Effect of Rock Trenching Vibrations on Nearby Structures

Alan Atalah, P.E., M.ASCE[1]

Abstract: Trenching to install deep gravity sewers and drains in medium-to high-strength rock requires large and heavy rock trenchers that produce high levels of vibrations that may affect the structural integrity of nearby utilities and buildings. Although not every vibration causes damage, owners often believe that their structures have been harmed by rock excavation. The resulting disputes can waste a great deal of time and money. In an effort to reduce structural damage and associated disputes, this paper provides guidelines for the safe distance between rock trenchers and nearby buildings and underground structures. Vibration data at different distances from the trencher centerline were collected from five trenching projects in Northwest Ohio. The data analysis suggests a moderate relationship between the vibration level and the distance from the source of vibration. In addition, the risk of damage to nearby structures dissipates significantly and quickly as the distance from the point of excavation increases. Rock trenching should not take place closer than 1.50 m for buried structures and 1.00 m for residential buildings. Beyond this safe distance, damage to nearby structures should not take place.

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Introduction

Trenching in medium-to-high-strength rock [with compressive strength between 138 MPa (20,000 psi) to 193 MPa (28,000 psi)] to install gravity sewers can damage nearby buildings and underground structures and cause disputes. Only large and powerful rock trenchers and hoe rams can provide the needed energy to dig deep in this rock, and they produce high levels of vibrations that may damage nearby structures. These vibrations distress owners of nearby underground structures and above ground buildings, who fear that resulting vibrations may damage their property. Associating vibrations with serious damage caused by earthquakes, volcanoes, and strong winds, people feel uneasy when their structures experience vibration or movement. The most common complaints about construction vibrations come from building owners who claim that their interior and exterior walls and foundations have been damaged (Wiss 1981). However, not every ground vibration or movement people can feel is strong enough to damage structures and utilities, and owners sometimes wrongly blame preexisting damage on nearby excavation.

The owners may not realize that most structures have some existing cracks or cosmetic damages caused by differential settlement, wind, thermal expansion, and contraction, etc. These flaws often go unnoticed until, alarmed by construction vibrations, the building owners check their buildings and find cracks they then attribute to recent construction. Such situations often lead to expensive and time-consuming disputes and litigation between the owners and contractors. The time and expertise needed to investigate the cause and age of damage to a building are costly and exhausting for all involved parties. Furthermore, these conflicts create a tense atmosphere that discourages cooperation and teamwork, and in the end, these disputes are usually settled without the full satisfaction of either party.

This research focuses on rock trenchers, which are cost effective and provide controlled trench width and depth. Trenchers simultaneously dig and pile the excavated material on the side of the trench; their booms are a digging chain with digging teeth that can be set in different patterns for optimal trenching productivity in hard material. The trencher teeth are replaceable carbide tipped to offer maximum strength and longevity. Despite their advantages, rock trenchers can cause the above-cited vibrations and disputes.

It is important to note that trenchers should be used under certain circumstances. Often, rock layers underlie one or more layer of soft soil, where most of the shallow utilities (e.g., water, gas, and cables) are installed. In these situations, rock trenchers cannot and should not be operated unless the soft soil has reasonable standup time without trench shoring. This paper does not address the damage to nearby structures caused by inappropriate use of trenchers in soft soils.

In an effort to reduce structural damage and avoid disputes associated with it, this paper offers guidelines for safe distance between rock-excavation operations and nearby buildings and underground structures. It does so by investigating the relationship between the vibration level and the distance from the source of vibration at five projects in Northwest Ohio.

Fundamentals of Vibration Analysis

When a trencher excavates through a rock formation, vibrations travel through the surrounding rock. Assuming that the vibration wave has a shape similar to the one shown in Fig. 1, the following terms can be defined:

1. *Peak particle velocity* (PPV) is the maximum rate of change of the particle displacement (U) with respect to time. The

[1]Associate Professor, College of Technology, Bowling Green State Univ., Bowling Green, OH 43403.

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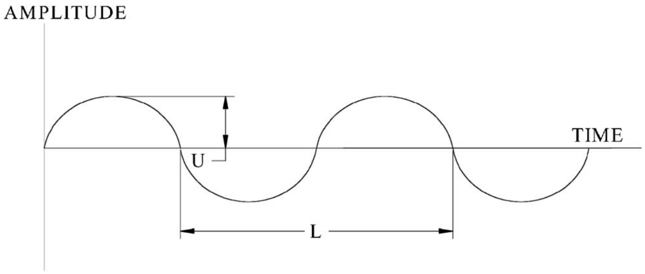

Fig. 1. Typical vibration wave

velocity amplitudes are given in units of mm/sec or in./sec (Dowding 1996).

2. *Frequency of the vibration* is the number of oscillations per second. The frequency units are given in Hertz (cycle/sec). The dominant frequency is the frequency at the maximum particle velocity, which is calculated for the half-cycle that has the peak velocity (Dowding 1996). The dominant frequency is referred to as *frequency* throughout this paper.

The particle velocity can be visualized by the movement of a bobbing cork during a passing wave. The *particle velocity* is the speed with which the cork moves up and down. The *propagation velocity* is the speed with which the wave passes the cork. The measured particle velocity has three components: (1) longitudinal (long), which is the horizontal direction from the source of vibration to the point of monitoring; (2) transverse (trans), which is the horizontal perpendicular direction to the longitudinal one; and (3) vertical (vert), which is the vertical direction perpendicular to both preceding direction planes. The peak vector sum (PVS) is vector sum of the peak particle velocities in the longitudinal, vertical, and transitional directions (Atalah et al. 1998).

Cosmetic cracking of structures is unlikely until particle velocities exceed 25 to 100 mm/sec (1 to 4 in./sec). In contrast, people complain about particle velocities less than 13 mm/sec (0.5 in./sec) (Dowding 1996). Wiss (1981) stated, "The human body is an excellent detector of vibration, but a poor measuring device." Humans can perceive a steady state vibration at particle velocity of 0.3 mm/sec (0.01 in./sec) (Wiss 1981).

The potential for cosmetic cracking of buildings correlates closely with the PPV of a particle in the ground as opposed to its displacement or acceleration (Wiss 1981). This is likely because in one-dimensional plane wave propagation, in a linear elastic medium, maximum strain is directly proportional to maximum particle velocity. The blasting industry has found that PPV correlates with the distance from the source of vibration to the point of measurements (Dowding 1996). Wiss (1981) presents in Fig. 2 the approximate relationship between PPV and the distance from many operating construction pieces of equipment (the vibration source). This research aims to add to this body of knowledge by exploring the applicability of similar relationship in rock trenching operations (between PVS generated by the trencher and distance from the trencher to the point of observation).

Research Objectives

Before beginning rock trenching in densely populated urban areas, it is important for the contractor to know how the surrounding facilities and infrastructure will be affected. All parties involved in the trenching project must know how far away from certain structures they must be to carry out their work safely. The inability to determine safe limits has resulted not only in damage

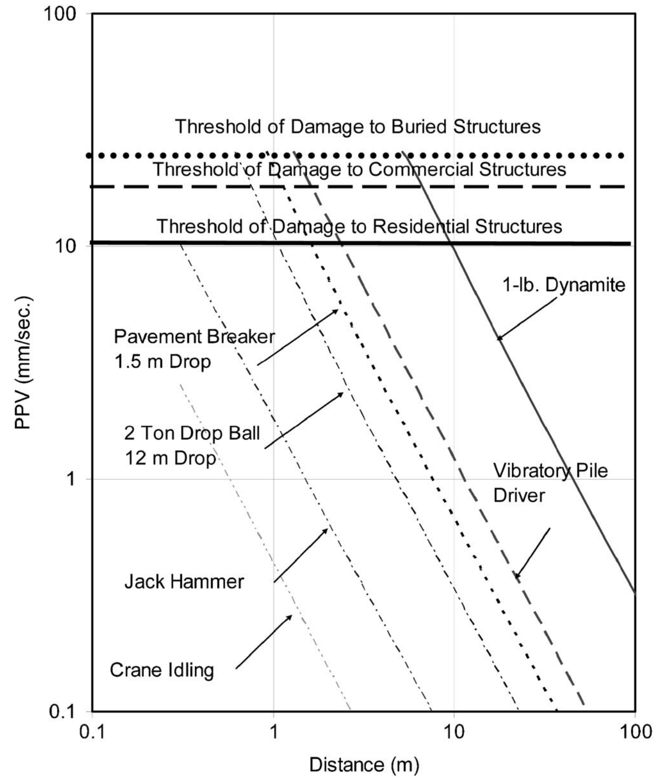

Fig. 2. Attenuation lines of the velocity versus distance from different construction sources. Reprinted with permission from Wiss (1981).

to nearby structures (and consequent disputes), but also in an unjustified fear of rock trenching when it is in fact the least costly and disruptive method.

This research investigates the relationship between PVS and the distance from the trencher boom when trenching rock and presents a relationship line similar to those shown in Fig. 2. Its goal is to determine the safe operating limits for trenching in proximity to critical buried utilities and occupied buildings.

Research Methodology

The basic idea of this research was to collect and analyze sets of vibration data related to PVS, frequency, and the distance from the source of vibration from different rock-trenching jobs. Vibration data were collected from five jobs in Northwest Ohio: One in Fremont, one in Findlay, one in Risingsun, and two in Bowling Green. The trenchers used in this research project were large-size Vermeer track trenchers (models ranged from T655 to T955). The teeth on these trenchers were 2.50 cm (1.00 in.) shank mounted on 2.50 cm (1.00 in.) base plates with the "V" pattern shown in Fig. 3. In addition, a set of vibration data was collected from a hoe ram project in Fremont, Ohio. In each job, several sets of vibration data at different distances from the excavation points were collected.

The researcher planned the offsets from the trench centerline according to the typical layout shown in Fig. 4. Note that the longitudinal direction is parallel to the trencher, the transverse direction is perpendicular to the trencher, and the vertical direction is perpendicular to the other two directions. For example, the first set of data was collected as the trencher passed by the geo-

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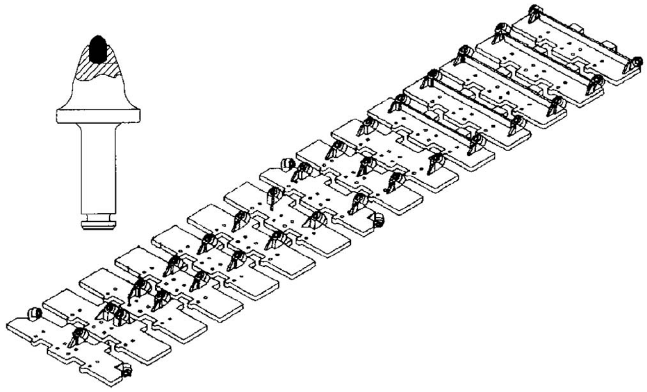

Fig. 3. Shape and pattern of the teeth on the trenchers tracks

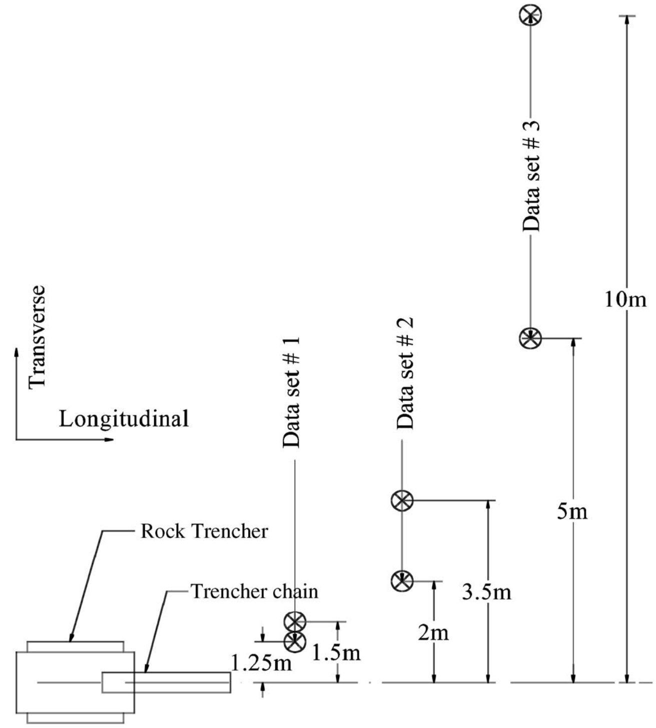

Fig. 4. Typical job site layout showing the locations of geophones during vibration monitoring. All distances are in meters.

phones, which were located at 1.25 m (4 f) and 1.5 m (5 f) offsets from the trench centerline. During trenching, the ground vibrations were monitored and recorded along with the distances between the centerline of the trencher and the vibration monitoring points. During the actual data collection, the actual offset distances slightly varied from the planned ones in each job depending on the site condition.

Although the characteristics of the excavated rock (such as compressive strength) are relevant, rock analysis information was not acquired due to limited funds. However, Dave Beard of Vermeer Sales of Ohio stated that the encountered rock could be described as solid dolomite with compressive strength ranging from 138 MPa (20,000 psi) to 193 MPa (28,000 psi). Mr. Beard has more than 30 years of rock excavation experience in Northwest Ohio, and he has arranged the trenching jobs for this research. In addition, the average speed of trenching in these jobs was 2.50 cm/min (1.00 in./min) (D. Beard, personal communication, 10/19/2005). In previous trenching jobs in some spots in Bowling Green, the rock was so hard that the trencher teeth ground instead of chiseled the rock. These indications validate the hypothesis that this rock has medium-to-high strength.

Ground Vibration Measurements

The vibration data were collected by an Everlert III seismograph from Vibra Tech Engineers, which allowed the simultaneous recording of data from two three-axis geophones (vibration monitoring devices). In the continuous mode, the seismograph collected data at a rate of five to six events per minute; each event included a record of the PPV, PVS, frequency, velocity time chart, etc. in the event report. An example report is shown in Fig. 5. The seismograph recorded the PPVs and frequencies in longitudinal, vertical, and transitional directions and calculated the PVS for each event. The seismograph was set with the following specifications: The particle velocity range was up to 250 mm/sec (10 in./sec), the resolution was 0.13 mm/sec (0.005 in./sec), the accuracy level was 3% at 15 Hz, the sampling rate was the standard 1,024 samples per second per channel (8,192 for eight channels), and the frequency response range was 2 to 300 Hz.

Vibration Data Analysis Procedures

The vibration data were tabulated in a separate spreadsheet for each job as shown in Table 1. The longitudinal distances between the trencher tip and the geophones changed with every event, whereas the vertical and transverse ones were constant for each data set. The longitudinal distances were measured at the beginning and the end of each data set; the distance at each event was interpolated based on the speed of the trencher and the time stamp on each report. The PPV components (long, trans, and vert), PVS, and frequency were added to the spreadsheet from each seismograph event report. The data analysis continued by plotting PPV components versus frequency and PVS against the distance from the trencher boom on a log/log scale. Regression analysis between log of the sloped distance and log of the PVS was conducted to calculate the regression parameters such as sum squares of errors, total sum of squares, correlation factor, slope, and intercept to calculate and plot the upper limit of the 95% prediction interval (PI). The sloped distance was the vector sum of depth, transverse, and longitudinal distances in three-dimensional space between the geophone and the trencher boom tip.

The researcher theorized that PVS at each vibration event has an inverse relationship with the sloped distance from the trencher chain. Each of the following equations mathematically represents this relationship:

$$\log(\mathrm{PVS}) = C_1 + S\log(D) \quad \text{or } \mathrm{PVS} = C_2 \times (D)^s \tag{1}$$

where C_1, C_2, and S=constants; and D=sloped distance between the excavation spot and the monitoring point. S=slope of the relationship line between log of PPV and log of D; S lies between −1.00 and −2.00. Determining the values of C_1, C_2, and S and their potential ranges enables the researcher to determine the safe distance for buried pipelines and surface structures from trenching operations. The safe distance is estimated based on governing PVS versus distance, provided the nearby structures were in sound structural condition. The PPV component in a certain direction can be plotted against the distance component in that direction between the trencher tip and the geophone. However, PVS plotted against the sloped distance is a more accurate graph because PVS is the vector sum of the three velocity components.

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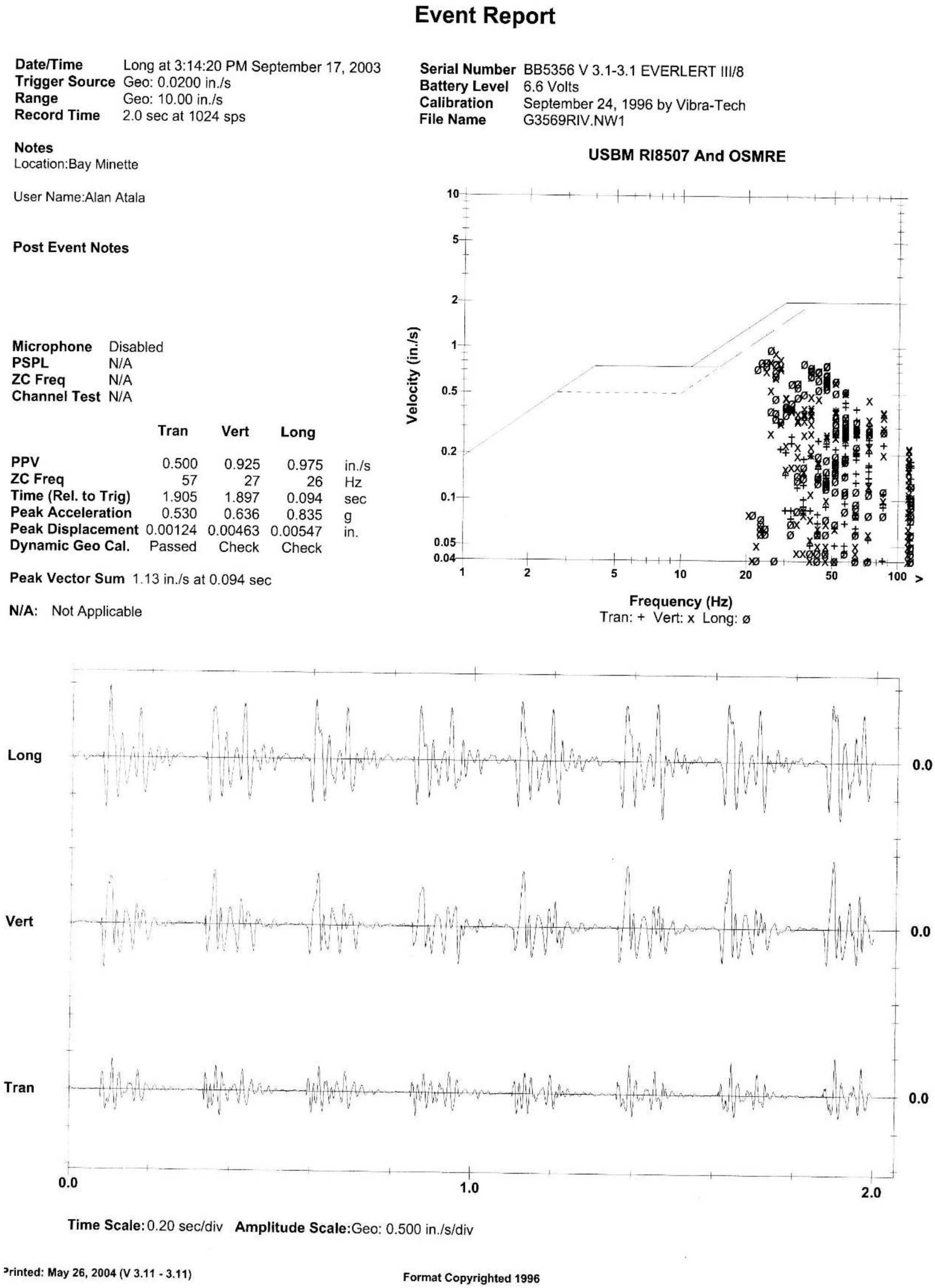

Event Report

Date/Time	Long at 3:14:20 PM September 17, 2003	**Serial Number**	BB5356 V 3.1-3.1 EVERLERT III/8
Trigger Source	Geo: 0.0200 in./s	**Battery Level**	6.6 Volts
Range	Geo: 10.00 in./s	**Calibration**	September 24, 1996 by Vibra-Tech
Record Time	2.0 sec at 1024 sps	**File Name**	G3569RIV.NW1

Notes
Location:Bay Minette

User Name:Alan Atala

Post Event Notes

Microphone	Disabled
PSPL	N/A
ZC Freq	N/A
Channel Test	N/A

	Tran	Vert	Long	
PPV	0.500	0.925	0.975	in./s
ZC Freq	57	27	26	Hz
Time (Rel. to Trig)	1.905	1.897	0.094	sec
Peak Acceleration	0.530	0.636	0.835	g
Peak Displacement	0.00124	0.00463	0.00547	in.
Dynamic Geo Cal.	Passed	Check	Check	

Peak Vector Sum 1.13 in./s at 0.094 sec

N/A: Not Applicable

Time Scale: 0.20 sec/div **Amplitude Scale:** Geo: 0.500 in./s/div

Printed: May 26, 2004 (V 3.11 - 3.11)

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Fig. 5. Example event report

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Table 1. Example Spreadsheet Analysis

	Distance to geophone								Frequency							
Time	Depth (m)	Transverse (m)	Longitudinal (m)	Sloped (m)	Peak transverse (cm/sec)	Peak vertical (cm/sec)	Peak longitudinal (cm/sec)	PVS (cm/sec)	Transverse (Hz)	Vertical (Hz)	Longitudinal (Hz)	Long distance (X)	Log PVS (Y)	XY	$X2$	$Y2$
8:19:12	2.896	4.262	1.651	5.412	1.277	2.682	0.639	2.835	39	17	32	0.733	0.453	0.332	0.538	0.205
8:19:23	2.896	4.257	1.651	5.407	1.022	2.554	0.766	2.580	26	17	51	0.733	0.412	0.302	0.537	0.169
8:19:34	2.896	4.251	1.651	5.402	1.149	2.809	0.639	2.860	15	20	64	0.733	0.456	0.334	0.537	0.208
8:19:45	2.896	4.245	1.651	5.398	1.405	2.426	0.639	2.480	64	17	100	0.732	0.394	0.289	0.536	0.156
8:19:56	2.896	4.239	1.651	5.393	1.149	2.682	0.511	2.758	26	18	57	0.732	0.441	0.322	0.536	0.194
8:20:06	2.896	4.233	1.651	5.389	1.277	2.682	0.766	2.707	51	15	28	0.731	0.433	0.316	0.535	0.187
8:20:17	2.896	4.228	1.651	5.384	1.149	2.682	0.766	2.733	34	18	24	0.731	0.437	0.319	0.535	0.191
8:20:28	2.896	4.222	1.651	5.380	1.022	3.065	0.766	3.116	32	23	28	0.731	0.494	0.361	0.534	0.244
8:20:39	2.896	4.216	1.651	5.375	1.532	2.554	0.894	2.605	26	11	43	0.730	0.416	0.304	0.533	0.173
8:20:50	2.896	4.210	1.651	5.370	1.149	2.554	0.639	2.631	43	17	57	0.730	0.420	0.307	0.533	0.176
8:21:01	2.896	4.204	1.651	5.366	1.022	2.809	1.022	2.937	34	16	37	0.730	0.468	0.341	0.532	0.219
8:21:33	2.896	4.187	1.651	5.352	1.277	3.065	0.894	3.065	39	11	47	0.729	0.486	0.354	0.531	0.237
8:21:44	2.896	4.181	1.651	5.348	1.149	2.937	0.766	2.963	51	12	39	0.728	0.472	0.343	0.530	0.222
8:21:55	2.896	4.175	1.651	5.343	1.277	2.809	0.766	2.809	37	17	27	0.728	0.449	0.327	0.530	0.201
8:22:06	2.896	4.170	1.651	5.339	0.894	2.299	0.766	2.345	100	12	39	0.727	0.370	0.269	0.529	0.137
8:22:16	2.896	4.164	1.651	5.334	1.149	2.426	1.277	2.477	18	10	34	0.727	0.394	0.286	0.529	0.155
8:22:27	2.896	4.158	1.651	5.330	1.022	2.426	0.766	2.493	73	11	57	0.727	0.397	0.288	0.528	0.157
8:22:38	2.896	4.152	1.651	5.325	1.277	2.809	0.894	2.835	20	17	34	0.726	0.453	0.329	0.528	0.205

Table 2. Recommended Threshold of Damage (Wiss 1981)

Class	Description	PPV (mm/sec)
I	Structures of substantial construction	100
II	Relatively new residential structures in sound condition	50
III	Relatively old residential structures in poor condition	25
IV	Old residential structures in very poor condition	12

The governing PVS thresholds employed throughout this paper are based on the charts of PPV-frequency envelopes from the United States Bureau of Mines (USBM) and the Office of Surface and Mining (OSM). These thresholds are the governing criteria for the onset of cosmetic damage to one or two-story residential structures such as the cracking of plaster or wallboard (Dowding 1996). Note that these charts indicate that structures are more sensitive to low-frequency vibrations (especially less than 10 Hz), and if the frequency of the vibrations is low, a lower governing PPV should be adopted. Table 2 presents an example of governing limits of PPV based on the type and status of the structure (Wiss 1981). The recommended safe level for residential buildings in the United States and Canada is 50 mm/sec (2 in./sec) and in Sweden is 75 mm/sec (3 in./sec) for construction blasting (Wiss 1981).

Buried structures, in contrast to above ground structures, can tolerate much higher levels of vibration. Dowding (1996) presented three case studies of buried structures that were subjected to high levels of PPVs [as high as 193 mm/sec (7.6 in./sec)] without any reported damage. He also presented a theoretical explanation for the response of restrained structures. In his views, the ground strains and controls the response of the buried or restrained structures, whereas unrestrained structures (above ground) have the capacity to amplify selectively incoming ground motions. The three case studies involved blasting near a concrete culvert, a pressurized gas pipeline, and a pressurized water pipeline. The gas and waterlines experienced velocities as high as 168 and 193 mm/sec (6.6 and 7.6 in./sec), respectively, without any leak or loss of pressure. All three projects involved inspection for blast effects. The pipelines were inspected for leaks, and the culvert was inspected for cracks. No failure had been reported since the blasting took place. In fact, all the steel pipelines were operating during the testing and blasting that produced the above-mentioned velocities (Dowding 1996). Based on Dowding's research, the PVS control limit for pipelines and buried structures can be safely assumed at 125 mm/sec (5 in./sec), unless the existing pipeline is in poor structural condition.

Of course, if the existing pipelines and structures are in poor structural condition, lower governing limits should be used. As with any analytical prediction used in geotechnical engineering, the results are most effective as an aid to engineering judgment and experience (Atalah 2004).

Research Findings

The ground vibrations findings are presented here in two groups: (1) PPV versus frequency; and (2) PVS versus distance from the trencher tip.

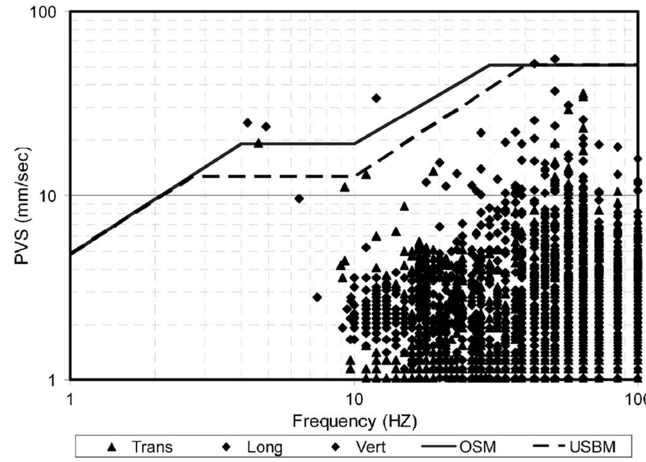

Fig. 6. PVS versus frequency for the five trenching projects

PPV versus Frequency

Fig. 6 presents the collected vibration data for the combined five trenching jobs in terms of PPV versus frequency and the threshold lines established by USBM and OSM. Only four events of the 1,306 events (shown in Fig. 6) had PPV components higher than these established thresholds. For this paper, the adopted PVS governing limit for residential buildings can be safely assumed as 50 mm/sec (2 in./sec), because the frequency readings for more than 98% and 80% of the collected vibration data were higher than 10 Hz and 30 Hz, respectively, as shown in Fig. 6. Fig. 7 shows PPV versus frequency for the hoe ram job in Fremont, and it indicates that few events had PPV components that were higher than the above-cited thresholds. The geophones in these events were located less than a half-meter from the hammer inside the trench.

PVS versus Distance from the Trencher Tip

Linear regression analysis was conducted to investigate the relationship between the following two variables: (1) Log of sloped distance between boom tip and geophones; and (2) log of PVS. The correlation coefficient for the combined data from the five jobs was −0.56, which indicates a moderate correlation between the two variables. The correlation coefficients between the two

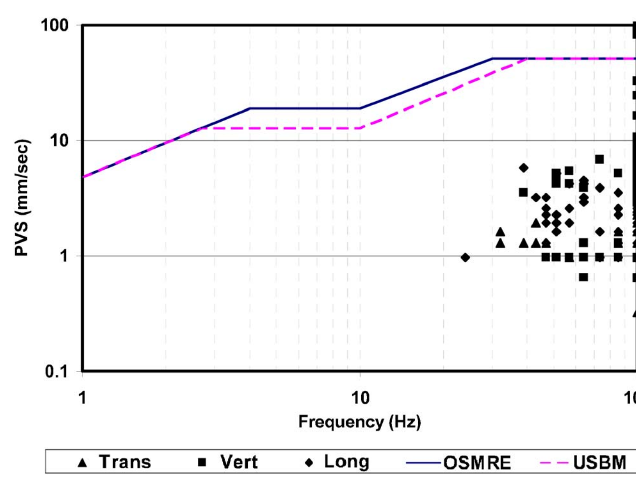

Fig. 7. PVS versus frequency for hoe ram project

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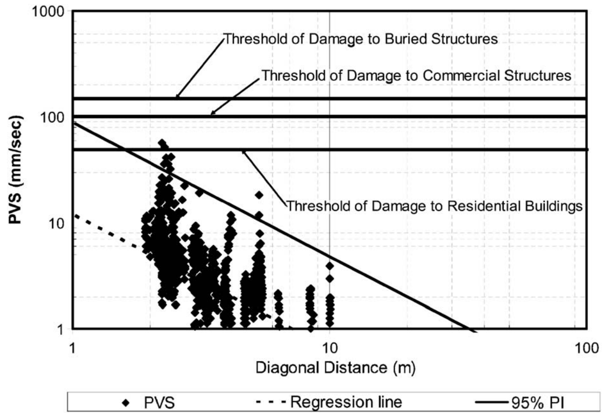

Fig. 8. PVS versus distance from the trencher tip for all the combined vibration data

variables for the Findlay, Fremont, Risingsun, first Bowling Green, and second Bowling Green sites were −0.65, −0.13, −0.67, −0.65, and −0.66, respectively. These coefficients suggest that the regression line is moderately predictive of the level of PVS at a given distance from the trencher tip—except for the Fremont job, where the correlation was weak.

Because the correlation in the hoe ram job was weak (correlation coefficient ≈ 0), conclusions about the safe distance from the hoe ram cannot be drawn. The reason for this weak correlation may be the method by which the hoe ram breaks the rock. The short cycles between the chipping actions of the trencher teeth provide a constant source of vibrations. In contrast, for the normal hoe ramming operations, the hammer chisels and pounds the rock at the same spot for a few moments until the hammer ultimately fractures and breaks the rock. During this period of chiseling and pounding, the seismograph senses and records a large number of events of low-in-magnitude PPVs. Whenever the rock is broken, an event or two of higher movements are recorded. During the above-mentioned chiseling, cracking, and breaking cycles, the distance from the hoe ram tip to the monitoring point does not change. To reduce this problem in future research, it may be helpful to raise the trigger level of the seismograph to around 10 mm/sec (0.4 in./sec) so that it records only the higher-level PPV.

Fig. 8 presents the PVS versus distance from the trencher boom for the combined data from the five trenching jobs. The regression line is the linear regression line that represents the relationship between PVS and distance from the trencher boom. The 95% upper-limit PI shown in Fig. 8 indicates the line below which 95% of the PVS values are predicted to be. The horizontal lines at PVS=50, 100, and 125 mm/sec (2, 4, and 5 in./sec) are the thresholds stated earlier for damage to residential, commercial, and buried structures, respectively. The regression line intersects the 50 mm/sec (2 in./sec) horizontal line around the 0.30 m (1 f) distance from the trencher tip. Eq. (2) represents the relationship between the two variables: PVS and the distance between boom tip and geophones (D)

$$\log(\mathrm{PVS}) = 1.08 - 1.265 \log(D) \tag{2}$$

The line of 95% upper-limit PI shown in Fig. 8 indicates the following:

- There is a 95% probability that residential structures in sound condition are safe at a distance of 1.50 m (5 f) or more from the trencher tip, because the 95% PI line intersects the safe limit for residential structures of 50 mm/sec (2 in./sec) around 1.50 m (5 f).
- There is a 95% probability that buried structures are safe at a distance of 1.00 m (3.3 f) or more from the trencher tip, because the 95% PI line intersects the safe limit for buried structures of 125 mm/sec (5 in./sec) at 1.00 m (3.3 f).
- Relatively old residential structures in poor condition and historical buildings have lower thresholds for damage than the above-cited structures; therefore, a longer safe distance is needed. There is a 95% probability that these buildings are safe at a distance of 5 m (16 f) or more from the trencher tip.

Conclusions

In medium-to-high-strength rock similar to the encountered rock in this research, there is a moderate correlation between the distance from the excavation spot to nearby structures and the level of vibration (in terms of PVS) for rock trencher operations. A safe distance of 1.50 m (5 f) is recommended for residential structures if they are in sound structural condition. In addition, the results of the statistical analysis suggest a safe distance of 1.00 m (3.3 f) for buried structures. Rock trencher excavation should not be permitted at shorter distances. Most rock formations and main underground pipes are deep enough and far enough away from buildings, which suggest that most residential or commercial buildings are relatively safe. Although ground vibrations (from a trenching operation) may be noticeable to a person standing on the surface close to a rock trenching operation, the levels of vibrations are unlikely to damage nearby structures, except those at extremely close distances. The overall finding of the analysis is that vibrations from the rock trenchers quickly fall to levels that do not cause cosmetic damage to buildings as the distance from the trencher increases. This risk dissipates significantly and quickly as the distance from the excavation spot increases. This knowledge will not only help contractors avoid causing structural damage, it may also help investigators ascertain whether such damage was likely caused by construction vibrations in owner/contractor disputes.

The statistical analysis of the collected data indicated that there was no correlation between the distance from the tip of the hammer and the level of vibration in the hoe ram excavation. However, in this case, the levels of the recorded PPV and PVS were mostly lower than the thresholds of damage established by OSM and USBM.

The limitations of the study include lack of specific data about the rock characteristics, which affects the slope of the relationship line between log (PPV) and log (distance). However, it is a valid hypothesis that the strength of excavated rock is medium-to-high. The safe distance conclusions are based on the aggregate data from the five projects, which reduce the impact of this lack of the specific data. Therefore, the research adds to the body of knowledge about rock-trenching vibration. Finally, more studies that collect data about the rock characteristics are recommended. The correlation level between the two variables is moderate in this study; therefore, its findings should be augmented with engineering judgment and experience.

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