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# Blast Vibration Measurements Near and On Structure Foundations

By David E. Siskind and Mark S. Stagg

**UNITED STATES DEPARTMENT OF THE INTERIOR**

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Blasting near structures often involves measurement of vibrations for the assessment of damage potential. Several methods of measurement are in use worldwide, but there is no consensus as to which methods are technically sufficient and yet practical for all situations. This Bureau of Mines study examined five methods of vibration transducer placement to determine the best method for monitoring blasting vibrations. The methods examined were burial in soil next to the structure; attachment to the foundation at ground level, to the basement floor, or to a surface slab; and burial at a distance from the structure in undisturbed soil. Typical surface mine production blasts were used as vibration sources. With the exception of the basement floor measurements and some of the distant measurements, waveforms were similar and amplitudes were generally within 10 to 30 pct. The low-frequency part of the wave (5 to 10 Hz) was particularly uniform in measurements obtained by all five methods. Differences in peak values were mostly from the minor shifts in phase of the high-frequency components, which are of less significance to structural response and potential damage than the low-frequency waves (5 to 20 Hz). Shallow surface burial resulted in good signal detection and the least chance of mechanically induced error.

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Vibration record at:

## ILLUSTRATIONS--Continued

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### UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| dB | decibel | lb/ft$^3$ | pound per cubic foot |
| ft | foot | m | meter |
| g | acceleration of gravity | mm | millimeter |
| Hz | hertz | ms | millisecond |
| in | inch | m/s | meter per second |
| in/s | inch per second | pct | percent |
| kg | kilogram | s | second |
| lb | pound | | |

# BLAST VIBRATION MEASUREMENTS NEAR AND ON STRUCTURE FOUNDATIONS

By David E. Siskind[1] and Mark S. Stagg[2]

## ABSTRACT

Blasting near structures often involves measurement of vibrations for the assessment of damage potential. Several methods of measurement are in use worldwide, but there is no consensus as to which methods are technically sufficient and yet practical for all situations.

This Bureau of Mines study examined five methods of vibration transducer placement to determine the best method for monitoring blasting vibrations. The methods examined were: burial in soil next to the structure; attachment to the foundation at ground level, to the basement floor, or to a surface slab; and burial at a distance from the structure in undisturbed soil. Typical surface mine production blasts were used as vibration sources.

With the exception of the basement floor measurements and some of the distant measurements, waveforms were similar and amplitudes were generally within 10 to 30 pct. The low-frequency part of the wave (5 to 10 Hz) was particularly uniform in measurements obtained by all five methods. Differences in peak values were mostly from the minor shifts in phase of the high-frequency components, which are of less significance to structural response and potential damage than the low frequency waves (5 to 20 Hz).

Shallow surface burial resulted in good signal detection and the least chance of mechanically induced error.

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## INTRODUCTION

Blasting is widely used for rock fragmentation for mining, quarrying, and construction. When structures are nearby, blast-produced ground vibrations are routinely measured to establish and demonstrate environmentally sound design practice and to insure that vibration levels are not excessive. Federal, State, and/or local regulations often require the monitoring of blast vibrations.

Methods and instrumentation for blast monitoring have changed over the years as a result of new developments and needs, and different practices have been adopted around the world. The relatively few original studies of blast-produced cracking in residences involved a variety of measurement methods.

In this study of production blasting at three midwestern surface coal mines, the Bureau of Mines investigated the three most common methods of measuring blast vibrations near residential structures. These methods are (1) direct attachment to the foundation at ground level (2) shallow burial in the soil next to the foundation and (3) measurement on a nearby concrete surface slab (e.g., driveway). In addition, some measurements were made at distances from the structures, in presumably undisturbed ground, and on basement floors. The investigators sought to answer the following questions:

1. Does measurement in the ground next to a foundation give an accurate indication of the vibration transferred into the structure for houses on slabs? For houses with basements?
2. What is the relationship between outside ground vibration and masonry basement wall vibration?
3. Does the presence of a house and its basement excavation influence the vibration wave character as compared to a similar measurement in undisturbed ground?
4. Are existing outside monitoring techniques appropriate, or is it necessary to measure inside on the foundation as recommended by a major blasting firm to the International Standards Organization Technical Committee 108/SC2 on Structure Vibrations (<u>1</u>)[3]?

## BACKGROUND

### TECHNICAL CONSIDERATIONS FOR BLAST MONITORING

Ground vibration measurements are made for one of two purposes: to derive predictive equations of generation and propagation and to assess the potential for damage to nearby structures. In the first case, the vibrations themselves are under study. In the second, the important considerations are how the vibrations couple with the structures to produce vibrational responses and how the vibrations are altered by the existence of the structures and their foundation excavations. These latter considerations, involving both the vibrations and the structures, were the concerns of this study. Accordingly, the study was complicated by variations in soil-structure interaction, response characteristics, and the presence of excavated and filled ground.

Two basic monitoring methods are used for blasting near structures: (1) measurement in or on the ground near the structure and (2) measurement somewhere on the structure, usually on the foundation. Both methods have their adherents, but neither is suitable for all conditions. Both have been used in vibration-damage studies.

#### <u>Measurement Outside the Structure</u>

Vibrations measured outside and near the structure represent the structure's vibration environment. The records obtained are "pure" and unfiltered, except where the vibration character is changed by the structure through wave interaction or by the foundation excavation as a

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[3] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

result of changes in the transmitting medium. When response spectra modeling is desired, it is the record from the outside measurements that is used as the excitation motion (2-4). Vibrational response to the incoming vibration wave will vary according to the structure's stiffness, mass, and frictional properties, and also according to how well the structure fits the single-degree-of-freedom simple harmonic case. Recent Bureau studies of a limited and well-defined class of structures (residences of two or fewer stories) found the outside vibration measurement method to be the most suitable method for determining structure response (5-6).

### Measurement on the Structure

The alternative technique involves direct measurement on the foundation, usually at ground level. An advantage of this approach is that it accounts for the soil-structure interaction by quantifying the actual structure response, at least at the point of measurement, making a separate assessment of the soil-structure interaction unnecessary. However, the measured vibration is no longer "pure" because it includes a transfer function. Its character is dependent on both the source, including the generation and propagation influences, and the receiving structure, which has its own responses and conditions variability. The measured motion is no longer the excitation motion for the structure as a whole from the ground vibration but instead is the response of one part of the structure to the excitation motion of another (e.g., the foundation vibration excites the superstructure).

An additional problem with inside measurement is determining where to measure the maximum value. Studies of full-scale masonry walls by the National Bureau of Standards found a wide variation in the local state of strain for a uniform overall input (7).

In cases where the locations of maximum strain (or motions) are known, measurements at these points are the best means of assessing vibration impacts. The Bureau of Mines conducted a long-term fatigue study at one structure and measured strains at many internal points (7). The researchers chose the locations of high-strain points for the superstructure based on observations of cracking in many other structures. However, they felt far less confident in choosing such locations for the masonry basement wall.

### Measurement Accuracy

Aside from deciding where to measure, there are problems in assuring that the records obtained actually reflect the state of motion. In addition to the problems of equipment specifications, there are mechanical concerns of impedance matching, transducer slippage and rotation, and mount resonances. The practices used by the Bureau in its studies are intended to minimize such mechanical errors; however, these errors are a matter of concern when nonburial techniques are used (6). Past practices and rationales for avoiding mechanical measurement errors are discussed in the next section.

## PREVIOUS STUDIES

### Mounting Methodology

Most past research on blast vibration measurement was concerned with mechanical problems of gauge mounting. This research was recently summarized in RI 8506 (6). The common finding of these studies was that higher frequencies are the cause of several problems, because, at a given vibration velocity, a higher frequency means a greater acceleration. Above 1 g, an unattached measuring device separates from the surface being measured. In addition, previous research showed that unstable geometry and combinations of horizontal and vertical motion can cause unsecured transducers to slip, tip, or fall at aceleration levels much lower than 1 g. Any combination of frequency and velocity that yields accelerations above 0.2 g is a potential monitoring problem.

Duvall investigated stability and slippage problems with self-contained seismographs (8). He found that seismographs meeting some special conditions with respect to support and center of gravity could be used up to approximately 0.5 g. Duvall determined that seismographs not meeting these conditions should be clamped to the surface for measuring vibration levels above 0.1 g.

Fogelson examined system response linearity and the problems of seismograph slippage and tipping (9). For the three systems Fogelson tested, he found that slippage began to occur above 0.2 to 0.4 g of horizontal acceleration and produced nonlinear responses. A combination of simultaneous horizontal and vertical motion would probably give lower values.

Both of these studies involved instrumentation which is no longer in use; however, the general principles they established are unchanged. In recent Bureau studies of modern seismic systems with separate transducer packages (typically boxes or cylinders) containing three orthogonally mounted transducers and having height-to-base ratios of unity or less, it was found that burial or some form of clamping was required for vibration levels higher than 0.2 g (6).

## Spike Mounting

Two studies compared transducer placement on or in the soil (10-11). Methods included placing transducers on spikes, flat plates, spiked plates, spiked cubes, and spiked corner angles, and inside boxes. As with the previous slippage problems, responses become irregular at higher frequencies. Johnson, in tests using various spiked gauges, found that they tended to "ring" or resonate at specific frequencies (10). With the spike as an anchor, the relatively heavy transducers were acting as inverted pendulums. Using the criteria of good reproducibility after repeated mounting and in hammer-blow tests, the recording of accurate waveforms, and the absence of ringing, Johnson concluded the best measurement method was to place gauges in a thick-walled aluminum box buried in the soil.

Gutowski (11) also examined mounting methods, with results similar to Johnson's. He found that spiked gauges worked well for vertical motions but did not couple well in the horizontal directions. In addition, Gutowski studied flat plates on the ground mounted flush with the surface. These were also subject to uneven support and unwanted resonances at higher frequencies.

The problem of partial resonance of surface-placed vibration-measuring transducers was examined in two analytical studies (12-13). Magnifications and phase shifts, which are influenced by transducer weight and base dimensions, were predicted at high frequencies. Skipp reviewed measurement methods and concluded that burial and tamping the soil around the transducer alleviated these resonance problems (14).

## Impedance Matching

In addition to avoiding coupling and resonance problems, mounting vibration transducers inside boxes allows selection of the box density for impedance matching to the average soil. Duvall has described the use of a 3-component thick-walled gauge box with an average density of 100 lb/ft$^3$ (1,600 kg/m$^3$) buried 9 to 12 in (0.23 to 0.30 m) deep (15). Duvall's objective was to provide impedance matching to insure that the transducer box would move with the ground and act transparent to the waves. However, imperfect matching should not be a problem if the box size is less than one-half the shortest wavelength of concern and if the box is in tightly compacted soil.

## Rayleigh-Wave Measurement

Studies by Gutowski (11) and Clark (1) were concerned with different aspects of measurement of Rayleigh waves. Gutowski estimated wavelengths for a specific case in clay and assumed a frequency of 50 Hz and a propagation velocity of 150 m/s. His concern was that when the transducer mount size is a significant fraction of the Rayleigh wavelength (estimated at 3 m) an accurate measurement would not be made. Gutowski's assumed values may not be realistic for blasting, and his assumed frequency of 50 Hz is high for a wavelength as short as 3 m.

Clark was concerned with accurately measuring Rayleigh waves near buildings to assess their structural vibration response (1). Rayleigh waves are vertically polarized surface waves having amplitudes which decrease with depth. Figure 1, adapted from Clark (1), shows this decrease as a function of fractions of a wavelength (λ) for both the vertical and horizontal components. Significant amplitude reductions begin at depths of 0.5λ and 0.05λ for the vertical and horizontal (or more specifically, longitudinal) components, respectively. As the vertical motion greatly exceeds the horizontal within 1.0λ of the surface, the first rather than the second value becomes the critical depth. Above this depth the vertical or largest component of the Rayleigh wave should be within 10 to 2 pct of a surface measurement. Where the longitudinal motion is important, depths greater than 0.1λ will have considerably reduced vibration amplitude.

According to Clark, the structure foundation is mainly affected by the Rayleigh wave acting at the bottom of the foundation, and therefore the preferable method of measurement is on the foundation itself. For measurements made in the ground, Clark recommended applying reduction factors for clay formations as follows:

$$F = \frac{\text{Foundation vibration}}{\text{Ground vibration}}$$

= 0.62 for plate (slab) on ground with depth of 1 m

= 0.40 for foundation with basement depth of 2 to 3 m

= 0.40 for 10-m-deep foundation supports or piles to bedrock.

This formula and the factors of reduction are from traffic vibration studies; it is not known how well they apply to the wave characteristics associated with blasting.

From figure 1, it is apparent that Rayleigh wavelength is important. Gutowski's estimated Rayleigh wavelength of 3 m appears abnormally short for blast-generated ground vibration. Clark does not give typical wavelengths, but shows dominant frequencies as high as 20 Hz for a sediment thickness of less than a few meters. At a Rayleigh-wave propagation velocity of 1,000 m/s (e.g., for clay), the wavelength at 20 Hz would be 50 m (160 ft). In the study of blast vibration described in this report, the Bureau found Rayleigh wavelengths of 89 and 98 m. In a previous study at the Ayrshire surface coal mine, a site with a thin soil cover gave two Rayleigh wavelength measurements of about 200 m. Only for very short wavelengths (e.g., 3 m) does 0.5λ equal depths of concern for shallow-basement structures typical of residences.

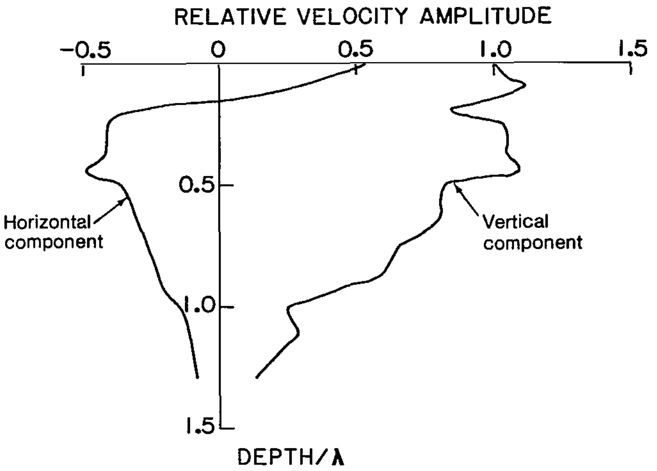

FIGURE 1. - Rayleigh-wave amplitude profile versus depth below ground surface, after Clark (1).

## CURRENT MEASUREMENT PRACTICES

Most measurements for the assessment of potential vibration impact on structures are made following methods the Bureau has used in its research (5-6, 15-16) and the Swedish practices described by Clark (1). In most cases, a transducer box is buried in the soil next to the foundation, or the transducer is attached directly to an interior foundation wall at or near ground level. In practice, transducers are attached at approximately one-third of the wall height above the floor.

For convenience, transducers are often placed on top of a surface—on the ground (usually spiked in soil) or on a concrete walk, roadway, or foundation surface.

This practice is satisfactory for low-level vibrations but is increasingly risky as amplitudes and/or frequencies increase.

High-profile transducer systems, such as the HS-1 "tree" configuration (figure A-22 in reference 6) should not be used unclamped or unattached except at the lowest acceleration levels (<0.05 g). For the more common low-profile transducers (e.g., VLF-LP-3D in the same figure), the previously mentioned criterion of firm attachment or burial above 0.2 g is appropriate (6).

## DESCRIPTION OF TESTS OF BLAST-MEASUREMENT METHODS

### TEST SITES

Bureau researchers made blast vibration measurements at four sites, three near St. Clairsville, OH, at two different R & F Coal Co. surface coal mines, and one at the AMAX Inc. Ayrshire surface coal mine near Evansville, IN. At all four sites, measurements were made near or on residential-type low-rise structures with full masonry basements, allowing comparisons of records for a variety of methods of transducer placement. The sites and structures are described in table 1 and are shown in figures 2-7 (except for the mine office at Parlette, OH). Plan views of the four test areas, including structure orientations, transducer placements, and shot distances and directions, are shown in figures 8-11. All shot distances are from the indicated survey point (S).

### TEST BLASTS

The test blasts were typical surface mine production rounds, multidelayed and multidecked. The closest blast was shot 1, at 130 m from the Schnegg residence, and the farthest over 1,500 m from the training house at the Ayrshire Mine. Charge sizes per delay ranged from about 10 to 100 kg. Since the primary concern of this study was the vibration wave received at nearby structures, the only blast-design criteria of interest was sufficient distance to permit development of the long-period surface wave vibration components in addition to the direct first-arriving body waves. Six blasts were measured at the three sites in Ohio, and 17 blasts were measured at the single site in Indiana (at the Ayrshire Mine).

TABLE 1. - Test structures

| Structure | Location | Construction | | Concrete slab[1] | Blast | Figures |
|---|---|---|---|---|---|---|
| | | Superstructure | Basement | | | |
| Schnegg house. | St. Clairsville, OH, west pit. | 2-story, all brick, 12- by 11-m plan. | Stone block, floor 1.5 m below ground. | Garage slab 6.7 m from house. | 1<br>6 | 2-5, 8 |
| Mine office. | Parlette, OH. | 1-story, wood frame, 14- by 15-m plan. | Concrete block, floor 2 m below ground. | Garage slab 18 m from structure. | 2-3 | 9 |
| Fador house. | St. Clairsville, OH, east pit. | 1-story, wood frame, 9- by 8-m plan. | Concrete block on sloping ground, floor depth of 1.5 m at SW corner. | Garage slab on north end of house. | 4-6 | 6, 10 |
| Training house. | Ayrshire Mine, Evansville, IN. | 1-story, wood frame and brick, 25- by 12-m plan. | Concrete block on sloping ground, floor depth of 2.5 m at east end. | Walkway next to house. | 7-22 | 7, 11 |

[1] Slabs used for surface measurements.

FIGURE 2. - West end of St. Clairsville mine showing Schnegg property.

FIGURE 3. - Schnegg house at St. Clairsville site.

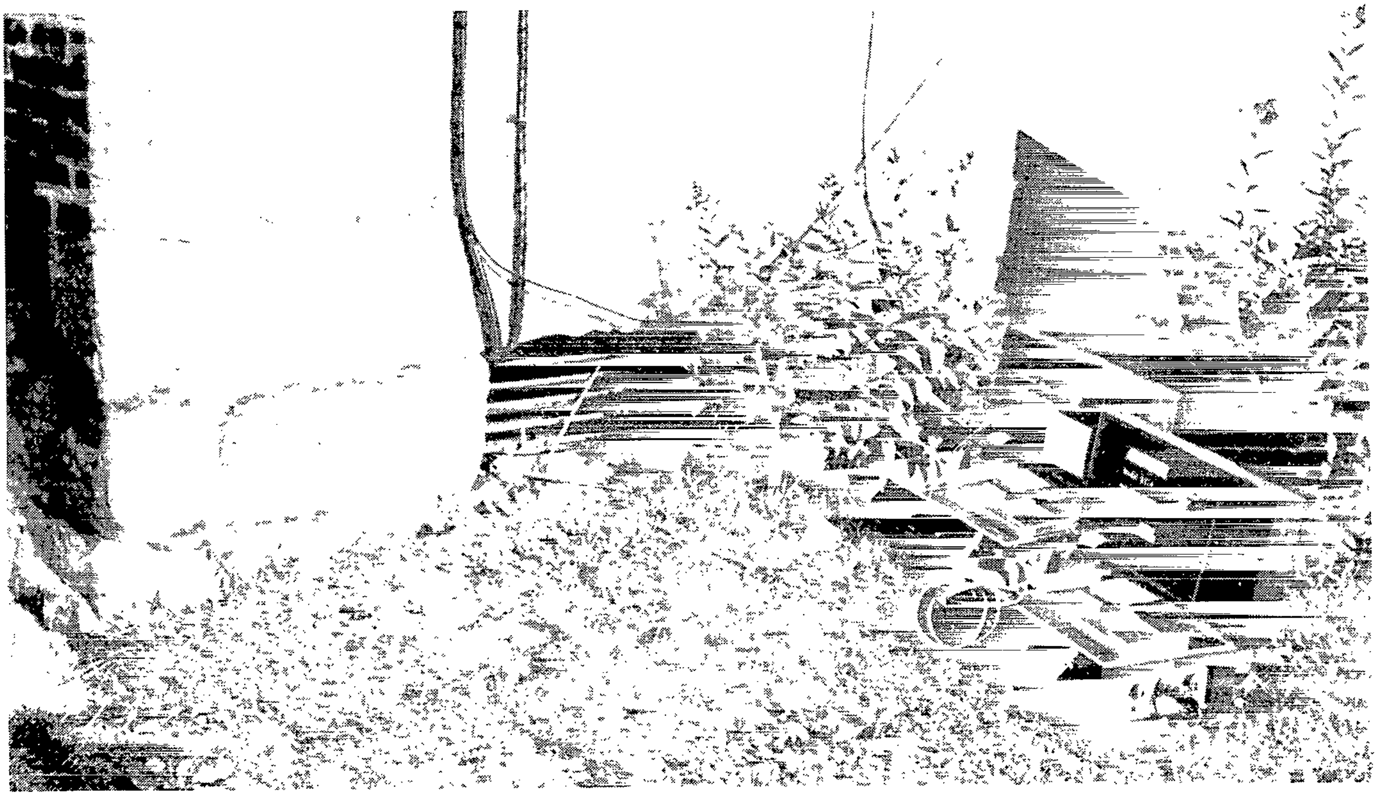

FIGURE 4. - Schnegg house foundation. (See also figure 5).

FIGURE 5. - Velocity gauge transducers on Schnegg foundation window sill and in the ground.

FIGURE 6. - Fador house at St. Clairsville site.

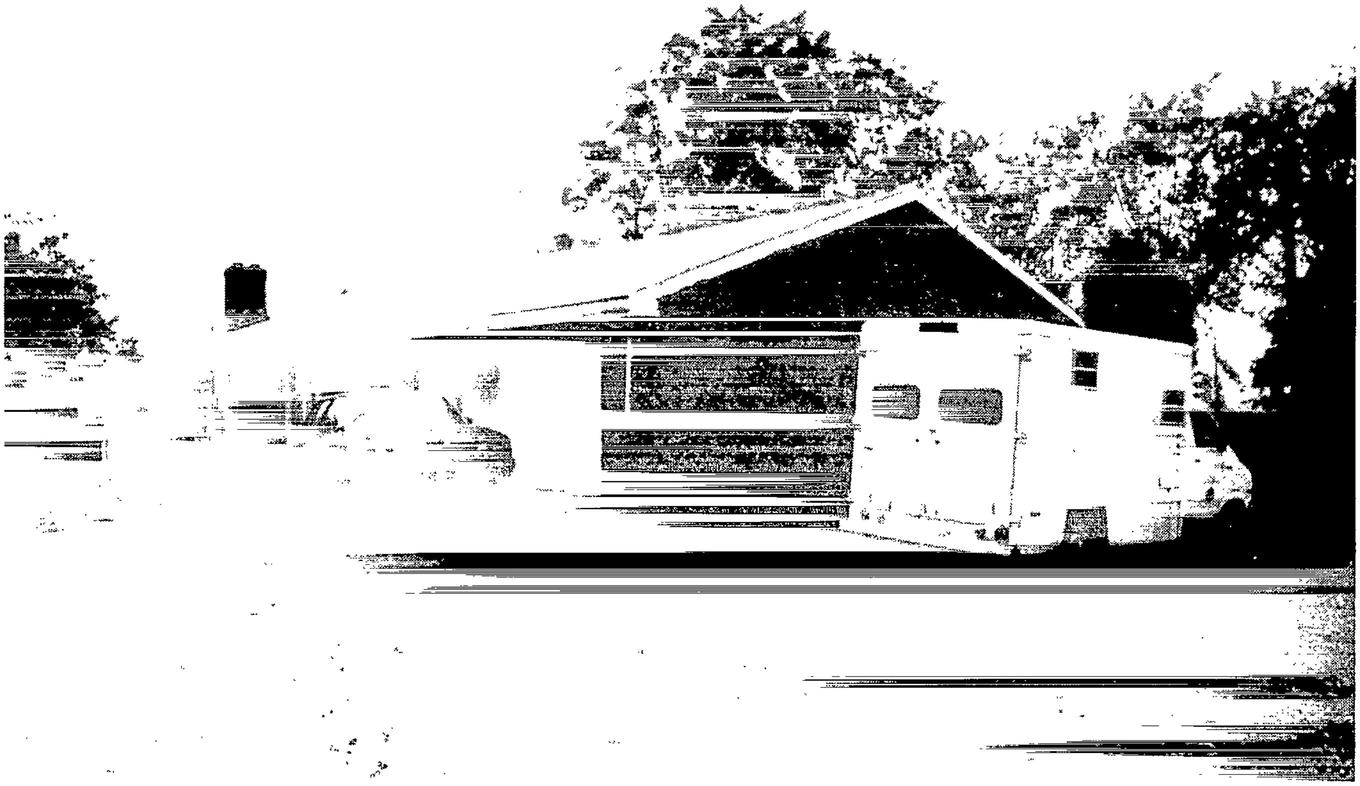

FIGURE 7. - Ayrshire Mine training house at Evansville.

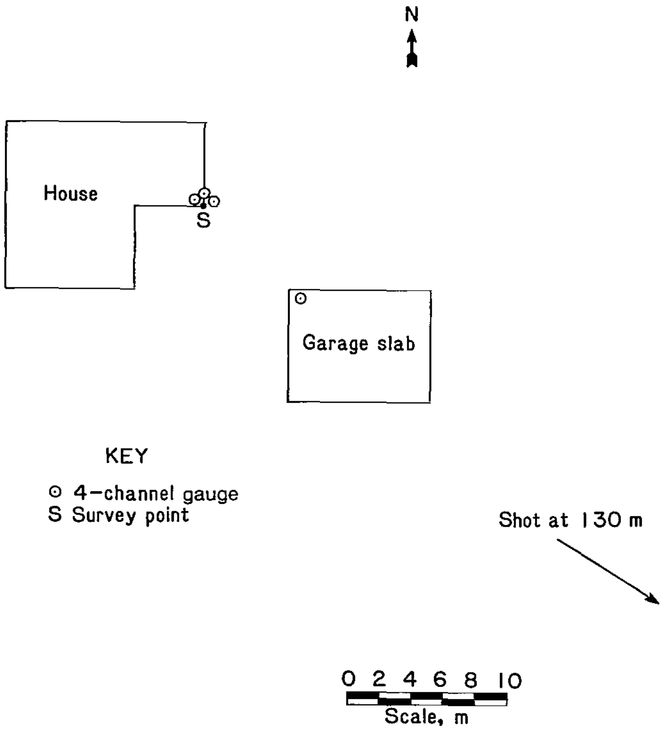

FIGURE 8. - Structure, transducer, and shot orientation for Schnegg house.

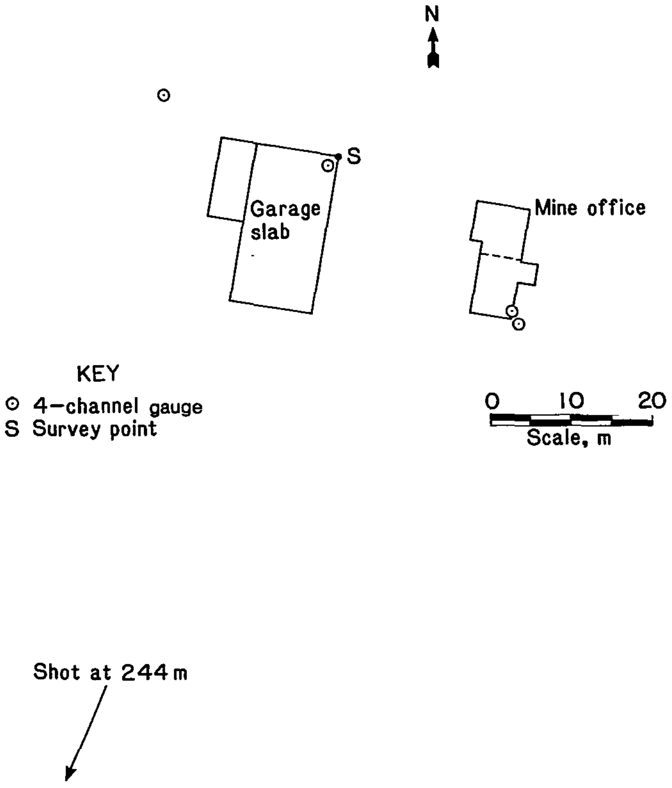

FIGURE 9. - Structure, transducer, and shot orientation for mine office at Parlette site.

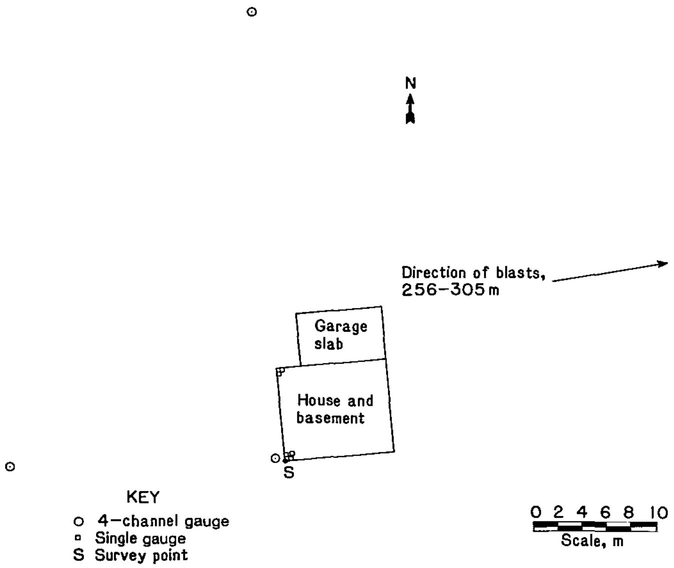

FIGURE 10. - Structure, transducer, and shot orientation for Fador house.

## INSTRUMENTATION

The researchers used two velocity-measuring systems for this study. Surface, buried, and ground-slab measurements were made with 4-channel Dallas Instruments, Inc., model ST-4 seismographs[4] (reference 6, figures A-5 and A-6). Foundation and other structural-motion monitoring was done either with model ST-4 seismographs or single-component integrating accelerometer (particle-velocity) transducers (reference 6, figures A-28 and A-31). For propagation velocity and wavelength determination, a tie-in was made between seismographs through the unused airblast channel, providing a common time base. The instrumentation maps, figures 8-11 in this report show where and which kinds of sensors were used at the four sites.

Because each structure and site was different, totally uniform methods could not be used. At the Schnegg house (fig. 8), ST-4 units were used throughout, including on the basement floor. A ground-level foundation measurement was made on a window sill, with the transducer firmly wedged in place (fig. 5). Because of the firmness of the soil, the "buried"

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[4] Reference to specific products does not imply endorsement by the Bureau of Mines.

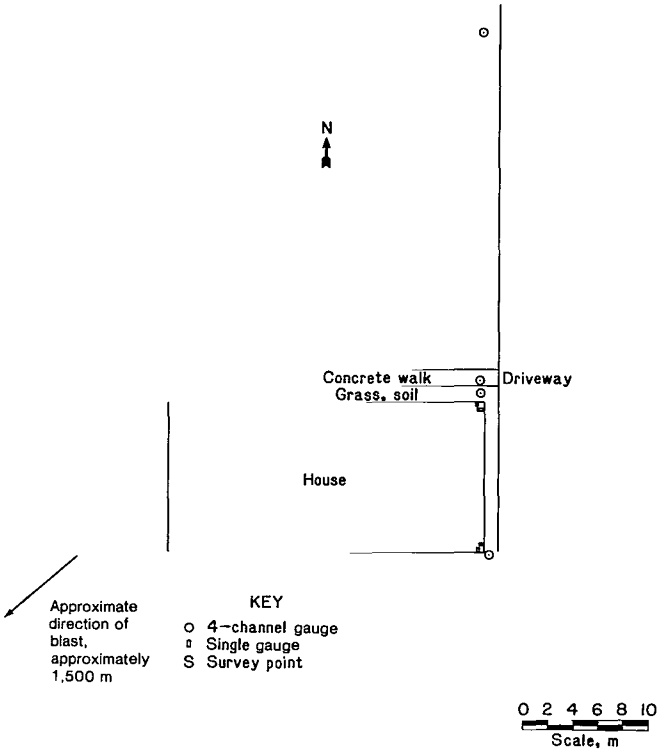

FIGURE 11. - Structure, transducer, and shot orientation for Ayrshire Mine training house.

transducer was only placed in the ground with the top approximately flush with the surface. Loose dirt was then packed around the cylindrical case.

The mine office at Parlette was similarly monitored with ST-4 seismographs. Because inside mounting was not practical, an ST-4 unit was bolted to a bracket on the outside foundation wall just above the ground (fig. 9).

The Fador structure, a modern house with a full-size concrete-block basement, was monitored for three blasts. Both corners on the west side were instrumented for high- and low-corner responses in three directions of motion. The east side was not accessible. An ST-4 transducer was completely buried outside the southwest corner. In addition, two seismographs were installed at a distance from the structure (fig. 10). However, the upward sloping ground to the north made the results from the northern unit too confusing to interpret.

At the Ayrshire Mine training house, measurements were made similarly to those at the Fador structure. Seventeen production shots were monitored at distances and charge weights exceeding those of the previous Ohio tests. Because the 17 shots were similar, only one, shot 13, was analyzed for this report. The selection criteria for a typical Ayreshire measurement were clean signals and the largest number of working channels. All 17 Ayrshire Mine shots produced similar results.

## EXPERIMENTAL RESULTS--MEASUREMENTS FROM DIFFERENT LOCATIONS

Direct side-by-side comparisons were made of the vibration records obtained through various monitoring techniques. Of 775 time histories from the four sites, virtually all those from the Ohio sites were plotted. Representative plots are shown in figures 12-18. The single plot for the Ayrshire Mine training house (shot 13) is shown in figure 19. Slight variations in record amplitudes in the figures are not significant because of interchannel variations and occasionally different gains. All recordings were individually referenced to a calibration standard by channel. Measured peak values are given in table 2, showing simple comparisons for measurements made near and on the structures and also at distances removed from the structures. To supplement the time-history record comparisons, Fourier spectra were obtained from many of the recordings. Typical spectra are presented in figure 20.

## OUTSIDE VERSUS INSIDE MEASUREMENTS

### Buried Versus Slab on Surface

As mentioned previously, measurements are often made with transducers on the surface rather than buried or mounted, for convenience. This case compares unmounted surface slab measurements with those made using the shallow-burial method. The slab measurements are assumed to also apply to a structure with no subgrade basement.

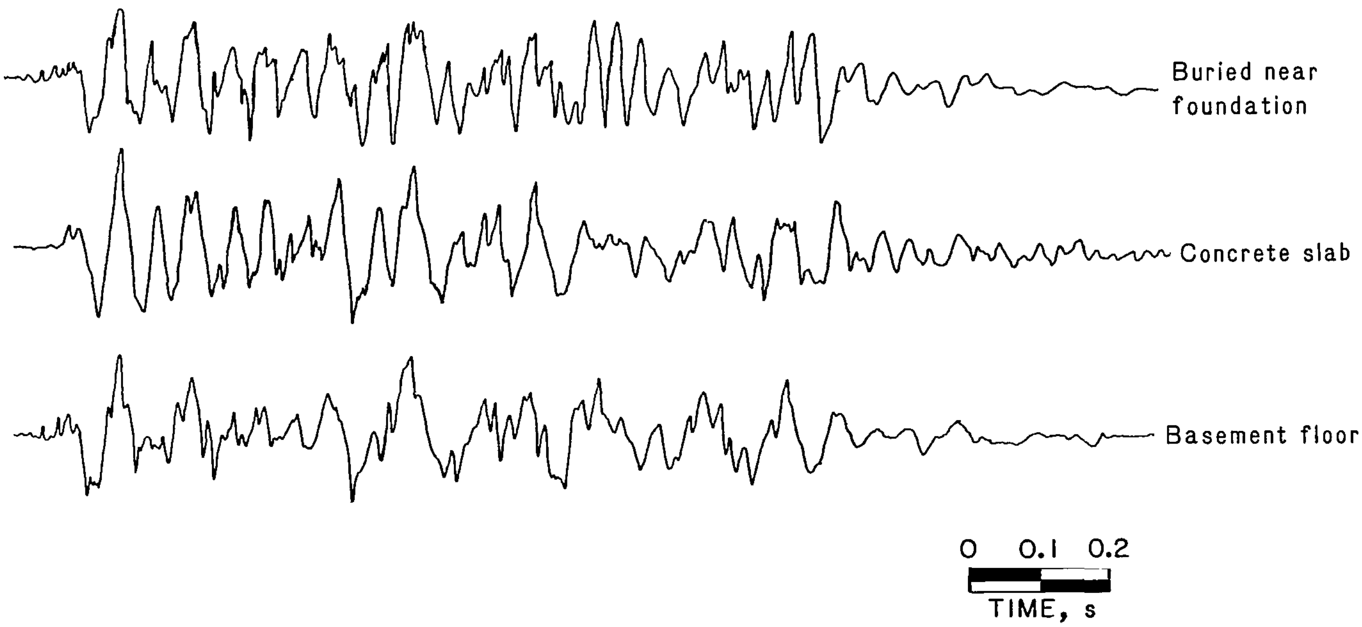

FIGURE 12. - Vibration record at Schnegg house, shot 1, longitudinal.

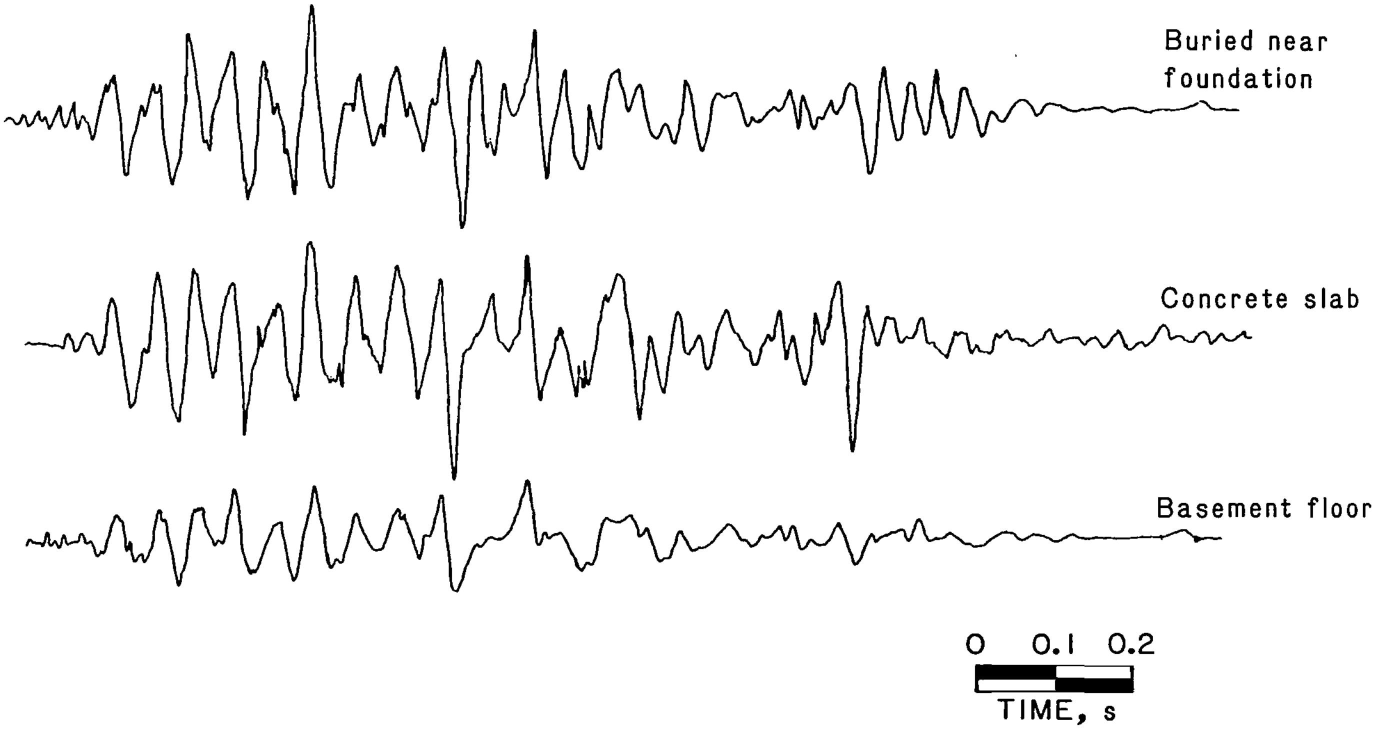

FIGURE 13. - Vibration record at Schnegg house, shot 1, transverse.

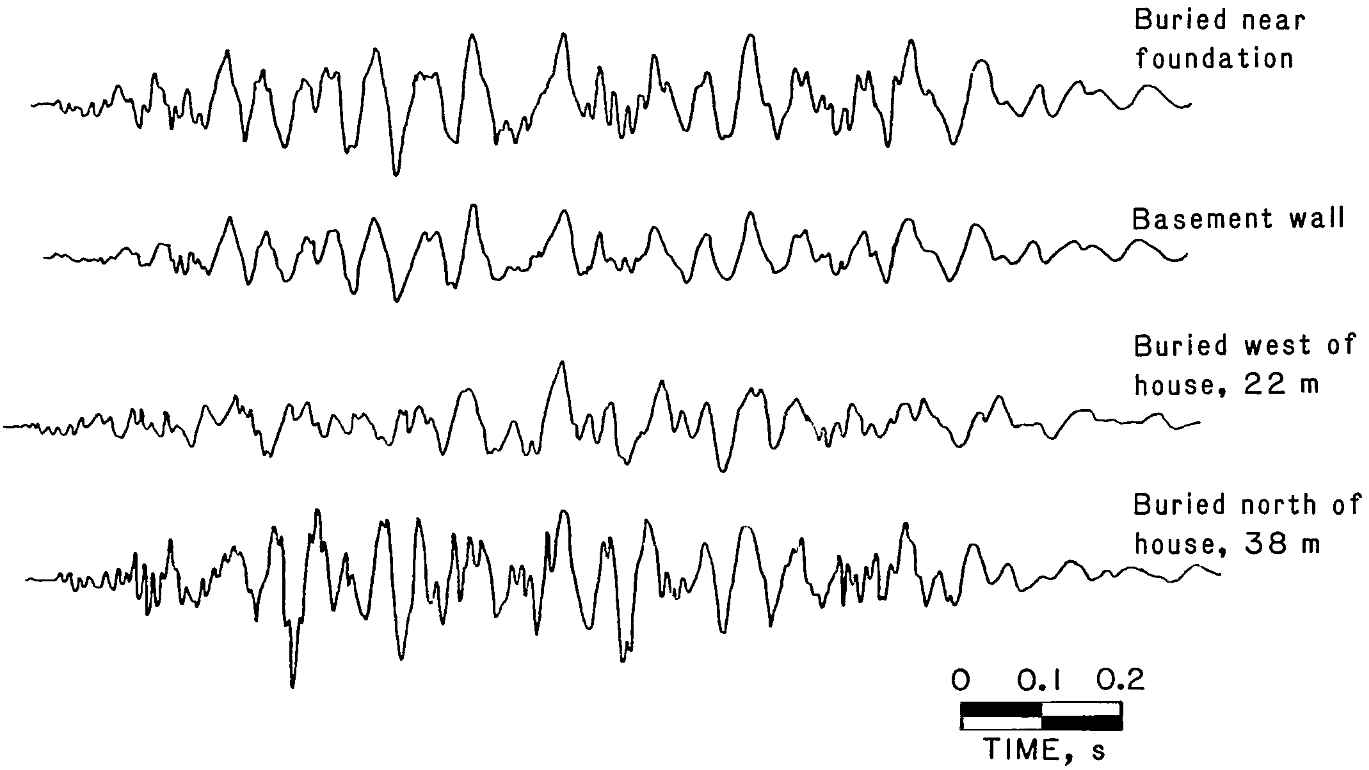

FIGURE 14. - Vibration record at Fador house, shot 5, vertical.

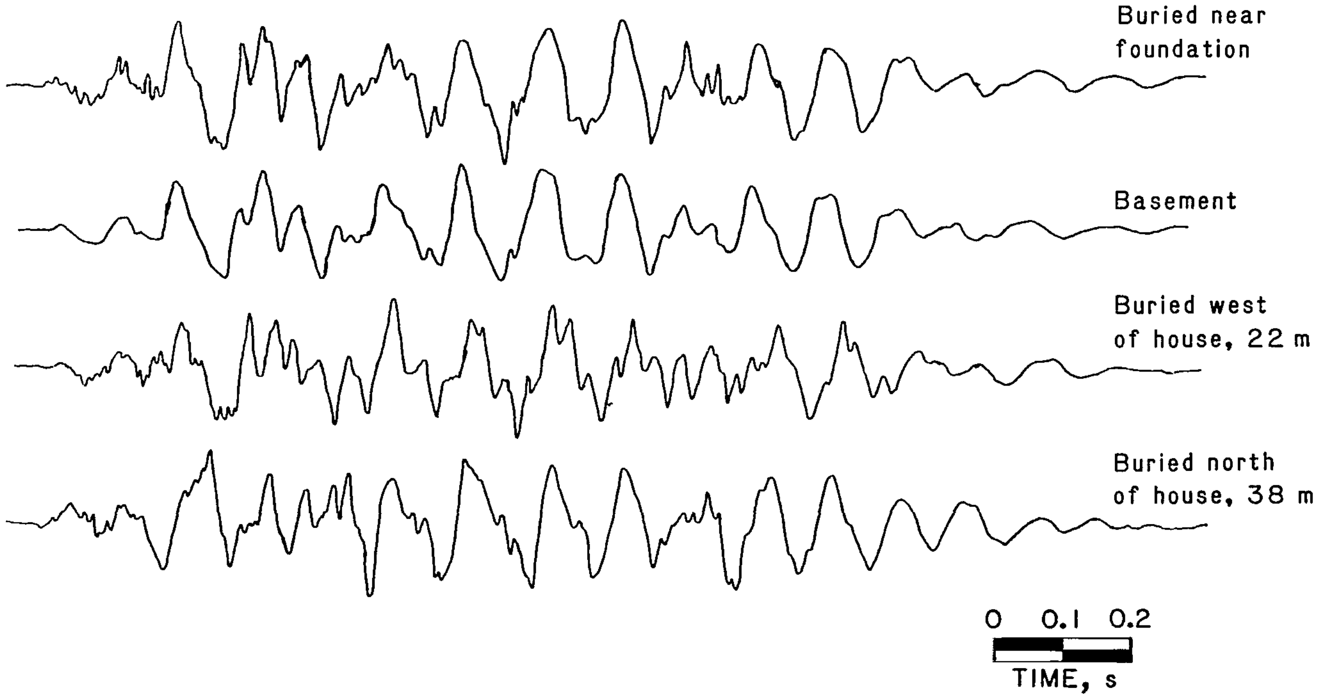

FIGURE 15. - Vibration record at Fador house, shot 5, longitudinal.

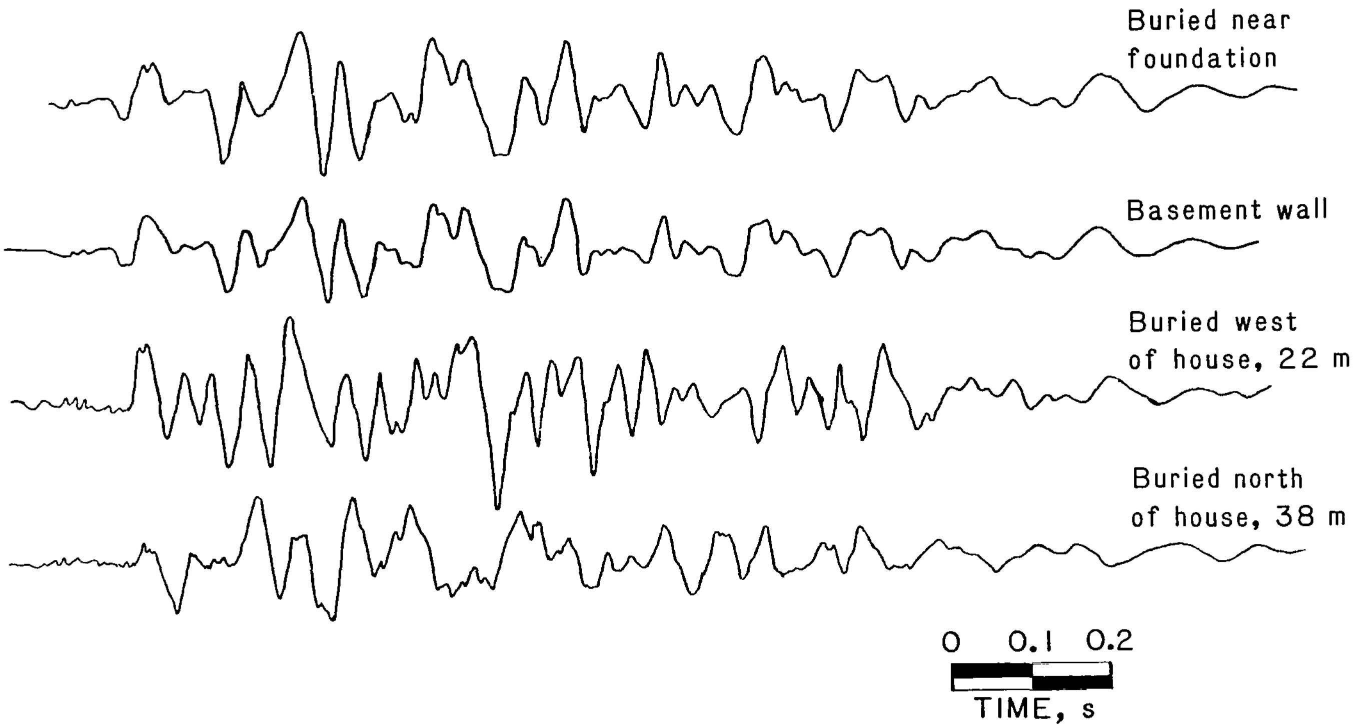

FIGURE 16. - Vibration record at Fador house, shot 5, transverse.

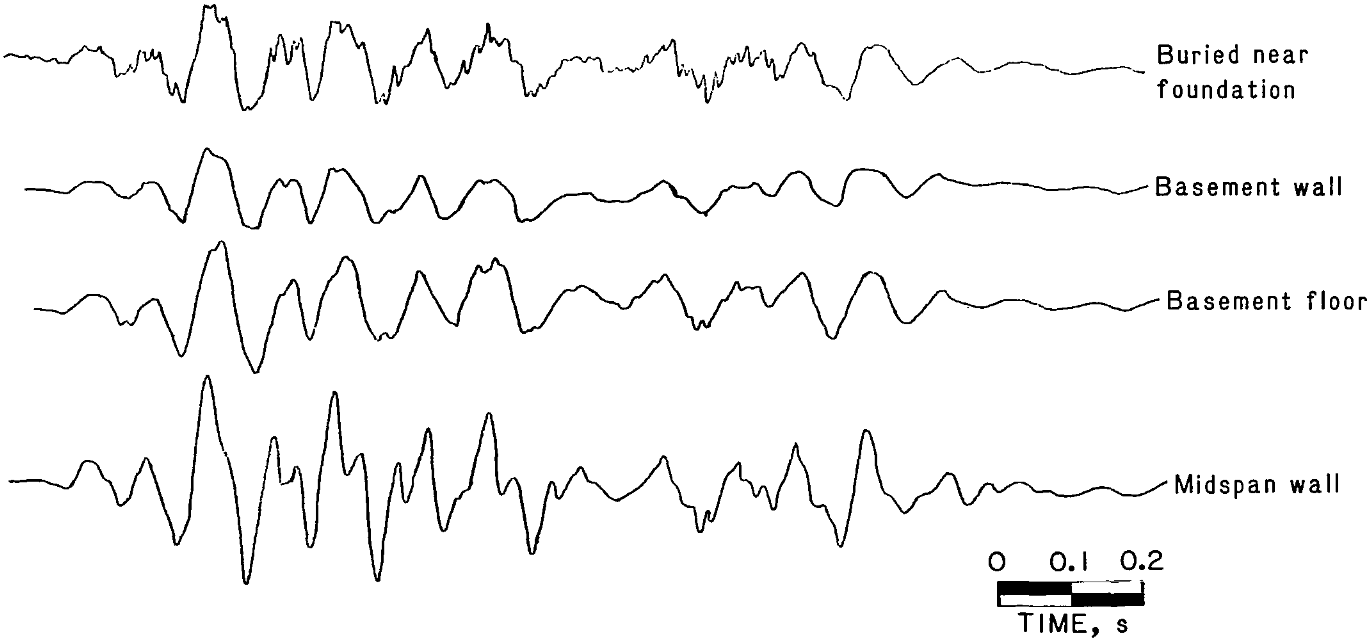

FIGURE 17. - Vibration record at Fador house, shot 6, longitudinal.

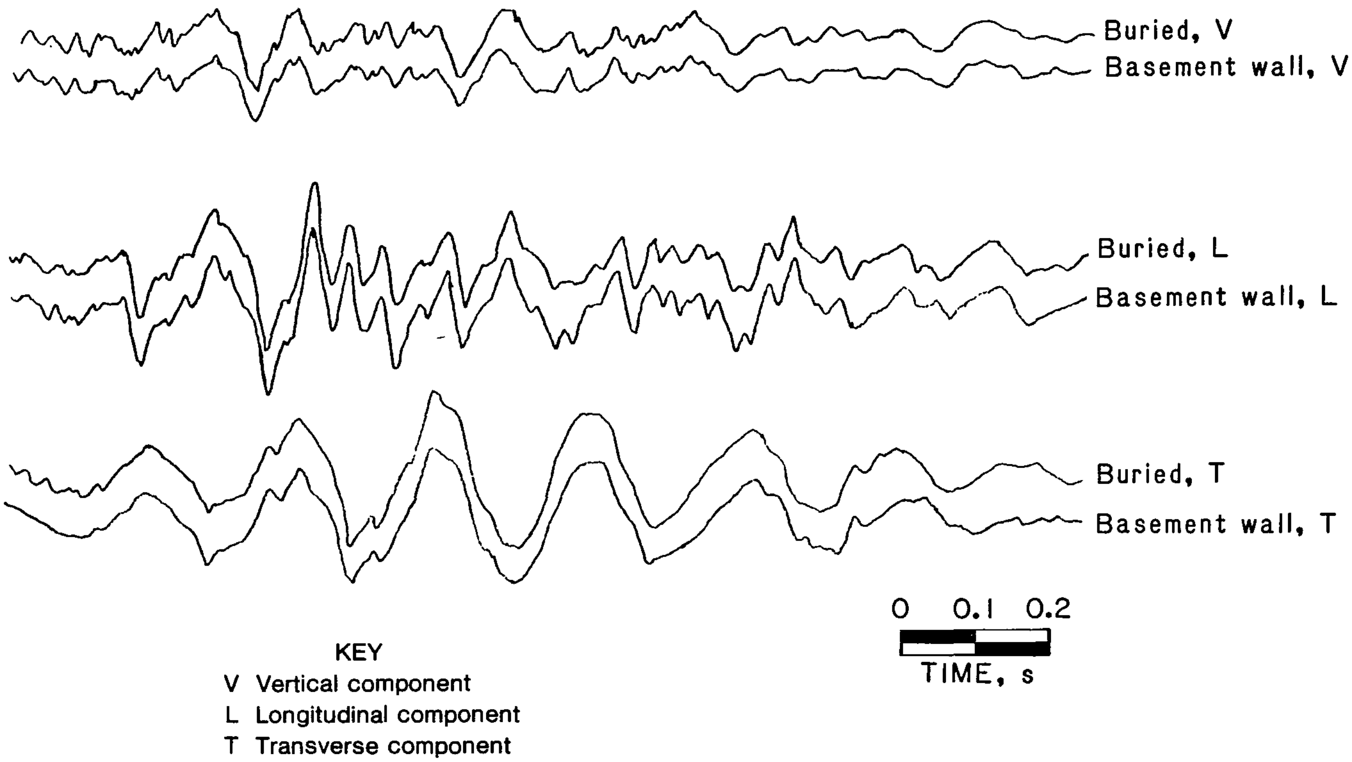

FIGURE 18. - Vibration record at Schnegg house, shot 6, three components.

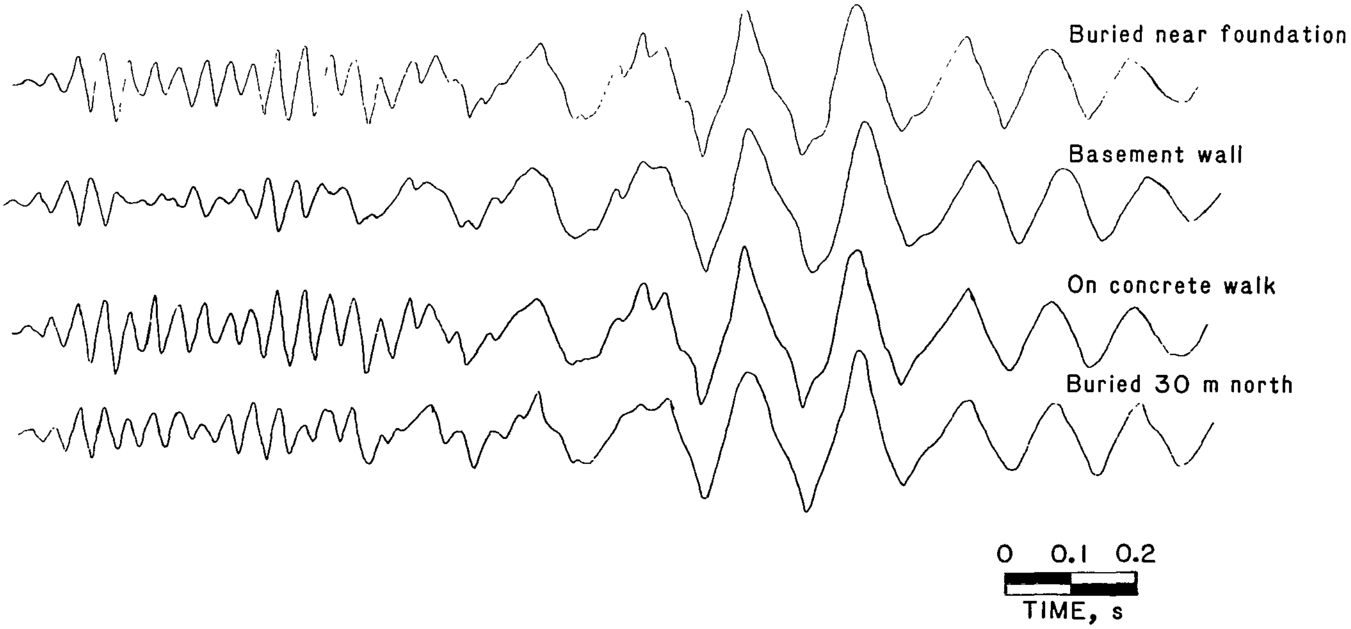

FIGURE 19. - Vibration record at Ayrshire Mine training house, shot 13, longitudinal.

TABLE 2. - Vibrations levels[1] measured near and on test structures, millimeters per second

| Structure | Shot | Component | Measurement location | | | | |
|---|---|---|---|---|---|---|---|
| | | | Ground level, buried | Ground surface, on slab | Ground level, on foundation | Basement floor | Away from structure, buried |
| Schnegg house. | 1 | V | 8.13 | NM | NM | 5.33 | NM |
| | | L | 6.60 | 8.89 | NM | 3.30 | NM |
| | | T | 7.11 | 10.40 | NM | 3.81 | NM |
| Mine office. | 2 | V | 3.05 | NM | 1.52 | NM | NM |
| | | L | 4.83 | 3.56 | 3.30 | NM | [2]2.79 |
| | | T | 4.57 | 3.05 | 3.81 | NM | [2]3.30 |
| Fador house. | 4 | V | NM | NM | 1.52 | 1.37 | NM |
| | | L | NM | NM | 1.29 | 1.02 | NM |
| | | T | NM | NM | 2.01 | 1.83 | NM |
| Do..... | 5 | V | 2.79 | NM | 2.29 | 2.03 | [3]2.29 |
| | | L | 3.30 | NM | 3.56 | 3.05 | [3]4.06 |
| | | T | 2.79 | NM | 2.79 | 2.03 | [3]4.06 |
| Do..... | 6 | V | 3.30 | NM | 3.05 | 2.79 | NM |
| | | L | 4.57 | NM | 4.32 | 3.81 | NM |
| | | T | 3.30 | NM | 3.05 | NM | NM |
| Schnegg house. | 6 | V | .86 | NM | .89 | NM | NM |
| | | L | 1.88 | NM | 1.91 | NM | NM |
| | | T | 1.78 | NM | 1.52 | NM | NM |
| Training house. | 13 | V | .43 | .38 | .41 | .04 | [4].51 |
| | | L | 1.47 | 1.52 | .89 | .14 | [4]1.70 |
| | | T | 1.45 | 1.50 | 1.19 | .14 | [4]1.60 |

NM Not measured.
V Vertical.
L Longitudinal.
T Transverse.

[1] Peak particle velocity.
[2] 22.5 m from structure.
[3] 22 m from structure.
[4] 30 m from structure.

In figures 12 and 13 the "buried" and "slab" traces are nearly identical to about 0.7 s for both the longitudinal (fig. 12) and transverse (fig. 13) components. Beyond 0.7s, it is likely that phase differences were producing the varied wave interference, since the transducers were separated by 8 m. Buried components have additional high frequencies riding on the predominately lower frequency waves, and the peak values are strongly susceptable to the resulting wave interference. As shown in table 2, the slab peak-particle-velocity measurements were higher by about 25 pct at the Schnegg site, but lower by about the same amount at the mine office. The reason for this inconsistency is not known.

As shown in figure 19, similar measurements at the training house produced records for the "buried" and "concrete walk" traces which were nearly identical, including peak values.

## Buried Versus Foundation at Ground Level

Nearly all the tests examined this case, a structure with a below-ground basement floor. This was the case of concern to Clark (1). Five sets of values in table 2 compare burial at ground

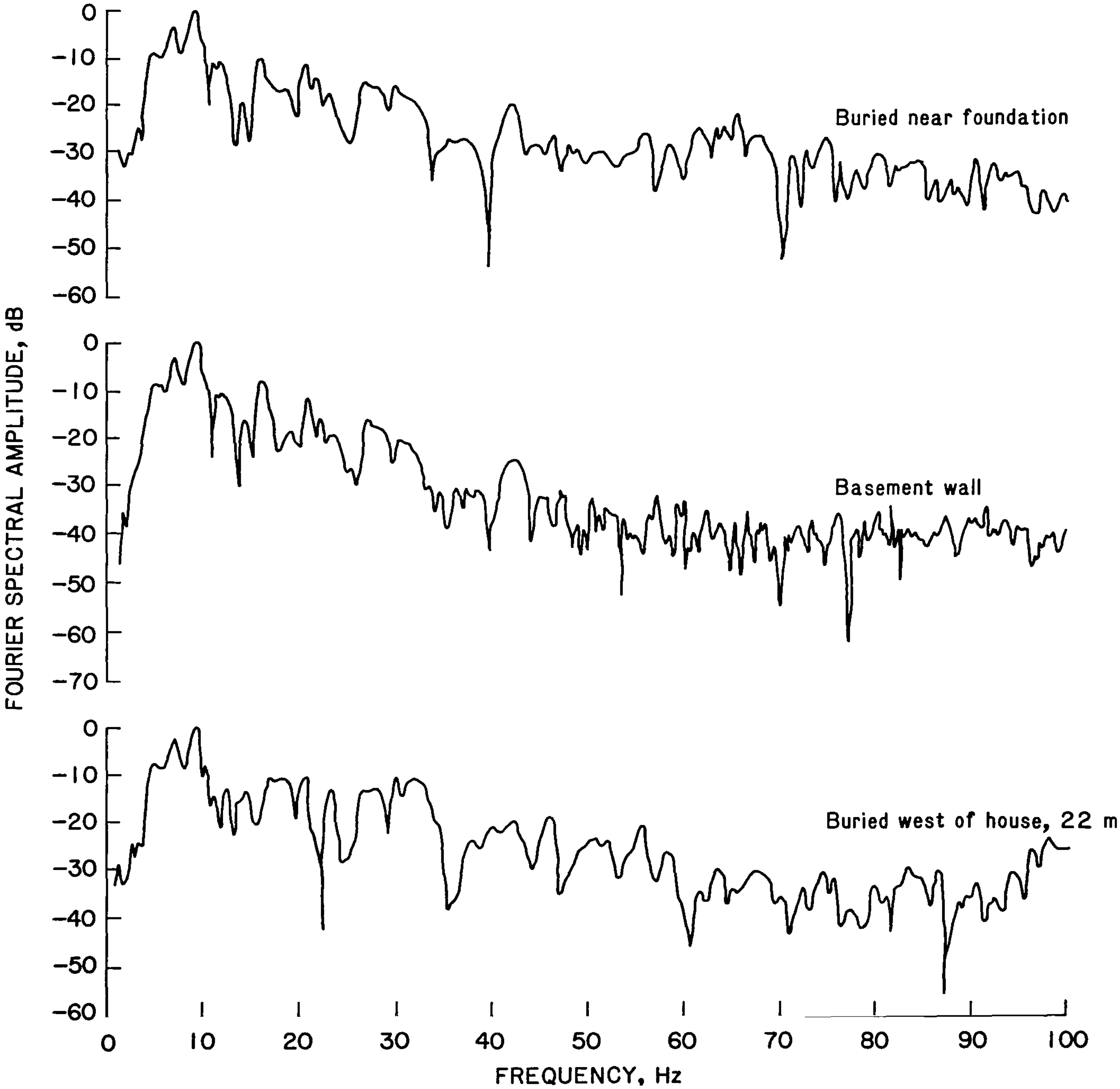

FIGURE 20. - Spectra from three velocity records obtained near Fador house, shot 5, longitudinal.

level versus measurement on the foundation at ground level. Except for the measurements recorded at the mine office, the peak values are all in good agreement. At the mine office, a thin angle-bracket was used to hold the heavy transducer, and the abnormally low values, particularly for the vertical component, are thought to have been caused by insufficient rigidity of the mounting. In figures 14-16, the "buried near foundation" and "basement" traces show that except for the high-frequency motion, the three components of the buried transducer are virtually identical to those measured on the structure, peak for peak and wiggle for wiggle. Figure 20 shows that the spectra for the longitudinal components are identical below 10 Hz.

Results from the training house (fig. 19) are more ambiguous. The records appear identical (top two traces in figure 19, showing longitudinal or western horizontal components). However, the peak values are somewhat in disagreement, and as these two facts are contradictory, a calibration error is suspected.

## DEPTH EFFECTS FOR STRUCTURES WITH BASEMENTS

### Foundation at Ground Level Versus Deep Floor

Consistent with Swedish observations (1) and previous Bureau studies (5), vibrations below ground, e.g., at the basement floor, were observed to be of lower amplitude than those near the surface. Specific comparisons between two structural wall measurements at different depths are shown in figure 17, "basement wall" and "basement floor" traces, which had peak-particle-velocity amplitudes of 3.05 and 2.75 in/s, respectively. Although similar in their overall form, phase differences produced minor changes in the waveform details and peak values (table 2).

### Buried Versus Basement Floor

As with the previous comparison of the foundation wall vibrations at two different depths, the basement floor amplitudes were consistently lower than those near the surface. Table 2 shows three sets of measurements for sublevel basement floors compared to those made using the surface-burial method. The basement floor peak-particle-velocity values were about 25 pct lower.

In figures 12 and 13, the "buried" and "basement floor" traces are similar in their beginnings and then vary slightly throughout. Compared to other inside measurements, the basement floor records are smoother than those from the outside buried gauge, being deficient in high-frequency motion.

At the Fador house (figure 17, "buried" and "basement floor" traces), the records were very similar except that there was again less high frequency and reduced overall amplitude at the floor position.

## MEASURING FROM A DISTANT LOCATION

This experiment involved a series of compromises. What was desired was a vibration record of what would be measured if a house and its foundation excavation were absent. This requires measurements at least one or more wavelengths from a structure; however, such separation introduces problems of different travel paths, directions, distances, underlying geology, and soil characteristics for the vibration recorded at the house and at a distance.

The relevant records are the three sets of "buried" traces in figure 14-16. All three components of motion are shown for burial next to the Fador house and in what appeared to be undisturbed soil 22 m farther from the blast (west); an additional gauge was placed in the only other clear place, 38 m north and uphill from the structure (fig. 10).

The records from the western gauge and the one at the structure are similar, particularly for the horizontal components. While minor changes in phase are evident, the basic waveforms are preserved, particularly at low frequencies. The spectra in figure 20, for the two "buried" traces, show this general similarity, particularly below 20 Hz.

The northern buried transducer at 38 m gave mixed results. Only the longitudinal component had a family resemblance. Most likely, the uphill site did not have the same soil thickness and geological character; it is also likely that the wave being monitored for comparison purposes was not really the same wave. No conclusions were made from this measurement.

The peak values, as given in table 2, are subject to random and unpredictable phase changes. Therefore, it is not surprising that they differed by as much as 30 pct. However, in terms of structural impact, the close similarity of the dominant low-frequency character is far more significant than the shifting of phase of the high-frequency parts of the vibration wave, which couple poorly to structures.

An example of the effect of phase shifting on peak-particle-velocity values is shown in figure 16. The "buried west of house" trace has a sharp peak of 4.06 mm/s. However, on the "buried near foundation" and "basement" traces, the interfering waves making up this peak are slightly shifted and result in a significantly lower value of 2.4 mm/s. This phase shift would have no significance to structural response but would give widely differing peak velocities. Possible solutions to this dilemma are signal smoothing; weighting; or the use of velocity exposure level, response spectra, or some other kind of signal-energy assessment, rather than simple peaks.

Another comparison of near and far measurement is shown in figure 19, in the two "buried" traces. Again, the waves are similar overall and essentially identical in their low-frequency character. As with the Fador house, the vibration values are slightly higher at the distant gauge.

## CONCLUSIONS

At the four sites examined in this study, the specific measurement methods used around structures appear not to be critical at low vibration levels. Five gauge locations were examined: surface slab, buried in the ground at the structure, mounted on the foundation wall at ground level, mounted on the foundation wall at the basement floor, and buried at a distance of approximately 20 m from the structures. The waveforms for all three components, vertical, longitudinal, and transverse, were found to be similar for the five measurement locations. This was particularly true for the low-frequency part of the wave, which is of most concern for vibrational response of structures. Low frequency for this study was 5 to 10 Hz.

Considerable differences were noted for the high-frequency part of the waves, mostly in the beginnings, which correspond to the multiple arrivals from the various delayed holes. It is likely that these differences were primarily a result of the varied wave paths to different monitoring positions leading to uneven and irregular wave interference. The high frequencies are of less concern for structural response, as discussed in a previous Bureau report on structure response from blasting (5).

Because peak values are influenced by the way specific vibration or wave modes interact, they were found to vary irregularly between the different methods. However, they were generally within 20 to 30 pct and not consistent with the systematic 0.40 factor for foundation depths of 2 to 3 m predicted by Clark (1). This demonstrates one of the weaknesses of a simple peak-particle-velocity criterion and overreliance on interpretation of precise values.

Vibration levels below grade, such as on the basement floor, were consistently lower, suggesting differential displacement for the wall top and bottom. Apparently, vibrational energy does decrease with depth.

Rather than recommending a specific measuring method, it is recommended that consistency be used at any one site. Where the option is available, shallow soil burial is still the desired method and was found least likely to introduce additional mechanical error.

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