Response of Test House to Vibroseis Vibrations and Environmental Forces

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ABSTRACT

In response to public concerns about the damage potential of vibroseis vibrations from seismic exploration, Fina Oil and Chemical Company (now Total E&P USA, Inc.) sponsored full-scale testing of a typical residence. The test house was vibrated by four vibroseis trucks on both soil and asphalt surfaces at declining separation distances. Ultimately, the vibrators were 13 feet (4.0 m) from the front porch and 10 feet (3 m) from the front sidewalk. Peak particle velocities of the ground motions were about 1 in./second (0.4 cm/second) at the house foundation. As expected, the responses of the superstructure were strongly dependent on the frequencies of the ground motions. No damage to the house of any kind was produced by these vibrations, even though the vibrators were operating at 90% maximum output. Tests were also conducted away from the house to explore the vibration intensities and attenuation characteristics of the ground motions generated. The resulting vibrations were compared to previous work and found to be consistent with those results. Changes in crack width and associated weather-induced changes in temperature, humidity, and other environmental factors were recorded every 2 hours for 1 year. Environmental effects are known to produce larger crack responses than vibrations that conform to common standards and regulated limits, a fact demonstrated again in this case. Response motions in the house were also recorded during common household activities, including hammering nails, slamming doors, and use of the fireplace. In the vicinity of the input forces, some of these activities generated greater response than did the vibroseis excitation.

THE VIBROSEIS METHOD

Vibroseis seismic exploration employs four to six in-line truck-mounted vibrators to generate a seismic signal. Each truck is equipped with a vibrator pad positioned at the center of balance of the truck. The pad is lowered to the ground, and the truck is lifted hydraulically so that its full weight is resting on the pad. A typical exploration signal at the vibrator pad consists of a sinusoidal ground displacement that sweeps from a low frequency to a high frequency during an interval of 10 to 20 seconds. A sweep may be repeated at one location several times before the trucks are moved forward to generate the next exploration signal. The vibrator pads are operated in unison so that the generated signals can be of low intensity and still provide useful data. The method can be used in residential areas without causing damage, whereas explosive energy sources might not be accepted.

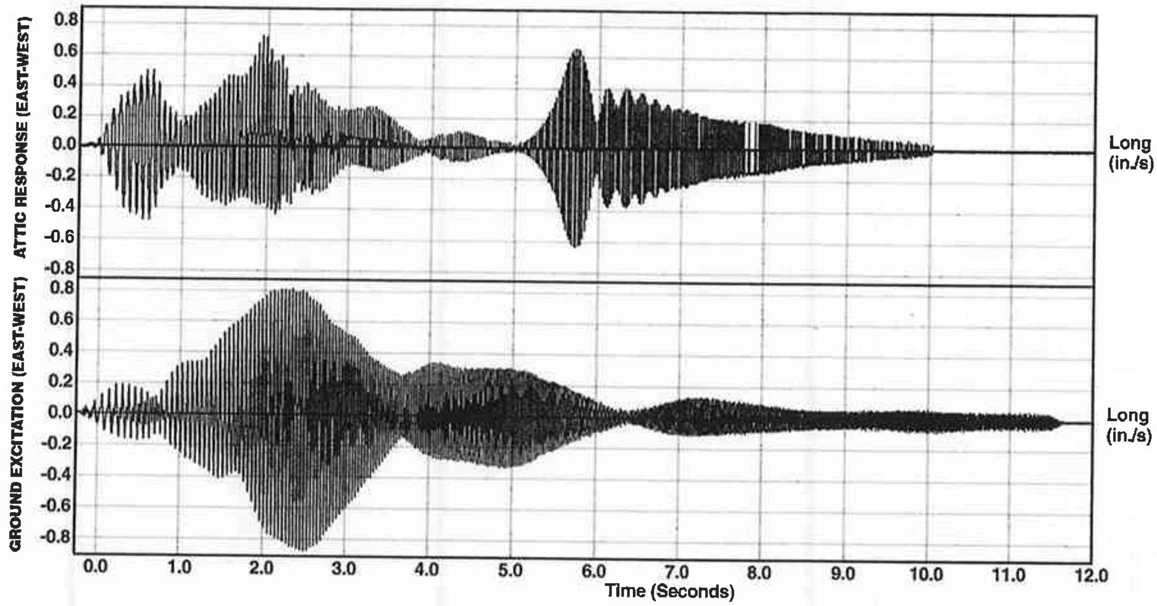

Figure 1. Transverse component of structural response in the attic of the test house (top trace) compared to the ground excitation (bottom trace) at one of the nearby monitoring stations. 1.00 in. = 2.54 cm.

Computerized signal enhancement technology makes it possible to use the lower-intensity vibroseis signals to study the subsurface geology to considerable depths using seismic reflection techniques.

GROUND VIBRATIONS

Although a vibration sweep may last from 10 to 20 seconds (12 seconds in the seismic exploration case duplicated herein), no single frequency has a duration of more than a fraction of a second. In that sense, the vibrations may be regarded as transient. Figure 1 shows the time histories of the transverse component of structural response (measured in the attic along the short axis of the test house) and the corresponding component of ground excitation at one of the nearby monitoring stations on the east side of the test house. Excitation motions are shown to be transient and time varying in character. Structural response is also shown to be time varying and dependent on the excitation frequency. The response was negligible after 10 seconds, so the ends of the traces were clipped. All three traces for each location are shown later in Figure 13, along with additional discussion.

As shown in Figure 2, ground vibrations die out (attenuate) with distance from the source in a manner that is similar to that of many forces in the universe. At small distances from the source, there is a rapid drop in the intensity. At greater distances, the intensity continues to drop, but the incremental decay in intensity decreases as the distance increases. This behavior is called an exponential decay. The exact manner in which this decay takes place depends on the characteristics of the source, the surface conditions, and the local geology. Surface conditions affect the coupling of the vibrators to the ground. For instance, loose or low-density surface materials may inhibit the transmission of energy from the vibrator pad into the medium because of poor coupling.

Figure 2 is a linear plot of a portion of the readings from the present study, with the vibrators operating at 90 and 30 percent of maximum output. A linear graph is one in which the axes are divided into equal portions as the values increase. The upper curve in Figure 2 shows a representative upper bound line for a group of readings taken next to the test house (low readings are not shown). At greater distances, the curve is representative of tests in the open field to the northwest of the test house. Although a point-to-point decay curve for vibroseis is not as regular as that for a point source, it is a simple matter to determine an upper bound line of regular form that can be used for prediction purposes. In routine practice, most readings would fall well below that line. That was true in this case. For the curve in Figure 2 at 90 percent drive, that would be below 0.45 in./second at 100 ft (1.1 cm/second at 30.5 m) and below 0.1 in./second at 300 ft (0.3 cm/second at 91.4 m).

Some readers may be more familiar with earthquakes than mechanical vibrations, and this perspective requires a word of caution. Most earthquake criteria and reported data are expressed in units of acceleration, a result of instrumental limitations in measuring large displacements. The use of peak acceleration to compare motions from industrial vibrations is highly questionable because of the effects of differing frequencies that induce different movements and different strains in structures. To make a meaningful comparison between earthquake motions and mechanically induced motions, it is important to consider both particle velocity and displacement. At a given acceleration level, displacements are inversely proportional to the square of the dominant wave frequencies. Thus, a Rayleigh wave from a low-frequency high-magnitude earthquake might generate a similar acceleration to an industrial vibration wave, but the corresponding ground displacement could be as much as hundreds or even thousands of times greater than that of a comparatively high-frequency mechanical or industrial vibration. It would be highly inaccurate and misleading to suggest that such an earthquake event and mechanical vibration would have the same damage potential.

Vibrators can be operated at intensities less than 90 percent of the maximum. Operating at lower intensities moves the entire curve downward, as shown in Figure 2 for the 30 percent drive. This reduction in intensity can be employed when vibroseis trucks approach structures.

It is seen in Figure 2 that all the data points for a given output do not fall exactly on a single line. Because the vibrator pads are operating in unison, the outgoing waves will be in phase when the distance from pad sources is a multiple of the wavelength for that part of the signal sweep, and if the surface conditions and geology are uniform. However, the vibration intensities will be lower when the waves are out of phase according to the varying frequencies and varying distances from the vibrator pads to the monitoring station, and according to non-uniform ground conditions. This is illustrated also in Figure 1 and again in Figure 13. In an urban setting the lack of uniformity would also include such items as buried utilities, basements, tunnels, changes in pavements, and added or removed soil. The result is that the vibration intensities are usually considerably below the typical upper bound for that particular fleet of vibrators and their input level. A broad range of results is common for this activity.

The dotted line in Figure 2 shows a representative upper bound line for similar vibrators operating at very close distances from all types of structures and facilities in the Los Angeles Basin, often in the range of 8 to 10 ft (2 to 3 m). In that distance range, the vibrators were often operated at a reduced output of 45 to 60 percent of maximum. Further discussion is provided by Oriard (1994, 2002).

At small distances, decay of the vibroseis ground vibration does not have the same relationship to distance as that from conventional point sources such as a single charge of explosive. Starting beside the edge of a jacking pad, the vibration intensity is first determined primarily by that single vibrator. As the observation point moves away, other vibrators begin to contribute, and the vibration does not attenuate as rapidly as it would for a point source. Beyond a distance that is roughly equal to the length of the line of vibrators, often about 120 to 180 ft (36.6 to 54.9 m), the decay relationship more closely resembles that from a point source.

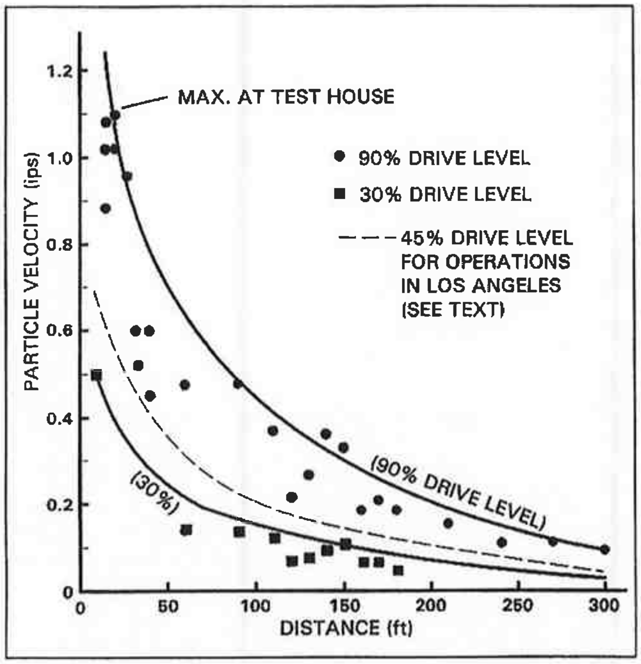

Figure 2. Vibration decay with distance, truck-mounted vibrators. 1.000 ft = 0.3048 m.

Another significant fact illustrated by Figure 2 is the dimension of a structure compared to the distance from the vibration source. In this case, the residence dimensions are 80 ft (24.4 m) north/south by 35 ft (10.7 m) east/west. At small distances, there is a significant loss of energy as the ground waves pass under the structure, for example, traveling from 15 to 55 ft (4.6 to 17 m) in the present case. At large distances, that dimension is usually not significant, say traveling from 715 to 755 ft (218 to 230 m).

HUMAN RESPONSE TO GROUND VIBRATIONS

One of the most important aspects of any vibration excitation is the response of people in the area. Humans can perceive very low levels of sound and vibration and may wonder if the perceived events have some damage potential to their homes. When they examine their homes carefully, they will often find pre-existing defects and conclude that damage did indeed occur. When the defect does not reveal its age directly, it is helpful to compare the defect to the intensity of vibration that would be required to cause such a defect or to judge whether or not vibration at any intensity could cause such a defect. For example, shrinkage or warping of lumber cannot be caused by any level of vibration, no matter how intense.

Many homes have loose objects whose movement is very sensitive to vibration and useful first indicators of motion intensity. In a typical home, there are curio shelves, wall hangings, top-heavy furnishings, and loose items left

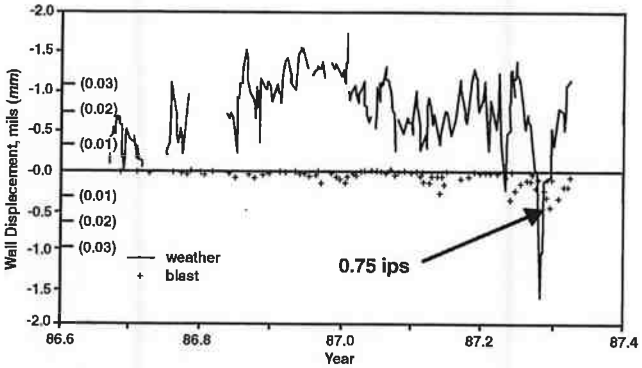

Figure 3. Comparison of crack displacements caused by weather changes (solid line) with those produced by surface coal mine vibrations (+) (Dowding, 1996).

lying about. It is reasonable to expect that there would be extensive movement, perhaps even falling and scattering of loose objects, before the first signs of threshold (cosmetic or finish) cracking in the wall coverings within a structure. See Oriard (1999) for an extensive discussion of this subject. A number of objects and furnishings were placed in the test house to illustrate this point.

Paradoxically, most homeowners are unaware that common household activities will often generate more intense effects than external vibration sources that concern them, and people are far more sensitive to sound and vibration than are their houses. There have been many studies of the human response to sound and vibration. Some of these are reviewed in Bureau of Mines (BuMin) Bulletin 656 (Nicholls et al., 1971) and again in BuMin Report of Investigations (RI) 8507 (Siskind et al., 1980). These studies verified that there are many household activities that generate vibrations that are well above the perceptible range, but because they are from known sources, owners may not be alarmed. Such household activities include slamming doors, driving nails into walls, walking across second-floor framing or through the attic, and jumping from chairs or steps. Also of interest are the structural strains induced by the weight of heavy furniture and heavy appliances, the effects of household activities such as cooking or showering, which affect interior humidity, and the effects of indoor temperature variations from localized heating such as fireplaces. A hot fire in a fireplace can cause large temperature-induced stresses and strains, which can lead to cosmetic cracking. This study explored the vibrations and effects generated by several common household activities.

ENVIRONMENTAL EFFECTS

There are several factors that have a strong influence on the pre-existing condition of any building. Some of the common dominant factors include the age of the building, the construction materials, the design, the construction quality, type and distance of trees and other vegetation, and the depth and clay content of the active soil zone. Aging factors include drying, curing, shrinkage, and warping of materials. Homeowner maintenance is required to minimize ongoing decline and deterioration. Regional rainfall and climate may greatly influence the frequency of needed maintenance and the effectiveness of common maintenance procedures.

Other changes are cyclic, brought on by both short-term and long-term changes in the temperature and humidity, either inside or outside the home. Besides the direct effects on the structure itself, weather cycles can also affect the underlying soils. If the soil beneath the home contains expansive clays, cyclic changes in soil moisture can cause serious damage, particularly in arid parts of the country. An example of the effects of weather-induced changes in humidity on crack width are shown in Figure 3 (Dowding, 1996). Other similar measurements are shown in BuMin RI 8896 (Stagg et al., 1984). When the data from BuMin RI 8896 are plotted, a regression line would show that an outside temperature change of 27 degrees can generate strains in one of the gage locations approximately equivalent to more than 8 in./second (20 cm/second) ground vibration, as explained by Oriard (1994, 1999, pp. 65–70). Although that may come as a surprise to some, such relationships would have to exist to account for the extensive damage caused by these environmental forces. In another study, Mathewson et al. (1980) provide a description of over 400 single-family brick veneer houses in Texas that were damaged by environmental forces, particularly soil movement. In contrast to these powerful environmental effects, it is rare to find any damage to buildings caused by man-made mechanical vibrations that conform to typically employed codes, statutes, and/or industry standards.

TESTING OF A SINGLE-FAMILY DWELLING

In response to public concerns about the damage potential of vibroseis vibrations, a test house was vibrated by four vibroseis trucks on both soil and asphalt surfaces at declining separation distances. This work was undertaken by Fina Oil and Chemical Company (now Total E&P USA, Inc.) to record in detail the effects of vibroseis excitation.

The test house, located near the town of McAllen, Texas, is a single-story, single-family dwelling supported by a shallow concrete slab-on-grade foundation. This house is typical of construction for the area and was built some time before being purchased for use as a test house. As shown in Figure 4, it contains three bedrooms, 1 ½ bathrooms, living room, dining room, kitchen, breakfast area, laundry room, and attached two-car garage. It faces approximately east on a relatively flat lot. At the time of the tests, the lot was covered with wild grasses and was lightly landscaped with small trees and shrubs.

The living room features a fireplace and hearth in the west wall with an exterior masonry chimney. Bedrooms and bathrooms are located in the southern part of the building. Family living areas are in the central part, and the garage and laundry are located in the north end. During the vibroseis testing, the living room was furnished to represent conditions in a typical occupied residence. These furnishings included couch, chair, end tables, decorative curios and centerpieces, and wall hangings. The dining room was also furnished, but only with utility tables and stands for test equipment. The kitchen was stocked with common cooking utensils and tableware. A portion of the living room is shown in Figure 5.

Before testing, an asphalt street section complete with curbs was constructed parallel to the house front at a distance of 50 ft (15 m) from the front wall to the near curb. A concrete driveway was constructed to connect this street section to the garage entrance.

The primary structural system above the foundation is a wood frame with wood-framed interior partitions. The roof system consists of a custom-framed, gable structure decked with plywood and surfaced with three-tab composition shingles. Interior walls were clad with gypsum wallboard and finished with conventional architectural materials such as paint, wallpaper, and stained wood. Exterior walls were clad with brick veneer and wood siding, which can be seen in Figure 6.

To provide a simulation for common residential block construction, the garage door was removed, and the opening was filled with non-reinforced concrete masonry units (CMUs). The exterior of the CMU wall was finished with sand-cement stucco applied directly to the CMU wall face (no lath), consistent with local construction practices. The stucco surface was textured and painted. Shrinkage crack development was monitored visually in the new stucco and documented for the differences between areas in the shade and those exposed to the sun. The block units remained exposed without stucco on the interior side, providing another condition for testing and observation.

The soil supporting the house and in the surrounding pasture was a hard dry sandy clay. The clay was moderately to slightly expansive. The plasticity index varied from 18 to 28 between the ground surface and about 7½ ft (2.3 m). Below about 7½ ft (2.3 m), there was an increasing content of calcareous material and increasing hardness. By a depth of 13½ ft (4.1 m), the blow count was 50 blows for an advance of 1.0 in. (2.5 cm). Groundwater levels were monitored using a screen-tipped pipe set in a cased hole at a depth of 15 ft

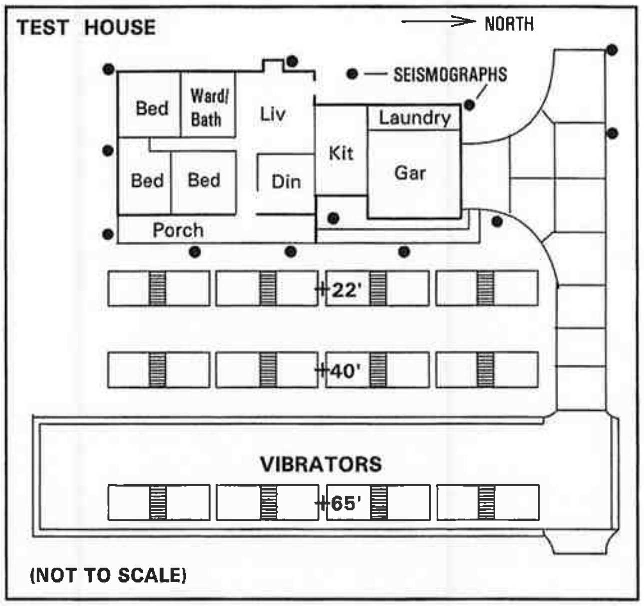

Figure 4. Plan view of test house and closest vibrator test positions.

(4.6 m). The screen-tipped riser pipe was isolated from the surrounding soil by the casing and was marked to permit periodic measurements of any relative changes in elevation between it and the soil surface.

THE VIBRATION SOURCE

The ground vibrations in the present tests were generated with Mertz M18/612 Vibroseis vibrators mounted on two-axle rubber-tired vehicles. Four vehicles were "stacked" or placed in a straight line. The maximum dynamic output of each unit was 44,000 lb (1.96 kN). The test input varied from 30 to 90 percent of the available force. The vibration sweeps covered a frequency range from 10 Hz to 72 Hz in 12 seconds. Twelve sweeps per location was typical for the present tests.

Figure 6 shows the trucks lined up next to the test house. This view is taken from the north end of the house looking south. It shows the concrete driveway in the foreground, with the sidewalk and front porch in the center of the photo. The new asphalt street is located to the left of the trucks. The weather station can be seen projecting above the roof at the far south end of the house. Figure 7 shows the trucks as viewed from the east, looking toward the front side of the house. The length of the line of vibrators is greater than the length of the house.

Figure 4 illustrates the proximity and orientation of the four vibroseis pads at the three closest vibration locations in front of the house. Other tests were conducted at greater distances to the north and northwest of the house. Surface conditions at the locations on which the vibrator pads were placed included asphalt and wild grass areas.

Figure 5. North end of dining room shown with the furnishings included in the testing program.

For the tests closest to the house, the vibrator pads rested on a grass-covered soil surface, somewhat irregular in contour though generally flat.

THE TEST INSTRUMENTATION

The house was extensively instrumented inside and outside. Instrumentation included 34 displacement transducers, six accelerometers, two triaxial seismometers, 16 triaxial seismographs, 34 thermocouples, 11 tilt sensors, and one weather station. The large majority of the displacement transducers were mounted across existing cracks to measure both dynamic and long-term changes in crack width and were calibrated to 0.0001 in. (0.0003 cm) using a micrometer fixture. (Manufacturer's certificates of calibration were used for the accelerometers, seismographs, seismometers, and tilt sensors.) Three of the displacement transducers were mounted in the attic to measure changes in the full length and width of the house. With attached music wire, one transducer monitored the full length of the house, one the full width, and a third transducer monitored the width of the vaulted living room ceiling. The thermal coefficient of expansion for the transducers, assembled in their mounting fixtures, was determined in an oven. When installed for monitoring, each transducer had a thermocouple attached. Data from the thermocouples were used by the data logger in the calculation of actual crack movement.

House instrumentation was monitored during vibroseis activities to measure transient excitation and response. Monitoring was done for vibration at distances out to 767 ft (234 m). Dynamic response of the house was also measured during vibratory asphalt roller compaction during street construction, and driveway pavement cracks were monitored as the wheels of a passenger vehicle drove over them. To provide a comparison of typical household activities with vibroseis excitation, transient time histories were monitored during several common activities, including hammering nails into walls, slamming doors, and burning a fire in the fireplace. Several of the readings are reported later in this article.

Displacement across cracks was measured with linear variable displacement transformers (LVDTs) at all but seven locations. Figure 8 shows an LVDT spanning a crack in the gypsum dry wall. Changes in the overall dimensions of the attic were measured using cable extension position transducers (commonly known as string pots). One of these spanned the full length and one spanned the full width of the attic. A third spanned the vaulted living room ceiling. Calibration procedures included temperature compensation and enabled the data acquisition system to calculate true crack movements. Long-term instrumental drift was not a problem. For

Figure 6. Vibrators beside test house, looking south.

further discussion of such questions, see Dowding and Siebert (2000) and Dowding and Snider (2003). Data from the displacement transducers, thermocouples, and weather station were recorded at 2-hour intervals for approximately 1 year.

In addition to the seismometers, accelerometers, and displacement transducers used to monitor the structure response, the foundation and floor slab were monitored in three additional ways, as partially illustrated in Figure 9. Floor finishes were stripped from most slab surfaces, and existing cracks at the start of this study were outlined with a marker and dated to facilitate future examination. The floor surface was also permanently marked at 85 locations to allow consistent elevation measurements at any time using a SpectraPhysics red-light laser level. Tilt meters were installed to provide continuous monitoring of small changes in floor slope.

VISUAL BUILDING EXAMINATIONS

The condition of the test house interior and exterior was documented throughout the study year using written notes and photographs. At the start of testing, both instrumented and non-instrumented cracks were examined under magnification, outlined using a marker from origin to terminus, and dated. All cracks were similarly inspected at least monthly, and areas of stress concentrations around doors and windows that had not cracked were examined very carefully for any sign of damage. Floor surface elevations were measured at approximately monthly intervals for about 1 year and were measured more frequently during dynamic testing.

During vibration by the vibroseis trucks, each monitored crack was examined under magnification before and after each shaking event. Each monitored crack was also examined under magnification at the start and end of each day. Floor surface elevations were surveyed at the start and end of each day. A system of grid points was established in one uncracked bedroom wall. The wall area was examined with the same frequency as the monitored cracks under the same lighting by the same individual.

ENVIRONMENTAL MONITORING

Three months before the vibroseis monitoring, a weather station was installed to record exterior conditions. The weather station can be seen in Figure 6, mounted on a pole at the south end of the house. Weather conditions were monitored from March of one year to February of the following year with a Davis weather station that recorded temperature, wind speed, humidity, and precipitation.

Inside the house, the temperature was controlled. The air conditioner was set at 70 degrees F (21 degrees C) from May through October. Heating was set at 72 degrees F (22 degrees C) from December to the end of the tests in February the following year. Deviations in the interior climate occurred during the test involving use of the fireplace. A fire was built in the firebox to study its effects.

Figure 7. Vibrators beside test house, looking west.

Data from the house instrumentation were recorded at 2-hour intervals for a period of 1 year. The recording began before dynamic testing with vibroseis trucks. For the dynamic testing all data channels were removed from the data logger and connected to a dynamic data acquisition system. On completion of the vibroseis tests, all data channels were reconnected to the data logger. These data provide substantial information for comparison with dynamic response data.

Figure 10 compares crack displacements produced by long-term changes in the environment (such as seasonal temperature and humidity) with those produced by vibration for three different cracks. The first two are cracks in gypsum wallboard in the upper wall and at a ceiling-to-wall junction in the living room. The third is at a wood–brick juncture. The comparison shows that the environmental effects were much greater than those generated by the vibroseis activities. The greatest difference was noted at a wall–ceiling juncture at the north end of the bedroom hallway, where the environmental effects of weather cycles were 19 times greater than the vibroseis effects.

Figure 11 shows the displacement of a crack in the brick fireplace in the living room as a result of burning a fire in the fireplace. The figure shows typical rapid crack opening with the rise in temperature, followed by slower partial closing in an exponential time history as the temperature dropped back toward room temperature. During this test, the positive displacement (crack opening) reached a value of 0.039 in. (1 mm, zero to peak). There was no negative displacement (closing) below the beginning of the test because the room temperature was not lowered below its previous state during the test. For comparison, the vibroseis activities generated vibratory crack response with a maximum positive displacement (opening) of 0.002 in. (0.05 mm) and a negative displacement (closing) of 0.005 in. (0.13 mm) (both zero to peak).

Figure 12 is a more detailed illustration of the manner in which cracks in the house responded to the cyclic changes in the weather environment. This figure shows the response of a crack in the gypsum wallboard in the upper wall of the living room for a period of one week. Shown are the cyclic changes in crack displacement that accompanied the changes in temperature and humidity. Wind was also measured, but the moderate winds showed no definable correlation with crack displacements during that week.

FLOOR SLAB TILT

Floor slab tilt was monitored in the southeast bedroom from May 1997 through February 1998. For the southwest corner, a cyclic peak change of about 0.038 degrees was reached in early fall, with the tilt returning to its beginning position over a period of 9 months. For the south center of the slab, a similar tilt change progressed into early fall, then remained in that general orientation for the rest of

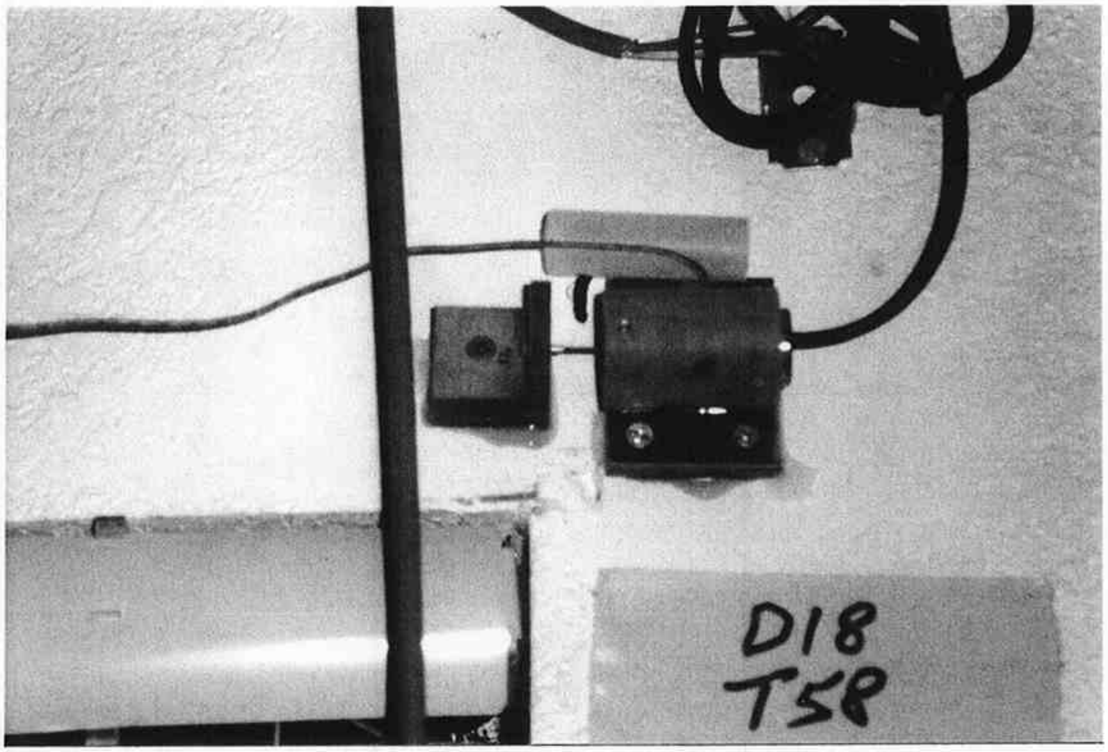

Figure 8. Typical crack-monitoring instrument.

the monitoring period, though showing short-term cycles during the following winter and spring.

SOIL MONITORING

Soil response was monitored using visual observations and elevation survey measurements that compared the relatively fixed screen-tipped pipe with the adjacent soil surface. Variations in groundwater were monitored using a tape and plug to probe the water surface depth in the screen-tipped pipe. Within the limits of precision for such measurements, no soil elevation changes were detected. This result is consistent with the low plasticity index of the soil, low rainfall, and the relatively thin layer of soil above the hard, calcareous base at 7½ ft (2.2 m) deep.

Only traces of water were found in the bottom of the screen-tipped pipe throughout the monitoring period, and evidence of clay shrink/swell was minor. Some soil shrink/swell clearly occurred beneath the floor slab to generate the measured tiltmeter response.

DYNAMIC TESTING RESULTS

For the series of attenuation tests in the open field northwest of the house, ground motions were monitored in different directions and distances. Seismograph arrays were placed at various angles to the line of vibrators and at a variety of distances, out to a maximum of 767 ft (234 m). Regardless of the seismograph positions relative to the truck line, the ground motion attenuated with distance from the vibrator pads in a fairly predictable fashion. Figure 2 shows a portion of the data, plotted as a linear graph. As in all such cases, the data points were scattered below the upper bound lines for any given set of conditions. The attenuation characteristics agreed with data obtained at other sites by Oriard (1994).

While monitoring the house response, vibrators were placed in lines both parallel and perpendicular to the long axis of the house. For the closest tests, the trucks were placed adjacent to and parallel to the house on both soil and asphalt surfaces, as shown in Figure 6. Shaking was noticeable inside the house, and containers with different fluid levels moved visibly at different times as the frequency changed. Doors, windows, cabinets, and drawers all vibrated perceptibly at different times as the input frequency changed.

Figure 13 shows the dynamic response of a position in the attic over the north wall of the living room compared to the excitation of the ground surface motion at a monitoring station on the east side of the house at the north end of the front porch. The maximum response at the attic station was 0.71 in./second (1.8 cm/second) and occurred in the transverse direction (the short east-west axis of the structure). It occurred at a time lapse of 2.0 seconds when the frequencies were on the order of 20 Hz. The second highest peak occurred at 5.7 seconds

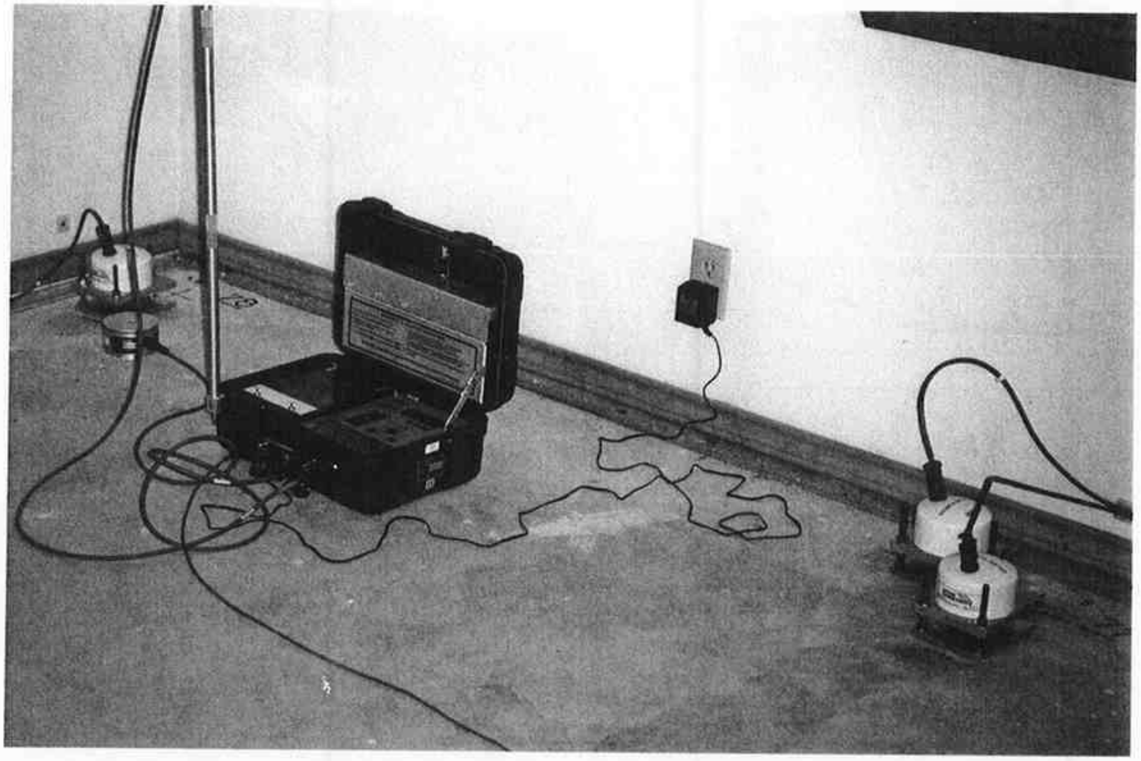

Figure 9. Floor-monitoring instruments.

when the frequencies were on the order of 40 Hz. The third highest peak occurred at about 0.67 seconds when the frequencies were on the order of 13.5 Hz, with an intensity of about 0.57 in./second (1.4 cm/second).

Although the peak at 13.5 Hz was not the highest intensity, it is of some interest because it showed a strong amplification over that of the base motion at that frequency and appears to represent a fundamental natural frequency of the superstructure or one of its major components. The house may not be a system with a single degree of freedom. The floor plan shows two dominant widths in rectangular shape, being wider to the south and narrower to the north, and the complexity of the attic framing may not be that of a single degree of freedom system.

The largest peaks in the responses of the vertical and longitudinal components in the attic took place at about 23 Hz, coinciding with some of the stronger phases of the ground motion seen in the figure. Also seen are responses at 13–14 Hz, but they are not amplified responses compared to the ground motion traces.

The attic motion could be compared to that registered

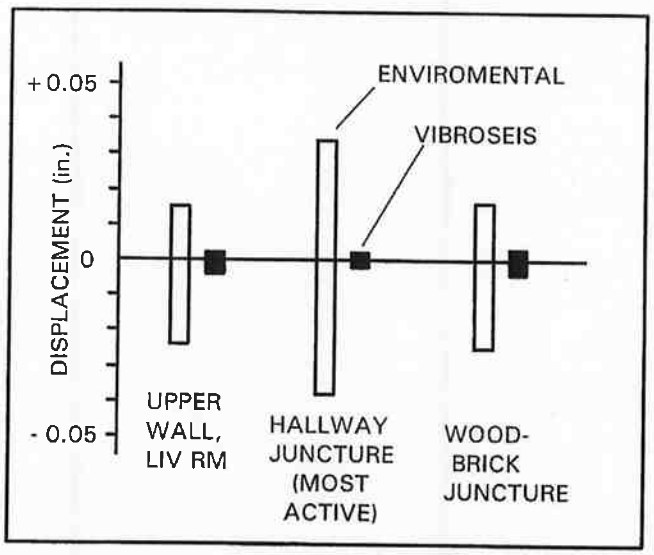

Figure 10. Crack displacements caused by environmental forces and vibroseis activities. 1.00 in. = 2.54 cm.

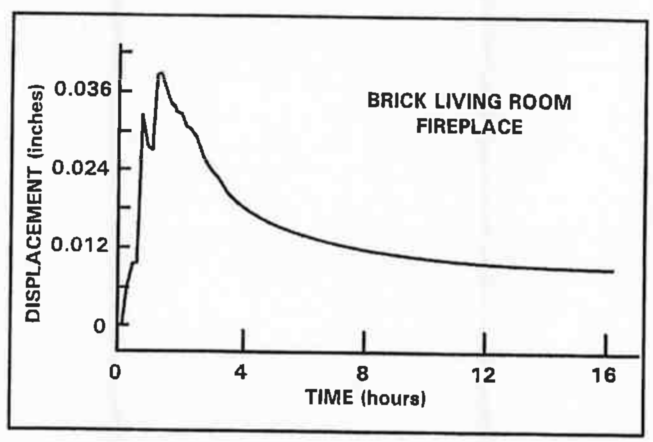

Figure 11. Crack response to a fire in the fireplace. 1.00 in. = 2.54 cm.

at any one of the ground motion monitoring stations in the vicinity. For illustration purposes for this paper, the attic response was compared only to the motion registered at the north end of the porch on the east side of the house (about center of the house front perimeter). When compared to that particular ground motion input, we see that the attic response in the transverse (E–W) direction at 13.5 Hz excitation shows an amplification of about 3.3 (0.57 in./second [1.4 cm/second]) response compared to 0.175 in./second (0.445 cm/second) ground excitation on the east side of the house—larger amplification if compared to the ground motion on the west side). The strongest ground motion occurred in the transverse (E–W) direction and reached a value of about 0.89 in./second (2.3 cm/second) at a frequency of about 23 Hz, past the peak of the attic response at about 20 Hz.

The ground excitation attenuated (decayed) from the east side to the west side of the house, passing through the floor slab under the house. The values were in the range of 0.9–1.0 in./second (2.3–2.5 cm/second) on the east side and diminished to values in the range of about 0.5–0.6 in./second (1.3–1.5 cm/second) on the west side. The base motion under the living room portion of the house would have been about 0.7 in./second (1.8 cm/second).

Comparison of the attic response with other nearby ground motions would vary according to the intensities and frequencies involved. Waves from the four separate vibrator pads would not always be in phase at any given observation point, and the responses would be compounded by complexities in the framing of the house, including the attic.

During vibroseis shaking close to the house foundation, it became important to consider the distances of individual vibrator pads from various features of the house. The distances to the edges of the nearest vibrator pads ranged from 15 to 19 ft (4.6 to 5.8 m) throughout the length of the house foundation. The distance to the front porch was 13 ft (4.0 m), and that to the front sidewalk was 10 ft (3.0 m).

At a 90 percent drive level, the foundation slab received a ground motion of about 0.9–1.0 in./second (2.3–2.5 cm/second) (maximum single component of the motion), varying slightly along the length of the house. The measured maximum was 1.08 in./second (2.74 cm/second) at the north end. During this test, the plastic light bulb cover in the hall bathroom shook loose, but there was no damage of any kind to the building.

Finally, for all dynamic testing, each monitored crack was examined under magnification at the start and end of each day. Each monitored crack was also examined under magnification before and after each shaking event. The floor was surveyed at the start and end of each day. A system of grid points was established in one bedroom wall to facilitate closer examination of an uncracked wall during dynamic testing. The uncracked wall area was

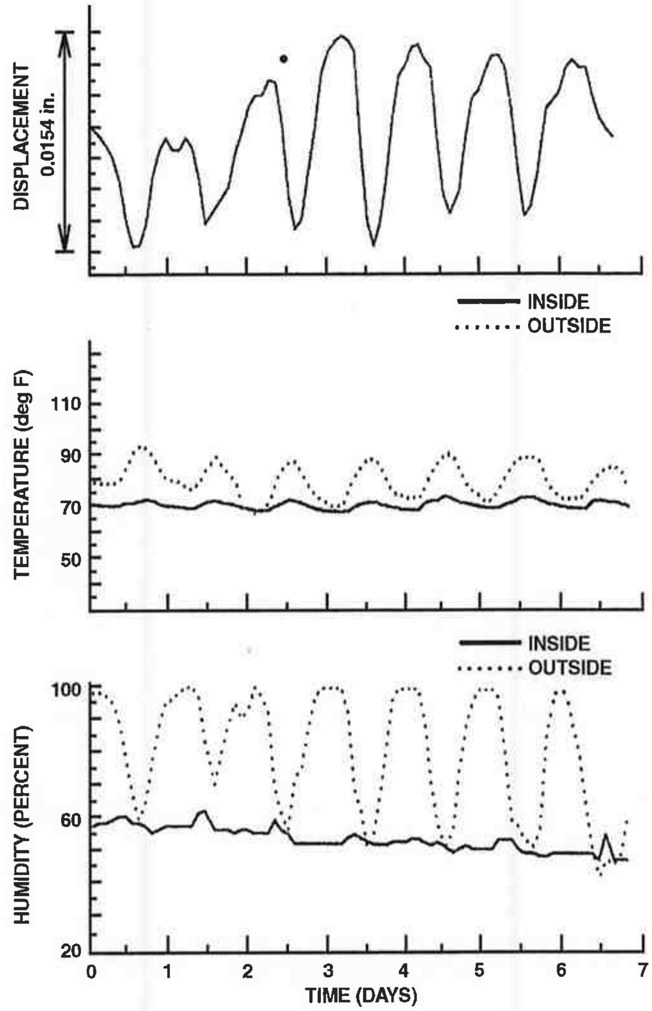

Figure 12. Weather effects on crack displacements. 1.00 in. = 2.54 cm; degrees F = (degrees C × 1.8) + 32.

examined with the same frequency as the monitored cracks under the same lighting by the same individual. Additionally, areas of stress concentration around doors and windows were examined for development of new cracks.

The importance of pre- and post-inspection for dynamic effects in environments with large environmental effects is illustrated by observation of a loosened tape joint. One morning inspection revealed that a tape joint in the bathroom had loosened slightly since the previous night as a result of continued environmental influences. Post-shaking inspections from the previous event confirmed that the tape joint had changed overnight and not as a result of shaking the day before. Further, the loose tape was not found in an area of stress concentration, and adjacent areas of the structure that would have elevated stress during shaking exhibited no similar finish problems. Thus, the loose tape joint did not result from shaking.

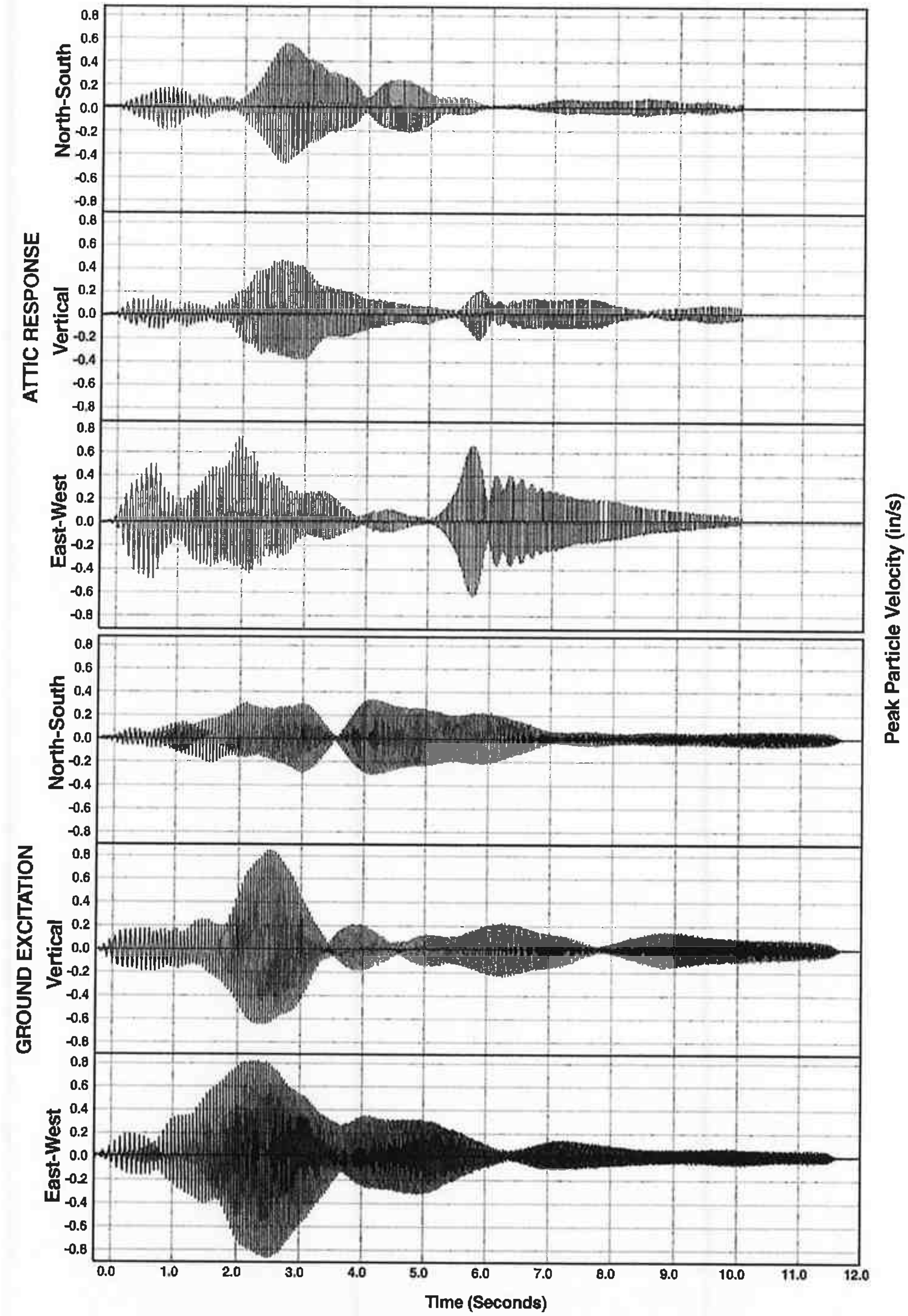

Figure 13. Response of a monitoring station in the attic compared to the ground excitation at the north end of the front porch. 1.00 in. = 2.54 cm.

HOUSEHOLD ACTIVITIES

Following the vibroseis tests, responses were measured for a few common household activities, including hammering a nail into the wall, slamming doors, and using the fireplace. Additionally, the daily and seasonal responses of existing cracks to normal environmental stresses were collected and plotted. Common household activities generate significant strains compared to external vibration sources but vary according to the nature of the activities, the distance from the source within the house, and the house construction, for example a slab-on-grade compared to a structural wood floor.

In the test house, the following typical responses to household activities were observed at the attic monitoring station above the north wall of the living room:

1. Hammering a 16d nail into the north wall of the living room: 0.860 in./second (2.18 cm/second).
2. Hammering a 16d nail into the south wall of the living room: 0.070 in./second (0.18 cm/second).
3. Hammering a 16d nail into the south wall of the northeast bedroom: 0.033 in./second (0.084 cm/second).
4. Back door slam: 0.560 in./second (1.42 cm/second).
5. Front door slam: 0.230 in./second (0.58 cm/second).

Tests were also conducted within a single wall to illustrate the high strains that are often generated in gypsum board around door and window openings when frames and trim are installed, repaired, or replaced after gypsum board installation. Shrinkage cracks at those locations are common. Hammering a nail in the south wall of the northeast bedroom generated peak particle velocities of 4.08, 4.90, and 5.01 in./second (10.4, 12.4, and 12.7 cm/second) at a distance of 3 to 5 ft (0.9 to 1.5 m). Those vibration intensities were many times greater than those generated by the vibroseis activities at any location within the building. No damage was done by any of the vibroseis or household activity tests.

Additional examples of vibrations generated by common household activities can be found in BuMin Bulletin 656 (Nicholls et al., 1971) and BuMin RI 8507 (Siskind et al., 1980). The effect that a fire in the fireplace had on a crack in the brickwork has been discussed and is shown in Figure 11. Although household activities are significant at times, the most important effects overall are the environmental effects. These include stresses and changes induced by such items as temperature and humidity cycles, aging, house and yard maintenance, soil conditions, and water control. Such effects are found to varying degrees in all houses.

CONCLUSIONS

Vibroseis trucks were used to generate ground vibrations adjacent to a test house at more than twice the normal particle velocity control level to determine the potential for cosmetic cracking. Distances between the vibrator pads and the house ranged from 767 ft (233 m) to only 13 ft (4.0 m) from the front porch. Ground vibrations expressed as peak particle velocity were of the order of 1.0 in./second (2.5 cm/second) for the closest tests, with the vibrators operating at 90% of maximum output. No damage to the test house of any kind, such as new cosmetic cracking or lengthening of existing cracks, was produced by these vibroseis activities.

Environmental forces from weather changes generated crack responses that were as high as 19 times greater than those generated by the ground vibrations. A fire in the living room fireplace caused a crack to open 0.039 in. (0.099 cm), followed by a slow exponential closing during the cooling period. Maximum ground vibrations only opened and closed this crack 0.002 in. and 0.005 in. (0.005 cm and 0.013 cm), respectively. (Neither the fire nor the vibration activity extended the fireplace crack.) Hammering nails into a wall generated peak vibrations in the nearby wall area up to 5 in./second (12.7 cm/second), which were far greater than those generated by the vibroseis activities.

Measurements before and after event observations reported herein show that even the most energetic of typical vibroseis activities are not a damaging influence on structures or common surrounding features such as pavements or utilities. Typical vibration-monitoring standards such as those found in the regulations of the Office of Surface Mining and proposed in U.S. Bureau of Mines Report of Investigations 8507 are sufficient to protect ordinary residences from damage. Those standards were shown to prevent threshold damage or cosmetic cracking, the most superficial interior cracking that develops in all homes independently of any external vibration. Data from this test house are available for further study.

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