VIBRATIONS INDUCED BY CONSTRUCTION TRAFFIC: A HISTORIC CASE STUDY

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ABSTRACT

Historically, specifications for limiting vibrations caused by highway construction (pile driving, paving, construction traffic, etc.) have been an extension of blast vibration specifications. Blasting forms an excellent foundation for construction vibrations, as blasting has attracted considerable field experimentation. There is a need, however, to develop specifications that can be applied to other forms of construction vibrations. In the United States, there have been a limited number of studies done on non-blasting construction activities producing damaging vibrations, namely construction traffic.

In many cases, various state and federal agencies have adopted empirical limits, in terms of peak particle velocity (PPV), in an effort to limit construction vibrations. Due to either the frequency of the ground motion or the natural period of the structure, these limits are commonly used where they do not apply. Generally, these empirical limits only apply to common structures, excluding those structures of historical significance.

This paper reflects an effort to research, compare, and condense those regulatory guidelines that currently exist concerning construction vibrations. A case study conducted in the historic district of Georgetown, Colorado is also presented. This nondestructive vibration testing investigation was performed to monitor vibrations and noise caused by construction traffic through the rustic mining town. Test procedures, data analysis, interpretation, limitations, and results are summarized.

INTRODUCTION

Vibrations induced in buildings are a frequent concern in cities around the world. Commonly, complaints are made by homeowners, as heavy construction vehicles travel at various speeds on adjacent roads, resulting in annoying vibrations and possible structural damage.

Passenger vehicles rarely produce perceptible vibrations to cause significant structural damage. Generally, traffic induced vibrations are caused by heavy vehicles. These vibrations are generated by road surface irregularities, namely: potholes, cracks, and uneven pavement joints. Dynamic interaction forces between the vehicle and pavement are created by these irregularities resulting in a generation of stress waves that travel through the adjacent soils. Vibrations produce damaging stress waves that quickly reach building foundations, causing them to vibrate.

Several factors may contribute to vibration levels, including: road condition, vehicle speed, vehicle weight, soil conditions, building characteristics, vehicle suspension system, season of the year, and distance between the structure and the road. When a large vehicle strikes an irregularity, an impact load, as well as an oscillating load due to the “axle hop” of the vehicle are generated. The impact load generates ground vibrations that are predominant at the natural vibration frequencies of the soil, whereas the axle hop generates vibrations at the hop frequency, which is a characteristic of the vehicle’s suspension system (Hunaidi and Gallagher, 2001). Vibrations can be amplified if the natural frequency of the building coincides with the natural frequency of the soil.

Soil type and stratification can influence the level of vibration greatly. Vibration levels increase as soil stiffness and damping decrease. Traffic vibrations appear worst in areas underlain by a soft silty clay layer between 7 meters and 15 meters deep (Hunaidi and Tremblay, 1997). The natural frequencies of the soil may coincide with the natural frequency of the structures at these locations. Seasonal variations and the moisture content of the soil are also a consideration when measuring vibrations. In locations where the topsoil freezes, vibration levels can be less than half those in other seasons.

Traffic induced vibrations are also a major concern in historic structures. In older buildings, materials may be weathered and weakened. Often, the structural system may be difficult to assess due to existing damage or building materials with little known strength characteristics. Only after careful consideration of the structure should allowable vibration levels be set. Some European countries have established vibrations limits for historic structures. These limits often range from 10 to 20 percent of the limits applicable to new construction.

GROUND VIBRATIONS

Three main wave types are generated when a vehicle strikes an irregularity. They include: compression waves (P), shear waves (S), and surface waves (R). These wave types can be further categorized into body or surface waves. Body waves, which include P and S-waves, propagate through a body of soil or rock while surface waves, also called Rayleigh waves, generally travel along the ground surface. P-waves involve successive compression and dilatations of the materials through which they pass. They are similar to sound waves and the direction of particle motion is in the direction of travel. P-waves have the ability to travel through both solids and fluids. Shear waves, or S-waves, cause shearing deformations as they travel through a medium. The direction of particle motion is perpendicular to the direction of travel. S-waves cannot travel through fluids, as fluids have no shearing stiffness. Surface waves result from the interaction between body waves and the ground surface. Surface waves produce large ground motions and transmit large amounts of energy, when compared to body waves. Rayleigh waves are produced by an interaction between S and P-waves and the ground surface. Rayleigh waves have both vertical and horizontal components of particle motion.

Construction induced vibrations propagate through the ground primarily by means of Rayleigh waves. The amplitude of these waves diminishes as the distance from the source increases. This attenuation is due to geometrical spreading and material damping. Geometrical spreading is described as the decline in energy of the expanding surface over which the energy is spread. Material damping is thought to be the energy required to overcome friction for each cycle of motion, or wavelength. Material damping in soil is related to soil type, moisture content, and soil temperature. Attenuation generally increases with higher frequencies, as a higher frequency will pass through more cycles in the same distance as its lower frequency counterpart.

Rayleigh waves dominate over body waves at large distances for blasting and construction vibrations. As Rayleigh waves only travel on the surface, their energy is spread over a cylindrical area rather than the spherical surface characteristic of body waves, resulting in less attenuation (Dowding, 1996). Rayleigh waves travel at low frequencies, decreasing the affect of material damping, allowing them to arrive at their destination with decreased attenuation characteristics.

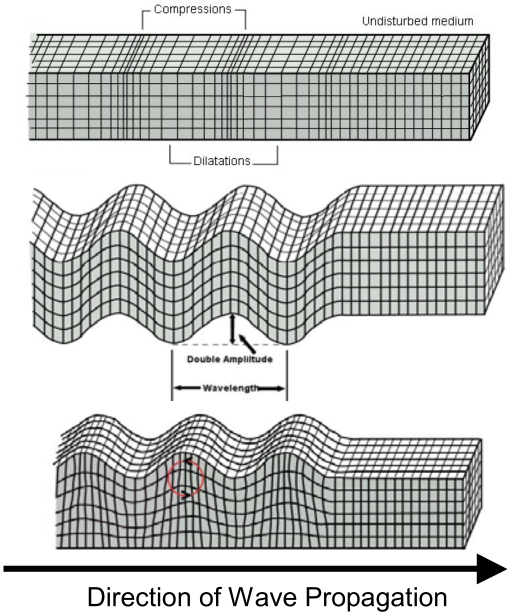

Figure 1. Wave types. (From top, P-wave, S-wave, Rayleigh wave)

VIBRATION INSTRUMENTATION

The function of vibration monitoring equipment is to measure and record ground motion. Vibration instrumentation consists of a sensor and recorder. The sensor, or geophone, is made up of three independent units placed at right angles to one another, one in the vertical direction, and the other two in orthogonal horizontal directions. The sensor is essentially an electromagnetic transducer, which converts ground motion into electrical voltage. A wire coil suspended in a magnetic field is contained within the sensor. The coil is suspended in the magnetic field by springs or hinges and is free to move. Ground motions will cause the unit to vibrate. Movement of the coil relative to the magnetic field will generate an electrical voltage proportional to the velocity of coil movement.

The recorder functions as a transfer mechanism by changing the electrical voltage back into motion. Most portable field units combine a small computer with an oscilloscope to serve as the recorder. The oscilloscope can display real time events, while the computer serves as long-term storage.

Seismographs typically measure particle velocity, but there are displacement and acceleration seismographs. Some velocity seismographs can be equipped to produce either a displacement or acceleration record. A typical seismograph produces a visual record of three wave traces, one for each direction of motion. An additional acoustic wave trace may be produced if the seismograph is equipped with a microphone.

CRITERIA AND GUIDELINES

For years, many regulatory agencies throughout the world have attempted to establish limiting vibration criteria. Various state and federal agencies have adopted empirical vibration limits, based on blasting research; to serve as a blanket guideline for all construction induced vibrations. Due to either the natural frequency of the ground motion or natural period of the structure, these limits are commonly used where they do not apply. There seems to have been a general downward trend of regulatory limits on construction induced vibration, in the tendency to input safety factors into these limits. Over the years, vibration limits have become more conservative and may no longer be appropriate for use in certain situations. As with most generalized guidelines, they must be used with extreme caution and careful consideration.

Most available guidelines are based on frequency-velocity control bounds. Studies have shown that velocity seems to correlate closely with observed damage. Frequency plays a large role in vibration related structural damage. Common structures have a low natural frequency, typically less than 30 Hz. Structural vibration is exponentially increased if the vibration frequency falls within the bounds of the natural frequency of the structure. This phenomenon is commonly known as resonance. Thus, low frequency vibrations are potentially more of a concern than their high frequency counterparts.

Commonly used in the United States, the Office of Surface Mining (OSM) has established a vibration regulation. The OSM regulation is a modification of an appendix of U.S. Bureau of Mines (USBM) Report of Investigation 8507 (Siskind et al., 1980). Blast produced ground vibrations from surface mining were studied to assess their damage and annoyance potential. Direct measurements were made of ground vibration produced structure responses and damage in 76 homes for 219 production blasts (Siskind et al., 1980). The threshold of damage was defined on visual observations of cosmetic cracking, as these cracks occur at the lowest vibration levels. Structural resonance caused by low frequency vibrations, initiating increased movements, proved to be a significant finding during this investigation. Prior to this study, the commonly used vibration criteria were independent of frequency.

Human sensitivity to vibrations was also a consideration of this study. Humans are extremely sensitive to vibrations. Vibration problems would not exist, if this were not the case. Studies on human response to vibrations have been carried out for many years by many researchers. Their research was collaborated by Siskind in USBM RI 8507. It must be noted that individual response to vibrations will vary, but most people are likely to complain if vibration levels are just slightly higher than the “noticeable” threshold (ANSI, 1983).

Response	PPV
Noticeable	0.5 mm/s
Troublesome	5.0 mm/s
Severe	17.8 mm/s

Table 1. Human response to vibration (from Siskind).

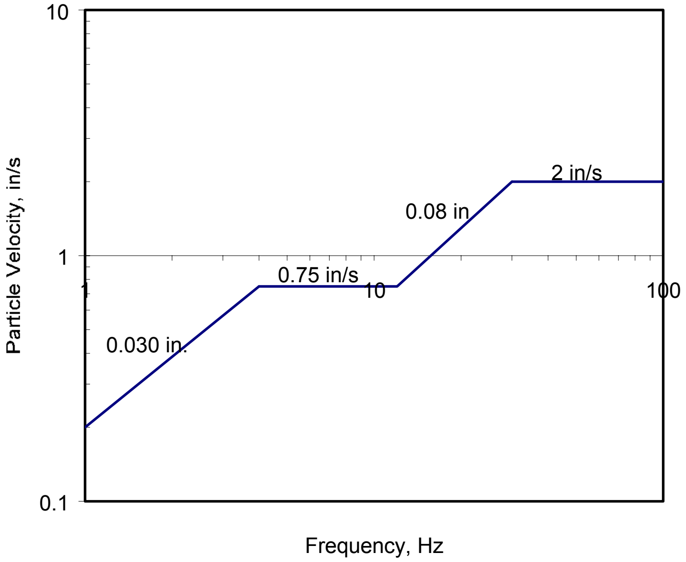

Figure 2. USBM Recommendation RI 8507.

The German DIN 4150 standard is based on human annoyance factors. A majority of the problems associated with vibrations will be human tolerance levels to its effects. Human tolerance is controlled by scientific, psychological, and socio-economic factors, making such a strict definition of what represents a nuisance impractical.

PPV Guide Values (mm/s)			
	Frequency		
Structure Type	**< 10 Hz**	**10-50 Hz**	**50-100 Hz**
Offices and industrial premises	20	20-40	40-50
Domestic and similar construction	5	5-15	15-20
Other buildings sensitive to vibrations	3	3-8	8-10

Table 2. German DIN 4150 Standard.

The Swiss have developed a standard that includes both blasting PPV and traffic or machine induced PPV. The Swiss standard contains a category for structures of historic significance, but appears to be very conservative. Despite the limitations inherent in these standards, some form of frequency control is necessary to limit construction vibrations in an appropriate manner for both the owner and contractor.

Building class (1)	Vibration source (2)	Range of frequency, in hertz (3)	Peak particle velocity, in millimeters per second (4)	Peak particle velocity, in inches per second (5)
I[a]	Machines, traffic	10-30	12	(0.5)
		30-60	12-18	(0.5-0.7)
	Blasting	10-60	30	(1.2)
		60-90	30-40	(1.2-1.6)
II[b]	Machines, traffic	10-30	8	(0.3)
		30-60	8-12	(0.3-0.5)
	Blasting	10-60	18	(0.7)
		60-90	18-25	(0.7-1.0)
III[c]	Machines, traffic	10-30	5	(0.2)
		30-60	5-8	(0.2-0.3)
	Blasting	10-60	12	(0.5)
		60-90	12-18	(0.5-0.7)
IV[d]	Machines, traffic	10-30	3	(0.12)
		30-60	3-5	(0.12-0.2)
	Blasting	10-60	8	(0.3)
		60-90	8-12	(0.3-0.5)

[a] Buildings in steel or reinforced concrete, like factories, retaining walls, bridges, steel towers, open channels; underground chambers and tunnels with and without concrete alignment.

[b] Buildings with foundation walls and floors in concrete, walls in concrete or masonry; stone masonry retaining walls; underground chambers and tunnels with masonry alignments; conduits in loose material.

[c] Buildings as mentioned previously but with wooden ceilings and walls in masonry.

[d] Construction very sensitive to vibrations; objects of historic interest.

Table 3. Swiss Standard for vibrations in buildings.

CASE STUDY
BACKGROUND

Guanella Pass Road (Colorado Forest Highway 80) was originally constructed in the 1950's as a scenic route through the Pike and Arapaho National Forests. Forest Highway 80 was designated as a Colorado and Federal Scenic Byway in 1991. Guanella Pass Road travels roughly 38 km (23.6 mi) through forest, shrub land, and alpine tundra habitat. Elevations along the roadway vary from 2,588 m (8,490 ft) at Georgetown, the northern terminus of the road, and rise to 3,547 m (11,637 ft) at Guanella Pass. The original road surface and geometry were not originally designed to handle the increased recreation traffic in recent years.

The Federal Highway Administration (FHWA) Central Federal Lands Highway Division (CFLHD) began design studies on the road in the early 1990's. One such study, conducted during the summer of 2001, was to test and evaluate five alternative surface types to be used in place of a gravel surface. The intent of the study was to identify a surface that would provide the benefits of a hardened surface, with less erosion and lower maintenance, while still providing for a rustic driving experience.

It became necessary during the test program to haul construction materials through Georgetown, using 10-wheel end dumps with a loaded weight of approximately 25 tons. Due to tight corners and buildings in close proximity to the road, only one haul route was made possible, which traveled by several historic structures. Compliant with the City of Georgetown, the FHWA and Olson Engineering conducted a vibration and noise study during the hauling operation to monitor potential effects on these historic structures. Many of the monitored structures were originally erected during the mid to late 19th century and were constructed of a "soft brick" milled in town during the silver mining era.

Figure 3. Condition of monitored structures.

VIBRATION MONITORING

Initially, 12 Mini-Seis II units were installed at vibration sensitive locations along the haul route. The 12 locations were selected based on a field survey and input from local residents. Most of the seismographs were placed on the ground, within 3.0 m and 6.1 m of the roadway shoulder. One seismograph was placed on the roof of one building to monitor any vibration amplification through the structure. An exterior structural assessment of each monitored location was also conducted. Notes and photographs of each structure were taken to document any existing damage.

The seismograph units were capable of measuring vibrations in three orthogonal directions with a frequency range of 2 to 250 Hz and were equipped with microphones. Trigger levels were set as low as possible, either 0.25 mm/s or 1.0 mm/s. Vibration levels were monitored under ambient conditions and during haul hours. The units were routinely monitored and data was downloaded periodically.

CONTROLLED TESTING

As part of this investigation a controlled test, using a known source, was conducted. A loaded belly dump, weighing 40 tons, was used as the source for the controlled testing. The truck traveled at prescribed speeds of 16 kph (10 MPH), 32 kph (20 MPH), and 48 kph (30 MPH) over a 20 mm irregularity. Vibrations were monitored by two fixed geophone spaced 3 m apart. One geophone was set 0.9 m to 1.5 m from the shoulder of the southbound roadway. The second geophone was placed 3 m from the first geophone, perpendicular to the road. A seismograph was also placed 0.15 m from the second geophone. Vibration levels generated by passing passenger vehicles were also monitored.

RESULTS

The following results were extracted from a report prepared for the Federal Highway Administration by Olson Engineering. Results from the vibration measurements were compared against the Swiss standard, developed by the Swiss Association of Standardization. The Swiss standard includes a category for “objects of historical interest or other sensitive structures,” which was found to be appropriate for use in this investigation. This standard limits the PPV at between 3 and 5 mm/sec, depending on the frequency range.

Testing conducted under ambient conditions (before hauling started) yielded a maximum PPV of 78.23 mm/s (3.08 in/s). This event was possibly due to a direct strike on the unit. There were a number of readings taken during ambient conditions that resulted in a PPV greater than the Swiss limit of 3.0 mm/s (0.12 in/s).

Table 4, provided by Olson Engineering, summarizes the maximum PPV at each of the 12 seismograph locations during ambient conditions and during periods of truck traffic. Testing conducted during truck hauling activity indicate a maximum PPV of 3.81 mm/s (0.15 in/s) at the Hammill House.

Address	Ambient PPV		Construction Traffic PPV	
	mm/s	in/s	mm/s	in/s
505 2nd St.	4.318	0.17	2.6035	0.1025
207 Rose St.	1.524	0.06	1.905	0.075
200 Rose St.	0.762	0.03	1.016	0.04
301 Rose St.	0.508	0.02	-	-
300 Rose St.	0.762	0.03	2.413	0.095
Hammill House (front)	78.232	3.08	1.016	0.04
Hammill House (back)	0.762	0.03	3.81	0.15
6th and Rose St.	2.286	0.09	1.524	0.06
927 Rose St.	4.826	0.19	0.635	0.025
601 2nd St.	-	-	-	-
311 Argentine St.	1.524	0.06	-	-
6th and Rose St. (roof)	0.762	0.03	0.508	0.02

Table 4. Maximum Peak Particle Velocity at instrumented locations.

Vibration levels experienced during periods of construction traffic were generally lower than those vibrations commonly generated in this area. Only one record during truck traffic was higher than the 3 mm/s (0.12 in/s) limit established in the Swiss standard for buildings of historical significance. Further analysis indicates that the record is within acceptable limits because of the associated high frequency (170.6 Hz).

Evaluation of acoustical levels produced similar results. Noise levels measured under ambient conditions produced a maximum of 142 dB, while levels reached a maximum of 122 dB during periods of truck traffic. At the end of the test period, a final structural assessment was conducted. The assessment revealed that no visible damage had taken place on the monitored structures.

Vibration measurements under controlled conditions indicated PPV’s that ranged from 0.0381 mm/s (0.0015 in/s) to 0.348 mm/s (0.0.137 in/s). Vibrations induced by passenger vehicles ranged from 0.0508 mm/s (0.002 in/s) to 0.2032 mm/s (0.008 in/s). Table 5 provides a summary of the controlled testing results.

In addition to actual velocity measurements under controlled conditions, data was collected to measure soil attenuation. The attenuation data was collected by measuring the change in peak velocity between the geophone array at known distances from the traffic. An instrumented hammer was also used to strike the road surface at a known distance from the array. The collected data indicated an attenuation factor of 2.5 to 3.5 per 3.0 m of distance.

Vehicle	Direction of Travel	Speed (kph)	PPV (mm/s)	
			Geophone 1	Geophone 2
Car	south	~40	0.0508	0.0094
SUV	south	~48	0.0787	-
Tow Truck	south	~56	0.203	-
End Dump	north	~48	0.2413	0.0762
Belly Dump	south	16	0.1905	0.0686
Belly Dump	north	16	0.0889	0.0381
Belly Dump	south	32	0.0098	0.0762
Belly Dump	north	32	0.2489	0.07112
Belly Dump	south	48	0.348	0.1372
Belly Dump	north	48	0.2311	0.0762

Note: Geophone 1: 1.5 m. from southbound traffic

Geophone 2: 4.5 m. from southbound traffic

Table 5. PPV measurements during controlled testing.

RECOMMENDATIONS

In all cases, vibration levels appeared well below the established Swiss criteria. It was then the recommendation of the FHWA to the city of Georgetown that future construction traffic, to the level that was studied, would not produce structurally damaging ground vibrations. Because of geometric constraints within the city, future construction traffic will most likely be limited to the type and weight that was studied.

SUMMARY

As our nation's infrastructure continues to age, more structures will become increasingly susceptible to damage caused by construction vibrations. It will become necessary to monitor structural response by the use of non-destructive techniques, such as vibration measurement. Many regulatory guidelines have been developed and put into practice, but as construction techniques and materials change these criteria must be verified and deemed appropriate for the given situation.

Several forms of vibration criteria have been presented, as well as the results of an investigation on vibrations induced by construction traffic. The reader is cautioned that the measurement results presented are applicable only to the site at which the measurements were made. The vibration performance of various equipment and geologic site conditions should be evaluated on a site-by-site basis.

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