Coping with Construction-Related Noise and Vibrations

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Overview of Potential Concern

Noise and vibration associated with construction at Colleges, Universities, Hospitals and other research institutions often has the potential to adversely affect sensitive equipment in nearby buildings. A recent example of this is the New Laboratory Science Building at UMass which is situated near a number of animal and science buildings. The UMass project will be used as a case study to illustrate some important concepts related to construction vibration and noise.

Construction Vibration Considerations

The common concern related to construction vibration is building damage. In the 1960's and 70's the US Bureau of mines conducted a number of studies to try to determine safe levels of vibration due to blasting. The studies suggested that minor cosmetic damage (cracking plaster etc.) could be avoided if the ground vibrations at the structure were limited to 0.5 to 2.0 inches per second. Construction projects typically adopt criteria that are somewhere in this range.

The potential impact of construction vibration is not just limited to damage-level vibrations. It is possible that neighboring buildings could contain sensitive operations and equipment that are affected by vibrations well below the "building damage" level, perhaps three orders of magnitude lower, on the order of 500 micro-inches per second.

Even though construction is temporary, the user might not be able to tolerate being "put out of business" for even a few months. Particularly in a university setting, many research grants are tied to progress milestones and long disruptions can have significant funding implications.

Criteria for Sensitive Equipment and Animals

Many items of sensitive equipment have very detailed and specific vibration criteria. Usually these are frequency dependent and reflect the fact that instruments are more sensitive to vibration at some frequencies than others. Criteria are often expressed in varied units; acceleration is typical for MRIs whereas displacement is common for electron microscopes.

Unfortunately, early in the design process the building owner often does not know what specific equipment will be housed in the building. To help the design process, in the 1980's a set of Vibration Criteria (VC) curves were developed to help define classes of vibration sensitive equipment. These VC curves in turn were used to design vibration sensitive facilities. The VC curves are still widely used today, for example, 2000 micro-inches per second is a common criterion for general lab spaces.

Unfortunately, vibration effects on animals are not well understood. For design purposes, NIH recommends that the vibration levels in animal spaces be limited to 2000 micro-inches/second, but provide no guidance on accepted "safe" levels in animal spaces during construction. For construction projects where vibration is a concern, acceptable levels are often developed on a case-by-case basis using measurements of normally-occurring sound and vibration (normal daily levels without construction).

Typical Vibration Concerns

The greatest vibration and noise is typically generated during the excavation process. When comparing the levels generated at a distance of 25 ft from the equipment, blasting and impact pile-driving produce the most vibration (near 1 in/second). Most equipment produces vibrations above the threshold of perception which means that most people would be able to feel the vibration at 25 ft.

Analytical Prediction Method for Blasting

Prediction of blast vibration is well understood. Ground vibration depends on the charge size, the distance from the blast, and the rock propagation characteristics according to the equation:

$$V(in/s) = 242\left[\frac{\sqrt{W(lb)}}{D(ft)}\right]^{1.6}$$

where W is the weight of the charge and D is the distance to the blast site. "242" is a typical ground propagation constant, but blasters will often adjust this based on data from test blasts at the actual construction site. Blasters also ripple fire the charges to reduce vibration. The reason for this is that if the charges are separated by more than 8 milli-seconds, then can be considered as separate events. For example, rather than firing 10 lb all at once, it is much better to ripple-fire 5, 2 pound charges.

Whenever blasting is mentioned, people who are not familiar with it immediately get nervous. Blasting certainly produces considerable vibration, but it short-lived and it might be preferable to live with one ½ second blast per day rather than 8 hours of hoe-ramming, for example.

Analytical Prediction Method for General Construction

For any given source the vibration levels at 25 ft can be extrapolated to other distances using the equation:

$$V(in/s) = V(@\,25\,ft)\left[\frac{25}{D(ft)}\right]^{0.5}$$

where D is the distance from the source and the 0.5 exponent is often adjusted based on the local soil conditions. Additional adjustments are made to account for; 1) building soil coupling (a large masonry building would suppress vibration more than a single family house), 2) height in the building (generally vibrations decrease as one goes up in the building), 3) floor amplification (vibrations in the middle of a structural bay are generally greater than they are near the columns), and 4) equipment isolation systems. The final vibration prediction is then compared to the instrument criteria to see if there is a potential impact. Note that these same adjustments can also be used for predictions related to blasting.

On-Site Testing - Direct Method

Unfortunately, all of the adjustments in the analytical prediction method have uncertainty associated with them. Much better predictions can be obtained with on-site testing.

The direct test method uses representative equipment at the planned construction site to generate vibrations while measurements are made inside neighboring buildings. Prediction uncertainties are greatly reduced because the actual equipment is operating on the actual soil, the vibration propagation is through the actual soil with all of its complexities related to soil type and layering, the actual buildings are present so there are no uncertainties related to soil/structure interaction or the building's dynamic response, and finally, the vibrations can be measured at the actual equipment locations (or on top of the actual vibration isolation systems if any are installed).

The direct test method gives the most accurate predictions and it provides an opportunity for the building occupants to experience what the construction will be like. The construction data can be used to establish acceptability criteria going forward. The cons of this type of testing are: real construction equipment has to be mobilized which has associated costs; and because demolition probably hasn't been done yet, it might not be physically possible to get the equipment to where it is needed.

On-Site Testing - Indirect Method

An alternative to direct testing is indirect testing where a large drop weight is used to create the vibration, rather than construction equipment. The vibrations produced inside neighboring buildings are scaled up or down according to the equipment that is planned to be used at the site. The scaling is done based on measurements of ground vibration 25 ft from the drop weight. Even though actual equipment is not used, the rest of the propagation and response chain is accurately captured by the testing.

The indirect method is usually less intrusive because the vibrations generated by the drop weight are relatively small compared to those produced by real construction equipment. The method is relatively low in cost because it only requires the mobilization of a machine to drop the weight. The primary con is that the source levels still have to be estimated.

Impact Assessment

There is a clear distinction between operational vibration criteria and damage criteria. Operational criteria (the instrument's performance is affected) are well known, but few manufacturers provide, or even know, what levels might damage their instruments. Most users can tolerate disruptions, but they do want to know that their instruments won't have to be repaired because of the vibration – unfortunately this is not an assessment that can be readily made.

Once the predictions have been made, the potential impact on sensitive activities can be evaluated. If the predictions are well under the criteria then there is no issue. If the predictions are well over the criteria then, in a sense there is also no issue because the users know that they will be out of business during the construction. The third possibility is that the vibration predictions are close to the criterion, and there may be an impact, or the impact may vary depending on where the construction is on the site. For these circumstances, it may be advantageous to monitor the vibrations in real time during construction so users can know where they stand with respect to their instrument's capabilities.

Mitigation

In some cases lower-vibration construction methods can be employed, but generally there is not a lot that can be done at the source to reduce vibration. Often the best course of action is to get the work over with as quickly as possible. This lets the affected users schedule down time knowing that they will be able to continue their work when the worst part of the construction is over. One can try to schedule the worst activities during off hours although this may have cost implications and might run afoul of local noise ordinances. Don't discount the benefits of blasting – it does produce intense vibration, but it is over with in less than a second. A user might prefer one short disturbance per day rather than 8 hours of lower, but continuous vibration. And lastly, in some cases it might be possible to protect sensitive equipment with a local isolation system (this is not always possible, especially if the item has an isolation system already).

Monitoring During Construction

Construction vibration monitors have been around for many years. These systems are designed to measure relatively high levels like those associated with building damage. They are not well suited to measure very low levels of vibration related to sensitive equipment, nor are they able to measure vibrations simultaneously at a number of frequencies (most equipment criteria are frequency-dependent).

Recent advances in remote PC technology have made it possible to install analyzers with highly sensitive sensors in the field and be able to access them remotely. By connecting to the remote system over the internet, one can monitor the data in real time, control the systems if necessary, download data, and most importantly send email or text messages if certain pre-set thresholds are exceeded. The alarm capability can help users determine when their equipment is out of its operating range and can also be used by the construction manager to adjust their work to reduce vibration.

Case Study: New Laboratory Science Building (NLSB) at UMass Amherst

NLSB Overview

The NLSB is a new science building consisting primarily of 43,000 NSF of research laboratory space including a 13,000 NSF animal facility intended to pull investigators from multi-disciplines together in one facility. Lab support platforms include genomics, proteomics, shell area for an imaging suite, cell engineering, and similar fields. Offices, conference rooms and lounge spaces augment the vision of a research space shared by a diverse group of researchers. The NLSB will be a major element in establishing the Life Science Neighborhood, which includes the Integrated Science Building, Skinner Hall School of Nursing and research labs in the multi-part Morrill complex. The project is built for UMass Amherst by the Division of Capital Asset Management (DCAM) with additional funding from the UMass Building Authority (UMBA). Currently foundations are just about complete with the first steel pieces having been delivered in early February.

The total building envelope of 310,000 GSF sits on an urban site, sloped in two directions and connects to the existing Integrated Science Building below grade. An older building on the site had been removed, including foundations, and the site overall has an average depth of 8 feet deep of fill to establish finish grade. Lacustrine and fluvial deposit is layered under the fill and on top of glacial till. Foundations utilized spread footings and mat slab construction and extensive earth retention with several tiers of soldier piles and tie-backs was necessary.

Additional site work includes a steam line to the north and various utilities to the west through a confined path. Maintaining the safety of students, faculty and staff was an important aspect of the process and all logistical plans were developed with this in mind.

An existing 5,000 NSF animal facility is located in the portion of the Morrill complex closest to the NLSB (under an independent renovation), and a small portion of the ISB basement will house holding and procedure rooms. The primary focus of both facilities are rodents.

<u>University Concerns</u>

The University has had instances where vibrations from adjacent construction projects have created the perception of significant vibration affecting the activity of research or research animals. The noise generated by projects that utilized demolition or soil compaction equipment contributed to the impression of disruption. The subject of concern was the research animals, not equipment, researcher comfort, or the building itself. Anecdotal evidence suggests that the NLSB project, with its deep foundation and extensive footprint, is one of the most complex site development projects recently built on campus and has the potential for creating anxiety among the research animals.

<u>Criteria</u>

As noted above 2,000 micro-inches is the most often accepted threshold for new construction, and is recommended by the NIH. This level of performance is often exceeded simply by locating the vivarium on a slab-on-grade and often the A/E team will meet more stringent thresholds in terms of structure-borne vibration in vivaria due to the relatively small increase in cost. The 2,000 micro-inches was therefore used as an original benchmark or target for vibrations during construction.

In addition to intensity, duration and predictability are thought to play into the effect noise and vibration have on animals. Vibrations with sharp wave profiles such as impacts within a facility have the greatest effect, whereas those with a gradual build and subsidence such as mechanical cycles can be less threatening. Animals may acclimatize to some long term vibration patterns, such as those caused by rattling mechanical ductwork, or other noises that occur regularly.

<u>Approach – Direct Testing</u>

A day of direct testing was arranged by all parties to demonstrate the sub-surface vibrations likely to occur by the construction equipment. Five sensors were set up in the neighboring buildings in areas deemed most strategic. Special measures were taken to minimize disruption to the Morrill animal facility itself. A second acoustical consulting firm was hired by Whiting-Turner for independent validation of the data recorded by Acentech.

The first step was to establish the baseline vibration in each location to identify existing sources of vibration. Vivarium cleaning equipment and the impact of caging racks both created vibrations in excess of the agreed upon threshold. These vibrations occurred in an animal facility where no reports of disturbed animals were on file.

Five key sites were then selected to represent the areas that the equipment will be closest to the sensors. The heavy equipment used for the tests consisted of a five-ton roller, a ten-ton roller, a 20 –ton roller, an excavator with hoe-pac and a D7 or equivalent dozer. An eight-hour schedule was drafted by Whiting-

Turner with each of the above pieces of equipment running for a predetermined time at each of the five locations. The conclusion of this day-long test was that most equipment may be used on site without effecting the animals.

The other conclusion was the 2,000 micro-inch critera was more stringent than necessary for the temporary conditions of a construction project, particularly when it was demonstrated that short, sharp vibration peaks were already encountered in the facility. The alarm threshold was increased to 3,000 micro-inches.

Real Time System

All parties agreed it was advantageous to keep a monitoring system in place throughout the entire construction schedule, to protect the animal research and aid in resolving the source of on-site vibrations. The sensors (Wilcoxon model 793L accelerometers) are linked to a spectrum analyzer and processed using MATLAB on a laptop computer. The root-mean-square narrow band vibration spectra (frequency distributions) were calculated every second continuously, converted to velocity, then condensed into 1/3 octave frequency bands. Every hour, the greatest (upper-bound) vibration in each frequency band was recorded and saved. The maximum hourly vibration levels in the attached figures provide the maximum measured level each hour in the 1/3 octave frequency bands from 3.15 Hz to 315 Hz.

Alarm Procedures

The monitoring data is distributed in the following ways: it is posted live on a limited access website for key people to monitor; it is consolidated into monthly reports; and it is the basis for the autodialer alarm system. Although the alarm trigger is the immediate method of communication among the University and Whiting-Turner staff, all data is distributed to the team for their review in a more methodical manner.

Conclusion

Mitigating concerns over vibration, particularly those at the small scale, requires sound construction planning and third-party verification. Early discussion and investigation during the design phase such as those above will allow the Owner, Users, Architect and Consultants, and Construction Manager to work as a team. Two key elements are required to build the trust among this group: reliable data and clear communication. A rigorous benchmarking and monitoring program and pro-active project management are the means to this end. The NLSB team hopes to continue the success of the vibration monitoring throughout construction; at this point in time no complaints on animal health or interruption to science have been lodged.