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An experimental study of vibration attenuation performance of several on-grade slab configurations

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ABSTRACT

There are several instances in the literature in which particular positions are taken regarding the nature of the floor supporting sensitive equipment such as advanced electron microscopes. Assertions are made that one methodology is better than another at reducing vibrations. However, very little experimental evidence has been provided to support those positions. This paper presents the results of an experimental *in situ* study of several slab configurations at a single location—the site of a nanotechnology facility that was about to be constructed at the University of Alberta. Three configurations were constructed: (a) a large solid slab of moderate thickness; (b) a smaller slab "island" of greater thickness (900 mm) surrounded by a thinner slab, both resting directly on soil and separated by a gap; and (c) another island of the same dimensions, but resting on four concrete piles. The three locations were instrumented and measurements taken allowing comparison of the performance of these configurations at attenuating ambient vibrations and vibrations due to a nearby heel-drop impulse. The ranking of the three must be based upon excitation type and frequency range of concern.

Keywords: vibration control, research laboratories, attenuation, slab-on-grade, pile-supported slab, isolated slab, foundation vibration, soil dynamics

1. INTRODUCTION

The National Institute of Nanotechnology (NINT) at the University of Alberta in Canada will be the first dedicated nanotechnology facility in Canada and among the first in North America. Several innovative aspects of this facility are discussed in other papers at this conference,[1,2] but this paper focuses on one very specific issue that has been the subject of disagreement for a number of years.

During the NINT design, questions arose concerning the relative merits of solid slabs *vs*. thick "islands" *vs*. thick islands with pile supports. The literature is somewhat inconsistent regarding the use of islands *vs*. solid slabs,[3,4,5] and there is little information regarding the comparative benefit of placing piles beneath an island. The intent of the study was to compare performance of these three types of slabs. The dynamic features to be compared were (1) stiffness, (2) mobility, (3) the attenuation of ambient site vibrations, and (4) the attenuation of near-field point-source vibrations.

Figure 1 (at the end of the paper) shows schematically the layout of the experiment. The components may be described as follows:

- On the west side of the experiment was a solid slab, measuring 8850x3850x300 (approx. 29 ft x 12.6 ft x 12 in). The concrete's design compressive strength was 25 MPa (3600 psi). The slab was supported directly on 1.1m of compacted granular fill atop undisturbed soil. The center of this slab was denoted Location B.
- On the east side was a slab of about the same size, with two "islands" surrounded by 1m strips. The two islands are 3000x2500x900 (118 in x 98 in x 35.4 in), and were separated from the surrounding slab by a structural break of about 50 mm. The two islands were supported thus:
    - The south island was supported directly on 500mm of compacted granular fill atop undisturbed soil.

- o The north island was supported on four concrete piles, 400mm dia. x 7.5m length. The slab itself was suspended above the granular fill by a 150mm void form; the slab was not in direct contact with the soil.

Measurements were made at the following locations, identified on Figure 1:

Location	Description
A	A small (300x300x100) concrete pad, intended to serve as a representation for the "freefield" case.
B	Center of large solid slab
C	Center of large slab with two islands, on the strip separating the two islands.
D	Center of island without piles
E	Center of island with piles

In addition, point loads (in the form of repeated heel drops) were applied at locations B and C, as well as at A_1 and A_2.

The following measurements were made and are discussed in this paper:
- Hammerblow tests of mobility and dynamic stiffness at Locations B, D and E
- Comparisons of relative amplitudes (pairs of locations) due to ambient excitation. This condition represented the "normal" random excitation that occurs the majority of the time.
- Comparisons of relative amplitudes due to heel drop excitation. This condition represented the special case of impact loads in the "near field", such as dropped loads.

2. HAMMERBLOW EXCITATION AND DRIVE POINT PROPERTIES

These tests involved the use of an instrumented hammer for generating repeated blows to the concrete and an accelerometer to measure response within a few centimeters of the point of load application. The hammer contains a force sensor, which provides an electric signal proportional to force. The accelerometer provides a signal proportional to acceleration. These two signals are input simultaneously into a two-channel spectrum analyzer (SignalCalc ACE), which carries out digital signal analysis. The analyzer was configured to using force and response windows, and trigger on the impact. Each set of saved data consisted of the average of three hammerblows.

Figure 2 shows a set of plots obtained for Location B, representative of this type of measurement. The top plot (a) shows accelerance, the spectral quantity that represents acceleration divided by force. The middle plot (b) shows coherence, a measure of the "quality" of a hammer test. A value of 1 indicates perfect correlation between input and output. A value of 0 indicates that there is no relationship between input and output (i.e., the hammer has not provided enough excitation at a particular frequency for the resulting response to rise above the ambient). In this case, the coherence lies above 0.8 at frequencies above 10 Hz. The bottom plot (c) shows dynamic stiffness [accelerance divided by $\omega^2 = (2\pi f)^2$]. The horizontal portion at low frequencies (but with good coherence) approximates the "static stiffness". A solid horizontal line shows our estimate for the static stiffness, $5.3\text{x}10^8$ N/m ($3.0\text{x}10^6$ lb/in).

The stiffness measured in this manner at Locations D and E, on the thick islands, was not as clearly defined. The dynamic stiffness curve did not asymptote to a horizontal line as did the curve at B. This suggests that the dynamics of the islands is somewhat more complex, and may only be defined using a spectrum. In the low frequencies the spectrum approximates a constant mobility [accelerance divided by $\omega = (2\pi f)$, or velocity divided by force].

Alternative approaches are available for approximating the static stiffness of these two locations, making use of some simplifying assumptions.

Figure 3 shows the mobility spectra for Locations B, C, D and E. Note that the mobility curve for Location E shows a "hump" centered about 78 Hz. This is indicative of a resonance. We can assume that this system is acting as a single-degree-of-freedom (SDOF) spring-on-mass oscillator with the concrete block being the mass and the piles (and some of the soil into which they penetrate) acting as the spring. The simple definition of the resonance frequency of a SDOF oscillator is

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

in which f_n is the resonance frequency, k is the spring stiffness, and m is the mass. We can use the block mass of 16,200 kg (35,600 lb weight divided by g) to calculate a stiffness of 3.9×10^9 N/m (22.1×10^6 lb/in), or 9.8×10^8 N/m (5.5×10^6 lb/in) per pile. Incidentally, the modal damping loss factor associated with this resonance is approximately 0.4 (20% of critical).

The theory for a plate on elastic foundation gives us a relationship in which point stiffness may be related to plate thickness, Young's modulus of the plate, and the subgrade modulus of the halfspace below the plate.[6,7]

$$k = 8\sqrt{SD} \tag{2}$$

where S is the subgrade modulus and D is the plate rigidity, a function of the plate's elastic modulus and plate thickness cubed. Given a measured stiffness and known thickness and elastic modulus of the plate, we can derive a value for the subgrade modulus as

$$S = \frac{k^2}{64D} \tag{3}$$

The stiffness of a discrete footing is approximately

$$k = SA \tag{4}$$

where A is the area of the footing.

We can use the stiffness obtained at Location B to estimate the value of S for this soil configuration. We can assume that the same value of S applies for the island at Location D, and that the island may be treated as a discrete footing, allowing us to use Equation (4). (There is some error in this assumption, as the thickness of the granular fill is different at the two locations, but we will assume that this difference is negligible.) This calculation yields a stiffness of 5.9×10^8 N/m (3.4×10^6 lb/in). The stiffness values obtained in this study are summarized in Table 1. The stiffness of the slab-on-grade and the island without piles are about the same. The calculated stiffness of the island with piles is about 6 to 7 times that of the other two.

Table 1. Summary of measured and calculated stiffness coefficients.

Location	**Condition**	**Stiffness**	
		Measured	**Calculated**
B	Slab-on-Grade	5.3×10^8 N/m (3.0×10^6 lb/in)	---
D	900mm Island w/o Piles	---	5.9×10^8 N/m (3.4×10^6 lb/in)
E	900mm Island w/ Piles	---	3.9×10^9 N/m (22.1×10^6 lb/in)

3. COMPARISON OF PERFORMANCE WITH AMBIENT EXCITATION

It has been documented that the presence of a building—or even a slab alone—will modify the ambient vibrations at a site. (A thorough discussion of the process is beyond the scope of this paper; the interested reader may consult Ref. 5.) One of the primary reasons for performing the present study was to determine the difference (if any) in the manner in which these three options (slab-on-grade, island without piles, and island with piles) treated ambient vibrations on a single site.

The measurements were made with a pair of accelerometers recording data simultaneously at two locations. The output from these sensors was amplified and fed into the same spectrum analyzer which was configured with Hanning window, 50% overlap, and averaged for 20 samples. In this configuration, the frequency response function (FRF) yielded a spectrum indicating the relative amplitude (by frequency) of one location with respect to the other. Between 2 and 3 sets of data were taken for each setup.

Figure 4 shows a typical data set for this type of measurement. These data compare Location D with location B, in the North-South direction. The top plot (a) shows the raw comparison spectra (in three colors), which represent the ratio of amplitudes at D divided by those at B. The log mean spectrum is shown as a heavy black line. This spectrum is an average of the logarithms of the three spectra, and are also moving averages over a frequency range of 3.125 Hz. This tends to “smooth” the data to facilitate easier comparison. The middle plot (b) shows the log mean with the mean ± one standard deviation of the block of data used in the average. The bottom plot (c) shows the coherence.

Several comments are in order, since these spectra are fundamentally different from those arising from the hammerblow tests.

- The coherence is no longer a measure of the “quality” of the transfer function. In this instance it is a measure of how similar the vibrations are at the two locations (in this context, “coherent” is closer to the meaning implied by “coherent” *vs*. “incoherent” light sources). A high coherence says that the vibrations are quite similar, probably from the same source. A low coherence says that the “source” is diffuse, without directionality and an orderly phase relationship.
- The amplitude ratio spectra are evaluated with respect to their position relative to a value of 1. A value of unity means that the vibrations are identical (hence no advantage of one location over the other). A value less than one indicates that the second location experienced greater attenuation at that frequency than the first one, meaning that the second location is “better” at that frequency. A value greater than one indicates that the first location experienced greater attenuation than the second, meaning the first location is “better” at that frequency. Some of both may be observed in Figure 4.
- Theory dictates that the amplitude ratio will tend to unity as the frequency tends toward zero. This is not observed here at frequencies below 4-5 Hz because the amplitudes are so low that the transfer function is performed on the “noise floors” of the sensors, which are inherently incoherent. In (b) and subsequent usages of the mean curves, the low frequency data will be omitted.

Figure 5 summarizes the log mean spectra relating the three test cases to the freefield. The following observations may be made:

- The attenuation at frequencies less than 10 Hz is quite small, as would be expected.
- The solid slab attenuates about 50 percent at most frequencies above 10 Hz, but at a few frequencies the attenuation is only on the order of 25 percent. There is little difference between the three directions. The attenuation is the least in all three directions at frequencies between 30 and 40 Hz.
- The attenuation provided at frequencies between 20 and 40 Hz by the island without piles (Location D) is greater in the vertical direction (over an order of magnitude) than in the horizontal directions (50 to 90 percent). The attenuation in all three directions decreases between 30 and 40 Hz. The vertical attenuation is more than an order of magnitude at frequencies above 50 Hz.
- The vertical attenuation provided by the island with piles is more than an order of magnitude at almost all frequencies above 15 Hz. The horizontal attenuation in the east-west direction is about an order of magnitude up to about 65 Hz, and above that it increases. The north-south attenuation is negligible in a narrow band centered around 35 Hz.

Figure 6 compares pairs of locations.

- The top plot (a) compares the island without piles (Location D) with the solid slab (Location B). At frequencies up to about 20 Hz, the island performs better, the difference being as much as 12 decibels (a factor of four). At frequencies between 20 Hz and 50 Hz, the difference is negligible, and at some frequencies the vibrations in the north-south direction are worse on the island. At frequencies above 50 Hz, the island clearly performs better.
- The middle plot (b) compares the island with piles (Location E) with the solid slab (Location B). At frequencies up to about 20 Hz, the difference is about the same as it is for Location D (above). The vertical component performs better on the island than on the slab at all frequencies. At frequencies between 20 and 50 Hz, the difference is again negligible, with a slight exceedance in the north-south direction at frequencies between 30 and 40 Hz. At higher frequencies, the island performs better—much better in the horizontal directions at frequencies above 75 Hz.
- The bottom plot (c) compares the island without piles to the island with piles. (A spectral value less than one indicates that the island with piles performs better than the one without piles.) We see that the pile-supported island performs better in all directions at all frequencies (except for the minor excursion in the north-south direction at frequencies near 32 Hz). At frequencies below 30 Hz, the differences in the horizontal direction are quite small; at frequencies above 60 Hz, the difference is an order of magnitude.

4. COMPARISON OF PERFORMANCE WITH POINT EXCITATION

Several measurements were made which employed heel drop excitation at selected locations. This simulated nearfield point loading, similar to that which might be associated with a dropped gas bottle or pedestrian activity.

Figure 7 shows the results of these tests. A comparison with the curves presented previously should lead to the observation of a major difference. The spectra are all quite different in nature. We see values considerably greater than one at a number of frequencies. This requires some explanation.

There is a clearly defined hump in the right half of Figure 7(a). Compare this with the hump in mobility shown in Figure 3 for Location E. The mobility peak corresponds to the SDOF resonance of the concrete mass on the pile springs. We did not see this excited by the ambient loading, but impact loading excites it. We believe this is due to the coherent nature of the single point source, as opposed to the diffuse nature of the ambient vibrations.

Figure 8 makes this clearer. It compares E with D, with one curve for ambient and the other for heeldrop excitation at B. We see that the ambient curve has the same hump, but less pronounced than the heeldrop curve. The coherence of the point source changes the relative performance of the two.

5. CONCLUSIONS

With regard to ambient excitation, the three systems must be examined in terms of frequency ranges. The following table attempts this.

Frequency Range	Ranking (best to worst)	
	Vertical	Horizontal
0 to 20 Hz	E, D, B	E/D, B (no significant difference between E and D)
20 to 50 Hz	E, D, B	B, D/E
50 to 100 Hz	E, D, B	E, D, B

Performance in the vertical direction (generally dominant in a vibration environment), the ranking is clearly E, D, B. Horizontally, it is not as clear cut. The solid slab is best at middle frequencies; E is the best at high and low frequencies.

When we consider only nearfield point loads, the ranking changes.

Frequency Range	Vertical
0 to 20 Hz	E, D/B
20 to 50 Hz	E, D/B
50 to 100 Hz	B, D, E

There is no obvious “best” approach that applies in all cases. We recommend that the selection be based upon the occurrence probability of events being considered. In other words, the ambient condition occurs much more than the impact case, so we recommend that it govern. Also, horizontal is generally less than vertical, so vertical should govern. Applying this logic, the approach using piles is best.

Similar conclusions may be drawn for piles supporting larger areas of slab, though the resonance frequencies might be shifted. (The shift would be up or down depending upon whether the mass per column decreases or increases.)

The stiffness of the slab-on-grade and the island without piles are about the same. The calculated stiffness of the island with piles is about 6 to 7 times that of the other two. This supports the argument that a pile-supported block provides better load resistance than other forms. However, one must be careful to avoid the resonance, as there might be some amplification.

It should be noted that a Keel/Slab system[8] will provide the best attenuation at higher frequencies, but at the cost of increased vibration amplitudes below 4-6 Hz. The decision to use one scheme over another must be based in part upon the needs of individual research projects. It was found during the design of the Advanced Measurement Laboratory at NIST that not all experiments were amenable to the high compliance at low frequencies. Other activities, such as nanoprobe development, are more responsive to higher frequencies and the low frequency motion associated with the airspring resonances are simply perceived by the equipment as rigid body motion at frequencies well below internal resonances.

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Figure 1: Test Layout

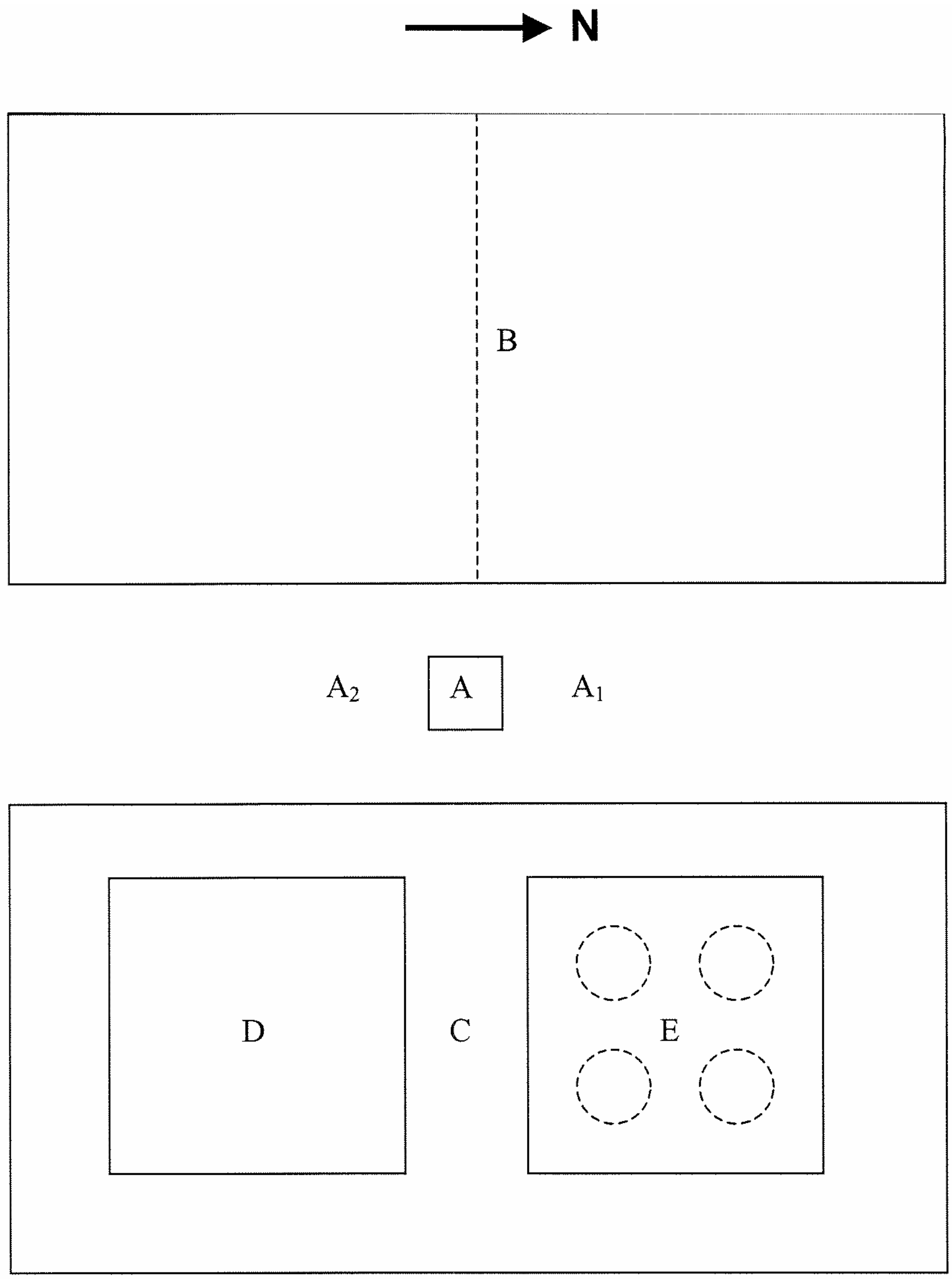
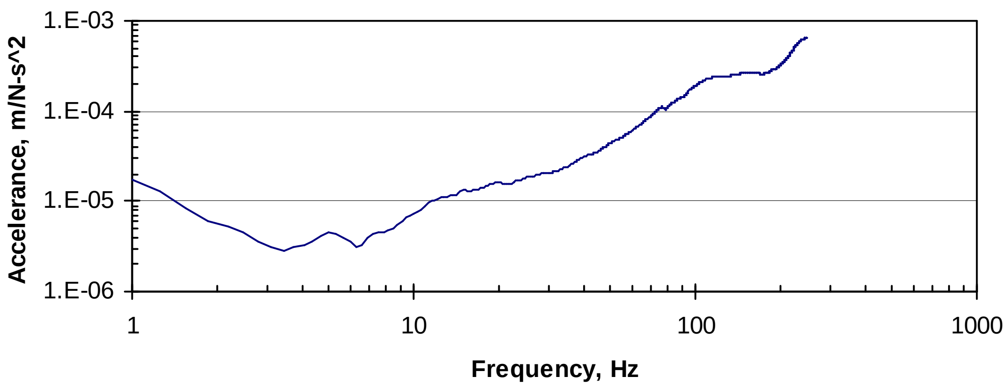
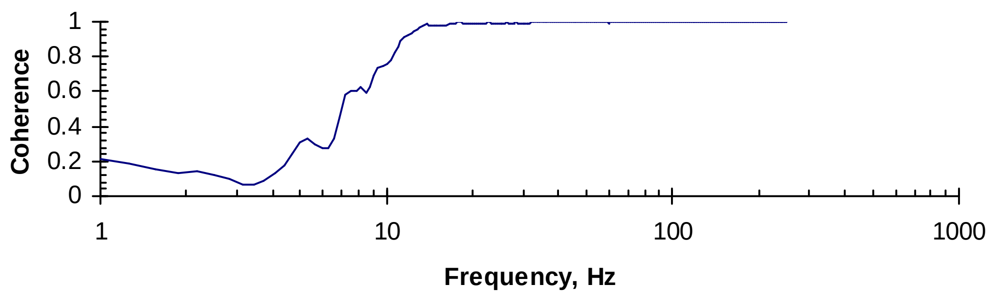


Figure 2: Typical Hammerblow Data – Location B

a) Measured Accelerance



b) Coherence



c) Dynamic Stiffness

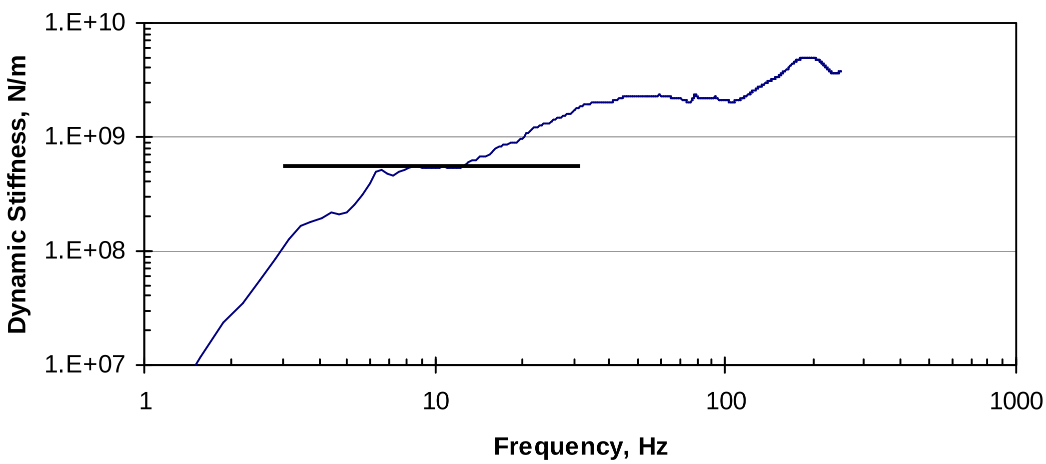


Figure 3: Drive Point Mobility as measured at four locations

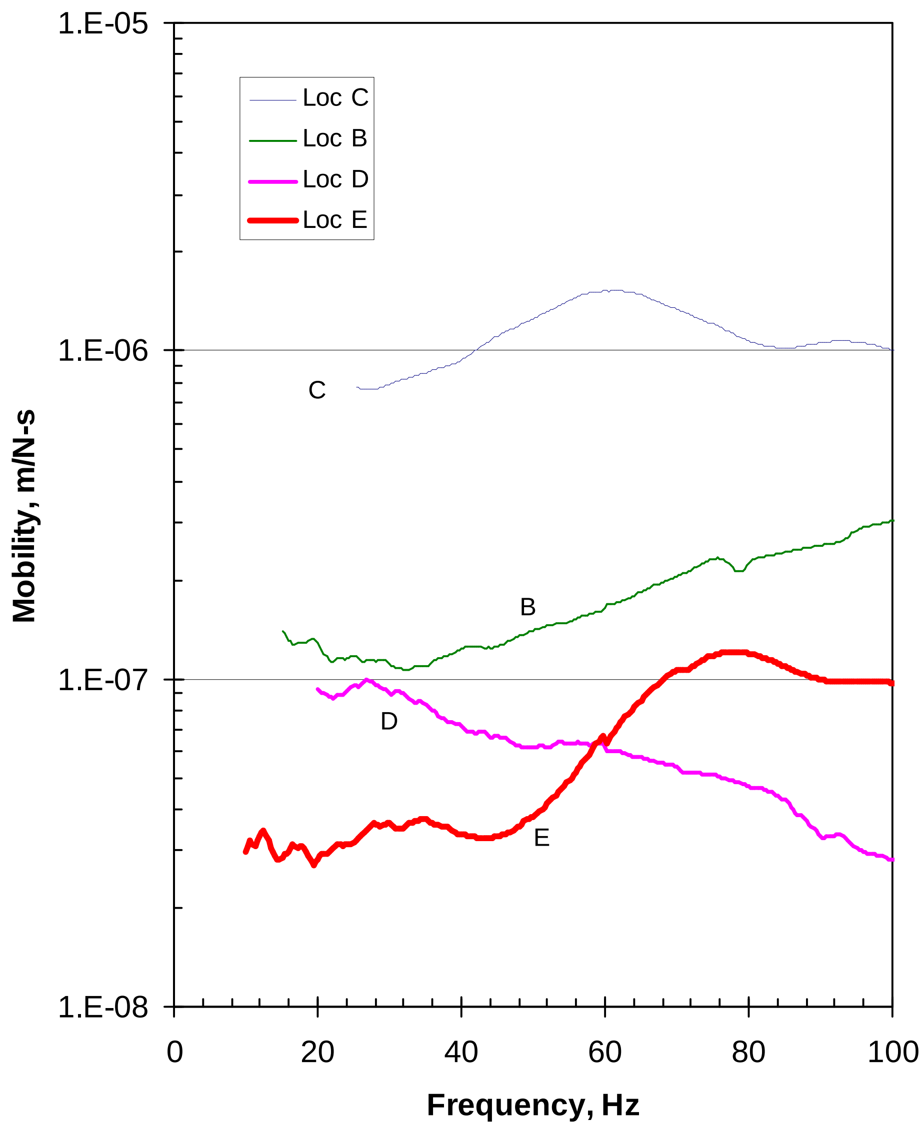


Figure 4: Typical Comparison Data, Location D w.r.t. Location B, North-South

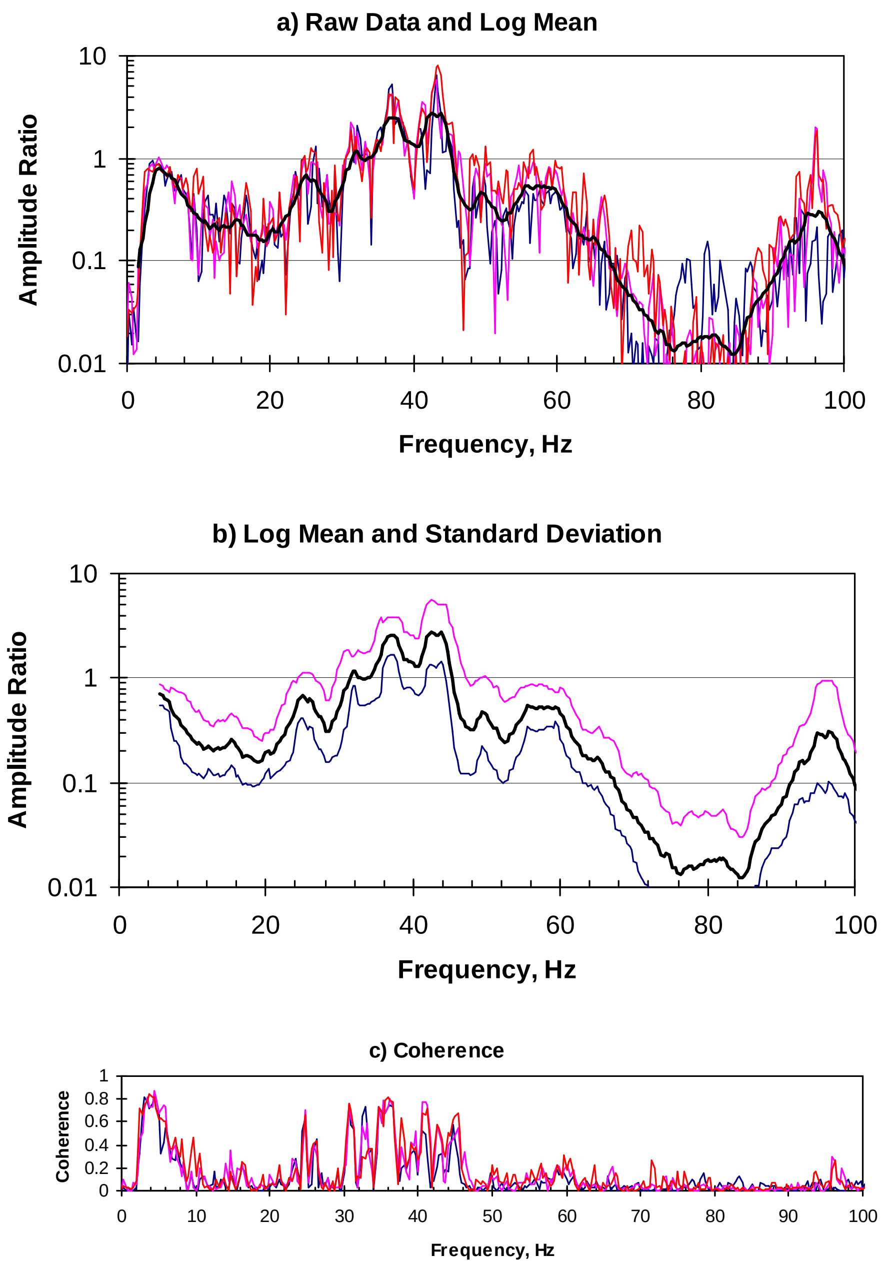


Figure 5: Summary of Comparisons with Freefield (Location A)

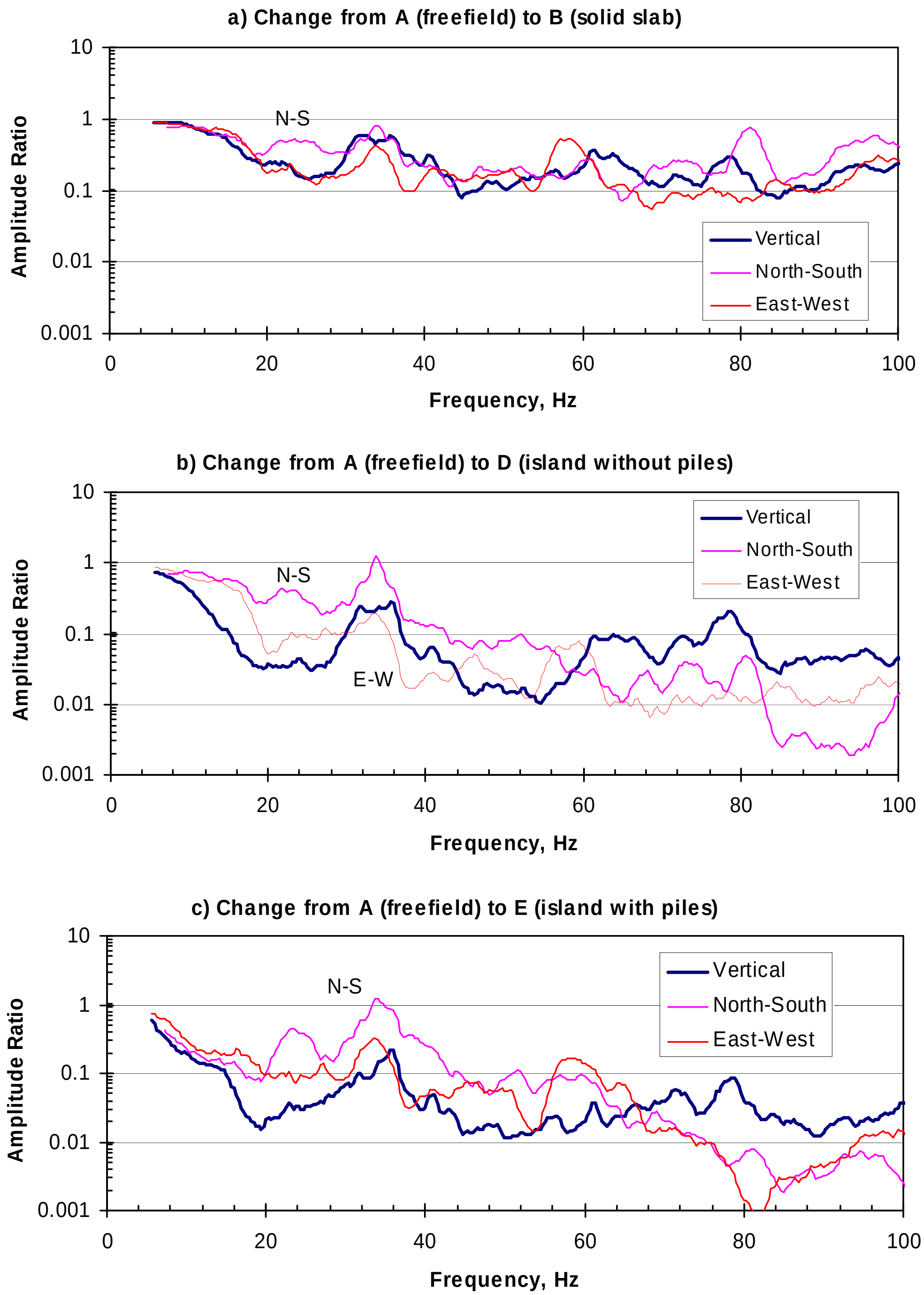


Figure 6: Summary of Comparative Measurements

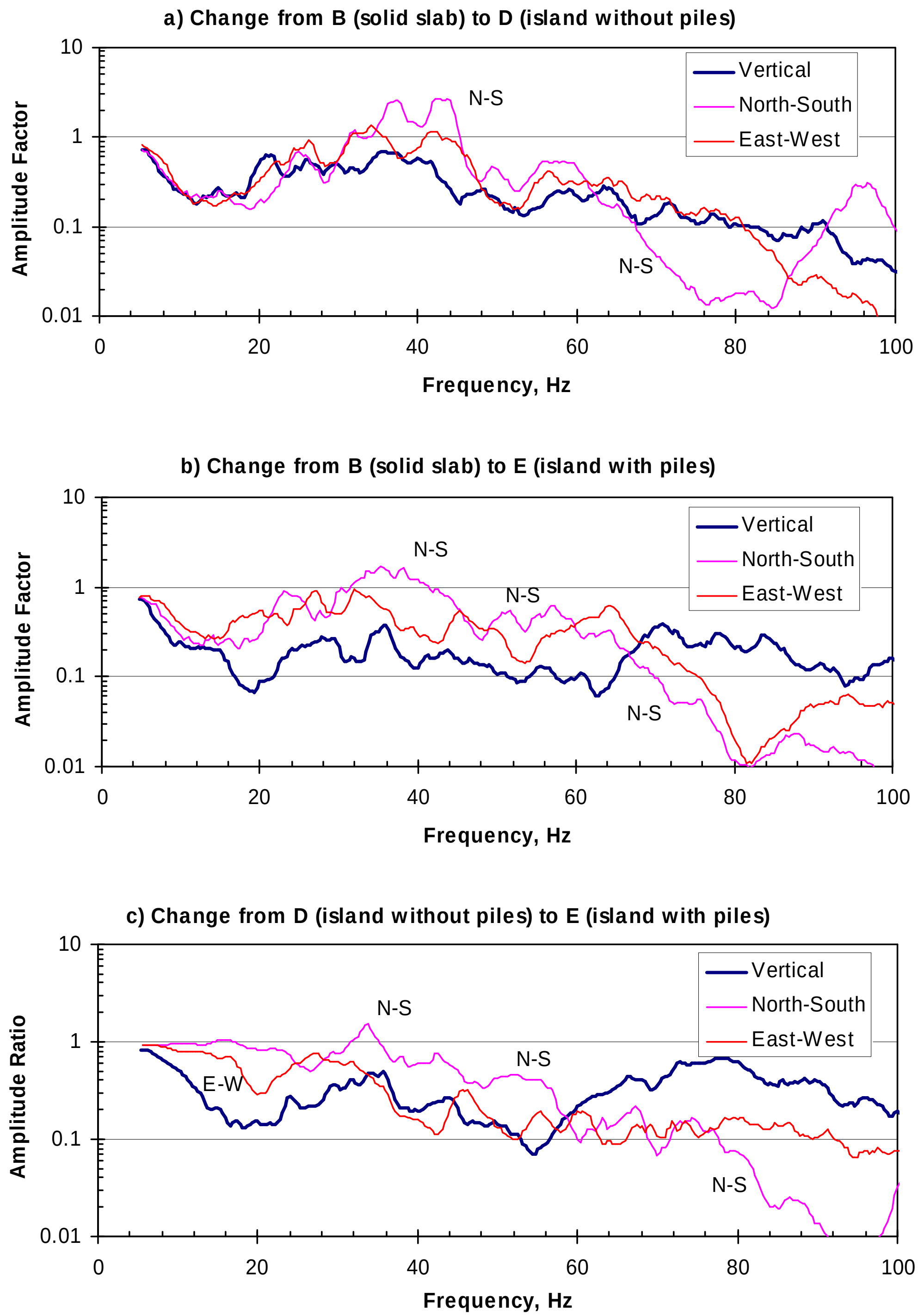
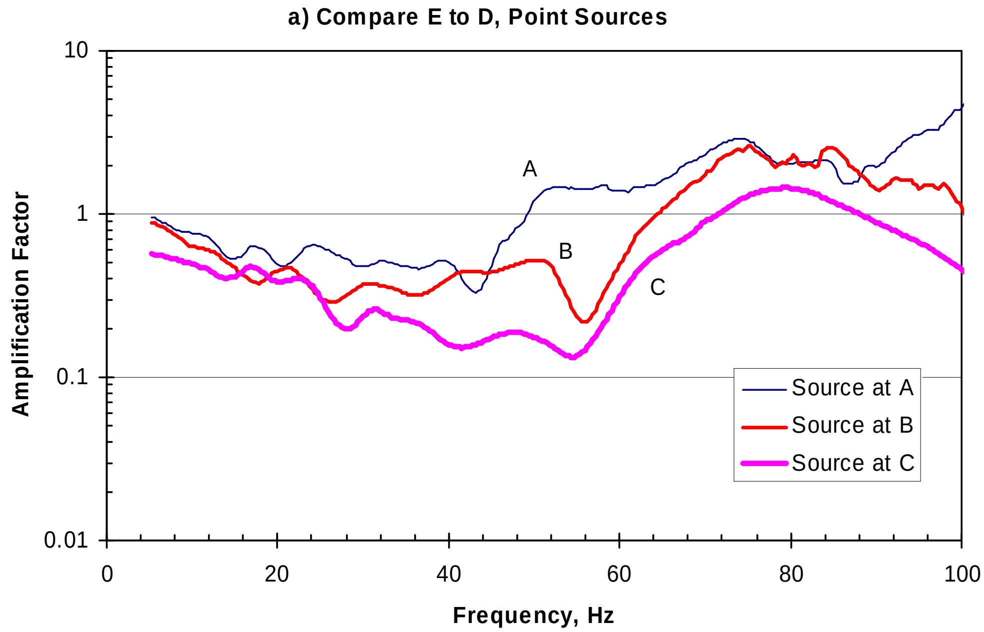


Figure 7: Response to Point Sources



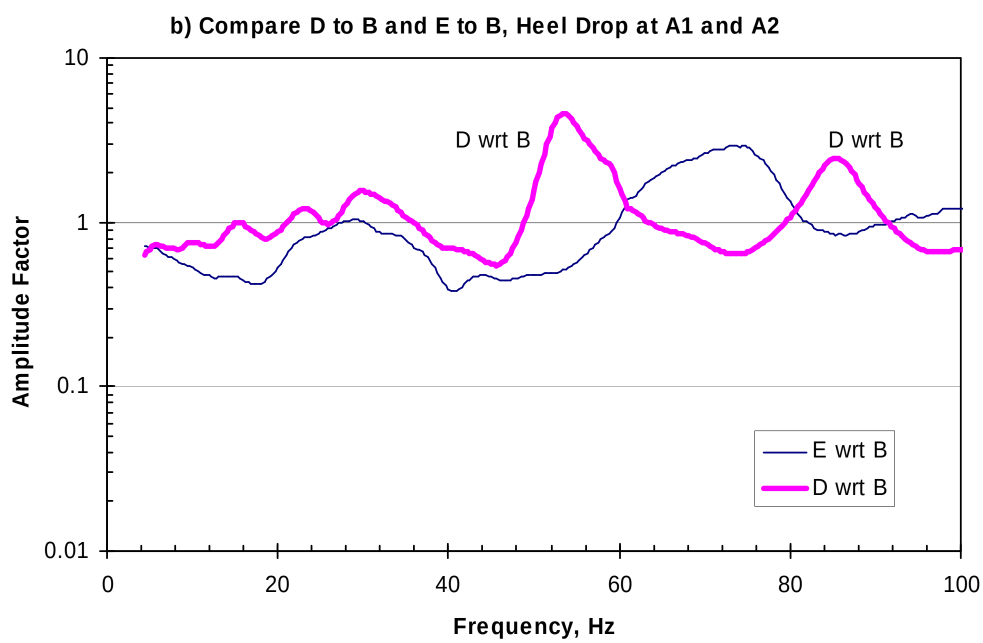


Figure 8: Compare Point Source and Ambient