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PERSPECTIVES

The Impact of Construction Vibration on Adjacent Structures

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OVERVIEW

Complaints are often raised when construction activities are carried out in a densely-populated area or near vibration-sensitive facilities. Early phases of construction projects often generate vibrations in the near-surface soils. These construction activities can include removal of existing bridges, buildings, or hardscape. The activities can also include soil excavation, pile driving, site clearing, truck traffic, or compaction with vibratory equipment.

In the last four decades, significant research has been performed and major progress has been made in the fields of earthquake, mining, and offshore engineering. From these advances, engineers have a better understanding of the stress-strain relationship of soils as they are affected by static, cyclic, and dynamic forces. Adapted for vibration analysis, we can now model these man-made forces as plane waves through the soil or rock mass for blasting and pile driving activities. Similarly, we can model man-made forces as surface waves for compaction and other types of similar site development and construction.

Vibration analysis based on structural, geotechnical, and construction engineering can be performed to determine extent of impact as opposed to the subjective criteria of human perception. This paper outlines the basics of a construction vibration analysis.

CONSTRUCTION EQUIPMENT EFFECTS & HUMAN PERCEPTION

In residential or commercial construction, the majority of construction-related vibration typically occurs during the early phases of construction. Three primary activities which cause most, if not all, of the vibration-related damage claims in construction:

- Site clearing and removal;
- Site grading and soil compaction; and
- Installation of deep foundations.

Site clearing includes the removal of existing vegetation, buildings, and pavement. This process is often performed with vibration-inducing equipment such as excavators, dozers, loaders, large trucks. Additionally, even explosives are used in some cases with the demolition of large structures.

Once the site has been cleared, fill soil may be brought into the site. Fill is used for grading to raise the ground elevation for drainage purposes, or if the building pad elevation needs to be higher than the existing ground elevation. Fill is typically placed in 6-to-12-inch lifts and must be compacted in order mitigate future settlement issues. Compactors, most commonly referred to as “rollers,” are used to densify soils on larger sites. Rollers are heavy vehicles with a large metal drum roller, which compresses the soil as it is driven over the fill. Rollers are oftentimes equipped with mechanical vibrators, which improves the compaction performance of the roller. Smaller rollers, vibratory plate compactors, and jumping jack tampers are used on smaller sites, or to compact soils in areas with limited access, such as within the excavation for a building’s footings. Plate compactors, as seen in Figure 1, are engine-powered, walk-behind equipment that also utilize the benefits of vibration to compact soil.

Figure 1 *- Plate compactor in use on residential site*

Vibration is typically used in soil compaction equipment because it improves the efficiency of the equipment by directing energy into the substrate which overcomes the friction between soil particles, causing the soil particles to re-align and fill in the void spaces, thus resulting in greater soil density and preventing excessive building settlement.

When vibratory equipment is used, it results in improved density in less time and effort and increases the depth of penetration of the compaction equipment. In other words, the higher the mechanical energy that a machine delivers into the soils, the better and faster the compaction. While use of vibratory equipment has its obvious advantages in construction, it also can create adverse effects on adjacent buildings, facilities, and people. If proper precautions are not taken, site compaction methods can be at opposition with neighboring building occupants.

For larger buildings, buildings constructed on poor soil, or buildings constructed near open water, oftentimes a deep foundation system is required to support the building. Concrete, steel, and timber piles are the most common types of deep foundations, and they are installed by driving them into the ground with a large hammer, or by vibratory methods. Both installation methods with generate large vibrations which can be an annoyance to and/or damage adjacent properties.

A human will sense vibrations at levels much lower than that which is required to damage a structure. Based on a study on the subjective response of humans to vibrations, performed by the United States Bureau of Mines (USBM), vibrations were classified as being “barely perceptible” to humans at levels as low as 0.011 in/sec; and vibration levels were categorized as “severe” at levels as low as 0.301 in/sec. However, the same USBM study evaluated the response of residential structures to vibrations and found that the minimum vibration level to damage older homes with plaster-on-lath construction is 0.50 in/sec; and 0.75 in/sec for newer drywall construction homes.

Vibrations travel through the ground, and are transmitted through the foundation to the walls, floor, and roof. The first signs of vibration-related damage will appear on the interior planes of vertical load-bearing walls, as these walls resist the lateral swaying and movement caused by vibrations. Almost all finish materials are rigid and inflexible in nature; examples include cementitious stucco, interior plaster, interior gypsum wall board, and wall tiles. Damage to rigid finishes would first appear as cracks at the weakest locations in the wall first, which is generally at the corners of window and door openings.

The building components can vary from flexible, such as wood and steel, to rigid, such as masonry and concrete. These components are then typically covered with decorative and cosmetic finishes. Damage resulting from vibrations will affect flexible components at connections, which are the most rigid portions of a flexible assembly. Conversely, damage to rigid components will appear as cracks or post-construction differential settlement. Rigid components will generally be affected by vibrational forces before flexible components.

VIBRATION ANALYSIS

Construction vibrations are a known nuisance and can damage existing structures if they are not properly monitored and accounted for. As a proactive means to mitigate vibration damage claims, nearby buildings should be inspected prior to and after construction, and monitored during construction.

For example, on roadway projects in the state of Florida, the Florida Department of Transportation requires vibration monitoring on nearby structures. Based on Chapter 108-2 of the FDOT Standard Specifications for Road and Bridge Construction, during construction of retaining walls and foundations for bridges, buildings, and structures, all nearby structures within 200 feet of sheet pile installation/extraction, and within 100 feet of soldier pile installation/extraction must be inspected, surveyed, and monitored for settlement. In addition, when performing roadway compaction operations, all nearby structures within 75 feet of vibratory compaction operations must be surveyed and monitored for settlement.

A pre-construction survey should document the condition of the structure and all existing cracks in order to determine whether any new cracks appeared during construction. Vibration levels can be monitored during construction with a seismograph to determine if the vibration levels exceeded the building damage threshold. However, many times, vibration monitoring is not performed, and pre- and post-construction surveys are not available. Therefore, vibration analyses can be performed to estimate the vibration levels which would have been present at the property and compare them to the minimum vibration level required to damage a structure. According to Florida Statute 552.30, direct ground vibrations generated by construction mining activities is limited to the maximum standards set by the United States Bureau of Mines Report of Investigation No. 8507 (1980). While these regulations specifically apply to mining, they are commonly applied to construction operations. These maximum standards include:

- 0.75 inches per second (approximately 19 mm per second) for typical gypsum wallboard joints
- 0.5 inches per second (approximately 13 mm per second) for plaster lathe wall covering

As depicted within Figure 2, the maximum peak particle velocity allowed for construction activity changes with frequency, and in most cases occurs between 5 and 20 Hertz.

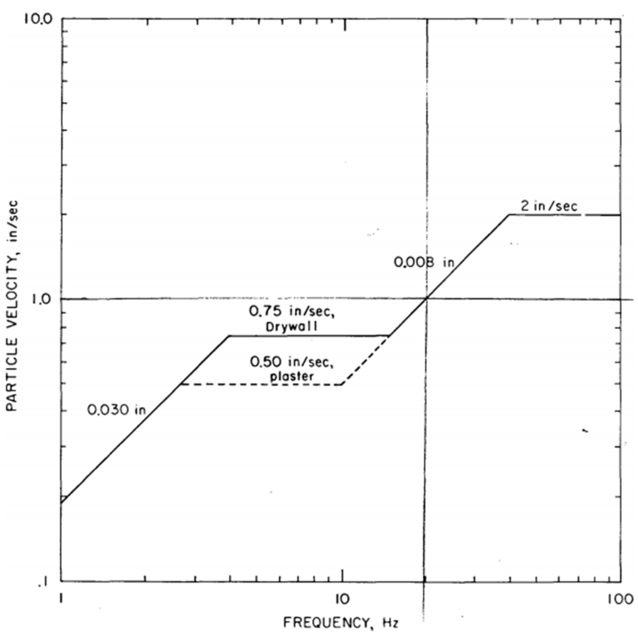

__Figure 2__ - Appendix B: U.S. Bureau of Mines Criteria for Direct Impact; RI-8507; November 1980

The analysis of construction vibrations on a given structure is a two-step process:

1. Considering direct effects to the structure caused by surface waves resulting in flexing walls and other building elements as the energy is absorbed and reflected through materials, and

2. Considering indirect effects on the foundation and walls as the vibration energy induces differential settlement

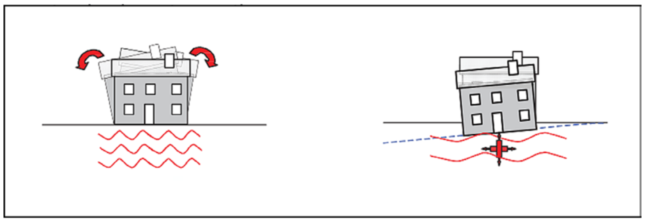

__Figure 3__ – A building's reaction to direct dynamic effects (on left) and indirect settlement (on right)

Direct vibration damage is caused by vibration energy transmitted to the foundation through direct contact with the bearing soils. Ground vibrations travel most often, in construction, as surface waves. This type of wave decreases in magnitude, or attenuates, with greater distance from the source of the vibrations. This attenuation is the result of energy loss due to friction within the material, soil particles in this case, through which the wave must travel. For comparison to building impact vibration levels are often noted as a single number quantifying the peak particle velocity (PPV, in in/sec or mm/sec). In order to determine the vibration level which could have occurred at a property, the vibration-inducing equipment must be identified, and the distance between the vibration source and the building must be determined. Numerous studies have been performed to determine the ground attenuation rate associated with various construction equipment. In addition, vibration charts are sometimes provided in the manufacturer's specifications for construction equipment. Figure 4 identifies several different types of machinery typically used on construction sites and plots the expected vibration level based on distance. As shown on the figure, the vibration level will decrease with increased distance from the source.

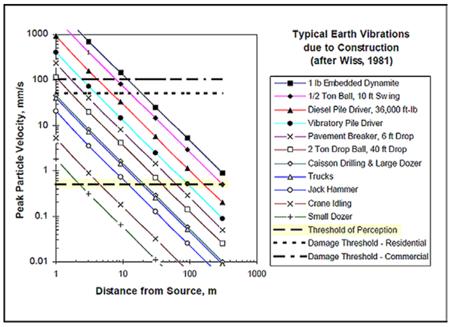

__Figure 4__ - Typical Earth Vibrations Due to Construction by J.F. Wiss

Indirect vibration damage refers to uneven movement in a foundation and/or walls of a structure, which can occur if the structure is minimally designed or constructed within a dry, loose sand profile and poorly compacted by the contractor. This can be analyzed using methods based on extensive research by K. Rainer Massarch and others. If vibration-induced shear strain in soils exceeds 0.01%, it passes the failure threshold and is considered “at risk of settlement” in granular soils or “loss of strength” in cohesive soils. The shear strain is determined from the shear wave velocity and the vibration velocity from the vibration source.

Shear waves vary with the volume of void space within a soil matrix, therefore a range of soil pressures and void ratios are used for calculation (Figure 5). Shear wave velocities values are plotted against peak particle velocity determined in Figure 4, then compared to the failure threshold in Figure 6.

For an assumed soil profile and depth of groundwater saturation, the vertical effective soil pressure in kilonewtons per square meter can be calculated. From Figure 5 and the effective stress, determine the Shear Wave Velocity, then use it on Figure 6 for the various void ratios.

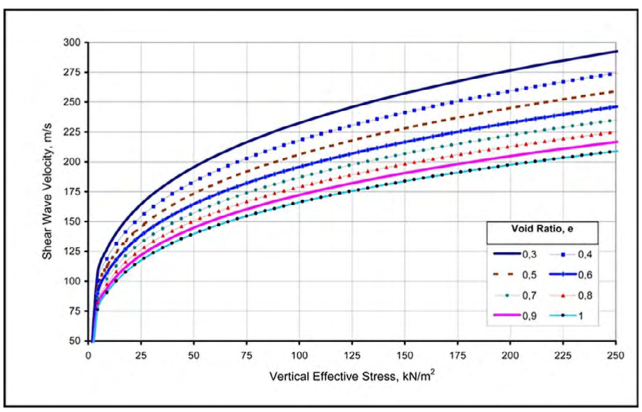

Figure 5 - Variation of shear wave velocity with vertical effective stress

In Figure 6, the resultant shear wave velocities in meter per second from Figure 5 are plotted at the measured or assumed peak particle velocity gathered by the seismograph, estimated from charts provided by the equipment manufacturer, or pulled from generalized construction equipment charts similar to that shown in Figure 4.

These points are compared to the failure threshold; if they exceed the failure threshold, then induced settlement cannot be eliminated as a possible source of any recent settlement-related distress noted by the engineer during the inspection of the structure. To determine the maximum induced settlement radius for the assumed equipment and soil conditions, the shear strain threshold vibration velocity is plotted on the particle velocity vs. distance chart (Figure 4) used previously and the radius from the point source is read from the distance axis.

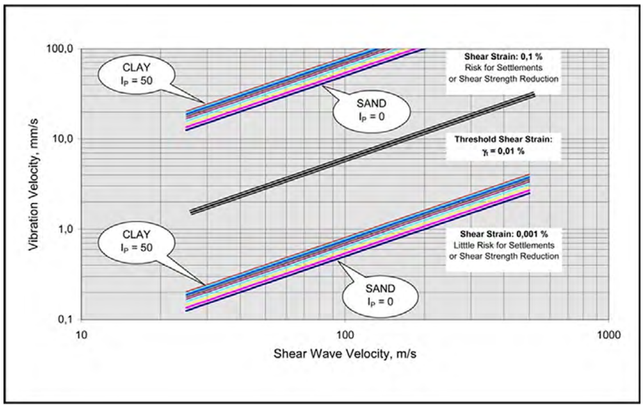

Figure 6 *- Estimation of risk for settlement or strength reduction from vibration velocity as a function of shear wave velocity for different levels of shear strain*

CONCLUSION

Construction often occurs near or adjacent to other existing structures. Claims and complaints often arise over real or perceived damages from vibration at construction sites. In the absence of actual peak particle velocity and recorded frequency data, a mathematical analysis of construction vibration can be performed by engineers to provide the interested parties a lateral radius of possible building damage. The methods used for this analysis are based upon and adapted from decades of research in the fields of earthquake and mining engineering, as well as studies specific to different types of construction equipment. The analysis input includes the easily acquired site conditions of soil texture, relative soil density, depth to groundwater table, lateral distance from vibration source, foundation geometry, and vibration source machinery type.

Both direct impact from surface waves as well as indirect impact from induced differential settlement of the bearing soils and settlement-related distress of the foundation and load-bearing walls is considered when performing construction vibration analysis.

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