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# The design of low vibration buildings
## Two case histories

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Two case histories are presented that illustrate two aspects of the design problem. The first is entitled "The Role of Special Foundations in the Design of Low Vibration Buildings." The second is entitled "The Role of Sprung Floors in the Design of Low Vibration Environments."

## Case history I: The role of special foundations in the design of low vibration buildings

> Mention is made in the literature of methods that may be used to protect buildings from high vibration levels on the ground. These include the use of deep trenches (as barriers between the vibration source and the buildings) and of deep pile supports. In this case history, I discuss the concept of foundation design on the basis of our field experience.

It is normal practice when selecting a site for a building that will house vibration-sensitive equipment to carry out a survey of the ambient vibration conditions existing on the site. If the ambient conditions are too high in comparison with the selected design goal for the completed building, we will generally advise against the use of that site.

Some years ago we encountered a site on which the levels generated by heavily-loaded freight trains adjacent to the site generated levels that were very high compared with our previous experience. The levels generated substantially exceeded reasonable design criteria over the total site that lay between 200 and 1500 feet from the railroad.

The measured vibration levels are summarized in Fig. 1. In this figure we also show the levels that we might expect on more conventional sites. Although we advised strongly against the use of the site for the proposed facility, the owner of the land asked us to explore methods that might be used to protect a building from the ground vibration, or to reduce the effects of the ground vibration in some other manner.

It seemed clear that the reason that this site was so strongly influenced by the trains was that the water table, which underlay the site at a shallow depth (about 3 to 5 feet), was very cohesive--in effect, the soil was water-saturated and the ground propagation process was effectively that of propagation through water.

Alexander Major,[1] comments on the effect of the ground water table on the design of machine foundations. He says that care is necessary since "... ground water transmits vibration to a great distance without damping." He also recommends that machine foundations be raised above the water level by some distance to reduce the interaction between the source and the primary path of transmission.

We decided to explore this technique as it might be applied to the receiver rather than the source.

We decided also to explore the benefits that might be gained by supporting a building on deep piles, the concept being that ground vibration is a surface wave effect--just as ocean waves are surface waves. If the building effectively could be supported on the soil at some substantial depth, or better still from bedrock at depth, then lower vibration conditions could, perhaps, be achieved.

Tests were carried out on the site at a distance of about 1200 feet from the railroad. The test configurations are illustrated in Fig. 2. The test slabs in Configurations (a) and (b) measured 5 feet by 3 feet by 1-foot thick. The elevated slab [Configuration (b)] lay on an 8-foot-high mound of compacted structural fill. The concrete piles in Configurations (c), (d), and (e) were 14 inch by 14 inch in section. The 52-foot depth achieved in Configuration (e) represented the "refusal" limit of the pile driver. All measurements were carried out with the transducers aligned vertically.

The measured results with freight trains passing showed no significant difference between the vibration levels measured on each of the test configurations over the frequency range of 5 through 100 Hz. The dominant vibrational energy lay in the 8 Hz one-third octave band,

and this lay, at all locations, close to the 60 dB level--agreeing with our earlier experience, summarized in Fig. 1. Typical narrowband spectra are shown in Fig. 3.

The book "Vibrations of Soils and Foundations" by Richart, Hall, and Woods[2] shows how the vertical and horizontal components of Rayleigh waves--the primary type of surface wave--fall with increasing depth below the surface of the ground. A significant decrease below ground surface intensity does not occur until a depth of about one-half wavelength or greater. At 8 Hz--the predominant frequency generated by the freight trains--the Rayleigh wavelength is probably about 100 feet. The longest pile, therefore, just reached the point at which a significant reduction in groundborne vibrational energy might be expected to occur. Unfortunately, by the time that we had reached this depth the longitudinal stiffness of the pile was very much limiting its performance.

This study has also shown that an elevated foundation has little or no benefit to offer. Perhaps if we were able to lift the railroad out of the water table we would reduce the vibration problem. Clearly, this is not an acceptable option.

On the basis of these studies, our client decided to locate his facility elsewhere.

### Case history II: The role of sprung floors in the design of low vibration environments

> The concept of physically isolating a building, or part of a building, from the vibration environment existing in the ground, using springs, is one that has been raised, and occasionally used, by designers in the past. In this case history we illustrate the limitations in this concept.

Steel springs or pneumatic (air) springs are often used to protect a vibration-sensitive process from the vibration environment on which it rests. Most electron microscopes for instance are provided, by the manufacturer, with pneumatic mounts.

While this technique is a very useful (in many cases essential) means of vibration control for an individual item of equipment, it cannot be used, in our experience, as a means of isolating a complete building or laboratory or floor. The reason, of course, is that the external vibration environment is only one of several sources that can influence a building. The relatively low stiffness that is necessarily created by an isolation system will make the system susceptible to disturbance by walkers and by mechanical sources that directly act on it.

The problem was aptly illustrated in a study that we undertook in a building within which the designer had constructed an isolated floor, taking the form shown in Fig. 4. The area of the floor was about 1200 square feet. The intent was that this floor would carry the photolithography equipment (aligners, steppers, inspection microscopes, etc.)--typically the most vibration-sensitive equipment used in the wafer fabrication process.

The vibration data that we obtained in this facility are summarized in Figs. 5 through 8. At the time of our measurements, the facility was unoccupied, although the clean room supply fans and associated building services (pumps, chillers, etc.) were operating.

Figure 5 shows that for frequencies above 8 Hz the sprung floor may have certain advantages over the slab-on-grade floor, but only at certain frequencies. Overall, its performance for frequencies above 8 Hz is essentially equal to that of the unisolated floor. For frequencies below 8 Hz, its performance is substantially worse than that of the unisolated floor--exceeding BBN Criterion D for frequencies below 6.3 Hz.

Figure 6 shows that with walkers the disadvantages of the sprung floor are very substantial compared to the slab-on-grade floor--at all frequencies. In fact, the slab-on-grade floor is virtually unaffected by the presence of walkers.* The sprung floor is strongly affected--by about one order of magnitude on average (20 dB).

In Figs. 7 and 8 I show the narrowband spectra corresponding to the one-third octave band plots. In Fig. 7(a) we very clearly see the resonance response of the sprung floor at a frequency of 4.5 Hz. In Fig. 4(b), with walker excitation, we see the presence of additional resonant modes at frequencies of about 31 Hz, 34 Hz, and 51 Hz, associated perhaps with rocking of the slab. Figure 8 shows the fairly typical ambient and walker response of an on-grade slab that is stiffly supported and well damped by the dirt beneath. The walker has virtually no effect, and the floor shows no distinct resonances within the 0 to 100 Hz frequency range.

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*For these tests, three walkers walked continuously within 6 to 12 feet of the transducer at a rate of about 100 paces per minute. The average walker weight was 150 pounds.

To conclude this case history, let me briefly discuss the technical reasons why a spring-isolated floor or, for that matter, a spring-isolated building, is hardly feasible as a means of vibration control--unless the floor or unless the building can be kept clear of vibration sources, be they human, robotic, or mechanical.

Ungar and White3 have shown that the velocity response ($V_w$) of a lightly-damped floor to walker excitation can be expressed as:

$$V_w = C_1/kf_o \tag{1}$$

where $C_1$ is a constant determined by the weight of the walker and the rate of walking (steps per unit time), k is the point static stiffness of the floor, and $f_o$ is the fundamental (dominant) resonance frequency of the floor.

A typical floor design for a modern high-tech microelectronics facility might take the form of a deep waffle, cast-in-place, concrete floor, supported on columns arranged on a square grid at a separation of about 18 feet. This floor, cast monolithically with its supporting columns, would have a point stiffness of about $2 \times 10^6$ lb/in. and a loaded resonance frequency of about 30 Hz. The "$kf_o$ product" for use in Eq. (1) would therefore be about $6 \times 10^7$ lb/in.-sec.

Now let's assume that, in order to protect this floor from ground vibration, we inserted soft air springs between the floor and the tops of the columns. To provide positive and efficient isolation in the frequency range 5 through 100 Hz, it would be necessary to design the isolation system to have a resonance frequency of no greater than 3 Hz--an equivalent air spring deflection of 1 inch. The typical weight (dead plus live load) of our floor per column would be about 70,000 lb.

The stiffness of each air mount would therefore be about $7 \times 10^4$ lb/in. Assuming some stiffness contribution from adjacent mounts, it seems reasonable that the effective point stiffness of the floor might be about $2 \times 10^5$ lb/in. At the resonance frequency of 3 Hz, the $kf_o$ product would be $6 \times 10^5$ lb/in.-sec, two orders of magnitude less than for the unisolated floor.

At the completion of this study we recommended to the owners of the building that they pump grout into the cavity occupied by the springs. In this way, we argued, the effects of the springs would be eliminated and they would end up with a very thick and stable platform for their photolithography process. This, we believe, is what they did.

## References

1. Major, A., Dynamics in Civil Engineering, Vol. 1, Chap. 4, Akademiai Kiado Budapest 1980.
2. Richart, F. E., Jr., J. R. Hall, Jr., and R. D. Woods, Vibrations of Soils and Foundations, Prentice-Hall 1970.
3. Ungar, E. E. and R. W. White, "Footfall-Induced Vibrations of Floors Supporting Sensitive Equipment," Sound and Vibration, pp. 10-13. October 1979.

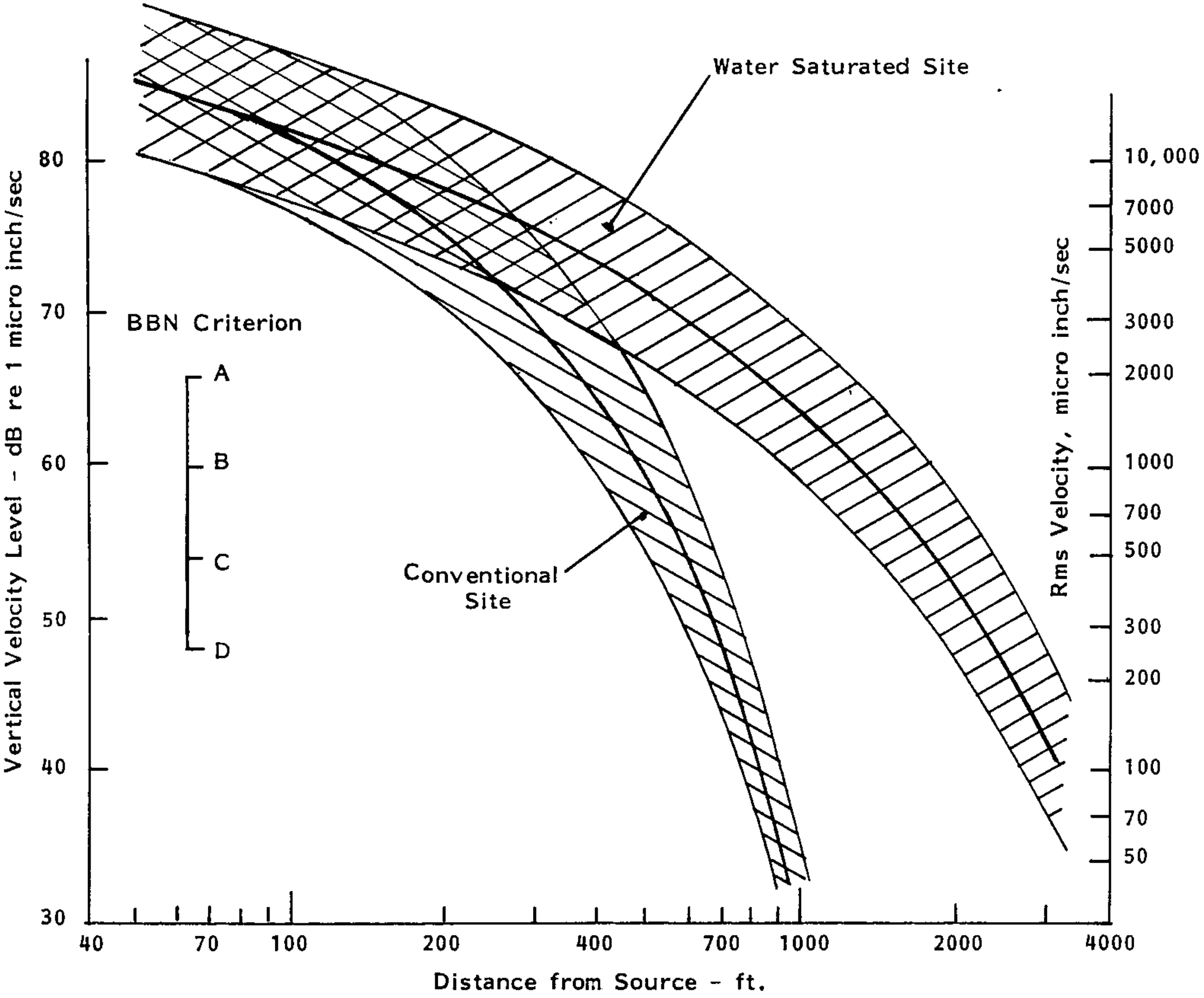


FIGURE 1. FREIGHT-TRAIN-GENERATED VIBRATION LEVELS VERSUS DISTANCE FOR WATER-SATURATED AND NORMAL SITES (IN DOMINANT 8 Hz ONE-THIRD OCTAVE BAND)

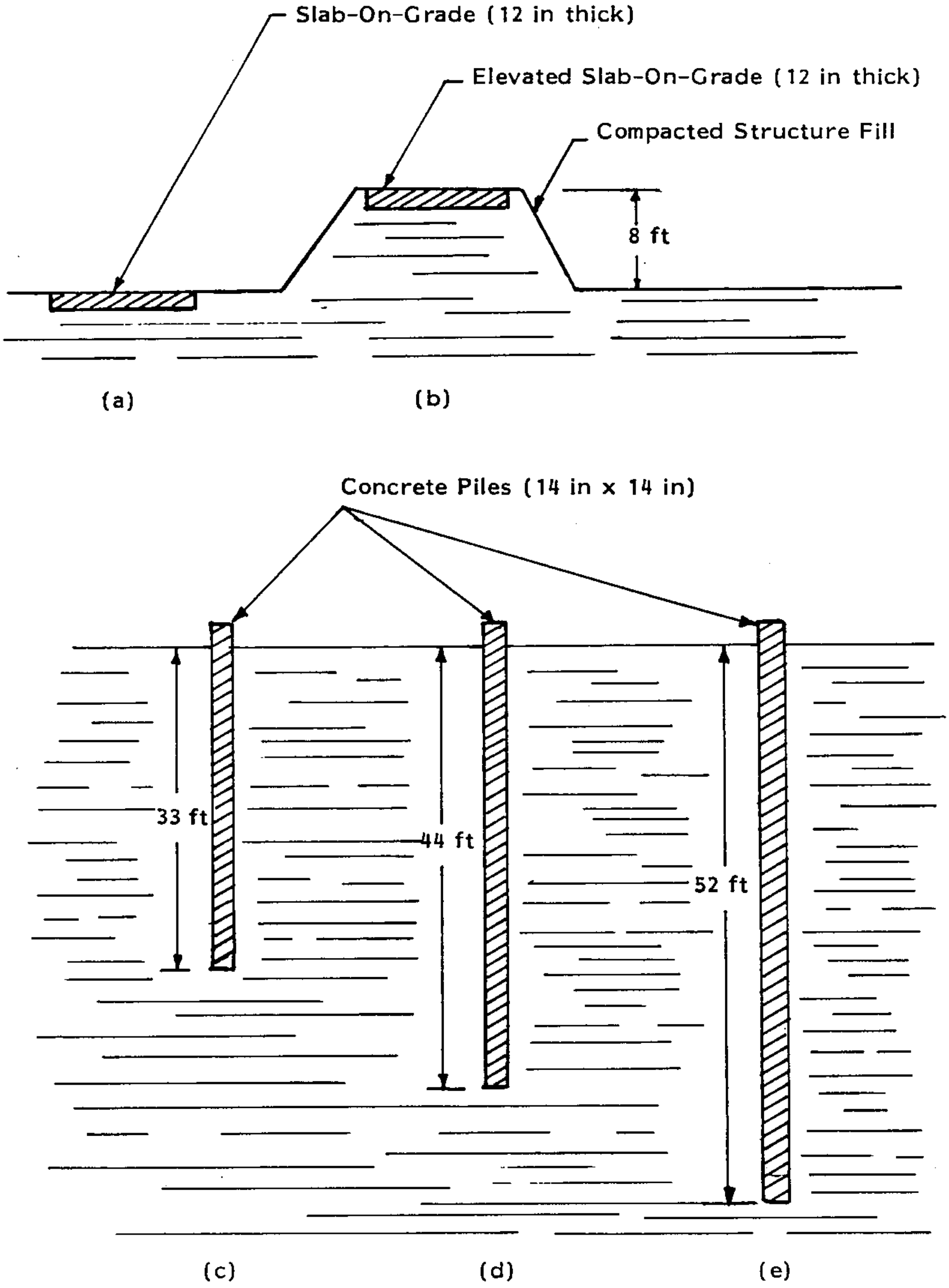


FIGURE 2. TEST CONFIGURATIONS USED IN VIBRATION STUDY

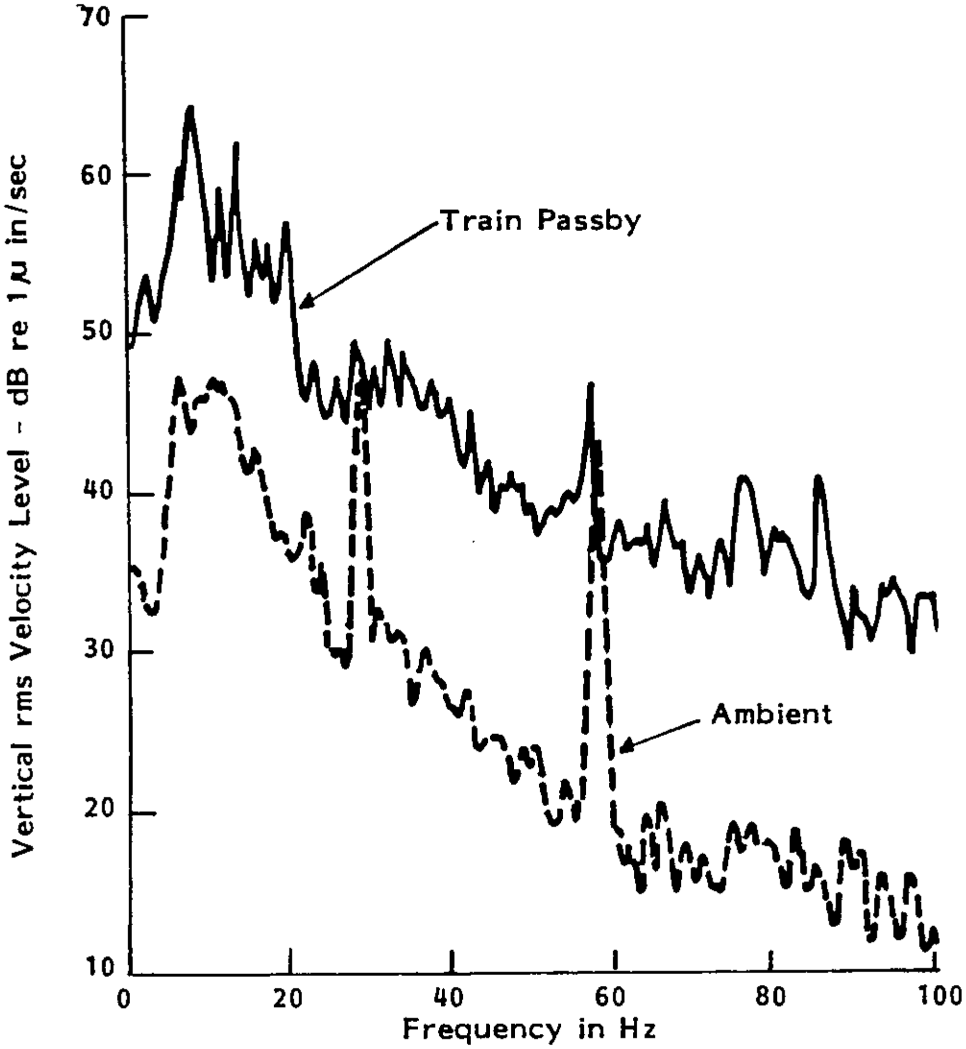


FIGURE 3. TYPICAL SPECTRA GENERATED AT 1200 FT FROM RAILROAD WITH AND WITHOUT TRAIN PASSING. (Bandwidth = 0.9 Hz)

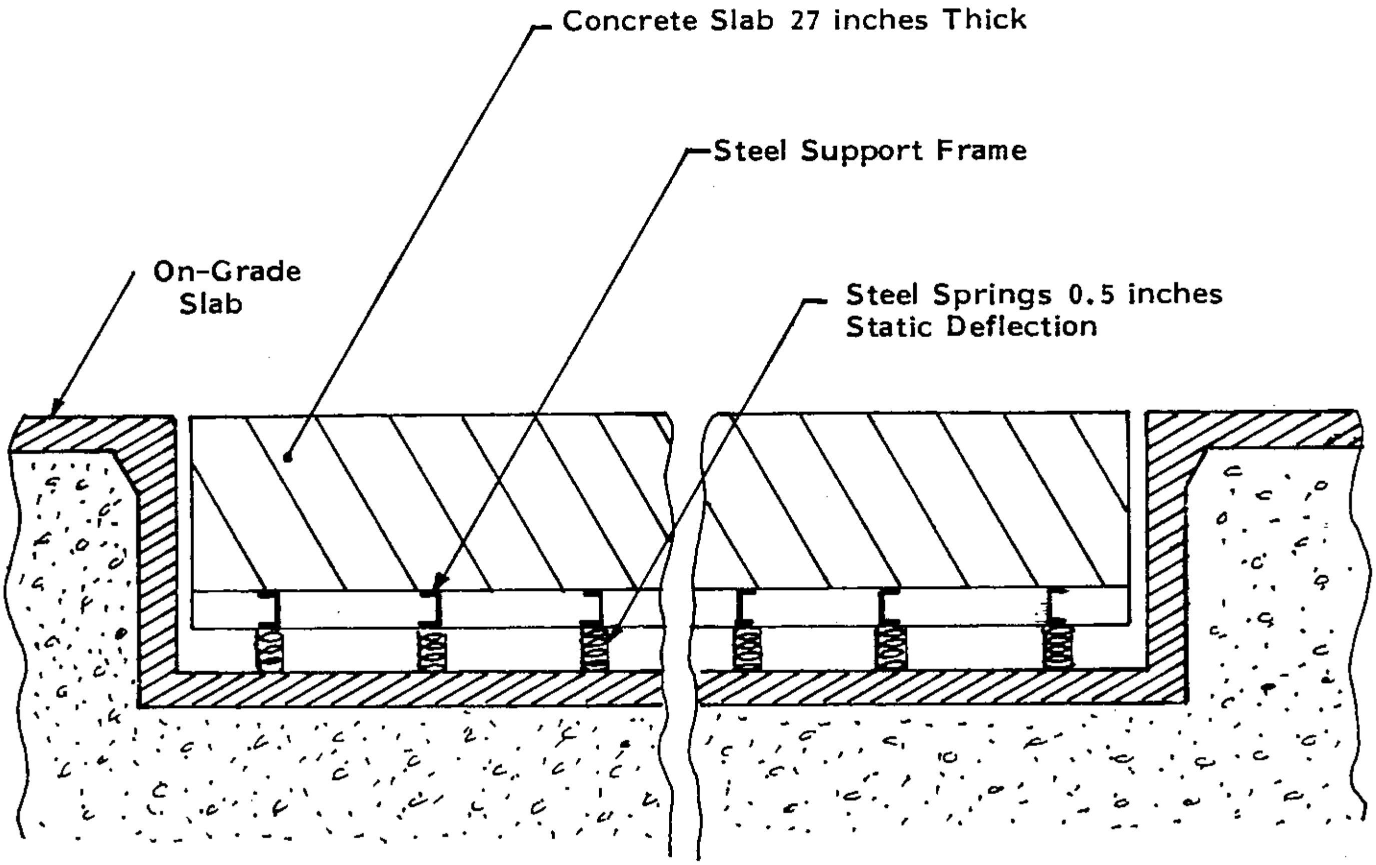


FIGURE 4. SECTION THROUGH VIBRATION ISOLATED CONCRETE SLAB

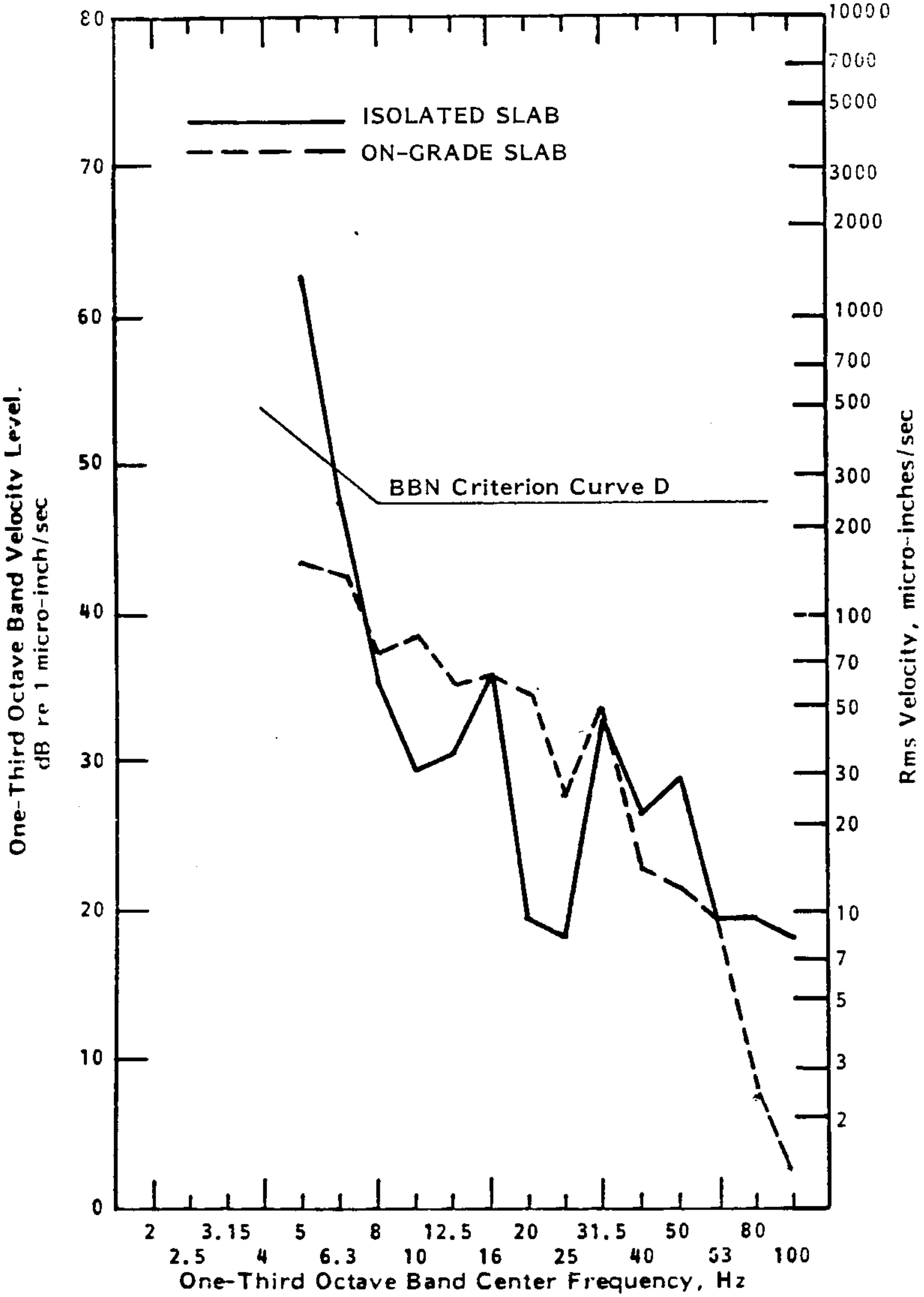


FIGURE 5. AMBIENT VERTICAL VIBRATION ON ISOLATED SLAB AND ON ADJACENT ON-GRADE SLAB (One-Third Octave Band Energy Average)

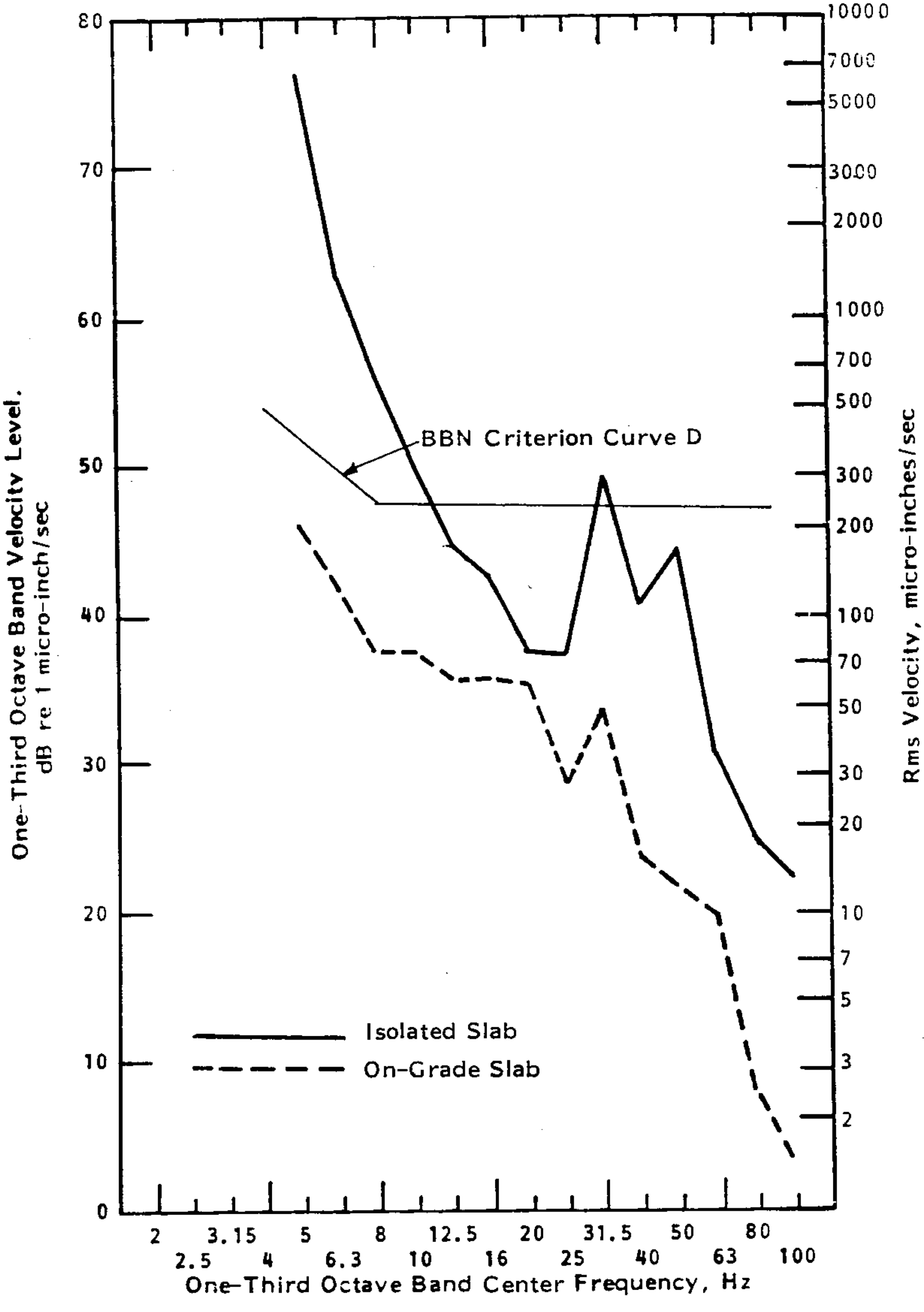
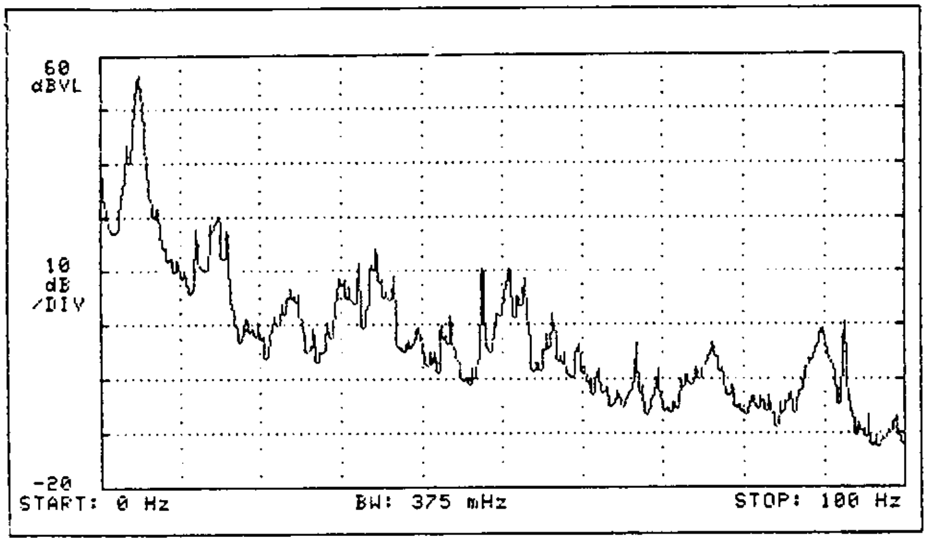
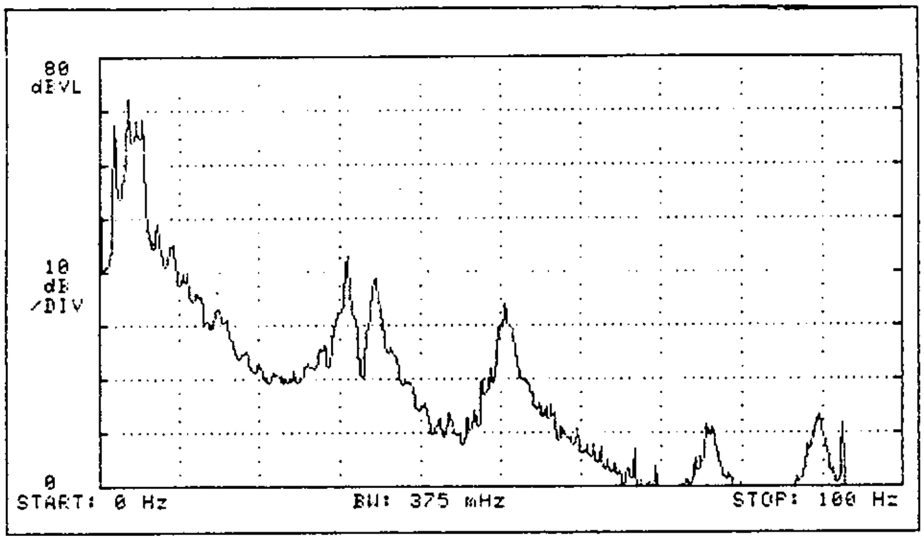


FIGURE 6. WALKER-INDUCED VERTICAL VIBRATION ON ISOLATED SLAB AND ON ADJACENT ON-GRADE SLAB

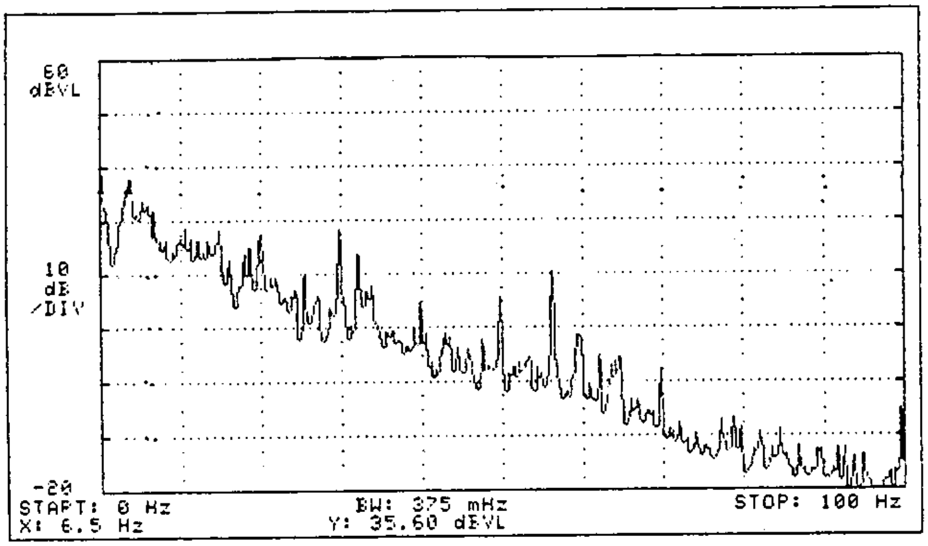


(a) AMBIENT

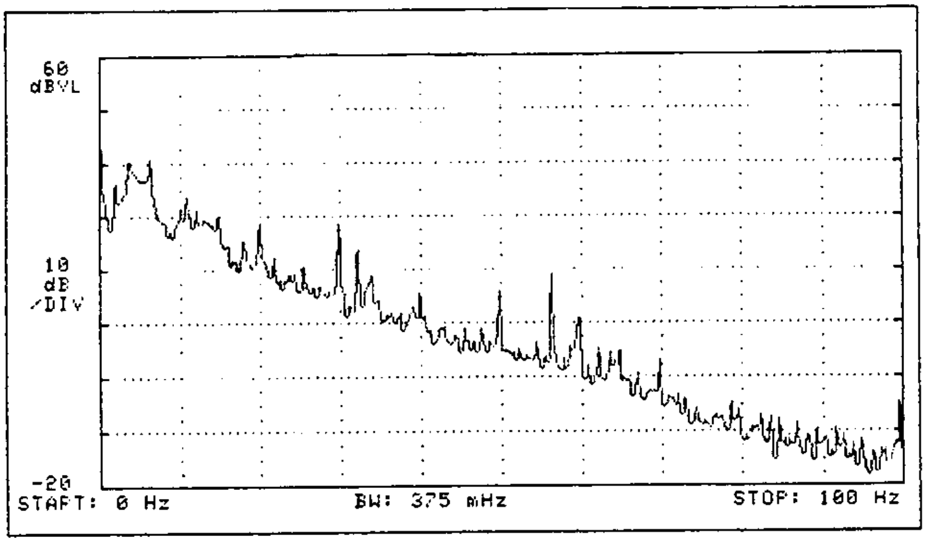


(b) WALKERS

FIGURE 7. AMBIENT AND WALKER-INDUCED VERTICAL VIBRATION ON ISOLATED SLAB (Narrow Band Energy Average - 0.375 Hz Bandwidth)



(a) AMBIENT



(b) WITH WALKERS

FIGURE 8. AMBIENT AND WALKER-INDUCED VERTICAL VIBRATION ON-GRADE-SLAB (Narrow Band Energy Average - 0.375 Hz Bandwidth)