DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

BONITO VIBRATION TESTS

Chaco Culture Historical Park

by

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INTRODUCTION

Chaco Culture Historic Park is a national park developed to protect and display unique Anasazi stone and adobe structures. The park is located in northwestern new Mexico and contains over 2,000 known archeological sites (Figure 1). Some of the most complex and best preserved archeological sites are large stone pueblo and kiva complexes located in the upper confines of Chaco Canyon near the Bonito bridge (Figure 2). A previous vibration investigation determined the shaking parameters of most of the main structures and established a safe induced vibration limit of 2 mm/sec peak–particle motion for the fragile structures (King and Algermissen, 1985). The heavier and larger modern tour vehicles made it necessary to replace the Bonito bridge with a new wider and more heavily constructed bridge. The National Park required that the ground shaking induced by the bridge construction activities would not exceed a 2 mm/sec peak–particle velocity ground shaking at Pueblo Bonito and Pueblo del Arroyo complexes.

OBJECTIVE AND SCOPE

The main objective of the vibration project was to document the vibrations that were induced into the archeological structures located near the Bonito bridge by the drilling operations and by the extraction of the bore–hole casings. The on–site Federal Highway Administration engineer and the appointed National Park representative were to be informed immediately if the induced motions at the archeological structures approached a 2 mm/sec velocity, the peak–particle ground motion limit.

Other objectives of this project were: a) determination of the risk to the archeological structures of ground vibrations induced by heavy truck traffic on the access roads, b) determination of the difference between the induced ground motions from a construction compacting–roller and the induced ground motion induced by a vibrator–compaction roller, and c) determination of the susceptibility of the walls of Casa Rinconada to vibrations that may result from large crowds and organized dancing in the internal court of the kiva.

Accomplishment of these objectives included determination of a number of parameters. The most important of these include: (1) the frequencies to which the structures are most sensitive, (2) the amount and type of vibratory energy induced by active or potentially active sources (particle velocities and spectra), and (3) the attenuation of that energy between the sources and the structures. This report investigates the general shaking parameters of the archeological structures, the attenuation of the induced vibrations from different vehicular sources, and the vibration parameters of some of the potential vibration sources. Many of these parameters were documented during a Chaco vibration–study project in 1985 and will be incorporated in this report (King and Algermissen, 1985).

ACKNOWLEDGMENTS

The authors acknowledge with gratitude the cooperation and help by the many National Park and Federal Highway personnel. Photographs by Elaine R. King.

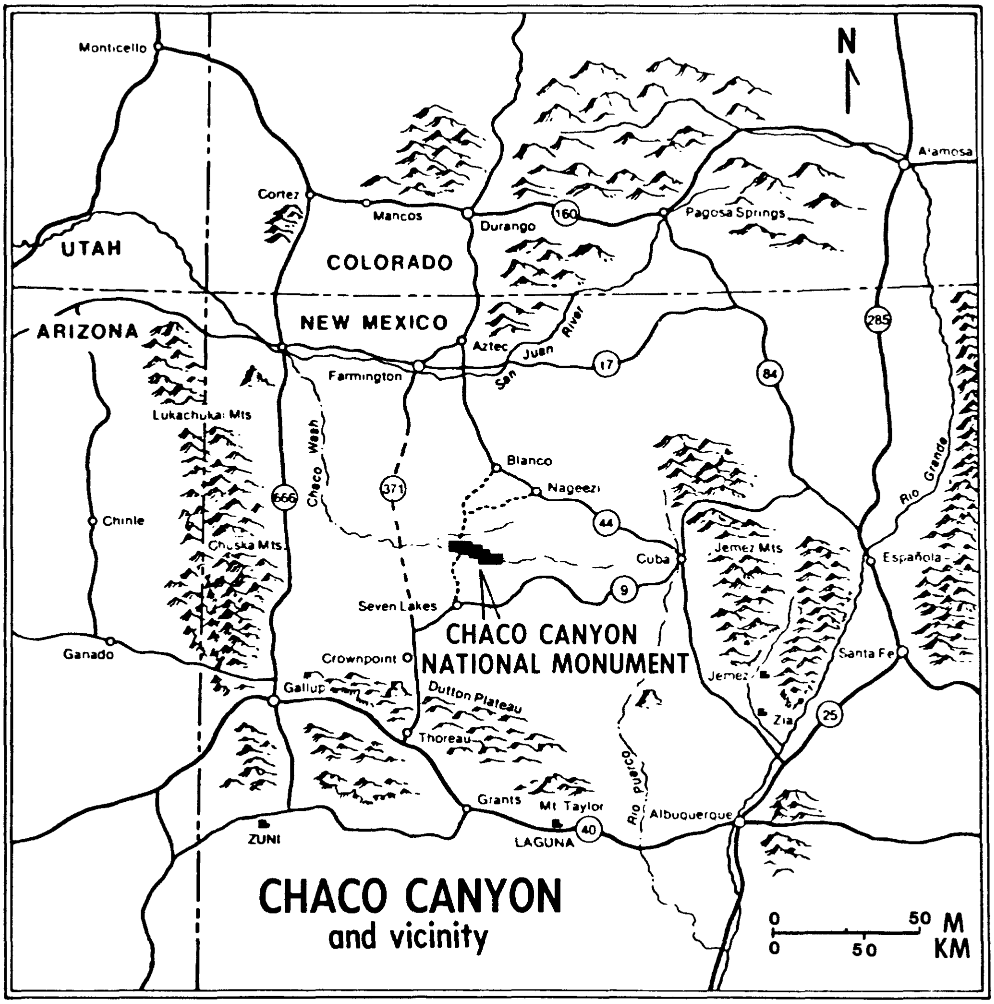

Figure 1. Location map of Chaco Canyon.

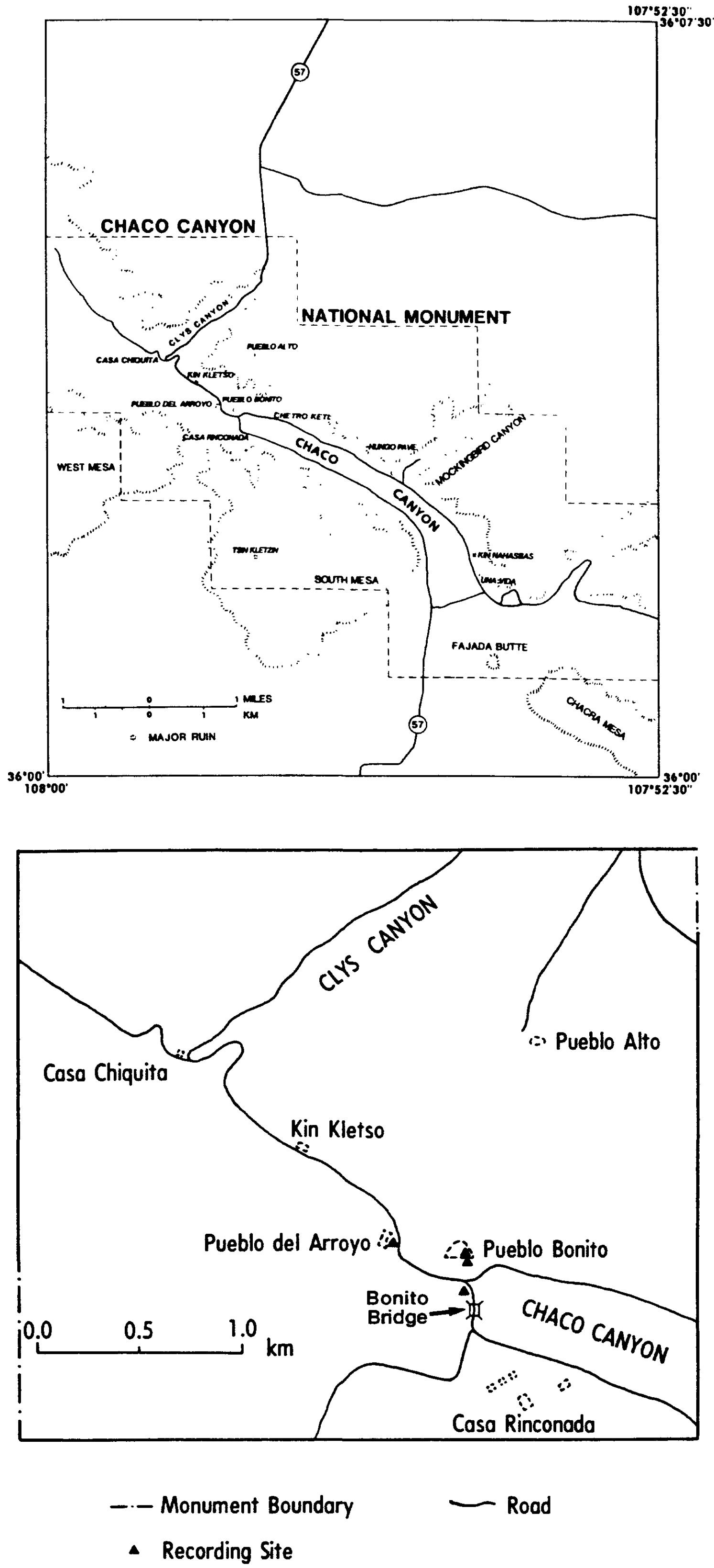

Figure 2. Chaco Canyon map showing the recording sites (▲) for the bridge and drilling activities.

FIELD MEASUREMENTS AND DATA ANALYSIS

Seismic field equipment used in the investigation of the induced vibrations and the structures' shaking parameters were portable, battery operated, digital–recording, three–channel seismograph systems. The seismographs recorded signals detected by a tripartite configuration of seismometers oriented parallel and perpendicular to the energy source or to the long axis of the structures being examined. The seismometers were triaxial velocity–sensing transducers with a sensitivity of 1.2 volts/cm/s, a natural period of 0.62 second and damping adjusted to 60 percent of critical. A series of calibration tests show that transducer sensitivities vary less than 10% from system to system (Carver and others, 1986). The analog signals were low–pass, anti–alias filtered at 50 Hz with a 7–pole Butterworth filter and digitized with a 12–bit gain–ranged A/D with 4 gain levels and a effective dynamic range of 18 bits. The data are digitally recorded on magnetic tape at 200 samples per second per channel.

Preliminary reduction and analysis of selected data were accomplished in the field using software developed for an Eurasian Seismic Study and field operations for the Loma Prieta earthquake (Cranswick and others, 1989, King and others, 1990). A digital cassette playback system was connected to a PC/AT–compatible portable computer. The system was used to calculate ground–motion particle velocity amplitudes and spectra. The data were reduced to amplitude normalized seismograms for visual inspection and selection of 30–second duration time windows for further analysis. Data in the selected time window were centered on maximum amplitude and tapered using a whole–cosine bell (Hanning window) before being processed and transformed by a standard Fast Fourier Transform program. Comparisons of the derived spectra were made visually and by computing spectral ratios. Spectral ratios were calculated by dividing the spectra derived from the vibrations that are being evaluated by spectra derived from the vibrations documented at a reference location.

Bridge Drilling Activities

The seismometers from the seismic recording systems were installed at the base of the south wall of Pueblo Bonito (wall nearest to the bridge construction), the top of the south Pueblo Bonito wall, at the base of the east wall of Pueblo del Arroyo (nearest to the construction) and at a free–field location approximately 90 m north of the drilling operations (Figure 2B). The seismic systems monitored the ground motions induced by the boring of the bridge foundation piling–holes and the extraction of a sand–filled casing from a piling bore–hole.

The preliminary results of the field analysis were submitted to the Federal Highway Administration field engineer and the National Park Service representative. Construction operations were stopped for a short duration for seismic data analysis when the drill had bored to an approximate depth of 2.5 m, an approximate depth of 12 m, and after the pulling of the borehole casing.

Seismograms of the test boring operation (Figure 3) indicate that no induced ground motions at the free field site, Pueblo Bonito, Pueblo Bonito wall, or the Pueblo Del Arroyo seismic sites exceeded the 2 mm/sec peak–particle velocity limit. The ground motions induced by the drilling at and above the depth of 12 m (Figure 3B) were less in amplitude than those derived from the drilling at or near the 2.5 m depth even though the vibration data from the deeper drilling had more bore–hole activities (moving of the crane, etc.). Spectra calculated from

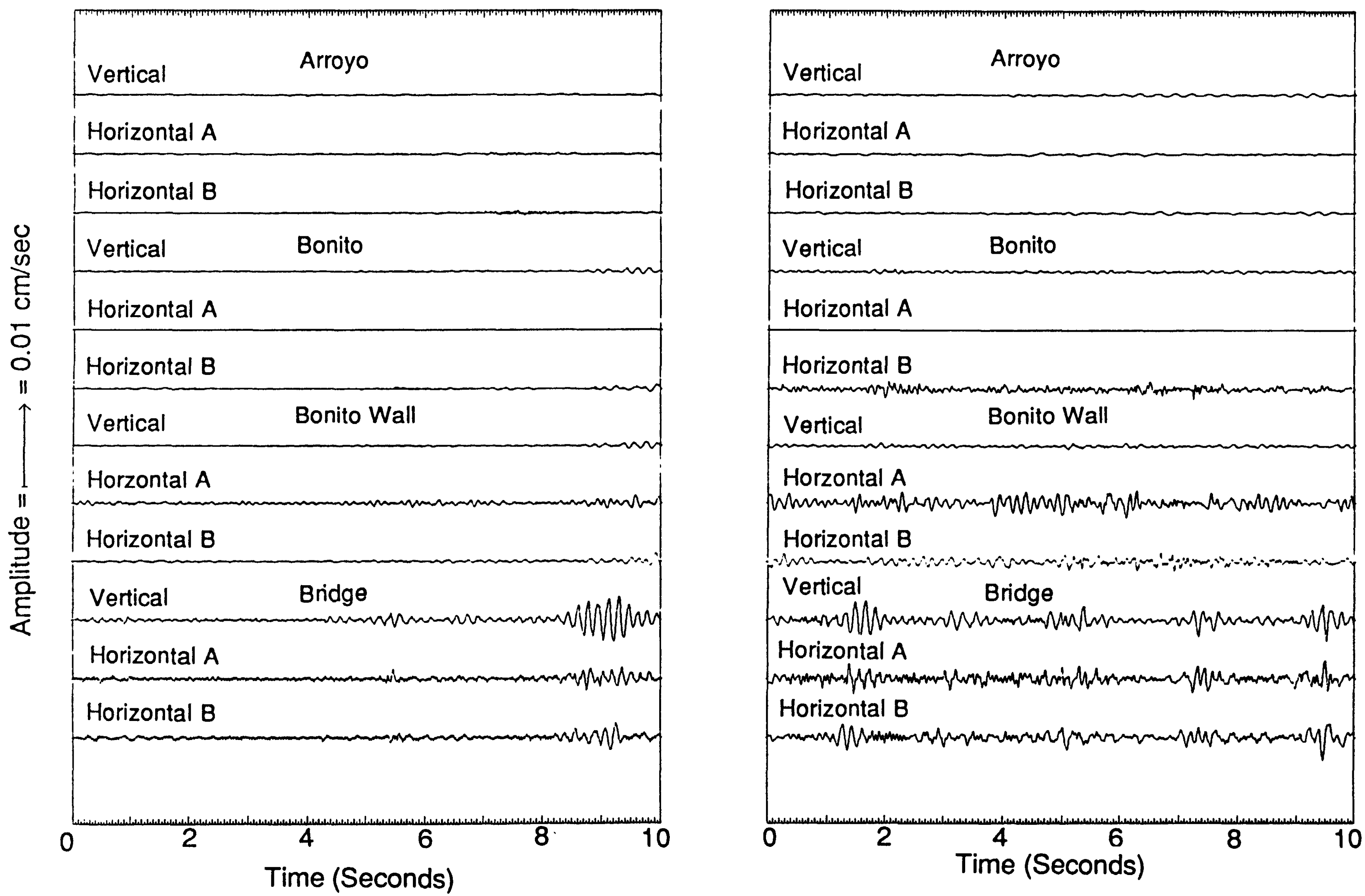

Figure 3 Seismograms showing induced vibrations from the drilling and drilling activities. A = drilling at 2.5m, B=drilling at 12m.

the induced ground motions produced by the drilling operations indicate that the drill induced vibrations have peak spectral motions at 7 and 17 Hz (Figure 4).

Extraction of the casing out of the bore–holes was thought to be a potential source of large induced ground motions. Motions induced from this activity were documented at the 90 m site and did prove to be greater than the ambient background but were still less than those induced by drilling (Figure 5).

Structure Response Testing

The procedure for obtaining the pertinent engineering vibration parameters (natural resonant frequencies and damping) of the structures generally included an analysis of data obtained from the horizontal shaking records obtained at the top and midpoint of the bearing walls of the structures (King, 1969). Vibration parameters of the walls at Pueblo Bonito and Pueblo del Arroyo were of principal concern to this project since each of the structural complexes were near the Bonito bridge construction (Figure 2). Distance ranges of the structures from the test bore holes were: Pueblo Bonito–174 m, Pueblo Bonito wall–175 m, and Pueblo del Arroyo–456 m. Vibration parameters for these structures were documented during a prior vibration study of the area (King and Algermissen, 1985). Therefore, only check–tests were made of the walls nearest the construction work to reconfirm the previously determined results. The vibration response tests of the walls showed that the periods of the walls are in the general range of 8–14 Hz (Figure 6, and Appendix 1–6).

Traffic and Attenuation

Vibration tests were made at several Chaco Canyon structures to determine the attenuation of ground shaking with distance from the vibratory source.d Attenuation tests were made in the vicinity of Una Vida, Hungo Pavi, Chetro Ketl, Casa Bonita, Kin Kletso, and Pueblo Arroyo (Figure 2). Attenuation functions at the above sites, with the exception of the Kin Kletso, should be similar since the shallow underlying geology (the vibration transmission medium) is similar at these locations (Bryon, 1954). Tests were made to assure that the attenuations were similar and that no unknown factors exist that may cause more vibration energy to be induced to the study complexes. The vibrations documented at each site are a summation of the direct and refracted wavelets which in general travel through the underlying, sandy, unconsolidated sediments with an approximate P–wave velocity of 530 m/s (King and Algermissen, 1985). The induced vibrations at the highway near Kin Kletso are transmitted to the structural complex by a large underlying shelf of deeply weathered Cliff House sandstone of upper Cretaceous age which has an approximate P–wave velocity of 680 m/s (King and Algermissen, 1985).

Two vibration sensing and recording instruments were deployed on a linear array at each of the sites at ranges of approximately 10 and 50 meters from the main highway. Due to the close proximity of the Kin Kletso structures to the road, a seismometer array could not be used; instead, single vibration–recording instruments were installed 11 m from the road at the east and west ends of the structure.

The main shaking source for the vibration tests was a 3/4 ton pickup–truck driving on the commercial highway nearest to the structures. Tests consisted of documenting vibrations induced by: (1) the pick–up truck during a normal drive–by at the 25 mph speed limit, (2) the pick–up while it was making an abrupt deceleration (stopping), and (3) the pick–up driving over a 4" x

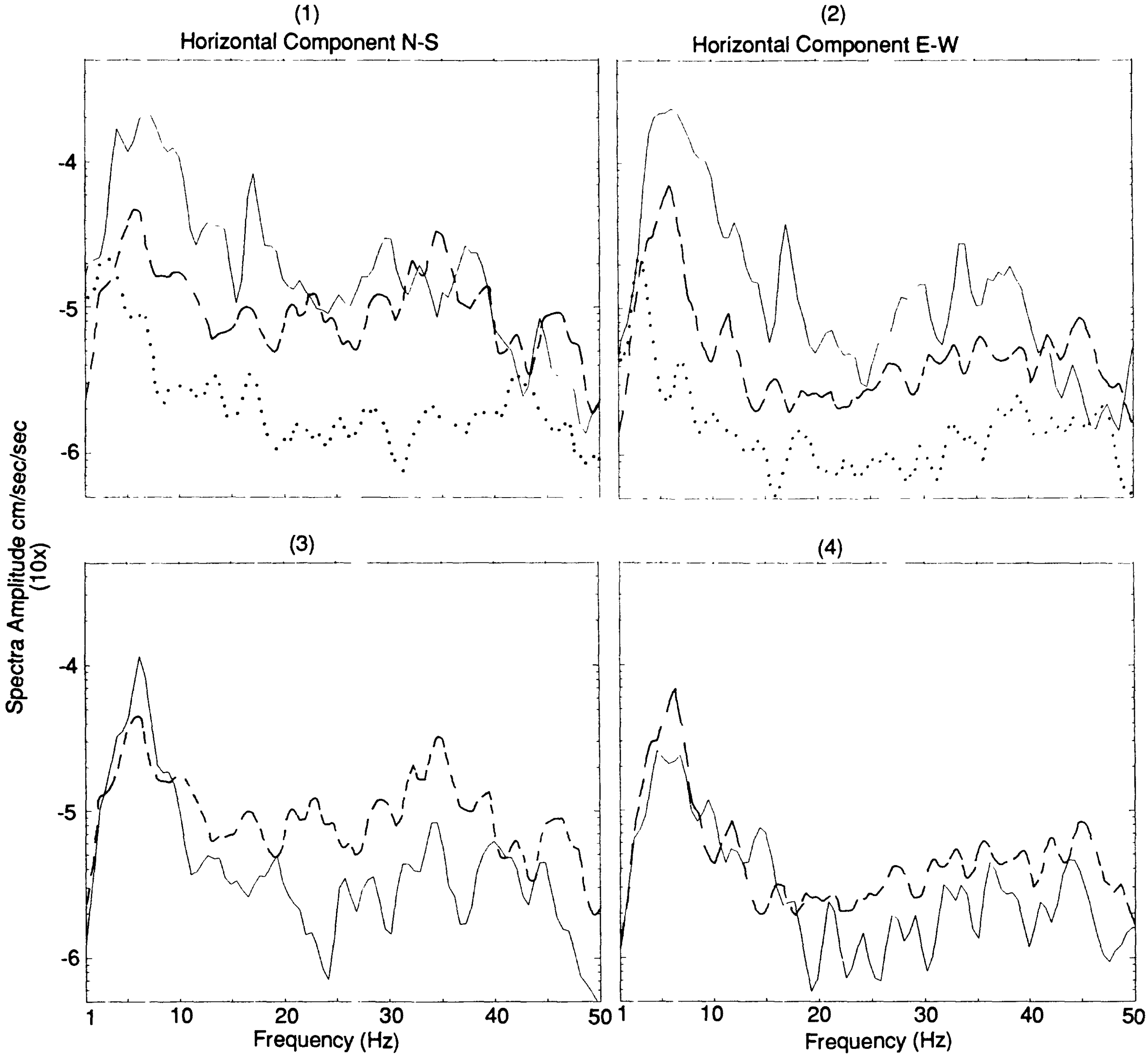

Figure 4. Spectra derived from drilling vibration tests. 1 & 2 --- = 90m site, - - - = Pueblo Bonito ground site, ... = Pueblo Del Arroyo site. 3 & 4 --- = Pueblo Bonito wall site, - - - = 90m site.

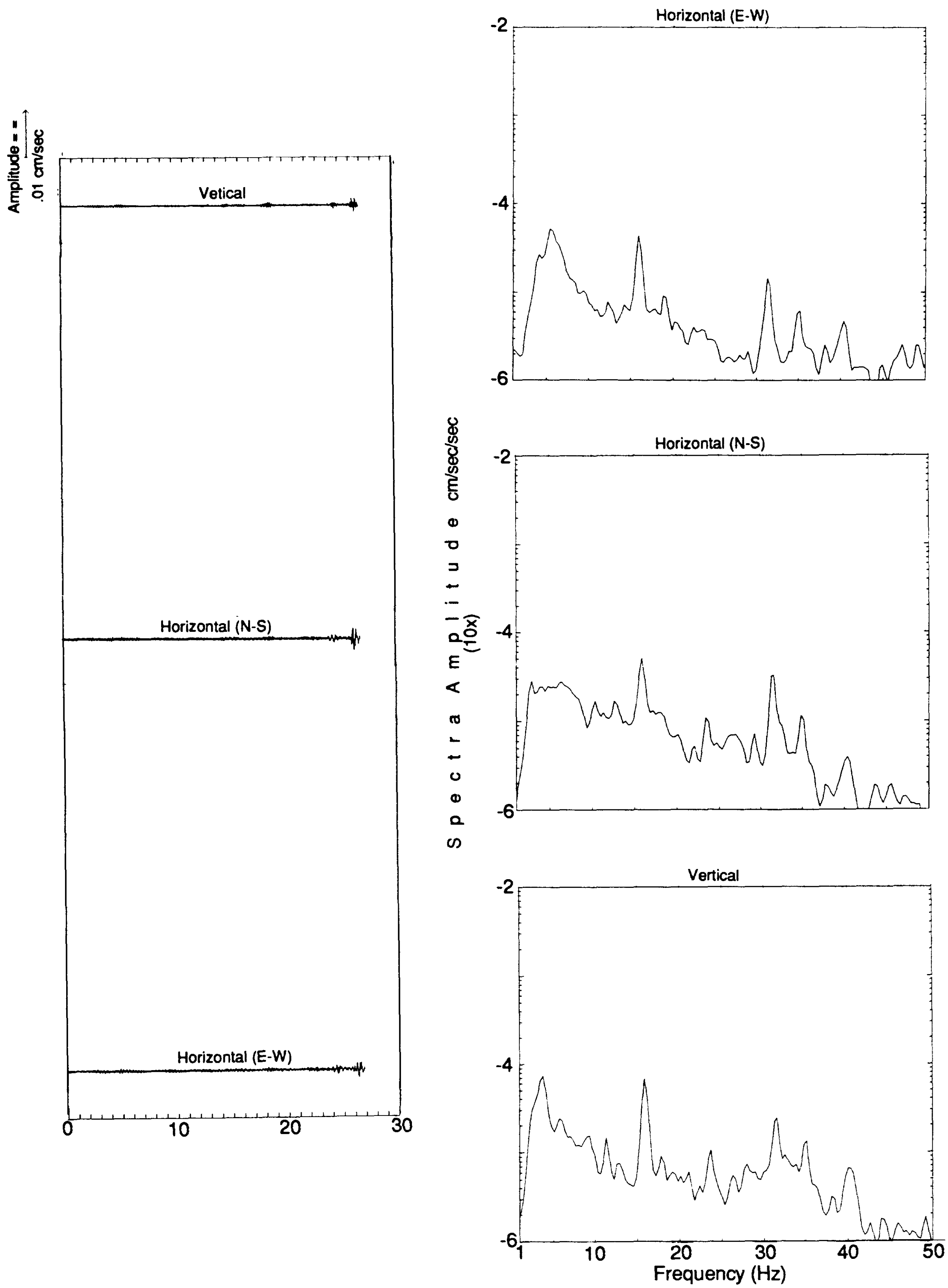

Figure 5. Seismograms and derived spectra from the 90m site. Vibration source was extraction of the casing out of the bore hole.

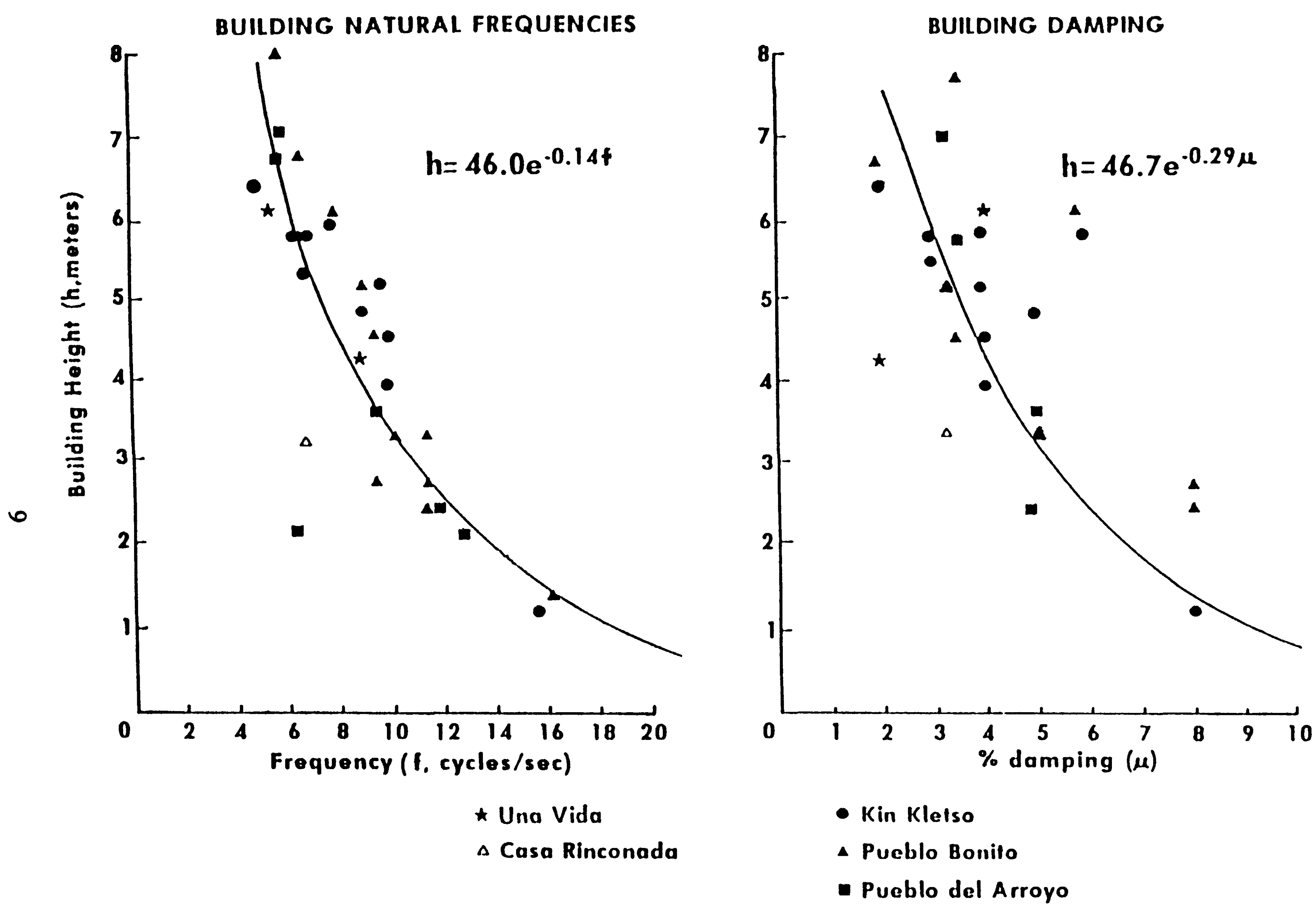

Figure 6. Relationship of wall height, natural frequency and damping for 4 Chaco complexes. (from King and Algermissen, 1985).

4" block (simulating a hole in the road). Figure 7 shows an example of the seismograms from the tests at Chetro Ketl. The induced vibrations from the occasional drive–by of two types of heavy vehicles (two passes by full water trucks, and two loaded 60,000 lb trucks) were also documented in this vicinity.

Seismograms from the vibration attenuation tests (Figure 7) indicate that a vehicle hitting a bump induces considerably more motion into the ground than the other sources tested at the same range. Spectra derived from the seismograms (Figure 8A) show that the spectral amplitudes produced by 3/4 ton pick–up truck hitting the bumps are larger in the 5–20 Hz frequencies than those derived from motions induced by the drive–by test and the deceleration test.

The deceleration spectral amplitudes are larger than normal drive–by spectral amplitudes at both the higher and lower the frequencies. Differences in the derived spectra from ground motions induced by a normal drive–by of a 3/4 ton vehicle and a fully loaded water–truck are shown on Figure 8B. The water–truck induces motions which show larger spectral amplitudes in the 2–7 and 25–30 Hz ranges.

Differences of the spectra from the induced sources are illustrated by dividing the spectra from the normal 3/4 ton truck drive–by into the spectra derived from the induced motions from the other sources (Figure 9). The approximate maximum spectra ratio value in the vertical component for motions induced by the bump is 110 at 9 Hz, a factor of 22 at 6 Hz for a water–truck, and a factor of 3.5 at 8 Hz for deceleration. The approximate maximum spectra ratio value in the horizontal components is 108 at 11 Hz for the motions induced by a bump, a factor of 22 at 4 Hz for the motions induced by a water–truck, and a factor of 10 at 11 Hz for deceleration. The maximum factor in the frequency band width of concern (walls' natural resonances 8–15 Hz) is approximately 108 for the motions induced by a bump, approximately 11 for motions induced by the water–truck, and approximately 10 for motions induced by decelerations.

Similar spectral ratios were also derived for the ground motions at 50 m range induced by a large 60,000–lb. truck drive–by, the decelerations of a 3/4–ton truck ratioed to the ground motions induced by a normal 25–mph drive–by of a 3/4–ton truck (Figure 10). The test indicated that spectral amplitudes from the motions induced by the 60,000–lb. truck have a maximum value of 28 at 4 Hz in the vertical component and a maxim value of 18 at 4 Hz in the horizontal direction.

Ground motion peak–particle velocity data determined from the attenuation tests for each distance at the different locations were averaged and plotted on a log–log graph to derive the attenuation functions (Figure 11). Data from the tests at Kin Kletso were not included in this analysis because the vibration transmission path at this site is through weathered rock whereas the other site vibration transmission paths were through unconsolidated sediments (King and Algermissen, 1985). Distance scaling functions for the different sources were derived by linear least squares regression. The variance in ground motions produced by each source is shown by the vertical bars in Figure 11 (a scatter of less than 12%). Distance attenuation scaling functions (slope of the graph) are also shown on Figure 11.

Construction Compaction Equipment

Construction equipment can generate a great deal of ground shaking. The ground shaking induced by vibratory rollers has been identified as a source of potential damage to archeological structures because the frequency of the induced vibrations often matches the natural frequencies

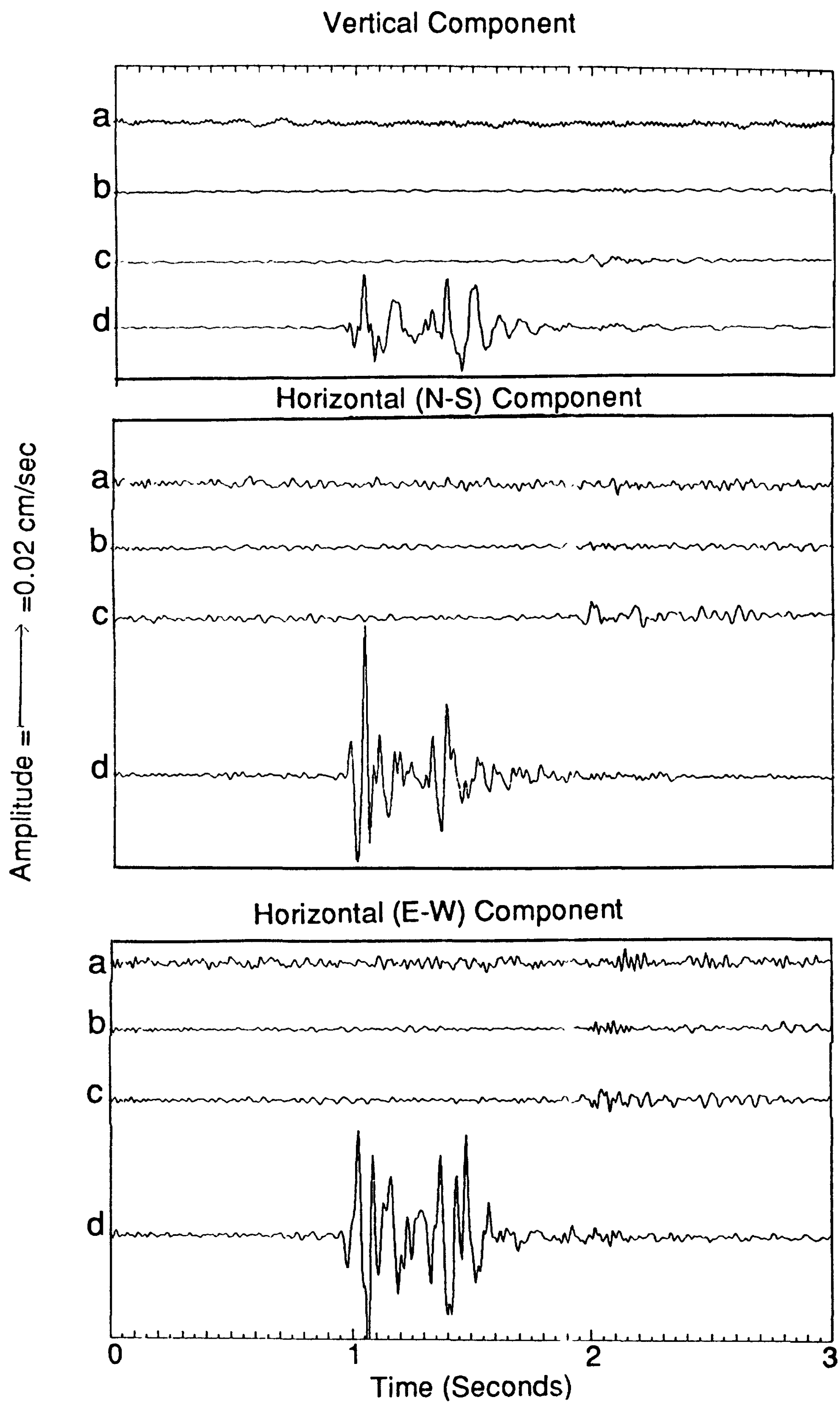

Figure 7. Seismogram comparison from attenuation tests. a = water truck drive-by, b = pick-up drive-by, c = pick-up deceleration, d = pick-up hitting bump.

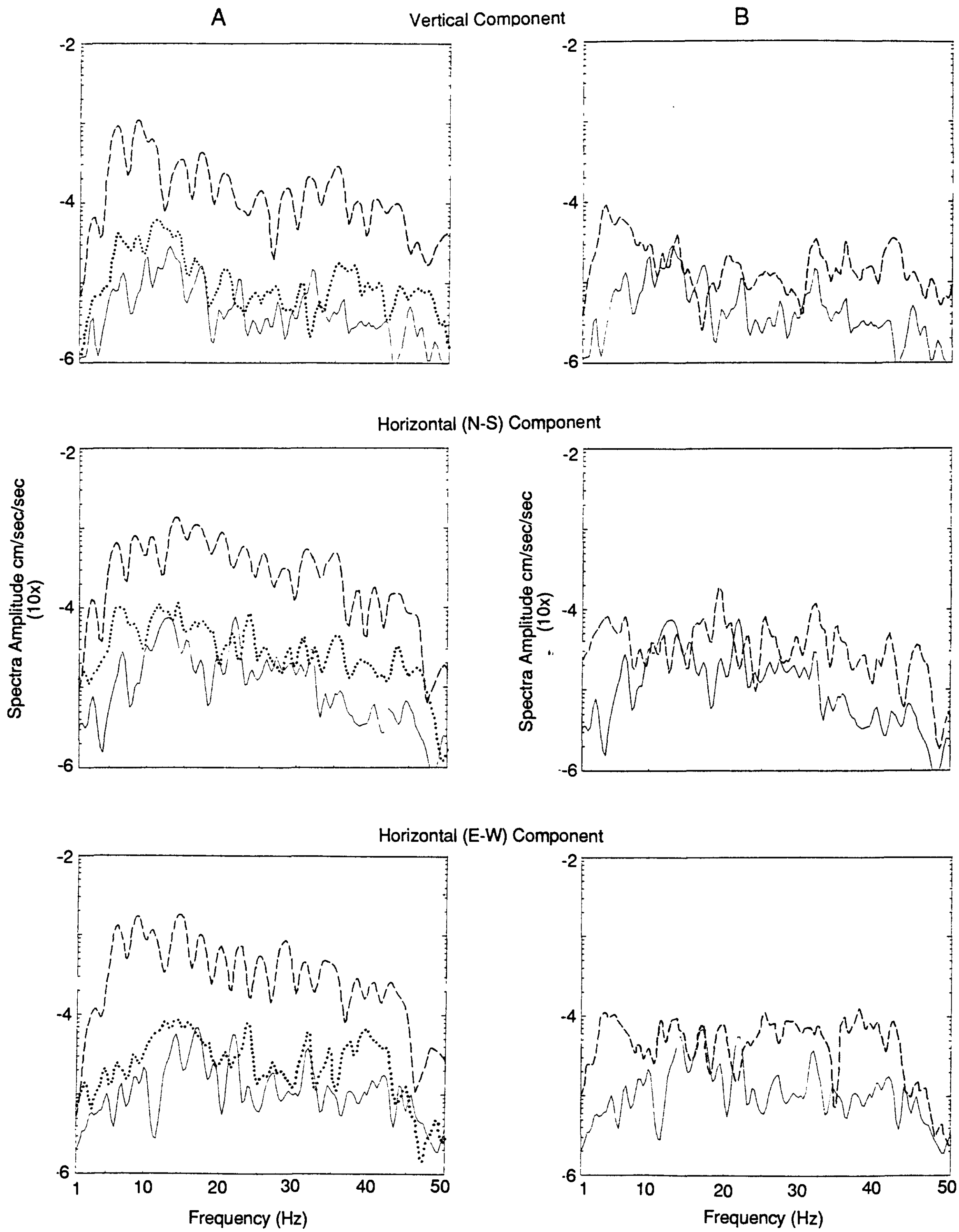

Figure 8. Spectra derived from the attenuation tests. A: --- = pick-up drive-by, - - - = pick-up deceleration, ... = pick-up hitting bump. B:--- = pick-up drive-by, - - - = water truck drive-by.

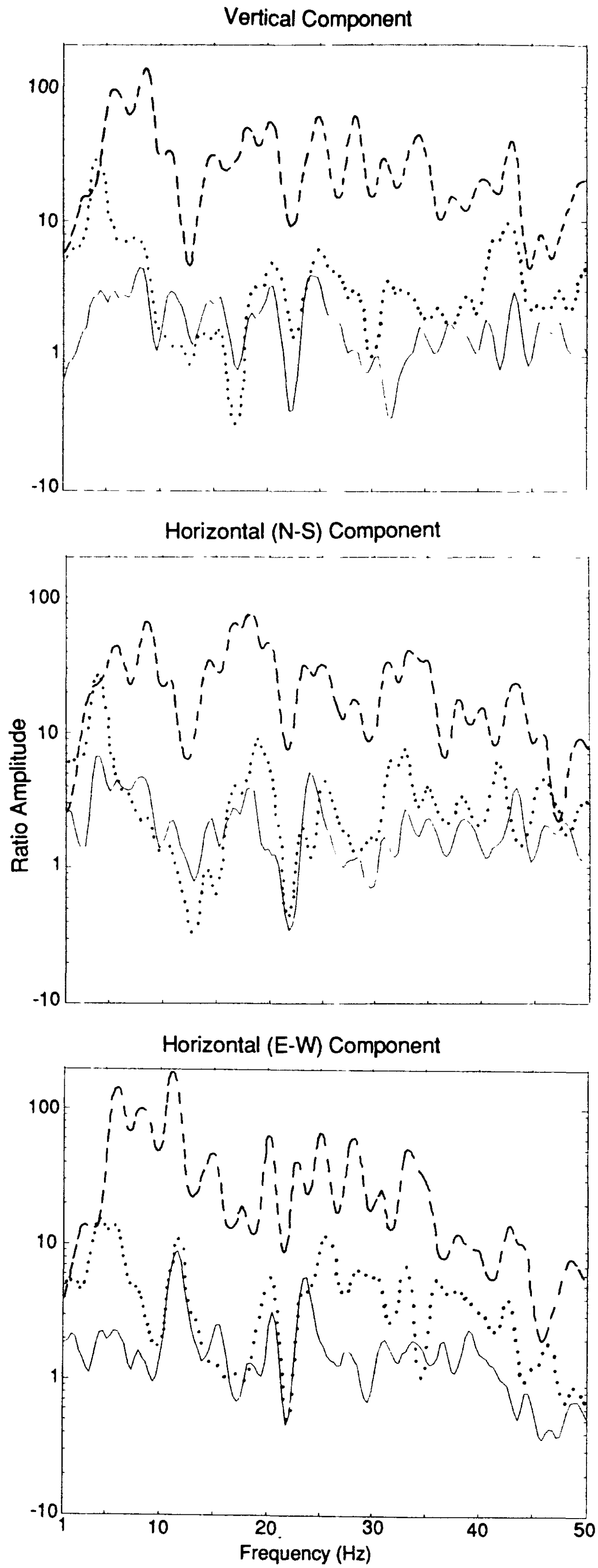

Figure 9. Spectral ratios from attenuation tests at 20m. Ratio denominator is the spectrum of pick-up drive-by induced ground motion. Numerators include: --- = spectrum from pick-up deceleration; ..... = the water truck drive-by; - - - = spectrum from the pick-up hitting bump.

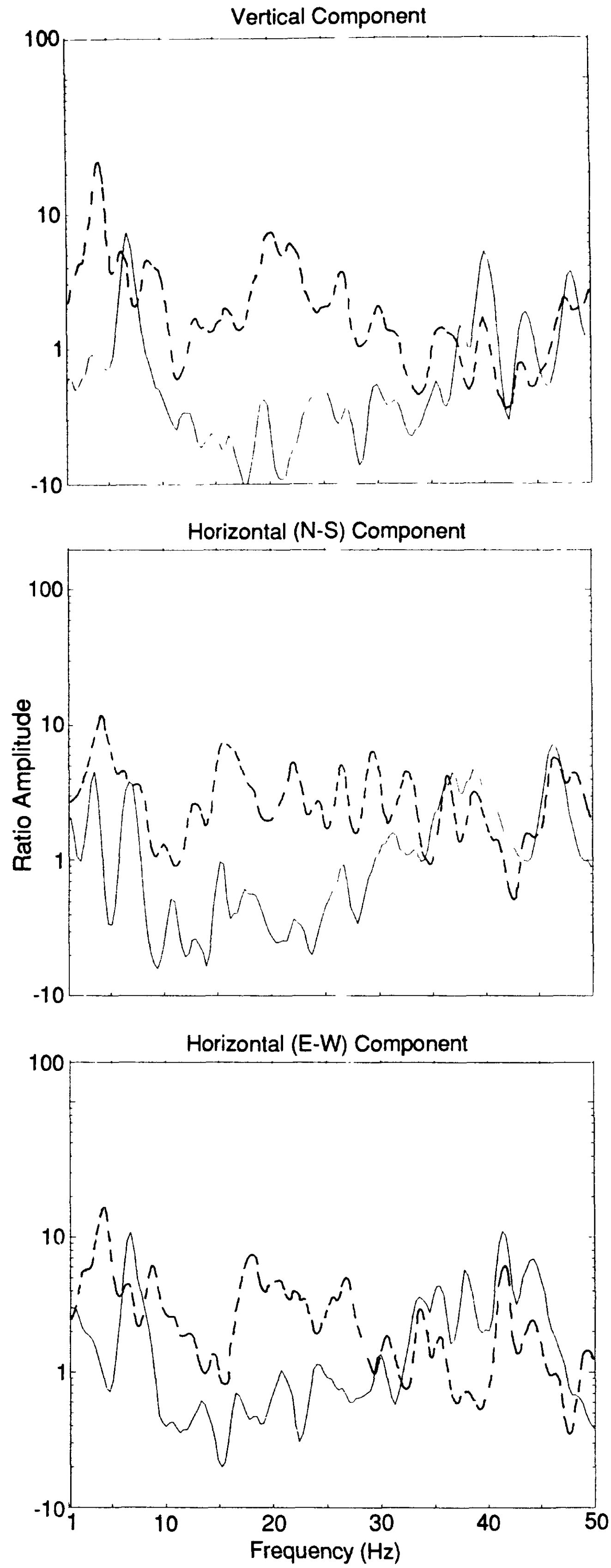

Figure 10. Spectral ratios for 60,000 lb truck and pick-up deceleration in comparison with 3/4 ton pick-up drive-bys at a 50m range. Numerators include: --- = spectrum of induced ground motions at 50m from pick-up deceleration; - - - = spectrum from the 60,000 lb. truck.

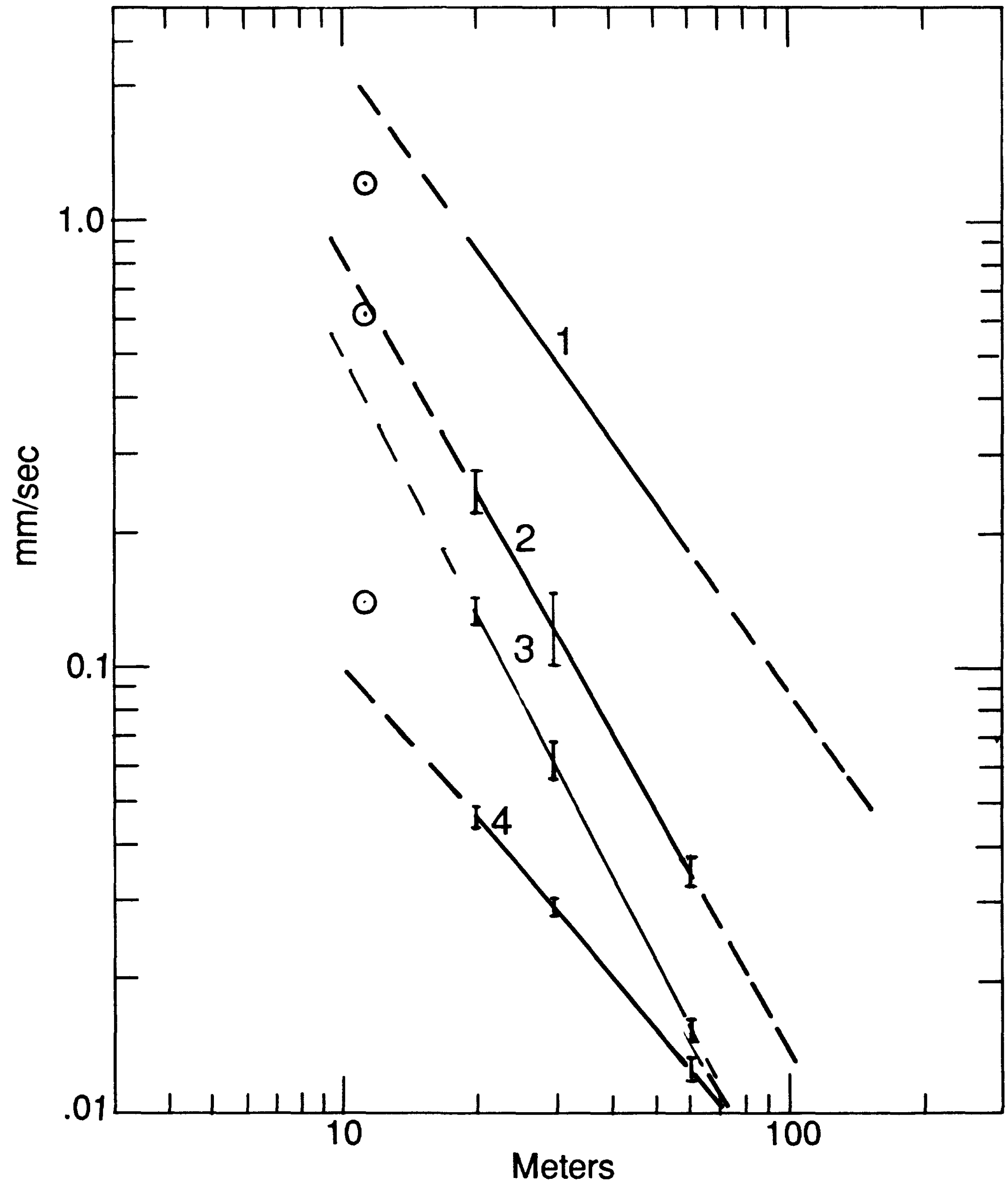

Figure 11. Induced ground motion values from the attenuation study. 1 = vibrating roller, slope function=$R^{-1.53}$, 2 = truck hitting bump, slope function= $R^{-1.78}$, 3 = pick-up deceleration, slope function= $R^{-1.80}$, 4 = pick-up drive-by, slope function=$R^{-1.21}$. 0=Kin Kletso tests. Vertical bars indicate the data maximum and minimum numbers.

of the walls (King and Algermissen, 1985). Vibrations induced by normal operation of a "SAKAI SU7OTF" type vibratory–roller were documented at approximate distances of 10, 30, and 50 m. Ground shaking caused by the compactor–roller was documented with the vibrator turned on and the equipment rolling and with the vibrator turned off and the equipment rolling. Seismograms from the compaction–roller (Figure 12) show that the peak–particle velocity motions increase by an approximate factor of 50 when the vibrator is used. Spectra derived from the seismograms (Figure 13) show that peak spectral amplitudes are approximately at 8, 18, and 31 Hz which are within the range of many of the walls.

Casa Rinconada Vibration Study

The National Park Service was also concerned about the future use of Case Rinconada for large meetings. Accordingly, selected walls and the lintels at this structure were re–tested for their natural frequencies and dampings (Figure 6). The Casa Rinconada structural members found to be most sensitive to induced shaking are the lintels on the north–west entrance to the kiva floor. The reason for this sensitivity is the low damping (2% critical) and natural resonance (5–8 Hz) of the viga–type lintels (Figure 6). Recorded seismic time–histories (Figure 14) show the maximum vibration motions induced to the lintels from normal walking and dancing on the kiva floor. The vibration seismograms show a maximum induced motion of approximately 0.12 mm/sec. peak–particle velocity at 32 Hz. Maximum motions induced to the lintels from the walking and jumping on the internal kiva bench is approximately 0.38 mm/sec peak–particle motion at 35 Hz. Motions induced in the lintels by dancing on the kiva floor is approximately 0.42 mm/sec at 31 Hz (Figure 14, Test 3). The vibration tests indicate that motions induced at the kiva floor are amplified by a factor of approximately two by the lintels. Spectra of the source motions (Figure 15) are moderately flat across the range of 15 to 50 Hz indicating that the vibration energy is being dispersed evenly across the bank–width and not concentrating in the frequencies to which the lintels are most sensitive.

CONCLUSIONS

No construction or trucking activities documented during this study period produced vibrations to the archeological structures which were above the specified maximum 2 mm/sec peak–particle motion level in the 1 to 20 Hz band–width.

The attenuation study analysis show that motions induced from a vehicle hitting a bump are much greater than motions induced by normal drive–by a 3/4–ton pick–up truck. Also, induced horizontal motions induced from the drilling operation, (assuming the drilling would be in similar material as the Bonito bridge) do not greatly exceed the maximum motions induced from a bump. The distance scaling functions from the attenuation analysis indicate that peak–particle motions induced at the free–field site by the drilling operations should be similar to the maximum amplitude of the motions documented on the top of the Bonito wall. Ground motions produced from the drilling operations were attenuated by the travel distance to the Pueblo Bonito locations as show in Figure 4–1 and 2; however, the signal amplitude decrease due to attenuation is offset in the 6–8 Hz frequency range (natural frequency; of the wall) by amplification from the wall.

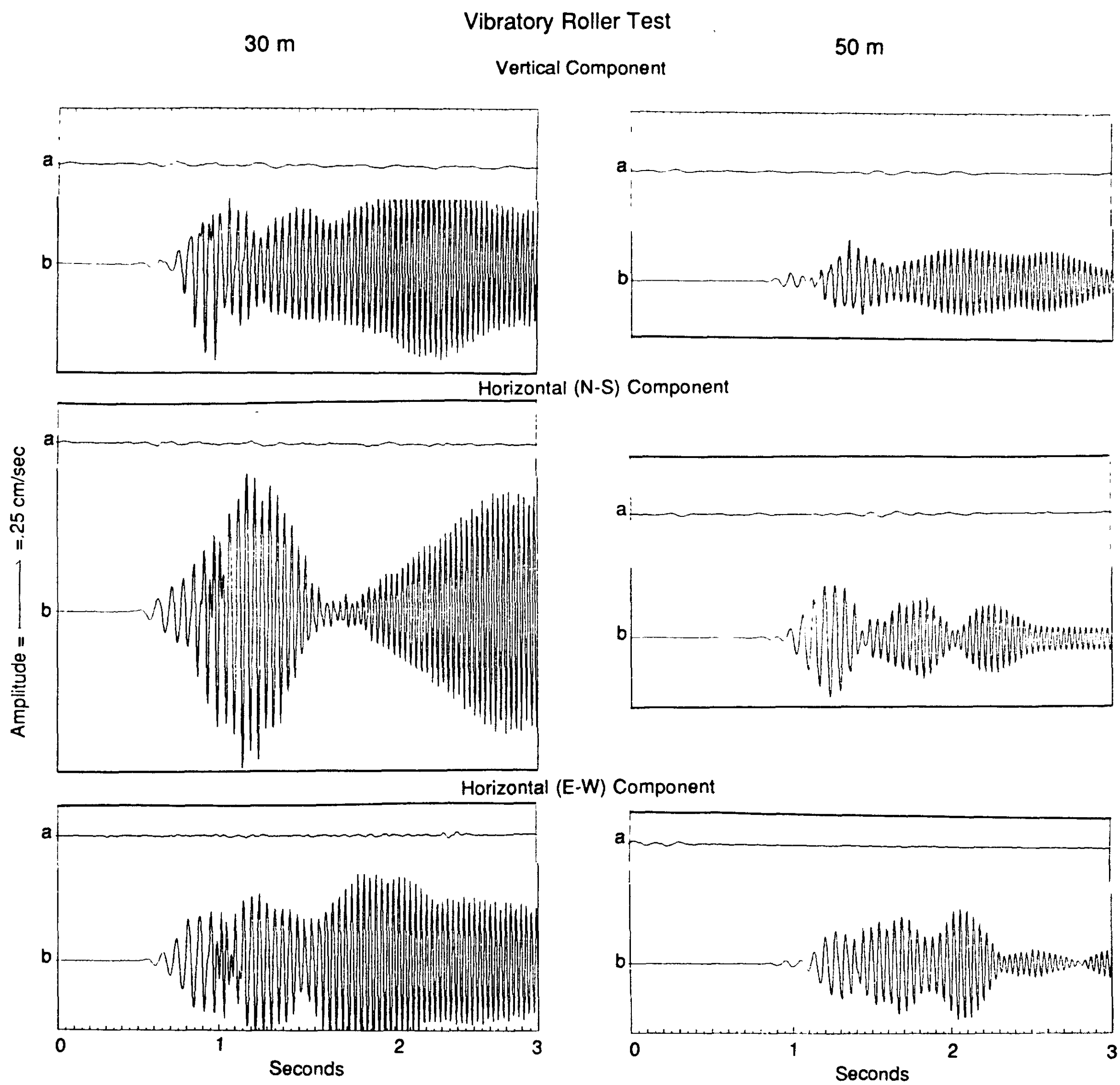

Figure 12. Seismograms of induced vibrations at 30m and 50m from a SAKAI roller (compactor). a = roller operating without vibrator. b = roller operating with vibration.

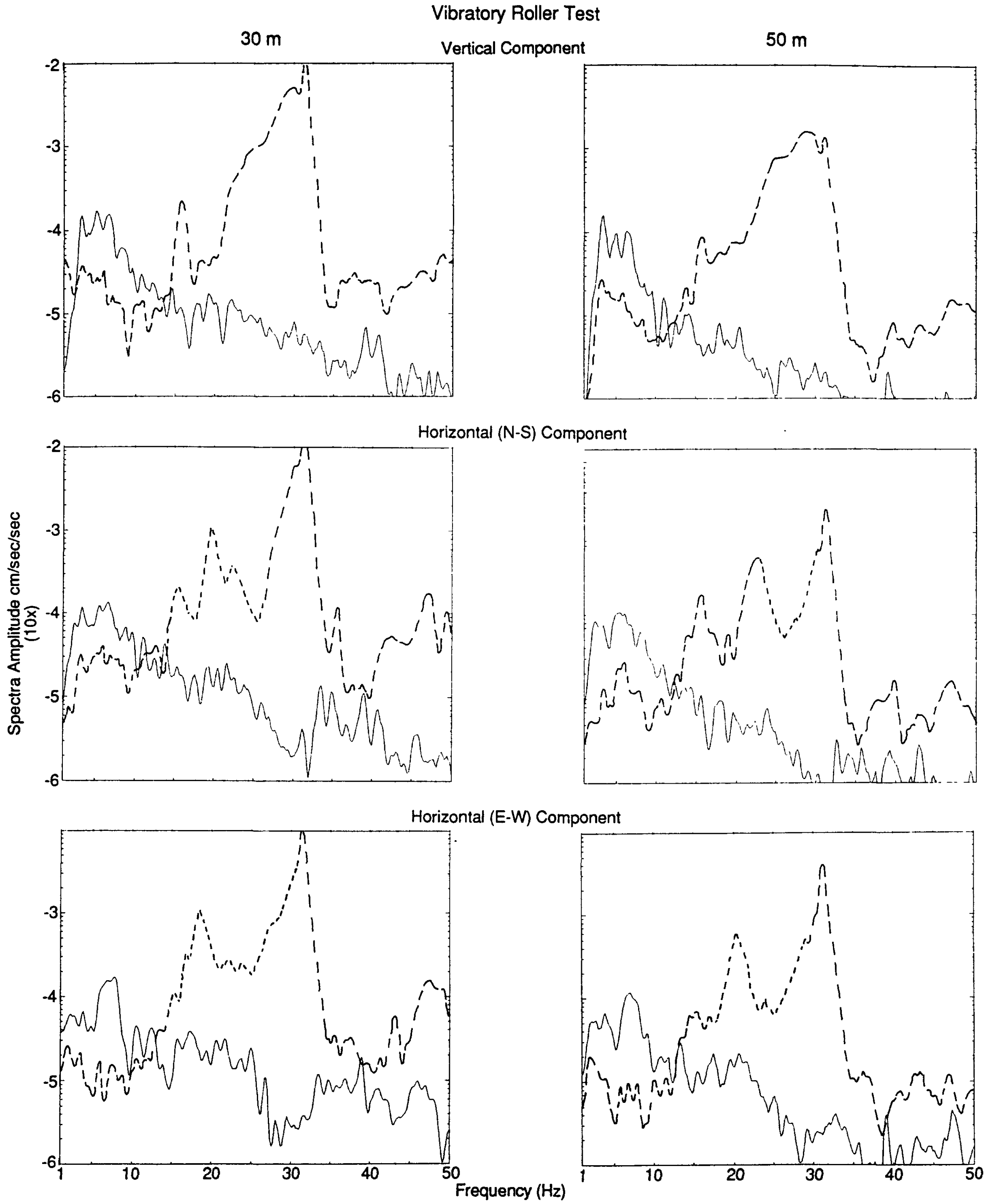

Figure 13. Spectra derived from roller-compactor-vibrator tests at 30m and 50m. --- = roller operation only, - - - = vibratory roller operation.

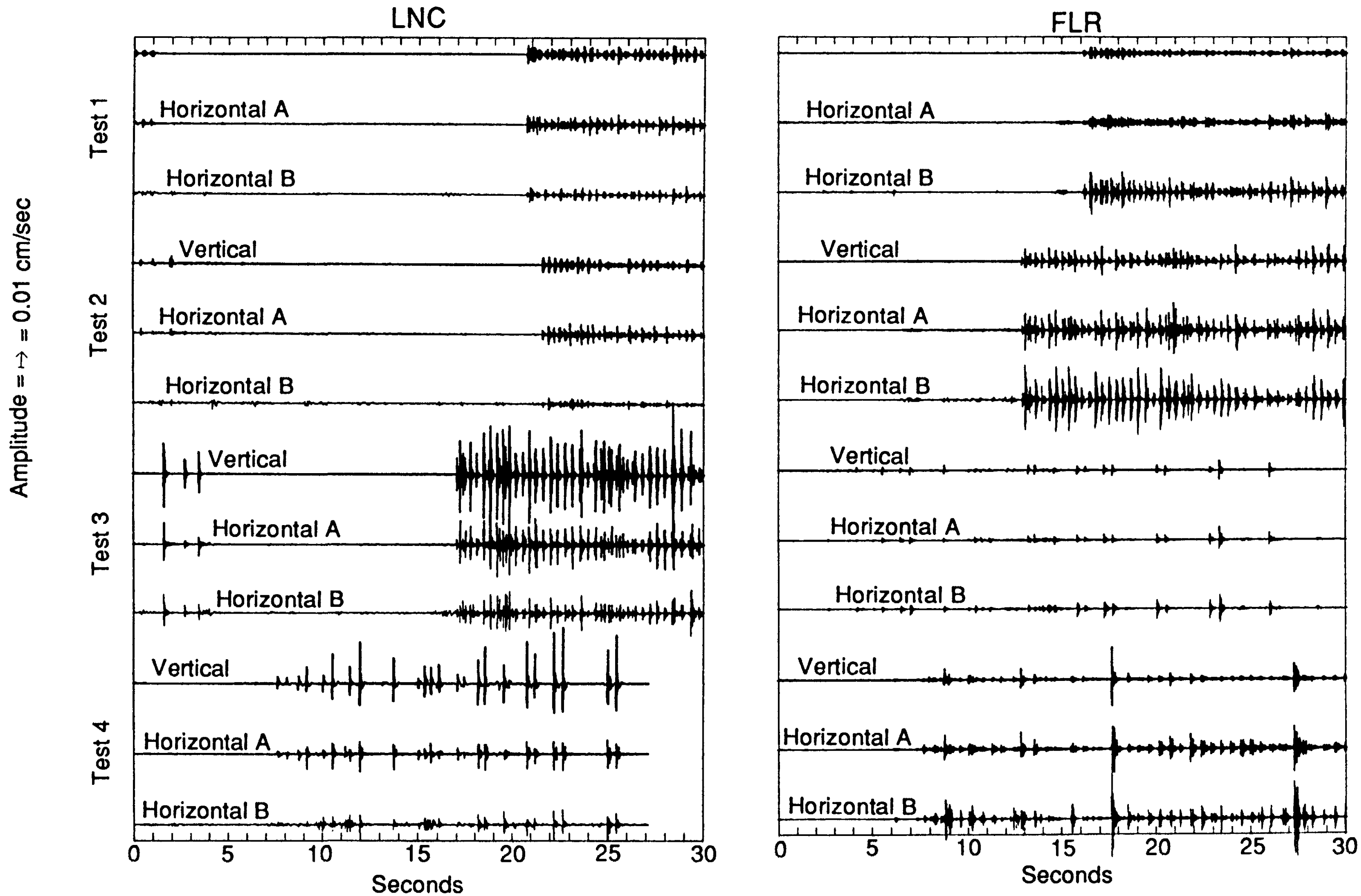

Figure 14. Seismograms from vibration tests at Casa Rinconada. LNC = the lintel at the northeast entrance. FLR = kiva floor. Test 1 and 2 are vibrations induced by normal walking of several people on the kiva floor; Test 3 is dancing on kiva floor; Test 4 is walking and jumping on kiva bench.

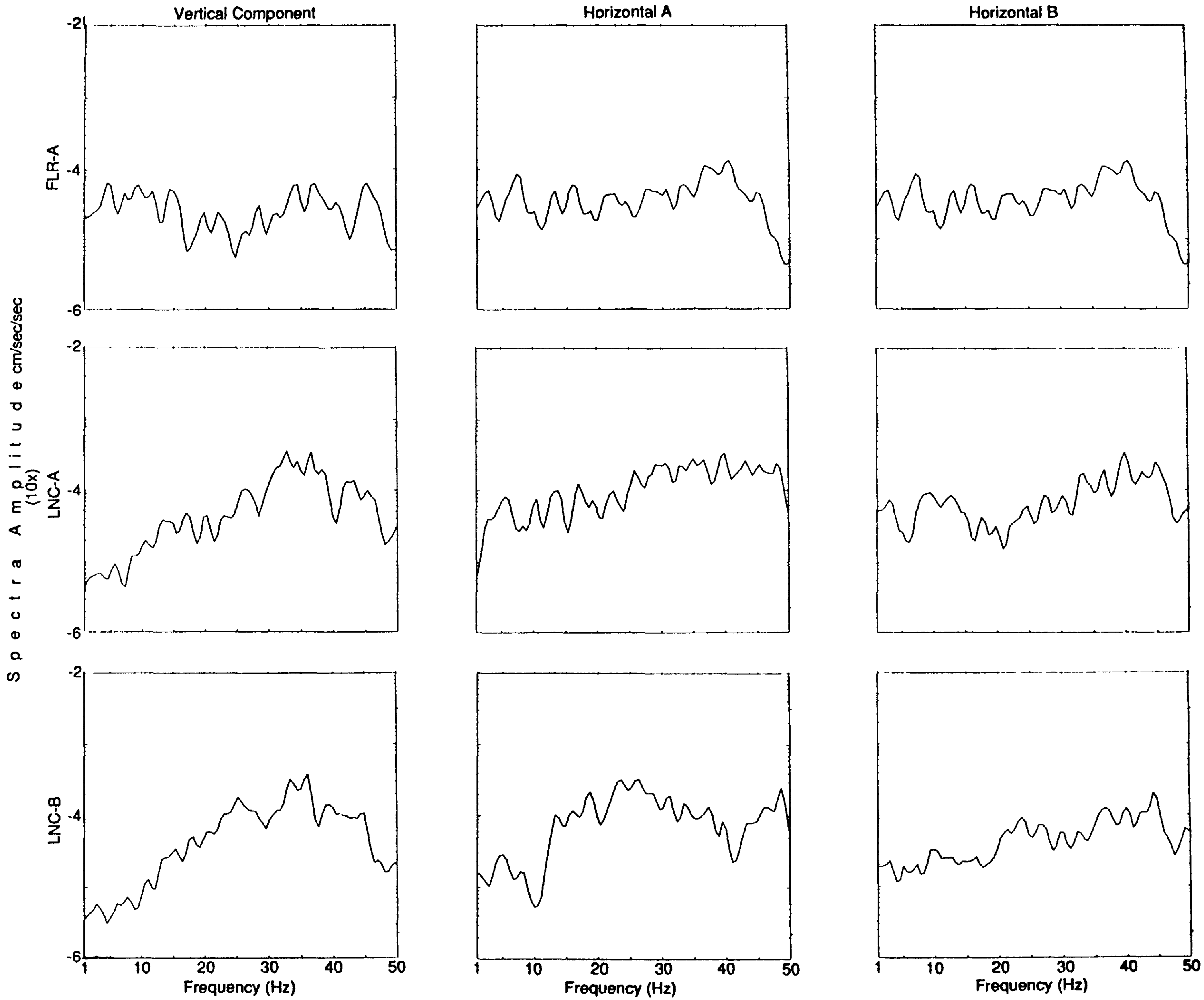

Figure 15. Spectra from vibration tests at Casa Rinconada. FRL = kiva floor, LNC-A = lintel at northeast kiva entrance , LNC-B = lintel off northeast alcove, south side. Source was personnel dancing on kiva floor.

Figure 16 shows comparisons of peak–particle amplitude values for different tests during this project. Analysis of the data indicate that rotary drilling of the piling holes can be a vibration–safe method to install pilings near sensitive archeological or historic structures in Chaco Canyon. The low level of drilling vibration is probably a result of the drilling method and the materials in which the holes were drilled. It is possible that if the materials which were bored by the drill were bedrock or gravel, the induced motions produced by the greater rotation resistance and bounce to the drill auger would be greater. Nevertheless, the induced motions from a drilling operations could increase by a factor of 20 above those that were documented and still be below the 2 mm/sec vibration limit. Comparing the data derived from this project with the past experience of vibrations induced from drilling (King and others, 1986), it is likely that a similar drilling operation in sand or gravel could be accomplished at approximately 100 meters from a sensitive archeological site without inducing motions above 2 mm/sec peak–particle velocity limit in the 2–15 Hz bandwidth.

The 60,000 lb. limit that the National Park Service placed on the truck loads was effective in reducing the induced vibrations. Our results indicate that vehicles with similar loads could probably operate in a normal drive–by status at a minimum range of 10 m from the archeological sites if the road is very smooth and the vehicle did not accelerate or decelerate. To be safe the distance should probable be doubled if there is the risk of deceleration because of stop signs, etc. (see Figure 16). The analysis also indicated that the amount of energy induced from vehicular traffic is directly related to the smoothness of the road. The analysis show that a rough road that is equivalent to a 4 x 4 inch bump can cause the traffic sources to generate approximately 10 times more motion into the ground than a similar induced ground motion on a smooth road. Also, the induced motions from traffic on a rough road is in the frequency range of the natural resonance of the archeological walls. Depending on the particular wall's natural frequency, the wall can then amplify this motion by a factor of 2 to 5 (King and Algermissen, 1985). Therefore, based on amplification by the walls, the attenuation functions and data show on Figure 16, heavy vehicle traffic on a rough road should be at least 30 m from a sensitive site. The noted exception to this range are the structures at the Kin Kletso complex. Parts of the Kin Kletso complex are constructed directly on sandstone bedrock which also is directly beneath the highway at this particular location. The bedrock will attenuate the induced vibrations at a much lower rate then the sandy, unconsolidated sediments underlaying the other sites. In general, the sandstone bedrock is not located immediately beneath the highway at other sites. The surface location of bedrock at Kin Kletso (with the much lower attenuation rate) accounts for the higher–than–normal induced vibration levels (Figure 16). Efforts should be made to keep the road adjacent to Kin Kletso smooth and heavy–equipment activities low.

The testing of the ground motions induced by a "SAKAI" type vibratory roller are similar to those found for a "BOMAG" roller in a previous study (King and Algermissen, 1985). It is apparent from the analysis that similar construction devices should not be used within approximately 15–30 m range from a vibration sensitive structure.

The attenuation functions developed in this report are similar to those developed from the tests in the King and Algermissen 1985 report. The zoning from the 1985 report is appropriate with the addition of the 100 m limit on shallow drilling into sand or gravel and the 30 m limit on heavy vehicles (with the exception of Kin Kletso complex).

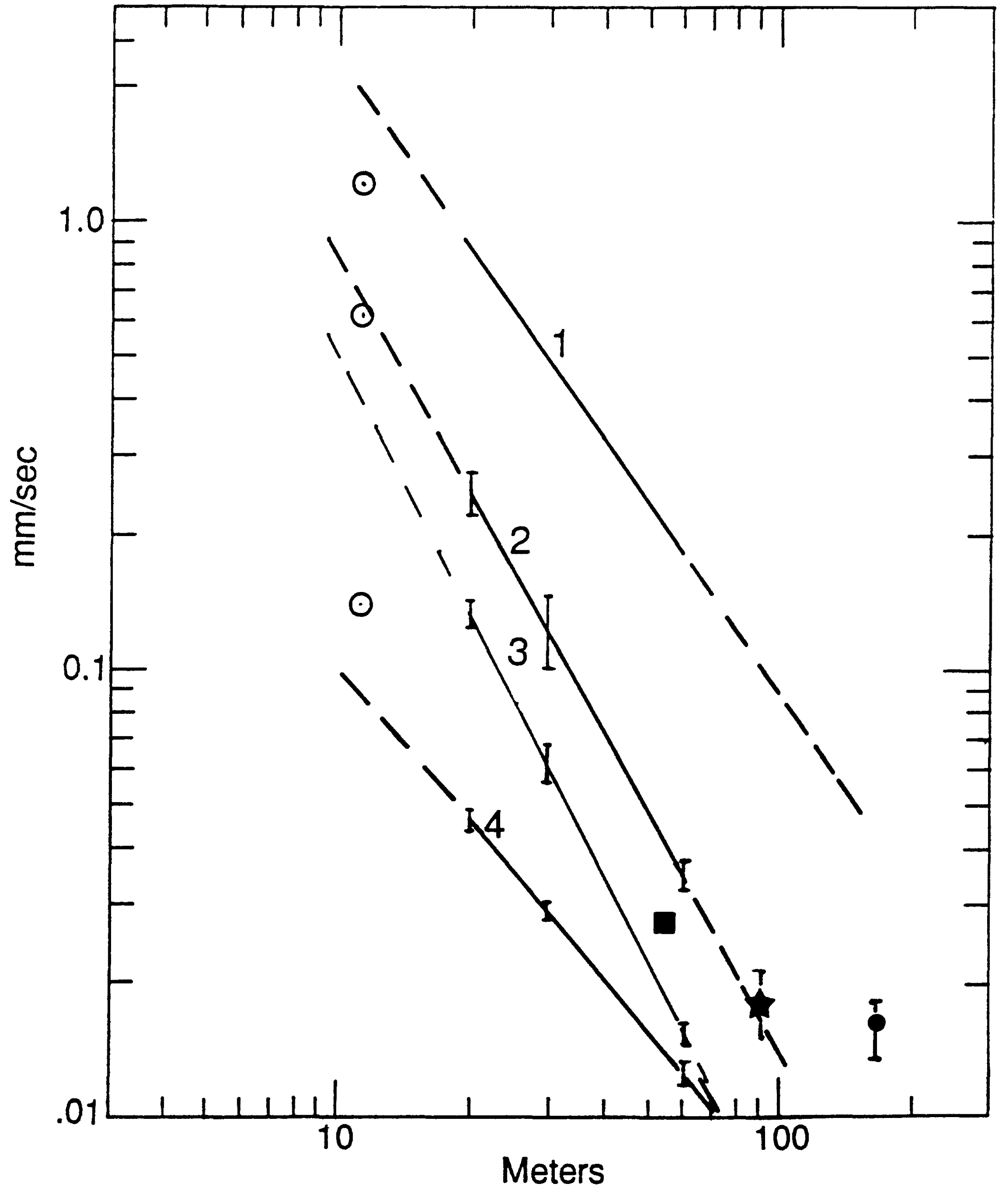

Figure 16. Induced ground motions values. Sources: 1 = SAKAI vibration roller, 2 = pick-up hitting bump, 3 = pick-up deceleration, 4 = pick-up drive-by, ⊙ = recorded at Kin Kletso, ■ = 60,000 lb. truck drive-by, ★ = drilling recorded at 90m, ● = drilling recorded on a Bonito wall. Vertical bars indicate the data variance.

The vibration study of Casa Rinconada has indicated that vibrations induced by personnel activities such as dancing on the kiva floor are at higher frequencies than the natural frequencies of the structures and are not a vibration threat to the complex. The source function from induced motions from native dancing is similar to a high frequency, pulse input rather than a singular–oscillatory source. However, the vigas which form the lintels are sensitive to vertical load factors which would limit the personnel use; that is, personnel or equipment should not be allowed on the walls with the exception of the kiva floor bench. It would also be prudent to not allow mechanical equipment on or near the walls–lintels without previous vibration testing.

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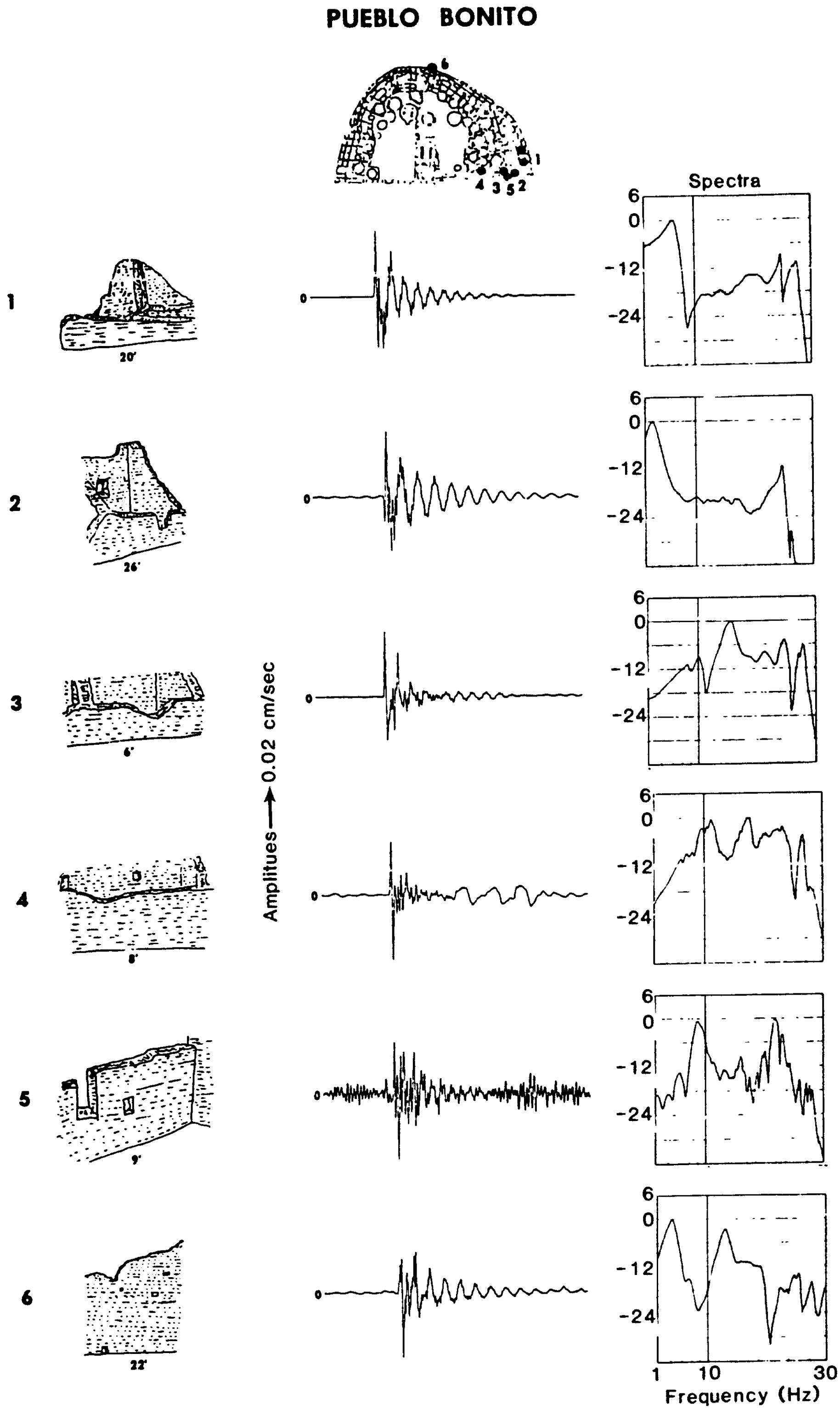
APPENDIX


PUEBLO BONITO
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1
4 3 5 2
Spectra
1
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2
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22'
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-24
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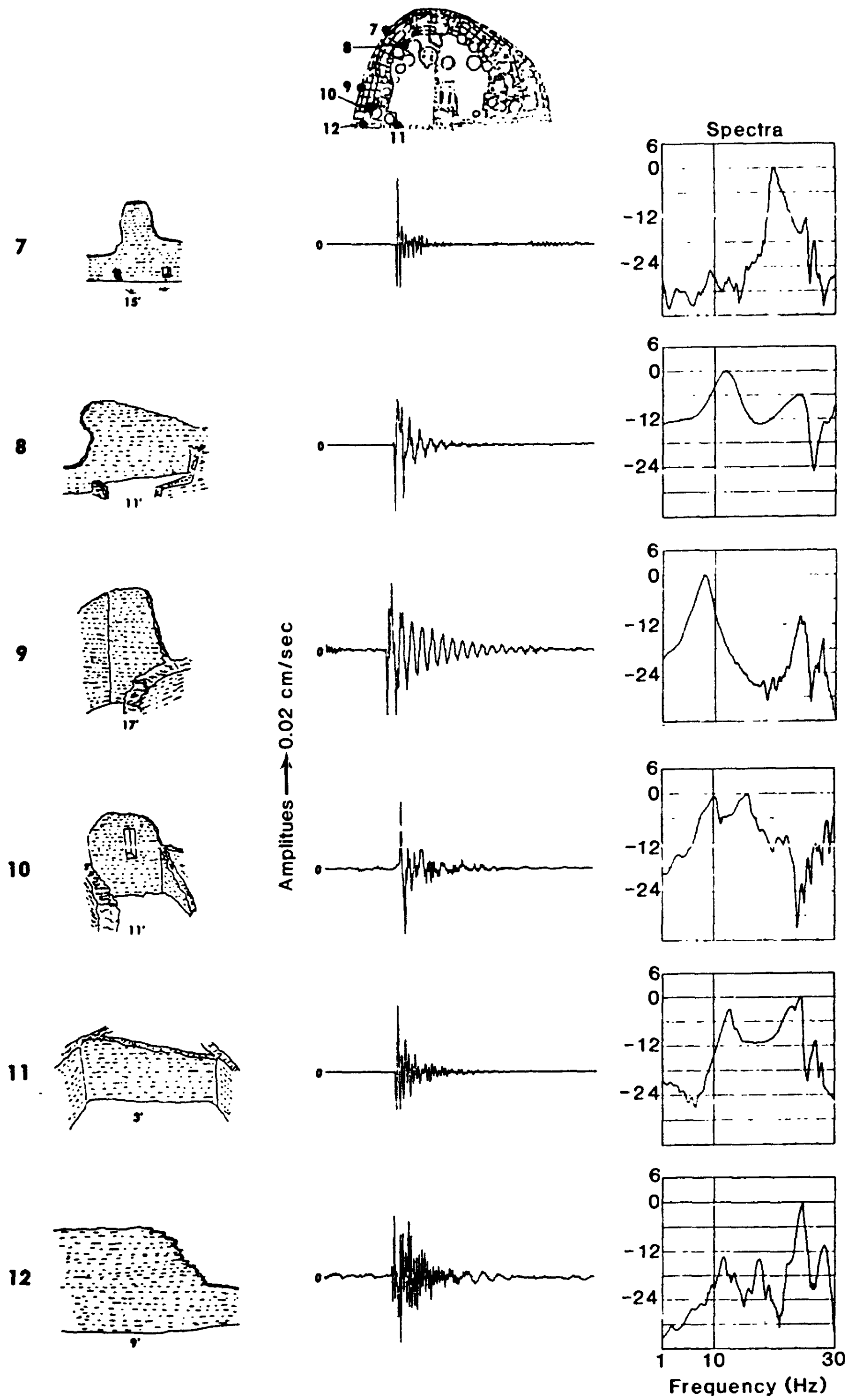
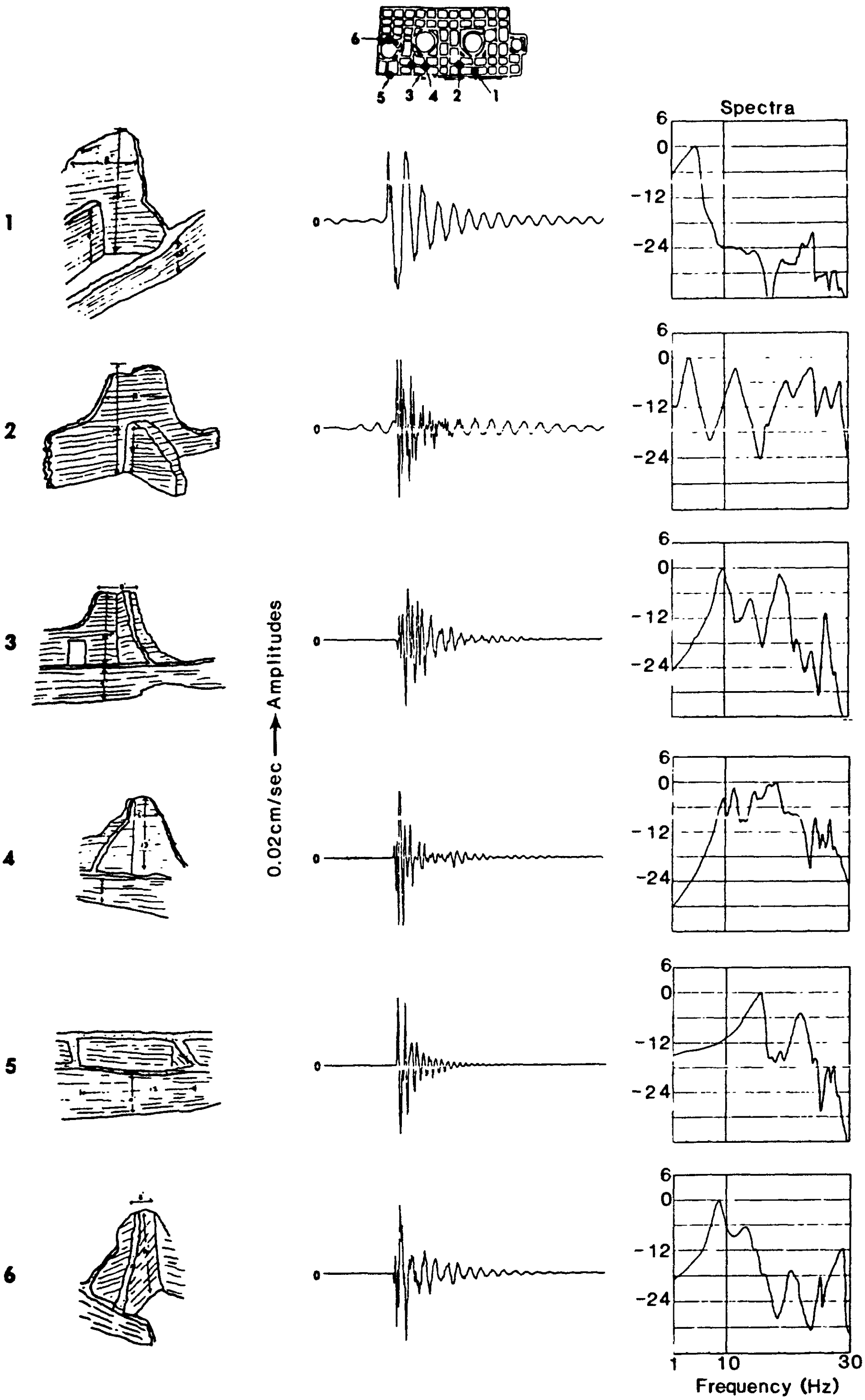
Frequency (Hz)

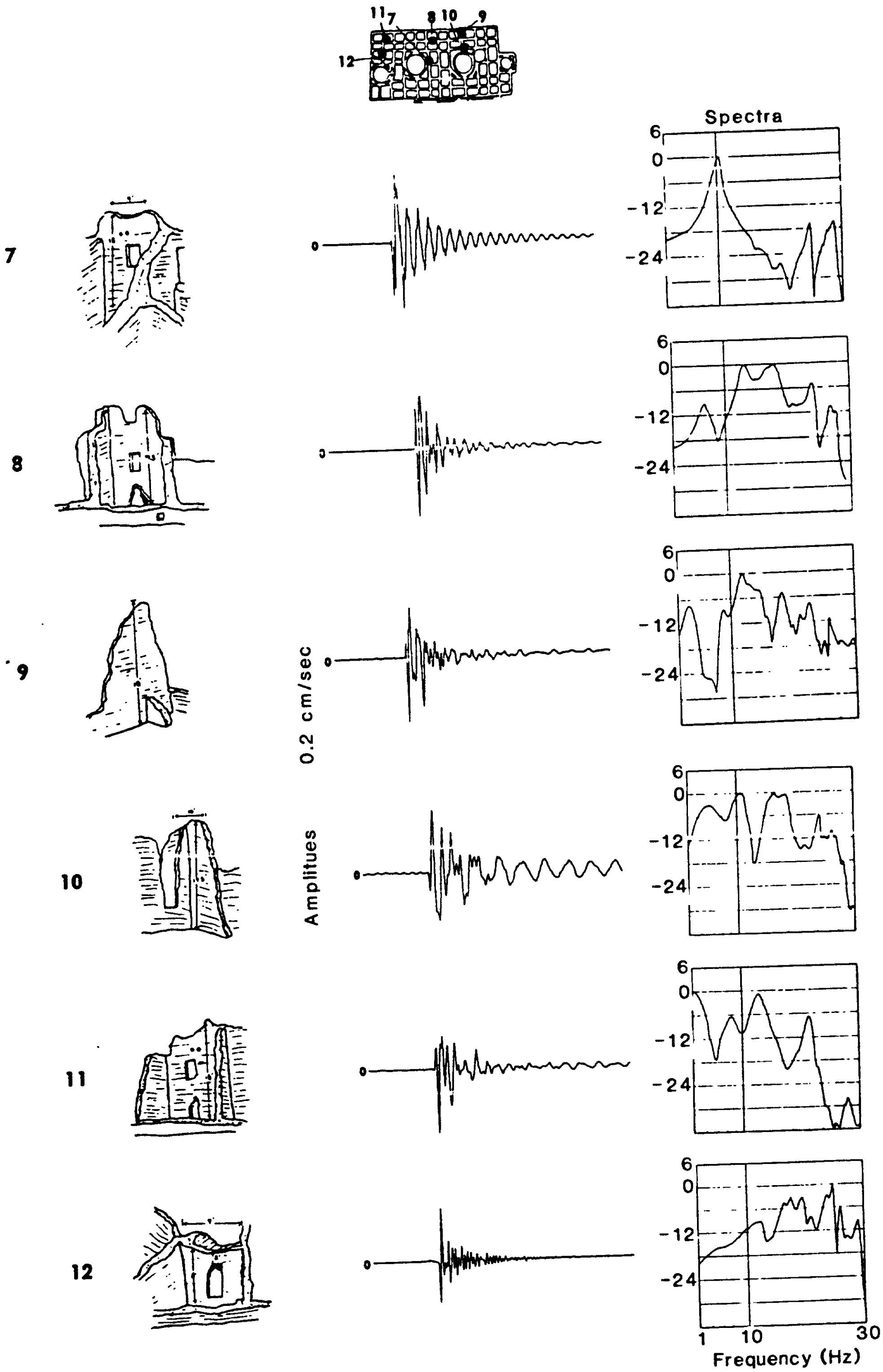
PUEBLO BONITO



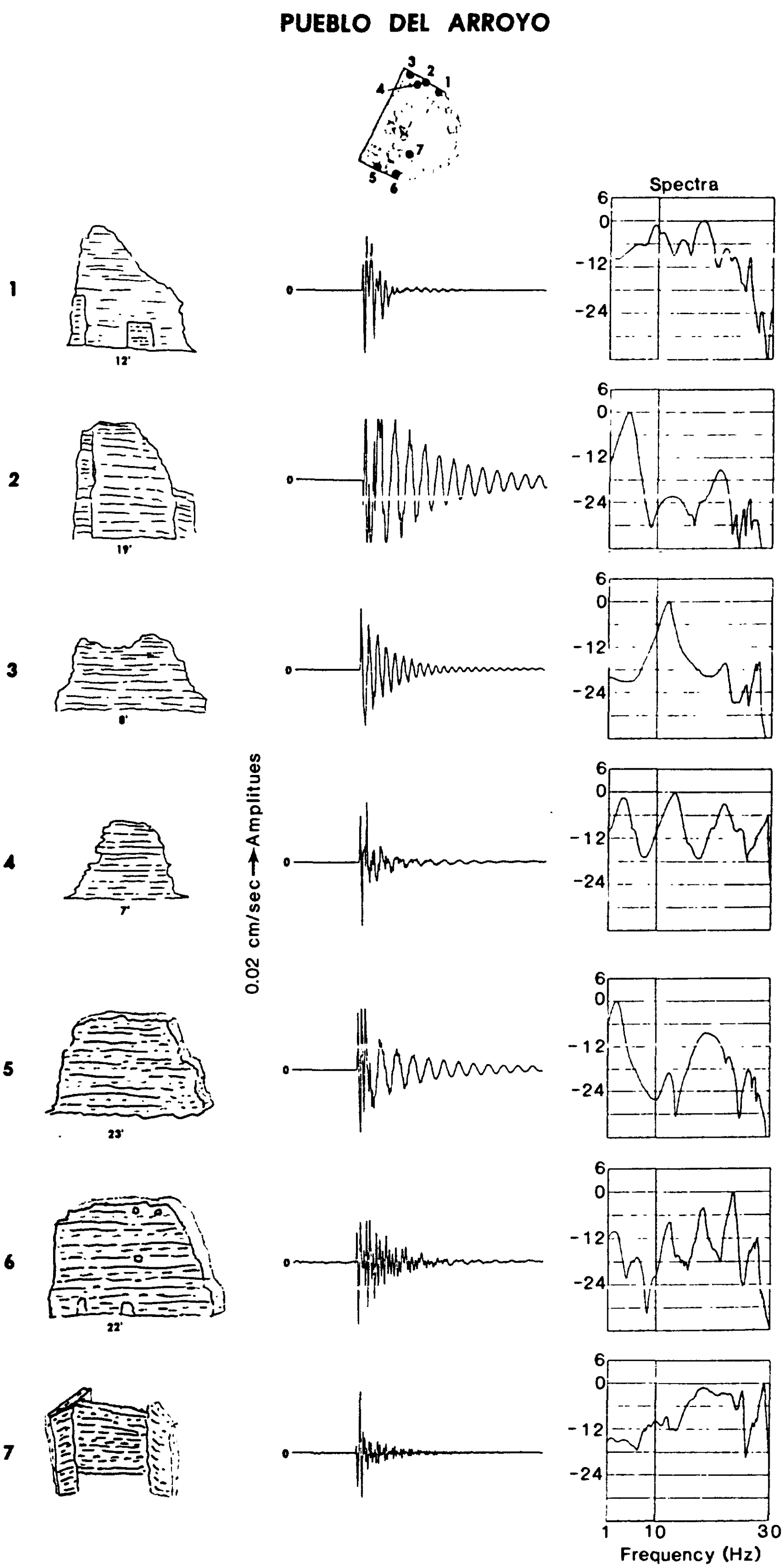
KIN KLETSO


6
5 3 4 2 1
Spectra
1
2
3
4
5
6
0.02cm/sec → Amplitudes
6
0
-12
-24
1 10 30
Frequency (Hz)

KIN KLETSO



11
7
8
10
9
12
Spectra
6
0
-12
-24
0.2 cm/sec
Amplitues
1
10
30
Frequency (Hz)


PUEBLO DEL ARROYO
Spectra
0.02 cm/sec→Amplitues
Frequency (Hz)
1
2
3
4
5
6
7
12'
19'
8'
7'
23'
22'
6
0
-12
-24
1
10
30

CASA RINCONADA