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The Effect of Buildings on Ground Vibration Propagation

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ABSTRACT

This paper discusses the effects of buildings on ground vibration propagation. 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 building once it has been constructed. Data will be presented illustrating how several factors—including building foundation stiffness, ground stiffness, and building geometry—all have an effect on the propagation from vibration sources.

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] However, the presence of a building can significantly modify the site vibrations.[1] A number of options are available to designers which will provide some attenuation of the free-field vibrations, though that attenuation will be dependent upon the building's mass and stiffness, as well as the nature of its attachment to the ground.

This paper summarizes seven case studies exploring various aspects of the so-called *building effect*. Three of those cases, discussed in Section 4, have been presented previously in the literature, though their data are presented in ways somewhat different from the original. These include: (1) placement of the entire building below-grade; (2) deliberate stiffening of the slab and foundation, anchoring it to bedrock, in order to attenuate rail-induced vibrations; and (3) use of "islands," with and without pile support, as a means to attenuate ambient vibration.

The four case studies in Section 5 have not been presented previously, and include: (4) a two-story frame residence and a comparison of the rail-induced vibrations of the first and second levels; (5) a five-story steel frame laboratory building and the manner in which it modifies the free-field vibrations due to nearby pile driving, (6) a large semiconductor production facility and the attenuation provided by the building shell at relatively low frequencies; and (7) simultaneous measurement of vibrations at the surface (free-field) and at depth (at the bottom of a hole for a drilled pier) to simulate the effect of below-grade placement of a lab in a basement.

The case studies are preceded by a brief discussion of the typical site vibration study and a review of the effects of adding a building to a free-field site.

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2. CHARACTERIZING SITE VIBRATION

A vibration site study is usually conducted at potential building sites to characterize the ambient ground vibration. This is important to know as it indicates the potential vibration that would be experienced at the site. This vibration is typically a factor of many sources such as nearby mechanical equipment, vehicle traffic, and of course soil properties. Ambient vibration measurements (time averaged) are usually taken on the site surface at multiple locations to attain a statistical analysis of the overall vibration levels. These surfaces can range from paved parking lots to grass or dirt fields which often require the use of a driven metal spike or cast concrete block to create a rigid measurement platform. The vibration is measured in three axes (triaxial) to quantify the vertical and horizontal components of the vibration.

3. POTENTIAL EFFECTS OF A BUILDING ON THE SITE

The 'building effect' is a known phenomenon in which site vibration levels are altered due to the presence of a building. As most of the ground vibration propagates in the form of Rayleigh (surface) waves, the presence of a building will certainly introduce an impedance change in the propagation path along the surface. Some important factors that influence this change are the geotechnical properties of the soil, the building's mass and stiffness, and the relationship between the building geometry and the wavelength. The change in vibration level, whether an attenuation or an amplification, is quite frequency dependant and not easily predicted. Amplification of the vibration is often the result of resonances inherent of the building. Attenuation usually results from 'wavelength averaging', in which the ground vibration amplitude is averaged out (attenuated) when the ratio of the wavelength and building length approach an integer. In this case, the building stiffness should be very stiff with respect to the soil stiffness.[3]

4. PREVIOUS CASE STUDIES

In this section, we present some aspects of cases published elsewhere—by ourselves or by others—which illustrate the building effect. In some cases, new or reformatted data are presented to clarify particular points.

Case 1: Ground Vibration Below Grade versus At-Grade

The NIST Advanced Measurement Laboratory was constructed with two wings located at grade and two underground wings, the floors of which were located 14m below grade. The below-grade placement provided greater thermal stability as well as a certain amount of vibration attenuation. The latter occurred in part because of the stiffening effect of the "box"—similar in concept to the "building effect"—but also due to the reduction in Rayleigh wave amplitude below the surface.[4] Figure 1 shows the attenuation provided by the below-grade placement, in terms of the mean-plus-sigma velocity spectrum of the below-grade spaces divided by mean-plus-sigma spectrum for the at-grade spaces.[5] (In both cases, the sigma represents the spatial statistical distribution.) At frequencies of 20 Hz and less, the horizontal reduction was 3 to 5 dB or more, and the vertical reduction was 8 to 10 dB or more.

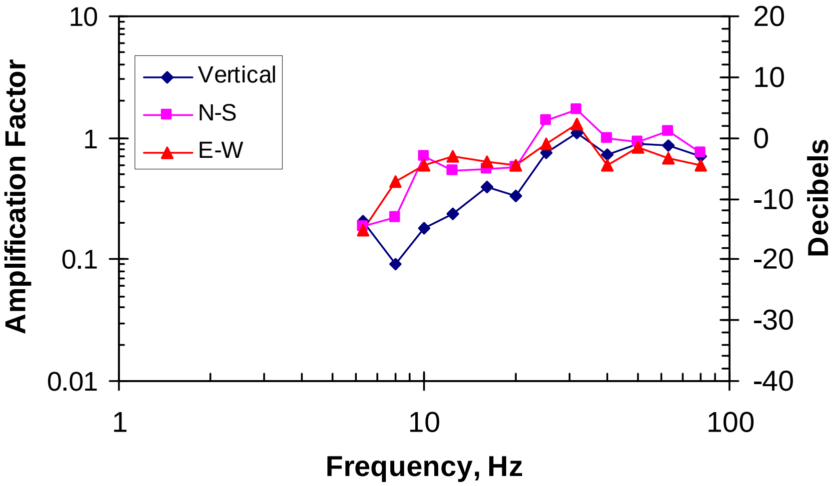

Figure 1: Attenuation provided by placement of lab at 14m below grade.

Case 2: Stiffened Foundation-Slab System

The designers of the Belknap Research Building at the University of Louisville were faced with a somewhat unique challenge, in that the campus is bounded on three sides with well-used freight rail lines. The facility was intended for research at the nanometer scale, and a vibration criterion on the order of 6 μm/s (or better) was deemed appropriate. The first site exhibited adequate ambient vibrations (without trains), but maximum horizontal and vertical vibrations (with trains) were on the order of 180 and 84 μm/s, respectively, centered around the 5 Hz one-third octave band. That site was rejected in favor of a site farther from the tracks that generated the highest amplitudes.[6]

At the second site the maximum vibration amplitudes were on the order of 30 and 12.5 μm/s, respectively. (The maximum horizontal train-induced vibrations were also significantly higher in the E-W direction than in the N-S, despite the fact that the rail lines were on three sides of the site. [6])

The structural engineer designed a complex foundation scheme that involved drilled caissons attached to bedrock, the tops of which were embedded in a thick slab with a connection detail designed to transfer rotation. In addition, the building was oriented such that its long axis was in the direction of the highest horizontal amplitudes. Upon completion of the structure, the reported maximum train induced vibrations in the vertical, E-W and N-S directions had amplitudes of 7.8, 5.2 and 7.6 μm/s. The energy average ambient vibrations were less than 1 μm/s in all three directions. The changes due to the structure in maximum train-induced velocity levels were 4, 15, and 3 dB, respectively. The horizontal maxima occurred in the 5 and 8 Hz one-third octave bands, respectively.[6,7]

Case 3: Island versus Solid Slab

Researchers who would occupy the National Institute for Nanotechnology (NINT) at the University of Alberta wished to see quantitative comparisons between the several types of foundations being considered: (a) simple, but somewhat thick, slab-on-grade; (b) "island" of even thicker slab-on-grade, surrounded by a joint; and (c) island supported on four piles. A study was staged at their site designed specifically to produce this information. The comparisons were made via transfer functions between pairs of triaxial measurements.[8]

Figure 2 compares the vertical and two horizontal components measured on the large slab-on-grade with those measured in the free-field, using ambient vibration as excitation.[8] The presence of the slab provides at least 4-5 dB attenuation at most frequencies between 16 and 100 Hz, and as much as 20 dB attenuation at some frequencies. The attenuation approaches zero dB as the frequency approaches zero, demonstrating the frequency dependence of the building effect.[3]

Figure 3 compares the vibrations on the slab-on-grade island with those on the conventional slab-on-grade.[7] In the vertical direction, we observe additional attenuation of at least 4 dB at frequencies above 10 Hz, increasing to about 20 dB at 80 Hz. However, at frequencies between 30 and 45 Hz, we see that the horizontal components are actually *worse* on the island than on the surrounding slab. This is consistent with other observations.[3,8]

Figure 4 compares the two types of islands—pile-supported versus slab-on-grade.[8] We see further improvement in vertical attenuation, but less additional horizontal improvement. When represented in decibels, the improvement is additive. Thus, at 20 Hz (for example), the vertical attenuation provided by the pile-supported island with respect to free-field is 14 + 10 + 16, or 40 dB. The attenuation spectra for this case are shown in Figure 5.

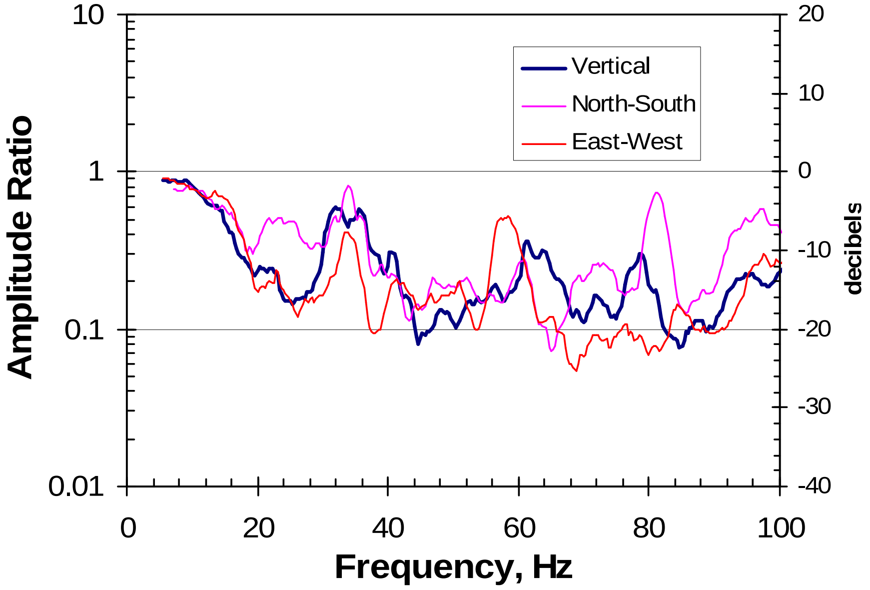

Figure 2: Transfer functions between free-field and conventional slab, ambient excitation.[8]

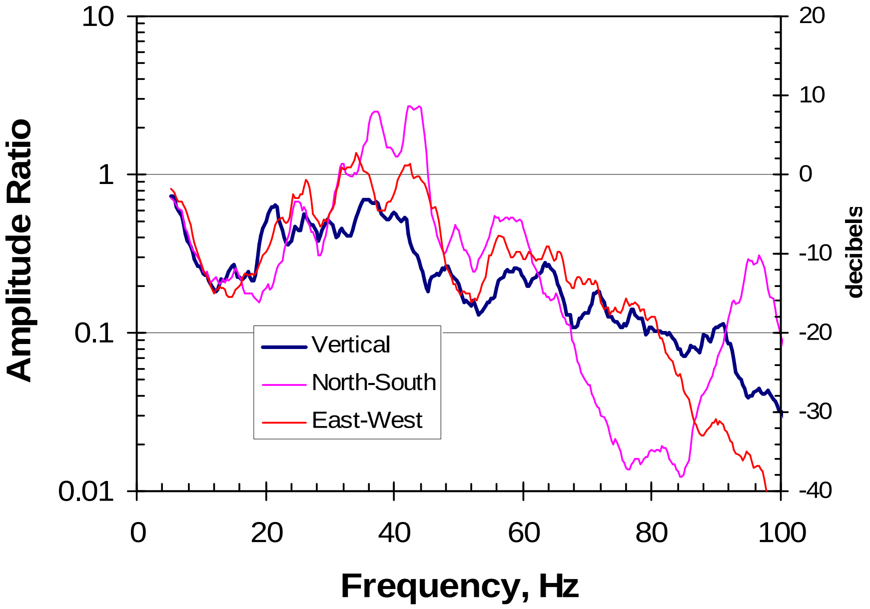

Figure 3: Transfer functions between conventional slab-on-grade and "island" slab-on-grade, ambient excitation.[8]

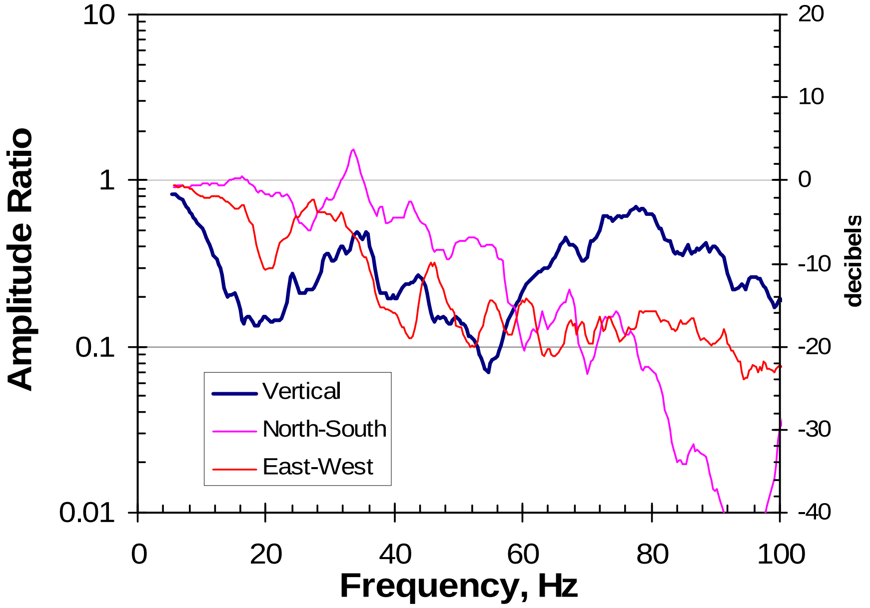

Figure 4: Transfer functions between island slab-on-grade and pile-supported island, ambient excitation.[8]

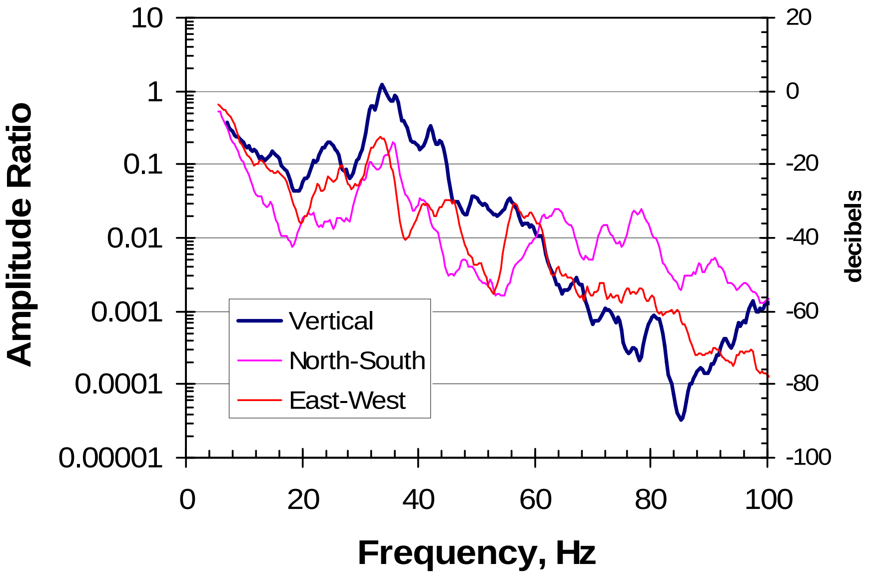

Figure 5: Transfer functions between free-field and pile-supported island, ambient excitation.[8]

5. NEW CASE STUDIES

In this section, we present four cases not previously published which illustrate the building effect. The cases include a two-story frame residence subjected to rail excitation, a five-story steel frame building subjected to vibrations from pile driving., a large semiconductor building subjected to shaking using a large shaker, and surface versus subsurface vibration due to vehicle traffic.

Case 4: Two Story Frame Residence

A two-story frame residence near a railroad track was instrumented with two sets of triaxial accelerometers, one on the first floor (a slab-on-grade), and the other near the center of the second floor. The six channels were recorded simultaneously and subsequently post-processed to obtain one-third octave band velocity spectra. The intent of the measurements was to document the difference in vibrations between the two levels. (Prior measurements at the location had determined that there was little difference between the at-grade vibrations outside the house and those obtained at the interior measurement location on a thin slab.)

Figure 6 shows the pairs of spectra measured at the two levels, arranged by direction. Note that there is a significant difference in response between the two levels for horizontal motion (X and Y), but not vertical. Upon first inspection, the change in amplitude between the two levels appears similar. Figure 7 shows the amplification spectra between Level 1 and Level 2. It should be noted that the horizontal amplification is at different frequencies (8 and 10 Hz bands), though in both cases, the amplification itself is similar (about 7.8x, or about 18 dB). If one were to compute the vector sum of amplitudes at each level, and then examine the amplification, a single peak with a much lower factor is found (about 3.6x, or 11 dB, at 8 Hz). Clearly, in this case, the measurement of ground-level or outdoor vibration is not representative of the eventual vibration environment on the second level.

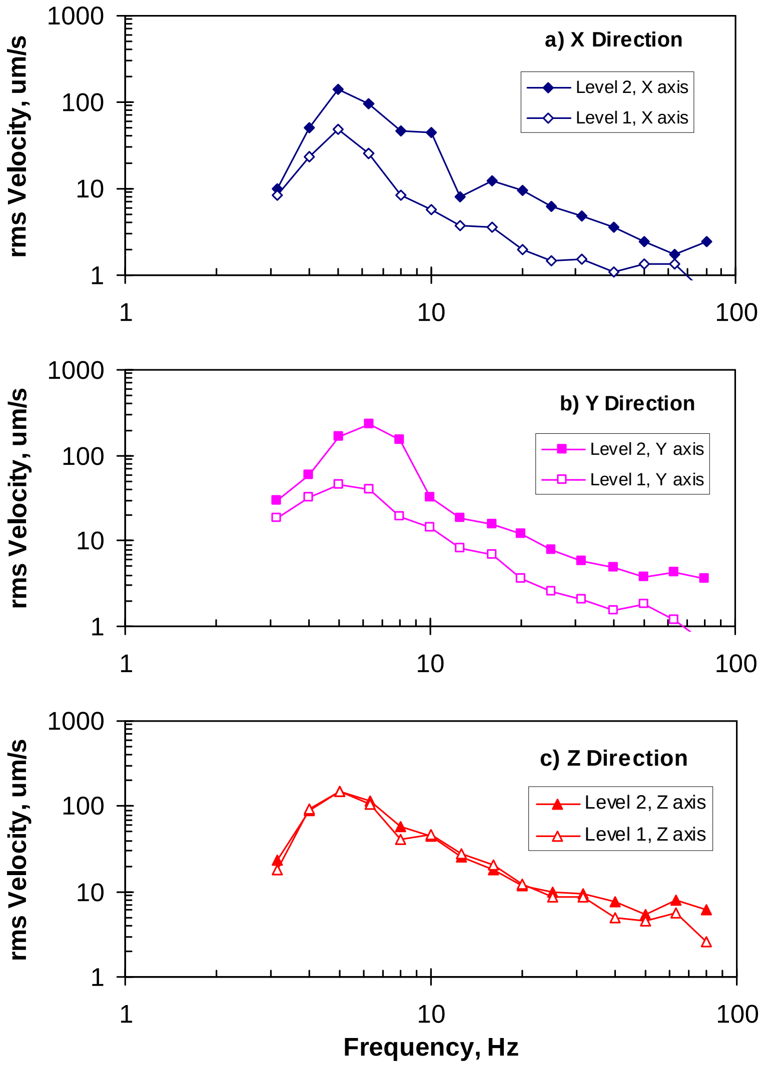

Figure 6: Vibrations measured on two levels inside frame residence during passage of one train. X direction is parallel to tracks; Y is perpendicular; Z is vertical.

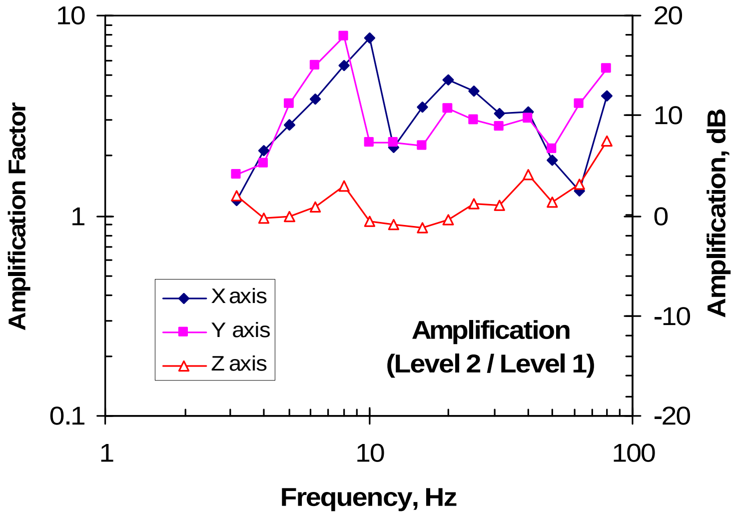

Figure 7: Amplification between Level 1 and Level 2.

Case 5: Five-Story Steel Frame Laboratory Building

A five-story steel frame laboratory building with a deep pile foundation, supported on a deep clay formation, was instrumented with two sets of triaxial accelerometers, one outside the building to use as a free-field reference, and the other placed at two locations inside the building. One of the interior positions was at the middle of a bay on the first floor—a thick slab supported on closely spaced piles. The other was at a midbay location on the fifth floor.

Figure 8 shows the pairs of transfer functions in three directions measured as piles were driven at a nearby building site to the west. Portions of the spectra with coherence less than 0.1 have been removed. Except at what appears to be the lab building's pile resonance frequency (about 18 Hz) the vertical vibrations at the first floor were attenuated by about 10 dB at frequencies below 27 Hz and amplified at the floor resonances of 31 and 37 Hz. The 5th floor vibrations were amplified at several resonance frequencies, including the pile resonance. Horizontal vibrations were attenuated on both floors by at least 12 dB at all frequencies. On the fifth floor, the attenuation was 20 dB or more at most frequencies.

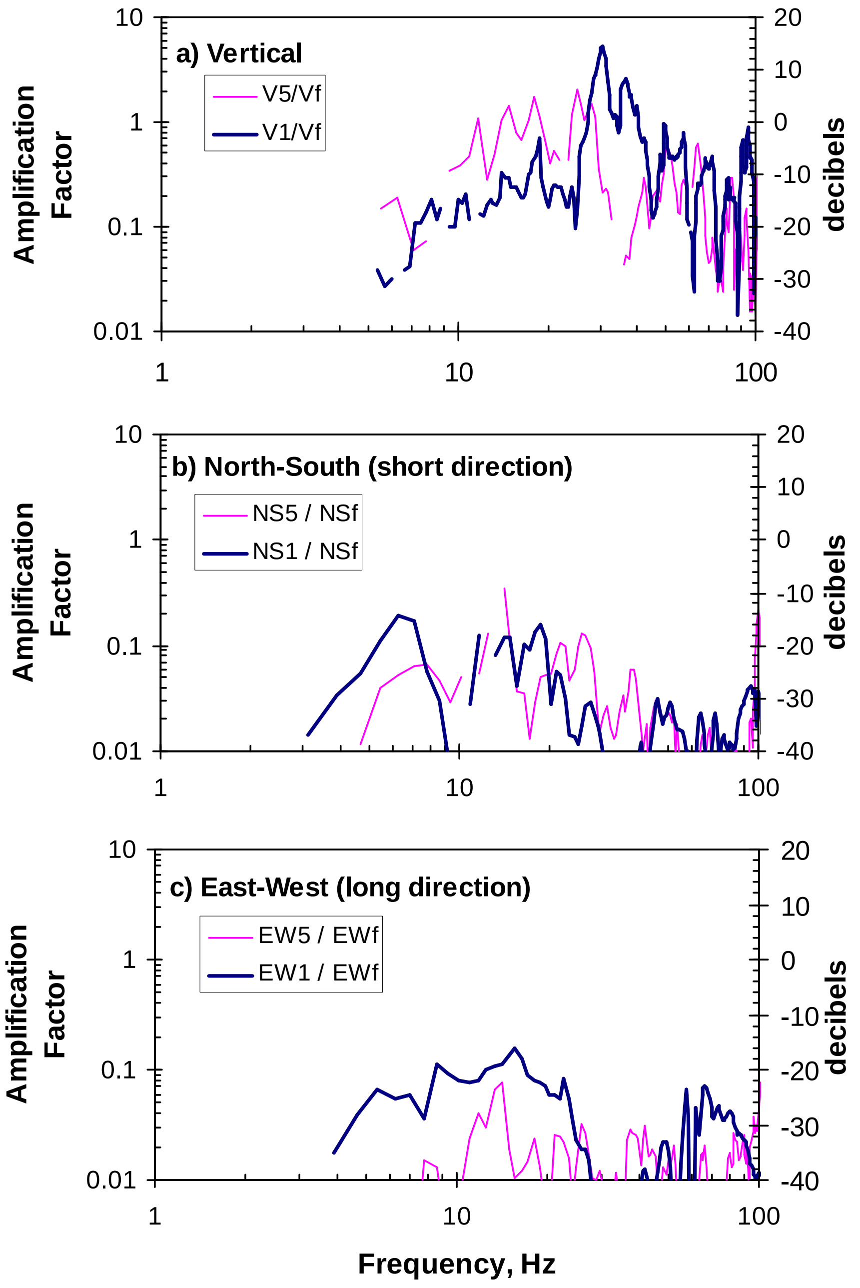

Figure 8: Frequency response functions between two interior locations in a five-story research building and a reference location outside the building, during nearby pile driving at a site west of the facility.

Case 6: Vibration Propagation onto Slab versus Ground with Shaker Excitation

In this case, we compare the transfer functions between ground-to-slab and ground-to-ground vibration measurements. An excitation shaker was bolted onto a concrete block at a distance of 50m from a semiconductor building and the vibration response was measured at the building on the on-grade slab. At the same time, the vibration response was also measured on the ground at an equal distance away from the source as shown in Figure 9. This provides a straight comparison between vibration propagation onto a slab, and into the free field.

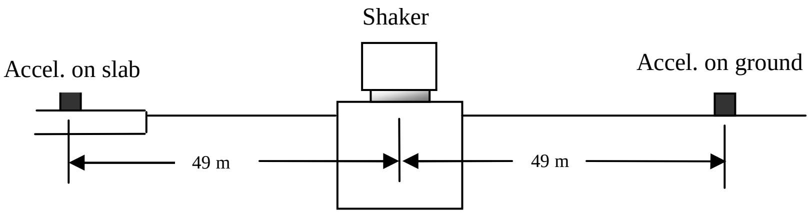

Figure 9: The vibration was measured on the slab and on the ground at equal distances from the shaker.

The data presented in Figure 10 is the ratio of the transfer function to the slab versus the transfer function to the ground position. This is shown as an amplification factor in dB with Negative dB values representing attenuation. In the vertical direction, very little difference was observed until about 9 Hz, where there is some amplification that remains unexplained. In the horizontal directions, it can be seen that there is attenuation primarily in the North-South direction, which is the longest length of the slab. In the sense of the wave averaging phenomenon, the slab in the North-South direction encompasses a higher portion of the wavelengths allowing for the attenuation.

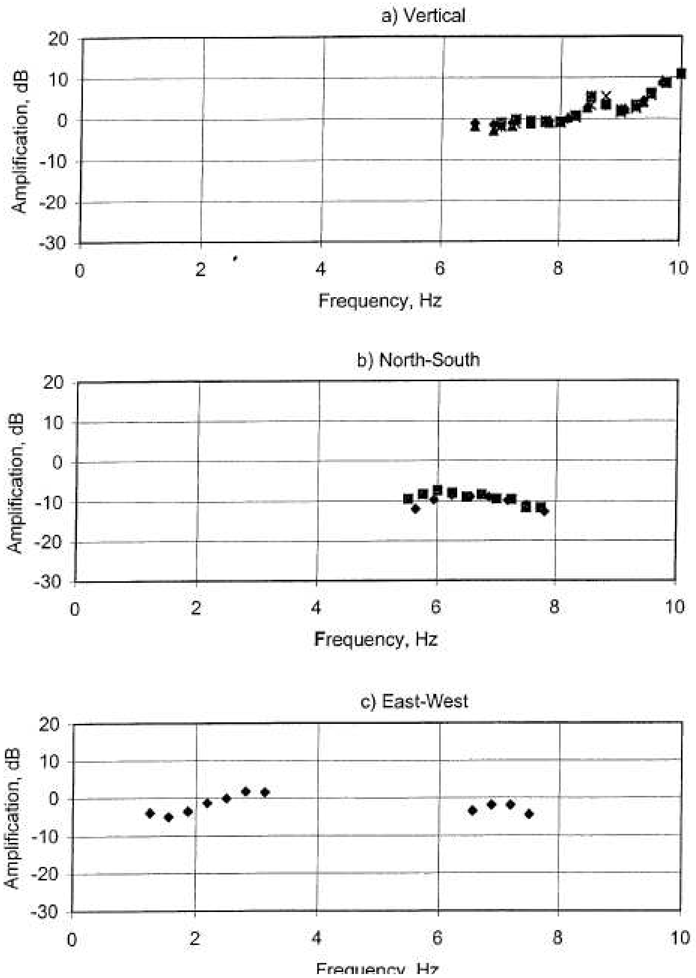

Figure 10: Ratio of slab transfer function over ground transfer function.

Case 7: Surface versus Subsurface Vibration

In this case, we compare vibration measured on the surface with below-surface measurements. A 6m deep hole was dug to measure the subsurface vibration from passing vehicular traffic about 15m away. Measurements were taken at the surface level of the hole and at the bottom of the hole simultaneously with a two channel analyzer. These measurements were carried out several times to capture multiple vehicle passages. Figure 11 shows a representative peak hold vibration velocity measurement for a bus. As one can see, the subsurface levels are significantly lower than the surface vibration levels, about 30 dB less in the vicinity of 20 Hz. This is evidence of the reduction in Rayleigh waves with depth. Every set of down-hole measurements exhibited a reduction when comparing surface to below surface measurements. These results provided the data to show that vibration sensitive equipment located at a basement level on this particular site will not be significantly affected by traffic, therefore allowing the construction of the building.

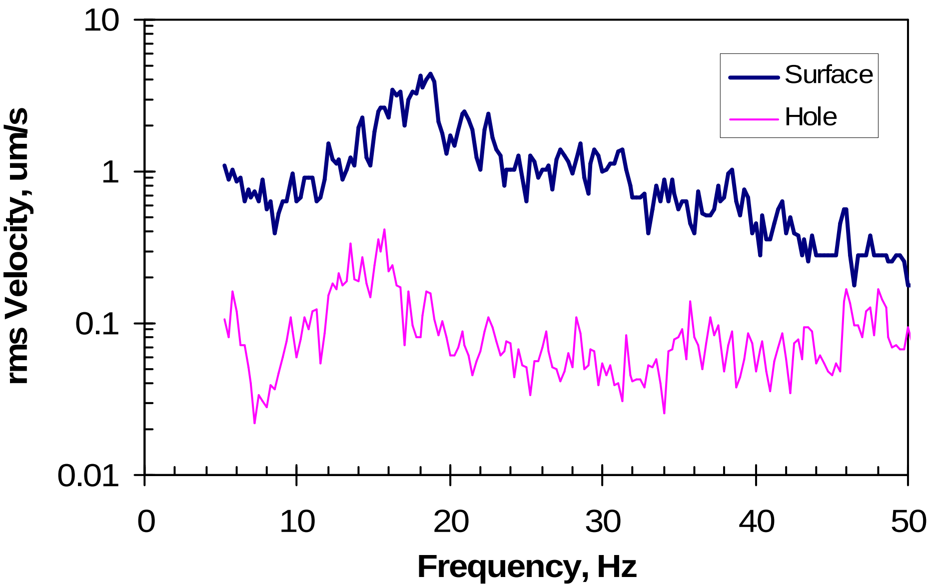

Figure 11: Comparison of Surface to Subsurface Vibration in a 6m Deep Hole

6. CONCLUSIONS

The presence and characteristics of a building will alter vibrations from what would be measured under free-field conditions. Several case studies have been presented which document selected aspects of this behavior. In the majority of cases, free-field vibrations are associated with surface waves. A building disrupts the continuity of the surface and, in many instances, provides an impedance mismatch in the propagation path.

A number of generalizations may be drawn from the data presented here. The building effect is a function of the ratio of the dynamic properties of the soil and structure (i.e., their stiffness, mass or density, etc.). A stiff or massive building (or one that is both) will probably attenuate vibrations by apparent “stiffening” of the site. A light or flexible building may provide very little attenuation (or even amplification, as in the case of the wood frame residence at the second level). The building effect is generally less significant at very low frequencies. To some extent, the building effect is a function of the building footprint; larger dimensions will attenuate horizontal vibrations at lower frequencies than will small ones. The amplitude of surface waves decreases with depth, so placement of a sensitive space at a significant depth may offer significant attenuation.

One can achieve rather dramatic results by combining some of these features. This was the case in the University of Louisville building, which combined a very stiff foundation with orientation of the building's long axis parallel to the direction of propagation of the maximum horizontal vibration.

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