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Effects of frequency and depth on attenuation of ambient ground vibration

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This article discusses the effects of below-grade building placement on vibrations measured prior to design and construction. Typically, site vibration studies are conducted on undeveloped locations (grass fields, parking lots, etc.) to assess the ambient vibration conditions for a potential building site. These results, though very important, do not necessarily represent the final ambient vibration conditions that would be observed in the basement or below-grade building once it has been constructed. How these phenomena may also be used in the design of low-vibration buildings is also discussed.

1 INTRODUCTION

In many cases, site vibration surveys for vibration-sensitive facilities are carried out in a *free-field* condition, meaning that a building is not present.[1, 2, 3] For buildings that will contain exceptionally sensitive instruments, or in cases where the environment may not be particularly conducive to low-vibration work, this is a necessary first-order estimate of the feasibility of the building project. However, the presence and position of a building can significantly modify the site vibrations.[4, 5]

A number of options that can provide some attenuation of the free-field vibrations are available to designers, and the degree of attenuation will be dependent upon the mass and stiffness of the building, as well as the nature of its attachment to the ground.[4] Relatively dramatic improvement of a building's vibration environment may arise from the use of a basement, or placing the building entirely below grade.[6]

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This essay summarizes three case studies examining the effects of below-grade placement of vibration-sensitive spaces, and presents a methodology by which performance at depth may be estimated using a combination of measurements at the surface and in a borehole. In both cases, as in many applications, the vibrations of concern were random ambient vibration not attributable to any specific sources.

2 THE EXPERIMENTS

It is well established that ground vibration at depths near the surface are composed predominantly of Rayleigh waves, and that their amplitude varies with depth. Vertical and horizontal components generally decrease according to relationships based upon depth as a fraction of wavelength, thus incorporating a dependence on frequency.[7]

The first case study was carried out a fixed depth at an alluvial site, and was intended to demonstrate the vibration attenuation at that depth (where the designers planned an imaging facility in a biotechnology complex). It is included to demonstrate some of the basic characteristics of at-depth vibrations, in both the horizontal and vertical directions, when compared to surface vibrations. The second case study was carried out at several depths at a predominantly sandy site, and was intended to demonstrate the attenuation available at several depths, as part of a study balancing construction cost with vibration performance. The third and final case compares the free-field versus subsurface measurement data from Cases 1 and 2 with relevant data from a completed building.

2.1 Case 1: Basic Characteristics

The test site was prepared in advance by drilling a 6m deep hole, equivalent to the planned depth of the future lab basement, at the shortest distance between that basement and a utility plant. Accelerometers were placed both on the asphalt at the surface near the top of the hole, and on the packed sand at the base of the hole.

Vibration data were measured simultaneously at these locations during ambient conditions and while the equipment in a nearby utility building was operated under different conditions. The ambient data will be examined here. At the time of the study, there was normal traffic on the nearby roadways, including automobiles, buses, and trucks.

Figure 1 shows frequency response functions (FRFs) of the data measured at depth with respect to that measured at the surface, in terms of magnitude, phase, and coherence. Two sets of spectra are shown, each measured at a different time.

Two distinct frequency zones may be observed, separated by the “dip” or *cutoff frequency*, at approximately 20 Hz, which we will denote f_0.

a) At $f < f_0$, the spectra are relatively smooth between about 4 Hz and f_0. The magnitude approaches a value of 1 as frequency approaches zero, reaches its minimum near $f = f_0$. The coherence stays between 0.9 and 1 and the phase remains close to zero.
b) At $f > f_0$, the magnitude spectrum becomes less smooth, the phase varies erratically, and the coherence is quite low, except for a few isolated frequencies. The solid circle symbols on the magnitude spectrum indicate the frequencies at

which coherence is greater than 0.5, where the magnitude may be seen to gradually increase. At frequencies greater than about 60 Hz, the magnitude is greater than 1.0, indicating that the vibration amplitude is greater at depth than at the surface.

Figure 2 compares the average of the two vertical FRFs from Figure 1 with that for the corresponding horizontal measurements (two orthogonal directions) at the same two locations. In the horizontal FRF there are still two distinct frequency zones, but the cutoff frequency is at approximately 17 Hz instead of 20 Hz. Additionally, there is a less pronounced dip in the magnitude and coherence spectra at approximately 13.5 Hz.

At low frequencies, the horizontal FRF lies almost entirely below the vertical FRF; at almost all frequencies above the crossover at 19 Hz, the horizontal FRF lies almost entirely above the vertical. This suggests that at low frequencies, horizontal vibrations are more attenuated at depth than vertical vibrations, but that the reverse is true at frequencies above f_0. In fact, at $f < f_0$, the ratio of horizontal to vertical FRF averages approximately 0.43 times (a -7 dB difference), while at $f > f_0$, the ratio is 3.6 times (an 11 dB difference).

Figure 3 shows the data from Figure 2 at an expanded frequency scale, allowing closer examination of the lower portion of the spectra.

2.2 Case 2: Varying Depth

A second set of measurements was carried on a site with medium dense to dense sand underlying a surface layer of fill. Three manholes were identified with three different depths, all located fairly close together. Traffic on a nearby street was used to simulate nearfield ambient conditions, and this was supplemented by the ever-present traffic on an expressway about two kilometers away. There was also ongoing construction and operating mechanical plants elsewhere on the campus.

A total of 4096 averages at each depth were evaluated due to ambient conditions and a variety of vehicle types and paths. Figure 4 shows the vertical-axis FRF magnitudes for the three depths. Each depth exhibits a different f_0, which shifts to the left as depth increases. When plotted as shown, with a logarithmic frequency axis, it becomes apparent that the shapes are similar (excluding the dip at 11 Hz in the 5.9m data, due to a nearby temporary mechanical source), suggesting a single characteristic curve.

The results of a shift of this sort is illustrated in Figure 5, after the frequency of each spectrum has been divided by the value of f0 shown as a function of depth in Figure 6. Curve-fitting suggests that this collapsed shape could be approximated at shifted frequency of less than unity by a portion of a cosine curve, and by an FRF magnitude of 0.1 at higher frequencies.

The shift function suggested in Figure 6 appears suitable for interpolation to other depths and a limited amount of extrapolation. When this is done, one could use the collapsed shape and the normalizing function together to estimate spectra at a variety of depths, using measurements made at the surface. The results of this process are shown in Figure 7.

2.3 Case 3: A Completed Below-Grade Facility

The Advanced Measurement Laboratory (AML) at the National Institute of Standards and Technology (NIST) campus in Gaithersburg, MD, was constructed with five wings—one above-grade, two at-grade, and two completely below-grade. The at-grade and below-grade wings were built with nearly identical slab-on-grade floor systems. An extensive post-construction vibration evaluation was carried out, with some of the results reported elsewhere.[6]

A large quantity of triaxial floor vibration measurements were made in each wing over a period of two days. The data for each wing were combined statistically using a protocol for surveys of large spaces.[2] The mean spectra obtained in a below-grade wing were divided by the corresponding spectra from one of the at-grade wings, simulating the FRF spectra reported for Cases 1 and 2. These are shown in Figure 8, where a similarity to Figure 3a may be noted.

3 SUMMARY AND CONCLUSIONS

Vibrations were measured at several locations at selected depths and compared with vibrations at the surface by means of frequency response functions. When expressed in that form, the FRF exhibits several features, as illustrated by the data from the first site:

- There are two regimes, separated by a cutoff frequency, f_0. The characteristics of the two regimes are markedly different.
- The maximum attenuation is at f_0, on the order of an order of magnitude. There is no attenuation at $f = 0$.
- At $f < f_0$,
  - the coherence is quite high, indicating that at depth the vibration at any frequency in this range is closely correlated with that of the surface.
  - the vibration at the surface and depth are in phase
  - the variation of attenuation with frequency may be approximated by cos $(\pi * f / (4 * f_0))$
- At $f > f_0$,
  - the coherence is generally quite low, indicating that at depth the vibration at any frequency in this range is uncorrelated with that at the surface, or appears that way due to the low amplitude of the data with respect to the noise floor of the measurements.
  - the vibration at the surface and depth have no clear phase relationship (which may be due to the noise floor issue discussed above)
  - the may be a wide variation of attenuation with frequency, and there may even be apparent amplification (FRF > 1)
- The horizontal FRFs differ slightly from the vertical. The cutoff frequency is slightly less, which creates the condition that at $f < f_0$, the FRFs for the two horizontal directions both have lower magnitudes than the vertical.

The data from the second study, which were measured at three different depths, indicate that the FRFs may be shifted by means of a frequency scale factor. When expressed as a function of shifted frequency, the three FRFs (at $f < f_0$) collapse into a single cosine curve.

From examination of similar data from other sites, it appears that a generalization of a simplified "rule" at $f < f_0$ may be made for a given site, but that generalization is not "portable" from one site to another due to varying geotechnical conditions.

For a given site, the simplified rule may be obtained using FRFs at several depths, either in a single hole or multiple holes, and then using the rule to estimate spectra at depth using spectra measured at the surface.

Furthermore, examination of data measured after completion of NIST's Advanced Measurement Laboratory, where extensive vibration studies were carried out, it appears that the relationships discussed here (with regard to the role of f_0) also apply to operating facilities.[6]

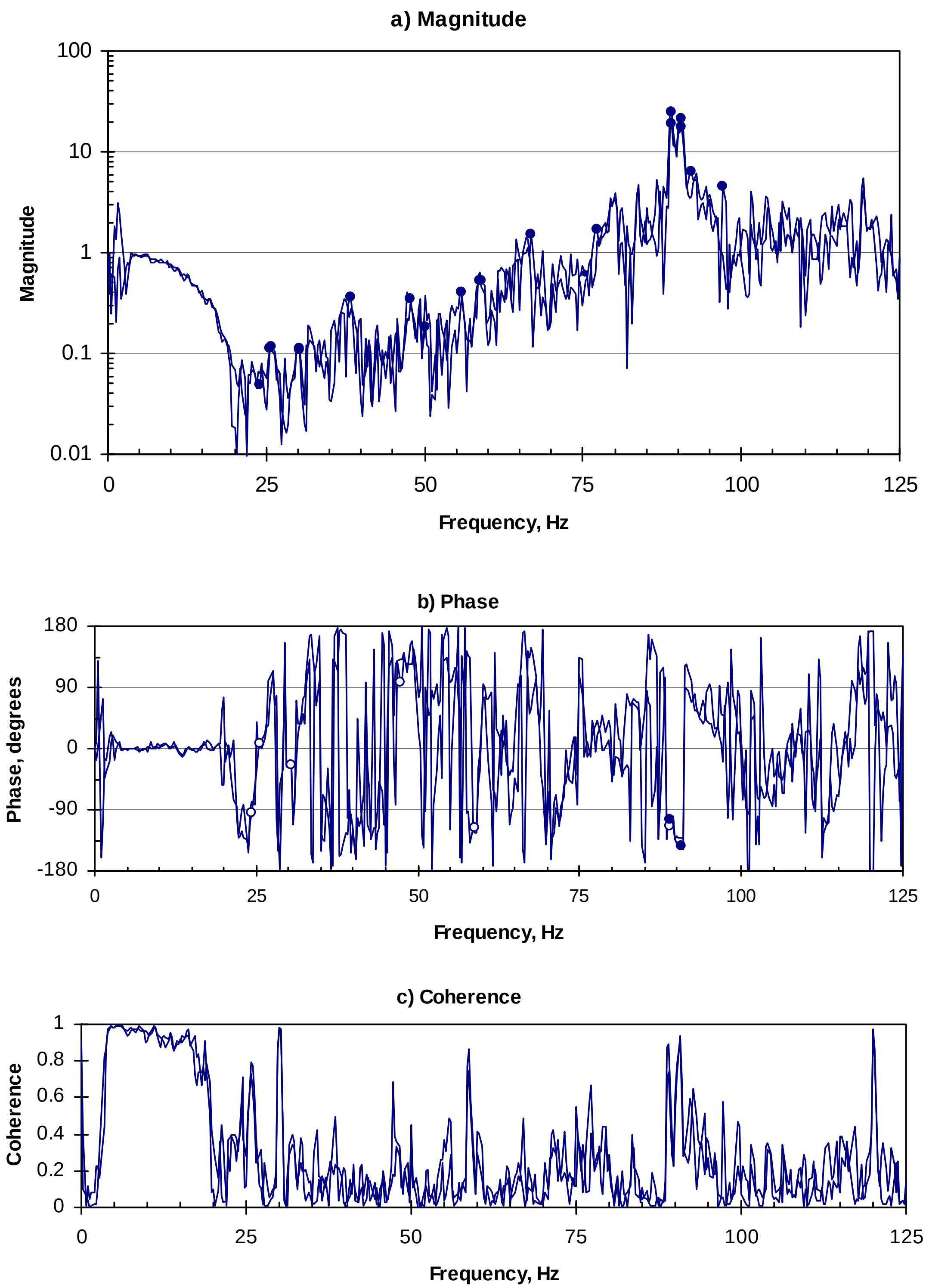

Fig. 1 - Frequency response function measured at two different times showing vertical vibrations measured at -6m compared to those of surface, ambient conditions.

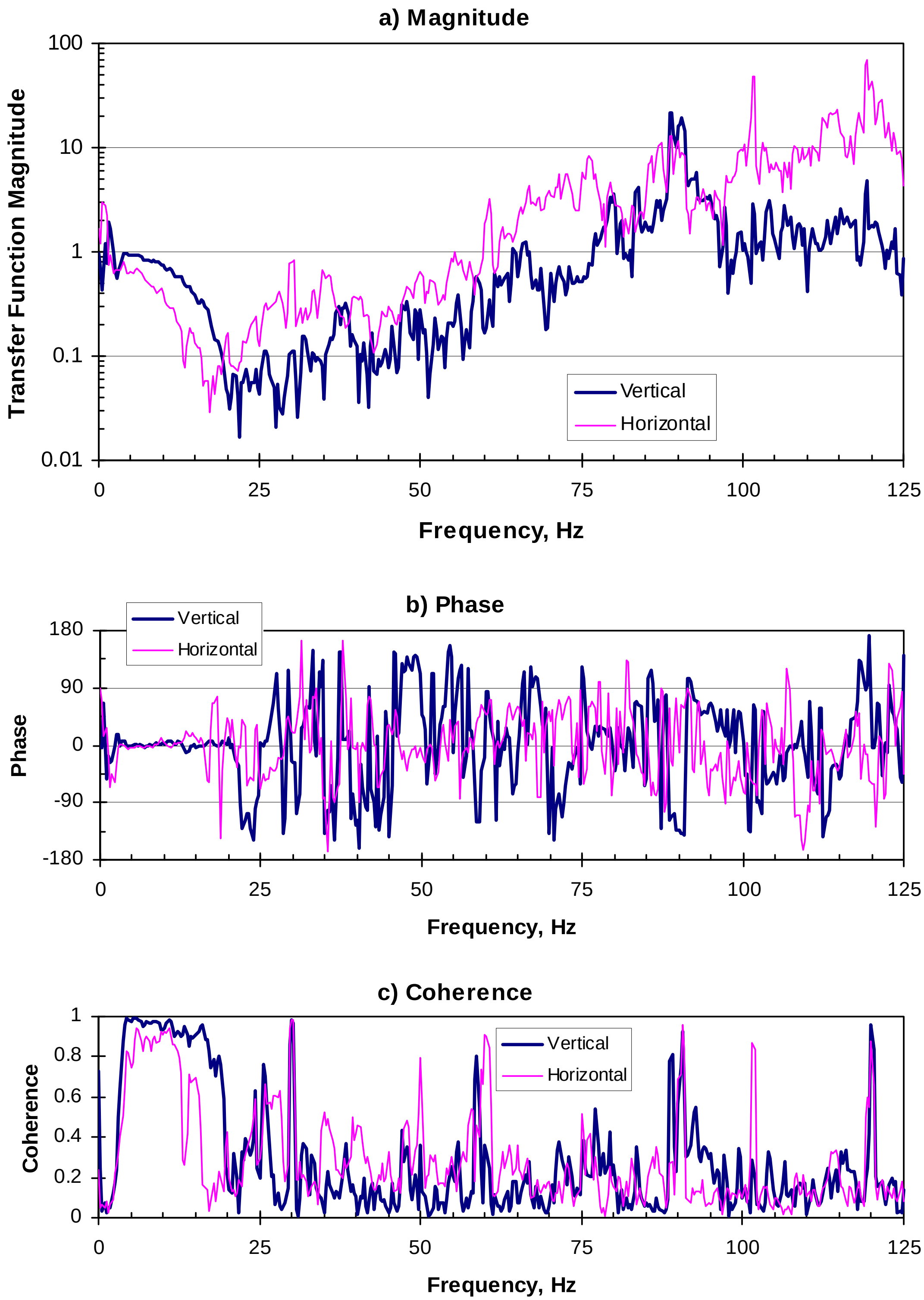

Fig. 2 - Averaged frequency response functions comparing vertical and horizontal directions measured at -6m compared to those of surface, ambient conditions.

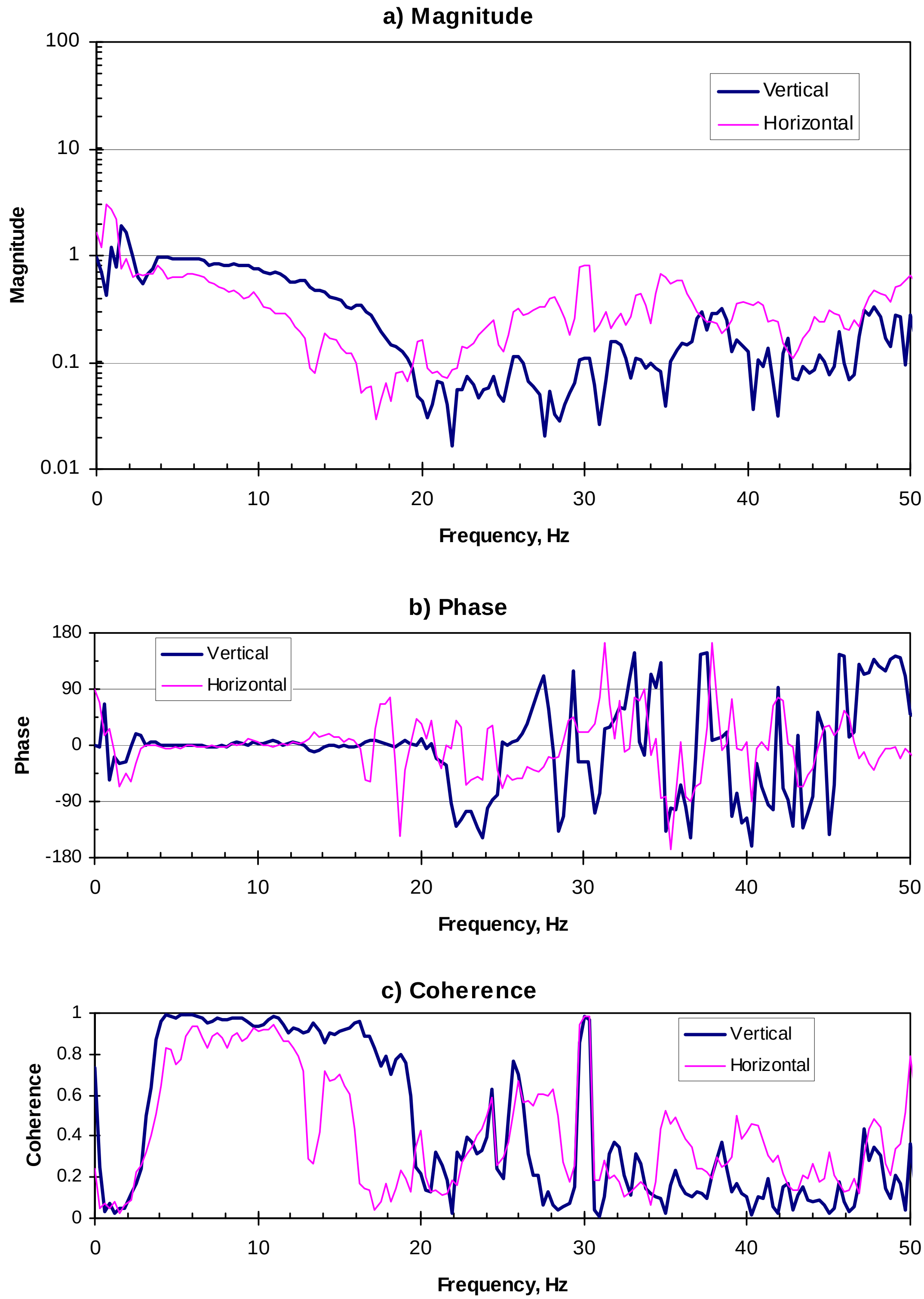

Fig. 3 - Averaged frequency response functions with expanded frequency scale comparing vertical and horizontal directions measured at -6m compared to those of surface, ambient conditions.

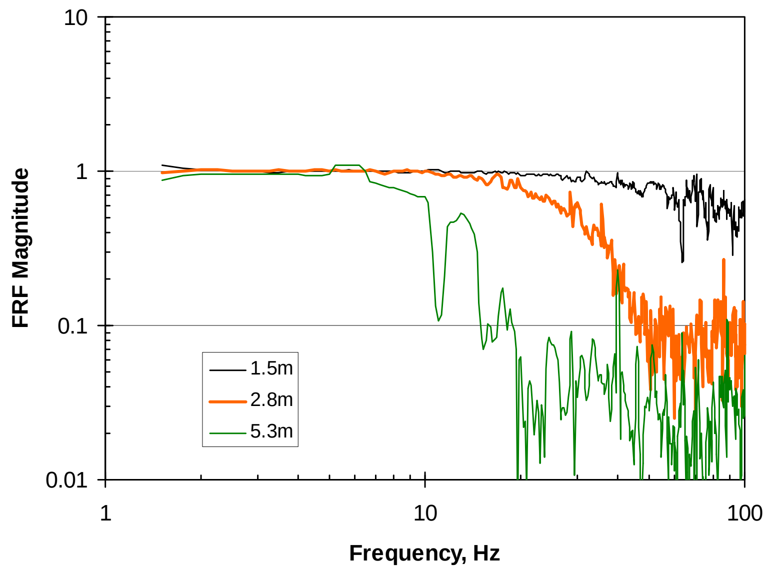

***Fig. 4 -** Frequency response function magnitudes measured in three different holes, each at a different depth, vertical direction, various ambient conditions.*

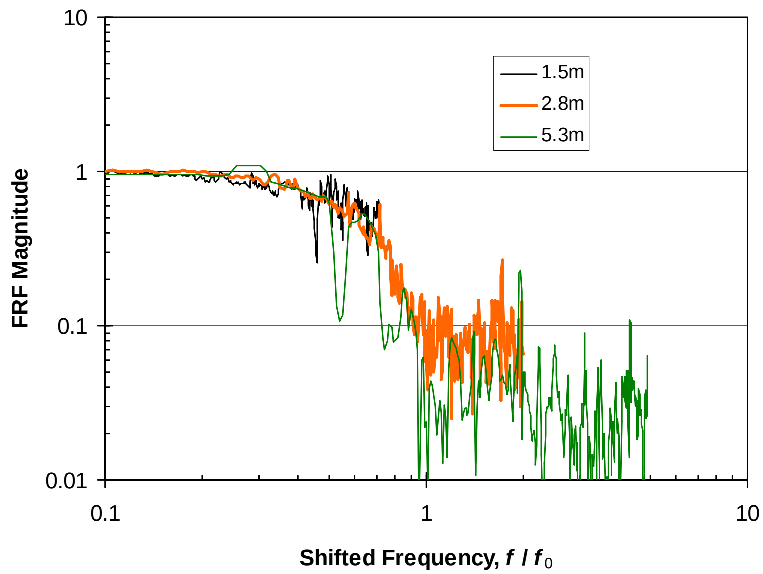

***Fig. 5 -** Frequency response function magnitudes measured in three different holes, each at a different depth, vertical direction, various ambient conditions, shifted in frequency by factor of $1/f_0$.*

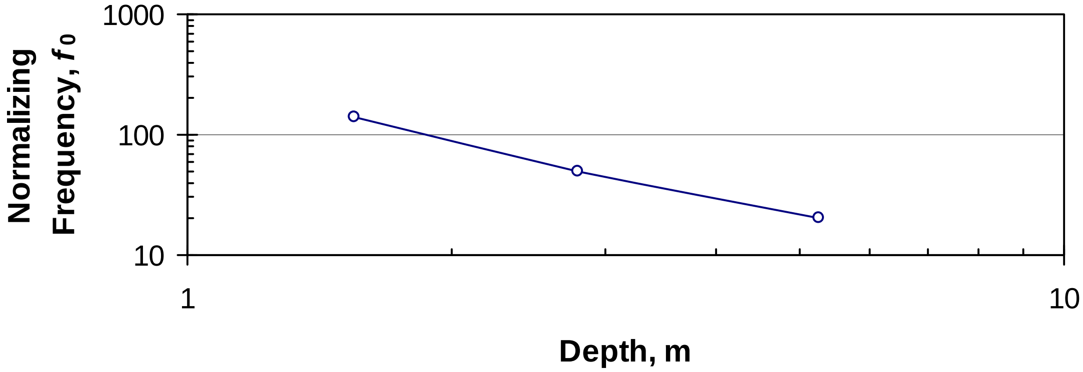

Fig. 6 - Effect of depth on shift frequency, f_0.

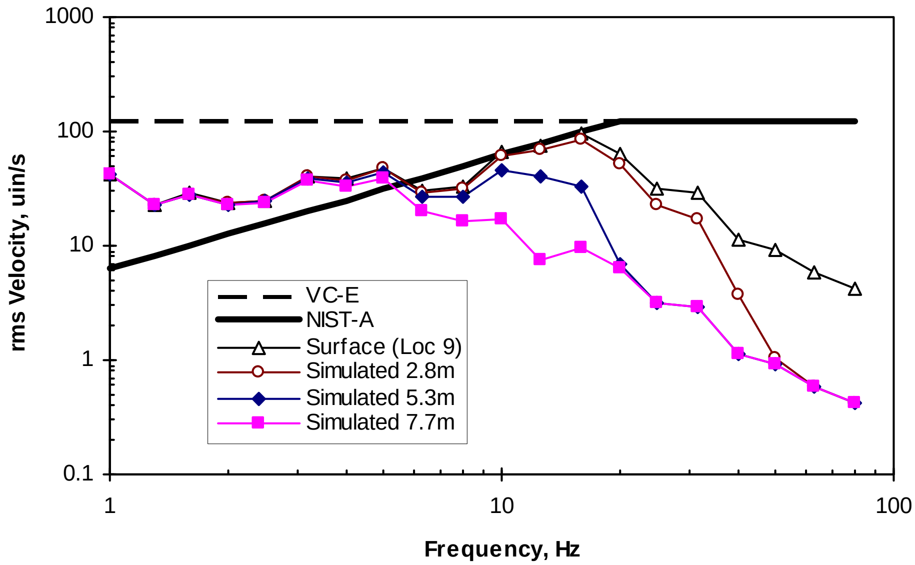

Fig. 7 - Vertical vibration spectra estimated for several depths.

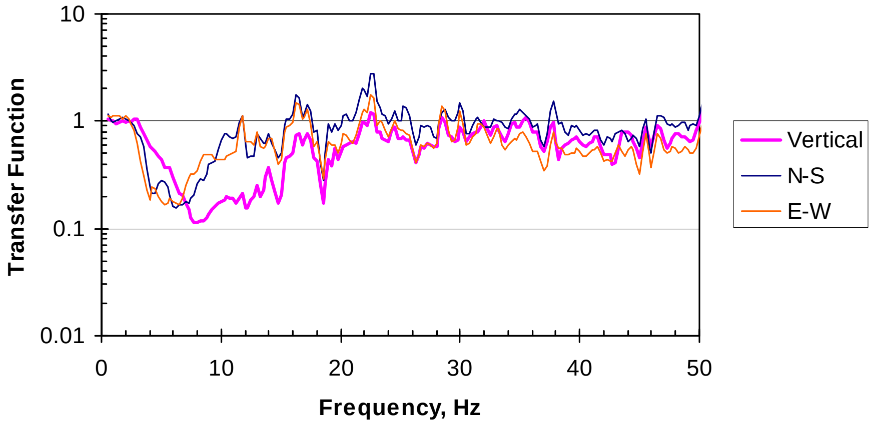

Fig. 8 - Approximations of frequency response functions comparing vertical and horizontal directions in an at-depth wing of the NIST AML with respect to an at-grade wing.

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