DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

A Vibration Study of the Archeological Ruins, Hovenweep National Monument, Utah-Colorado

By Kenneth W. King[1] and S. T. Algermissen[1]

Open-File Report 87-181

[1]U.S. Geological Survey
Denver, Colorado 80225

CONTENTS

ILLUSTRATIONS

TABLES

A VIBRATION STUDY OF THE ARCHEOLOGICAL RUINS, HOVENWEEP NATIONAL MONUMENT, UTAH-COLORADO

INTRODUCTION

Hovenweep National Monument is located on the Colorado Plateau north of the San Juan River. The National Monument straddles the border of southwest Colorado and southeast Utah (fig. 1). Hovenweep National Monument contains six groups of unique, ancient, stone-adobe structures. Four of these groups are in Colorado and two in Utah. The builders of the structures now in ruins were part of the Anasazi culture that developed along the San Juan River system in the Four Corners region. Around 1200 A.D. the Hovenweep Anasazi people began building the existing structures at the head of small draws and on the rims of box canyons. The Hovenweep ruins are unlike any other Anasazi structures of the southwest in architecture and general setting.

Most of the structures are tall stone towers that, except for narrow peepholes, generally have no windows and very narrow entrances. Due to their appearance, the massive masonry pueblos were referred to as "castles" by the early explorers. The Hovenweep archeological ruins are noted for their square and D-shaped towers, which can exceed 6 m in height. The structures are constructed of excellent masonry of layered coursed-stone style and most have their foundations on the sandstone bedrock. The only evident structural weaknesses of the archeological ruins are the top plate sections which show damage caused by the failure or removal of the horizontal logs that were used for the roof supports. These logs had either failed or had been removed for other construction or firewood by people who occupied the area after the demise of the Anasazi culture.

These unique archeological structures in the Monument show general deterioration from natural erosion and human destruction. Fortunately, the National Park Service protection has stemmed the relic hunters and general damage by the public but there is a need for further regulations which will protect the unique sites from potential future damage from vibrations induced by commercial activities and public use. The most effective regulations would protect the archeological ruins without being an unnecessary impediment to exploration and to development of natural resources and without undue restriction of public access to the areas adjacent to the structures. Artificially-induced vibration from commercial endeavors may be a potential hazard to the Hovenweep archeological ruins. Typical sources of induced vibrations are explosions from oil or mineral explorations and activities of earth-moving equipment such as bulldozers, rippers, and graders for pipeline and road construction.

This report describes the results of a vibration study of the more fragile of the archeological structures and a study of vibration attenuation of induced ground motions from explosions, trench construction, and local traffic in the areas adjacent to the Square Tower group of ruins. The results of these tests are used to suggest a vibration zoning of the archeological sites. The zoning shows the areas that are acceptable for public use, traffic, general construction and exploration work.

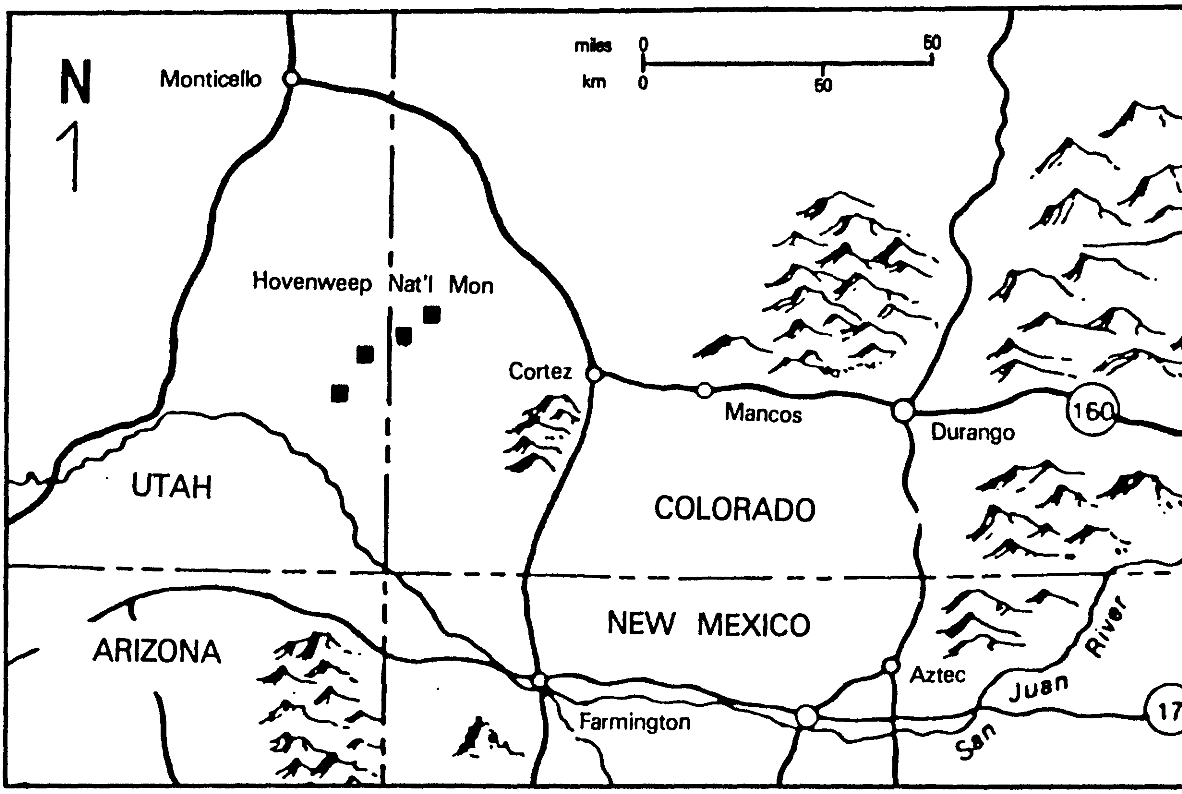

Figure 1. Map showing location of the Hovenweep National Monument, Utah-Colorado.

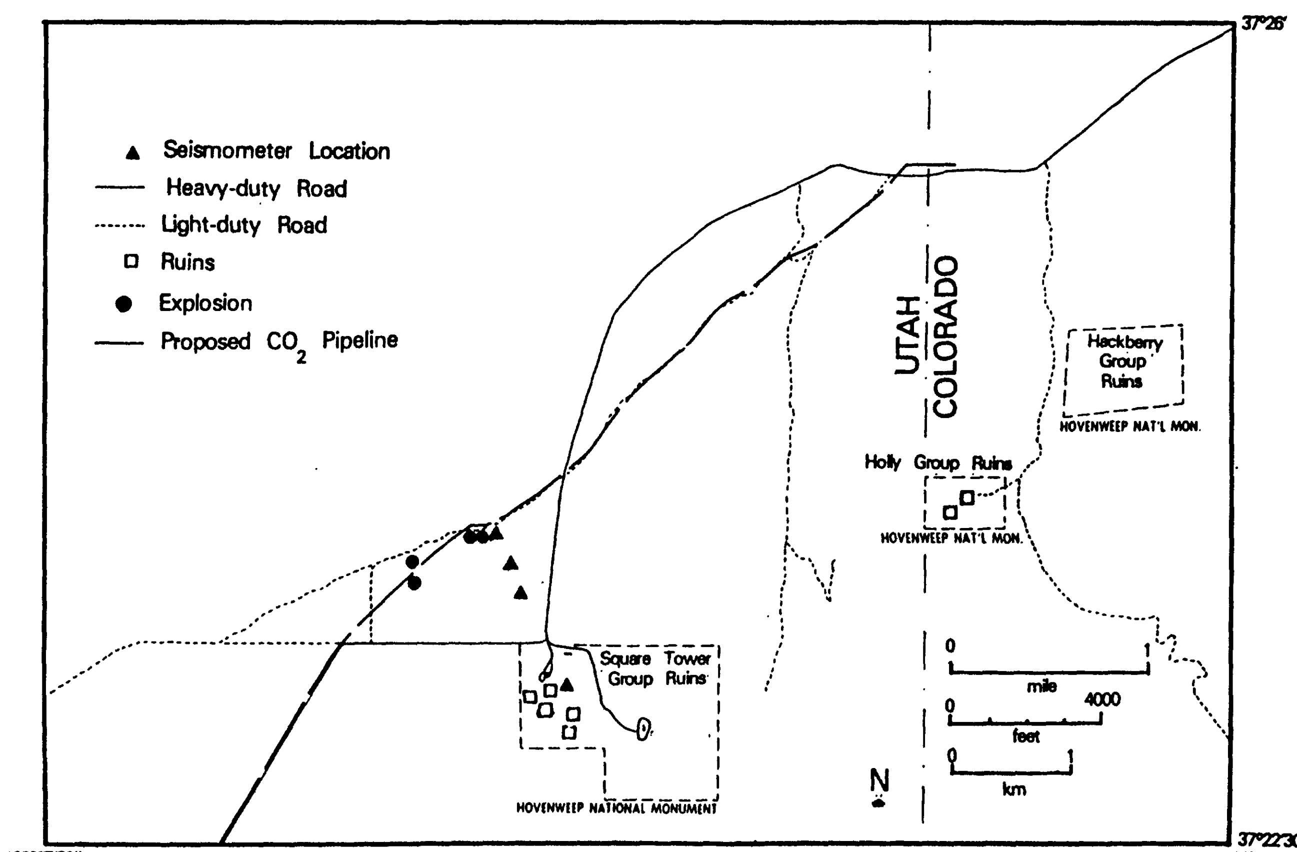

Figure 2. Map showing location of groups of ruins of the Hovenweep National Monument, Utah-Colorado.

STRUCTURAL TESTS

Most of the visible archeological ruins in the areas of concern appear to be carefully planned multi-story structures of generally square, rectangular, or D-shape plan. Vibration testing was conducted at the Square Tower archeological ruins group and the Holly archeological ruins group . The Hovenweep Castle of the Square Tower group was used as the "standard site" as it is the most complex and the tallest archeological structure near public vehicular traffic and a pipeline construction area (fig. 2).

The natural frequency and damping characteristics of a structure are important parameters in the analysis of the response of the structure to induced vibrations. The natural frequency of the structure is important because ground shaking at or near this frequency can induce large motions in the structure. The damping of the structure is important because damping is a measure of the ability of the structure to dissipate shaking energy without damage. The archeological ruins are irregular, non-engineered structures that would be difficult to model; therefore, the test procedure for obtaining these parameters is empirical and consisted of installing horizontal component, velocity motion-sensing seismometers on the top of the wall at the horizontal mid-point of the support walls of the structures (fig. 3). Several minutes of ambient seismic background noise and a number of artificially-induced vibration events are recorded. The vibrations recorded in this study to obtain the damping and natural frequency of the structures were man-induced, forced vibrations. The man-induced forces were kept in close synchronization with the structures' natural frequencies. The resulting vibrations of the structure after the input source motion ceased was recorded and analyzed. The technique has been described in detail by Hudson (1964). The seismic records from the top of the walls were analyzed to obtain the approximate percentage of critical damping using:

$$D=\frac{1}{2\pi}\left[-\ln\left(\frac{X_{n+1}}{X_n}\right)\right]$$

where D is the percent of critical damping and X_n is the velocity amplitude for the nth cycle of motion.

Vibration from traffic, D-8 Caterpiller bulldozer ripping rock, and test explosions were recorded on selected walls and at sites located approximately 6 m from the walls' bases on the surface of the ground (fig. 3). From a structural response standpoint, the horizontal components of the induced vibrations are the most important component because they cause the principal damage to the buildings. Therefore, only the horizontal components are analyzed in this report (Hudson, 1964). These data were analyzed to determine the Fourier amplitude spectra response of the walls and to derive the structural transfer function from the free-field site to the top-midpoint of the walls (fig. 4).

The spectral characteristics of the ground motion and of the induced structural vibrations are displayed in a form considered most suitable for the study of the structural response. The walls of the ruins respond to vibration sources as single-degree-of-freedom oscillating systems with fairly well-defined frequencies. The Fourier amplitude spectra are measurements of the final amplitudes of an array of simple oscillators as a function of

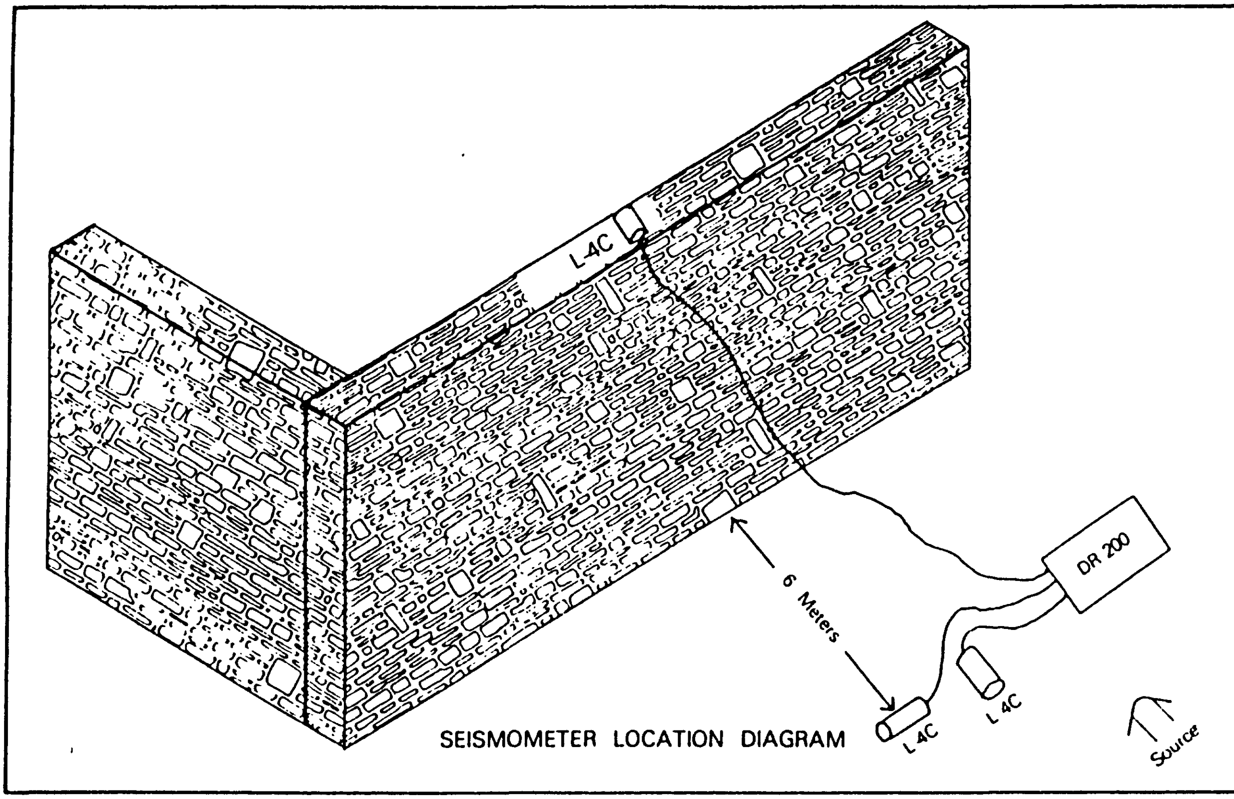

Figure 3. Figure showing the deployment of seismometers during wall tests.

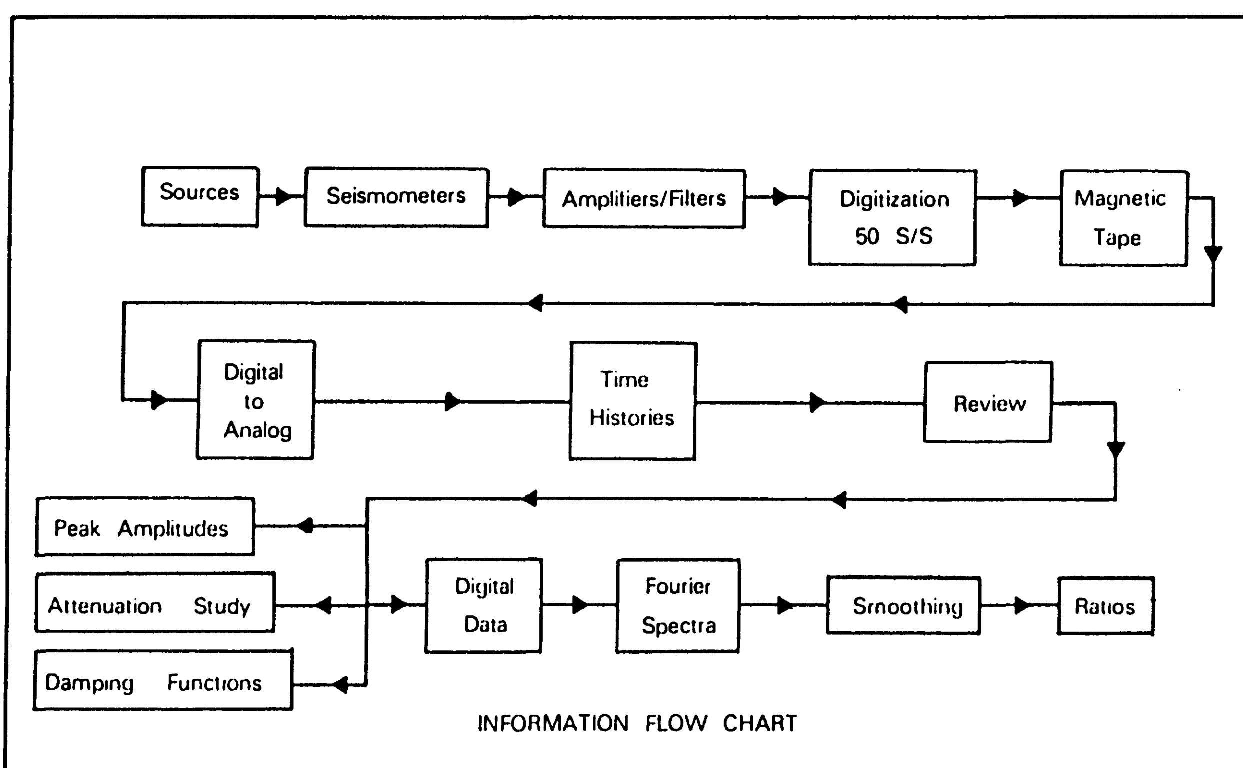

Figure 4. Block diagram showing the data to analysis flow.

frequency. The transfer function (TF) was calculated using: TF=Sw/Sg , where Sw=spectal amplitude in the 1.0-20.0-Hz frequency band at the recording site on top of the wall and Sg=spectral amplitude at the recording site on the ground (free-field) near the base of the wall. The spectral amplitudes and transfer functions indicate those frequencies at which large amplitudes can occur at the top of the walls since certain frequencies of the ground motion are selectively amplified by the wall. The ground motion frequencies that are amplified depend on the natural frequency and damping of the wall (Trifunac, 1975).

The Castle walls are probably the most sensitive to induced ground motion of the two groups of ruins tested, because of their proximity to vehicular traffic, state of deterioration, and their heights. The approach taken is to scale and/or set suggested ground motion standards for the most sensitive structures and assume the less sensitive structures will have a lower vibration risk factor. The North and East wall of Hovenweep Castle of the Square Tower group were used for the transfer function analysis since these are the walls nearest to the public parking lot.

WALL TESTS

As previously stated, the most important structural response characteristic needed from the ruins are the natural periods of vibration and damping of the component walls. The structures are most sensitive to induced ground motions in the frequency band near the natural frequency of vibration of the structures rather than to induced vibrations with frequencies quite different from the natural frequencies of the structures. The damping of the walls indicates the amount of vibrational energy absorbed and the elasticity of the walls (Housner and others, 1972). Knowledge of the damping, the natural frequencies of the structures, and an estimate of the ground-motion transfer function (between free-field and the wall) can be used to establish acceptable and unacceptable levels of induced ground motion in the structures. Twelve pertinent walls were selected for the seismic testing (figs. 5, 6). The natural frequencies for the walls varied from 9.5 Hz to 3.0 Hz with damping values in the range of 2.4-5.4 percent (table 1).

Levels of shaking in the structures related to road traffic were tested by installing horizontal motion sensing seismometers on the top-midpoint of the wall under test and similarly oriented seismometers approximately 6 m from the wall on the ground (fig. 3). Both seismometers were approximately 50 m away from the traffic or from the input vibration source. The light traffic source consisted of a 1980 Dodge sedan moving through the parking lot at 10 mi/hr. The heavy traffic test consisted of recording the induced motions from a 3/4-ton drill truck travelling at the same speed and location as the vehicle used in the light traffic test. The peak particle velocities measured on the wall from ambient background, light traffic, and heavy traffic are, respectively: 0.7 mm/sec, 1.6 mm/sec, and 2.3 mm/sec on Castle wall no. 1 (bldg. 1, site B) and 0.8 mm/sec, 1.7 mm/sec, and 2.1 mm/sec on Castle wall no.2 (bldg. 3, site A) (fig. 7). The transfer function, the ratio of the wall to ground response (Sw/Sg) indicates that the predominant frequencies of heavy traffic vibration input is similar to the natural frequencies of the walls; and as a result, the ground motions in that frequency range (3-4 Hz) are greatly amplified (fig. 8). The response transfer functions are a comparison of the total amplitudes of that particular frequency during the seismic time

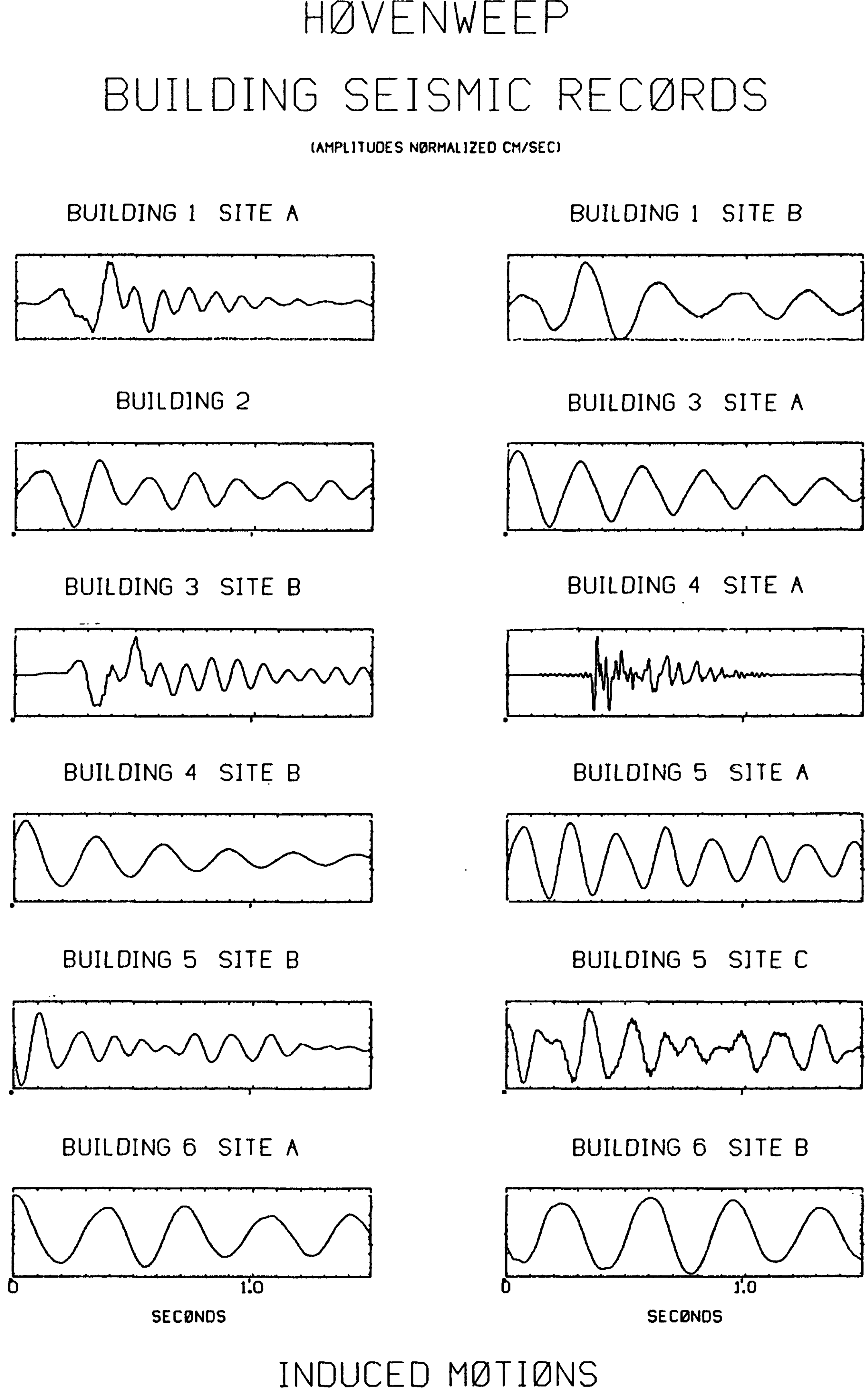

Figure 5. Building seismograms recorded at Hovenweep National Monument. Building and site designations as in Table 1

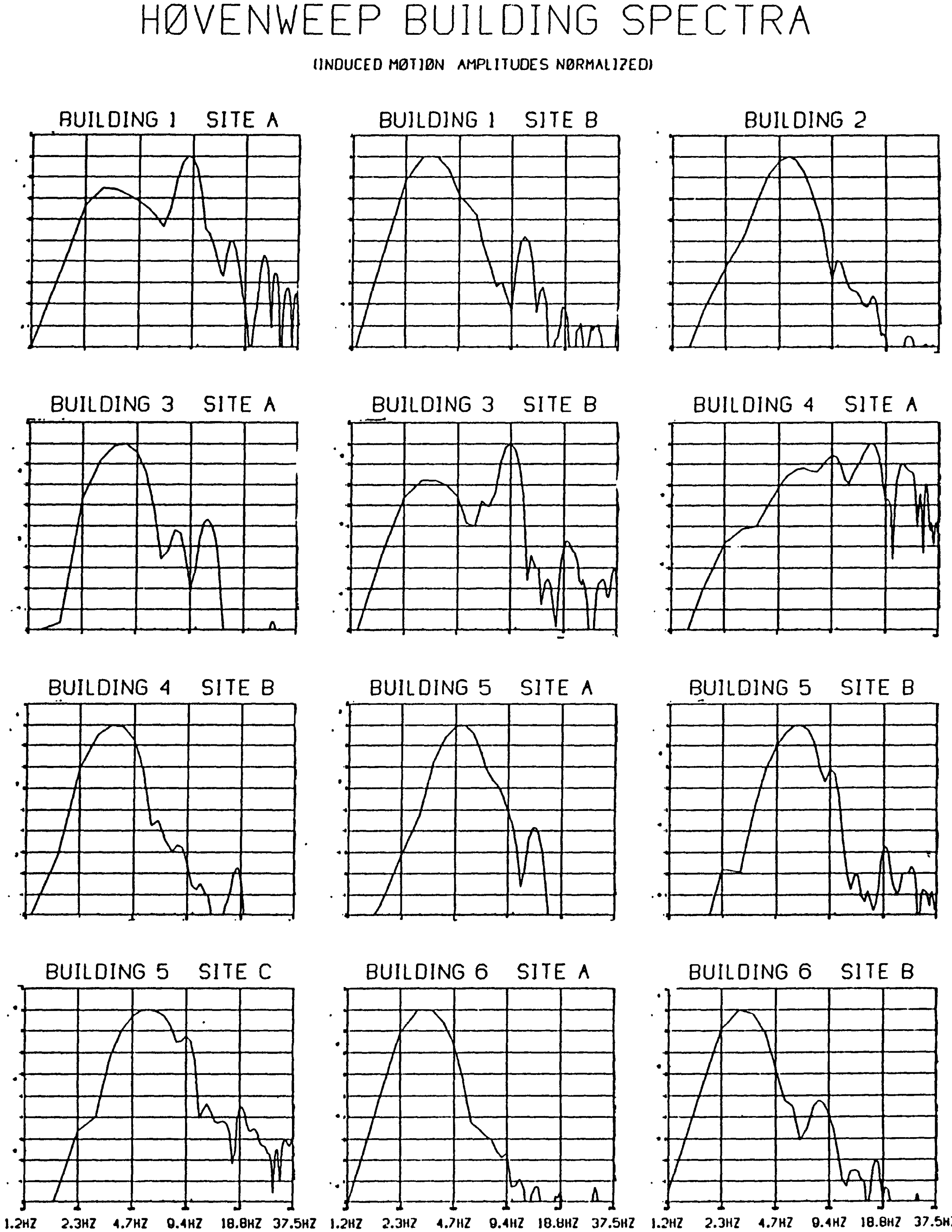

Figure 6. Fourier amplitude spectra from the buildings at Hovenweep National Monument. Building and site designations as in Table 1 . Amplitudes are normalized to maximum spectral amplitudes in each spectrum; amplitude and frequency scale divisions represent factors of 2.

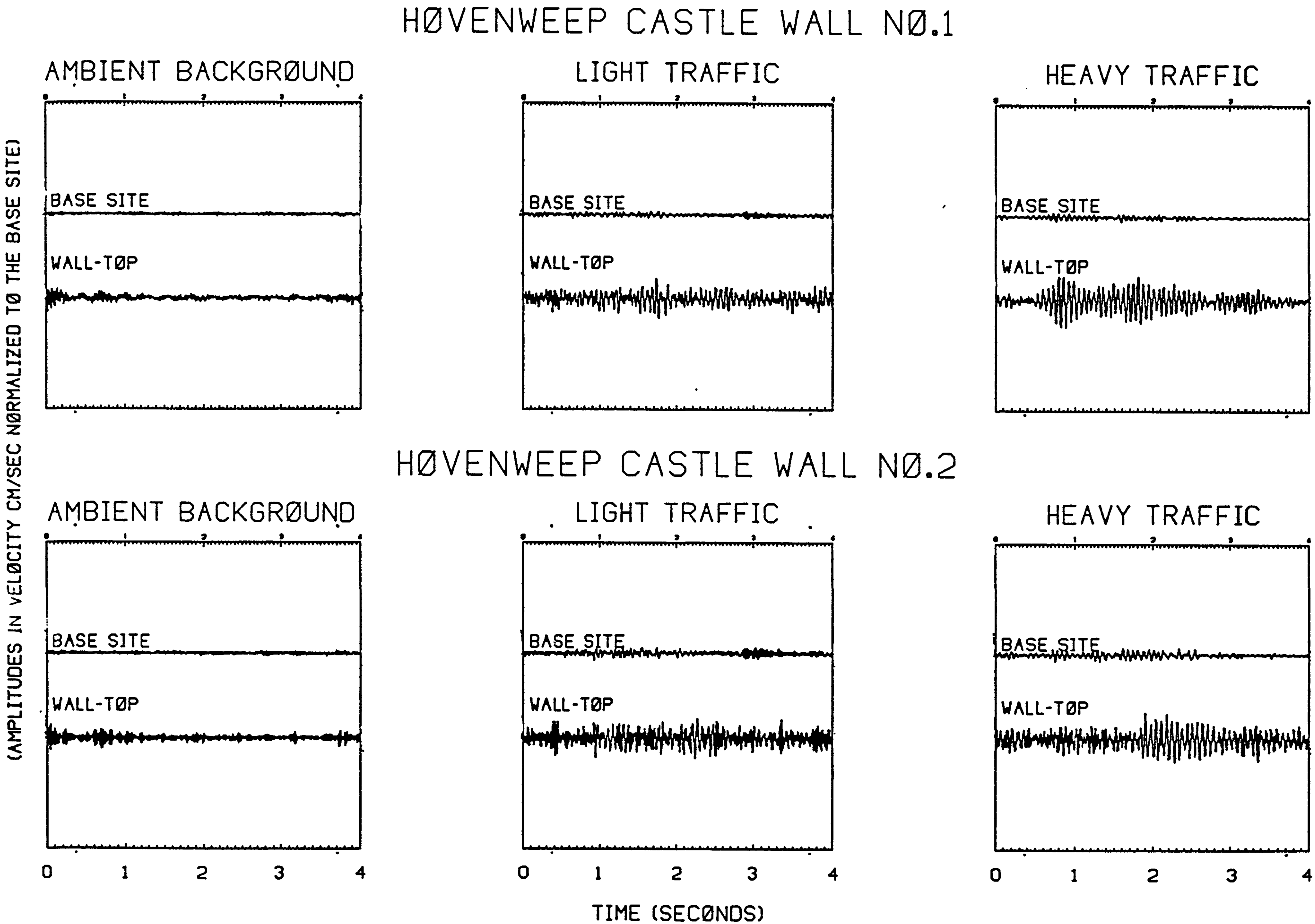

Figure 7. Time histories of horizontal motions measured perpendicular to the wall's long axis. Base site is on the ground 6 meters from the wall's base. 'LIGHT TRAFFIC' is a moving automobile at 50 meters from the wall and the base station; "HEAVY TRAFFIC' is a moving truck at 50 meters from the wall and the base station.

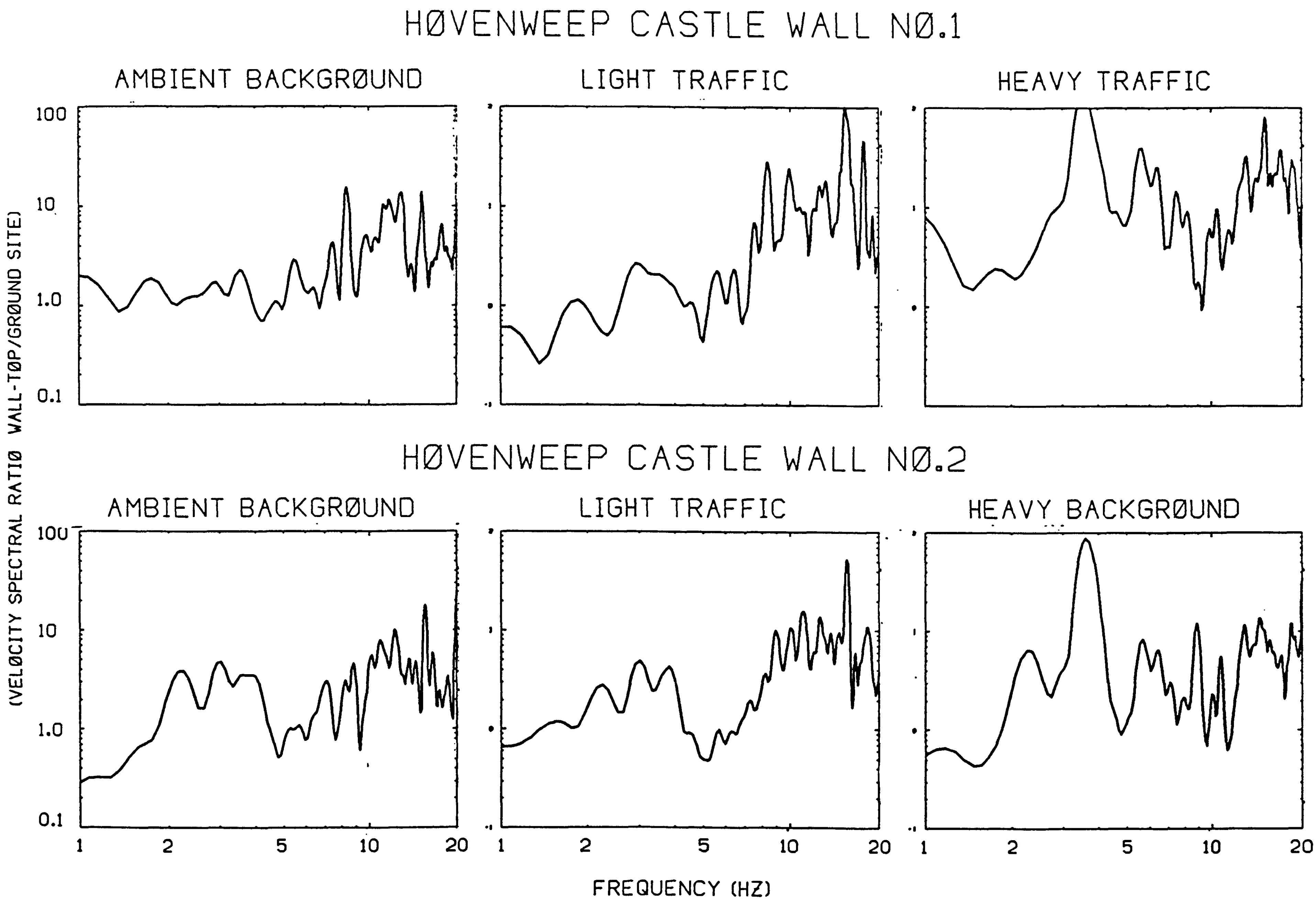

Figure 8. Spectral ratios of wall-top spectra/ground site spectra. "LIGHT TRAFFIC' is a moving automobile at 50 meters distance from the wall; 'HEAVY TRAFFIC' is a moving 3/4 ton drill truck at 50 meters distance from the wall.

TABLE 1

Structure	Location		Height (meters)	Natural frequency (Hz)	Damping percent
Bldg. 1, Site A	Hovenweep Castle,	NW	4.0	9.0	3.5
Site B		E	4.9	3.3	2.4
Bldg. 2, Site A	Hovenweep Castle	CIR	3.1	5.3	3.0
Bldg. 3, Site A	Hovenweep House	W	5.2	3.5	3.8
Site B		CIR	4.9	9.3	4.5
Bldg. 4, Site A	Holly Edge House	W	3.1	9.5	4.0
Site B		E	5.2	3.8	3.0
Bldg. 5, Site A	Hovenweep West	SW	3.4	5.0	5.4
Site B		SE	2.4	6.2	3.6
Site C		N-CIR	3.1	5.9	3.5
Bldg. 6, Site A	Square Tower	S	5.8	3.1	2.8
Site B		W	2.1	3.0	2.8

history analyzed and are not a simple comparison of the peak amplitude recorded. The peak amplitude values indicated the maximum amplitude of the wall at some instant of time, whereas, the spectrum indicates the maximum induced amplitude of the wall for each frequency of ground motion of interest.

ATTENUATION TESTS

Induced ground motions from two test explosions were recorded at various distances from the input sources to establish the general attenuation of the vibrations from the source explosion on the archeological ruins. The test explosions consisted of 225 kg and 450 kg of ammonium nitrate in 50-m-deep boreholes. The shot holes were drilled totally within the same sandstone formation that the foundations of the Hovenweep Castle walls are located. The induced ground motion from the test explosions were recorded by three-component velocity-sensing seismic systems with sensing elements oriented orthogonally on the ground surface. The systems were located at ranges of 110 m (sta. L10), 280 (sta. L20), 550 m (sta. L30) and 1,275 m (stas. L4B, L4T) from the source (fig. 1). The time histories are shown on figures 9 and 10. The peak particle amplitude comparisons show an obvious amplification of the induced seismic energy by the structure walls.

Induced ground motion from a D-8 Caterpiller bulldozer and from vehicular traffic were also recorded at various distances to study the vibration attenuation between the sources and the ruins. The bulldozer was pulling a one-tooth ripper in 0.5 m of sandstone. The induced vibrations were recorded by three-component seismic systems located at 50-, 70-, 100-, and 200-m ranges. Ground motions induced by traffic were recorded at 20-, 30-, and 50-m ranges. The traffic consisted of several automobile sedans.

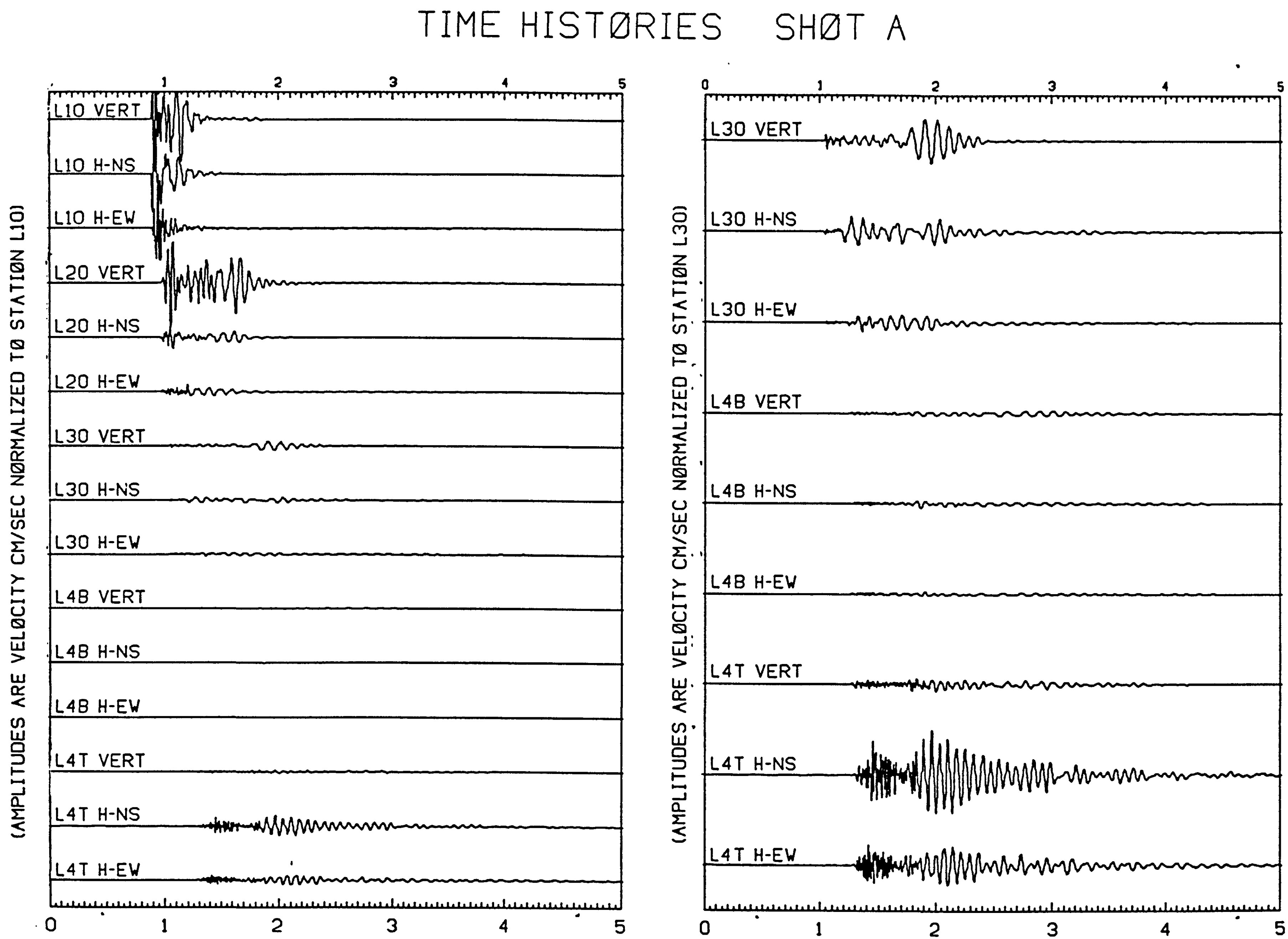

Figure 9. Time histories of Shot A, recorded at seismograph stations. Components are designated by VERT, H-NS and H-EW. Stations L-30, L-20 and L-4 are 110, 280, 550 and 1,275 meters respectively from the explosion.. The amplitudes of the left frame are normalized to station L-10 and the amplitudes of the right frame are normalized to station L-30.

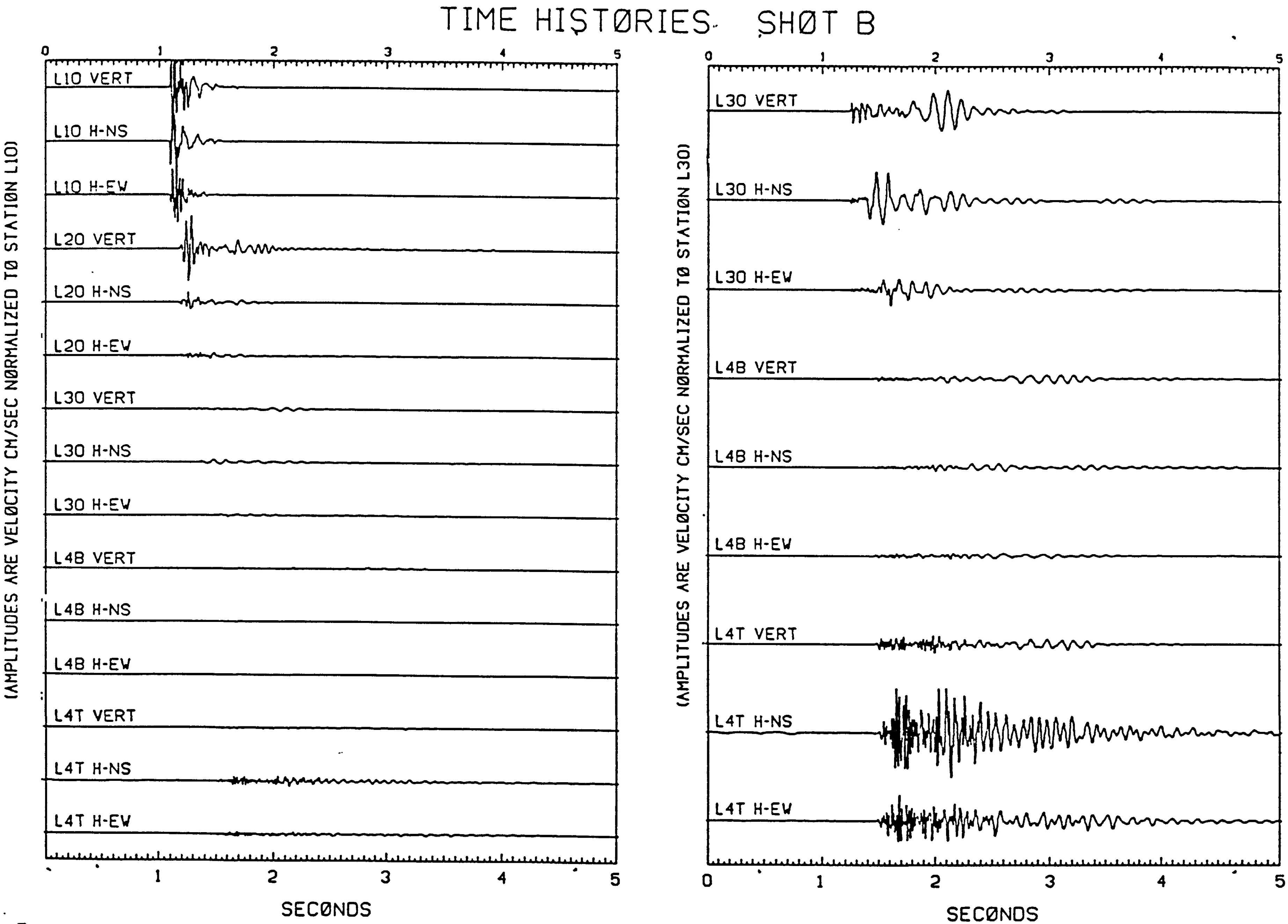

Figure 10. Time histories of shot B, recorded at stations L-10, L-20, L-30 and L-4, at distances of 110 m, 280 m, 550 m, and 1,275 meters respectively. Components are designated by VERT, H_NS, and H_EW. Amplitudes are normalized to station L-10 (left) and L-30 (right) At station L-4, B and T designate bottom and top of wall respectively

A least squares analysis of the attenuation of peak horizontal ground motion with distance from the test explosions shows an attenuation of the peak particle velocity proportional to R to the power of -1.75 where R is the distance from the recording station to the test explosion in meters. Peak particle velocities at constant distances are also proportional to W to the power of 0.25 where W is the charge size of the test explosive in kg. A similar analysis of the data recorded from the D-8 Caterpiller bulldozer gave an attenuation with distance proportional to R to the power of -2.78 and for traffic an attenuation with range (R) proportional to R to the power of -3.38 (fig. 11). The attenuation of the ground motion induced by the bulldozer is greater than the the motions induced by the explosions and less than the motions induced by the traffic because the frequencies of the induced motions from the bulldozer are, in general, higher than the frequencies induced by the explosions and lower than the frequencies induced by the traffic. Higher frequencies will dissipate the energy much faster and thereby attenuate at a faster rate than lower frequencies. Figure 11 shows the attenuation of the various sources in the Hovenweep Castle area.

Figures 12 and 13 show the transfer functions of the ground response to the wall response (bldg. 1, site B) for the test explosions. The transfer function analysis shows that the walls will amplify the ground motion frequencies at the natural frequencies of the walls by factors as high as 50 and attenuate those frequencies not in resonance with the walls' natural frequencies by factors as low as 9.

DISCUSSIONS

The basic assumption made here is that the National Park Service will not permit the Hovenweep National Monument ruins to be subjected to larger amplitude of induced ground motions than they do at the Chaco Canyon National Monument. The suggested maximum induced-vibration level for Chaco Canyon National Monument is 2.0 mm/sec (King and Algermissen, 1985). The 2.0-mm/sec peak-particle velocity ground motion is very conservative. We suspect that larger ground motions are possible from natural sources such as earthquakes and wind storms, but we do not believe this should affect the allowable industrial or culturally-induced maximum vibration level.

The 2.0-mm/sec peak-particle velocity level is not, in fact, measured at the source or at the ground level bút measured on the structure itself. Therefore, we believe that the upper limit of ground velocity induced at the base of the structures should be 0.1 mm/sec in the 1.0-10.0 Hz frequency band. This velocity is based upon the attenuation relationship derived from several sources of vibrations and allows for amplification of the ground motion by the structure without damage to the upper levels of the structure. While a velocity of 0.1 mm/sec at the base of the structures is extremely conservative, the value is appropriate for the unique, fragile structures at Hovenweep. It is possible to limit the peak ground velocities to 0.1 mm/sec in the vicinity of the structures because of the small area involved.

Normal automobile traffic should be kept a distance of 30 m from the base of the structures and heavy traffic and trenching equipment should be kept a distance of 65 m from the structures. Buried explosives of 225 kg should be at least 900 m from the archeological ruins. Buried explosives not greater than 450 kg should be at least 1,200 m from the ruins. Vibration equipment

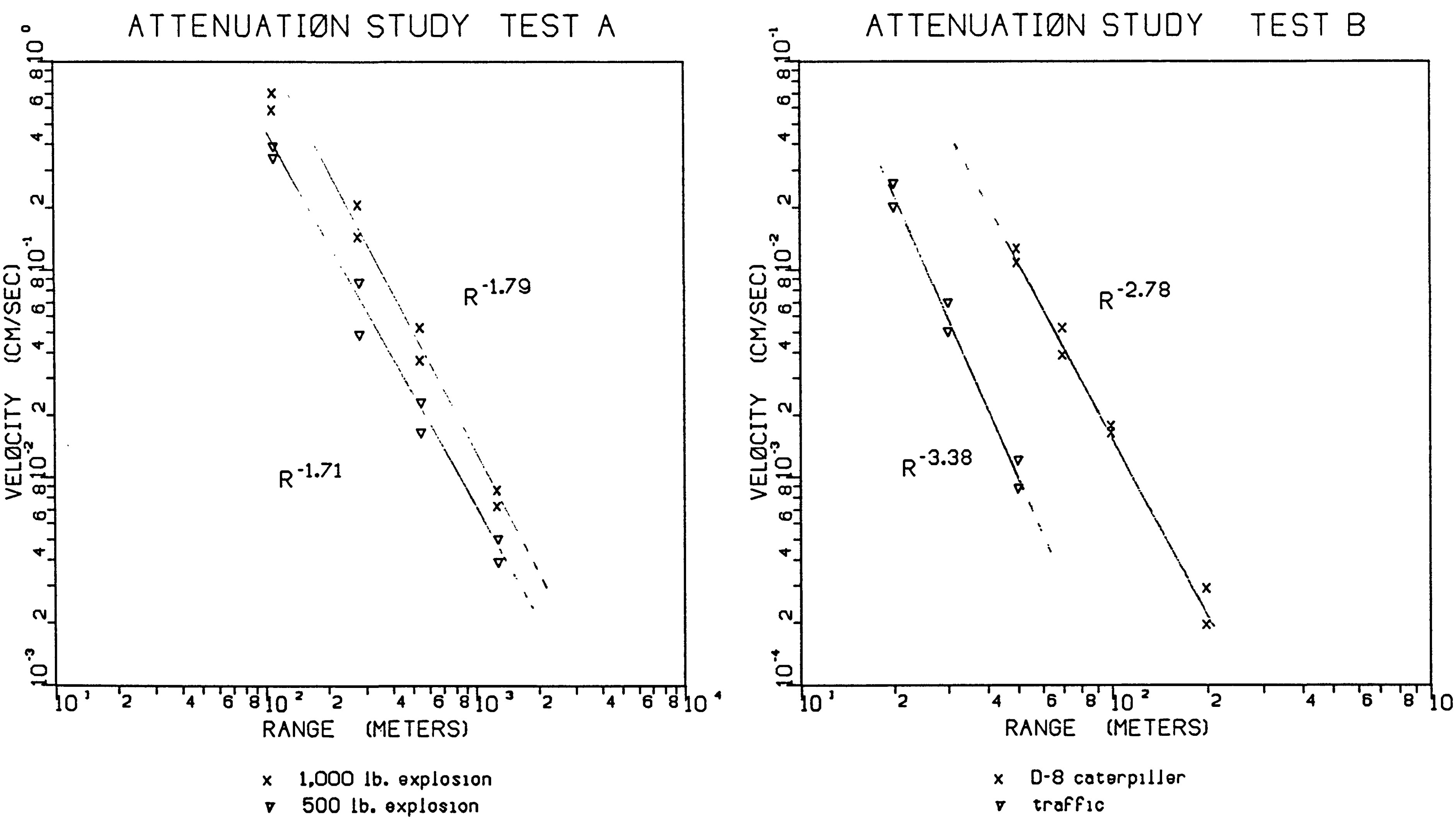

Figure 11. Horizontal peak velocity particle motion plots for explosion sources (test A) and traffic (test B). Slope of best-fitting straight line is range or distance exponent.

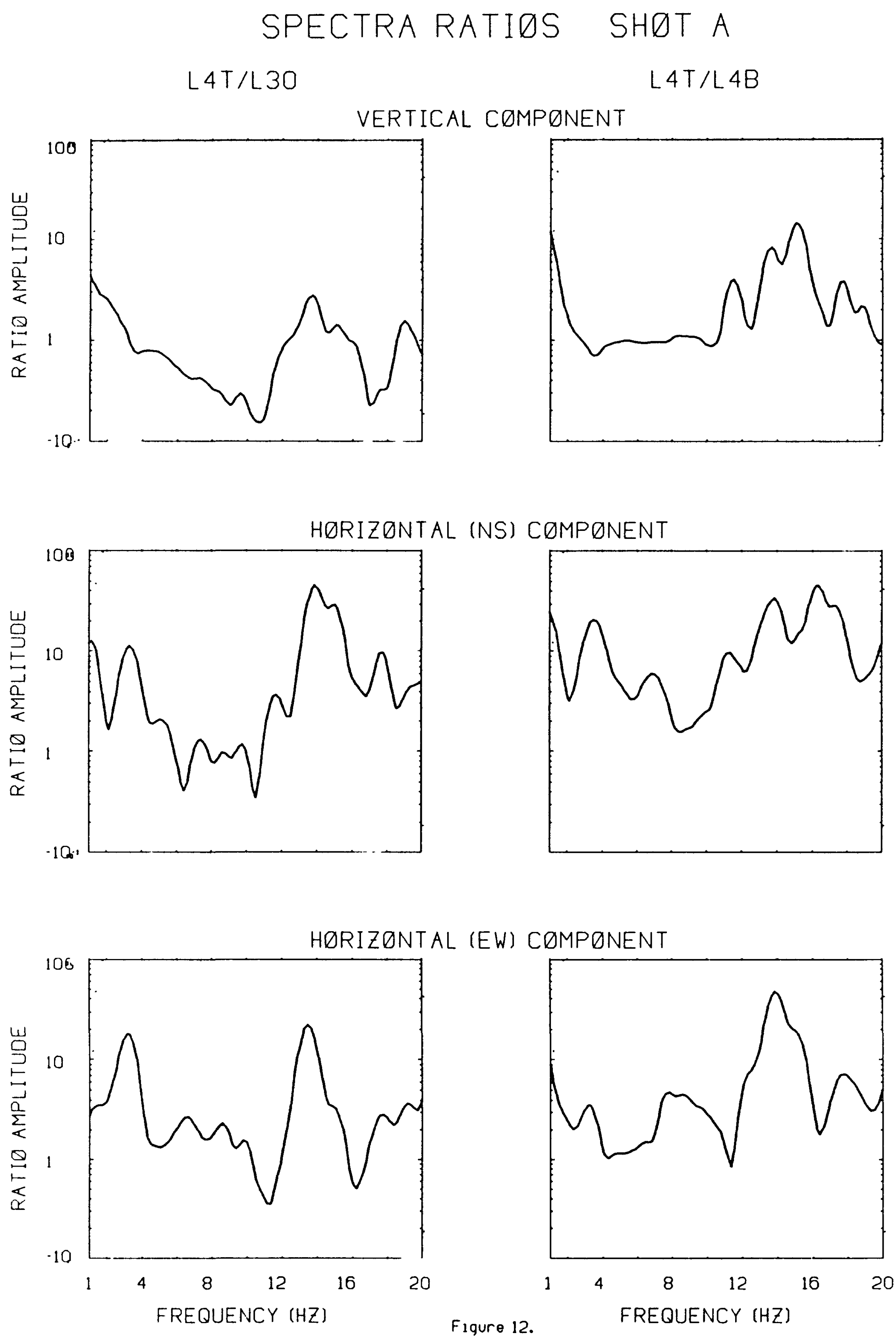

Figure 12.

Spectral ratios of wall-top spectra/ground site spectra and station 30 spectra. Induced motions are from shot A.

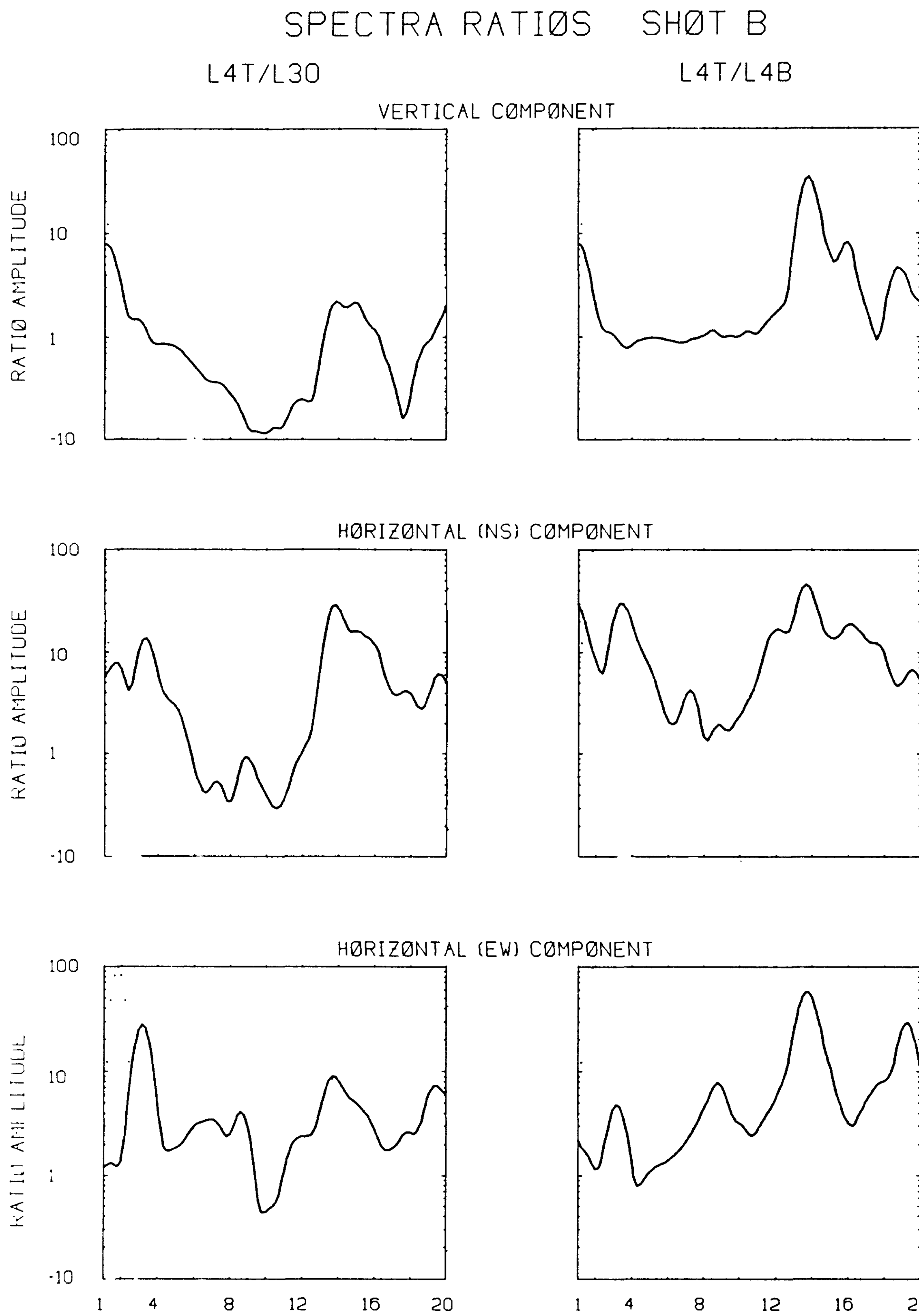

Figure 13.

Spectral ratios of wall-top spectra/ground site spectra and station 30 spectra. Induced motions are from shot B.

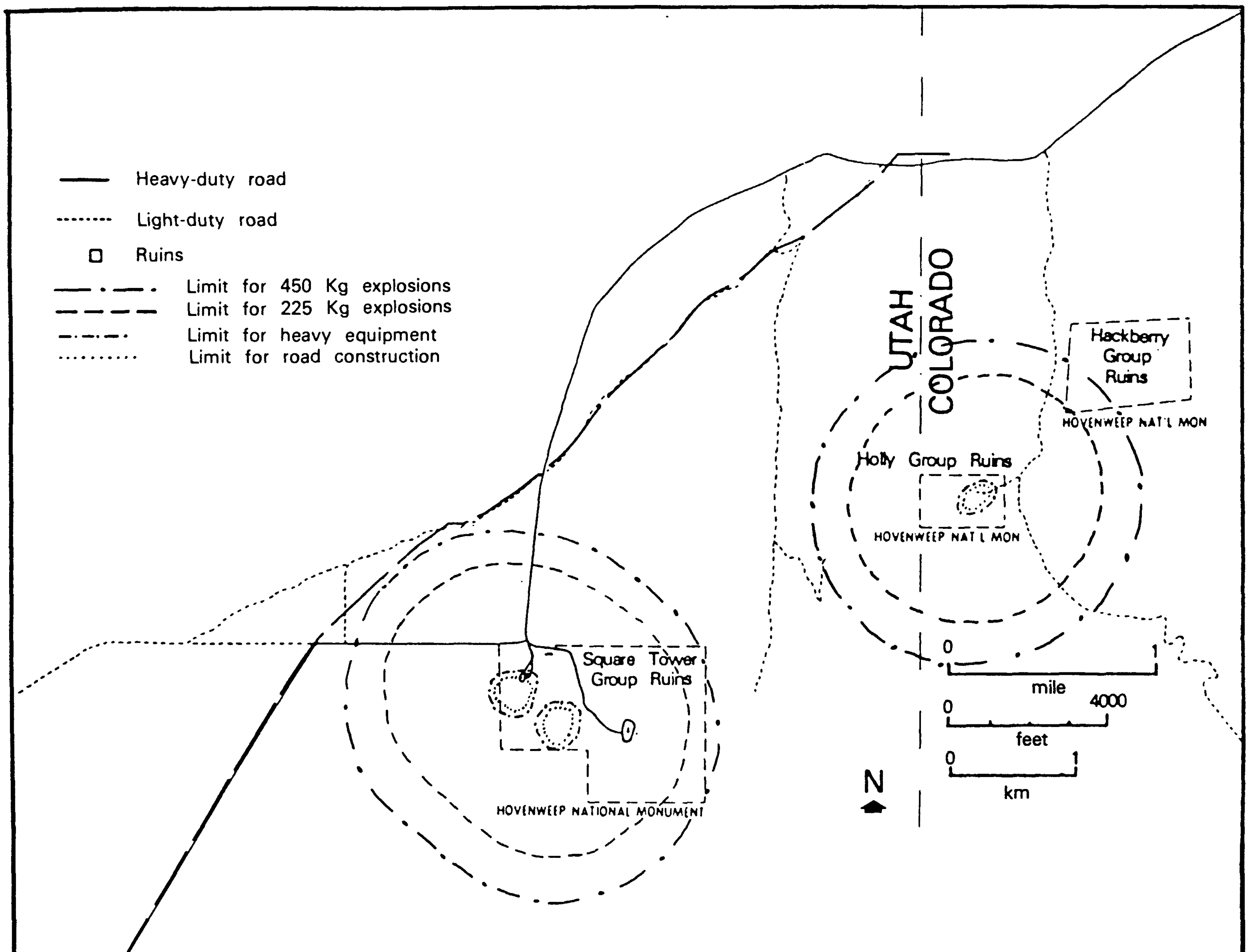

Figure 14. Proposed zonation of Hovenweep National Mounment showing zones within which various seismic sources should be excluded.

with an input of approximate 2,000 kg (as designated by the manufacturer's specifications) in the range of 1-10-Hz frequency should not operate closer than 100 m from the base of the ruins. A suggested zoning map using these criteria is shown on figure 14.

REFERENCES CITED

Housner, G.W., and Jennings, P.C., 1972, The San Fernando, California, earthquake: Earthquake Engineering and Structural Dynamics, v. 1, p. 5-31.

Hudson, D.E., 1964, A new method for measurement of natural periods of buildings: Seismological Society of America Bulletin, v. 54, no. 1, p. 233-243.

King, K.W., and Algermissen, S.T., 1985, Seismic and vibration hazard investigation of Chaco Culture National Historical Park: U.S. Geological Survey Open-File Report 85-529, 59 p.

Trifunac, M.C., 1975, A study on the duration of strong earthquake ground motion: Seismological Society of America Bulletin, v. 65, p. 581-626.