The Role of Buildings and Slabs-on-Grade in the Suppression of Low-Amplitude Ambient Ground Vibrations

Hal Amick, Tao Xu, and Michael Gendreau
Colin Gordon & Associates, San Bruno, California USA

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Abstract—**This paper discusses the manner in which the stiffness of a slab-on-grade or building will alter the free-field vibrations at a building site. This phenomenon is dependent upon the rigidity of slab or foundation in the direction of wave propagation, and the relationship between wavelength and the dimension of the slab or foundation in the direction of wave propagation. Measurements from field studies are used as examples.**

Keywords—**Ground vibration, soil-structure interaction, slab-on-grade**

INTRODUCTION

The presence of a building on a site may alter the site vibration environment with respect to what it might be in the absence of that building. The phenomenon is well documented in the seismic literature for large-amplitude motions, but the issue is of interest to the designers of vibration-sensitive buildings, as well. In those cases, the amplitudes are generally quite small. [1-4]

There is some evidence in the non-seismic literature of the existence of a "building effect", in which the coupling between a building foundation and the soil it rests upon leads to a frequency-dependent attenuation. The data become quite limited at frequencies below about 20 Hz, as the historical interest in the subject has related to propagating vibrations that are re-radiated as noise inside a building. [5] The concern with vibration-sensitive buildings extends to much lower frequencies. [6]

This paper reports data from several studies specifically examining the building effect, particularly at low frequencies. It first examines a related phenomenon, the "slab effect," in which the presence of a slab suppresses the horizontal components of surface waves.

The slab effect contributes to the building effect overall. The slab effect becomes important in its own right if "islands" are to be cut out in a larger slab (to support items of particular sensitivity, such as electron microscopes). If cutout islands are employed, it can be shown with measured data that the horizontal vibrations are more severe on the "isolated" section of slab, contrary to popular belief.

VIBRATION CONCERNS FOR VIBRATION-SENSITIVE BUILDINGS

Many processes involved in advanced technology applications are highly sensitive to vibrations. Among these processes are precision metrology, molecular-scale imaging, nanotechnology, high-energy physics, long-beam-path laser applications, biotechnology research, and the R&D and production of semiconductors. Typically, the work carried out in these facilities requires environmental conditions more sophisticated than those provided by buildings intended for conventional occupancy. In many cases, vibrations are of concern.

In general, vibrations pose a problem for research and microfabrication equipment because at internal resonances they generate internal relative motion along a beam path that either blurs an optical image or causes an electron beam to deviate from its intended path. This may lead to such things as incorrect placement of a molecule in nanofabrication, for example, or short circuits in microprocessors. [6]

The ultimate objective of vibration control design is to limit the extent of these internal disturbances by limiting building vibrations where the equipment will be installed. (The broader field is discussed in a number of other sources, including another paper at this conference [7].)

Vibration control design involves the coordination of several aspects of dynamics, including the two special cases of building effect and slab effect. These differ somewhat from traditional soil-structure interaction, in that amplitudes are extremely small and amplitude-dependent properties generally are not of concern. In addition, vibration control for advanced technology may involve frequencies of up to 100 Hz or more. Thus, the seismic literature is not entirely helpful.

The vibrations come from a number of sources. Those inside the building include mechanical systems, people walking and engaging in other activities, and impact loads from objects being dropped. Exterior sources include traffic, mechanical systems in neighboring buildings, construction activities, and the ever-present seismic ambient. [1, 8, 9]

SOIL-STRUCTURE INTERACTION AT LOW AMPLITUDES

The building effect or slab effect is analogous to a phenomenon associated with watercraft. Imagine the difference in performance between a ship and a small craft such as a fishing boat. On rough seas, the small vessel responds to waves with wavelength both small and large, and the ride can be rather rough. A large vessel responds only to the waves of long wavelength, and is far less responsive to the shorter waves. The large vessel can span over the crests of smaller waves, in essence canceling them out. The smaller vessel also averages, but only averages those that are being spanned by its shorter length. This phenomenon is sometimes called "wavelength averaging" (though the term is a bit deceptive). It affects wavelengths that are *shorter* than the vessel in question.

The concept of wavelength averaging may be illustrated using Figure 1, which shows two wave trains, each with a different frequency (assuming the same medium), and four foundation or slab sizes (with respect to the direction of propagation). The wave type is not particularly important, though with a slab-on-grade or an on-grade building, the waves are predominantly Rayleigh waves.

The actual dimensions are not particularly important, only the relationship between the foundation dimension and the wavelength. One must also have some understanding of the stiffness of the building or slab in the direction of wave propagation, relative to the "stiffness" of the surface. A relatively stiff element (such as a very thick slab on soft soil) will tend to resist surface deformation; a relatively flexible element (such as a membrane) will offer little resistance.

Usually, one may assume that a slab is stiff with respect to horizontal motion and flexible with respect to vertical motion. A building will probably behave similar to its slab-on-grade in the horizontal direction, but the vertical stiffness will be more complex to assess. Only the stiff slab or building will tend to suppress wave propagation, and only in the stiff direction.

The motion of the foundation in its "rigid" direction will be equal to the surface motion averaged over the dimension of the foundation perpendicular to the wave motion. The effects of wavelength averaging on the four foundations in Fig. 1 are as follows:

Foundation 1 – This is analogous to the small boat on the sea. When subjected to long-wavelength ground motion such as (B), the foundation motion is essentially the same as that present without the foundation. With short-wavelength motion such as (A), the foundation moves with the support, but the amplitude is somewhat less than the ground motion without the foundation.

Foundation 4 – This case shows a foundation of a size equal to one wavelength of the long-wavelength motion and many wavelengths of the short-wavelength motion. If the rigid foundation is equal to one wavelength, i.e., waveform (B), then the average over that wavelength is zero, and the motion is suppressed. Likewise, if it is equal to an integer number of wavelengths, e.g., waveform (A), then the average is also zero.

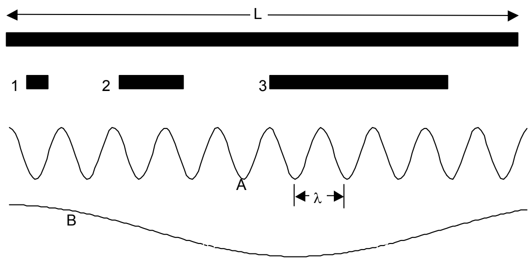

Fig. 1: Illustration of "wavelength averaging" with two wave trains and four foundation or building sizes.

Foundations 2 and 3 – These two cases represent increasing fractions of wavelength (but less than 1) with respect to (B) but non-integer multiples of wavelength with respect to (A). The response in these cases is intuitively less obvious.

The motion of a rigid foundation subjected to a propagating waveform is, in a manner of speaking, attenuated by waveform averaging, as a function of the ratio of dimension, L, to wavelength, λ. When this ratio approaches zero, the attenuation factor approaches unity; when the ratio is equal to an integer, the factor is zero. Figure 2 shows the general form of the attenuation factor as a function of the ratio. In general, a rigid foundation will act as a low-pass filter that provides an attenuation factor less than 0.2 (about 14 decibels) whenever the dimension exceeds about $0.8L$.

The key to exploiting this feature lies with the ability to recognize when a foundation approximates rigidity with respect to the supporting medium's tendency to move. A concrete slab on grade approximates rigidity in the horizontal plane, but is moderately flexible with respect to resisting vertical motion where it must make use of bending stiffness. However, the bending stiffness will vary with thickness, so the ability to suppress vertical motion will also be thickness-dependent. If a structure is introduced, the situation becomes more complicated. For

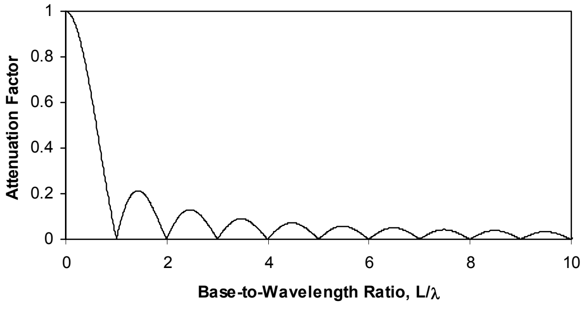

Fig. 2: Attenuation provided by wavelength averaging for a foundation of infinite stiffness in the direction of wave propagation.

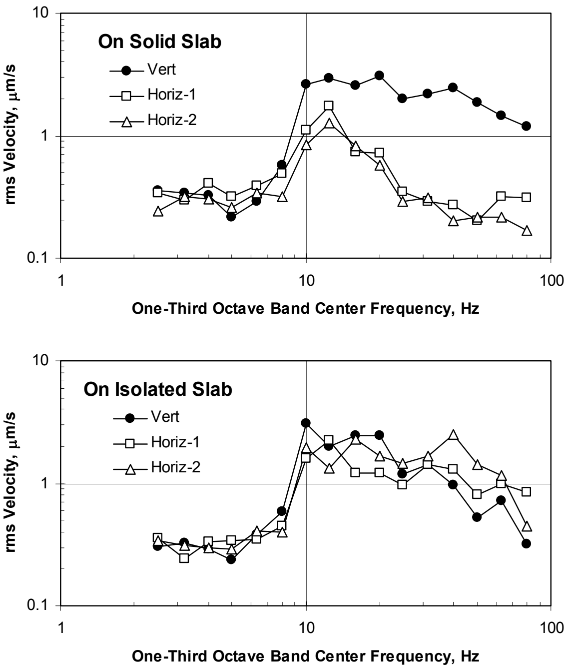

Fig. 3: Triaxial vibration measurements on a 6" thick slab-on-grade floor with 6 ft x 6 ft "isolated" slab as an "island" within the solid part. On solid part (top) and "isolated" part (bottom).

example, if a building is supported on discrete footings or piles, without an on-grade slab connecting them, the suppression likely will not occur.

The following sections provide illustrations of how this effect does and does not apply to slabs and buildings, using measurements from several field studies.

EFFECT OF A SLAB

Quite often, designers are faced with compromises in which a change in a particular design feature provides improvements in some respects and degradation in other respects. One such design feature is the use of so-called "isolation breaks" in slabs-on-grade, sometimes recommended to provide attenuation of vibrations in advanced technology applications.[1] Their use involves a tradeoff between horizontal and vertical performance.

The tradeoff is that vertical vibrations may also affected, but not in the same way. This is best illustrated by measured data. Figure 3 shows one-third octave band velocity spectra measured at two locations in one laboratory on a 150mm thick slab on grade. One of the measurement locations is on a 1.8m x 1.8m segment of slab that has an "isolation break" around its perimeter. The other location is nearby, on the uncut portion of slab. The sets of spectra are different, but the nature of the difference is not immediately obvious. There is very little change in the maximum spectral amplitude in the vertical direction. On the other hand, the horizontal vibrations appear much lower on the solid slab than on the isolated one. There are other less obvious changes as well.

Some clarity may be brought to the comparison of the two cases by looking at the change introduced by the isolation of the "island". To do this, we divide the isolated slab spectra by the corresponding solid slab spectra, and express this either as a decimal fraction or as decibels (dB) using Eq. (1) for each pair of points at a given frequency.

$$Change(f) = 20 \times \log\left(\frac{V(f)_{isol}}{V(f)_{solid}}\right) \qquad (1)$$

The resulting spectra are shown in Figure 4. A value less than 1 (or a negative value of dB) indicates a reduction provided by the isolated slab; a value greater than 1 (or a positive value of dB) indicates the isolated slab *increases* the amplitude. We see, in general, the following: (1) the only significant changes are at frequencies greater than 10 Hz; (2) vertical amplitudes are *decreased* by the "isolation"; and (3) horizontal amplitudes are *increased* by the "isolation." The greatest reduction in vertical vibration is about 11 dB; the greatest increase in horizontal is about 22 dB.

The decision whether to use an isolation joint must involve a consideration of whether the decrease in vertical vibration will offset the increase in horizontal vibrations. The difference between vertical and horizontal sensitivity varies from one type of equipment to another.

The usual reason for putting a joint in a slab is to isolate the "island" from vibrations generated on the slab nearby, such as those generated by a dropped hammer a meter or so away from a sensitive instrument. One may assess the performance of such a joint by means of a hammer test in which a spectrum of the response to a

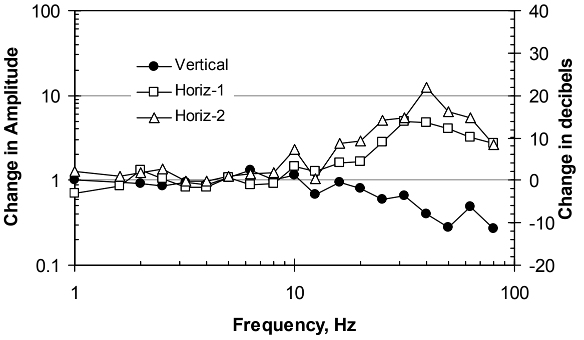

Fig. 4: Change in amplitude of the "isolated" slab with respect to the "solid" slab.

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[1] These are gaps in the slab, extending to its full depth, similar to an "expansion joint." It might be filled with a non-hardening filler, but the intent is to break the continuity of the concrete itself. There is no set term for a joint for which the intent is vibration control. The basis for placement is different from that of expansion joints.

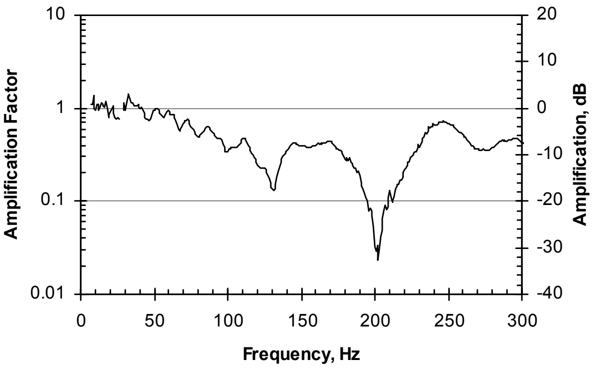

Figure 5. Change in amplitude provided by a joint in a 300mm slab-on-grade.

hammerblow at some distance in which the waves cross the joint is divided by the spectrum from a similar test without a joint. Figure 5 shows this spectrum using 1.4m paths in a 300mm slab, with and without a full-depth joint. (An amplification factor less than one represents attenuation.)

It is evident in Figure 5 that between 0 and 50 Hz, the attenuation is negligible; at 100 Hz it provides a reduction of only about 0.4, less than 10 decibels. The dip near 200 Hz is due to the measurement location (at a distance of 1.4 m from the hammer) being on a nodal line[2] of the resulting standing wave. The reduction at higher frequencies (other than that associated with nodal lines) is of the same order of magnitude. The assessment of whether this is useful enough to offset the increase in horizontal vibration due to the presence of the joint (discussed above) requires a case-specific judgment based upon the needs of the specific system of concern.

EFFECT OF A BUILDING

The literature contains several references to the building effect, but for the most part this is associated with propagation of train- or subway-generated ground waves into buildings, where the resulting structural vibrations generate audible sound. [5 Nelson] Thus, most of the attention has been focused on frequencies greater than 20 Hz. Very little representative data exist at frequencies less than 20 Hz, in the 6 to 15 Hz frequency range in which many sites have their predominant vibrations. The authors have carried out several studies attempting to document results of other forms of excitation and at other frequencies.

One study involved the vibrations generated by driving long piles into deep clay (Bay Mud) as new buildings were added to a research campus. The concern was that pile driving during construction of future buildings would degrade the vibration environment in the buildings already in use. The owner wished to have an assessment of the extent of that degradation.

One part of the study involved measurement of the transfer of site vibrations into a multi-story laboratory building, using the driving of test piles as the source. (A separate study was carried out to develop a site-dependent model for the attenuation of ground vibration with distance from the pile driver. Together, these two studies allowed a prediction of the impact inside the building as a function of both distance and the building effect.)

An attenuation factor quantifying the building effect may be obtained from the frequency response function dividing the motion at a point inside the building by that at a free-field location outside the building, between the source and the interior measurement location. Figure 6 shows the attenuation factor for horizontal vibrations, using two interior locations—the first floor and the fifth floor. Note the similarity to Figure 2, especially the manner in which the curves trend toward zero at low frequencies.

The behavior is quite different in the vertical direction, shown in Figure 7. The attenuation factor at low frequencies is much lower than in the horizontal direction, and doesn't show the same characteristic shape. This may be due to the fact that the building is supported on deep piles, tying together a very large bulb of soil.

Note also that the 1st floor spectrum shows amplification at 30 Hz, the fundamental resonance frequency of the floor slab. (This building does not have a slab-on-grade; there is a shallow crawl space beneath a thick slab.) The 5th floor spectrum shows similar resonance peaks at 18 and 25 Hz. All buildings exhibit this characteristic of amplifying ground motion in the vertical direction. However, with many advanced technology facilities the frequencies are higher because the structural components are stiffer. [10]

A major category of advanced technology facility contains those built for commercial fabrication of

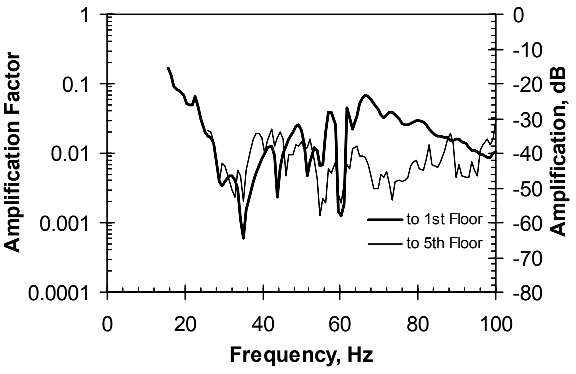

Fig. 6: Frequency response functions (FRFs) showing the amplification of the horizontal component of pile driving vibrations, outside the building to ground floor and to fifth floor.

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[2] A "nodal line" is the line on a vibrating surface that does not move during vibration in a particular deformed shape.

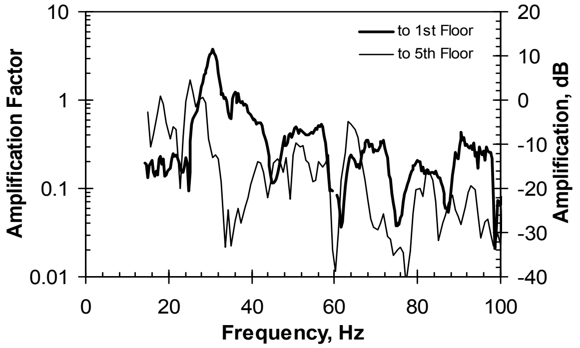

Fig. 7: Frequency response functions (FRFs) showing the amplification of the vertical component of pile driving vibrations, outside the building to ground floor and to fifth floor.

semiconductor products. Generally, these facilities are quite large and are usually very stiff for control of internally-generated vibrations. Concerns about the vibration effects of a proposed high speed rail line to be built near a major science park led to a study of vibration transfer into a typical building of this type. The results were used to adjust the free-field spectra predicted by others, allowing accommodation of the building effect into the final impact assessment.

This study was carried out using large rotating-mass shakers of the sort used to shake buildings and dams. Both horizontally and vertically inclined shakers were used. The shakers were used in open areas some distance from the building, simulating waves arriving from a distance. Large, deep foundation blocks were built to support the shakers. The shakers could only apply sinusoidal loading over a limited frequency range, and the dynamic force was dictated by frequency and rotating mass.

The study determined that the vertical attenuation between free-field and the elevated production floor was on the order of 0.3 times (10 dB) at frequencies between 4 and 8 Hz. Below this frequency range, the attenuation tended toward zero; above this range, the attenuation became very path-specific. In the horizontal direction, the attenuation depended upon whether the force axis and the receiver axis were along the same line or at some perpendicular distance. In the first case, the attenuation factor is between 0.4 and 0.14 (8 to 17 dB) at frequencies between 2 and 8 Hz, tending toward zero as frequency decreased. When the force axis was at some perpendicular distance from the measurement axis, the range of attenuation is about the same, but with the opposite slope, tending toward 0.1 (20 dB) as frequency decreased toward zero.

CONCLUSION

A phenomenon which might be called a “building effect” or “slab effect” has been presented, along with several demonstrations based upon field measurements. Attenuation factors as low as 0.1 may be obtained, depending upon the directional component under consideration. The presence of the effect depends upon the rigidity of the slab or foundation, and its ability to resist the deformations associated with a particular waveform. The extent of the attenuation depends in part upon the relationship between wavelength and the foundation’s dimensions.

Within limits, this process can be taken into account when designing facilities for vibration-sensitive processes, where vibration sensitivity must be considered over a wide frequency range. The process is more easily analyzed for horizontal vibration of a slab-on-grade, where the slab is approaches rigidity in the horizontal plane. The horizontal vibrations of a multistory building appears to exhibit behavior similar to the slab-on-grade. Vertical vibrations are more complex, as the stiffness in the vertical direction is not as uniformly distributed.

More work is needed to more thoroughly document the nature of the phenomenon in multistory buildings.

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