Effects, detection, and mitigation of voids beneath slabs-on-ground

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A slab that is in solid, uniform contact with the subgrade does not usually exhibit a significant (high-Q) resonance, and the stiffness is relatively constant in frequency. There tends to be very little resonance response to impact loading, such as footfall. However, if there is a void of significant horizontal dimension beneath the slab, it will typically result in a resonant system, the frequency of which depends upon the horizontal extent and support conditions around the void. Footfall excitation of a slab over a void will be much more severe than without the void, and may cause problems if the floor is to support vibration-sensitive equipment or processes. The resonance frequency is observable using an impulse response test. The void may be corrected using several methods of injection. The paper examines several case studies in which voids were identified, characterized, and repaired, presenting data and methodologies.

1 INTRODUCTION

A concrete slab-on-ground[*] is one of the most popular of all floor types for many applications, especially research facilities, where, of various options, they usually may be designed to provide the best floor vibration environment. Because they are stiff and uniformly supported, they do not exhibit the resonance characteristics of a suspended slab. As a result, they are much less responsive to footfall.

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[*] Although many people use the expression “slab-on-grade”, the term preferred by the American Concrete Institute is “slab-on-ground”.

Occasionally, the quality of a slab-on-ground is degraded because the slab separates from the subgrade, leaving a void. This can occur due to either deformation of the slab during construction or deformation of the subgrade after construction.

If a void is of large horizontal area, the floor will take on the characteristics of a suspended floor, exhibiting resonance and becoming more responsive to footfall and mechanical excitation. In a laboratory space, this could render the floor unfit for the lab equipment supported on it. Separation from the soil can also weaken the floor and lead to cracking.

The effects of a void may be mitigated by filling the void with grout or a high-density foam, either of which will harden and replace the missing subgrade material. The horizontal extent of the void can be detected using impulse response measurements, and the efficacy of the injection can be documented using similar measurements after the mitigation.[1] This paper presents the results of several projects in which these methods were used successfully.

2 DYNAMIC CHARACTERISTICS OF A SLAB-ON-GROUND

A slab-on-ground may be considered a plate on an elastic foundation, assuming that both the plate and the soil are elastic and contribute to the dynamic properties of the system. When a vertical point load is applied to the center of a slab, it will deform downward in a dish shape with the maximum deflection occurring beneath the load. The local reaction pressure of the soil against the underside of the slab will be a function of the deflection in that vicinity. It has been shown that the reaction pressure of an elastic foundation beneath a plate is associated with its *modulus of subgrade reaction*, a property of the soil.[2]

Situations arise in which it is necessary to document the proper placement or maintenance of a slab on the soil, validating good contact with the subgrade or detecting the presence of voids.[1] In other instances, it is necessary to predict the behavior of a slab on soil in response to vibratory loading. Experimental modal analysis (EMA) provides the tools for such measurements, but has not yet seen a great deal of usage in civil engineering, though it is quite commonplace in other disciplines.[3] Its most frequent current usage in civil engineering appears limited to the measurement of foundation stiffness and for evaluation of concrete properties.[4, 5, 6, 7, 8, 9] It is more commonly found in research settings than in day-to-day construction and evaluation in the field.

We have observed in our research that a slab that is in solid, uniform contact with the subgrade does not usually exhibit a significant (high-Q) resonance, and that the stiffness is relatively constant. A void of significant horizontal dimension, however, will result in a significant resonance, the frequency of which will depend upon the slab thickness as well as the horizontal dimensions and edge conditions of the void. We have observed that these resonance frequencies, when meaningful in the sense that degradation of an advanced technology vibration environment is created, typically fall between 20 and 50 Hz. This resonance behavior is observable using certain types of dynamic measurement techniques.[1] Similar measurements may be used to document the efficacy of repairs.

Mobility is one of several frequency-dependent representations of response available using modal analysis. It represents, in the form of a spectrum, the velocity of a location on a structural system or component in response to an applied force. In the case applicable here, it represents the measured velocity spectrum of a slab responding to a hammer blow, divided by the measured force spectrum associated with that blow. Figure 1 shows a set of mobility spectra measured near the edge of a well-supported 300mm thick slab-on-ground and at several distances from that edge. The spectrum maintains the same shape, but shifts downward, indicating that the stiffness is increasing, but otherwise the dynamic behavior remains unchanged. The peak at 93 Hz appears to be a heavily damped resonance associated with the free edge of the slab. There are no other resonances evident.

3 VOIDS

Occasionally, the performance of a slab-on-ground is degraded because the slab is separated from the subgrade soil, leaving a void. If this void is of large horizontal area, the floor will behave more like a suspended floor, exhibiting resonances and becoming more responsive to footfall and mechanical excitation. In a laboratory space, this could render the floor useless, as discussed in a subsequent section. Also, in some settings, separation from the soil might weaken the floor construction and lead to cracking of the slab.

A void can form for a number of reasons, including curling or subgrade settlement. Settlement may be due to non-uniform compaction, and can easily occur in the backfill to retaining walls, particularly if there is wall movement. Voids can also be produced when water flows horizontally beneath the slab, washing away the subgrade.

We characterize the simplest voids as “interior” or “exterior” depending on the relative location of the void with respect to the bearing area. These are defined schematically in Figure 2 and Figure 3, respectively. A slab with an interior void behaves as a suspended slab, supported at its edges, with one predominant resonance frequency. A system with an exterior void behaves as a cantilever spanning outward from the edge of the supported area. There will likely be multiple resonance frequencies.

4 RECOGNIZING VOIDS

The presence of a void may not be readily apparent visually. Because of their nature, interior voids tend to be invisible. However, voids arising due to curling may exhibit some clues, as indicated in Figure 4, which shows two abutting 300mm thick slabs beyond a joint separating them from a 125mm thick corridor slab. At the time the slabs were poured, they were finished to a stringent flatness tolerance. After curing, at the time the photograph was taken, there was a “step” at the near edge of the far slabs at the intersection, with a vertical separation of about 10mm. There is a much smaller step between the two 300mm slabs, but it is less obvious because of the cracking, which occurred when a construction fork-lift drove over that spot and the corner fractured. These slabs had curled into a “dish” shape—lower at the center than at the four corners. This was confirmed by a careful survey with instruments resolving to less than a millimeter in elevation.

Curling can also occur along an interior shrinkage crack. The vertical height of the resulting void may only be a few millimeters, and may not be evident with a straightedge. However, this void—and the ones discussed in the previous paragraph—are all clearly evident with impulse tests using an instrumented hammer and measuring the slab response.[10]

Figure 5 shows drive point mobility spectra measured at two locations on a slab with an interior void. Figure 6 shows a similar pair of spectra from a slab with curling, which produces an exterior or perimeter void. The spectra measured over voids differ considerably from those measured where there is solid support. The mobility spectra above voids clearly demonstrate the presence of resonance peaks. The spectrum for the interior void (Figure 5) exhibits a single peak (31.3 Hz), but the exterior void (Figure 6) exhibits several peaks (the first two being at 23 and 35 Hz). The multiple peaks tend to be present with the exterior void because of the complexity and irregularity of the perimeter cantilever structure, but a relatively simple interior void tends to have a more simple pattern of modeshapes.

5 EFFECT OF VOIDS

The presence of a void beneath a slab may lead to an increase in vibrations, particularly those due to footfall. Figure 7 shows the floor plan of a laboratory on a single 300mm slab, approximately 8 x 8m in area. The measurement locations shown (186 and 188) are just two of many on this slab used to identify the void area, and are used here for illustration. The hammer test results from these two locations are shown in Figure 6, in the form of mobility spectra.

Ambient and footfall vibrations were measured at the two locations shown as well as the hammer test measurements reported in Figure 6. Footfall was induced by a 100kg person walking at 85 paces per minute (ppm) and passing approximately 600mm from the sensor. The ambient measurements were processed using both linear average (LA) and maximum hold (PH) signal processing. The footfall was measured using maximum hold (PH) processing.

Figure 8 shows the vibrations measured at Location 188, on the solidly supported portion of the slab. (The mobility should be read on the right axis; all other data refer to the left axis.) All of the vibration, including footfall, is less than VC-F.[11] The maxima are summarized in numeric form in Table 1. There are no resonances evident in the mobility spectrum. The peaks in the 50 Hz band of the ambient spectra are tonal and due to mechanical equipment.

Figure 9 shows the vibrations measured at Location 186, on a portion of the slab near the edge and cantilevered over the void. All of the vibration, including footfall, has increased in amplitude. Some of this increase is due to the nearness of the edge, but most—particularly that associated with footfall—appears to be due to the cantilever support. The maximum vibration due to footfall is approximately VC-C.[11] (The maxima are summarized in numeric form in Table 1, which also gives the ratios between the two sets of measurements.) There are multiple resonances evident in the mobility spectrum, one of which aligns with the peak in the footfall spectrum and one which aligns with the peaks in the 31.5 and 50 Hz bands of the ambient spectra, increasing the potential for response to the tonal vibrations due to mechanical equipment.

The last two columns of Table 1 provide a comparison of similar measurements at the two locations. It should be noted that the increase in footfall vibration amplitude is similar to the increase in mobility at the apparent resonance frequency of the slab over the void—about an order of magnitude in this instance, or two and half VC classes.[11] While this relationship is not precise, we have observed a consistency in this behavior.

Figure 10 shows footfall and mobility data for a 150mm slab with a perimeter void. The numeric data are summarized in Table 2. Footfall vibration on the solidly supported slab approximately meets VC-E, but over the void, the amplitude of 60 μm/s exceeds VC-A. As with the 300mm slab, the maximum footfall response over the void coincides with the resonance frequency shown in the mobility curve, the same behavior exhibited by a suspended floor.

Figure 11 shows the footfall response on the 150mm and 300mm slabs, along with the max-hold ambient vibration. Both slabs are underlain by identical subgrades, and the same walker and pace rate were used. The spectrum shapes for the footfall vibration are quite similar, differing by between 6 and 8.5 dB at nearly all frequencies, resulting in VC-E and VC-F performance. This suggests that the amplitude of footfall vibration of a slab-on-ground varies with the slab stiffness parameters. On the other hand, the response is spread over a wide range of frequency, rather than being concentrated near a resonance frequency as evident in a suspended floor.

6 DEFINING A VOID

The impulse tests will suggest the presence of a void, but will not define its vertical dimension. This can be established by one or more cores in the slab and then measuring the distance the core moves into the hole after the drill is removed. This also serves as a positive confirmation of the presence of a void. (If there is no void, the top of the core will remain at the same elevation as the surrounding slab.)

In order to plan the remediation, it is desirable to know the location of the interior edge of each void. This can be found by using hammer tests to find where the resonance disappears and the slab becomes supported on soil. In the case of a void of unknown shape, a grid pattern can be used for investigation. If a perimeter void is suspected, the protocol can be simplified. In the case of the slabs in Figure 4, we progressed around the edge of each slab, performing hammer tests at about 12 positions (such as those shown conceptually in Figure 12), working from the edge toward the middle until the resonance peaks just disappeared. At that point, we indicated the "edge" by means of a paint mark sprayed on the slab. A typical sequence of mobility spectra from one position (Position 7 in Figure 12) is shown for a 150mm slab in Figure 13.

At the end of the exercise, the marks were connected, defining the perimeter of the bearing area. Cores were drilled near the corners to determine the height of the void. Estimating the volume of the void was a simple geometric exercise.

7 REPAIR OF VOIDS

As discussed above, the primary adverse vibration effects of a slab-on-ground with a void are associated with the decrease in stiffness and the resonance response to footfall loading. If the stiffness can be returned to normal (or nearly so) and the resonance eliminated, perhaps by filling the void, the problem can be resolved. We have successfully employed two approaches to void filling, and will discuss both of them below.

Both approaches involve drilling injection holes on a grid spaced about 450 to 600mm apart. If the void is along the edge of the slab (as is often the case with curling) then the closest holes should be that distance from the edge. The holes serve multiple purposes. Other than serving as an injection path, they vent air and filler material from the void as it fills and allow observation of the progress of the filler away from an injection hole.

Cementitious Grout: Fly ash-cement grout can be pumped into the void via the core holes, one hole at a time. The grout should be tested on site and should exhibit an efflux time of 10 to 15 seconds when flowing through a standard flow cone in accordance with ASTM C939.[12] When the pressurized grout has traveled to adjacent holes and returned up towards the surface, those holes may be plugged. This will allow the grout to migrate to other holes. After completion, all holes may be patched with a non-shrink high strength grout.

Expanding Polymer Foam: The void filling can also be accomplished using a two-component thermoset urethane expanding foam system specifically designed for concrete jacking and cavity filling in wet environments. The minimum apparent density, compressive strength, and compressive modulus should be on the order of 50 kg/m^3 (3 lbs/ft^3), 200 kPa (30 psi), and 10 Mpa (1500 psi), respectively, using test method ASTM D 1622.[13] The dimensional stability should allow less than 2% change over the full range of operating temperatures of the space, based upon test method ASTM D 2126.[14]

With either method (but perhaps moreso with polymer foam because it tends to expand) there is a risk that excessive pressure can fill the void but also lift the seated slab off the soil, creating a new void. It is advisable to try a trial injection, and then verify with hammer testing that the slab did not lift off. If it did, the pressure or methodology can be adjusted on subsequent injections. Once the initial injection has cured, the new void can be filled.

It seems intuitive that the grout injection would provide adequate stiffness, because its material properties can be similar to the concrete slab it will support. The same cannot be said of the foam. Its modulus and density are only small fractions of that of the concrete. The stiffness components—mechanically in series—are combined as the sum of the inverse of the stiffness of the individual components. In most cases, the injected layer is quite thin in the compressive (vertical) direction, so the flexibility (compliance) contribution is quite small.

The efficacy of the repair may be checked as the repairs proceed by testing the slab at repaired locations to verify that the resonance peak has been eliminated. We have found that this can be carried out rather quickly using a simple rubber mallet and obtaining only narrowband velocity spectra, rather than carrying out the more detailed mobility tests.

8 CONCLUSION

The formation of voids beneath concrete slabs-on-ground can cause degradation of their ability to resist dynamic loading, particularly footfall. There are several possible reasons for void formation, and details of those mechanisms are beyond the scope of this paper. However, voids can be detected using routine tools available to the vibration engineer, and then can be eliminated without removal of the slab.

This paper has demonstrated—using measured field data—the characteristics of slabs without voids as well as of slabs with exterior and interior voids. The adverse effects on ambient and footfall vibrations have been illustrated. Two approaches to mitigation—cementitious grout and expanding polymer foam—have been presented. It suggests a relationship between slab thickness and footfall response which appears to warrant further investigation.

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Table 1. Summary of measured maxima on 300mm slab with curling.

Quantity	Solid Support (Location 188)	Over Void (Location 186)	Ratio (186/188)	Increase (dB)
Maximum LA Ambient, µm/s	0.20	0.85	4.3	13
Maximum PH Ambient, µm/s	0.36	0.61	1.7	5
PH Ambient at 31.5 Hz, µm/s	0.19	0.85	4.5	13
PH Ambient at 50 Hz, µm/s	0.25	0.41	1.6	4
Maximum Footfall, µm/s	1.60	13.4	8.4	18
Maximum Mobility, m/s/N	2.94E-07	3.04E-06	10.3	20
Mobility at 22.6 Hz, m/s/N	2.27E-07	1.76E-06	7.8	18
Mobility at 35.1 Hz, m/s/N	2.62E-07	3.04E-06	11.6	21
Mobility at 50 Hz, m/s/N	2.43E-07	1.39E-06	5.7	15

Table 2. Summary of measured on 150mm slab with curling and a perimeter void.

Quantity	Solid Support (Location 5)	Over Void (Location 1)	Ratio (1/5)	Increase (dB)
Footfall at 2 Hz, µm/s	3.3	34.1	10.3	20
Footfall at 16 Hz, µm/s	2.2	37	16.8	25
Footfall at 25 Hz, µm/s	2.1	60.1	28.6	29
Mobility at 17.2 Hz, m/s/N	5.36E-07	5.40E-06	10.1	20
Mobility at 26.6 Hz, m/s/N	6.75E-07	7.87E-06	11.7	21

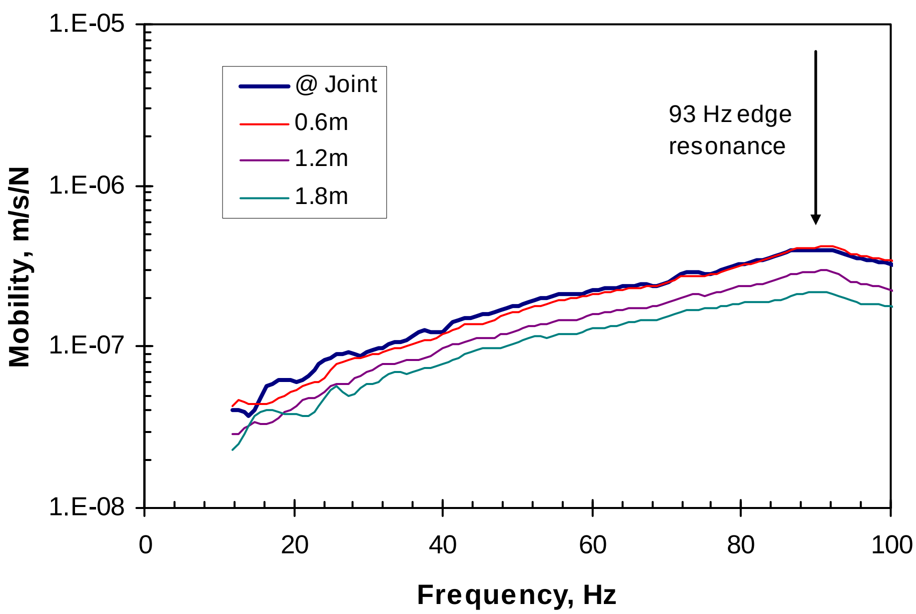

Figure 1. Drive point mobility at several locations at and moving away from the edge of a 300mm thick concrete slab-on-ground.

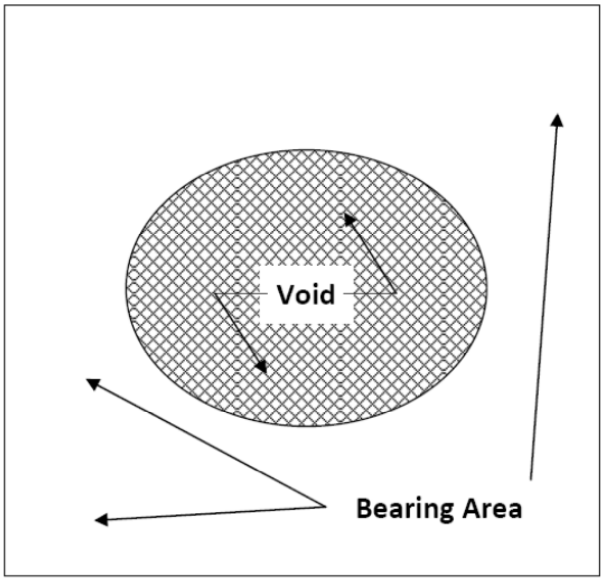

Figure 2. Representative "interior" void pattern, generally due to settlement.

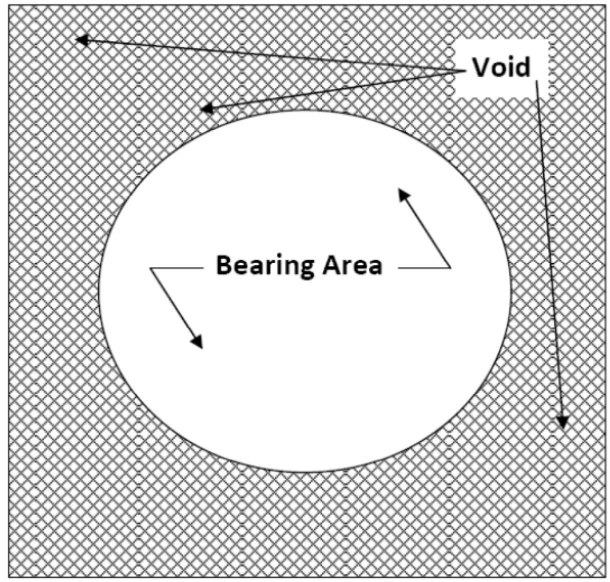

Figure 3. Representative "exterior" void pattern, generally due to curling.

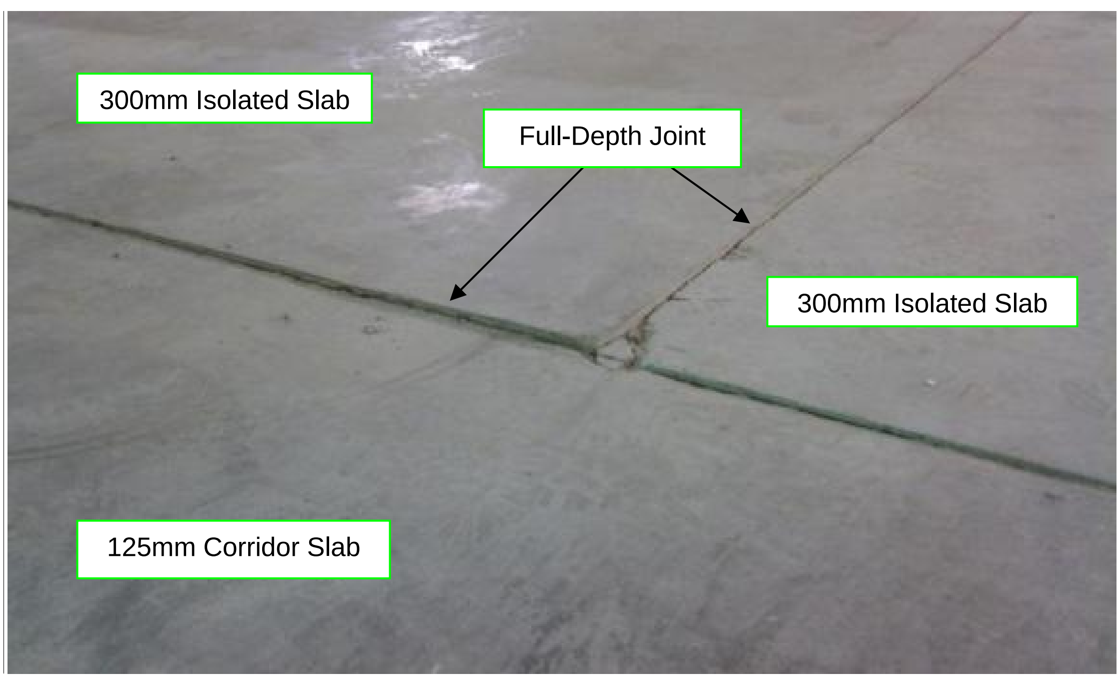

Figure 4: Differential movement and cracking in slabs with curling.

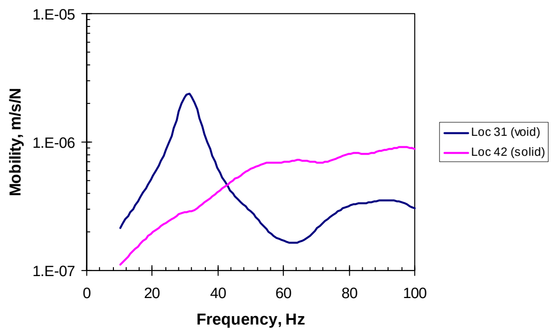

Figure 5. Measured mobility on 300mm slab with interior void.

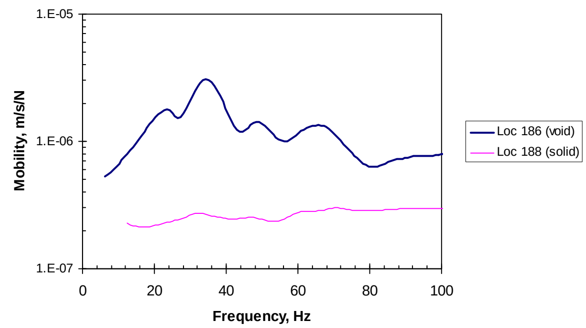

Figure 6. Measured mobility on 300mm slab with perimeter void due to curling.

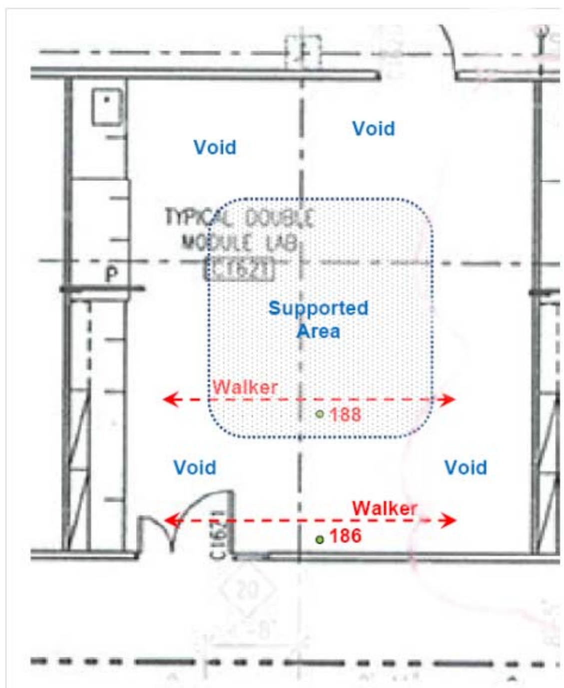

Figure 7. Walker paths and measurement locations on 300mm slab.

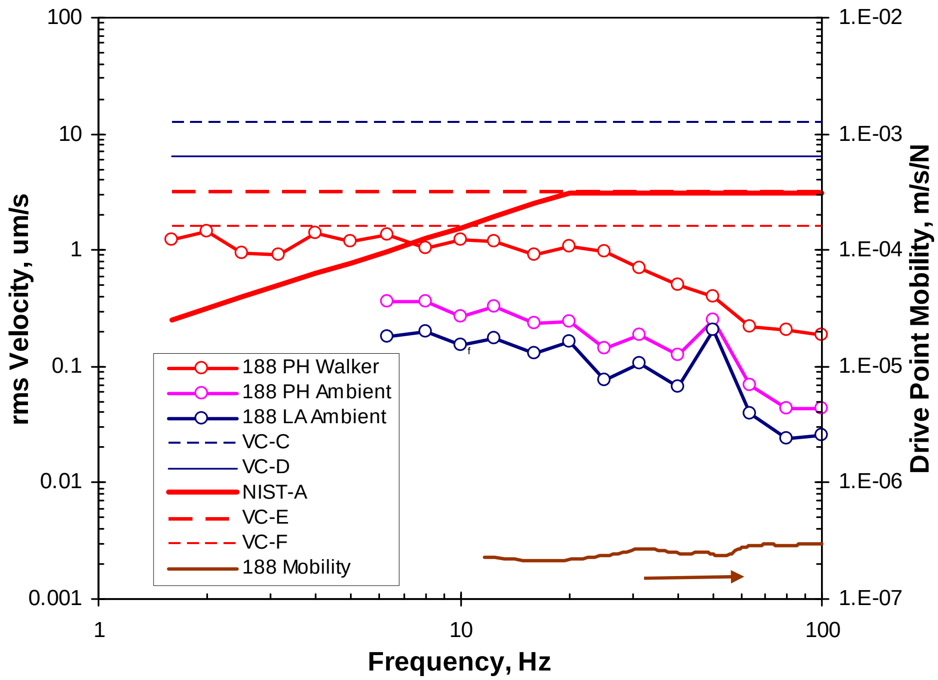

Figure 8. Vibrations measured at Location 188, on 300mm slab with solid support. (Criteria are discussed in Ref. 11.)

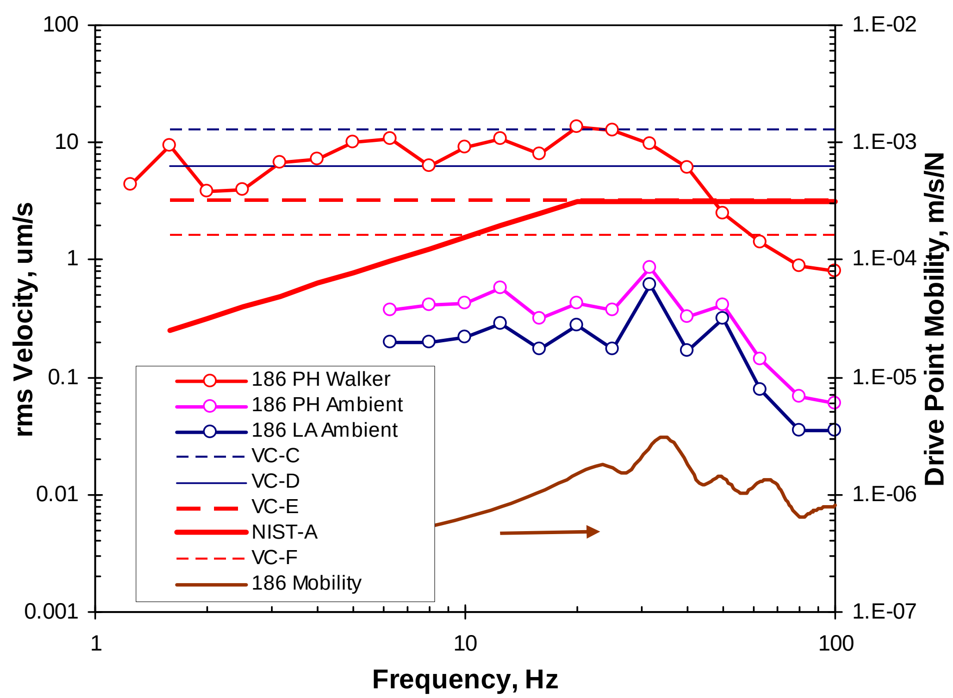

Figure 9. Vibrations measured at Location 186, on 300mm slab cantilevered over a perimeter void. (Criteria are discussed in Ref. 11.)

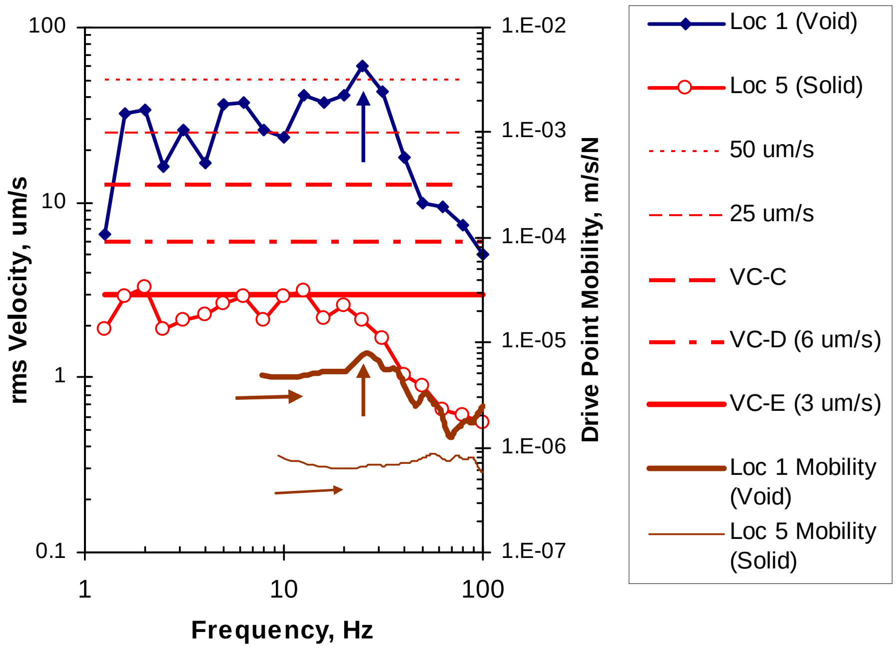

Figure 10. Vibrations measured at Locations 1 and 5, on 150mm slab with a perimeter void. (Criteria are discussed in Ref. 11.)

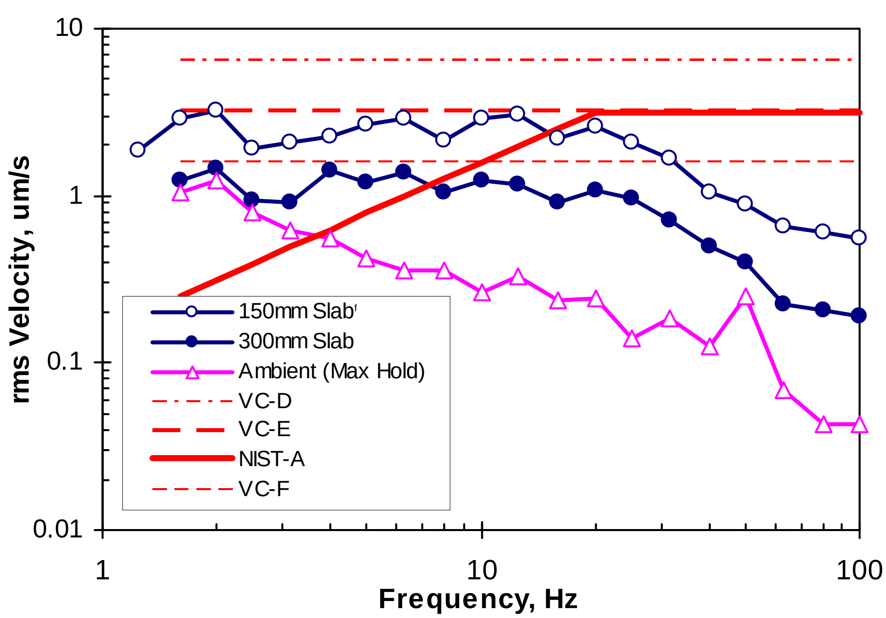

Figure 11. Footfall vibrations measured at Locations 188 and 5, on 300mm and 150mm slabs, respectively, resting solidly on identical subgrades. (Criteria are discussed in Ref. 11.)

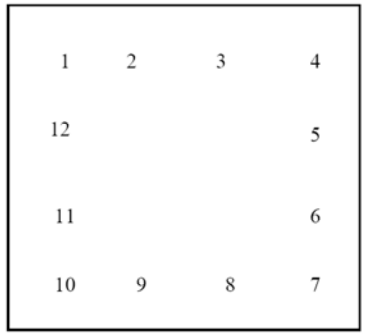

Figure 12. Typical hammer test pattern for curling.

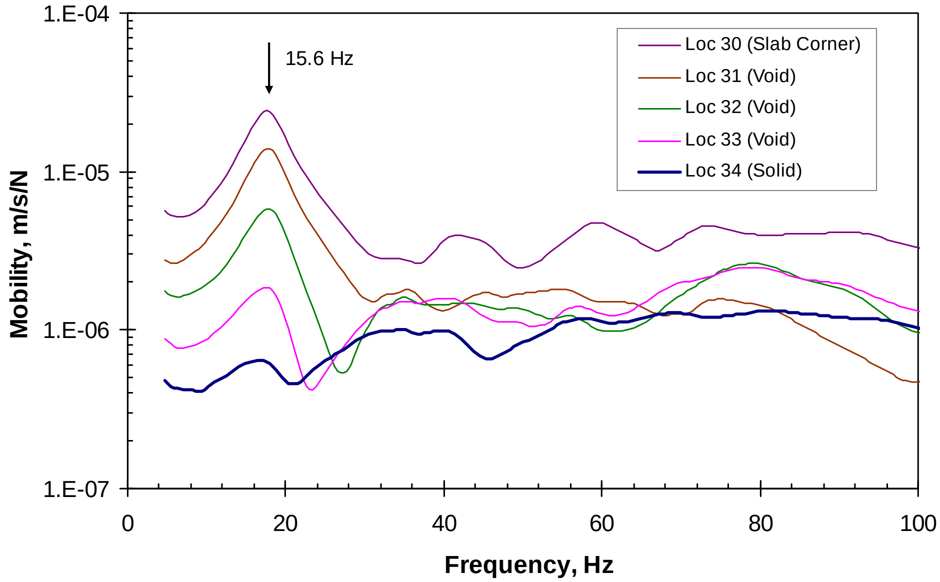

Figure 13. Series of mobility measurements on a 150mm thick slab, starting at corner and moving toward center from position 7 in Figure 10.