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Some Characteristics of Ground Vibrations at the SSC Site

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Based on analysis by K. Y. Ng and J. M. Peterson (April 1989), it appears that ground vibrations of sufficient amplitude of displacement with wavelengths in the region of 70 m to one km have the potential to interfere with the operation of the accelerator due to adiabatic (with respect to a bunch revolution) motion of the focussing elements of the lattice (quadrupole magnets). Because of the focussing aspect, relative transverse alignment variations in the quad separations in a cell distant from the interaction region (IR) can cause significant displacement of the centers of the focussed beams at the IR's ("missing"). A similar analysis for the multiple quads at the IR's leads to similar conclusions, but with enhanced sensitivity. For periodic ground vibrations the frequency is the wave speed in local material (rock, in the case of the main ring tunnel) divided by the wavelength involved. This is the origin of the restrictions given in the Invitation for Site Proposals for the Superconducting Super Collider (SSC), DOE/ER-0315 (April 1987) (ISP, p57): "The beams are sensitive to ground motion in the frequency range from a fraction of a hertz to several tens of hertz. At about 3 hertz there is a resonant response to the ground motion. However, by using a feedback system, ground motion of up to 0.5 thousandths of an inch (12.7 μm) amplitude at the interaction region and two thousandths of an inch (50.8 μm) elsewhere can be controlled. A larger ground motion may require a feedback system stronger than practical. Because there is considerable variation, data suggest that a railroad line should not pass within approximately 3,000 ft (914.4 m, or around one km) of an interaction point, unless measurements demonstrate that the ground motion is within the above tolerance. Major public roads or freeways should be no closer than about 600 ft (182.88 m or about 0.2 km) from an interaction point." A wavelength of 880 m and a frequency of 3 Hz corresponds to a wave speed of 2.64 km/s, about the speed of some seismic waves in chalk.

Studies of ground vibration have shown as a practical matter that of the sources of culturally produced vibration such as quarry or roadwork blasts, car and truck traffic, heavy equipment (earth moving) operations and trains, trains that would cross the main ring are the most important (Nelson, 1987; Skokoe, Rix, and Mok, 1987; TNRLC, Vol. 7, 1987; Lesmes, Morgan and others, 1988). Qualitatively, this corresponds to the fact that train cars and locomotives are very massive (up to around 62.5 tonnes = 6.25×10^4 kg) rather large (15 m to 30 m long) and may be moving rather quickly (45 mi/hr = 72.4 km/hr = 20.1 m/s) and their means of support (wheel carriages on the ends) loads and unloads the roadbed (ballast) with considerable force via the rails and crossties. The entire railroad structure (rails, ties, and ballast) flexes under this loading in a sort of modified square wave pattern, of frequency = 20 (m/s)/20 m = about one Hz. Any irregularities in wheels, rails, suspension or coupling will tend to produce additional acoustic power fed into the ground; e.g., a wheel with a flat spot is particularly noticeable. All the proposed SSC sites were located a sufficient distance from quarries that the effect of blasting in terms of ground vibrations is measurable but small. Ground vibration due to freeway traffic is of much lower amplitude than that due to trains because the highway deformation due to trucks is smaller than the railroad case, even though the masses of loaded trucks are of the same order of magnitude as that of railcars and the trucks move much faster. Again, experiments have shown that irregularities in the road surface such as breaks or potholes tend to cause much greater amounts of acoustic power to be fed into the ground. Heavy equipment operation close to the IR's is a potential concern, although the closest continuous such operation is associated with the quarries. Thus, trains (for reasons that are easy to understand and difficult to model) are the main source of concern about vibrations in the frequency range of a few Hz.

Two distinct types of wave can propagate through the body of an elastic solid, P waves (primary, push, longitudinal, alternate rarefaction/compression waves) and S waves (shear, shake, transverse, alternate back and forth waves). The P waves can also propagate through elastic fluids, while the fact that S waves cannot is of some importance in geophysics. In terms of the incompressibility (bulk modulus) k, the shear modulus (modulus of rigidity) μ and the density ρ, the squares of the wave speeds are

$$V_s^2 = \mu / \rho$$

$$V_p^2 = (k + 4\mu/3)/\rho$$

Among other things, these expressions show that the ratio V_p/V_s is always greater than root 4/3 = 1.155. One of the important formations in the site area is the Austin Chalk, that is composed of alternating beds of blue-gray, white-weathering, marly limestone and dark gray, gray-weathering, shaly limestone, both parted by beds of calcareous shale. Sedimentary rocks are deposited in relatively flat-lying beds; the dip of formations in the site region is about 0.65 degrees to the southeast. Since the sedimentary rocks often have different properties vertically than horizontally, the two possible S wave polarizations may have different speeds. Field measurements in the chalk have shown that for vibrations vertically (perpendicular to bedding planes) one finds that $V_p = 2.58$ km/s and $V_{sv} = 1.07$ km/s; for vibrations in the plane of the bedding, $V_p = 3.05$ km/s and $V_{sh} = 1.13$ km/s were measured (GSA, 1966). Measurements at the site by Tilford *et al.* (1988) give $V_p = 2.6$ km/s for weathered chalk and a range of V_p between 3.00 km/s and 2.76 km/s for unweathered chalk by refraction techniques. Since the elastic constants increase in value with depth faster than the density, the wave speeds increase from these values to $V_p = 6.030$ km/s and $V_s = 3.030$ km/s as the depth increases beyond about a kilometer or so (Dobrin, 1976).

As elastic waves spread outward from a source region, the displacement amplitude decreases with distance r from the source. This is due to two different phenomena. For spherical waves, geometric spreading gives a power decrease as the negative second power of r by conservation of energy, so the displacement amplitude decreases as $1/r$. Cylindrical (circular surface) wave displacement amplitudes decrease as the inverse square root of the cylindrical radius, and plane waves (or surface waves close to a line source) do not exhibit geometric spreading. Frictional heating of the rock grains results in wave absorption that is exponential in form, so that the amplitude decreases as $e^{-\alpha r}$ with attenuation coefficient α. Another way of expressing the attenuation is in terms of the quality factor Q, the ratio of (2π peak energy stored)/(energy dissipated per cycle of oscillation). Then the attenuation factor $\alpha = (\pi f)/(QV)$, where f is the frequency, V is the wave speed and Q the quality factor appropriate to a given wave type. This expression gives reasonable values of attenuation if Q is regarded as dependent upon the rock composition and degree of saturation and independent of frequency. In unconsolidated wet (water saturated) materials, the attenuation is relatively independent of frequency for values in the range of interest (a few tenths to about 100 Hz) so the quality factor concept is less useful in this case.

Clark, Tittman, and Spencer (CTS, 1980) performed precise laboratory measurements at frequencies of 5–20 kHz on small samples (about 1.4 cm diameter by 12.7 cm long) of selected sedimentary rocks, including the Austin Chalk. They measured the properties under varying conditions of water content, from a one micron vacuum to saturation. The rock parameters of the chalk were as follows: 26.7 percent porosity, bulk density of 1.94 g/cm^{-3}, grain density of 2.72 g/cm^{-3}, V_p = 2.7 km/s, V_s = 1.85–1.88 km/s, Q_p^{-1} = (0.63 to 1.68)$^{-3}$, Q_s^{-1} = (0.44 to 1.45)$^{-3}$ (vacuum to 35 percent relative humidity), Poisson's ratio 0.015. Under conditions of saturation Q_s^{-1} increased to 3.36×10^{-3}, or $Q_s = 298$. Representative values of $Q_p = 640$ and $Q_s = 700$ seem to best characterize the absorption in this laboratory sample. Because of the heterogeneity of the rock layers in the field, the effective Q for both types of waves is probably closer to 100. Laboratory measurements on chalk from Flamborough Head Pebble, England have $Q_p = 110$. Field measurements of Q_p greater than 273 were obtained at borehole depths of greater than 1.5 km in southeast Texas, in what seems to be the Austin Chalk. As a sample case, consider the attenuation coefficient for shear waves in saturated chalk: $\alpha = (\pi \times 1\text{Hz})/(298.1.85\text{ km/s}) = 0.0057/\text{km}$, or a e^{-1} distance of 175 km. A similar value of $\alpha(P) = 0.0057(700/640)/2.7 = 0.0023/\text{km}$ for P waves would have a e^{-1} distance of 433 km, so that frictional attenuation in the chalk at one Hz is very small. These attenuation factors may be multiplied directly by the frequency in Hz to obtain the absorption at higher frequencies. One of the results of this is that at large distances from broadband sources of noise such as quarry blasts or railroad trains, only the low frequency components survive. In terms of vibration effects, the frequency in Hz corresponding to a wavelength of one km is numerically equal to the wave speed in km/s. Thus, body waves in the frequency range of less than a few Hz are poorly attenuated and earthquake (teleseismic) waves of moderate sized events originating thousands of kilometers away can be detected quite easily.

Similar parameters for the Ozan Formation (Lower Taylor Marl), a calcareous claystone, are much less well known. The lower Taylor Marl is a fine grained, uniformly laminated calcareous marine shale, bluish black or dark gray when unweathered, which weathers to dark brownish gray to tan, darker in color than weathered chalk. The P wave speeds from site refraction studies (Tilford, *et al.*,1988) are in the range V_p = 1.38 km/s to 1.92 km/s, with a representative value of 1.76 km/s. The ratio of V_s/V_p for shales and claystones is in the range 0.3–0.7; if one assumes the ratio is 0.6, then V_s is 1.06 km/s, so a value of around V_s = 1.0 km/s would be reasonable. The marl has been compared to the Pierre Shale in terms of rock properties; for the Pierre Shale, Q_p = 32 and Q_s = 10 from field measurements. A white to limey marl from the Hunton Limestone from Oklahoma had a laboratory measured Q_p = 59.3; for a calcareous, dolomitic marlstone from Colorado (probably the Pierre Shale) a sample had Q_p = 45. A value in the range 30–60 for Q is probably reasonable for the Ozan marl. Then $\alpha(P) = (\pi)/(1.76.45) = 0.04$/km and $\alpha(S) = (\pi)/(1.06.30) = 0.1$/km are reasonable (under)estimates for a frequency of one Hz. Nelson (1988) gives a value of $\alpha(S) = 0.1$/km for "marly chalk". Dobrin gives a value of V_p = 2.15 km/s for the Pierre Shale, with $\alpha(P) = 2.32$/km at 50 Hz, or $\alpha(P) = 0.0464$/km at one Hz, in fabulous agreement with the values above.

The wave speeds in unconsolidated materials are much lower than in rock, so the attenuation is correspondingly greater. The range of values of V_p for alluvium (soil) measured on the site is in the range of 0.15 km/s to 0.24 km/s; Quaternary terrace deposits that underlie some of the site have values of 0.34 km/s to 0.38 km/s for V_p. Such materials typically have ratios V_s/V_p of 0.3 to 0.6; choosing a ratio of 0.45 as representative enables us to estimate V_p = 0.2 km/s and V_s = 0.09 km/s for soil and V_p = 0.36 km/s and V_s = 0.16 km/s for the terrace deposits. A mixture of loam, sand and clay from the Texas Gulf Coast was tested as having a value of Q_p = 2, or $\alpha(P) = \pi/(0.2)2 = 7.85$/km at one Hz. If we choose Q_p = 5 as a representative number for the terrace deposits, $\alpha(P) = \pi/(5.0.36) = 1.74$/km at one Hz. Similar or higher values probably obtain for the S wave attenuation.

By combining S and P waves subject to boundary conditions at the interface between different media, it is seen that such waves can travel along the plane of the interface as guided waves. In general, the waves traveling along the interface between two half spaces are called Stonely waves. The nondispersive combination of P and SV (S wave polarized perpendicular to the bedding layers) at a free surface forms an up and down surface wave known as a Rayleigh wave. Side to side waves (guided SH waves, polarized in the plane of the interface) called Love waves can propagate in a layer near a free surface. Such waves are dispersive from the guided wave viewpoint. Guided or ducted Stonely or SH waves can also propagate dispersively through the material.

The dominant near surface wave type is the Rayleigh wave. Such waves decrease in amplitude exponentially in the vertical direction. The characteristic surface wave speed V_r is the root of the equation

$$(V_s/V_r)^2 \{2 - (V_r/V_s)^2 - 4[1 - (V_r/V_p)^2]^{1/2}[1 - (V_r/V_s)^2]^{1/2}\} = 0\text{, or}$$

$$V_s/(V_r V_p)\,[2V_s V_p - (V_p/V_s)V_r^2 - 4\{(V_p^2 - V_r^2)(V_s^2 - V_r^2)\}^{1/2}] = 0.$$

Nelson (1988) suggests that V_r/V_s is about 0.9. By using this as an initial guess and iterating the above equation, the ratio is found to be about 0.93 for the Austin Chalk; for $V_p = 2.70$ km/s, $V_s = 1.87$ km/s, one finds $V_r = 1.74$ km/s. Using a similar ratio (0.955) for the alluvium with $V_p = 0.2$ km/s and $V_s = 0.09$ km/s yields $V_r = 0.086$ km/s from the equation above. For the marl, a ratio of 0.94 with $V_p = 1.76$ km/s and $V_s = 1.06$ km/s corresponds to $V_r = 0.997$ km/s.

The amplitude of such a Rayleigh wave in the half space $z < 0$ is (Hudson, 1980):

$$(\text{P wave amplitude}) \times \exp[\omega z\sqrt{V_r^{-2} - V_p^{-2}}\,] + (\text{SV wave amplitude}) \times \exp[\omega z\sqrt{V_r^{-2} - V_p^{-2}}\,],$$

where the amplitudes are also functions (ratios of polynomials) of the wave speeds. For example, at $f = 1$ Hz, the e^{-1} distance into the Earth is 756 m for the chalk, 467 m for the marl and 46 m for alluvium, for the SV wave amplitude term. (The P wave amplitude term is two or three times (respectively) as strongly damped, so the distances are shorter). As a consequence, the attenuation of Rayleigh waves should be about the same as the S wave attenuation.

The sample wave speeds for chalk, marl and unconsolidated material ("dirt") are listed in Table I, with representative values given and quantity ranges in parentheses. Where parameters have had to be inferred indirectly from literature values or are calculated from such values, the corresponding quantity is labeled with a question mark. The higher wave speeds and lower attenuations in the chalk and marl relative to the unconsolidated material are the most noticeable features listed. The e^{-1} depths h_R for the

Rayleigh waves are significant in terms of the formation thicknesses, so that the surface wave characteristics are probably a composite of the characteristics of the several media.

As in the case with optics, an incident wave is split into reflected and transmitted parts upon encountering a medium of different mechanical properties (characteristic wave speed) than the one in which it is propagating. In the case of P or SV waves incident on an interface, there will also be waves of the other kind (SV or P) generated, both in reflection and transmission (except when the critical angle is exceeded). Because the S waves carry a larger proportion of the wave energy below the surface, it is of interest to determine their amplitude ratio especially. Nelson (1988) states that the ratio of transmitted to incident shear wave amplitudes is $2\rho_1 V_1/(\rho_1 V_1 + \rho_2 V_2)$ where ρ_1 and ρ_2 are the density of the alluvium (soil) and the rock, respectively, and V_1 and V_2 are the respective S wave speeds. For V_1(alluvium) = 0.09 km/s and V_2(chalk) = 1.87 km/s and a density ratio of chalk to alluvium of around 1.2, this ratio is $2/[1+(\rho_2/\rho_1)(V_2/V_1)] = 2/(25.93) = 0.077$. This indicates that if a soil layer or railroad bed exists above the chalk, that most of the vibration energy will be confined to the layer of unconsolidated material and very little enters the chalk. This point should be checked by vibration monitoring.

Vibration monitoring is usually accomplished by emplacing geophones at locations of interest and examining their output. While it is possible to use accelerometers or displacement amplifiers, most geophones generate an electric signal in a coil fixed to the inertial mass of the system, that moves in the field of a magnet fixed to the outer case. There are usually coils for separately damping the motion electromagnetically. The geophone system then behaves as a damped driven (by the ground vibrations) oscillator with a velocity pickup. Assume that the ground oscillates as $y = Y_0\exp(i\omega t)$ to drive the mass with displacement $x = X_0\exp(i\omega t + i\phi)$. The equation of motion

Driving force = ma – restoring force – damping force

Restoring force = $-m\omega^2 x$ and damping force = $-2mG\,(dx/dt)$

gives the usual oscillator equation

$$mX_0\exp(i\omega t + i\phi)(\omega_0^2\omega^2 + 2i\omega\omega_0 G) = -m\omega^2 Y_0\exp(i\omega t)$$

with the velocity response to ground displacement

$$(\omega X_0/Y_0) = -(\omega^3 \exp(-i\phi))/(\omega_0^2 - \omega^2 + 2iG\omega\omega_0).$$

For $\omega \gg \omega_0$, this ratio is roughly proportional to ω, and for $\omega \ll \omega_0$, it is proportional to ω^3 so that the rolloff with frequency is relatively rapid at the low frequency end. The lowest frequency geophone commercially available for downhole deployment has a natural frequency $\omega_0/2\pi$ of one Hz. At 0.1 Hz, the response is down by 10^{-3} from that at the natural frequency, which is down in the level of seismic and electrical noise. More commonly used geophones are smaller in size and have a higher natural frequency, typically 4.5 Hz. Their smaller size makes it practical to cement three of them together in mutually perpendicular directions to form a triaxial array, in order to monitor each component of vibration independently. In practice, it is found that the vertical component of vibration tends to dominate in near surface locations so that arrays consisting of the larger one Hz geophones in vertical surface or downhole displacements are combined with the triaxial arrays to determine the probable maximum displacements at the lower frequencies. For vibration studies it is important to calibrate the geophone response. This is done by recording their output as activated on a hydraulic shaking table under controlled conditions of frequency and amplitude.

Vibration monitoring of transportation sources and quarry blasts were carried out on the site for TNRLC by Lesmes, Morgan and others (1988). They showed that the maximum displacement amplitude (all frequencies) was less than the ISP limits at tunnel depth for all these sources at the Midlothian (Waxahachie Creek), Red Oak, Ennis and Bardwell transportation corridors and in the vicinity of K1 and K5. The maximum displacement amplitude (broadband) that they measured at tunnel depth was about 10^{-3} in. = 25.4 μm at the Midlothian transportation corridor. The corresponding maximum displacement amplitude recorded at that location due to blasting at the TXI quarry near Midlothian was about 1.3×10^{-4} in. = 3.56 μm (TNRLC, Volume 7, p2, 1987). They not only obtained calibrated velocity spectra, but Fourier analyzed them to get displacement/frequency plots and used the inverse Fourier transform to obtain plots of displacement versus time for ground motion. They reported the absolute value of the broadband displacement maximum for each case (X_m). They took measurements at nominal distances of 50, 100, 500, and 1000 ft from the rail lines at the locations given above. At these distances the typical freight train appears as a line source. From these data, it is possible to infer a e^{-1} attenuation length for one Hz surface waves of 210 m (Bardwell) and 231 m (Midlothian), based upon records taken 100 ft or more from the tracks (Fig 1). The records show much higher vibration levels at the 50 ft distance, corresponding to contributions from waves of other than the Rayleigh type within the near field region of the vibration source (note that the wavelength of a one Hz Rayleigh wave is 86 m in soil, according to the velocity found above). These values are less than double the value of 127 m calculated for the alluvium alone (see above). The calculated estimates may easily be in error by a factor of two, and the composite nature of the media sampled by the surface waves mentioned above also comes into play.

At intermediate distances (10–1000 m) the contributions from P and S body waves will be much smaller than the Rayleigh waves due to geometric spreading of the cylindrical body waves in comparison with the line surface waves. The largest amplitudes at these distances are around 30.5 μm at surface distances of 50 ft (15.2 m) in the seismic peak at around one Hz (Fig 2). Since vibrations are reduced with depth by attenuation and spreading, this implies that the amplitudes found at tunnel depth will be considerably less than this, in agreement with the field measurements.

Because the e^{-1} distance of surface waves is around 220 m, they will be severely attenuated at several kilometers from the source, where a mixture of P and S waves will survive. As a practical matter, the amplitude of the waves near surface will be largely due to the S wave contribution until extremely large distances are reached. This allows the attenuation factors found for the chalk by laboratory methods to be checked against the field measurements of the maximum displacement amplitudes for geophones in shallow boreholes in the bedrock. The displacement maxima of the one Hz peak (X_f) and the broadband time records (X_m) found for a very large blast (the charge used was three times the size normally used in quarry operations) are given in Table III (Lesmes, Morgan and others, 1988; TNRLC, Volume 7, 1987).

In order to isolate the attenuation effects from the geometrical spreading of the wave, the latter must be taken into account. Let D be the e^{-1} distance. Then the wave amplitude far from the source has the space dependence

$x = (A/R)\exp(-R/D)$; take the natural logarithm,

$\ln x = \ln A - \ln R - R/D$ or $\ln x + \ln R = \ln A - R/D$

so that a plot of $\ln x + \ln R$ versus R has a slope of $-D$. The blast attenuation plot (Fig. 3) shows a much steeper slope for the plot of the broadband displacements X_m versus R than with the displacements of the one Hz peak X_f versus R, because of the greater attenuation of the higher frequency parts of the wave with distance. The plot of $\ln X_f + \ln R$ versus R is very flat and the error fairly large, so that the e^{-1} distance of 49 kilometers may be an underestimate. The displacements are given directly in Table III for reference purposes. While the attenuation is about a factor of ten larger than that predicted by the simple model, the degree of uncertainty attached to such low amplitude measurements is great enough that it is desirable to repeat the blast experiment in order to more precisely determine both the attenuation rate and the displacement amplitudes in the one Hz peak X_f.

Tentative Conclusions:

1. The wave speeds and attenuations in the marl and unconsolidated materials are poorly known at present and should be determined.

2. The surface waves at intermediate distances are attenuated with a 1/e distance of about 220 m.

3. The body waves at large distances are attenuated with a e^{-1} distance of roughly 50 km; while it does not appear that the true e^{-1} distance is much less than say 40 km, it could be much larger, of the order of 100 km. The true attenuation factors for the chalk are very important for prediction of the effect of vibrations on the machine, so that more and better data are needed in this area.

4. Even with low attenuation in the bedrock, the displacement amplitudes at tunnel depth in the sensitive wavelength region may be low enough to be correctable, because of the reflection at the bedrock/dirt interface and because the unconsolidated material absorbs a significant fraction of the wave energy. Further monitoring of displacement amplitudes at tunnel depth is needed to determine this point definitively.

5. The parameters found in this study are a good enough first order estimate that they are within a factor of two in most cases, and the probable ranges of some are known with considerable confidence. It should be possible to demonstrate on the basis of these parameters whether or not an uncorrectable problem exists with vibrations, and these values should be useful as guides to future monitoring and analysis.

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TABLE I. Representative value (range) of wave speeds; attenuation factors $\alpha_i = \pi f / Q_i v_i$ at f = 1 Hz.

Material Property	Chalk	Marl	Dirt
V_P(km/S)	2.70 (3.05-2.58)	1.76(1.92-1.38)	0.2(0.24-0.15)
V_S(km/S)	1.87(1.88-1.07)	1.06?*(~1)	0.09?
V_R(km/S)	1.74	0.997?	0.086?
h_R(m)	756	467?	46?
α_P(km^{-1})	0.0023	0.04?	7.85?
α_S(km^{-1})	0.0057	0.1?	7.85?
α_P^{-1}(km)	433	25?	0.127?
α_S^{-1}(km)	175	10?	0.127?

*Question marks indicate quantities estimated from the literature.

Table II. Surface wave attenuations, train data of amplitude displacements of the f = 1 Hz peak.

Distance D		x_f, Bardwell		x_f, Midlothian	
(ft)	(m)	(10^{-4} in.)	(μm)	x(10^{-4} in.)	(μm)
50	15.2	1.22	3.10	2.50	6.35
100	30.5	0.140	0.356	0.158	0.401
500	152.4	0.076	0.193	0.140	0.356
1050	320.0	0.022	0.051	0.065	0.165

For comparison:
ISP Limit $x_{max} = 5 \times 10^{-4}$ in. = 12.7 μm at IRs
= 20×10^{-4} in. = 50.8 μm elsewhere
Ennis train (50 ft) $x_{max} = 12 \times 10^{-4}$ in. = 30.5 μm

Table III. Spreading and attenuation of waves from a quarry blast with distance R from the source.

Location	R (km)	x_n (10^{-4} in.)	x_n (μm)	x_f (10^{-4} in.)	x_f (μm)
Station 1	2.46	10.0	25.4	0.43	1.09
GP-2	10.0	1.30	3.30	0.081	0.206
Station 3	18.0	1.00	2.54	0.075	0.191
GP-1	30.2	0.032	0.081	0.019?*	0.048?*

*Inferred.

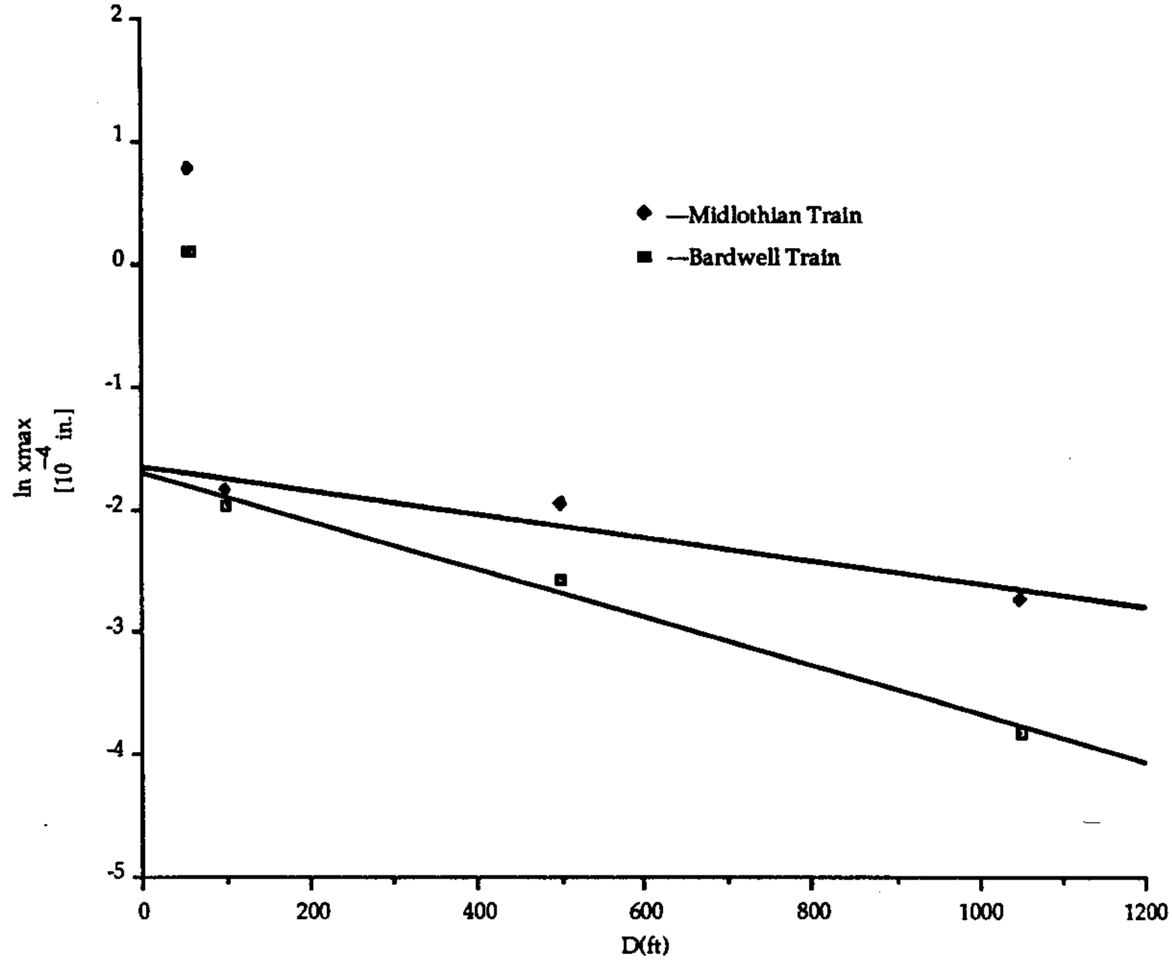

Figure 1. Surface Wave Attenuation

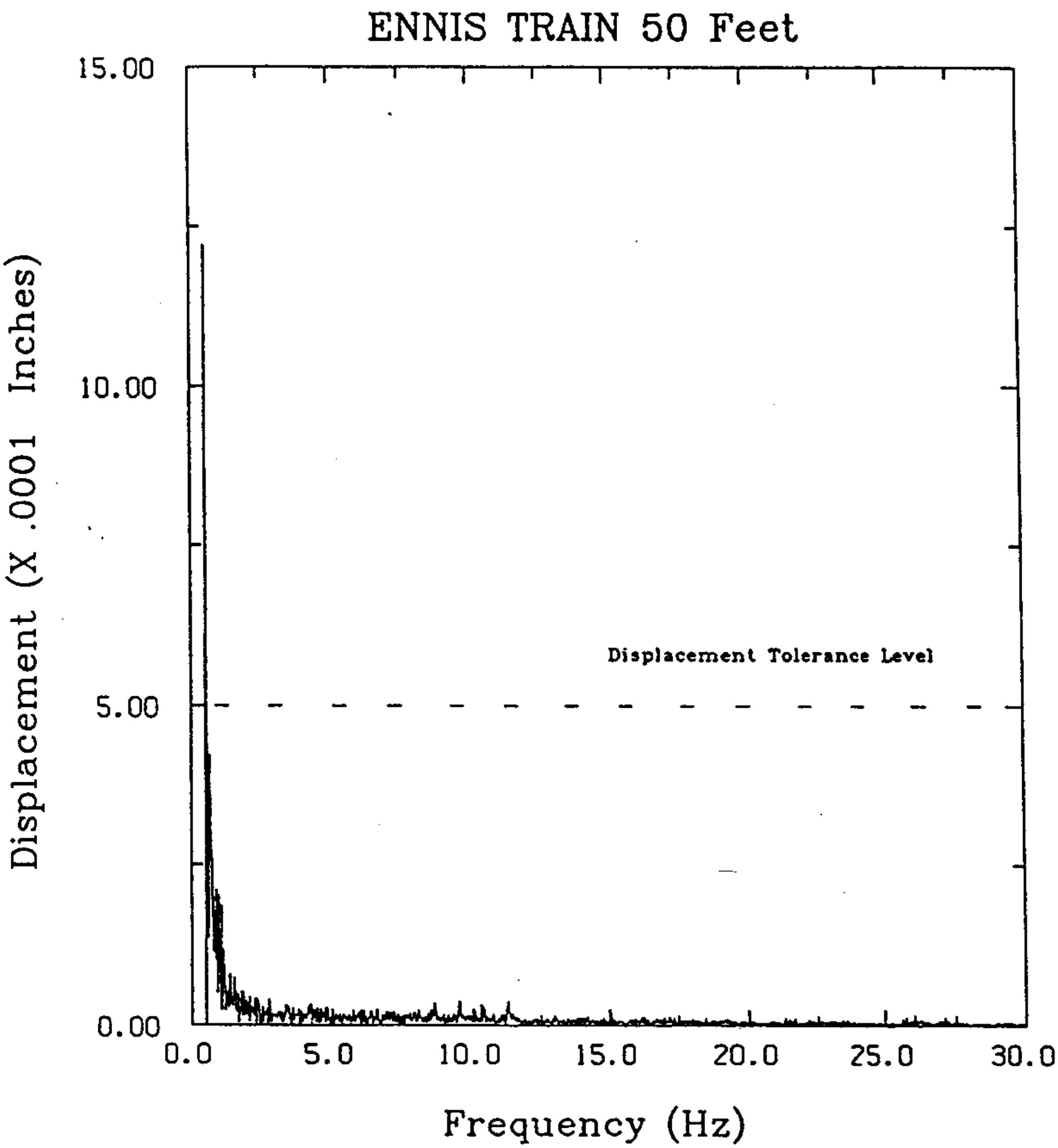
ENNIS TRAIN 50 Feet
15.00
10.00
5.00
0.00
Displacement (X .0001 Inches)
Displacement Tolerance Level
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Frequency (Hz)

Figure 2.

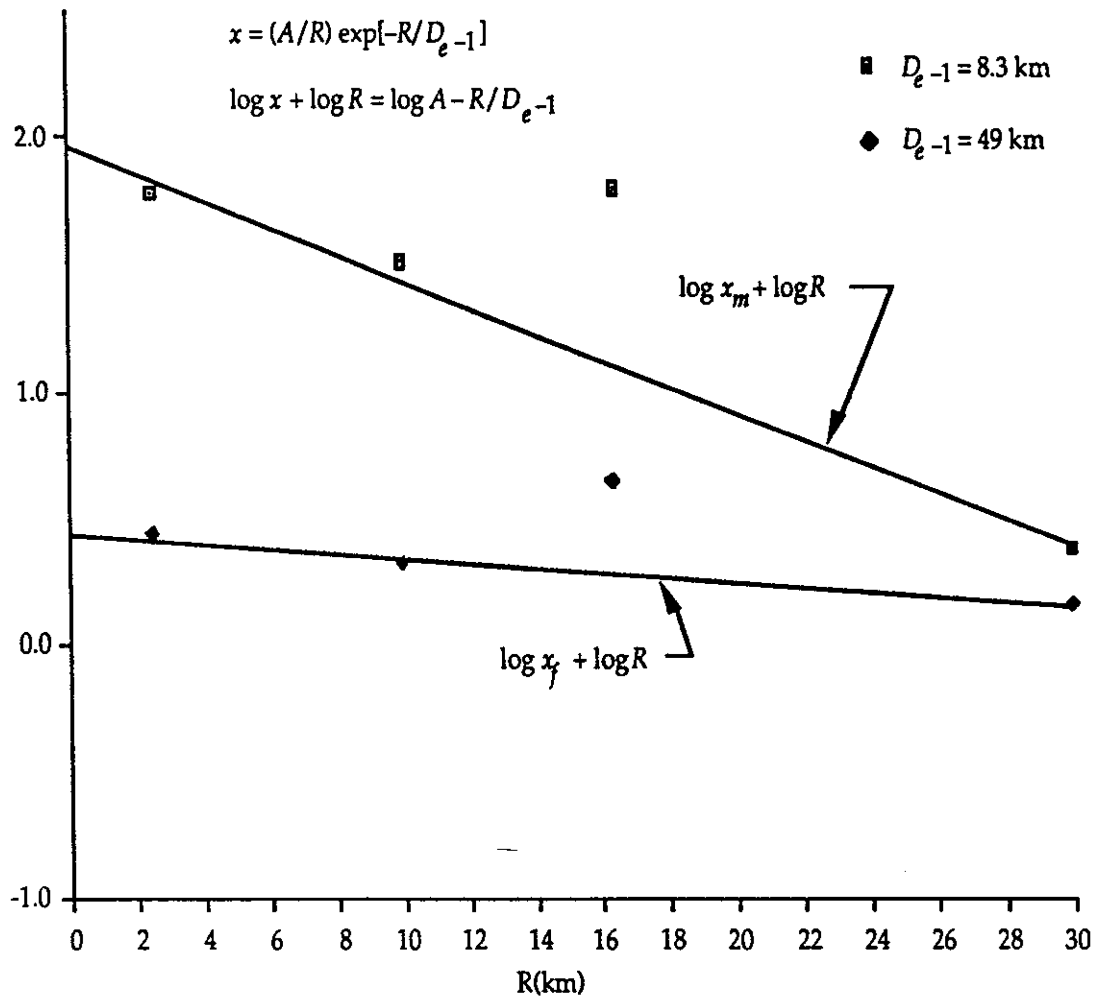

Figure 3. Blast Attenuation Plot