RESPONSE OF MANUFACTURED HOUSES TO BLAST VIBRATIONS

by

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ABSTRACT

Two house trailers and a modem modular house, all pillar-supported with cantilevered perimeters, were monitored for structural response to vibrations from surface coal mine blasts. Due to the large blast site distances, peak particle velocities measured in the ground beside the houses did not exceed 0.32 ips, and airblasts did not exceed 106 dB. However, the structures responded significantly to the ground vibrations, with maximum high-comer amplification factors as high as 8.5 in the horizontal directions. Vertical structural responses were as high as 10 times the vertical peak particle velocities in the ground, but appeared to be driven more by horizontal ground motions. No measurable airblast responses were observed. The natural frequencies of the structures ranged from 5 to 10 Hz.

INTRODUCTION

Through its coal regulatory program, the Ohio Department of Natural Resources, Division of Mines & Reclamation, has received dozens of blasting complaints over the years from occupants of manufactured houses. These houses include everything from traditional house trailers with paneled interiors, to modem modular-type houses with drywall interiors, fireplaces and large master bedroom/bath suites. The one common denominator for most of these dwellings is that they are supported by some type of pillars-often loosely stacked concrete blocks-and have a cantilevered perimeter. Complaints have ranged from rattling and breakage of freestanding or marginally fastened objects on shelves and walls, to allegations of drywall cracks, windows and doors out of alignment, roof leaks, plumbing leaks, and unleveling of the underlying support system.

At first glance, one would be inclined to dismiss complaints from people in manufactured houses, considering the marginal condition of many house trailers in rural America, and the haphazard and substandard manner in which many trailers are supported and leveled. As an example, the writer has observed trailers supported by tall, out-of-plumb stacks of loose concrete blocks, placed directly on the ground with no concrete pad or footer. There is also common knowledge of frequently cited (but mostly unpublished) measurements of high particle velocities sustained by manufactured houses during transportation to their destinations, with reportedly little or no damage to the houses.

Nonetheless, there are several reasons for studying the response of manufactured houses to blast vibrations. First, Public Law 95-87, the federal law under which the Office of Surface Mining (OSM) promulgated its blasting regulations, does not discriminate against the type or condition of houses to be protected. OSM expects blasting to be conducted in a manner to prevent damage to all houses, whether they are dilapidated, poorly supported trailers or modem wood-framed houses anchored to a concrete-block foundation around the entire perimeter. Second, the interiors of modem manufactured houses (trailers included) have drywall walls and ceilings, and any damage sustained during transportation to the house site is normally repaired after arrival and set-up. After being placed on a support system, the house may be subjected to the same or greater levels of blast-induced strains as conventional houses. Third, manufactured houses seem to "spring up" around surface coal mine areas like mushrooms after a rain. According to the U.S. Census Bureau, by 1998 manufactured houses accounted for nearly 25% of all new single-family housing starts.

The fourth and probably most significant reason is that the ground vibration and airblast limits recommended by the U.S. Bureau of Mines in RI 8507 (1980) do not really apply to manufactured houses. This fact becomes apparent after carefully reading the assumptions made by the Bureau's authors, and the data in RI 8507's Tables 1 and 3. On page 58 of RI 8507, the applicability of the Bureau's recommended vibration limits is clearly qualified by the statement: "Implicit in these values are assumptions that the structures are sited on a *firm foundation.. . .*" (Emphasis added.) It would seem obvious that pillar-supported manufactured houses with cantilevered perimeters would not qualify as having a *firm foundation.* Furthermore, only one of the 76 houses studied by the Bureau was a house trailer (structure #54). Of the six blasts relevant to the house trailer, the maximum charge-weights per delay were only 35 to 40 pounds, the highest peak particle velocity was only 0.07 ips, no natural frequency data were published, and no high-comer or vertical structural responses were published. (Some low-comer and midwall motions were published.)

Studies published by the Bureau and the private sector have well documented the phenomenon commonly known as "frequency matching." If the blast vibrations contain frequencies that tend to match the "natural" frequencies at which a house "likes" to vibrate-typically in the range of 4 to 12 Hz-the house will respond significantly. The Bureau (RI 8507) recorded upper-comer responses as high as 4 times the particle velocities measured in the ground beside the houses, with 1.5 being a typical amplification factor for conventional houses up to two stories high. Because of the amplification factor and the resulting strains across interior walls, the greatest potential for damage exists when a house is vibrated at or near its natural frequency.

But what about pillar-supported house trailers and other manufactured houses with entirely cantilevered perimeters? As previously mentioned, house trailers were, essentially, poorly represented by the 76 houses studied in RI 8507; and it is likely that few, if any, of the 76 houses were of modular-type construction supported by pillars. Are pillar-supported houses responding more to blast vibrations than conventional houses with firm foundations? What are their natural frequencies and how much amplification is typical? If they respond more than conventional houses, how should this be interpreted with regard to nuisance complaints and damage claims? Those are some of the questions that prompted the writer to measure the responses of three complainants' pillar-supported houses to blast vibrations.

PROCEDURE

Selection and Type of Manufactured Houses Studied

Selection of the three manufactured houses that were instrumented for structural response was based, primarily, on the fact that the owners/occupants filed blasting annoyance and damage complaints when at least two of the agency's seismographs were available to do such a study. Also, two of the three complainants had filed previous complaints. Another consideration was that previous monitoring at or near the complainants' dwellings revealed low-frequency, long-duration wavetrains, a phenomenon that has generated many complaints over the years.

Each of the three study sites was near a different surface coal mining operation in southeast Ohio. Each mining operation used blast designs unique to that mine site. The designs ranged from small blast patterns using 6¾-inch diameter holes and 30-foot depths, to very large casting shots using 12¼-inch diameter holes with large spacings and depths. However, the primary purpose of this study was to measure how the structures responded to blast vibrations, regardless of the type of blast that produced those vibrations. Therefore, only minimal blast design information will be presented in a later section of this paper.

The first structure studied was a house trailer manufactured around 1970, measuring 12' by 65'. It will be referred to as the "Canter trailer." It is poorly maintained inside and out, and is supported by loosely-stacked concrete block pillars up to five blocks high, with no concrete pads or footers under the pillars. A few of the pillars are significantly out of plumb. The Canter trailer site is on a hillside made of fill material left when a major highway was relocated to a higher elevation.

The second structure was a house. trailer manufactured around 1979, measuring 14' by 65'. It will be referred to as the "May trailer." It is maintained in fairly good condition, and is supported by loosely stacked concrete blocks, one to three blocks high, with no concrete pads or footers. Several pillars are significantly out of plumb. The May trailer site is just below the crest of a ridge, on a gentle slope.

The third and final structure was a 1995 modular-type house, measuring 28' by 68'. It will be referred to as the "Young modular." The house is maintained in excellent condition. It has a modem drywall-type interior, with spacious rooms, a fireplace, and a master bedroom/bath suite. The house was brought to the site in two sections and placed on a substantial series of concrete-block pillars of multiple block thickness. There are five rows of pillars across the width of the house, with five pillars in each row. Each row of pillars rests on a continuous concrete footer. The pillars are up to six blocks high on the downslope end of the house, and diminish in height toward the upslope end. There is also a non-loadbearing concrete-block wall under the entire perimeter of the house. The Young modular house site was cut out of a gently sloping hillside near the crest of a ridge.

Instrumentation Methods

The seismographs used to instrument all three structures were LARCOR models MR-4G (velocity-type transducer) and MR-1A (accelerometer-type transducer). These Mini-Recorders are essentially the same as the Mini-Seis units distributed by White Industrial Seismology, Inc. The data were downloaded with a laptop computer, then processed with the standard software provided with the seismographs.

For the **Canter trailer,** the transducer of the first seismograph was firmly coupled to the upper southwest comer of the trailer. A heavy-duty steel bracket was fastened with long screws through the vertical trim on the edge of the trailer, and a “c” clamp was used to secure the transducer in a horizontal position on the bracket. The microphone was fastened to the bracket with wire. The transducer of the second seismograph was buried about 6” deep in soil next to the southwest comer of the trailer. The radial directions of both transducers (ground and upper comer of trailer) were aligned parallel to the short axis (end wall) of the trailer. In this manner, the trailer response waveforms could be directly compared to the ground vibration waveforms, by overlaying each pair of waveforms on a light table and lining up the airblast arrivals. The trigger levels of the ground unit were set at 0.03 ips and 133 dB. The seismic trigger level of the trailer unit was set at 0.25 ips to minimize triggering from activities of the occupants. (This was determined by having the owner jump up and down inside the end of the trailer while observing the instant readings on the seismograph coupled to the trailer.)

For the **May trailer,** the transducer and microphone of the first seismograph were coupled to the upper southeast comer of the trailer, using the same fastening procedures as on the Canter trailer. The transducer of a second seismograph was coupled in the same manner to the lower southeast comer of the trailer, approximately 7.5’ below the upper-comer unit. The transducer of a third seismograph was buried about 6” deep in soil near the southeast comer of the trailer. The radial directions of all three transducers were aligned parallel to the short axis (end wall) of the trailer. The three seismographs were interconnected such that the two trailer units would trigger only when the ground unit triggered. The trigger levels of the ground unit were set at 0.03 ips and 127 dB.

For the **Young modular** house, the transducer of the first seismograph was coupled to the upper southwest comer of the one-story house, just below the roof, to a wooden structural member of the roof gable. The transducer of the second seismograph was buried about 6” deep in soil near the southwest comer. The radial directions of both transducers were aligned parallel to the short axis (end wall) of the house. The two seismographs were interconnected such that the house unit would trigger only when the ground unit triggered. The trigger levels of the ground unit were set at 0.03 ips and 133 dB. Incidentally, unlike the May trailer, a transducer was *not* coupled to the lower comer of the Young modular, in order to minimize damage to the vinyl siding of this newer home.

RESULTS

Canter Trailer

In the Canter trailer study, five blasts induced trailer responses that were high enough (greater than 0.25 ips) to trigger the upper-comer seismograph. The basic blast data in Table 1 present the approximate distance from each blast to the trailer, the maximum pounds detonated per delay (within any 8-ms period), the scaled distance factor relative to the trailer, and the peak particle velocity (PPV) and airblast levels recorded by the ground unit beside the trailer.

The combination of large distances and relatively small charge-weights per delay produced large scaled distance factors. Not surprisingly, the PPV’s did not exceed 0.24 ips. However, the trailer site-primarily fill material left when a major highway was widened and moved to a higher elevation-favored low-frequency, long-duration ground vibrations. The trailer site was separated from the blasting area by a ridge. The combination of topography and large distances produced airblast levels that did not exceed 106 dB.

Table 1. Basic Blast Data – Canter Trailer Study

SHOT #	APPROX. BLAST DISTANCE	MAXIMUM POUNDS PER DELAY	SCALED DISTANCE FACTOR	PEAK PARTICLE VELOCITY	AIRBLAST LEVEL
1	2,100'	276	126	0.24 ips	106 dB
2	2,050'	153	166	0.16 ips	106 dB
3	3,900'	406	194	0.09 ips	106 dB
4	4,000'	421	195	0.08 ips	106 dB
5	4,150'	471	191	0.07 ips	100 dB

Figure 1 is a complete waveform printout for the transducer and microphone coupled to the upper comer of the Canter trailer, showing how the trailer responded to Shot # 1. The maximum response of 1.52 ips occurred in the radial direction, parallel to the short axis (end wall) of the trailer. The radial direction of ground vibration was superimposed on the trailer response by matching the airblast arrivals recorded by the ground and trailer units. In Figure 1, only the airblast recorded by the trailer unit is shown, with an arrival time about a tenth of a second before the 2-second mark. The small acoustic oscillations before that point were generated by the trailer's response to ground vibration; they do not represent "true" airblast generated by the escape of gases and movement of rock upon detonation. Note that the trailer responses in all three directions-radial, vertical and transverse-showed no relationship to the 106-dB airblast arrival. This was true for all five shots.

As seen in Figure 1, the maximum trailer response in the radial direction (1.52 ips) was "driven" by a ground wave cycle that corresponded to the PPV of 0.24 ips, indicating an amplification factor of 6.3 (1.52 ips divided by 0.24 ips). In other words, the upper comer of the trailer oscillated at a velocity that was 6.3 times faster than the driving ground vibration. The natural frequency of the trailer was 5 Hz (+/-), and the ground vibration was comprised entirely of wave cycles at 5 Hz (+/-), indicating a perfect match from the standpoint of amplification. Highly similar frequency matching was observed for all five shots.

Table 2 summarizes the Canter trailer response data in the radial direction, parallel to the end wall, for all five shots. The amplification factors ranged from 3.3 to 6.7, with an average of 5.6. The amplifications in the vertical and transverse directions were not as high as the radial, and are not presented in this paper.

Table 2. Summary of Canter Trailer Response Data in the Radial Direction—Parallel to End Wall.

SHOT #	DRIVING GROUND VIBRATION AND FREQUENCY	MAX. TRAILER RESPONSE AND FREQUENCY	AMPLIFICATION FACTOR
1	0.24 ips @ 5.0 Hz	1.52 ips @ 4.9 Hz	6.3
2	0.12 ips @ 4.8 Hz	0.40 ips @ 5.0 Hz	3.3
3	0.065 ips @ 4.5 Hz	0.43 ips @ 5.1 Hz	6.6
4	0.075 ips @ 4.6 Hz	0.38 ips @ 5.4 Hz	5.1
5	0.063 ips @ 5.0 Hz	0.425 ips @ 5.4 Hz	6.7

Average Amplification Factor = 5.6

ODNR SEISMO. DATA/M. MANN& J. MARTIN/RECORDED AT:
Steven Canter, 364 Carmel Bathamia Rd., Thurman,OH
Geo. Coupled to Upper SW Corner of Trailer
Radial Dir. Parallel to Short Axis of Trailer
Approx. 2,100' E of Blast Site At
Waterloo Coal Co., Inc., Permit D-0594

Event Number: 002 Date: 4/1 5/1998 Time: 15:49
Acoustic Trigger: 133 dB Seismic Trigger: 0.25 in/s Serial Number: 920

Amplitudes and Frequencies	**Graph Information**
Acoustic: 106 dB @ 3.3 Hz.	*Duration: 0.000* sec To: 6.500 sec
Radial: 1.52 in/s @ 4.9 Hz.	*Acoustic: 0.15* Mb (0.04 Mb/div)
Vertical: 0.34 in/s @ 5.0 Hz.	*Seismic:* 1.00 in/s (0.25 in/s/div)
Transverse: 0.34 in/s @ 6.3 Hz.	*Time Lines at;* 1.00 sec intervals
Vector Sum: 1.58 in/s	

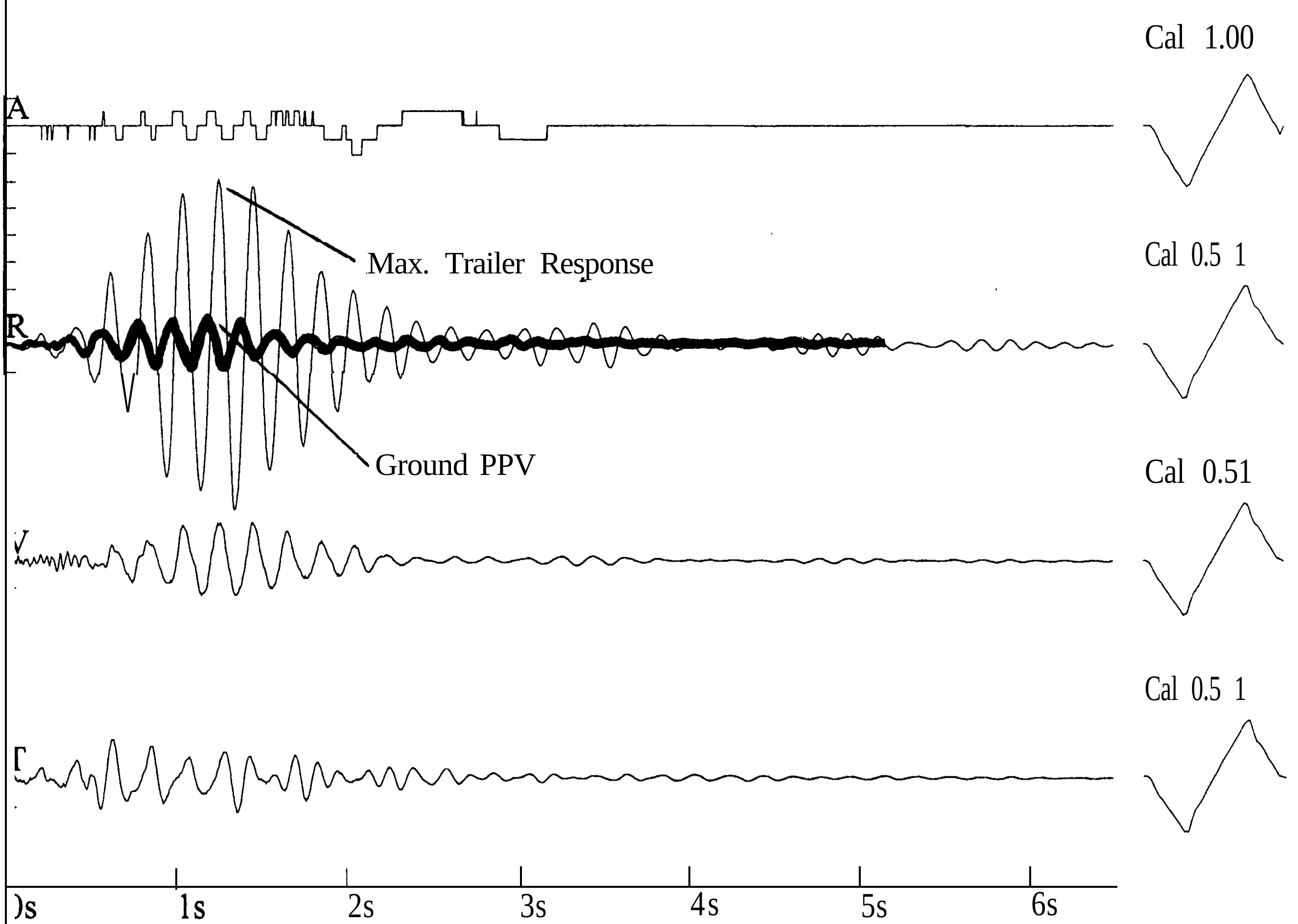


Figure 1.

Mav Trailer

During the May trailer response study, the ground unit recorded 15 blasts, all of which induced trailer responses that were recorded by the upper-comer and lower-comer trailer units. Table 3 summarizes basic blast data for the 15 blasts, and the PPV and airblast levels recorded by the ground unit. Despite the large maximum charge-weights per delay detonated during these casting shots, the very large distances (averaging 2.5 miles) produced large scaled distance factors, resulting in PPV's and airblast levels no greater than 0.32 ips and 106 dB.

Table 3. Basic Blast Data – May Trailer Study

SHOT #	APPROX. BLAST DISTANCE	MAXIMUM POUNDS PER DELAY	SCALED DISTANCE FACTOR	PEAK PARTICLE VELOCITY	AIRBLAST LEVEL
1	12,674'	2,700	244	0.11 ips	100 dB
2	13,380'	2,475	269	0.08 ips	100 dB
3	13,485'	2,025	300	0.05 ips	100 dB
4	13,056'	2,475	262	0.06 ips	100 dB
5	13,210'	2,760	251	0.15 ips	106 dB
6	13,120'	2,760	250	0.04 ips	100 dB
7	12,890'	2,704	248	0.19 ips	100 dB
8	12,782'	2,169	274	0.14 ips	100 dB
9	12,731'	5,175	177	0.28 ips	100 dB
10	12,884'	5,400	175	0.18 ips	100 dB
11	13,163'	5,400	179	0.32 ips	100 dB
12	13,195'	5,033	186	0.16 ips	100 dB
13	12,686'	10,350	125	0.09 ips	106 dB
14	12,572'	3,195	222	0.19 ips	100 dB
15	12,555'	3,600	209	0.16 ips	100 dB

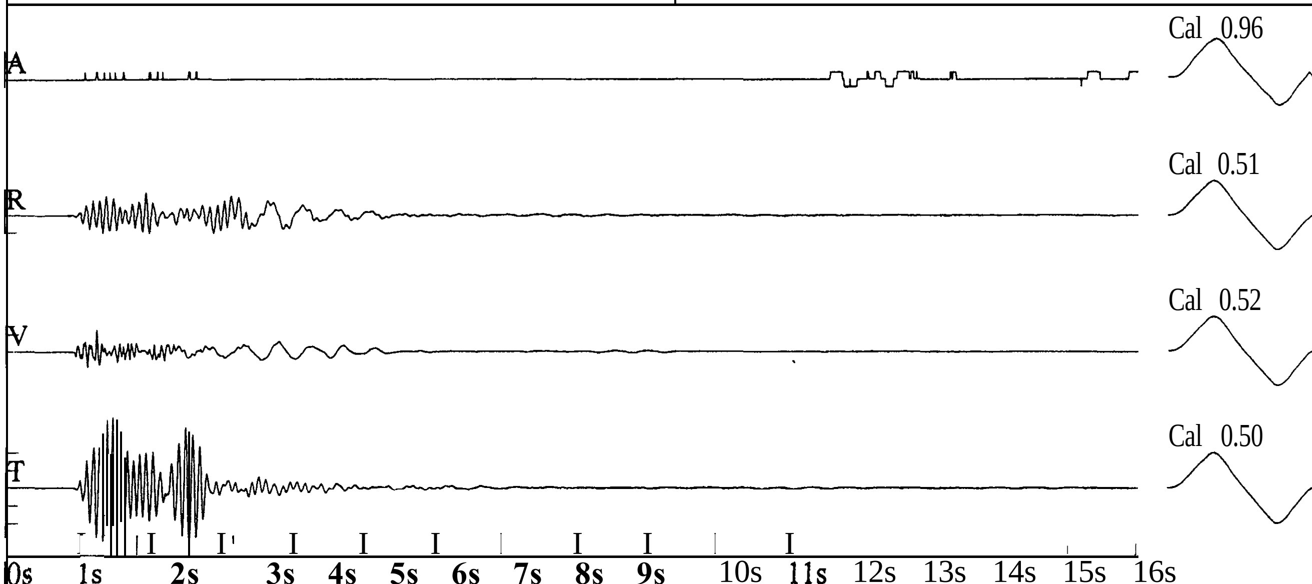
Figure 2 is a waveform printout for Shot # 11, which produced the highest PPV (0.32 ips) beside the May trailer. At the bottom of the page is a Fast Fourier Transform (FFT) analysis of frequency, with four graphs representing airblast and the three directions of ground motion. The graphs show energy concentrations at frequencies of about 2 Hz and 11 Hz in the radial direction, 2 Hz in the vertical direction, and 11 Hz in the transverse direction. Most of the waveforms recorded beside the May trailer had predominant frequencies from 9 to 11 Hz, but many also had trailing surface waves at about 2 Hz, and long durations, typically greater than 5 seconds.

Tables 4 and 5 summarize the May trailer response data for the radial and vertical directions, respectively. Each table compares the ground PPV to the maximum upper-comer trailer response for each shot, along with the frequency of the peak responses, as determined from an FFT analysis of five to ten cycles that included the peak. Each table also lists the maximum amplification factor for each shot, calculated by dividing the maximum upper-comer trailer response by the ground unit's PPV. Visual inspections of the waveforms showed that the radial PPV's closely matched the wave cycles that actually drove the maximum radial trailer responses. Table 4 also lists the maximum lower-comer trailer responses and frequencies in the radial direction.

ODNR SEISMO. DATA/M. MANN/RECORDED AT:
Steve May, 4475 SR 83, Beverly, OH
Approx. 13,163’ E of Blast Site At
Central Ohio Coal Co., Permit D-1084
Max. 5,400 lbs. Per Delay

Event Number: 034 Date: 10/7/1998 Time: 16: 12
Acoustic Trigger: 127 dB Seismic Trigger: 0.03 in/s Serial Number: 765

Amplitudes and Frequencies	Graph Information
Acoustic: 100 dB @ 0.0 Hz.	Duration: 0.000 sec To: 16.000 sec
Radial: 0.105 in/s @ 10.2 Hz.	*Acoustic:* 0.20 Mb (0.05 Mb/div)
Vertical: 0.1025 in/s @ 16.0 Hz.	*Seismic:* 0.32 in/s (0.08 in/s/div)
Transverse: 0.32 in/s @ 10.2 Hz.	*Time Lines at:* 1 .00 sec intervals



Fourier Analysis (Power Spectrum - Box Window)

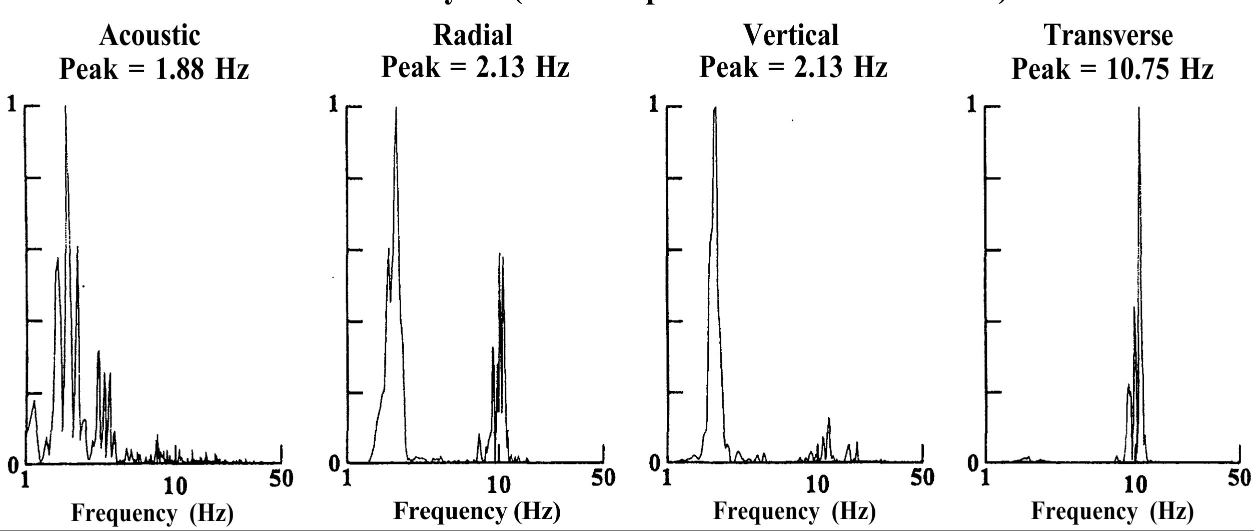


Figure 2.

Table 4. Summary of May Trailer Response Data in the Radial Direction—
Parallel to End Wall.

SHOT #	GROUND PPV AND FFT FREQ. ( )	MAX. LOWER-CORNER TRAILER RESPONSE AND FFT FREQ. ( )	MAX. UPPER-CORNER TRAILER RESPONSE AND FFT FREQ. ( )	AMP. FACTOR
1	0.07 ips (9.0)	0.09 ips (9.0)	0.12 ips (10.0)	1.7
2	0.04 ips (10.0)	0.05 ips (9.0)	0.13 ips (10.0)	3.3
3	0.03 ips (10.0)	0.04 ips (9.0)	0.08 ips (10.0)	2.7
4	0.03 ips (10.0)	0.05 ips (10.0)	0.09 ips (10.0)	3.0
5	0.08 ips (10.0)	0.08 ips (10.0)	0.18 ips (10.0)	2.3
6	0.02 ips (10.5)	0.04 ips (10.0)	0.05 ips (10.0)	2.5
7	0.09 ips (10.0)	0.15 ips (10.0)	0.22 ips (10.0)	2.4
8	0.06 ips (10.0)	0.11 ips (10.0)	0.15 ips (10.0)	2.5
9	0.07 ips (9.0)	0.17 ips (10.0)	0.25 ips (10.0)	3.6
10	0.07 ips (11.0)	0.16 ips (10.0)	0.17 ips (10.0)	2.4
11	0.11 ips (10.5)	0.23 ips (10.0)	0.31 ips (10.5)	2.8
12	0.08 ips (10.0)	0.12 ips (9.0)	0.20 ips (9.0)	2.5
13	0.06 ips (10.5)	0.11 ips (10.5)	0.11 ips (10.0)	1.8
14	0.07 ips (9.0)	0.14 ips (10.0)	0.18 ips (10.0)	2.6
15	0.08 ips (10.0)	0.18 ips (10.0)	0.20 ips (9.0)	2.5

Average Amplification Factor = 2.6

Table 5. Summary of May Trailer Response Data in the *Vertical* Direction.

SHOT #	GROUND PPV AND FFT FREQUENCY ( )	MAX. UPPER-CORNER TRAILER RESPONSE AND FFT FREQUENCY ( )	AMPLIFICATION FACTOR
1	0.05 ips (10.0)	0.19 ips (10.0)	3.8
2	0.02 ips (10.0)	0.12 ips (10.0)	6.0
3	0.01 ips (9.0)	0.09 ips (10.0)	9.0
4	0.01 ips (10.5)	0.09 ips (10.0)	9.0
5	0.03 ips (10.0)	0.23 ips (10.0)	7.7
6	0.01 ips (10.5)	0.05 ips (11.0)	5.0
7	0.05 ips (11.0)	0.33 ips (10.0)	6.6
8	0.04 ips (12.0)	0.21 ips (10.0)	5.3
9	0.05 ips (11.0)	0.45 ips (10.0)	9.0
10	0.06 ips (16.0)	0.26 ips (10.0)	4.3
11	0.10 ips (12.0)	0.46 ips (10.5)	4.6
12	0.05 ips (9.0)	0.22 ips (9.0)	4.4
13	0.08 ips (5.5)	0.13 ips (10.0)	1.6
14	0.05 ips (10.0)	0.24 ips (10.0)	4.8
15	0.06 ips (10.0)	0.29 ips (10.0)	4.8

Average Amplification Factor = 5.7

As seen in Table 4, the natural frequency of the May trailer was 10 Hz (+/-), and the predominant frequencies of all ground PPV's were also 10 Hz (+/-), indicating a close match from the standpoint of amplification. The amplification factors in the radial direction (parallel to the end wall of the trailer) ranged from 1.7 to 3.6, with an average of 2.6. The amplification factors in the transverse direction averaged 2.2, and the data are not presented in this paper.

For 11 of the 15 shots, the maximum lower-comer response (in Table 4) was significantly less than the maximum upper-comer response. For the other four shots, the lower- and upper-comer responses were nearly identical. A comparison of lower- and upper-comer waveforms for several shots showed that the positive and negative peaks matched favorably. This suggests that the lower comer moved in unison with the upper comer, despite the differing response velocities.

It is significant to note that the May trailer did not respond to the 2-Hz surface waves that, for many shots, followed the 9- to 1 l-Hz wave cycles. Also, the small airblasts, which arrived about 4 to 5 seconds after the ground vibrations and related trailer responses had diminished, produced negligible trailer response.

From the data in Table 5, the upper-comer *vertical* responses were much higher than the ground PPV's. Amplification factors ranged from 1.6 to 9.0, with an average of 5.7. However, a comparison of the waveforms revealed that the *transverse* ground motions might have driven the largest vertical trailer responses. Figure 3 illustrates this unusual phenomenon for Shot #9. By superimposing the transverse ground waveform over the vertical upper-comer trailer response, it can be seen that they are nearly identical in character through much of the waveforms (i.e., the peaks and valleys closely match). The only notable exceptions would be during the first several wave cycles and the last third of the waveform when the vertical response appears to be "ahead of' the transverse ground PPV. By contrast, the vertical *ground* waveform (not shown) bears little or no resemblance to the vertical trailer response.

Consequently, the high amplification factors calculated for the vertical direction might be a misrepresentation of what actually happened. If it is true that the transverse ground motion was primarily responsible for the vertical trailer responses, then the amplification factors should be re-calculated by dividing the maximum vertical response by the PPV of the *transverse* ground motion. When this is done, the vertical amplification factors range from 1.3 to 1.8, with an average of only 1.5.

The apparent phenomenon of the transverse ground PPV driving the largest vertical trailer responses might be explained by the nature of the trailer support system. The transducer was coupled to the southeast comer of the trailer's end wall, which, as with most trailers, is cantilevered. The nearest under-support would be at least several feet back from the end wall, and several feet back from the sidewall. In fact, the trailer's entire perimeter is cantilevered. It is, essentially, a lightweight, relatively unrestrained box when compared to a conventional wood-frame house that is fastened to its foundation.

Although the greatest amplifications occurred in the radial direction, the strongest ground motion from all 15 shots occurred in the transverse direction. The transverse PPV's were generally two to three times greater than the radial PPV's for most shots, and the vertical PPV's were even smaller than the radial PPV's. It is conceivable, then, that the movement of the relatively lightweight, unrestrained trailer could have been most influenced by the transverse ground motions at the May trailer site. But the exact mechanism responsible for the observed phenomenon is not understood.

May Trailer Response (Shot #9)

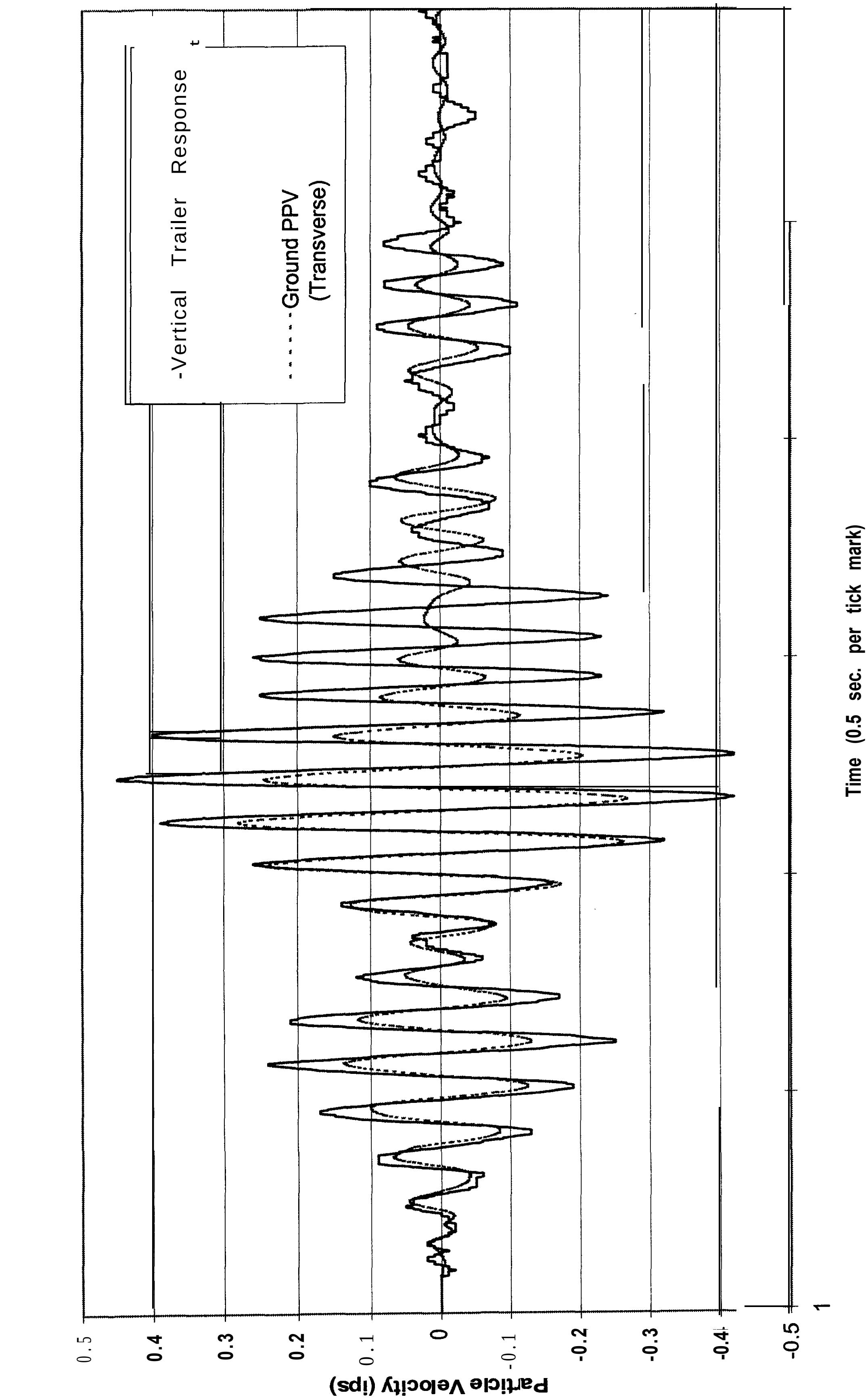


Figure 3

Young Modular House

During the Young modular house study, the ground and upper-comer house units recorded three blasts with complete waveforms. The basic blast data are summarized in Table 6. The scaled distance factors at the Young modular site were lower than any at the Canter and May trailer sites. Nonetheless, the highest PPV was only 0.23 ips, and the highest airblast level was only 106 dB.

Table 6. Basic Blast Data—Young Modular House Study.

SHOT #	APPROX. BLAST DISTANCE	MAXIMUM POUNDS PER DELAY	SCALED DISTANCE FACTOR	PEAK PARTICLE VELOCITY	AIRBLAST LEVEL
1	3,650'	1,324	100	0.09 ips	106 Db
2	3,650'	1,527	93	0.09 ips	106 dB
3	3,650'	1,911	83	0.23 ips	106 dB

Figure 4 is a waveform printout for Shot # 3, which produced the highest PPV (0.23 ips) beside the Young modular house. The FFT analysis shows energy concentrations at frequencies of about 5 Hz and 7 Hz in the radial direction, 4 Hz, 5 Hz and 7 Hz in the vertical direction, and 4 Hz in the transverse direction. Most of the waveforms recorded beside the Young modular, before and during the response study, had predominant frequencies from 4 to 7 Hz, and durations of 3 to 4 seconds.

Tables 7 and 8 summarize the Young modular house response data for the transverse and vertical directions, respectively. Each table compares the driving ground PPV and FFT frequency to the maximum upper-comer house response and zero-crossing frequency for each shot. Each table also lists the maximum amplification factor for each shot, calculated by dividing the maximum upper-comer house response by the particle velocity of the ground cycle that drove the maximum response.

Table 7. Summary of Young Modular House Response in Transverse Direction-Parallel to Long Axis of House.

SHOT #	DRIVING GROUND PPV AND FREQUENCY (FFT)	MAXIMUM HOUSE RESPONSE AND FREQUENCY (ZC)	AMPLIFICATION FACTOR
1	0.04 ips (6.4)	0.34 ips (6.4)	8.5
2	0.08 ips (5.6)	0.22 ips (5.4)	2.8
3	0.11 ips (3.8)	0.37 ips (4.9)	3.4

Average Amplification Factor = 4.9

Table 8. Summary of Young Modular House Response in *Vertical* Direction.

SHOT #	"DRIVING" GROUND PPV AND FREQUENCY (FFT)	MAXIMUM HOUSE RESPONSE AND FREQUENCY (ZC)	AMPLIFICATION FACTOR
1	0.04 ips (5.5)	0.15 ips (19.6)*	3.8
2	0.03 ips (5.3)	0.17 ips (7.4)	5.7
3	0.03 ips (5.3)	0.30 ips (6.6)	10.0

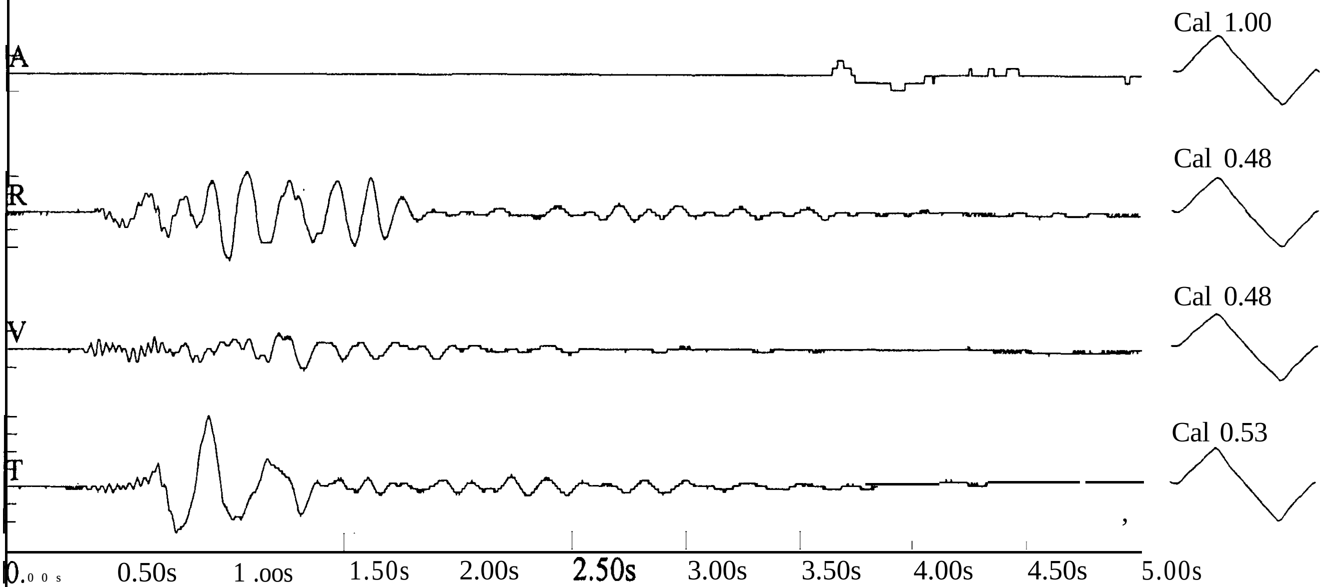
Average Amplification Factor = 6.5

*This peak appeared to be "riding" a lower frequency cycle of about 8 Hz.

ODNR SEISMO. DATA/M. MANN/RECORDED AT:
Judy Young, 9850 Buzzard Glory Rd., New Lex., OH
Approx. 3,650' from Blast Site At
Oxford Mining Co., Inc., Permit D-1086
GROUNDUNIT
Radial Dir. Parallel to Short Axis of House

Event Number: 010 Date: 3/5/1999 Time: 14:44
Acoustic Trigger: 133 dB Seismic Trigger: 0.05 in/s Serial Number: 922

Amplitudes and Frequencies	**Graph Information**
Acoustic: 106 dB @ 8.2 Hz.	*Duration: 0.000* sec To: 5.000 sec
Radial: 0.16 in/s @ 6.9 Hz.	*Acoustic: 0.20* Mb (0.05 Mb/div)
Vertical: 0.07 in/s @ *6.4* Hz.	*Seismic: 0.23* in/s (0.0575 in/s/div)
Transverse: 0.23 in/s @ 4.5 Hz.	*Time Lines at: 0.50* sec intervals



Fourier Analysis (Power Spectrum - Box Window)

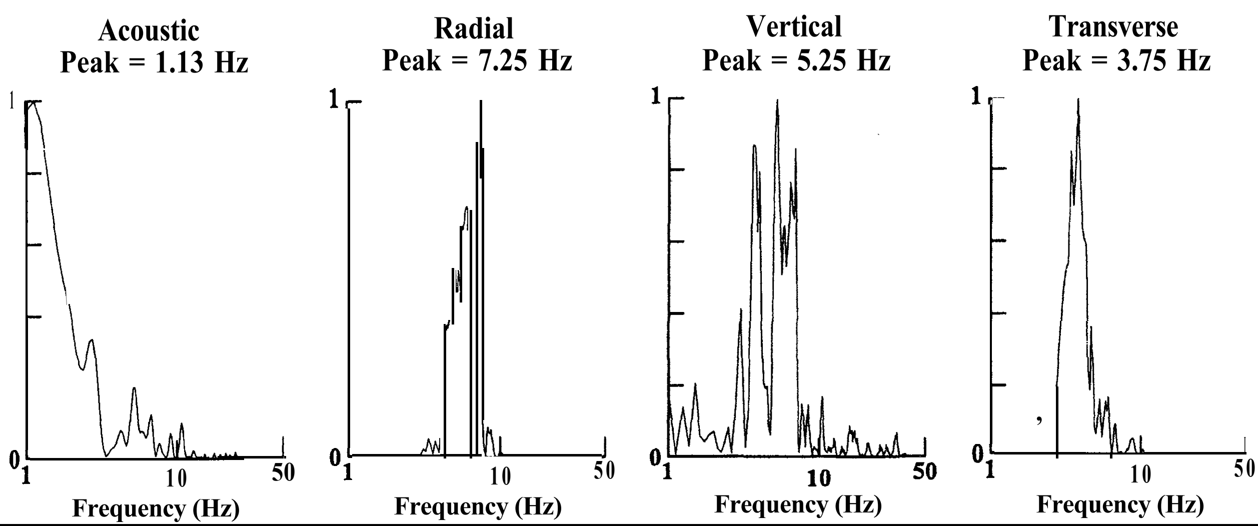


Figure 4.

From the data in Table 7, the natural frequency of the Young modular house was about 6 Hz (+/-), and the predominant frequencies of the ground vibrations ranged from about 4 to 6 Hz (+/-). The amplification factors in the transverse direction (parallel to the long wall of the trailer) ranged from 2.8 to 8.5, with an average of 4.9 for the three shots. The amplification factors in the radial direction were smaller, with an average of only 2.3, and the data are not presented in this paper. Note that, unlike the Canter and May trailers that responded more in the radial direction parallel to their end walls, the Young modular responded more in the transverse direction, parallel to the long axis of the house.

The vertical response data in Table 8 show amplification factors from 3.8 to 10.0, with an average of 6.5. As with the May trailer, the high vertical amplification factors for the Young modular house must be viewed with caution. This is because the vertical responses of the house appeared to be influenced more by the larger radial and transverse ground motions, rather than the smaller vertical ground motions. Thus, the actual amplification factors could have been somewhat less than 6.5.

All of the airblasts recorded at the Young modular house were only 106 dB. They arrived at about the time the ground vibrations and house responses had greatly diminished, and produced negligible structural response in the upper comer.

Damning Values

The damping value is an indicator of a structure's ability to absorb or dissipate the energy from the blast vibrations. It is expressed as a percentage, based on how fast the velocities of successive wave cycles (oscillations) of the structure decay. Using the equation in RI 8507 (page 30), damping values were calculated for the Canter trailer, May trailer and Young modular, using one representative waveform from each structure. The damping values ranged from 4 to 7 percent, but must be viewed only as estimates due to the small sample size, and the difficulty in picking a representative series of wave cycles that were not influenced by the continuation of ground motion beyond the peak structural responses.

SUMMARY OF FINDINGS

Three manufactured houses-two older house trailers and a modem modular-type house-were instrumented with seismographs to record how they responded to ground vibrations and airblasts generated by surface coal mine blasts in southeastern Ohio. All three structures were supported by pillars and had a cantilevered perimeter. The natural frequencies of the three structures ranged from 5 to 10 Hz, and the damping values ranged from 4 to 7 %. Those values were comparable to the data published in the Bureau's RI 8507 for conventional houses, with natural frequencies from 5 to 12 Hz and damping values of 2 to 10 %.

The upper comers of all three structures responded significantly to low-level ground vibrations that matched the natural frequencies of the structures. The maximum horizontal amplification factors ranged from 3.6 to 8.5. This contrasted sharply with the RI 8507 data, which reported amplification factors ranging from less than 1 to about 4, with 1.5 being typical.

Large vertical responses, ranging from about 6.5 to 10 times the vertical ground PPV's, were observed in the upper comers of the structures. However, comparisons of waveforms indicated that the vertical responses might have been driven more by the larger horizontal (radial and/or transverse) ground motions, thereby discounting some of the significance of those very large amplifications. Nonetheless, the large vertical motions observed in the structures contrasted sharply with the RI 8507 data, which reported vertical responses typically *equal* to the vertical ground PPV's.

CONCLUSIONS AND RECOMMENDATIONS

The three pillar-supported manufactured houses studied-two older house trailers and one modern modular-type house-exhibited much greater responses to blast vibrations than conventional houses with firm foundations. The amplification factors were significantly higher than the Bureau's findings for typical wood-frame houses, as reported in RI 8507.

Based on the findings of this study, people in pillar-supported manufactured houses might be subjected to greater structural response velocities, displacements and accelerations than people in conventional houses. At a minimum, this could create a greater potential for annoyance and personal property damage (i.e., items that fall and break). But most state and federal blasting regulations were not designed to prevent annoyance or damage to knickknacks, nor would it be practical to regulate based on such factors. At the very least, then, blasters, mine operators, consultants and government regulators should be particularly sympathetic to annoyance and knickknack-type complaints filed by occupants of pillar-supported houses.

Due to the relatively low ground PPV's (none higher than 0.32 ips) observed in this study, it is unlikely that the high amplification factors caused or contributed to any structural damages in the two house trailers and modular house that were studied. However, if higher ground PPV's could produce higher structural velocities proportional to the observed amplification factors, a ground PPV of 1 .0 ips could produce a high-corner structural velocity of 8.5 ips or greater, It would seem reasonable to question whether certain types of damage could become more likely under those conditions. Of particular concern might be cracking due to strains across drywall walls and ceilings, separations where additions meet the original structures, and disturbance of the pillar support system.

Further research on the response of pillar-supported manufactured houses to blast vibrations is strongly recommended. Such research should include a much larger sample of manufactured houses, higher ground vibration and airblast levels, instrumentation to determine if the houses are moving as a single box or exhibiting racking motions similar to conventional houses, and measurements of responses to natural and cultural stresses (e.g., wind, temperature and humidity changes, human activities, interior loading factors, and transportation stresses). The Bureau's ground vibration and airblast limits (RI 8507 and RI 8485) should then be examined for their applicability to pillar-supported manufactured houses. If necessary to prevent damage, different limits should be established for such structures.

REFERENCES

MANUFACTURED HOME MONTHLY, April 21, 2000, "Growth Dramatic," ***The Times Reporter,*** New Philadelphia, Ohio.

SISKIND, D.E., STACHURA, V.J., STAGG, M.S., and KOPP, J.W. (1980), "Structure Response and Damage Produced by Airblast from Surface Mining," U.S. Bureau of Mines, Report of Investigations 8485.

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