3-2004

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Repository Citation

Atalah, Alan; Hadala, Paul; and Sterling, Ray, "Ground Vibration Associated with Pipe Bursting" (2004). *Construction Management Faculty Publications*. 8.
https://scholarworks.bgsu.edu/construct_mgt_pub/8

SESSION 7B-3

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Ground Vibration Associated with Pipe Bursting

By

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Abstract

Pipe bursting is a trenchless pipe replacement technique that offers advantages of low cost, reduced surface disturbance, and the ability to replace an old pipe with a new pipe of equal or larger diameter and capacity. Concerns about the use of the method have centered principally on the ground movements and vibrations produced by the technique – particularly when existing pipe is being replaced by a larger diameter pipe – and also on any damage experienced by the replacement pipe as it is being pulled into the ground. These concerns motivated the Trenchless Technology Center (TTC) to conduct a research project to study the effect of pipe bursting on nearby utilities, pavements, and structures.

The focus of this paper is the vibration produced by the pipe bursting process and the safe distance for nearby utilities, pavements, and structures from the bursting head. The maximum velocity experienced by a point on or in the ground has been found by others to be a good indicator of structural damage potential resulting from other construction processes such as blasting and pile driving. A similar approach has been employed to determine the safe distance from the pipe bursting operation. Two perpendicular horizontal and vertical components of velocity were measured as a function of time at many points at varying distances from the head of the replacement device. This was done for several different replacement methods, pipe sizes, depths, types of pipes, and upsizings at eleven sites. Peak velocity versus distance relationships were developed and the results were compared to safe distance criterion used in the blasting industry and to data from other sources of construction vibration.

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Introduction

Trenchless pipe replacement (or pipe bursting, as it is commonly known) in the context of this paper is taken to include various static, hydraulic and dynamic methods of breaking an existing pipe and simultaneously installing, by pulling or pushing, a new pipe of equal or larger diameter. Pipe bursting involves the insertion of a cone shaped tool (bursting head) into the old pipe as shown in Figure 1. In a direct bursting operation, the head shatters the old pipe and forces its fragments into the surrounding soil by pneumatic, static, or hydraulic action. At the same time, a new pipe is pulled or pushed in (depending on the type of the new pipe) behind the bursting head. There are several variations of the process with different approaches to various aspects of the breakage and replacement.

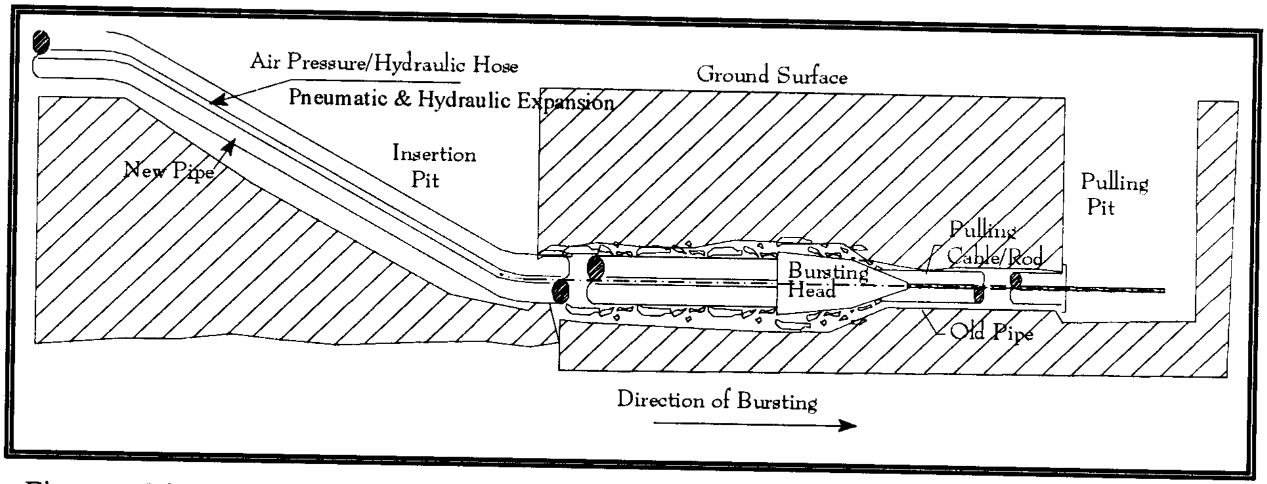

Figure 1 The Pipe Bursting Operation Layout

Fundamentals of Vibration Analysis

As the bursting head breaks the old pipe and is pulled forward, vibrations travel through the surrounding soil. Assuming that a component of the velocity at a point in the ground (the vibration wave) has a shape similar to the one shown in Figure 2, the following terms can be explained:

1. Maximum ground velocity -- more commonly known as Peak Particle Velocity (PPV) -- is the maximum rate of change of the particle displacement (U) with respect to time. The velocity amplitudes are given in units of inch/second (Dowding 1996). Since motion has

three (x, y, and z) components and is not purely sinusoidal as shown in the figure, the largest of the three maximum velocities is taken as the PPV.

2. Frequency of the vibration is the number of oscillations that occur in one second and is equal to 1/t. The frequency units are given in Hertz, where 1 Hertz equals 1 cycle/second (Dowding 1996).

3. Since velocity time histories are not purely sinusoidal but oscillatory, the dominant frequency is the frequency of the cycle containing the maximum particle velocity. It is calculated by doubling the duration of the half cycle that has the peak velocity (Dowding 1996). This dominant frequency is referred to as frequency throughout the paper.

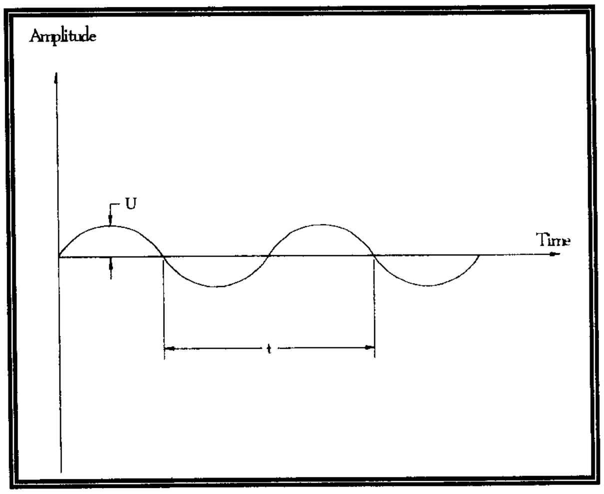

Figure 2 Typical Vibration Wave

The particle velocity can be visualized by the movement of a bobbing cork in water during a passage of a 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 (L), which is the horizontal direction from the source of vibration to the point of monitoring, (2) transverse (T), which is the perpendicular direction to the longitudinal one, and (3) vertical (V), which is the vertical direction perpendicular to both preceding direction planes. The peak vector sum (PVS) is the square root of the sum of squares of the three components. PVS can be expressed mathematically by the following equation:

$$\mathrm{PVS} = \sqrt{L^2 + T^2 + V^2} \qquad \text{Eq 1}$$

The potential for cosmetic cracking of buildings (or structural damage) due to construction and surface mine blasting has been found to correlate most closely with the peak particle velocity (PPV) of a particle in the ground as opposed to its displacement or acceleration (Dowding 1996).

This is likely because in one-dimensional plane wave propagation in a linear elastic medium, maximum strain is directly proportional to maximum particle velocity and brittle materials such as plaster, wallboard, brick, and plain concrete tend to crack at particular strain levels. Obviously cosmetic cracking occurs at lower PPV levels than structural damage. It has been found that the peak particle velocity correlates with the scaled distance from the source of vibration to the point of monitoring. The scaled distance is the distance divided by the square or the cubic root of the energy released to cause the vibration.

The Natural Frequency of Superstructures

It has been found that different superstructures respond differently to the same ground velocity versus time history. The maximum amplitude of structure's response to construction vibration occurs when the frequency of the vibration of the ground is equal to the natural frequency of the structure. The natural frequency of structure is the inverse of the time required for the structure to complete one cycle of free vibration. The following simple equation can be used to estimate the natural frequency (f_n) of buildings:

$$f_n = \sqrt{\frac{L}{0.05h}} \qquad \text{Eq 2}$$

where L=the width of the structure and h=the height of the structure (Newmark and Hall 1982). A study of data measured by the U.S. Bureau of Mines on 23 structures (20 of them were wooden structures) indicated that the average frequency was 7 Hz with a standard deviation of 2.2 (Dowding 1996).

Human Response to Vibration

Cosmetic cracking of residential structures is unlikely until particle velocities exceed 1 to 4 inches/second depending on the frequency of the motion and the frequency of the structure. On the other hand, humans complain about particle velocities less than 0.5 inch/second (Dowding 1996). Humans are much more sensitive to vibrations than structures. The response of a person on the second floor inside a building to ground vibration is a very complicated issue for the following reasons:

- If the excitation frequency is close to the natural frequency of the building, the person on the second floor feels much more vibration than the person on the ground does. If the ground excitation frequency is above the natural frequency of the building, the opposite is expected.
- If the duration of the exposure to the vibration is longer, a person becomes aware of the motion at lower levels of PPV.

Siskind et al. (1980) recast Wiss and Parmelee (1974)'s results in a plot of PPV against exposure time as shown in Figure 3. Wiss and Parmelee (1974) surveyed a population of respondents exposed to different levels of PPV for different exposure times. They categorized the perception of vibration into three levels: strongly perceptible, distinctly perceptible, and barely perceptible. For example, if more than 50% of the respondents stated that they were more than moderately annoyed by PPV of 1 inch/second for exposure time of 1 second, it was plotted on the strongly perceptible curve. The 95% lower limit prediction interval for strongly perceptible PPV was statistically calculated by Siskind (1980); it was 0.5 inch/second.

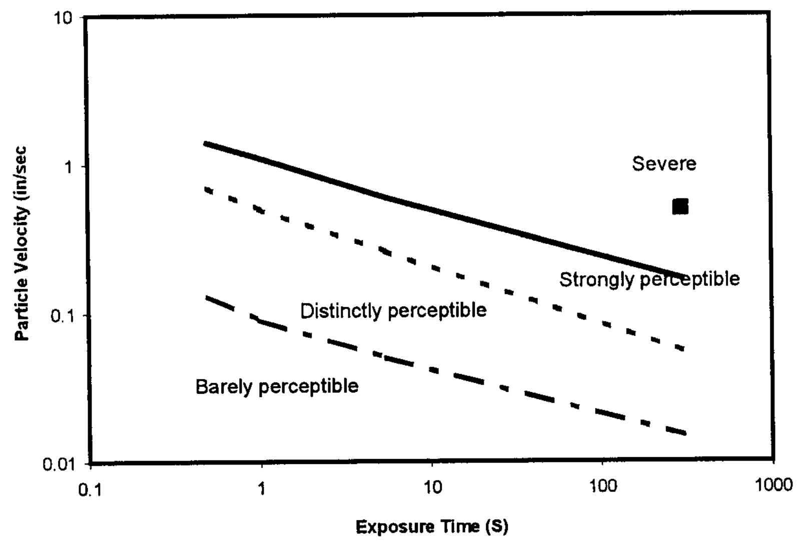

Figure 3 Human Response to Transient Pulses of Varying Duration after Wiss and Parmelee (1974) as Reported by Siskind et al. (1980)

Velocity Attenuation with Distance

Figure 4 presents the intensities of vibration from various construction operations. All the data presented in the Figure was obtained from actual construction sites. The vibration data were recorded on the surface of the ground or in residential or small commercial buildings. The response of a massive structure would be less. The graph represents approximate values, but it illustrates the PPV attenuation (i.e. decrease) with distance for the different sources. The slopes of the lines are also dependent upon the soil conditions (Wiss 1980). The threshold of damage to buried structures, pavement, and residential buildings adapted by Wiss are imposed on the graph.

The attenuation line of the relationship between PPV and the scaled distance from the source of the vibration (D) can be presented mathematically by any of the following equations:

$$\text{Log (PPV)} = C_1 + S \text{ Log (D)} \qquad \text{Eq 3}$$

or

$$\text{PPV} = C_2 \cdot (\text{D})^S \qquad \text{Eq 4}$$

Where C_1, C_2, and S are constants and S is the slope of the relationship line between log of PPV and log of D; S according to the hypothesis is negative. C is the PPV at a scaled distance of 1 unit.

The objective of this portion of the research is to determine whether this type of relation holds and, if it does, to establish the values of C and S or their potential ranges for the pipe bursting operation. This allows estimation of the distance from the bursting head farther than which buried pipelines, surface structures, or pavement will be safe from damage. The cut off distance can be estimated based on a controlling PPV or a controlling PPV/frequency chart or table (provided the structures are in sound condition). The most restrictive (controlling) criteria are for the onset of cosmetic damage to one or two story residential structures such as the cracking of plaster or wallboards.

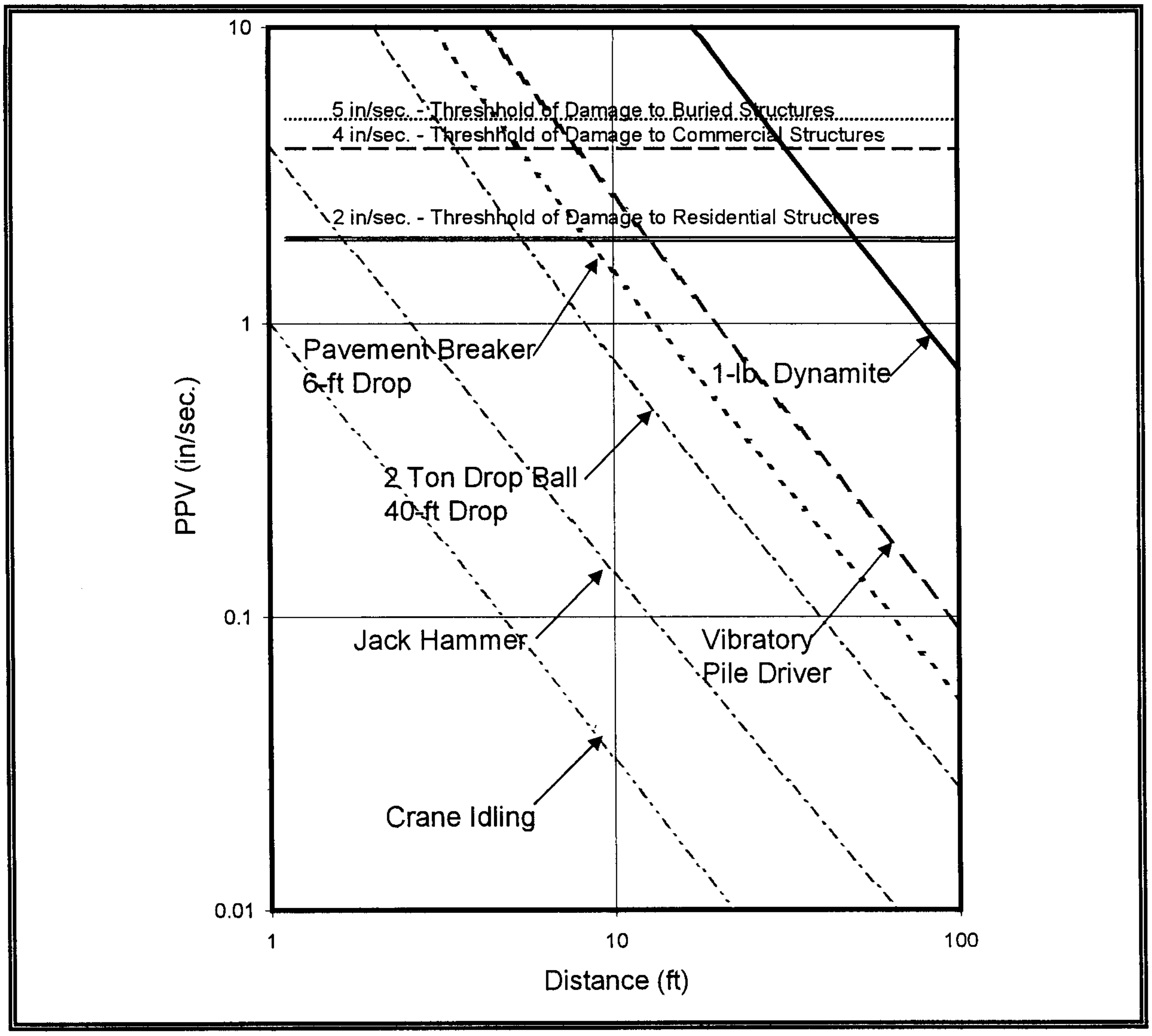

Figure 4 Velocity Attenuation Lines for Various Construction Sources (Wiss 1980).

Construction Vibration Control

The frequency of the motion at a point is a very important factor to be considered because structures respond differently to a given peak particle velocity depending on its frequency. For many structures, a wave with a frequency close to the fundamental natural frequency of a structure has greater damage potential than the one with higher frequency. Vibration in the blasting and construction industries is usually controlled by one of two controlling techniques: (1) relationships between the maximum allowable PPV and frequency and (2) maximum PPV independent of frequency. The first control technique establishes a relationship between PPV and frequency in the form of graphs or tables and is the more rational of the two. There are several PPV-frequency envelopes adapted by different standards making organizations such as the US Bureau of Mines (USBM) and the US Office of Surface Mining (OSM) in the US, DIN 4150 in Germany, BS 6472 in UK, GFEE in France, etc. The cut-off standards used in this paper are based on the USBM and OSM PPV-frequency envelopes.

The second control technique provides a certain limit that the PPV should not exceed. Many US and Canadian investigators recommend safe level of 2 inch/second for residential buildings; Sweden investigators recommend 3 inch/second (Wiss 1980). Dowding (1996) reported that buried structures could withstand particle velocities far in excess (at least 5.5 to 8.5 inch/second) of the typical 2 inch/second cautionary level. Usually, it depends on the type and status of the structure. For instance, a pipeline buried in rock may require a control limit between 5 to 10 inch/second while a plaster and lath wall may require a control limit of 0.5 inch/second (Dowding 1996). When using this second method, it is important that the frequency characteristics and duration of the motion be similar to those used in the tests in which the criteria were developed.

Dowding (1996) presented three case studies of buried structures subjected to a high level of PPV from blasting (as high as 7.6 inch/second) without any reported damage. He also presented a theoretical explanation for the response of restrained structures. The explanation is based on the concept that the ground constrains and possibly damps the response of the buried or restrained structures and those unrestrained above ground structures 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 water lines experienced velocities as high as 6.6 and 7.6 inch/second, 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 has been reported since blasting took place. In fact, all the steel pipelines were operating during the blasting that produced the above mention velocities (Dowding 1996).

The Southwest Research Institute (SwRI) conducted a blasting research program to develop procedures for predicting the maximum stresses in buried steel pipelines nearby explosive detonations in 1981. The research established relationships between the different variables that affect the level of displacement at a distance from the source of the explosion. The ground movement depends on (among many other variables) the nature of source of the explosion (point source, parallel line, angled line, grind line detonations, etc.). The relationship for point source detonations can be summarized by the following equation:

$$\frac{U}{c}\left(\frac{P_o}{\rho c^2}\right)^{0.5} = .00489\left(\frac{W_e}{\rho c^2 R^3}\right)^{0.790} \qquad \text{Eq 2.5}$$

Where $10^{-11} < w_e/\rho c^2 R^3 < 10^{-1}$ and

U = Peak radial soil particle velocity (feet/second)

R = Standoff distance (feet)

W_e = Explosive energy release (ft-lbs.)

ρ = Mass density of soil (lb.-second^2/foot^4)

c = Seismic P-wave velocity in soil (feet/second)

P_o = Atmospheric pressure (lb./foot^2) (Esparza et al 1981)

The PPV control limit employed in this study for pipelines and buried structures can be safely assumed at 5 inch/second unless the existing pipeline is in a very poor structural condition. For buildings and pavements, it can be taken as 2 inch/second. As with any analytical prediction used in geotechnical engineering, the results are most effective as an aid to engineering judgement and experiences (Chapman et al 1996). The analysis and discussion of the collected vibration data throughout the project is presented later in the paper.

Research Methodology

The principal data collected for each test site visited were: peak particle velocity and permanent ground surface movements. The latter are not presented in this paper. The procedures for each site were divided into three phases of activities. They were pre-bursting activities, during bursting activities, and after bursting activities.

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Pre-bursting Activities

Before the bursting took place, the following activities were performed:

- Collecting all available relevant information about the test site such as type of soil, depth, and type of ground surface, and size of pipe, percent increase in diameter, water table elevation, etc.
- Marking the centerline of the old pipe on the ground surface and measuring the length of the bursting run.
- Developing a monitoring point layout plan, similar to the one in Figure 5A, according to the actual site conditions, such as the length of the run, accessibility, etc. Later in the project, the typical layout was changed to that of Figure 5B for reasons discussed later in the paper.

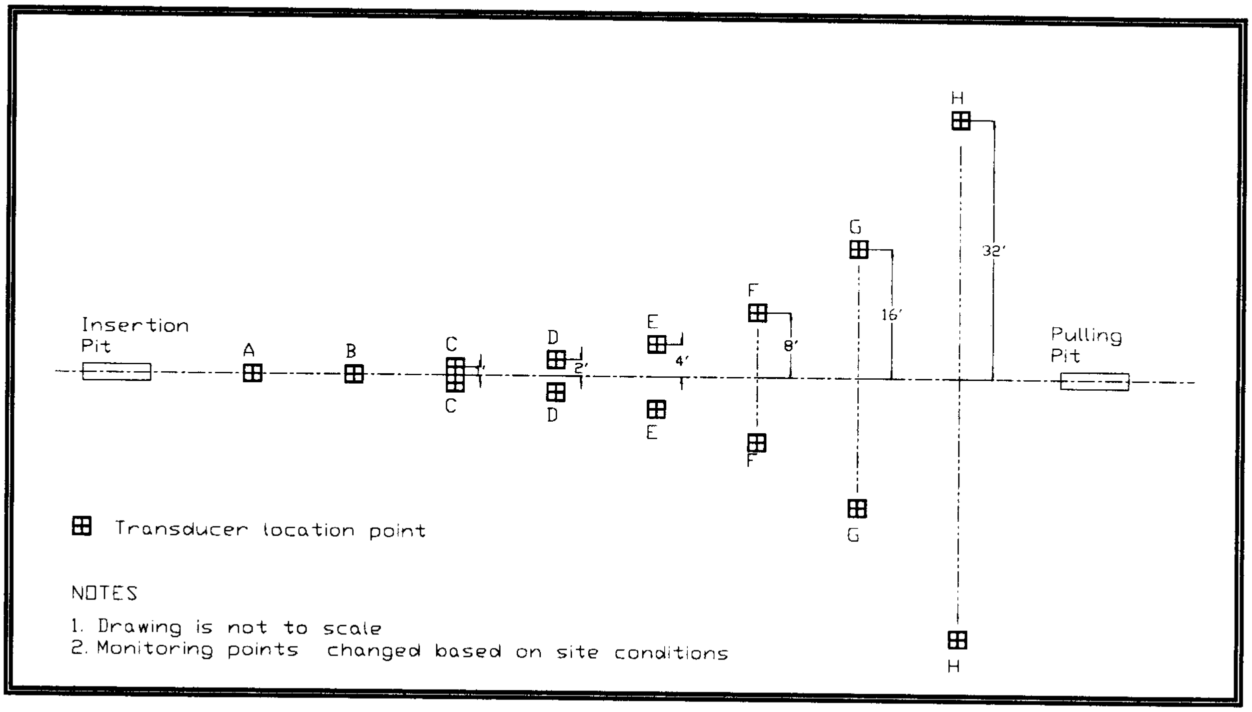

Figure 5A Initial Monitoring Plan for the Field Test Sites

- Marking the monitoring points on the ground surface according to the plan developed in the previous step.
- Collecting soil samples.
- Surveying and recording the elevation of the points along the pipe centerline.
- Marking the replacement pipe every ten feet.

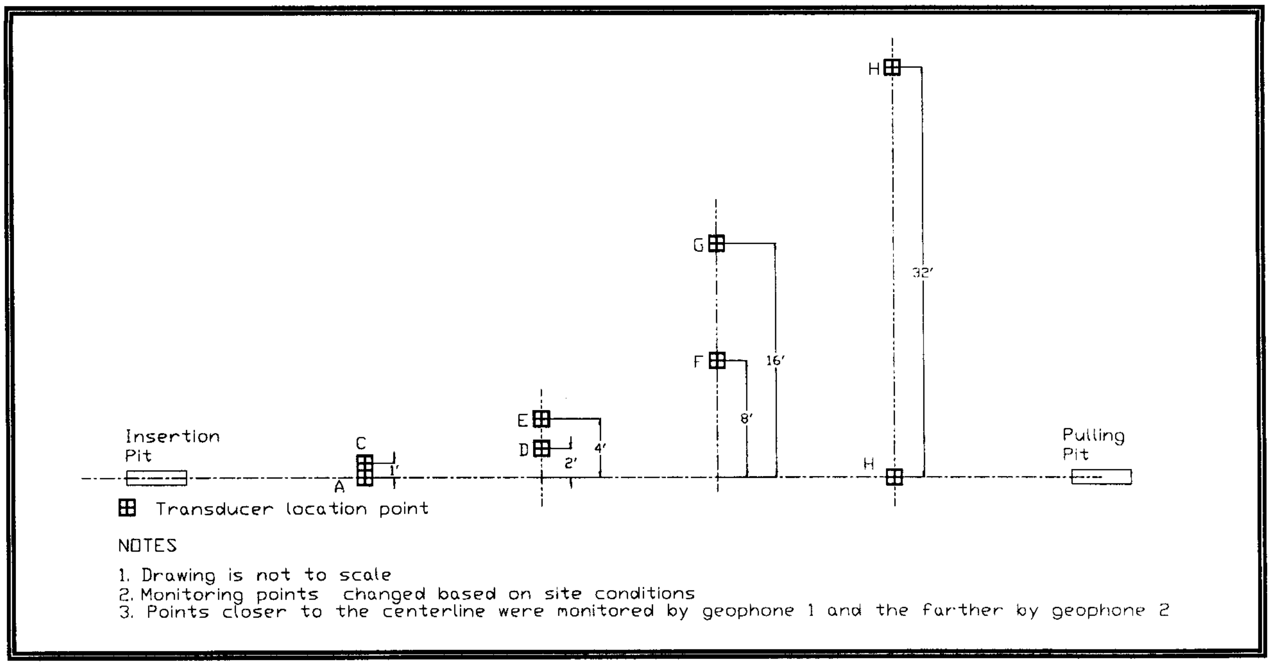

Figure 5B Modified Monitoring Plan for the Field Test Sites

During-bursting Activities

During bursting, the following activities were performed:

- Placing the geophones at points A and B on the centerline of the pipe and monitoring and recording the Peak Particle Velocity (PPV) as the bursting head was inserted through the pipe and passed under the geophones
- Recording the time and station number, as each mark on the replacement pipe passed by the station zero. The watch used was synchronized with the clock of the seismograph.
- Placing one microphone at six feet and the second at 30 feet from the pulling pit to record the noise levels from the machine. Observation and measurement quickly confirmed that the major noise source in a bursting operation is typically the compressor. Therefore, pipe bursting does not tend produce any noise higher than that from a conventional construction site employing a compressor. At later sites, the microphone was not used in order to utilize all the machine's memory to record as many events as possible.
- Moving the geophones to the points C at one-foot offset to measure the vibration levels as the bursting head passed by the points C.
- Repeating the previous step for points D, E, F, G, and H at the offsets indicated in Figure 5A or 5B.

- Recording the ground surface conditions (grass, pavement, driveway, sidewalk, etc.) and the position of the bursting head for any unusual events.
- Collecting detailed information about the hydraulic expansion cycle from the bursting machine operators for the hydraulic expansion and static pull systems. This activity was only performed on a limited number of sites because of shortage of site personnel.

Post-bursting Activities

After bursting, the following activities were performed:

- Re-surveying the elevation of the points along the pipe centerline.
- Analyzing the soil samples for soil type and a limited set of physical properties.

The vibration data were collected by an Everlert III seismograph from Vibra Tech Engineers, which allowed the simultaneous recording of data from two 3-axis geophones and two different microphones. The data were collected at locations above the centerline and at different offsets from the centerline as presented in Figures 5A and 5B. Times and bursting head locations were recorded during the bursting every ten feet using a watch synchronized to the clock in the seismograph. The seismograph can be run in four modes (single event, continuous, manual, and histogram), but only two modes were employed in this project: histogram and continuous. In order to utilize the limited memory of the seismograph to collect as much velocity data as possible as well as related data such as Peak Vector Sum (PVS), frequency, etc., the mode of monitoring was switched between the two modes. In the histogram mode, the seismograph recorded only the peak velocity for each time interval of 5 seconds using less memory than the continuous mode; however, it did not record the frequency and PVS data at every point. Therefore, frequency and PVS data were not available for every record. In the continuous mode, data were collected at a rate of 5 to 6 events per minute; each event recorded the PPV, PVS, frequency, and velocity time chart. In order to record as much vibration data as possible in the continuous mode, the typical monitoring plan shown in Figure 5B replaced the one shown in Figure 5A.

The seismograph has the following specifications:

- The particle velocity range is up to 10 inch/second
- The resolution is 0.005 inch/second
- The accuracy level is 3% at 15 Hz
- The sampling rate is standard 1024 samples per second per channel (8192 for 8 channel)
- The frequency response range is 2 to 300 Hz.

The data points associated with frequencies outside the range from 2 to 300 Hz or with particle velocity higher than 10 inch/second are not reliable because they are outside the specified operation range of the seismograph.

Table 3.1 lists the eleven test sites that were visited throughout the project. The table also includes the type of bursting system employed for each project, contractor, depth of cover, type and diameter of old pipe, soil type, diameter of the bursting head, monitored length, and monitoring time. The different upsizing percentages and the different soil conditions for each of the bursts prevent direct comparisons among the bursting systems.

Analysis Procedure

In the continuous mode, the seismograph records single events in sequence. For each event, the particle velocity is recorded for two seconds, and the PPV is the largest value recorded during the two seconds. In the histogram mode, the seismograph records the highest PPV value for the time span of 5 seconds. An event represents the highest PPV value every two feet of bursting head movement. The head position for each event was calculated through interpolation of the time/ station log. The geophone position for each event was recorded with all the relevant information such as depth, type of surface, etc. The data collected during the bursting for each job were tabulated in a spreadsheet. For each event, the vertical and horizontal distance between the bursting head and the geophone were calculated and added to the spreadsheet. The highest PPV component and its direction, PVS, and frequency were also added to the spreadsheet. In this paper, the expressions velocity and PPV mean the highest particle velocity component at each event. During the course of the project, the monitoring point layout plan was altered to the layout shown in Figure 5B, and the use of the microphone was eliminated to record more events in the continuous mode where the PVS and the frequency data were recorded for every point..

Table 1
Vibration Monitoring Test Sites

City and Street	Code Name	Bursting System		Original Pipe		Depth (ft)	Soil Type	Burster Φ (in)	HDPE Φ (in)	Length of the Run (ft)	Duration (hr:min)
		Type of System	Contractor	Type	Φ (in)						
Ruston 1	TTC Test Site # 1	Pneumatic	TT Technologies, Inc	VCP	8	6	Clay, clay-gravel, & sand	14.2	12.75	92	1:13
Ruston 2	TTC Test Site # 2	Static Pull, TRS	Kinsel Industries & Midsouth Trenchless, Inc.	VCP	8	6		15.5	12.75	92	1:59
Ruston 3	TTC Test Site # 3	Hydraulic Expansion.	Miller Pipeline Corp.	VCP	8	6	clay & silt	11.563	10.75	94	0:47
Ruston 4	TTC Test Site # 4	Pneumatic	TT Technologies, Inc	VCP	8	6		11.75	10.75	94	0:46
Baton Rouge, LA	Field Test Site # 1	Pneumatic	Magnolia Construction Co.	VCP	10	10	clay	14.5	10	270	3:25:17
Houston, TX - London St.	Field Test Site # 2	Pneumatic	PM Construction	VCP	6	3 - 11	clay	11	8.5	60	0:25:00
Houston, TX - Madrid St.	Field Test Site # 3	Static Pull	Kinsel Industries	VCP	6	6.5	clay	11	8.5	275	0:16:00
Houston, TX - New York St.	Field Test Site # 4	Static Pull, TRS	Kinsel Industries	VCP	6	9	clay	11	8.5	60	0:25:00
Tacoma, WA	Field Test Site # 5	Static Pull, TRS	Debco Construction	VCP	15	16	clay	22	20	270	1:16:49
Arlington, VA	Field Test Site # 6	Hydraulic Expansion	Miller Pipeline Corp.	RCP	10	10	clay	16	14	160	4:54:09
Minette Bay, AL	Field Test Site # 7	Static Pull, TRS	Midsouth Trenchless Inc.	VCP	8	5	clay	11	8.625	90	0:11:18

A summary of the vibration data was presented in two graphs for each job. The data analysis started with filtering the data for only the events that had a frequency recorded. The filtered data were used to plot the PPV or PVS versus the frequency associated with the peaks along with the USBM and OSM envelopes. This graph represented the compliance of the collected data with the standard blasting industry envelopes for the lower threshold of cosmetic building damage.

The data analysis continued with sorting the data according to the direction of the highest component then plotting the highest peak particle velocity (PPV) components and peak vector sum (PVS) versus the distance from the bursting head for every monitored event on a log/log scale. Regression analysis between log of the diagonal distance between the bursting head and the geophone and log of the PPV/PVS was conducted to calculate the regression parameters such as Sum Squares of Errors (SSE), Total Sum of Squares (SST), correlation factor, slope, intercept, 95% prediction interval (PI), etc. The 95% PI upper limit and the regression line were plotted together with the data points indicating the highest PPV attenuation line with distance from the source.

Results and Conclusions

The vibration data from all the projects have been compiled together and summarized in Figures 6 and 7. Almost all the measured ground vibrations were within the USBM and OSM threshold limits for building damage. In fact, only four readings with recorded frequency exceeded the threshold damage level, as shown in Figure 6, one of the readings (PPV=5.27) is unreliable because it was an anomalous reading and was considered to have been triggered by sources other than the bursting operation. Another two points are also unreliable because their frequencies were below 2 Hz, the specified frequency range for the seismograph. The fourth point is slightly above the OSM envelope with a frequency of 24 Hz and PPV of 1.93 inch/second. Only three data points, out of all the collected data points (2402) have PPV values higher than 2 inch/second. The first one is unreliable as discussed earlier, and the PPV of the other two points were 2.7 and 2.1, but no frequency data were recorded for them because they were recorded in the histogram mode. Only 88 points out of the 2402 points have PPV values higher than or equal to 1 inch/second.

The natural frequency of typical structures ranges from 5 to 11 Hz as presented earlier. 24 data points out of 832 points with recorded frequency have frequency of 11 Hz or less. 8 points out of these 24 data points were unreliable because their frequencies were less than 2 Hz. Only 7 data points out of the 832 data points were within the natural frequency range of typical structures. The highest PPV value among these seven data points was 0.1 inch/second. 97% of the data points with recorded frequency have frequency higher than the upper range of natural frequency for typical structures. 83% of these 832 data points have frequency higher than 30 Hz. This means that the majority of the frequencies of the pipe bursting vibrations are higher than the natural frequency of the building; therefore, higher allowable velocities could be permitted.

The pneumatic system is the only one that showed moderate correlation between the log of the PPV and the log of the distance from the bursting head. The velocity versus time histories recorded for this system, as shown in Figure 8, were more repeatable, less random, and quite different in appearance from those of the other systems. The slope of the regression line was steep; therefore, the velocity deteriorated quickly as the distance from the head increased, as shown in Figure 9. The range of data at a given distance is large but this is also characteristic of vibration data recorded in many other construction operations. The correlation coefficients between the two variables for the static pull (TRS) and the hydraulic expansion (Xpandit) systems were weak because of the duration of the energy releases in the machine cycle discussed in the next paragraph. However, the vibration levels were low and far below the USBM and OSM envelopes. The data on ground vibration is not comparable among the systems tested since the site conditions were different in every case. The overall finding is that ground vibrations at short distances from the bursting operation quickly fall to levels that will not cause even cosmetic damage to buildings. The tolerance of buried pipelines to vibration is typically much larger. In addition, 97% of the recorded frequencies are above upper limit of natural frequency range for typical residential structures and hence unlikely to cause damage.

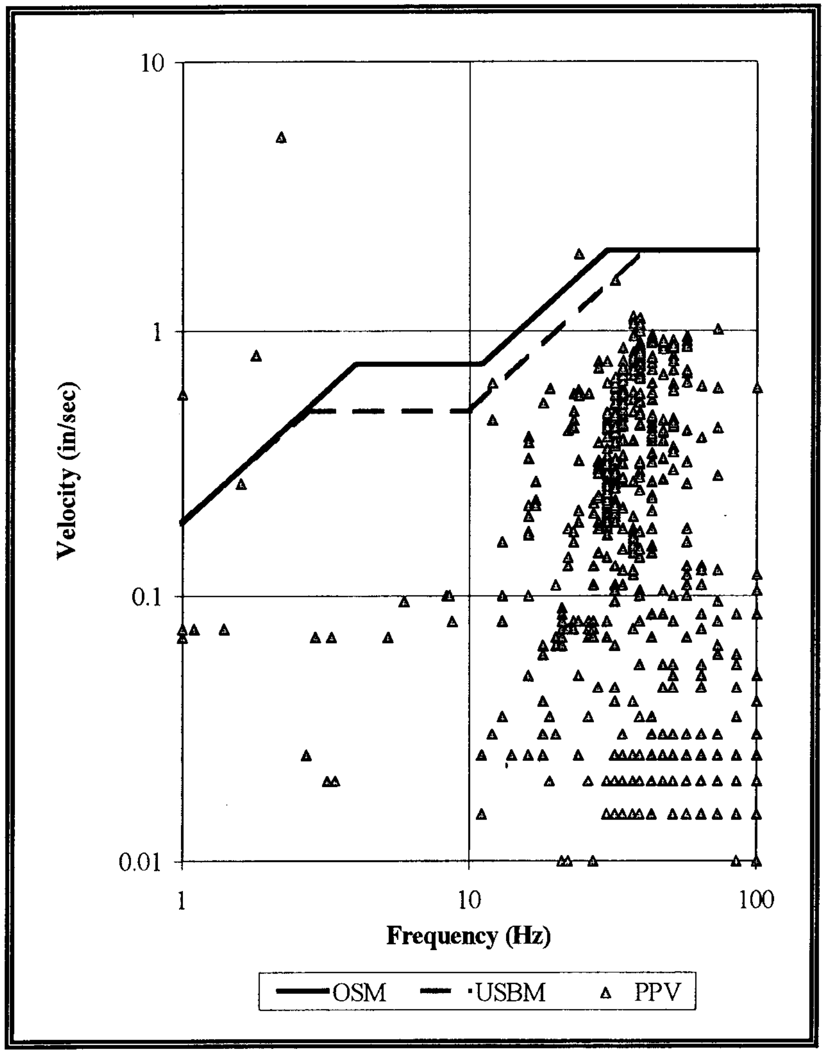

Figure 6 Compiled Peak Particle Velocity vs. Frequency for All the Test Sites.

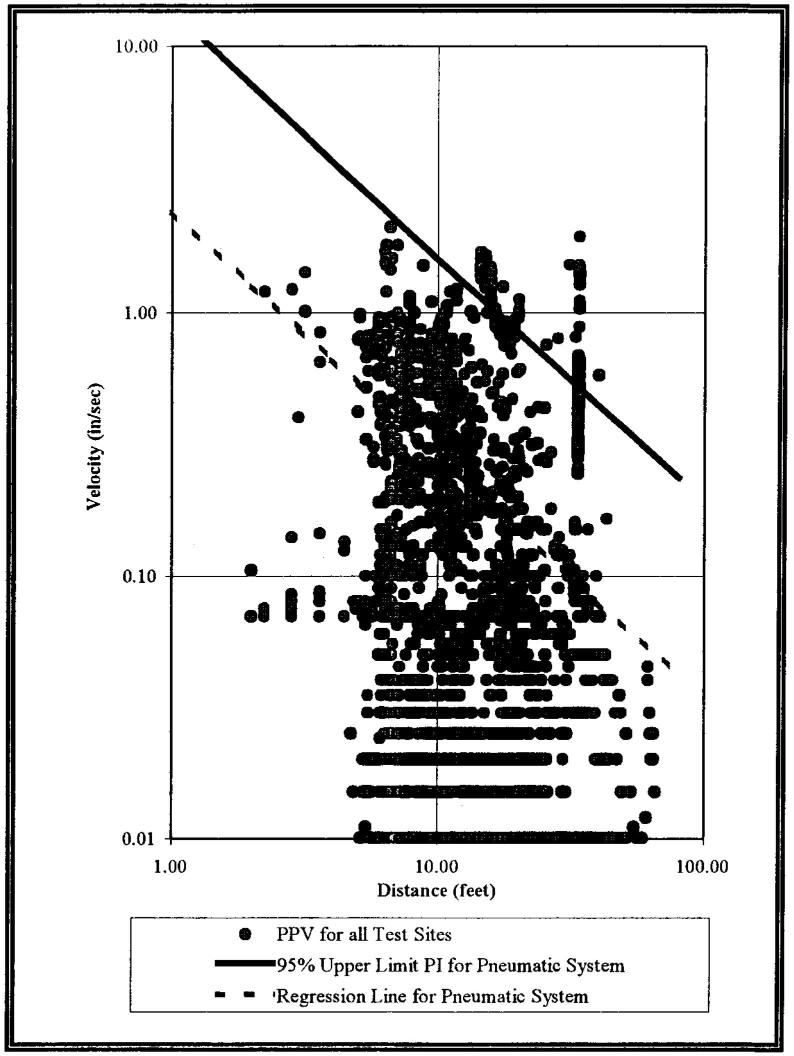

Figure 7 Compiled Peak Particle Velocity vs. Distance from the Head for All the Test Sites with the Regression Line and the 95% Upper Limit PI for the Pneumatic System

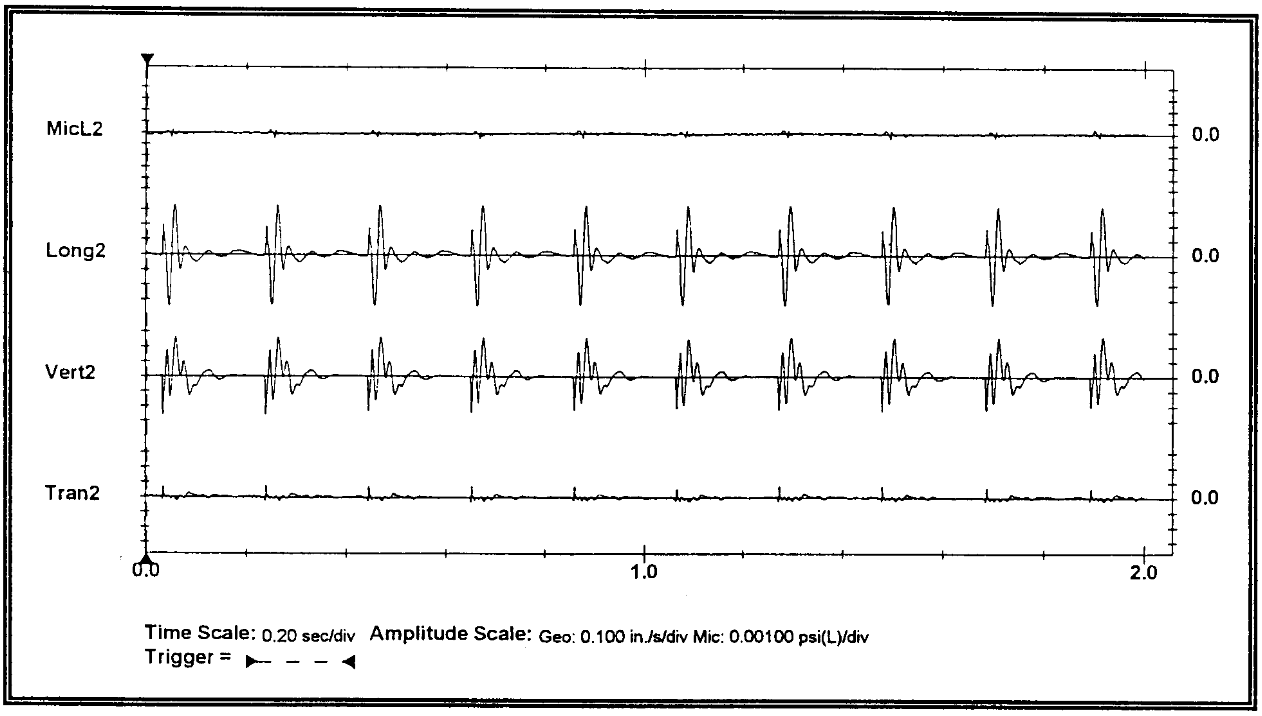

Figure 8 Velocity versus Time History for an Event from a Pneumatic Pipe Bursting Operation

The static pull (TRS) and hydraulic expansion (Xpandit) systems release their energy in cycles; each cycle lasts from a minute to a few minutes. The cycle starts with a high burst of energy for a few seconds to break the pipe. Then it takes at least a minute to start the next cycle. The seismograph monitors and records the vibrations resulting from the burst and their weak reflections throughout the cycle. The seismograph records the vibrations every five to ten seconds depending on the machine's monitoring mode. Therefore, one event records high velocity and a number of events record low velocity while the head and the geophone are essentially in the same location (the distance from the head is constant). The large number of events with low velocities dilutes the velocity readings recorded by the machine. This is believed to be the cause of the failure of the PPV and slant distance correlation hypothesis for these two systems. This does not happen with the pneumatic system that has an operating frequency of 200 to 500 cycles per minute. The pneumatic trenchless pipe replacement method is the only method designed to provide fast repeated impacts to the pipe to be burst. Consequently, there is less dilution of the velocity with the pneumatic system than with the other systems. This may be the reason why the velocities correlate better with distance.

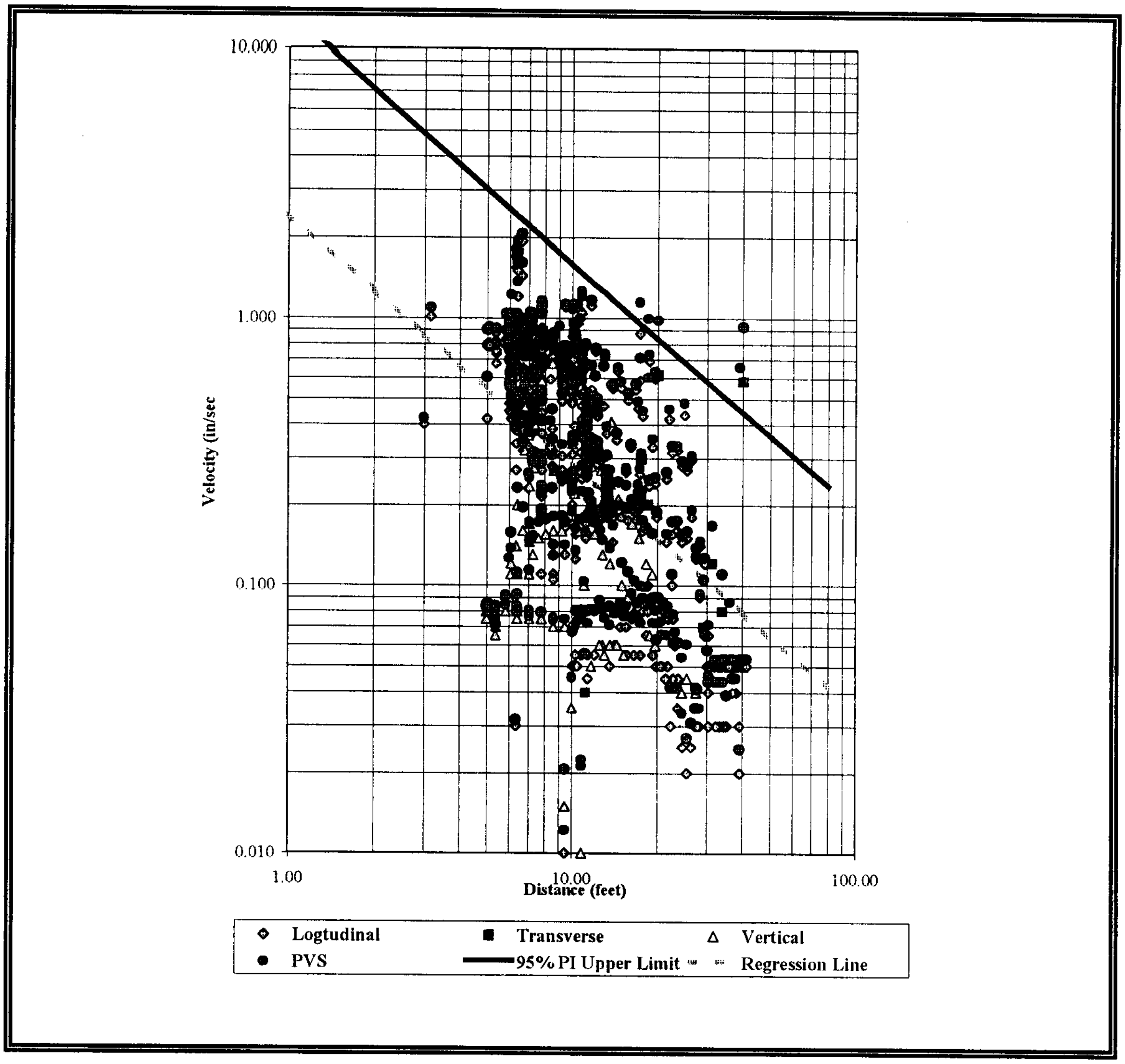

Figure 9 Velocity vs. Distance from the Head for All Test Sites that Employed the Pneumatic System

There are however other sources of energy release or impacts in all the methods that can produce some soil vibration and that can cloud the relationship against the distance from the bursting head. In the pneumatic method, vibrations may be transmitted from the head itself as well as the surface of contact with the pipe. Also, the back end of the air hammer in the pipe behind the head may also slap against the interior of the pipe and cause ground vibrations. For all the methods, the brittle fracture of the pipe ahead of the bursting head, sudden shears or collapses within the soil, and stick-slip along the soil-pipe interface may all cause some transmission of vibration energy.

Although the static pull (TRS) and hydraulic expansion (Xpandit) systems showed weak correlation between the PPV and the distance from the bursting head, the 95% prediction interval upper limit for the data collected from the pneumatic system (Figure 9) is a practical upper limit for these systems also. The majority of the PPV data collected from the static pull (TRS) and hydraulic expansion (Xpandit) systems were under this 95% upper limit, as shown in Figure 10. Figure 11 presents the 95% prediction interval upper limit for the data collected from the pneumatic system along with the attenuation lines of the velocity versus distance from different construction sources (Wiss 1980). Adapting the 95% prediction interval upper limit for the data collected from the pneumatic system as a conservative limit for the attenuation of velocity with distance from the head leads to the following results:

- The damaging level for buried structures (velocities higher than 5 inch/second) occurs at a distance less than 2.5 feet. Pipes closer than 2.5 feet from the line to be replaced should be exposed to provide stress relief to the existing pipe.

- The damaging levels for sensitive surface structures (velocities of 2 inch/second with frequency in the range from 30 to 100 Hz) are reached within distances of 8 feet from the bursting head. This will rarely be an issue when replacing pipes in a public right-of-way. 83% of the recorded frequencies were within the 30 to 100 Hz range.

The vibration levels present during trenchless pipe replacement will be dependent on the power/impact applied to the process. The reported results and their analysis reflect the equipment used at the sites monitored. Overall, it can be summarized that while ground vibrations may be quite noticeable to a person standing on the surface close to a trenchless pipe replacement operation, the levels of vibrations are very unlikely to be damaging except at very close distances to the trenchless pipe replacement operation.

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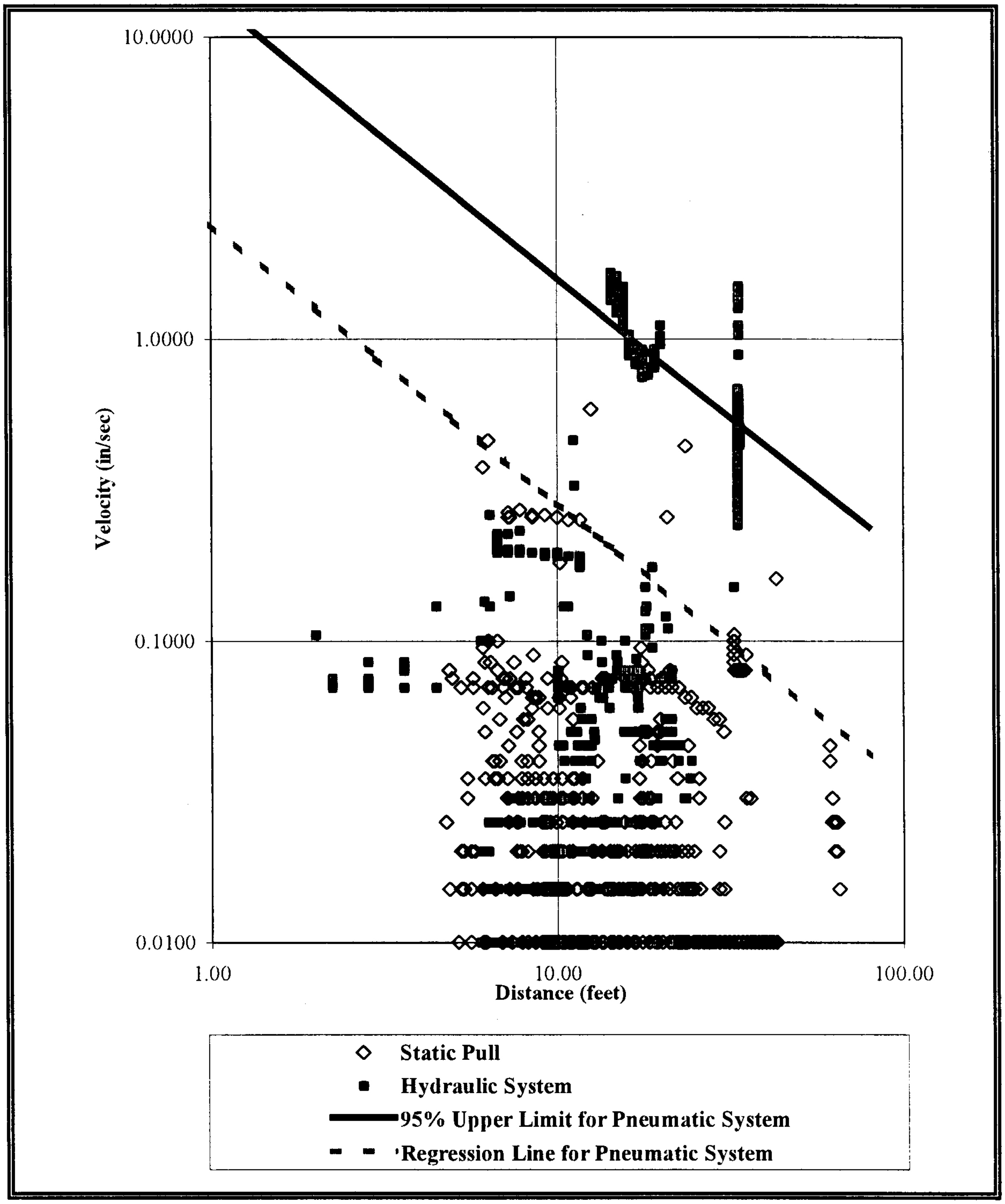

Figure 10 Compiled PPV from the Static Pull and Hydraulic Expansion Systems With the Regression Line and 95% Upper Limit PI for the Pneumatic System

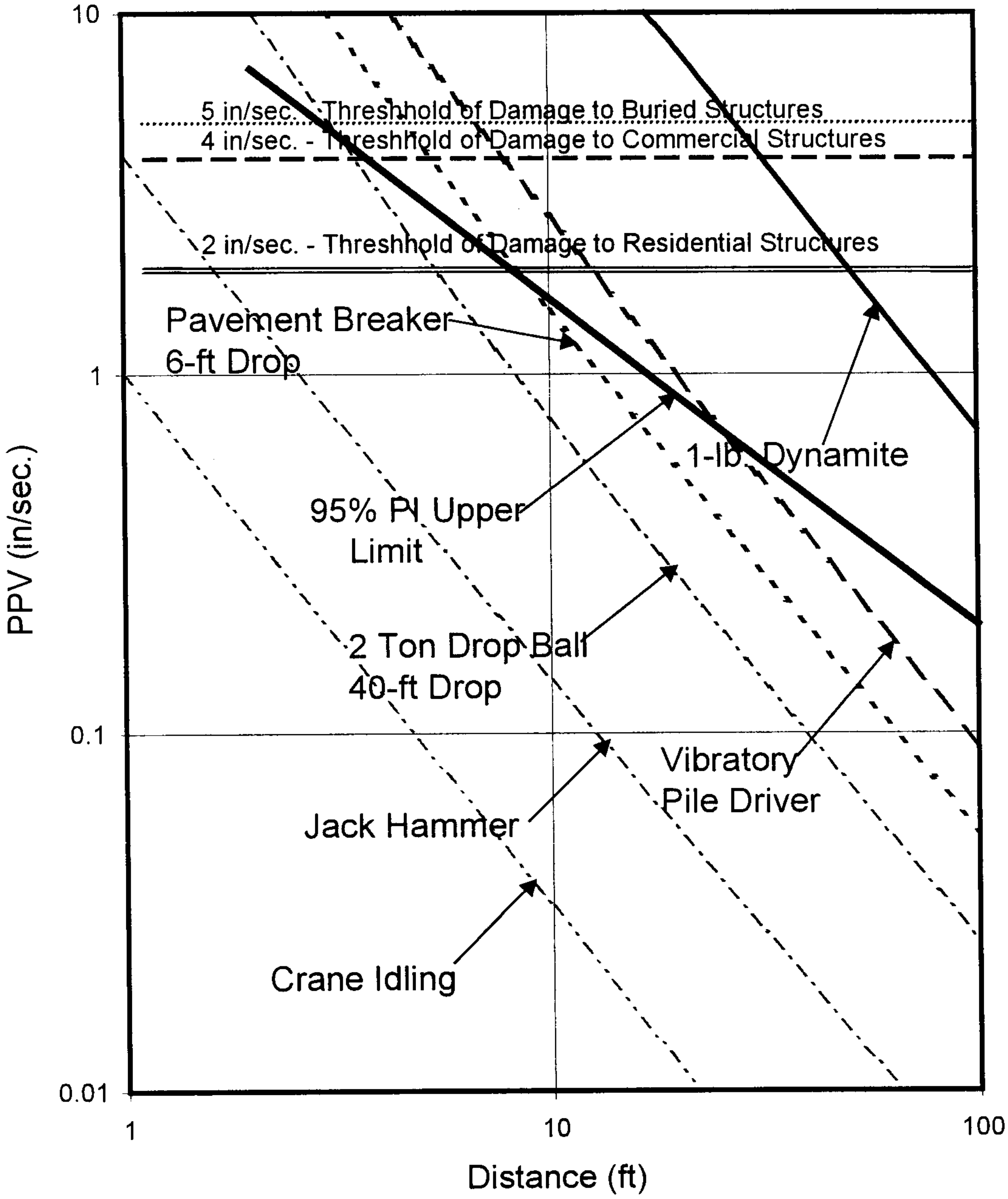

Figure 11 The 95% Prediction Interval Upper Limit for the Data Collected from the Pneumatic System Sites Along With the Attenuation Lines of the Velocity Versus Distance from Different Construction Sources (Wiss 1980)

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