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EXPERIENCE WITH COMMUNITY RESPONSE TO GROUNDBORNE VIBRATION FROM CONSTRUCTION ACTIVITY WHEN EVALUATED USING BUILDING DAMAGE CRITERIA, AND THE NEED FOR ANNOYANCE BASED CRITERIA

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INTRODUCTION

Construction of large-scale public works projects or large buildings, where heavy earth moving equipment and other large machinery are used, can be disruptive to community activity particularly where people live or work in close proximity to the construction site. In addition to visual and traffic impacts, the noise and vibration generated by construction equipment can be substantial and may significantly interfere with the lives of people in the surrounding community. When ground vibration is substantial, the community can be expected to respond negatively even when vibration magnitudes are below normally accepted thresholds for building damage. Substantial vibration is considered to be vibration that is generally accepted to produce discomfort in people when occurring for an extended period of time.

Recent experience indicates that use of a construction vibration criterion that is based solely on the avoidance of damage may allow building vibration that is generally unacceptable to large segments of the community. It is reasonable to expect that, as the duration of construction activity producing the vibration increases, the community's tolerance for vibration decreases. Conversely, for construction of very short duration, people appear to be willing to tolerate vibration that approaches the lower limits of conservative criteria set to minimize the risk of damage.

This paper examines vibration criteria typically used for construction in light of actual experience with community response to vibration from recent major public works projects involving tunnel mining, street excavation, and blasting in an urban setting. The need for annoyance based vibration criteria rather than criteria based solely on minimizing the risk of damage is discussed and possible criteria that consider the daily vibration aggregate as well as the duration of construction activity producing substantial vibration are proposed.

DISCUSSION

In order to set limits for construction vibration in sensitive community areas such as residential neighborhoods or near schools a means of measuring vibration that is reasonably predictive of human reaction must be established. There are two generally accepted measures of reporting construction vibration. Where building damage is the primary issue, the peak particle velocity (PPV) of the ground surface is normally used. However, where human response to vibration is an issue, it is not uncommon to use the root-mean-square (RMS) velocity if the vibration is semi-continuous or steady and non-impulsive in nature. If the vibration is caused by impacts such as pile driving, PPV vibration monitoring produces more meaningful data.

A practical issue is how to monitor vibration in the field efficiently as well as accurately. Where long-term monitoring of construction vibration is necessary, digital seismographs (with substantial data storage capabilities) have been found to be the most efficient means of recording data. However, commercially available monitoring seismographs are almost exclusively designed to measure and record ground motion PPV magnitude. The digital seismograph has been found to be the only really efficient means of continuously monitoring ground vibration over long periods of time. Consequently, the focus of discussion on vibration magnitude is in terms of ground surface PPV, but it should be recognized that there may be instances where RMS vibration measurements may be equally if not more appropriate.

The ground motion can be measured in three perpendicular directions if necessary. Commercially available digital seismographs allow this. If monitoring vibration for building damage, this should be done. If monitoring for annoyance of building occupants, it is usually sufficient to monitor just the vertical direction of ground motion. When standing or sitting, the human body is more sensitive to vertical motion, by a factor of approximately 3 to 1 compared with horizontal motion (ISO 2631-2[1]). It would, however, be prudent to also monitor horizontal ground motion, in case the horizontal vibration is considerably more than the vertical vibration.

A factor which is sometimes overlooked is the amplification of ground vibration that can occur in certain building types, particularly light weight wood frame structures. Measurements on buildings (e.g., Carman[3]) have found amplification factors in the range of 3 to 6 and higher for wood frame residences when comparing vibration measured at the ground surface and vibration measured on a wood floor supported by joists. This is particularly true in the frequency range of typical construction vibration. Consequently, it would not be unreasonable to assume that vertical floor vibration inside a residence could be on the order of five times the vertical vibration measured on the ground surface outside the building. This phenomena (of amplification) only affects what a person might experience inside the building and not the vibration at the building foundation.

For continuous vibration in buildings (without impulsive character), ISO Standard 2361-2[1] indicates that a 1/3-octave band RMS magnitude of 0.1 mm/sec is perceptible to humans for frequencies above 8 Hz. Below 8 Hz, human sensitivity to whole body motion decreases. Practical field experience with rail transit vibration indicates that humans are actually able to perceive vibration magnitudes as low as 0.05 mm/sec RMS and sometimes lower in unique individuals. If such vibration were sinusoidal in nature, the threshold of perception in terms of PPV would range from approximately 0.06 to 0.14 mm/sec. Whiffin and Leonard[2], in their research on vibration resulting from motor vehicle traffic on roadways, indicate a magnitude of 0.15 mm/sec PPV as the lower limit of perceptibility which is not dissimilar to the ISO base curve. For the purpose of discussion we adopt the 0.15 mm/sec PPV as representative of a nominal threshold for perceptibility.

In their research, Whiffin and Leonard[2] also establish that 5 mm/sec PPV is a "threshold for which there is risk of architectural damage to normal dwelling-houses with plastered walls and ceilings". They recognize that vibration of this magnitude would be annoying to people in buildings. The ratio of Whiffin and Leonard's perceptibility threshold to their lower limiting damage threshold is 1:33 (a substantial difference).

Recent experience with monitoring of construction vibration indicates that when vibration of 5 mm/sec PPV lasts for more than a few days even if intermittent, people in residences become extremely annoyed and concerned about building damage. Whereas, when construction activity lasts for a very short period of time (e.g., no more than a few days) experience indicates that higher levels of vibration are tolerated by the community as long as it can be made clear that buildings are not being damaged. To document evidence of building conditions it is prudent to perform a pre and post-construction photo survey of potentially affected buildings (examining foundation, walls, and ceilings for cracks).

When construction extends for long periods (e.g., more than a few days) and vibration is substantial, residents begin to worry more about building damage, even if the vibration levels are below normally accepted damage thresholds and even if no evidence of building damage can be found. If there is a perception that possible damage to an individual's property may be occurring and the vibration lasts for an extended period time legal action sometimes enters the picture; a situation that is best avoided.

Experience with major sewer tunnel projects in residential neighborhoods offer indications of the vibration magnitudes which tend to create complaints from homeowners and the severity of complaints received. The construction work included tunnel excavation with an 5.5 m diameter tunnel mining machine for soft tunnel mining, trenching of city streets for sewer line connections, and blasting for an associated hard rock tunnel. All but the blasting occurred in densely populated residential neighborhoods. All construction work on these projects was generally conducted during the day between 7 AM and 4 PM. The construction contractor was prohibited by contract from conducting nighttime work, except for the blasting which was located 1.5 km from all but one residence.

The tunnel mining in the residential neighborhood lasted for approximately one month, but perceptible vibration typically lasted for no more than 4 or 5 days at any one residence. Initially the tunnel was relatively shallow (10 m) but progressed to a depth of approximately of 25 m (due to the local topography) before further monitoring was considered unnecessary. Based on monitoring records, ground surface vertical vibration from tunnel mining ranged from 3.8 to 5 mm/sec where the tunnel was shallow and decreased to less than 1 mm/sec before monitoring ceased.

When vibration was below 1.3 mm/sec PPV, complaints were received at the outset of construction, but tended not to be vigorous. This observation appears to be consistent with the findings presented by Saurenman[4] that community complaints will be minor when the PPV from construction vibration is below 1.3 mm/sec. A limit of 1.3 mm/sec PPV can be used as a limit below which vibration should be maintained except for short periods (less than one hour in aggregate) or where activity lasts for no more than a few days such as in tunnel mining. If this were to be related to a statistical measure this would be equivalent to limiting the daily $L_{12.5}$ (i.e., level exceeded 12.5% of the time).

When vibration from tunnel mining or street excavation and subsequent roadway subgrade compaction exceeded 2.5 mm/sec PPV for more than a few days, homeowners tended to complain vigorously and express concern about their residence. Vibration that regularly approached 5 mm/sec elicited vigorous complaints, although vibration at these magnitudes lasted for only a few days at any one time. Based on this response, it is suggested that vibration that does not exceed 3.5 mm/sec PPV might be tolerated as long as it occurs for very short periods during a construction day (less than 10 minutes in aggregate). In terms of statistical measures, this would be equivalent to limiting the daily L_2.

For relatively continuous but fluctuating ground vibration from construction (such as with earth moving vehicles), a vibration limit that relates to general annoyance would be appropriate. A vibration magnitude of 0.5 mm/sec PPV would be equivalent to approximately 0.3 mm/sec RMS. Based on experience related to community response to transportation vibration, this would be perceptible but generally acceptable to the community as an L_{90} limit if the construction activity producing the vibration were to last for no more than a two to three months.

Based on this recent experience possible construction vibration criteria have been determined that could be applied to limit PPV magnitudes. These limits are similar to ones that have been used for construction of rail transit projects except that they are specified in terms of PPV instead of RMS vibration which is more customary when dealing with annoyance. PPV limits are indicated because of the availability of long-term monitoring devices that are designed to measure PPV.

Table 1 below indicates the proposed construction vibration limits that would apply to general construction vibration and possibly special construction vibration such as tunnel mining or tunnel boring. Pile driving vibration is excluded because of the highly impulsive nature resulting from pile driving.

Table 1 Proposed Construction Vibration Limits for Residential Areas During Daytime Hours of 7AM to 7PM for An Eight Hour Workday

Vibration Type and Permissible Aggregate Duration	Equivalent Statistical Measure	Peak Particle Velocity Limit*
Sustained ($\geq$1 hr/day)	L_{90}	0.5 mm/sec
Transient (<1 hr/day)	$L_{12.5}$	1.3 mm/sec
Infrequent (<10 min/day)	L_2	3.5 mm/sec

* Exclusive of pile driving vibration

In deriving the limits indicated in Table 1, it was assumed that in the daytime people may be at home some of the time but not necessarily every day for large blocks of time. Where people work at home and construction lasts for more than a week, experience indicates that vibration consistent with limits in Table 1 may not be acceptable to certain individuals. This situation can not be predicted and would have to be dealt with on a case by case basis. Where vibration was high (e.g., 3.5 mm/sec), experience indicates that the community would be willing to tolerate this condition, but only for a few days (no more than 2 or 3 at this magnitude).

Pile driving is unlike general construction vibration and more like blasting except that it is very repetitive and generally occurs for extended periods of time. Vibration limits for pile driving would have to be determined on a case by case basis depending on the nature of the community and the duration of pile driving. Based on experience, the upper limit indicated in Table 1 might be tolerated if vibration were to last for a short time.

CONCLUSION

Construction vibration limits have been derived that although permitting substantial vibration (i.e. vibration that would be very perceptible), would reduce annoyance by placing aggregate restrictions that allow lower vibration on a regular basis, but restrict higher levels of vibration to short periods of the day. These vibration limits are presented. Based on recent experience monitoring construction vibration in a residential neighborhood for an extended period of time, use of these limits would appear to result in generally acceptable vibration and thereby minimize complaints.

REFERENCES

1. International Standard, ISO 2631-2: 1989 (E), "Guide for the Evaluation of Human Exposure to Whole-Body Vibration - Part 2: Continuous and Shock-induced Vibration in Buildings", 1989.

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3. R. A. Carman, "Characterization of the Dynamic Response of Buildings to Groundborne Vibration", 121st Meeting of the Acoustical Society of America, May 1991.

4. H. J. Saurenman, "Vibration from Metro Rail Tunneling Operations", presented at APTA 1994 Rapid Transit Conference, Sacramento, California, June 1994.