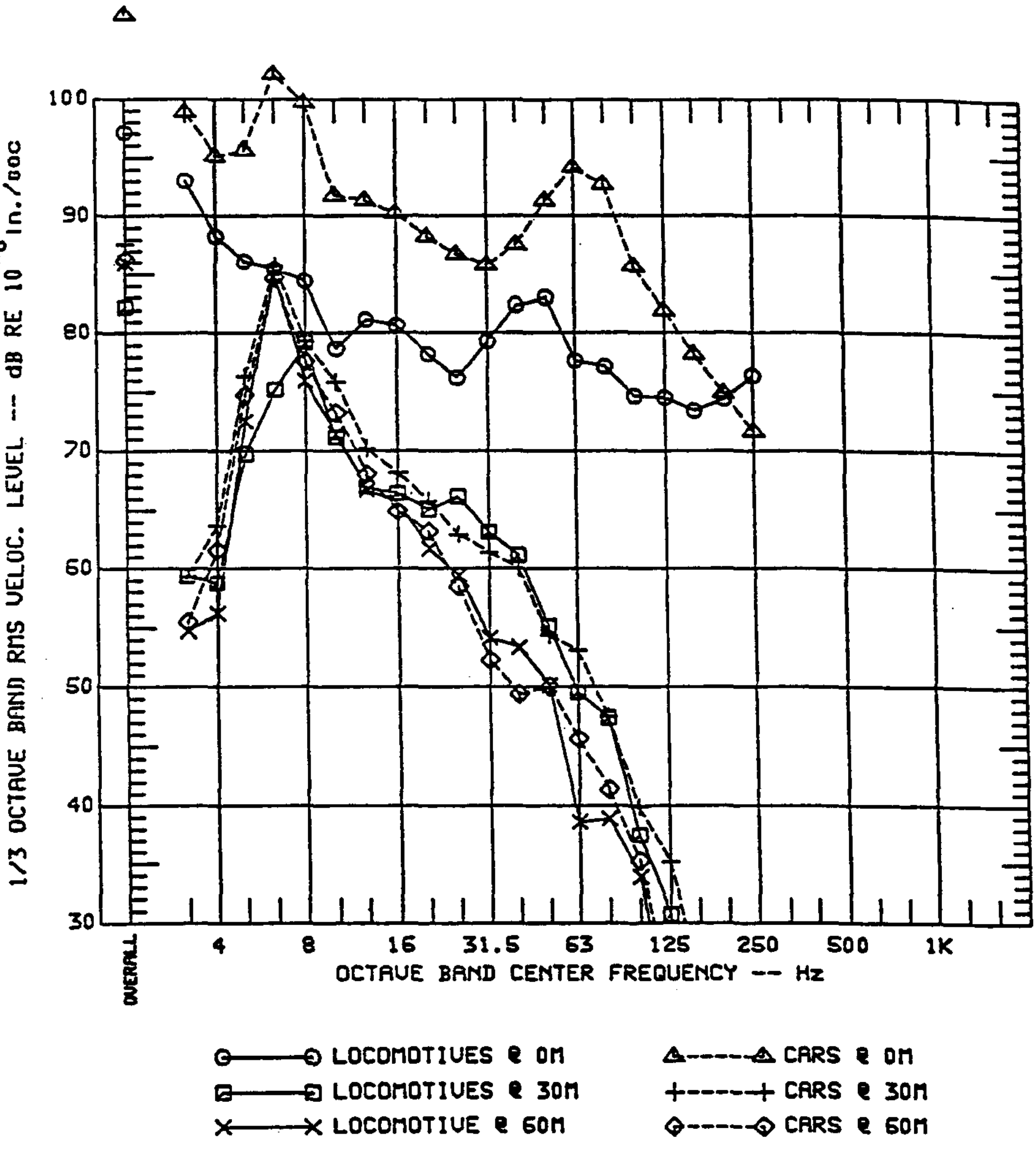

FIGURE A-8 AVG.GROUND VIBRATION -LOCOS.& CARS - N.TRK.
AFTER COMPACTION
MEDIUM SPEED TRAINS, APX. 30MPH
SITE 1

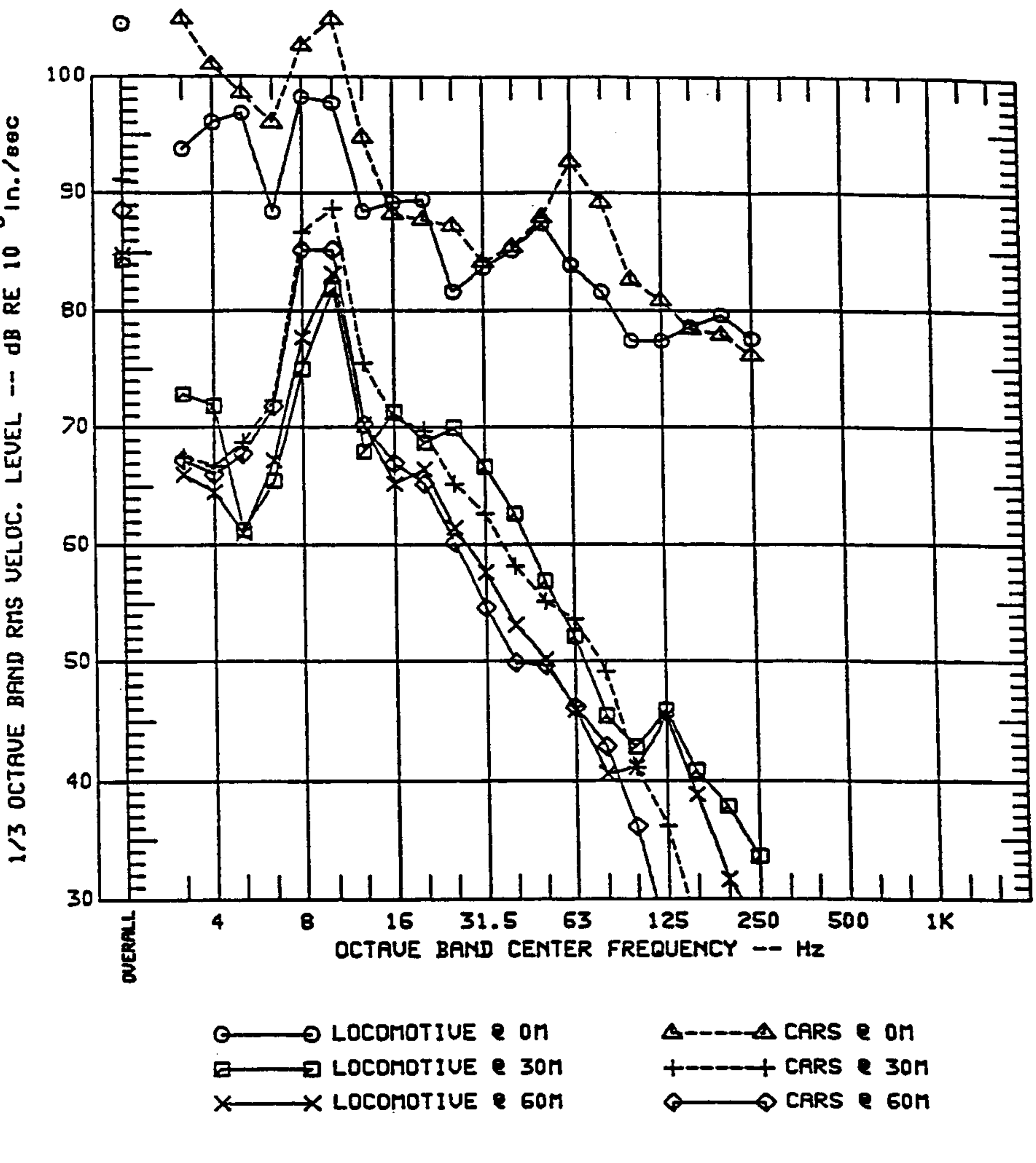

FIGURE A-9 AVG. GROUND VIBRATION - LOCOS.& CARS - N.TRK
AFTER COMPACTION
HIGH SPEED TRAINS, >40 MPH
SITE 1

FIGURES A-10 THROUGH A-15

Type of Vibration:	Surface Railroad - Illinois Central Gulf
Location:	Carbondale, Illinois
Measurement Dates:	April 15-18, 1985
Soil Type:	Generally silty clay or clayish silt with sand and/or gravel. Weathered rock at 25 to 30 feet depth
Additional Details:	Measurements made to characaterize existing ground vibration from railraod operations prior to relocation of tracks

TABLE A.1 NOISE AND VIBRATION MEASUREMENT LOCATIONS

Location Number	Station Number	Site Description
1	2993+80	Vibration measurements made west of railroad alignment near Elm Street and Amtrak depot.
2	2992+80	Vibration measurements made east of railroad alignment near Elm Street and residential buildings.
3	2959+00	Vibration measurements made east of railroad alignment near existing overhead walkway and SIU dormitories.

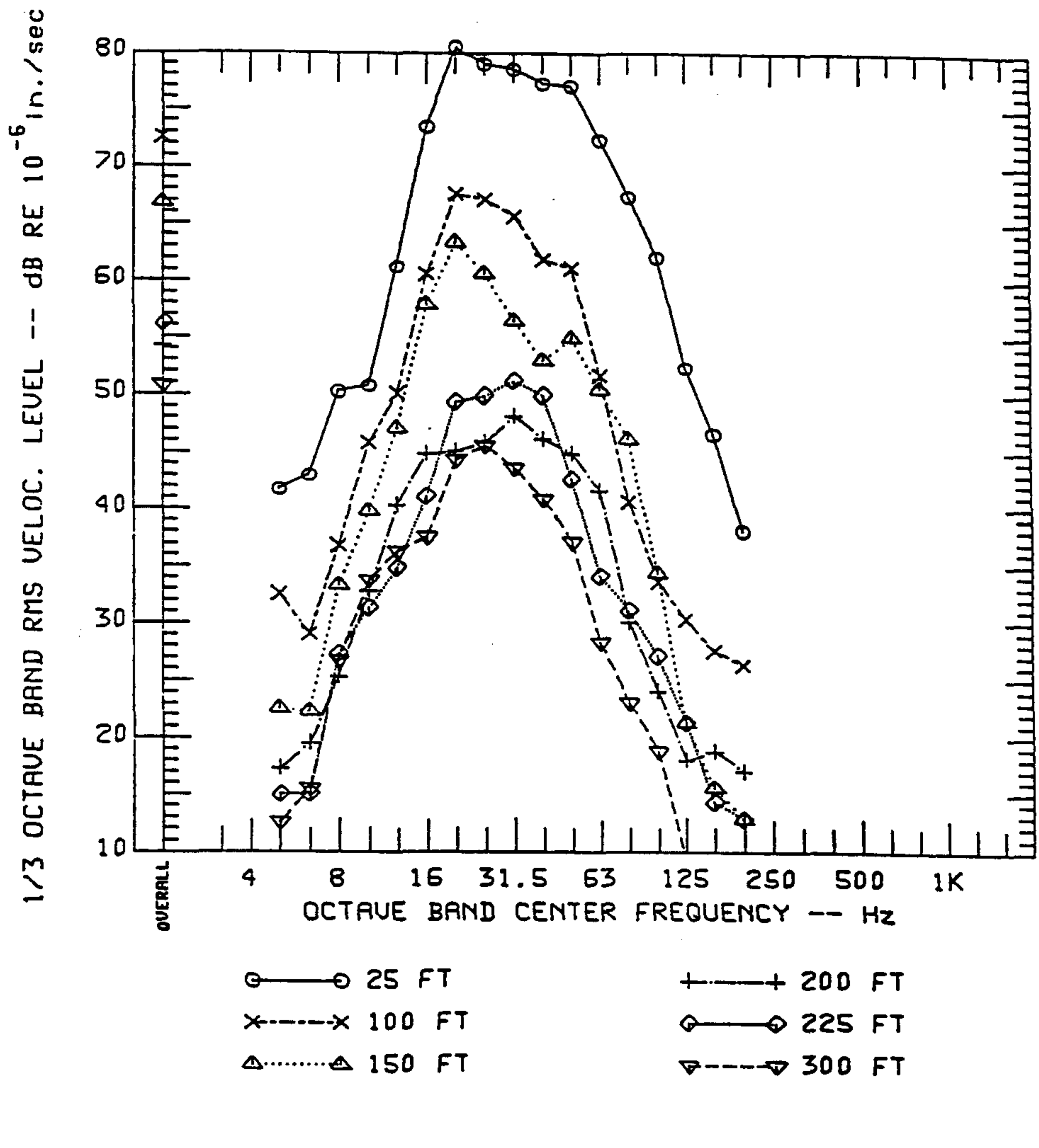

FIGURE A-10 GROUND VIBRATION FROM LOCOMOTIVES OF ICG FREIGHT TRAIN PASSBY AT LOCATION 1 - 8:40 AM, APRIL 16, 1985

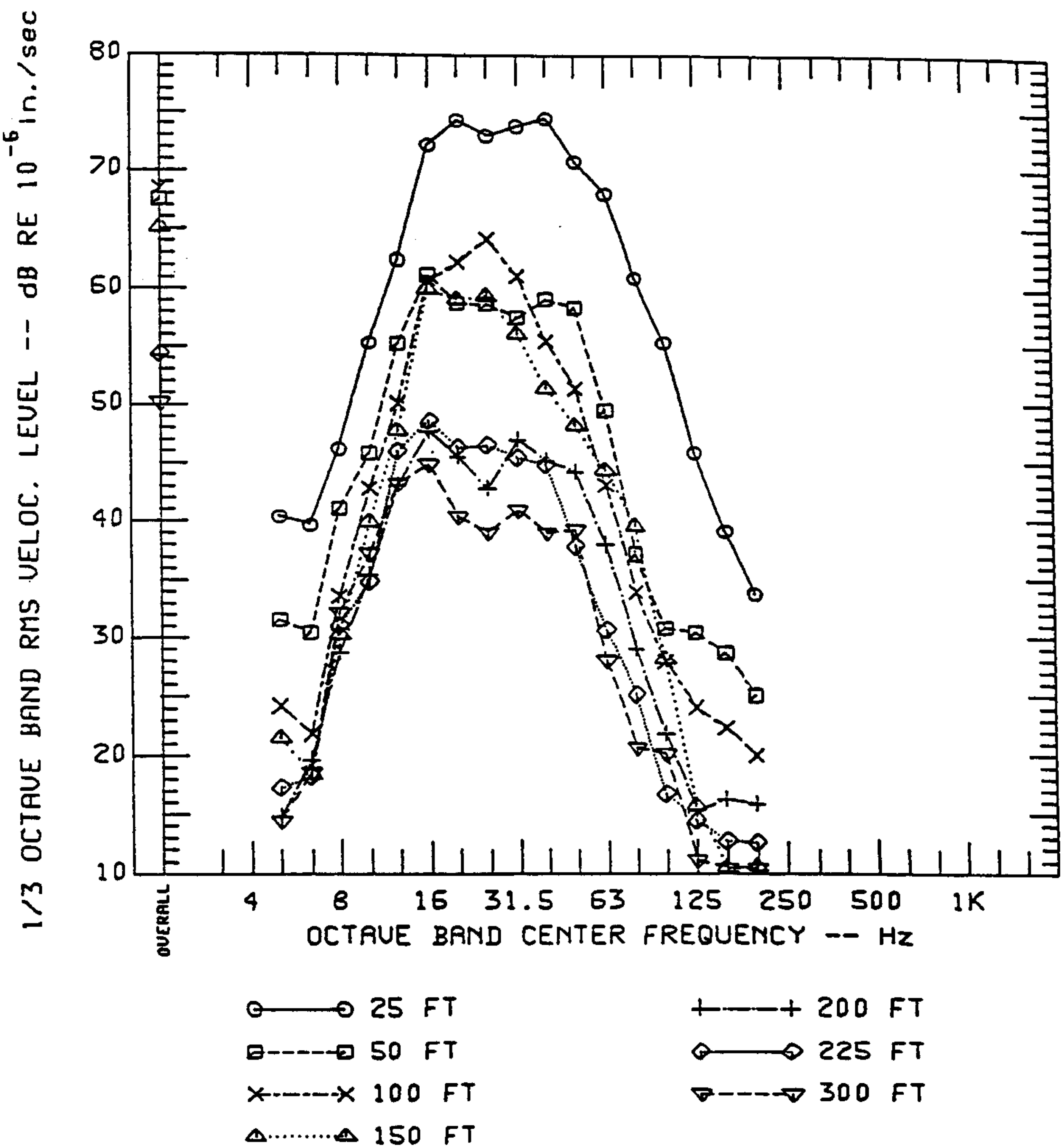

FIGURE A-11 GROUND VIBRATION FROM CARS OF ICG FREIGHT TRAIN PASSBY AT LOCATION 1 - 8:40 AM, APRIL 16, 1985

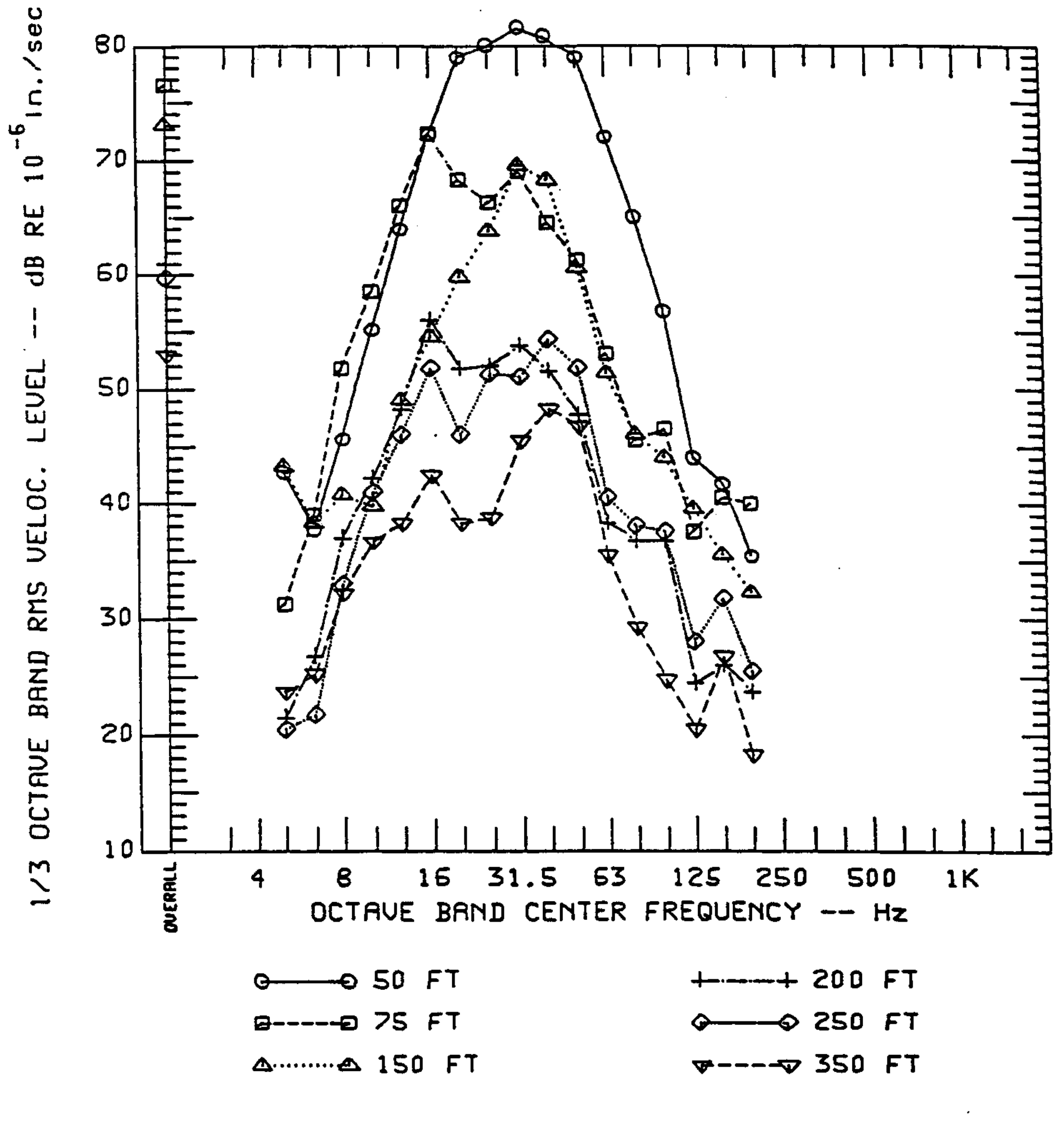

FIGURE A-12 GROUND VIBRATION FROM LOCOMOTIVES OF ICG FREIGHT TRAIN PASSBY AT LOCATION 2 - 2:45 PM, APRIL 16, 1985

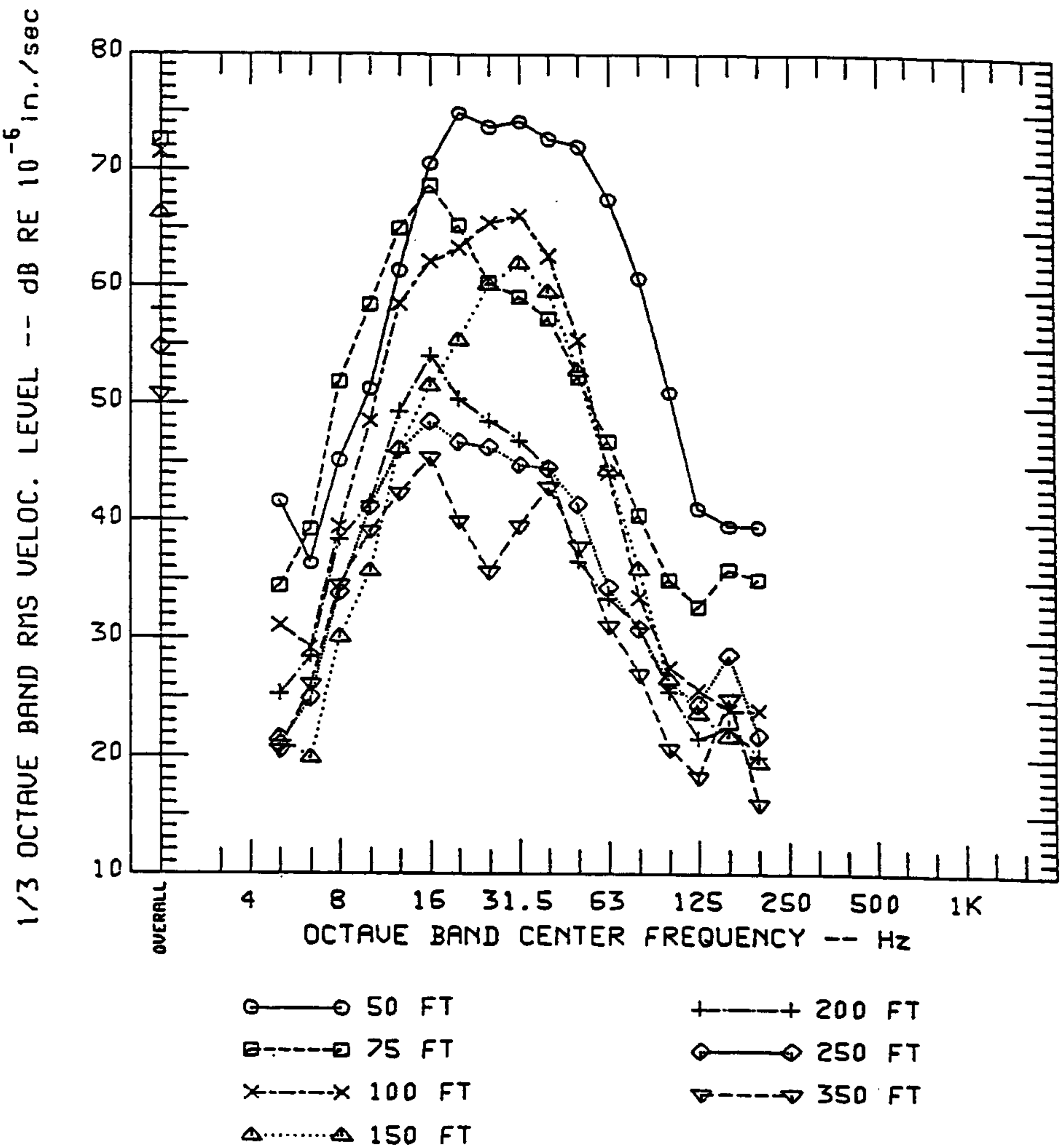

FIGURE A-13 GROUND VIBRATION FROM CARS OF ICG FREIGHT TRAIN PASSBY AT LOCATION 2 - 2:45 PM, APRIL 16, 1985

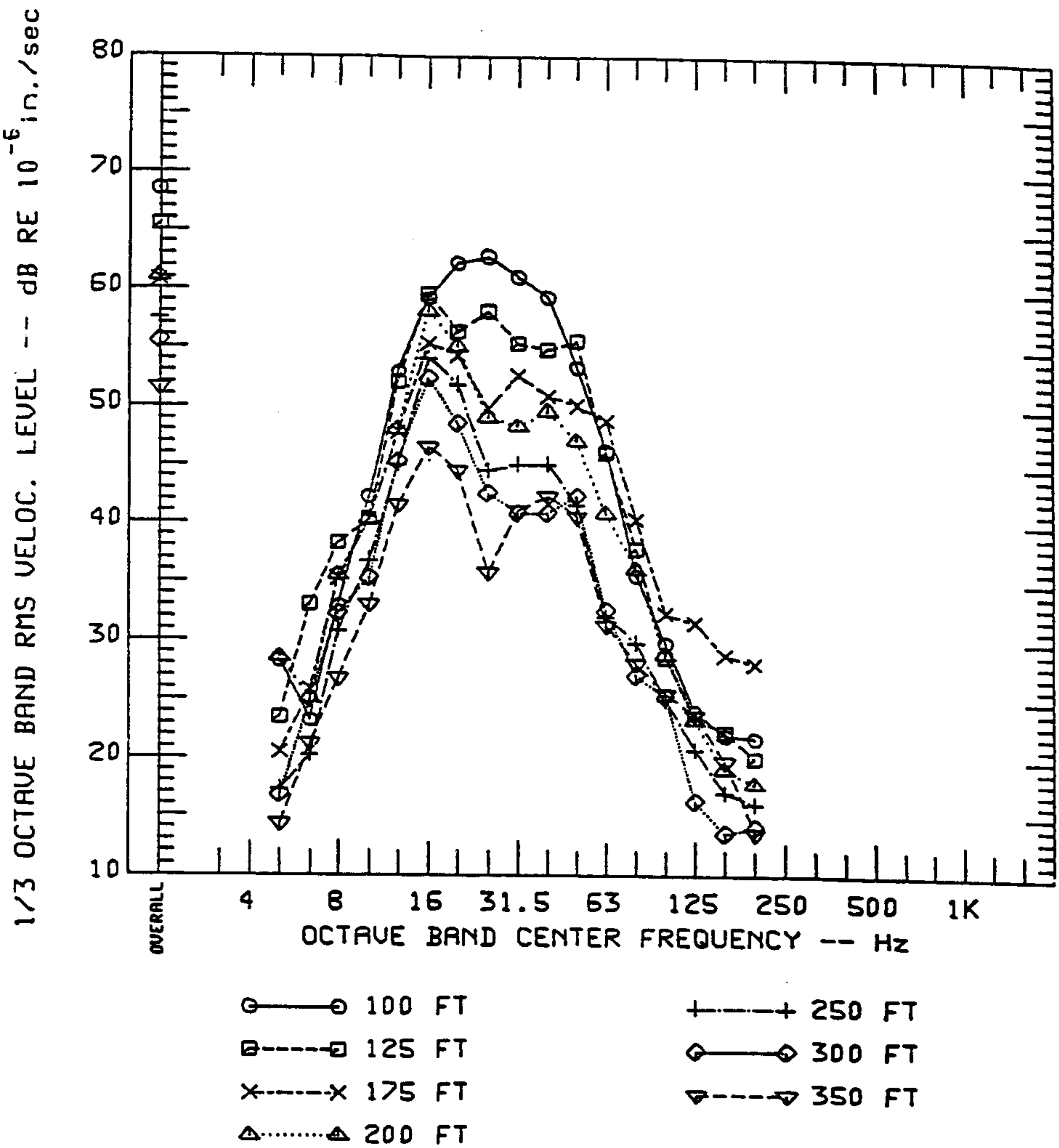

FIGURE A-14 GROUND VIBRATION FROM LOCOMOTIVES AND CARS OF ICG FREIGHT TRAIN PASSBY AT LOCATION 3 - 9:25 AM, APRIL 17, 1985

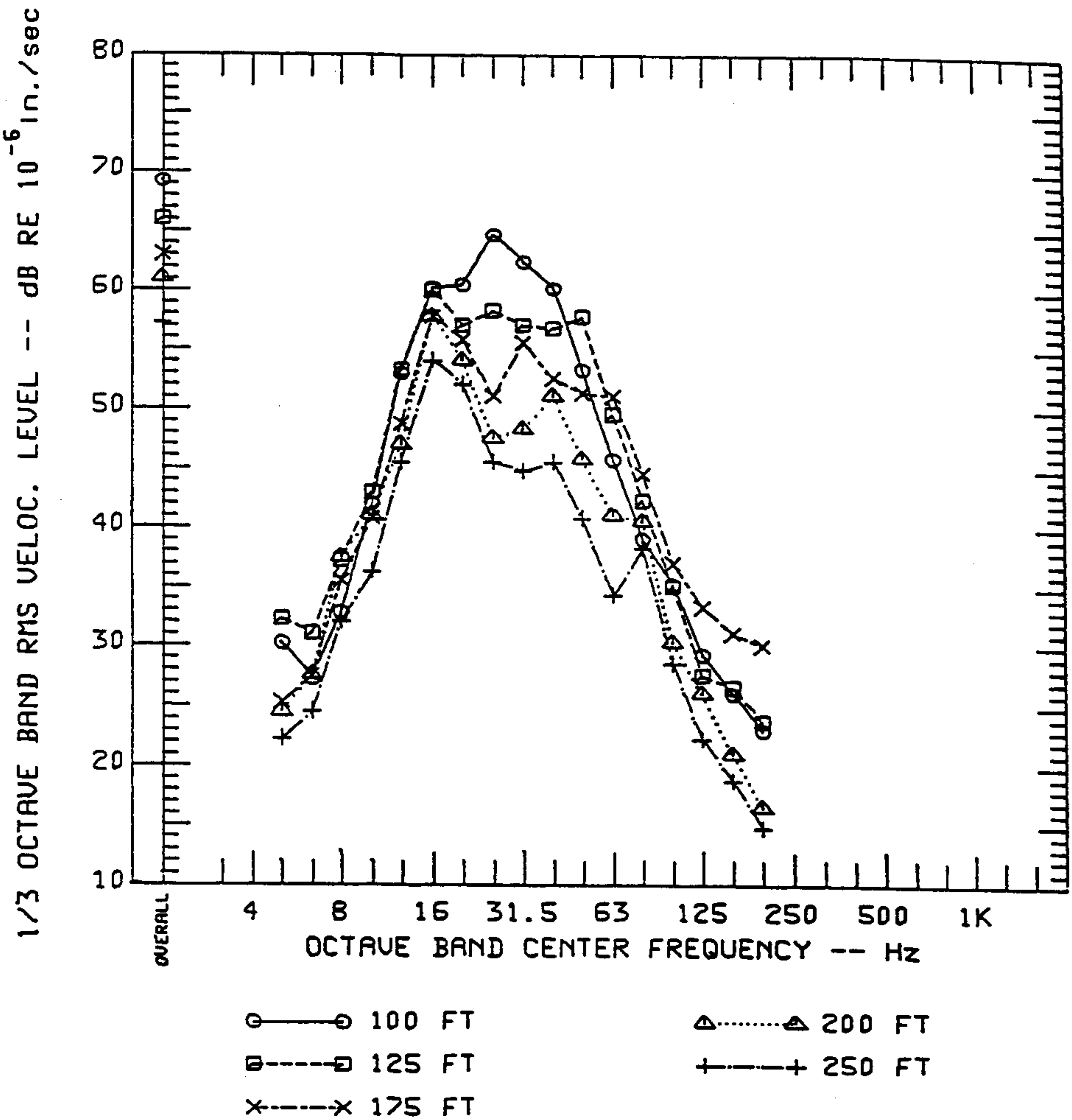

FIGURE A-15 GROUND VIBRATION FROM LOCOMOTIVES OF ICG FREIGHT TRAIN PASSBY AT LOCATION 3 - 2:00 PM, APRIL 17, 1985

FIGURE A-16

Type of Vibration:	Surface Railroad - Union Pacific
Location:	Marysville, California
Measurement Date:	April 28, 1986
Soil Type:	Alluvial - typical of Marysville Area. Adjacent to Feather River.
Additional Details:	Measurements made to document ground vibration from railroad operations. Tracks on 15' high berm.

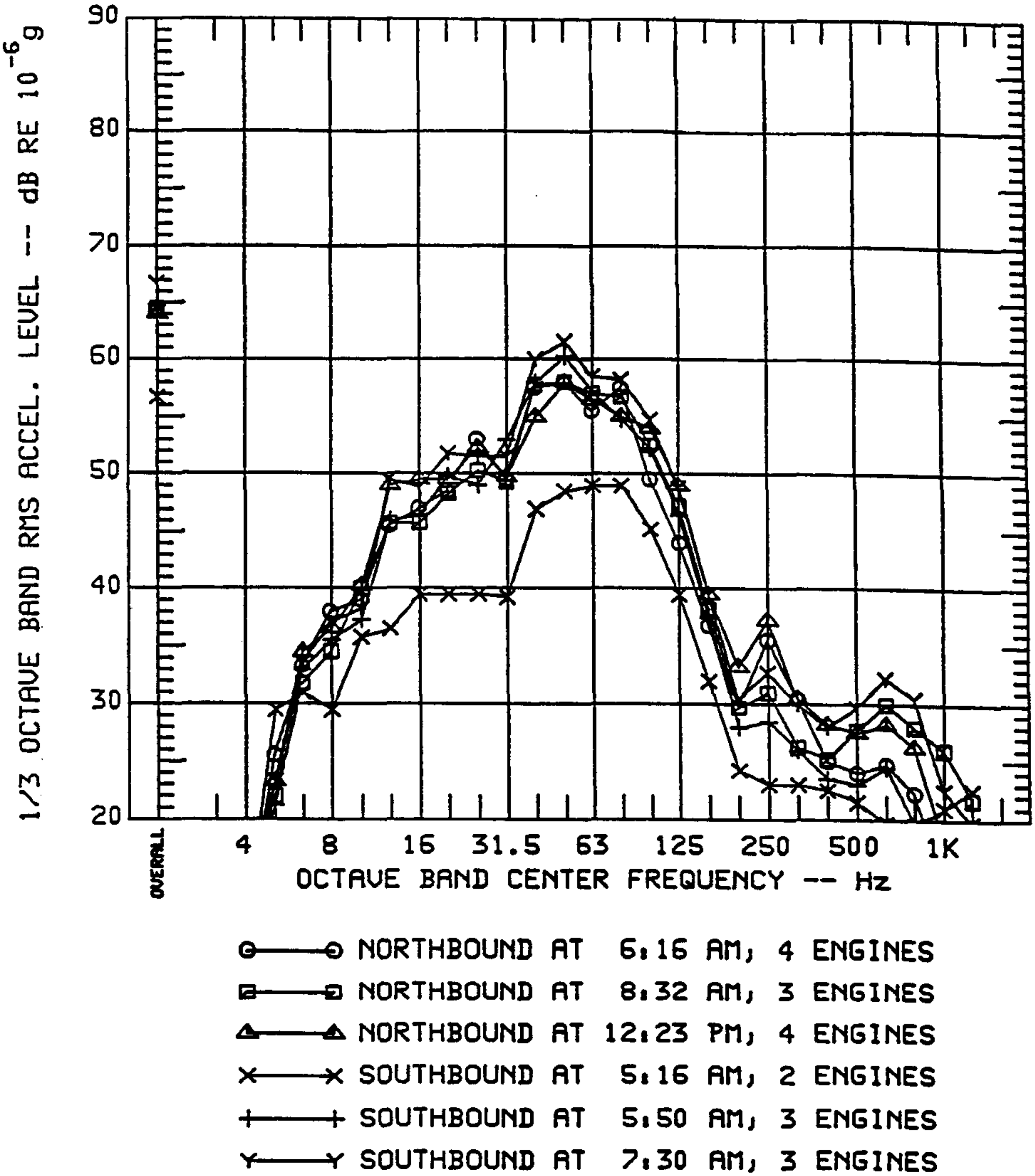

FIGURE A-16 ENGINE PASSBY VIBRATION AT 120 FEET

APPENDIX B

Ground Vibration from Freeway Traffic

FIGURES B-1 THROUGH B-2

Type of Vibration:	Surface Vibration - Freeway Traffic
Location:	Along Interstate 75 in Atlanta, Georgia
Measurement Date:	October 1, 1979
Soil Type:	Fill - dense brown silty medium sand with rock fragments
Additional Details:	Measurements made to characterize existing vibration prior to widening of the freeway

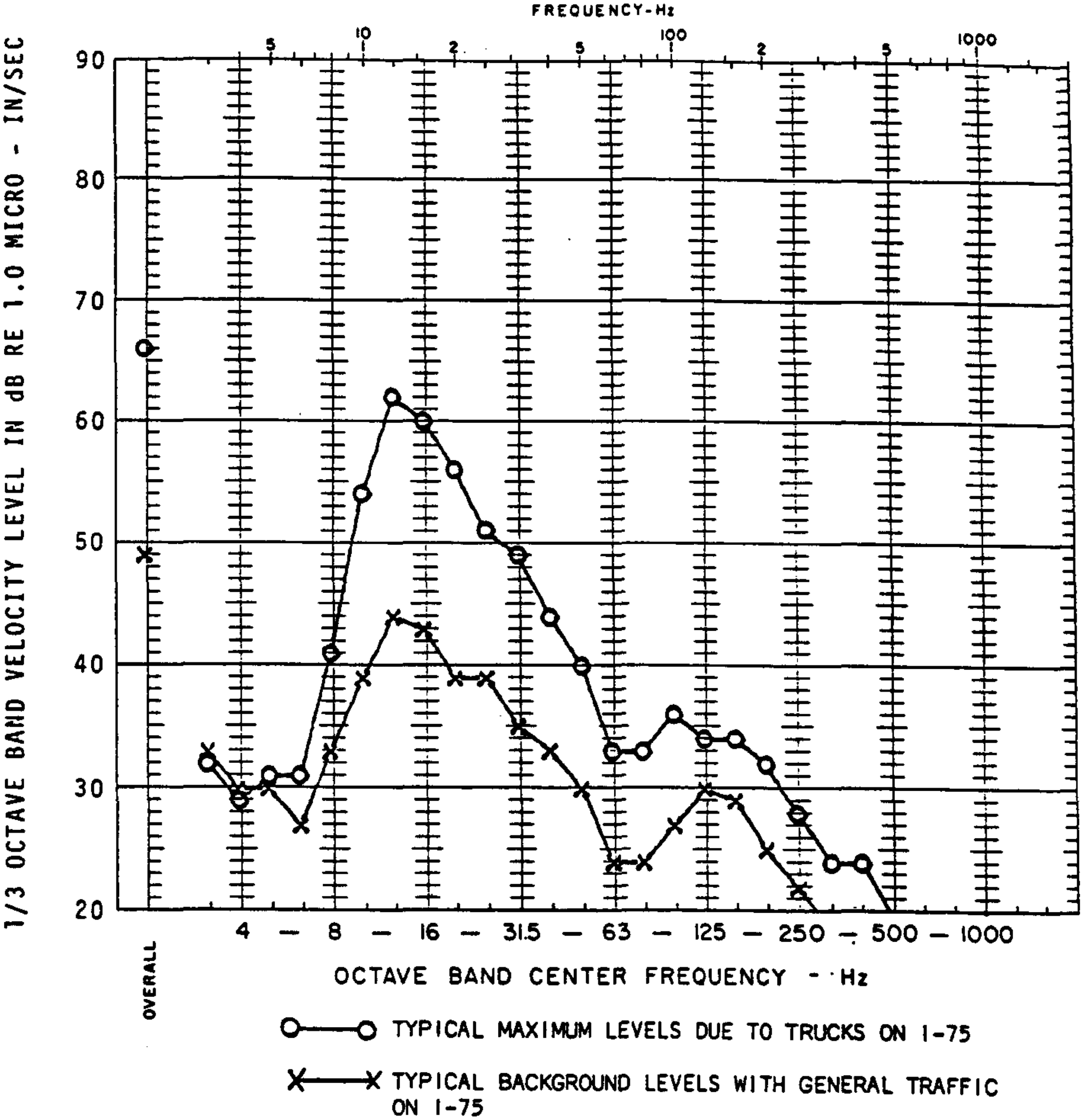

FIGURE B-1 FREQUENCY ANALYSIS OF GROUND VIBRATION AT APPROXIMATELY 25 FT FROM EDGE OF I-75

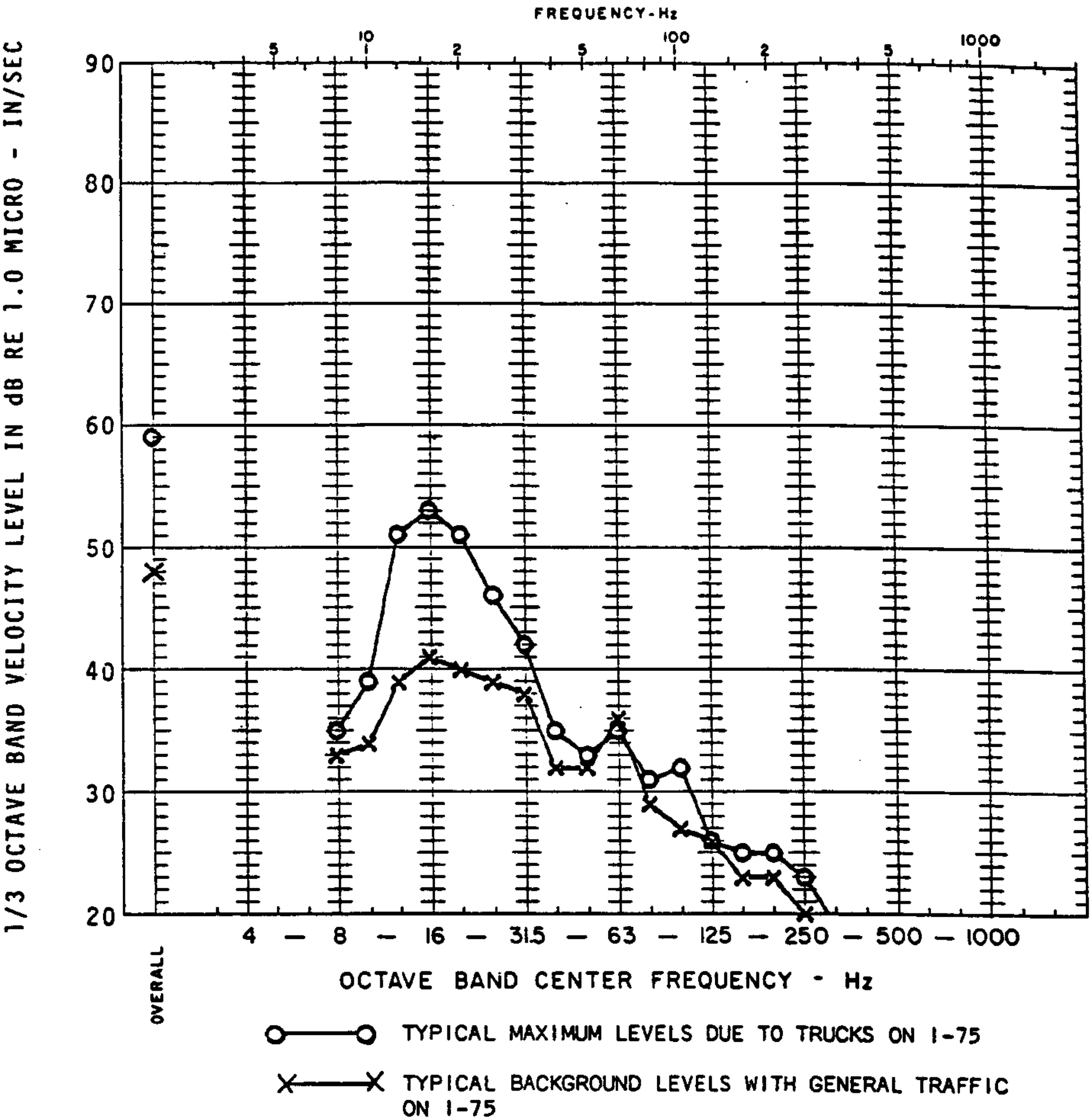

FIGURE B-2 FREQUENCY ANALYSIS OF GROUND VIBRATION AT APPROXIMATELY 175 FT FROM EDGE OF I-75

FIGURES B-3 THROUGH B-5

Type of Vibration:	Surface Vibration - Freeway Traffic
Location:	Along Interstate 80 in Reno, Nevada
Measurement Date:	December 12, 1978
Soil Type:	Unknown
Additional Details:	Measurements made to characterize existing vibration prior to modification of nearby railroad grade profile

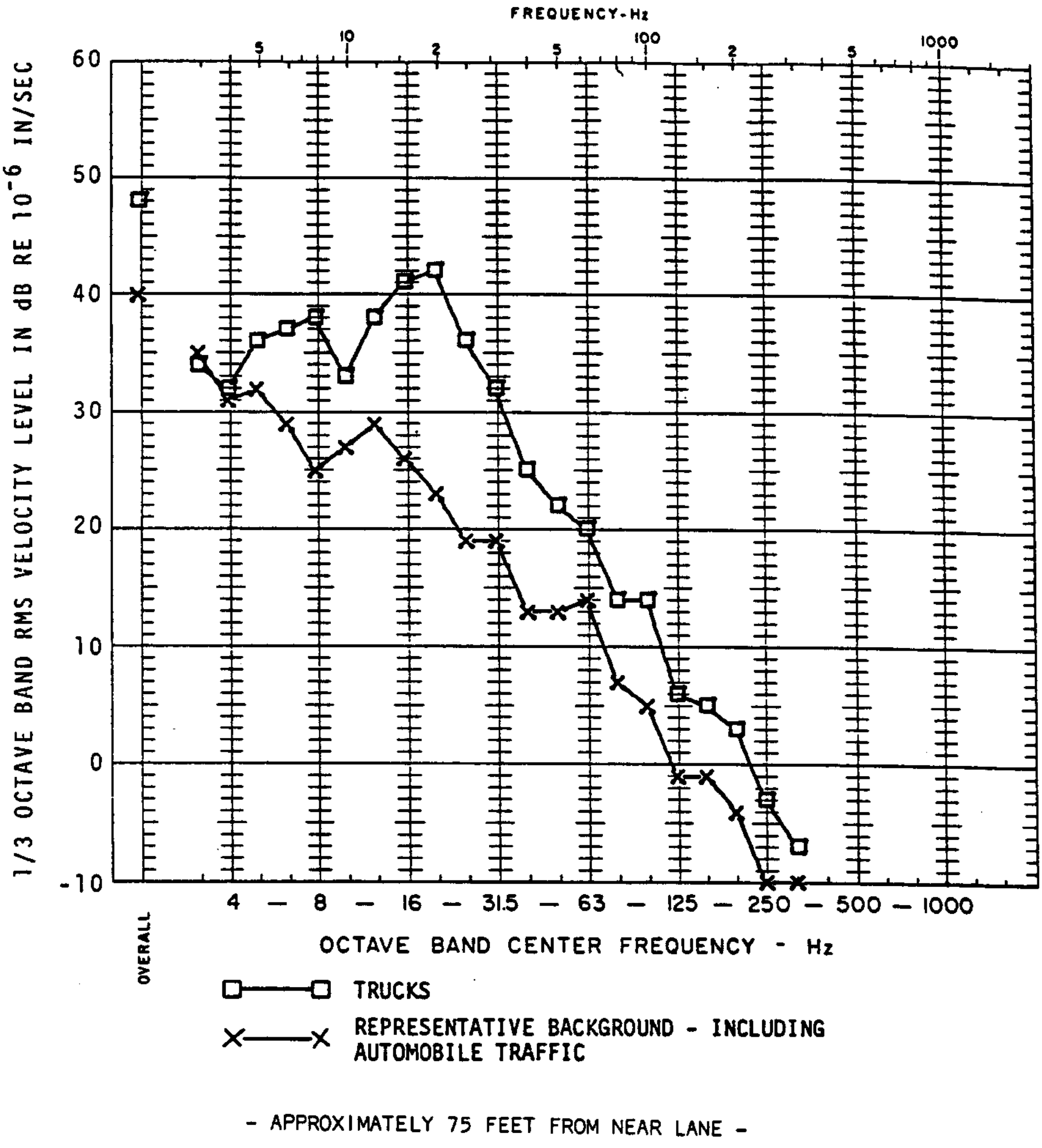

FIGURE B-3 GROUND-BORNE VIBRATION FROM WESTBOUND HEAVY TRUCKS ON DEPRESSED SECTION OF INTERSTATE 80 - TRANSDUCER MOUNTED ON CONCRETE ABUTMENT

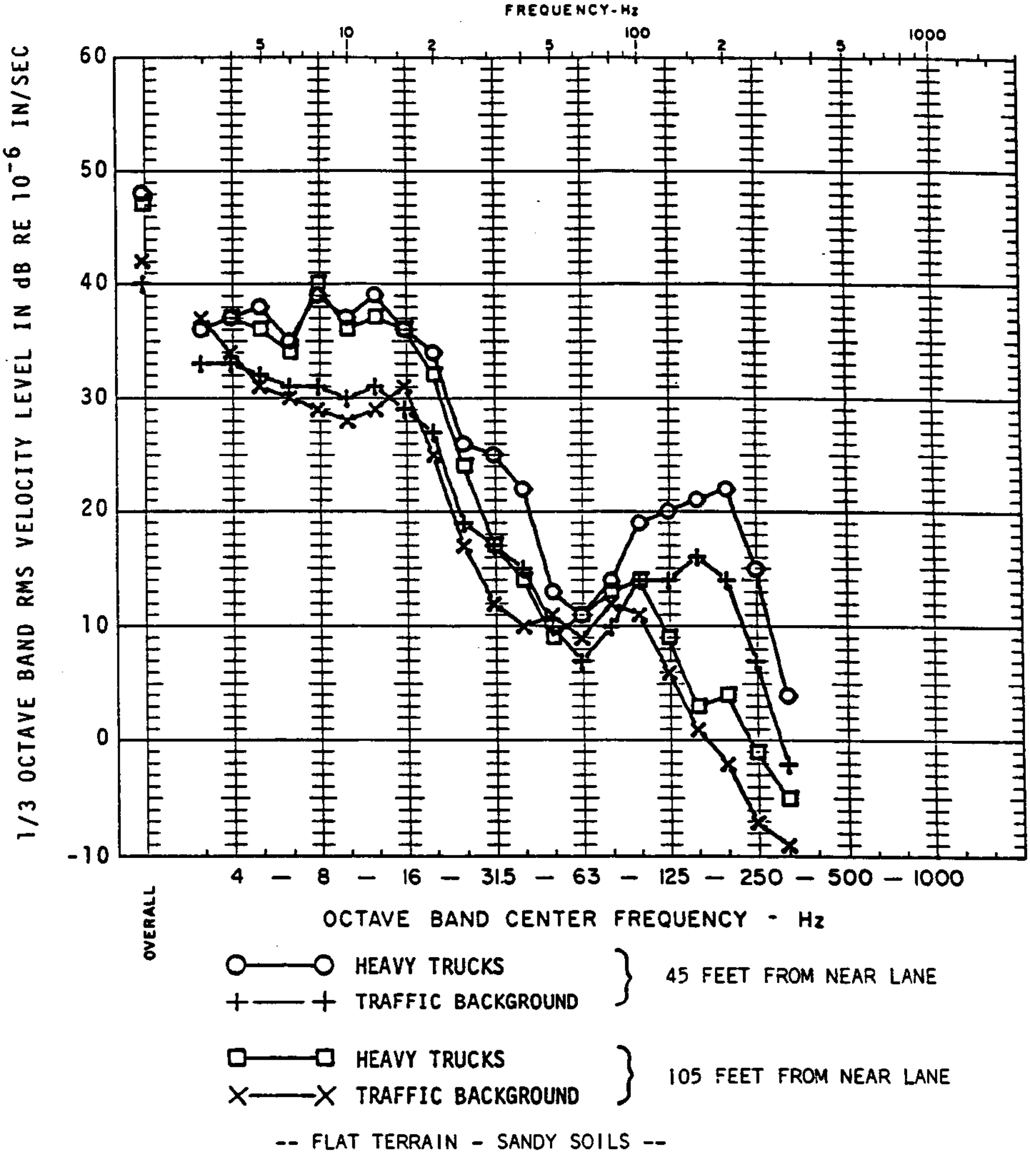

FIGURE B-4 GROUND-BORNE VIBRATION FROM WESTBOUND HEAVY TRUCKS ON ELEVATED SECTION OF INTERSTATE 80 - TRANSDUCER MOUNTED ON ROCK EMBEDDED IN SOIL

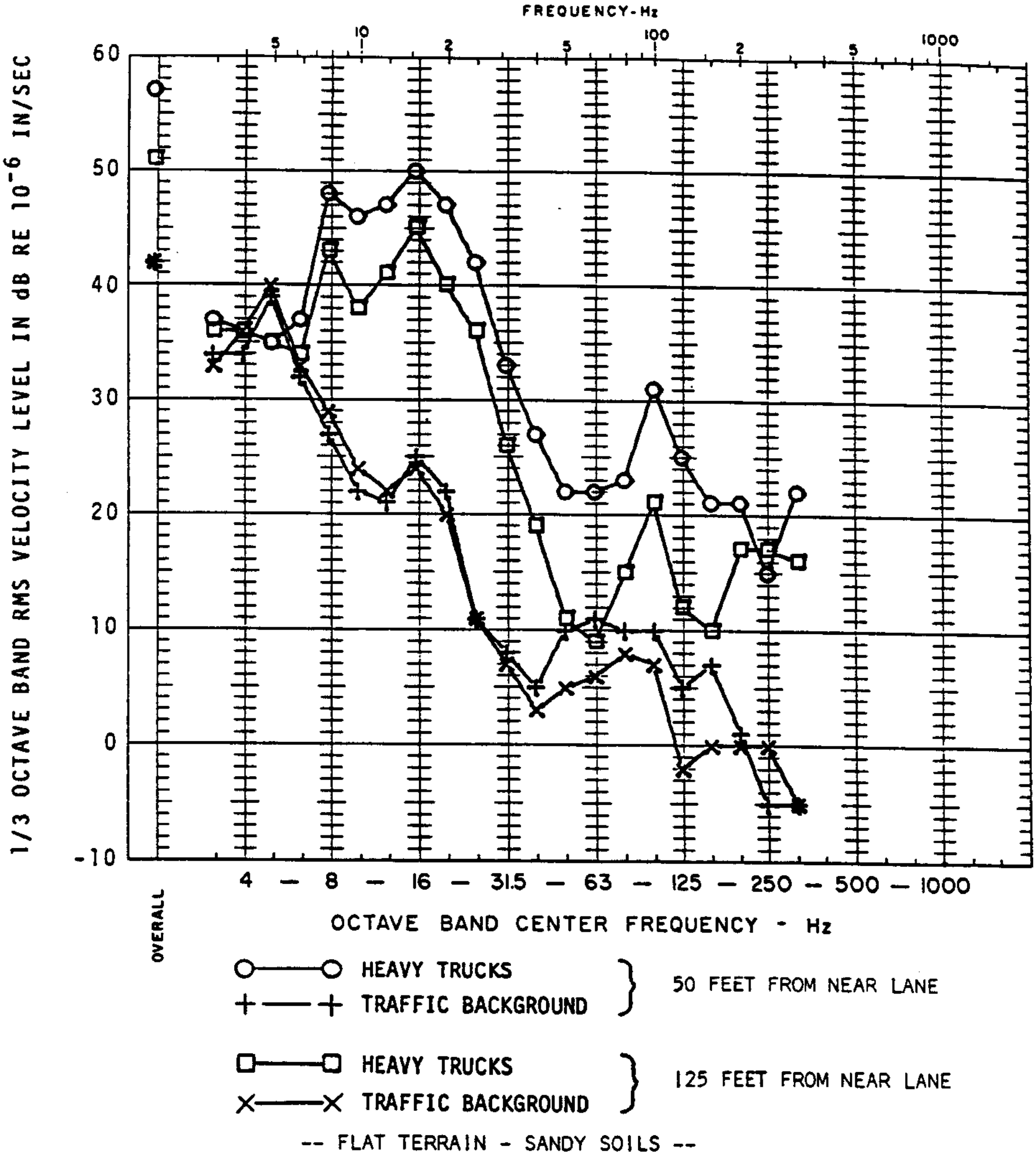

FIGURE B-5 GROUND-BORNE VIBRATION FROM WESTBOUND HEAVY TRUCKS ON AT-GRADE SECTION OF INTERSTATE 80 - TRANSDUCER MOUNTED ON ROCK EMBEDDED IN SOIL

FIGURE B-6

Type of Vibration:	Interstate Freeway
Location:	On sidewalk north side of South Grove Street, 60 feet from intersection of South Grove Street and South Banfield Street, Chicago, Illinois
Measurement Date:	November 1984
Soil Type:	Unknown - several miles from Lake Michigan
Additional Details:	Daytime vibration much higher than peak hour vibration because of slow traffic during peak hour periods.

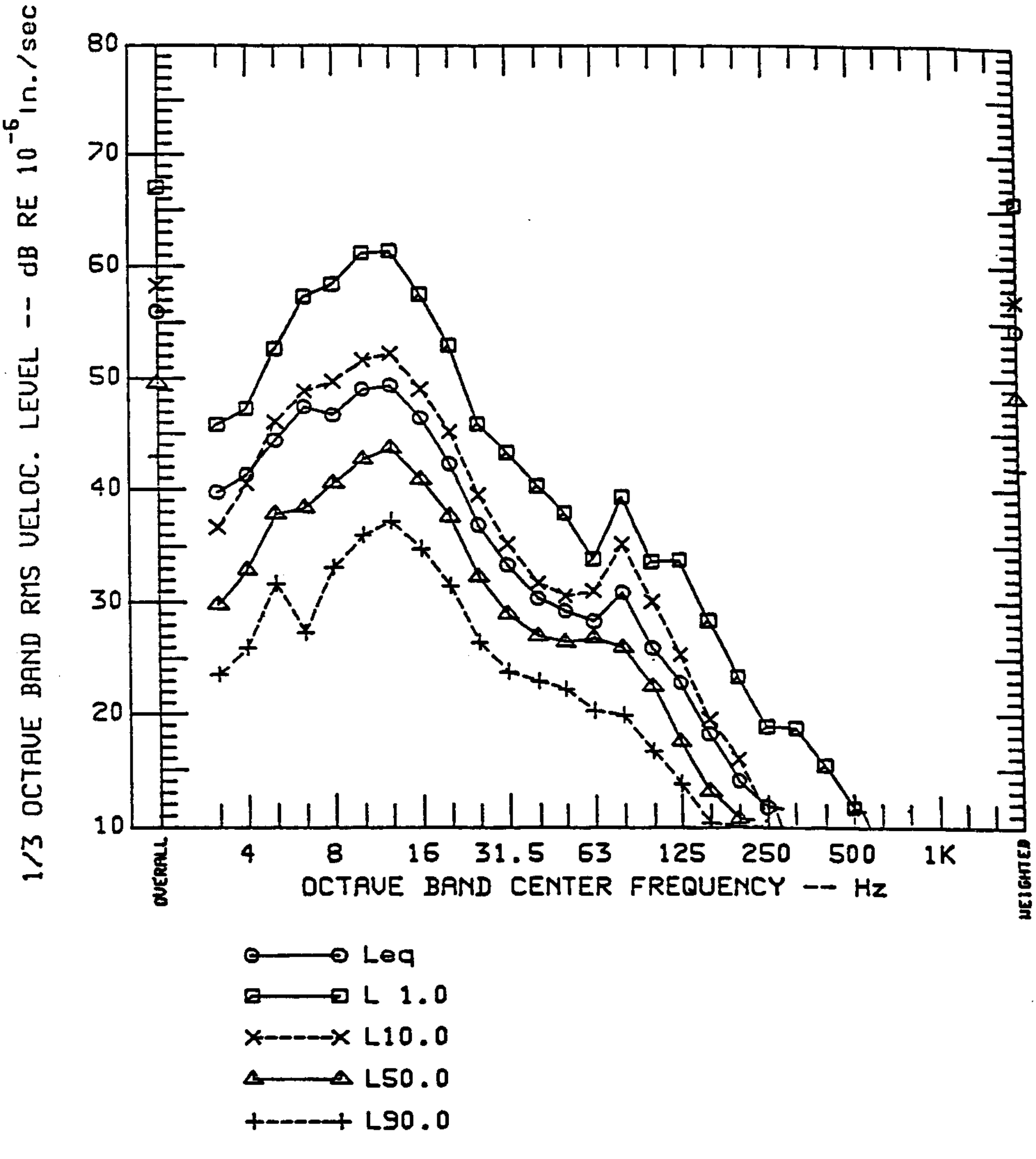

FIGURE B-6 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING THE DAY AT ABOUT 220 TO 340 FT FROM INTERSTATE 55 (STEVENSON EXPRESSWAY) CHICAGO, ILLINOIS

APPENDIX C

Ground Vibration from Street Traffic

FIGURES C-1 THROUGH C-2

Type of Vibration:	Surface Vibration - Street Traffic - 4 Lane Road
Location:	Along Piedmont Avenue in Atlanta, Georgia
Measurement Date:	April 16, 1984
Soil Type:	Generally micaceous silts with varying fractions of sand and clay
Additional Details:	Measurements made to characterize vibraion from existing street traffic prior to road modifications

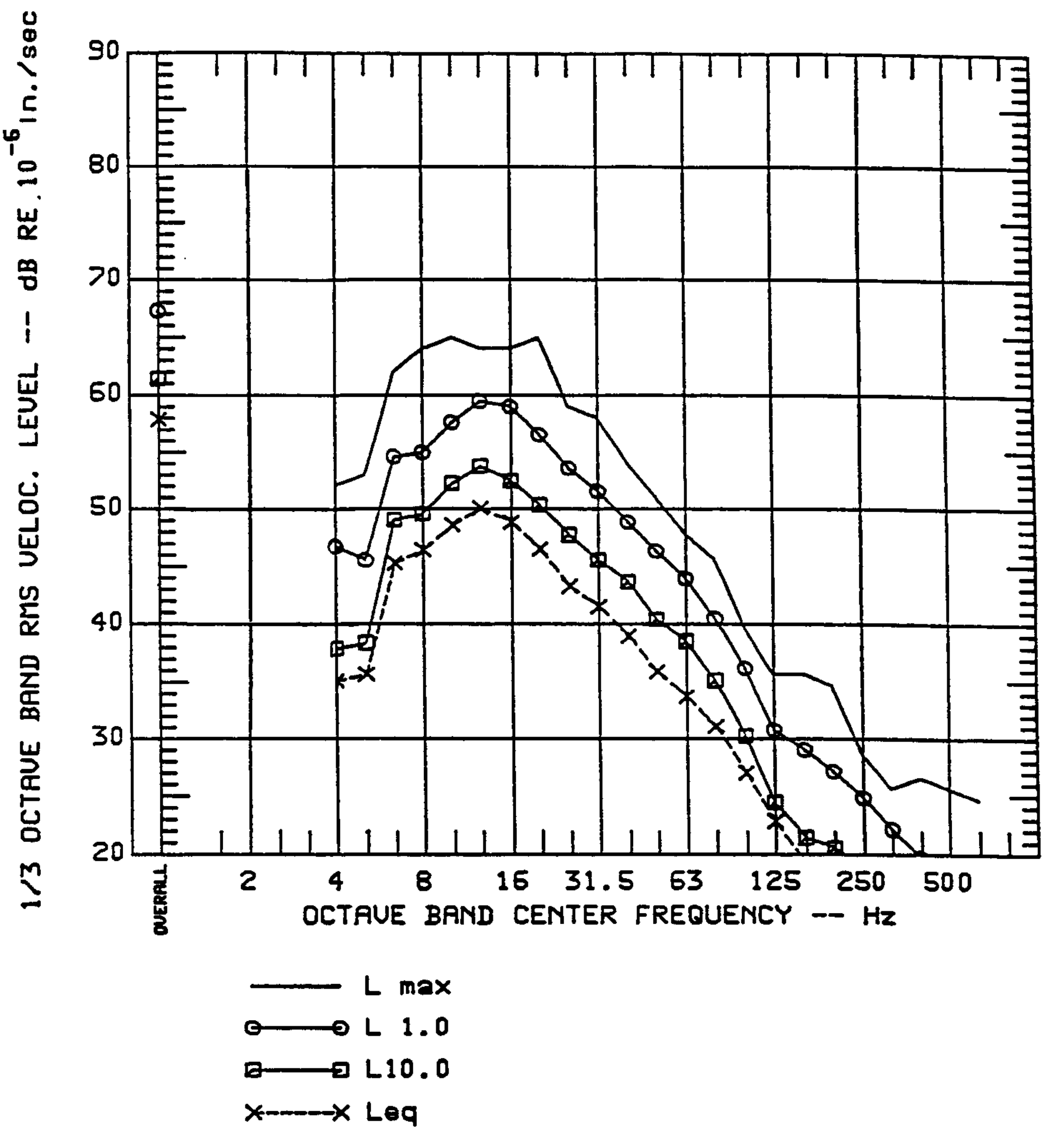

FIGURE C-1 GROUND VIBRATION AT 12 FEET FROM CURB OF PIEDMONT AVENUE

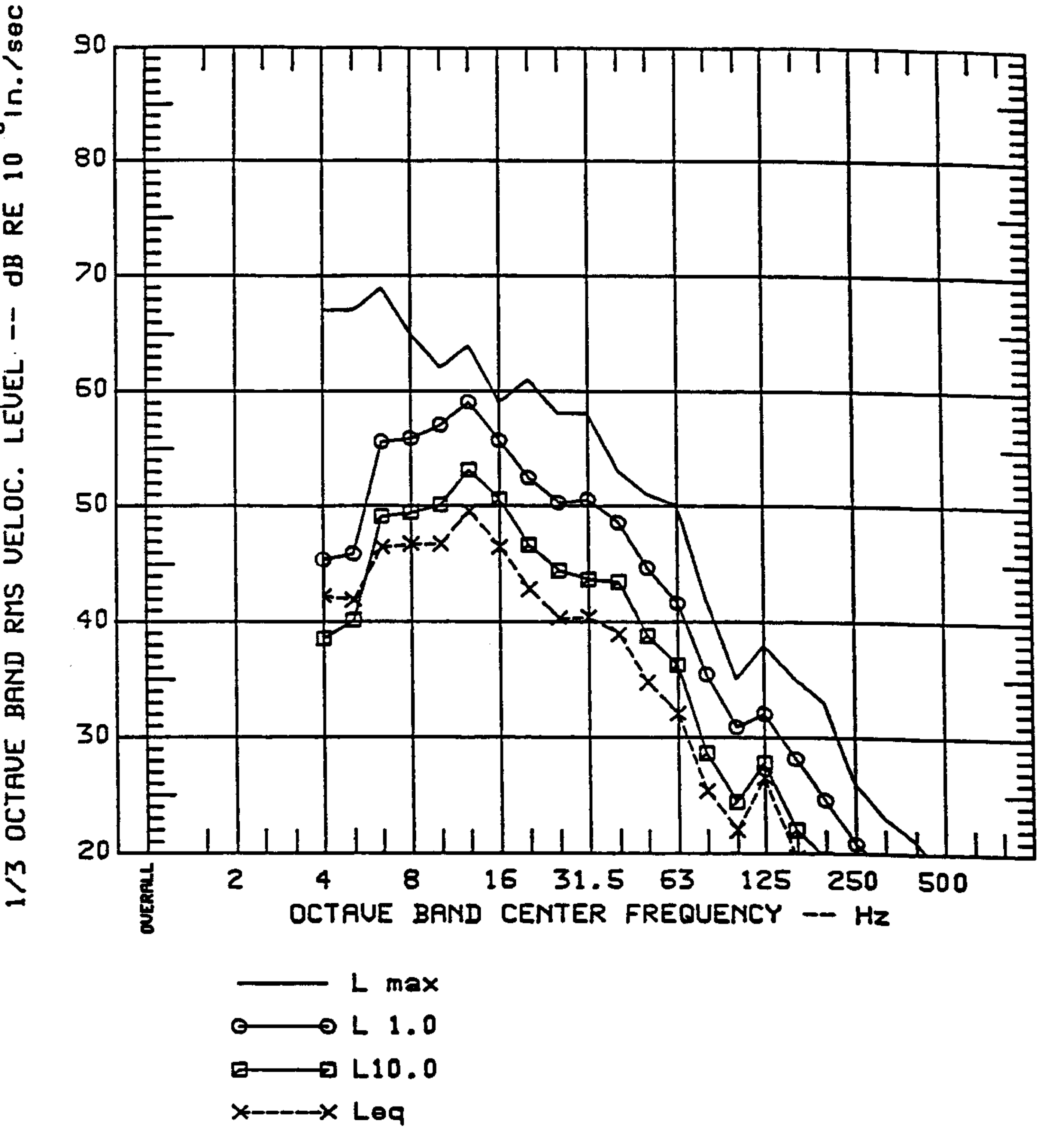

FIGURE C-2 GROUND VIBRATION AT 25 FEET FROM CURB OF PIEDMONT AVENUE

FIGURES C-3 THROUGH C-4

Type of Vibration:	Surface Vibration - Street Traffic - 2 to 4 Lane Roads
Location:	San Francisco, California
Measurement Date(s):	October 10-11, 1985
Soil Type:	Generally clay, silt, and sand mixed with gravel and sandstone fragments
Additional Details:	Measurements made to characterize vibration from existing street traffic along the proposed Muni J-Line Connection Project

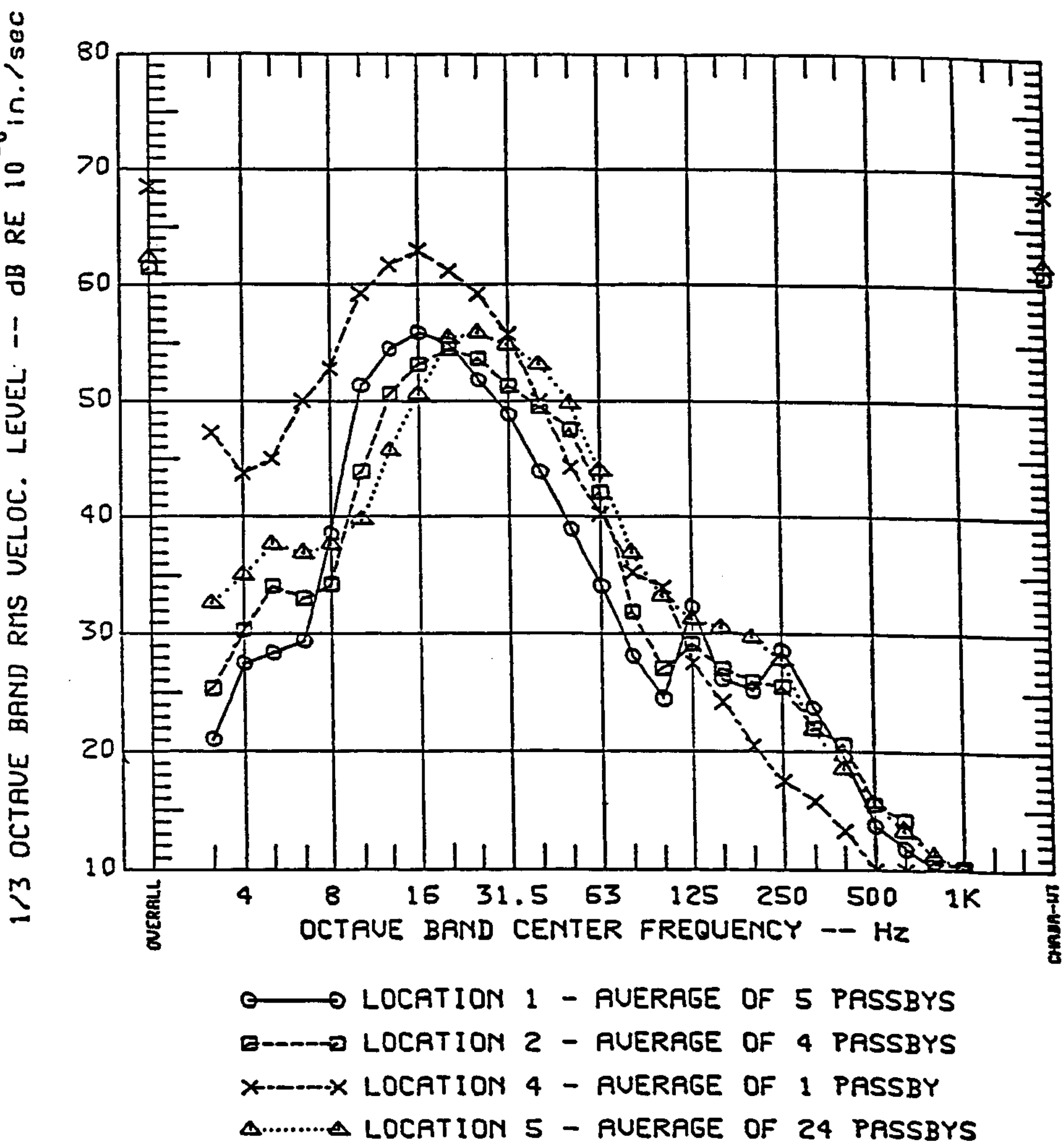

FIGURE C-3 GROUND-BORNE VIBRATION LEVELS FOR BUS PASSBYS ABOUT 20 - 35 FEET FROM CENTERLINE OF NEAR LANE

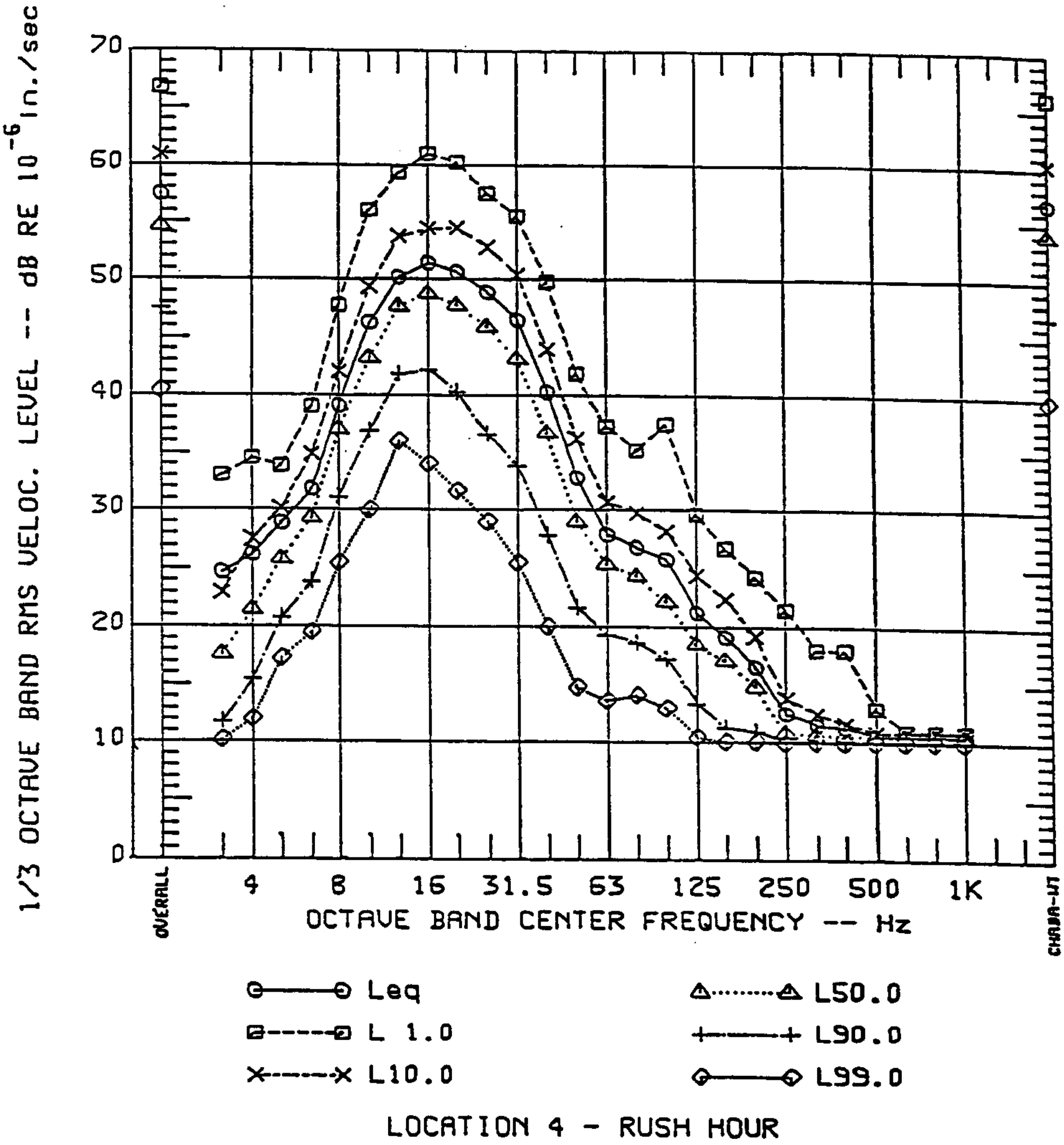

FIGURE C-4 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS ABOUT 20 FEET FROM CENTERLINE OF NEAR LANE

FIGURES C-5 THROUGH C-8

Type of Vibration:	Street Traffic
Location:	San Jose, California along Proposed Guadalupe Corridor
Measurement Date:	December 20, 1983
Soil Type:	Soils characteristic of downtown and northern San Jose - generally alluvial
Additional Details:	Measurements made to assess vibration from existing street traffic along proposed corridor for the Guadalupe lightrail transit system

TABLE C.1 LOCATIONS USED FOR EVALUATION OF THE NOISE AND VIBRATION ENVIRONMENT ALONG THE GUADALUPE CORRIDOR IN SAN JOSE, CALIFORNIA

Figure	Approximate Distance to Street Centerline (ft)	Site Description
C-5	75	North side of West San Carlos on concrete walkway of Center for Performing Arts at setback line. West San Carlos crosses the Guadalupe River approx. 110 feet west of measurement location.
C-6	50	Southwest corner of Clayton Ave and North First Street on sidewalk bordering Clayton Ave at setback line of building closest to North First Street.
C-7	65	West side of North First Street at setback line of apartment units. Measurement location on concrete driveway adjacent to 1461 North First Street.
C-8	90	ATARI parking lot at setback line of ACUTEST office building

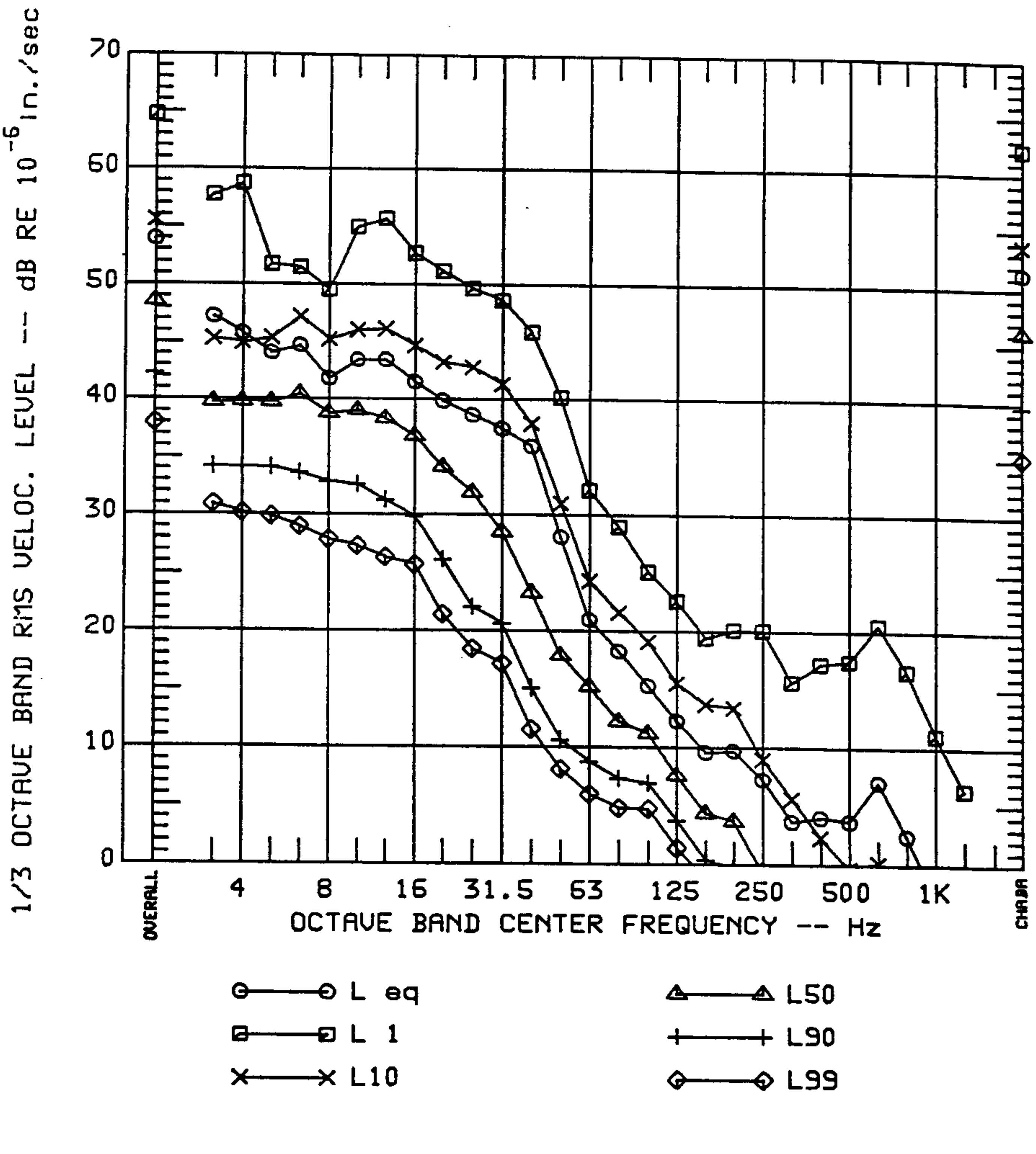

FIGURE C-5 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING THE DAY

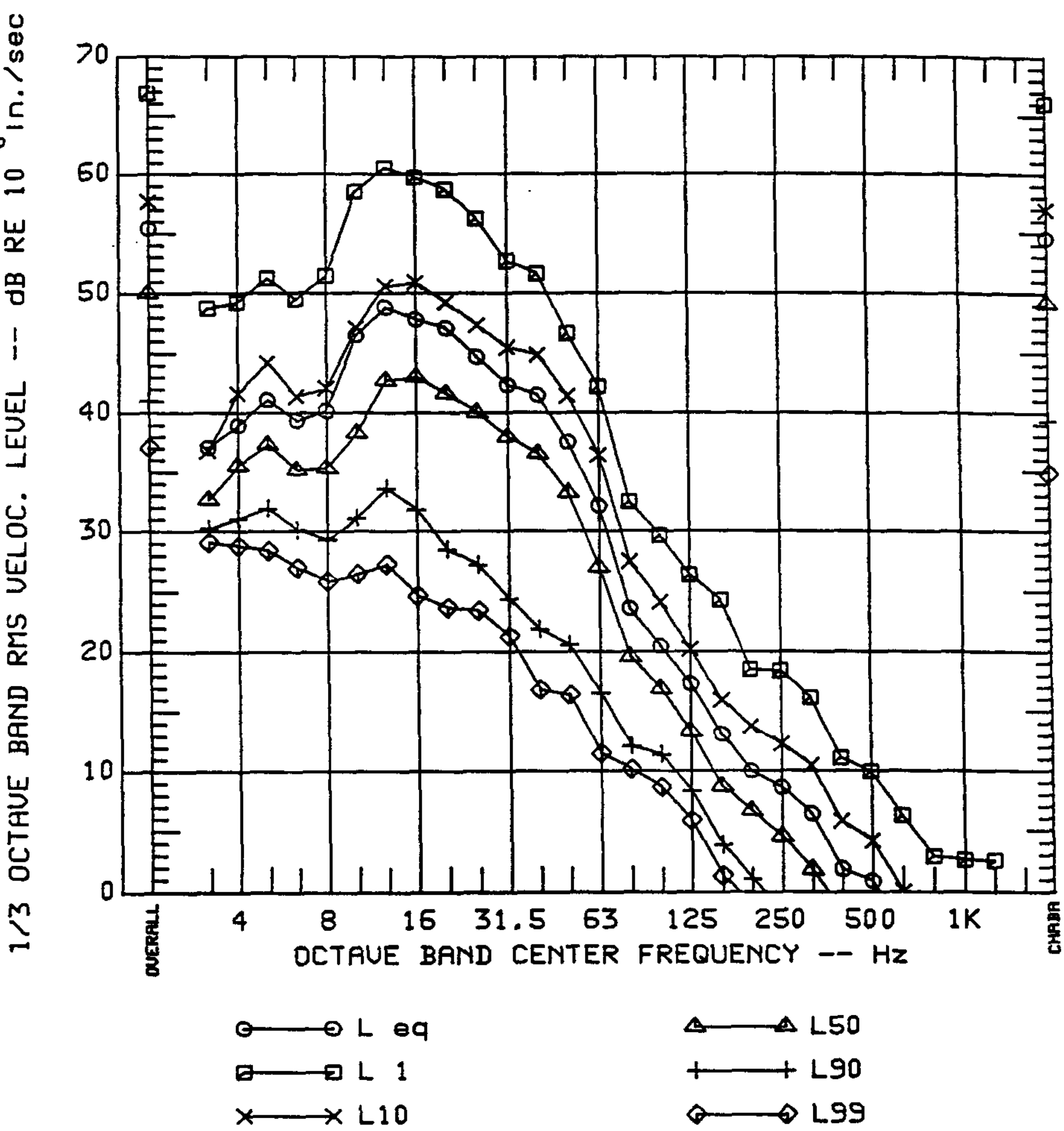

FIGURE C-6 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING THE DAY

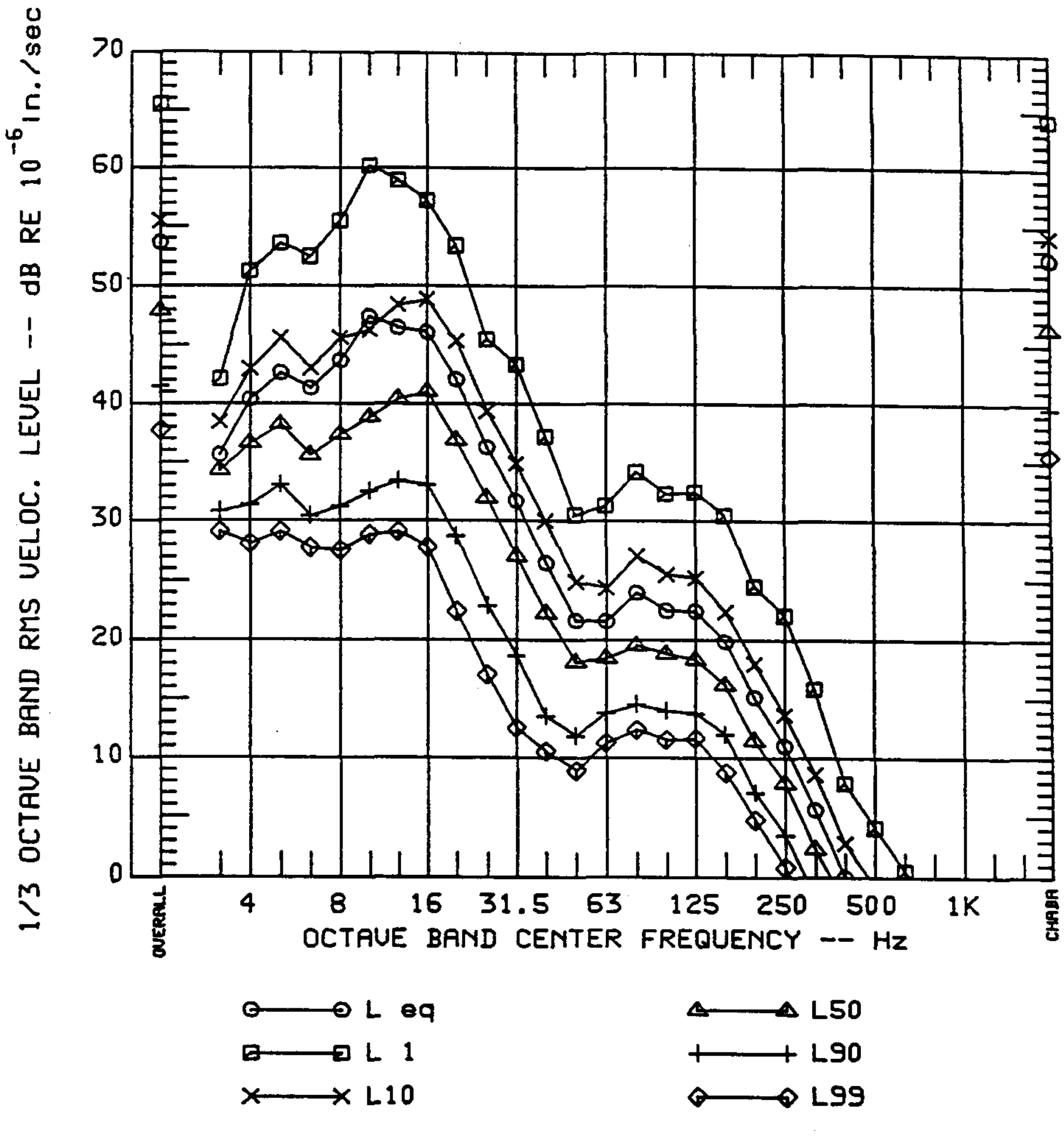

FIGURE C-7 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING THE DAY

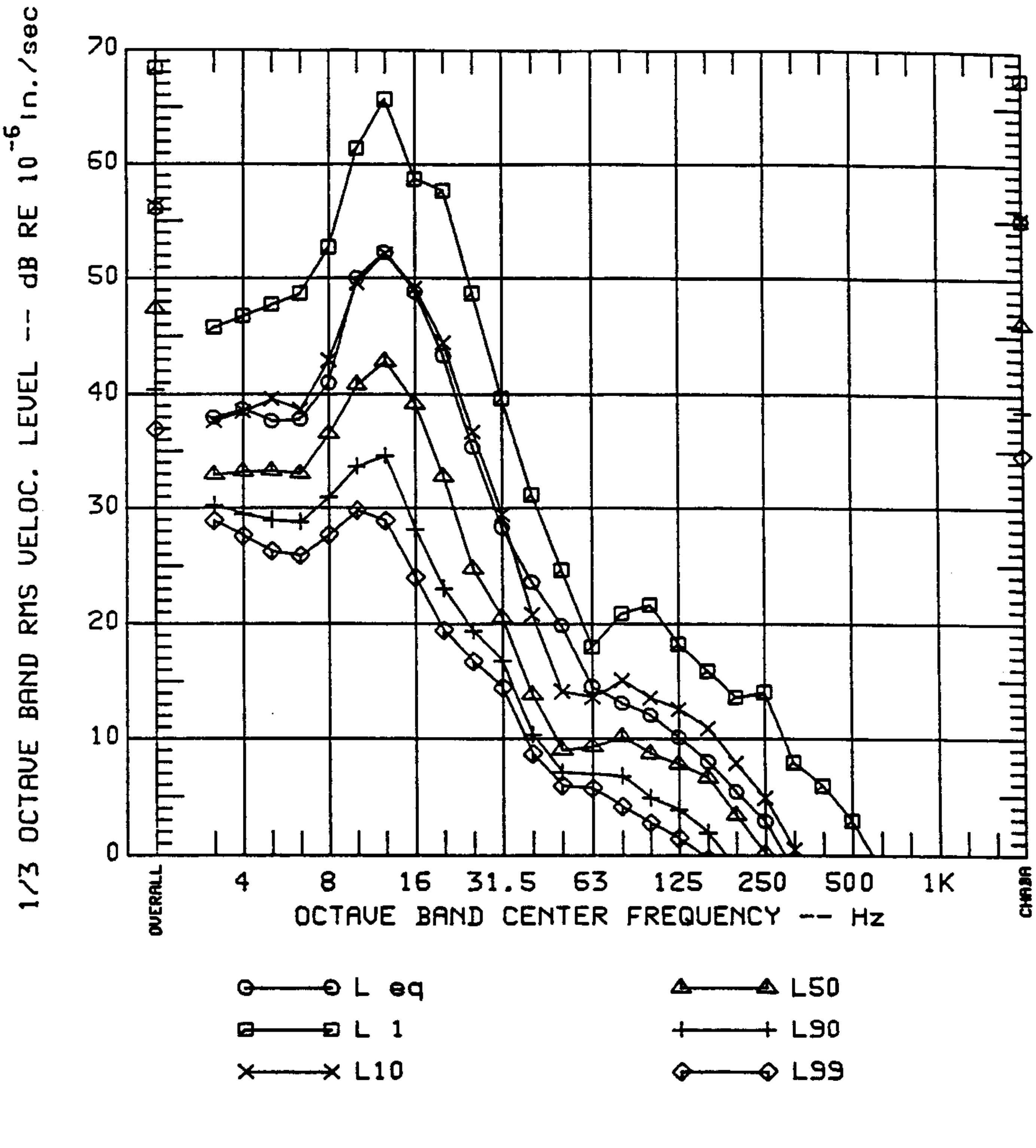

FIGURE C-8 ONE-THIRD OCTAVE BAND VIBRATION VELOCITY LEVEL STATISTICS DURING THE RUSH HOUR

APPENDIX D

Vibration at Various Depths from Rail Transit Trains

FIGURES D-1 THROUGH D-2

Type of Vibration:	Rail Transit Trains at Various Depths
Location:	Atlanta, Georgia
Measurement Dates:	August 7-8, 1985
Soil Type:	0-8' is fill (silt with gravel); 8'-24' is tan vs. stiff soil; 24'-33' is partially weathered rock
Additional Details:	Measurements made to assess vibration in basement levels of proposed building. Borehole site at about 110 feet from subway structure

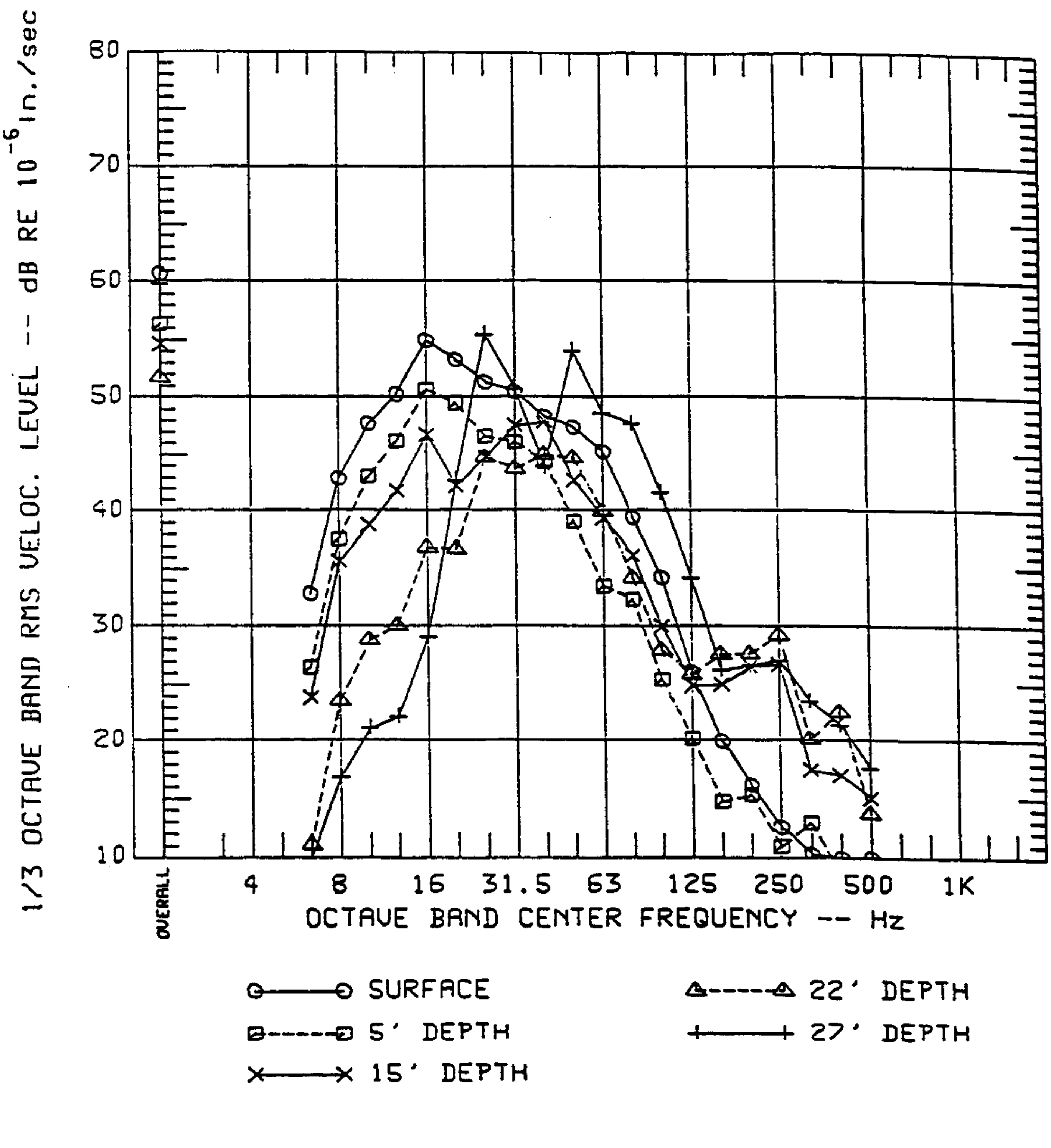

FIGURE D-1 GROUND-BORNE VIBRATION FROM NEAR TRACK MARTA TRAIN PASSBYS AT 110 FEET

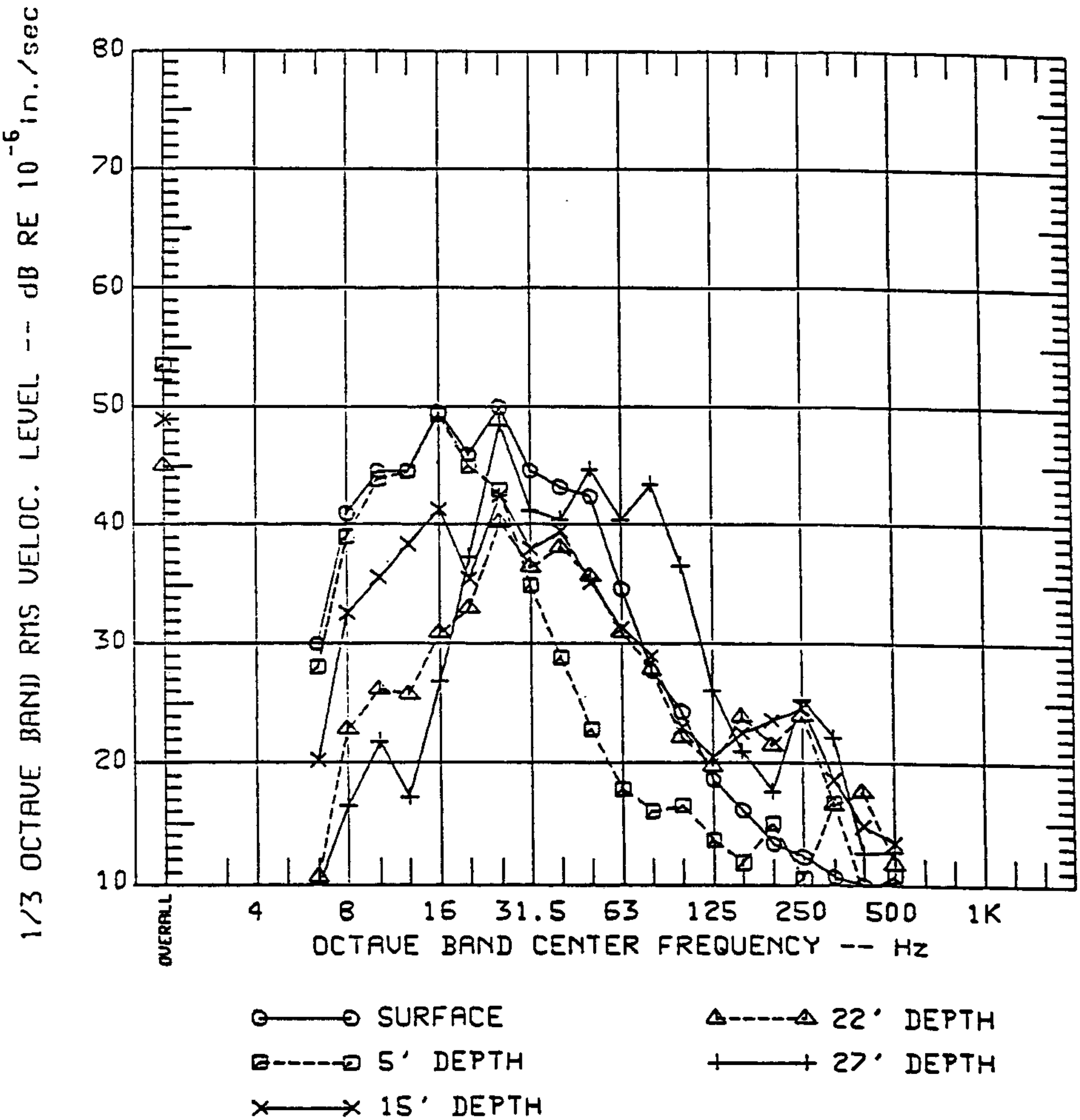

FIGURE D-2 GROUND-BORNE VIBRATION FROM FAR TRACK MARTA TRAIN PASSBYS AT 125 FEET

APPENDIX E

Ground Vibration from Construction Equipment

FIGURES E-1 THROUGH E-2

Type of Vibration:	Surface Vibration - Construction Activities
Location:	Along Interstate 85 in Atlanta, Georgia
Measurement Date:	October 3, 1979
Soil Type:	Generally fill - other characteristics unknown
Additional Details:	Measurements made to characterize vibration from construction activities which could occur near a computer facility

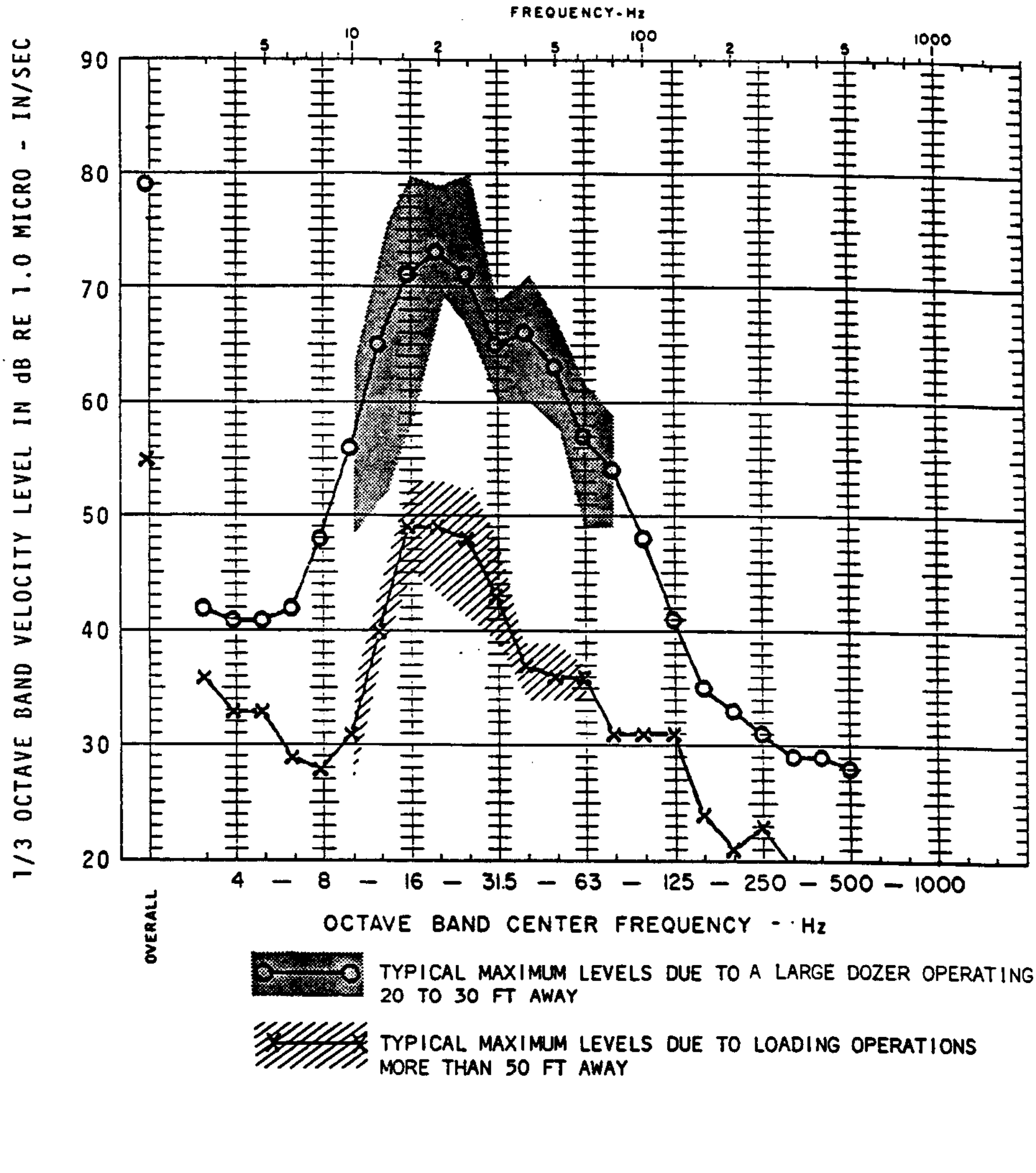

FIGURE E-1 FREQUENCY ANALYSIS OF GROUND-BORNE VIBRATION FROM CONSTRUCTION EQUIPMENT

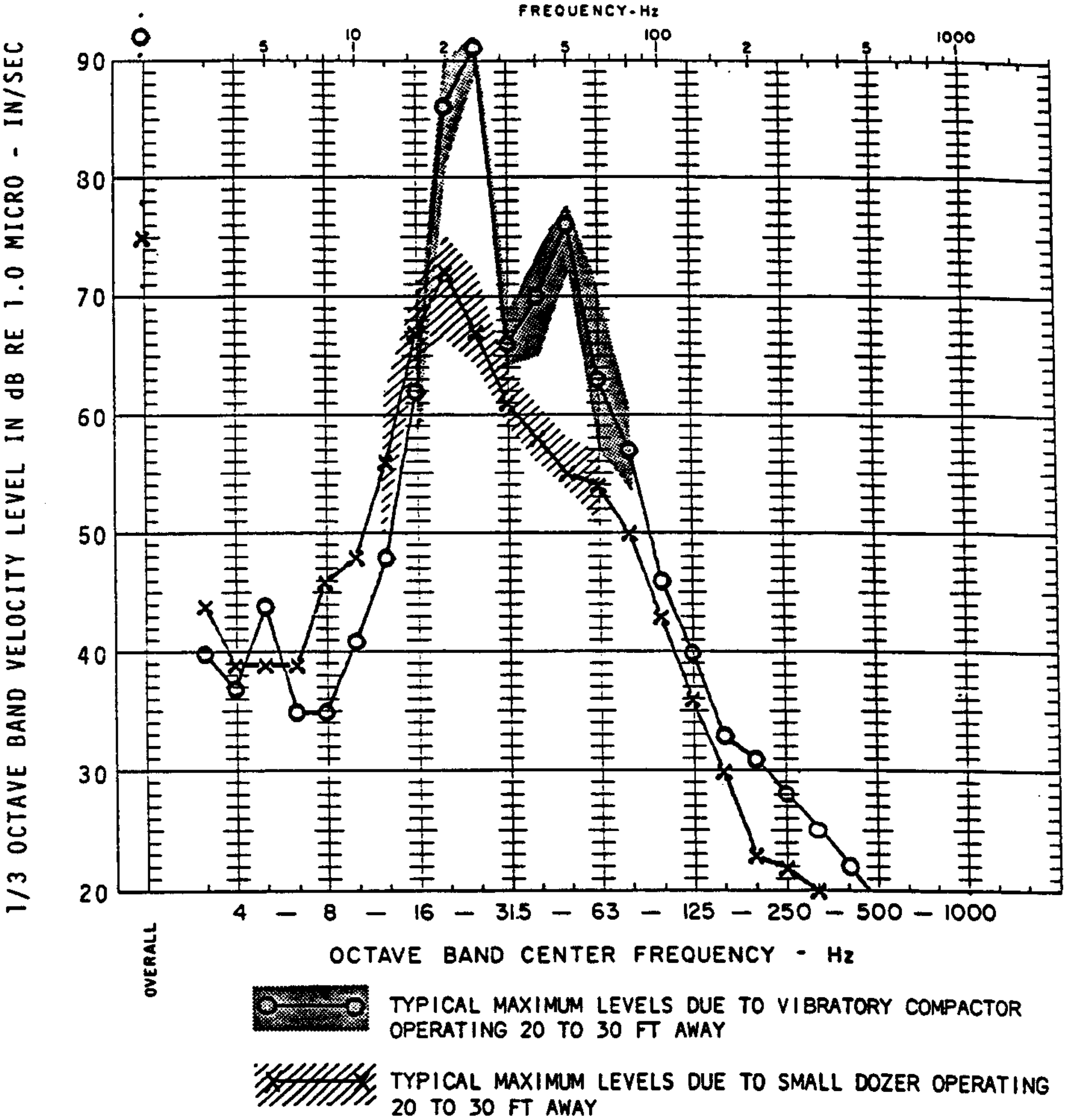

FIGURE E-2 FREQUENCY ANALYSIS OF GROUND-BORNE VIBRATION FROM CONSTRUCTION EQUIPMENT, ACCELEROMETER MOUNTED ON SPIKE IN SOIL

APPENDIX F

Ground Vibration from Pile Driving and Rock Drilling Equipment

FIGURE F-1

Type of Vibration:	Surface Vibration due to Impact Pile Driver
Location:	Along Interstate 85 in Atlanta, Georgia
Measurement Date:	October 3, 1979
Soil Type:	Generally fill - other characteristics unkown
Additional Details:	Measurements made to characterize vibration from pile driving activities which could occur near a computer facility

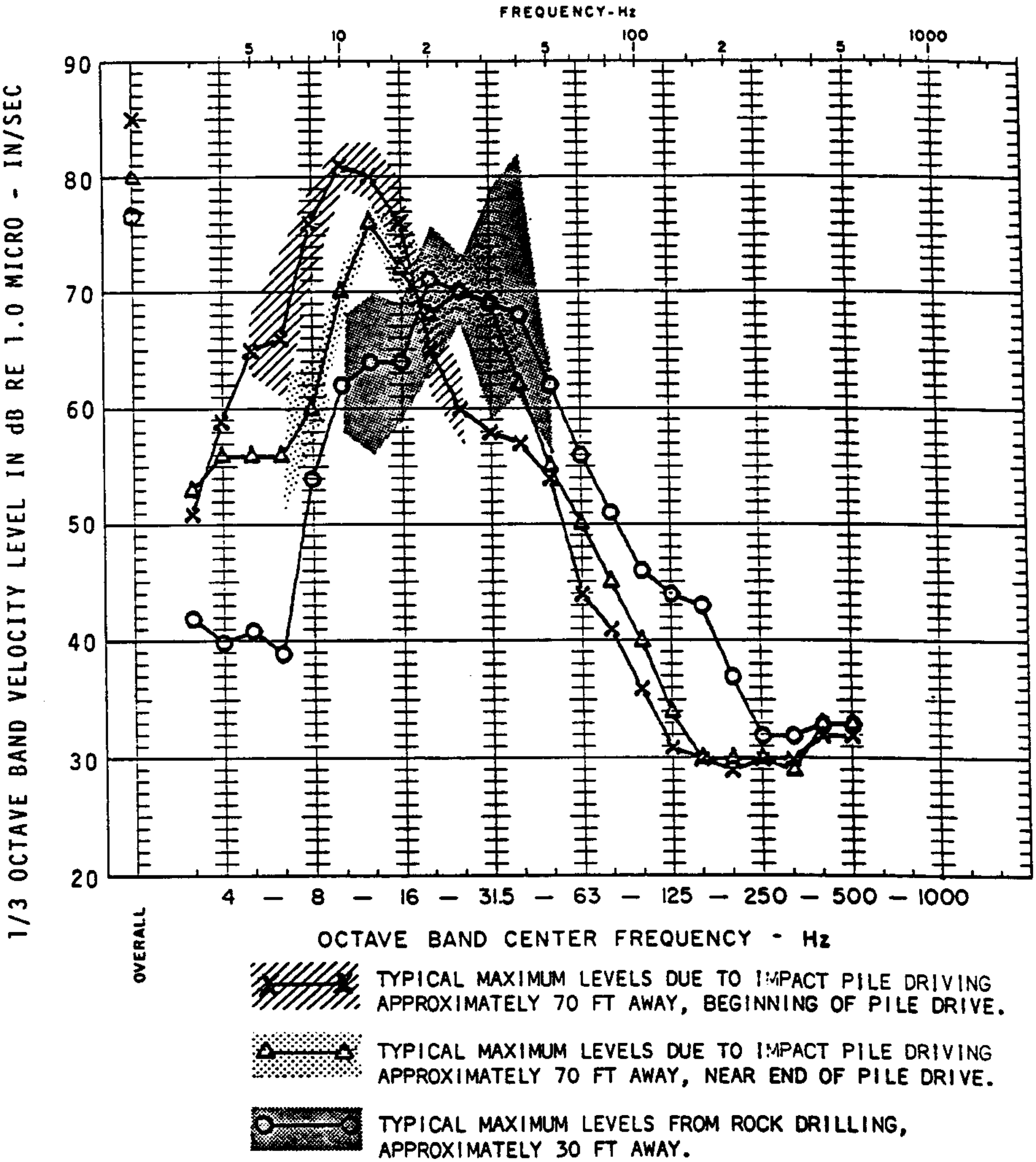

FIGURE F-1 FREQUENCY ANALYSIS OF GROUND-BORNE VIBRATION FROM CONSTRUCTION EQUIPMENT, ACCELEROMETER MOUNTED ON SPIKE IN SOIL

FIGURES F-2 THROUGH F-3

Type of Vibration:	Surface Vibration due to Sonic Pile Driver
Location:	Buffalo, New York
Measurement Dates:	May 21 and 22, 1980
Soil Type:	Unknown
Additional Details:	Measurements made during construction equipment operation at the NFTA LRRT construction project

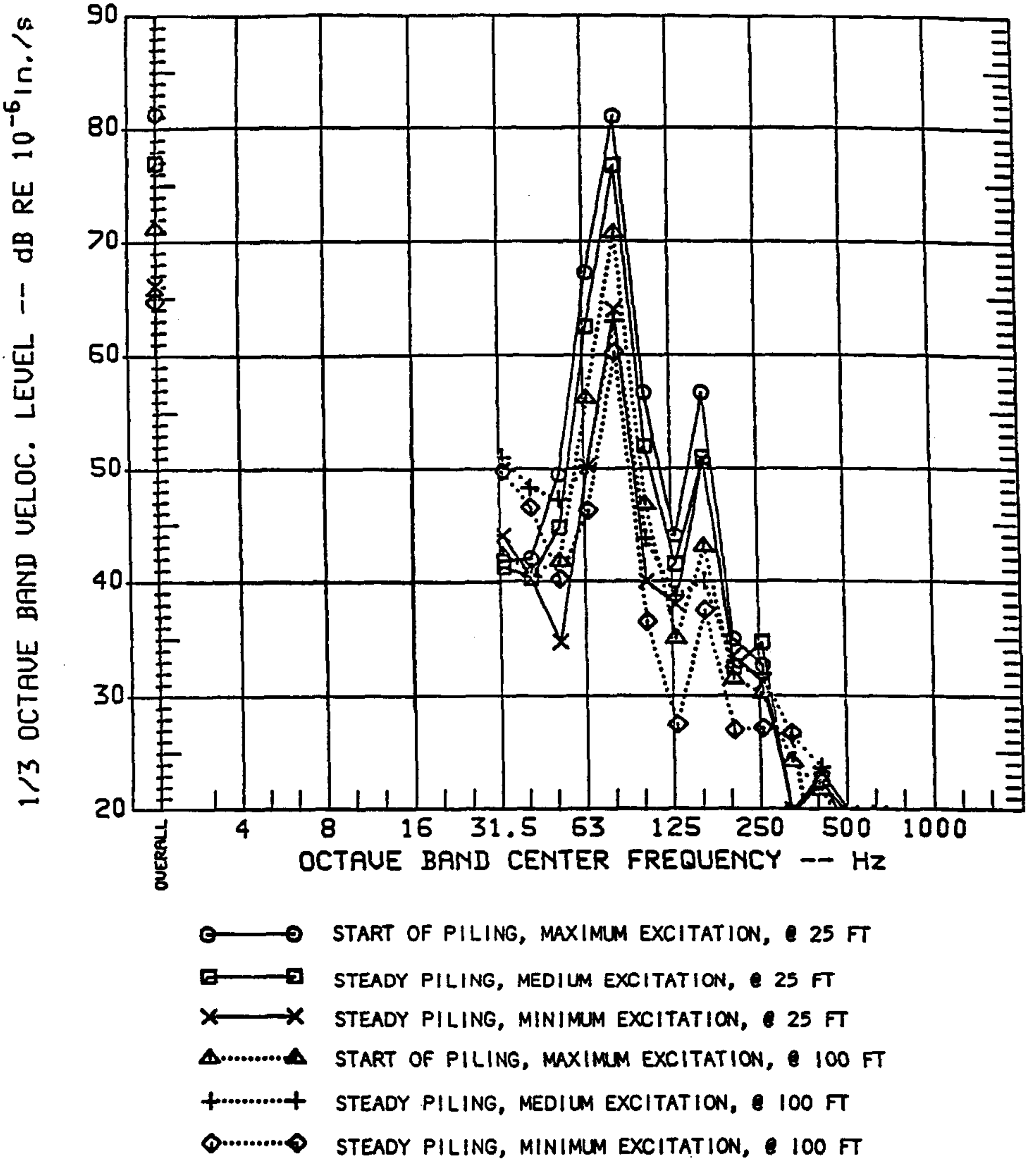

FIGURE F-2 GROUND-BORNE VIBRATION LEVELS FROM THE SONIC PILE DRIVER DRIVING 'H' PILES AS MEASURED AT THE SOUTHSIDE OF WEST UTICA STREET - MAY 22, 1980

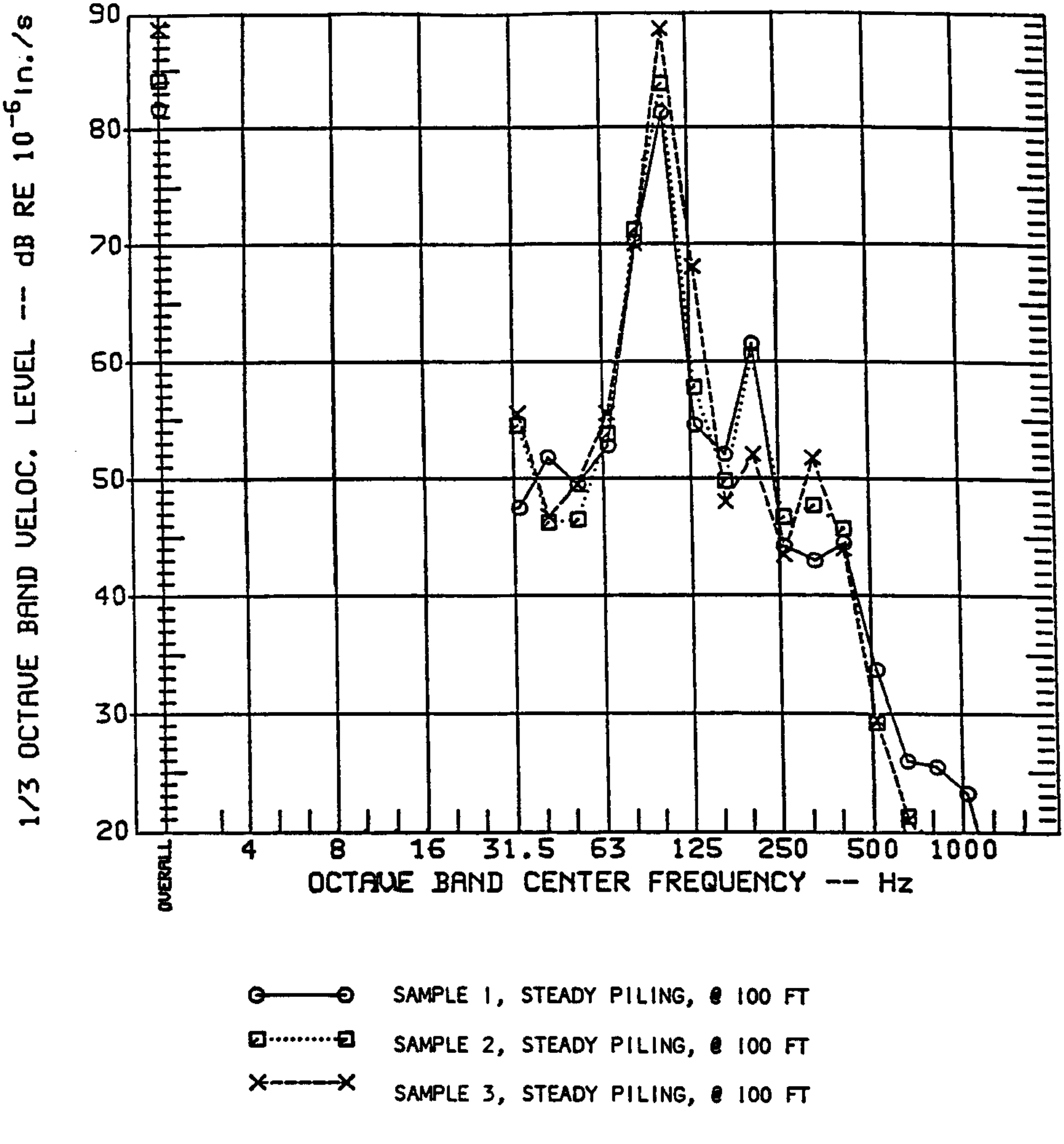

FIGURE F-3 GROUND-BORNE VIBRATION LEVELS FROM THE SONIC PILE DRIVER DRIVING 'H' PILES AS MEASURED AT THE SOUTHSIDE OF WEST UTICA STREET - MAY 21, 1980

FIGURE F-4

Type of Vibration:	Surface Vibration due to Rock Drilling Machine Operations
Location:	Buffalo, New York
Measurement Date:	May 20, 1980
Soil Type:	Unknown
Additional Details:	Measurements made during construction equipment operation at the NFTA LRRT construction project

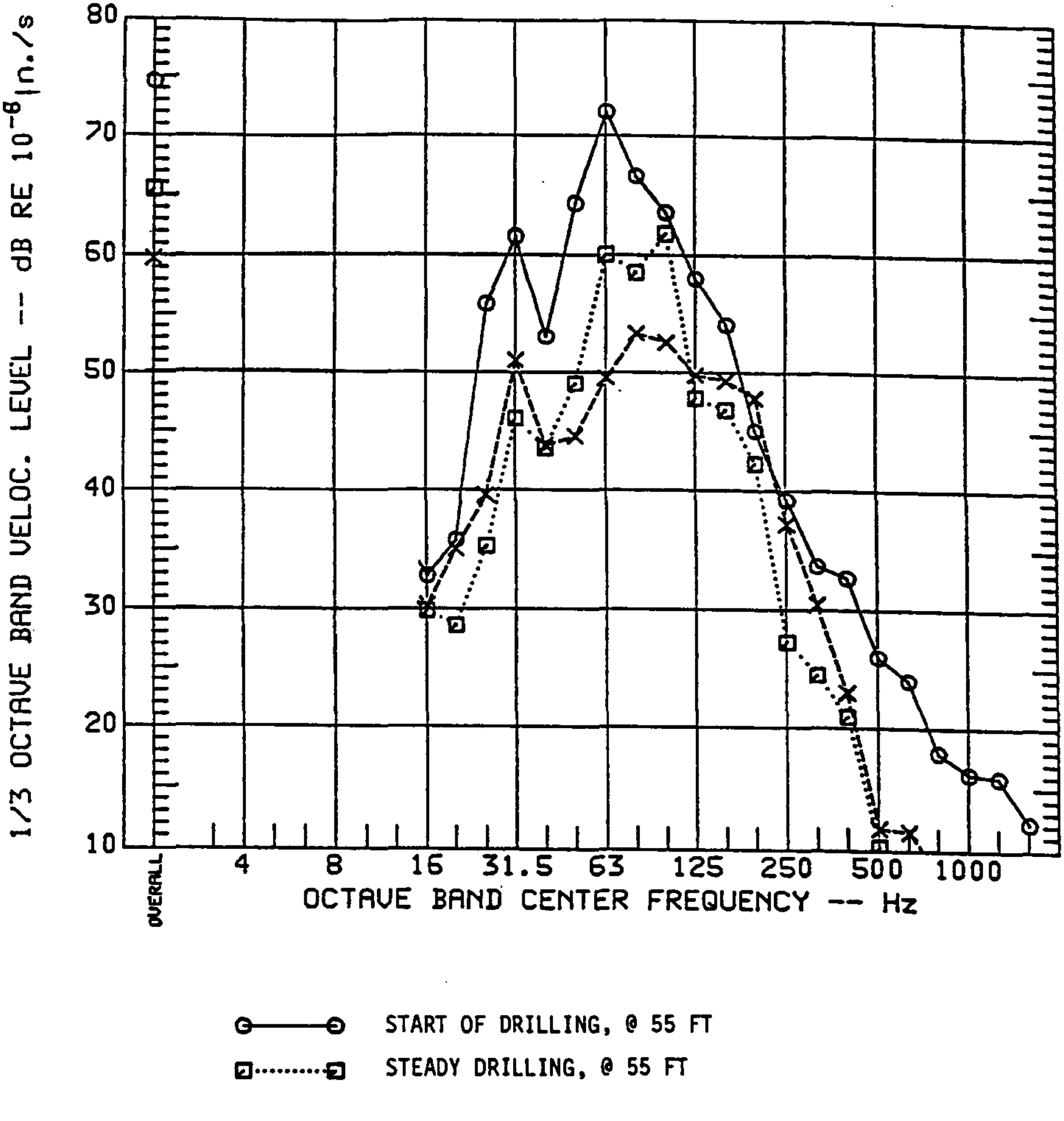

FIGURE F-4 SURFACE GROUND-BORNE VIBRATION LEVELS FROM THE ROCK DRILLING MACHINE AS MEASURED ON THE ASPHALTED SURFACE NEAR THE AMHERST SITE, INTERSECTION OF PARKER AND MAIN STREET - MAY 20, 1980

APPENDIX G

Ground Vibration from Blasting Operations

FIGURE G-1

Type of Vibration:	Surface Vibration due to Blasting Operations
Location:	Buffalo, New York
Measurement Dates:	July 30 to August 7, 1979
Soil Type:	Rock with surface soil layer
Additional Details:	Measurements made during the NFTA LRVS construction project

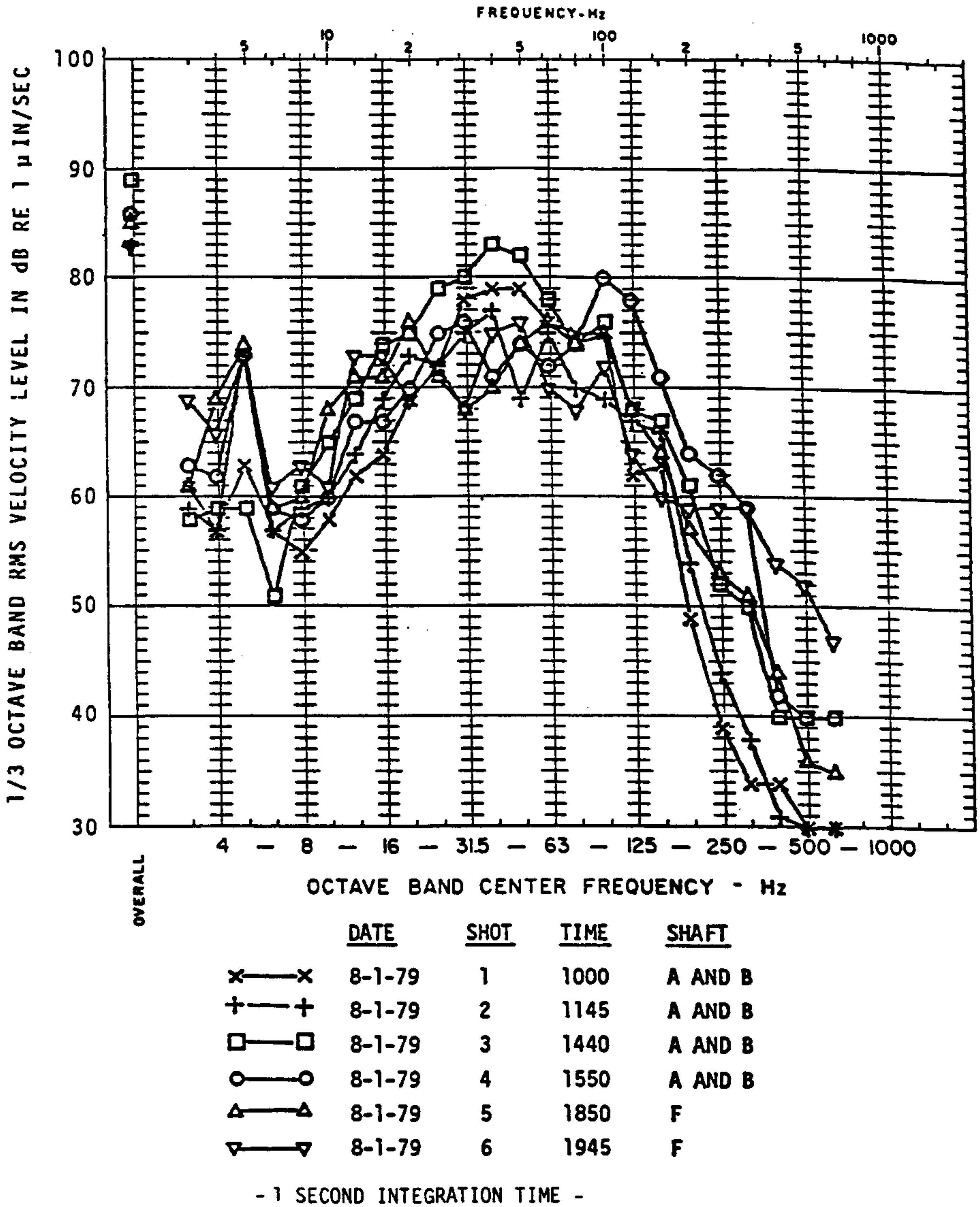

FIGURE G-1 TYPICAL EXAMPLES OF VERTICAL VELOCITY SPECTRA DUE TO BLASTING AT APPROXIMATELY 200 FT CHARGE WEIGHT UNKNOWN

APPENDIX H

Ground Vibration from Tunnel Boring Machine

FIGURES H-1 THROUGH H-3

Type of Vibration:	Surface Vibration due to Tunnel Boring Machine Operations
Location:	Buffalo, New York
Measurement Dates:	May 21, July 29 and 30, 1980
Soil Type:	Unknown
Additional Details:	Measurements made during Tunnel Boring Machine (TBM) operations at the NFTA LRRT construction project. Note that data is presented in terms of acceleration levels

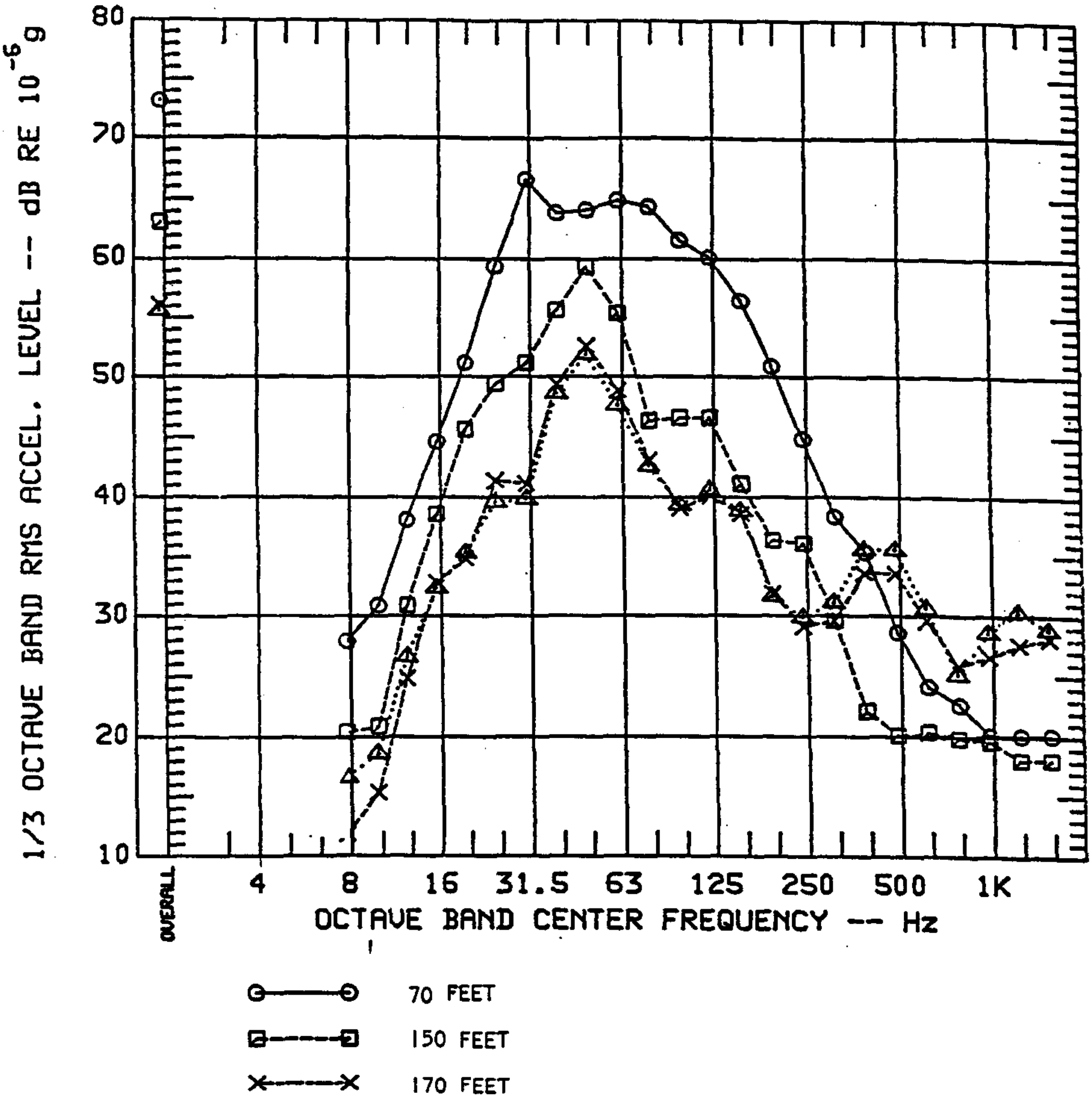

FIGURE H-1 SURFACE GROUND-BORNE VIBRATION OBSERVED AT VARIOUS HORIZONTAL DISTANCES FROM THE TBM OPERATION AT 40 FEET BELOW SURFACE - MAY 21, 1980

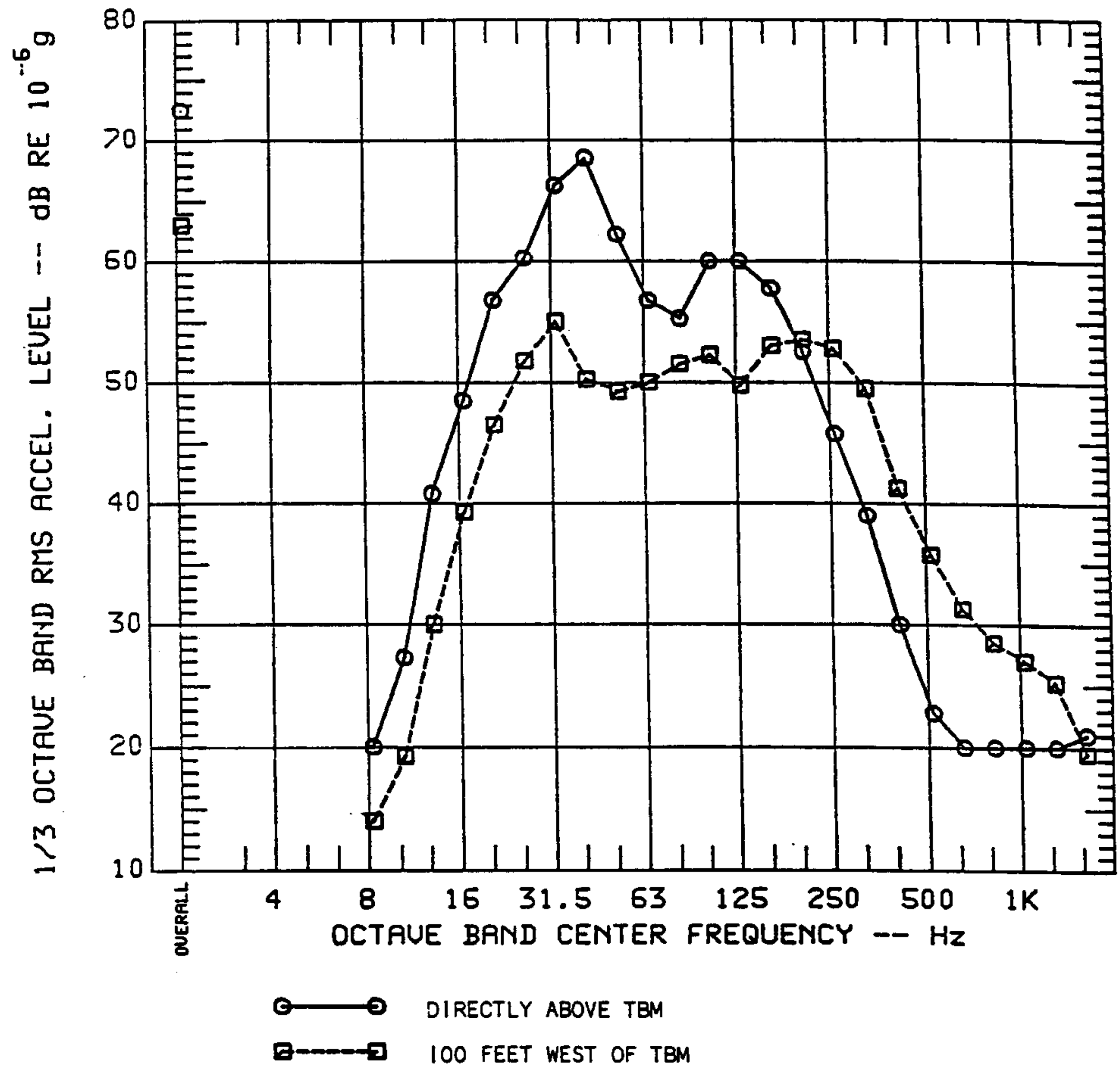

FIGURE H-2 SURFACE GROUND-BORNE VIBRATION OBSERVED ON SIDEWALK AND ASPHALT SURFACE WITH THE TBM OPERATING AT 40 FEET BELOW SURFACE - JULY 29, 1980

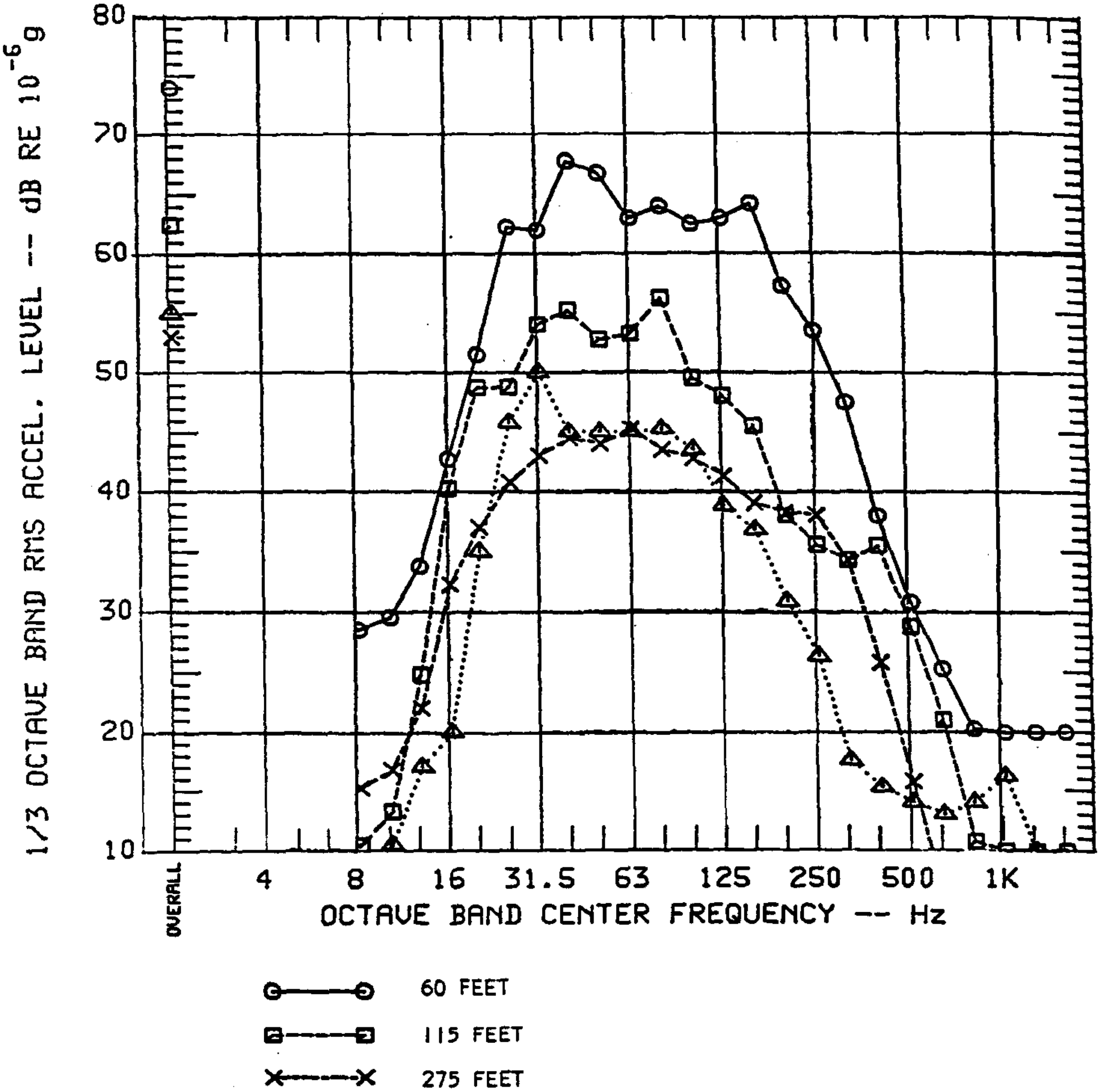

FIGURE H-3 SURFACE GROUND-BORNE VIBRATION OBSERVED ON THE CONCRETE SIDEWALK OF NORTHLAND IN FRONT OF LINCOLN MEMORIAL METHODIST CHURCH AT VARIOUS HORIZONTAL DISTANCES EAST OF THE TBM OPERATING AT 40 FEET BELOW SURFACE - MAY 21, 1980