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Earthquake Hazards in the Pacific Northwest of the United States

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SITE RESPONSE STUDIES IN WEST AND SOUTH SEATTLE, WASHINGTON

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Foreword

This paper is one of a series dealing with earthquake hazards of the Pacific Northwest, primarily in western Oregon and western Washington. This research represents the efforts of U.S. Geological Survey, university, and industry scientists in response to the Survey initiatives under the National Earthquake Hazards Reduction Program. Subject to Director's approval, these papers will appear collectively as U.S. Geological Survey Professional Paper 1560, tentatively titled "Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest." The U.S. Geological Survey Open-File series will serve as a preprint for the Professional Paper chapters that the editors and authors believe require early release. A single Open-File will also be published that includes only the abstracts of those papers not included in the pre-release. The papers to be included in the Professional Paper are:

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Rogers, A.M., Walsh, T.J., Kockelman, W.J., and Priest, G.R., "Earthquake hazards in the Pacific Northwest: An overview

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Nelson, A.R., and Personius, S. F., "The potential for great earthquakes in Oregon and Washington: An overview of recent coastal geologic studies and their bearing on segmentation of Holocene ruptures, central Cascadia subduction zone"

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ABSTRACT

The characteristics of ground response were determined using recordings of three local earthquakes for six locations in West and South Seattle, Washington. The recording sites were chosen to sample areas of various intensities, including those that experienced the maximum intensities (Modified Mercalli (MM) VIII) during the 1965 Seattle earthquake.

We define ground-response function (GRF) as the ratio of Fourier spectral amplitudes from seismograms at a site under investigation to a standard site on rock. The highest GRF's (5-12) we calculated were at Harbor Island, which had a MM intensity of VIII from the 1965 earthquake. Harbor Island is underlain by manmade fill. Similar GRF values and 1965 earthquake intensities were observed at manmade fill sites in Olympia, Washington (King and others, 1990).

GRF's for sites in both West and South Seattle were much lower, from 2.1 to 4.4. No site in Olympia experienced a MM intensity of VII or greater in 1965 without a GRF of 5.7 or greater. We conclude that ground amplification probably did not cause the anomalously high intensities (MM VIII) in West Seattle during the 1965 earthquake. Almost all of the observations that led to West Seattle receiving a MM intensity VIII were based on damage to chimneys. We closely inspected 15 chimneys in the area of greatest damage. The mortar of 7 of 15 brick chimneys was extremely deteriorated. Perhaps the poor condition of the chimneys contributed to the damage during the 1965 earthquake and thus inflated the MM intensity for West Seattle. We conclude that the original MM intensity VIII at West Seattle may be better described as MM intensity VII, which includes damage to weak masonry.

INTRODUCTION

The urban centers of the Puget Sound area are at significant risk from the occurrence of large earthquakes. The largest recorded earthquakes in the Puget Sound area (fig. 1) occurred in 1946, 1949, and 1965 (Thorsen, 1986). The 1949 Olympia area earthquake caused Modified Mercalli (MM) intensities of VIII in both Seattle and Olympia. The epicenter of the 1965 earthquake was about 25 km south of Seattle (Algermissen and Harding, 1965). It caused widespread damage, although the maximum MM intensity of VIII was concentrated in the Harbor Island and West Seattle areas (von Hake and Cloud, 1967). Mullineaux and others (1967) suggested that Harbor Island and West Seattle may have also experienced higher intensities than surrounding areas during the 1949 earthquake.

The studies described in this report were designed to determine if near surface geophysical factors exist that may cause Harbor Island and West Seattle to experience greater ground shaking during earthquakes. Six study sites were chosen in the area of interest (fig. 2). We recorded ground motion at these sites from three small earthquakes. These records were used to compute ground-response functions (GRF) for the six sites. GRF is the amplification of ground motion at a recording site (usually underlain by unconsolidated sediments) relative to ground motion recorded at a standard site (usually on rock). This method has been applied in several areas, including Los Angeles and San Francisco, California, and Olympia, Washington (Borcherdt and Gibbs, 1976; Rogers and others, 1979, 1985; and King and others, 1990). Seismic-refraction lines were also recorded at each of the six sites. The refraction lines provide information on the compressional-wave seismic velocity structure of the site from 0 m to 90 m deep. Finally, to answer the question of whether the houses and chimneys in West Seattle were more susceptible to earthquake shaking, we determined the natural frequencies and damping coefficient of 10 one-story residences in West Seattle.

DATA COLLECTION AND PROCESSING

From November 1987 to December 1988, we operated six portable digital seismographs in West and South Seattle to record site specific ground response (fig. 2). The recording sites were primarily chosen because they were at or near a documented 1965 intensity observation. We also wanted the sites to represent different surficial geologic units and to have a broad spatial distribution across West and South Seattle areas. Another consideration in recording site selection was to find sites that had sufficient space to allow drilling and seismic-reflection and refraction lines.

All study sites except the standard site (SEW) were located at or near locations where MM intensities V, VI, and VIII effects were reported from the 1965 earthquake. An intensity was not reported from the SEW site because no inhabited structures existed in the area; however, the surrounding area within two blocks of the site had intensity reports of IV or less. It is assumed that the probable intensity at the SEW site, which is located on rock, would have been IV or less (von Hake and Cloud, 1967), sites HAR and HIA were assigned a MM intensity of VIII; at site HIG, MM intensity values of VI were reported, and sites JEF and LIN experienced intensity V (fig. 2).

Three earthquakes were recorded by our seismographs during the deployment, and they were also recorded and located by the University of Washington permanent seismograph network (University of Washington computer hypocenter data file, unpub. data). Two M_L 2.8 earthquakes were located in the Puget Sound area and a third M_L 4.1 earthquake was recorded near Yakima, Wash. (fig. 1, table 1).

The portable digital seismographs used triaxial velocity sensitive transducers with a natural frequency of 1.7 Hz and a damping coefficient of 0.6 of critical. The seismometers were leveled, oriented, and calibrated at each site using standardized procedures (Carver and others, 1986). The seismographs used an internal trigger algorithm which discriminates between ground shaking induced by earthquakes and local disturbances such as traffic. Data were recorded digitally on cassette tapes that were played back into a computer for analysis using spectral analysis software (Cranswick and others, 1989).

The earthquake records were first displayed as amplitude-normalized seismograms to allow inspection and selection of a standardized portion of the time series for analysis. This standardized window was the same for all of the records; therefore, it was unnecessary to normalize spectral amplitudes for window length. A 20-second time window was chosen beginning with the P-wave arrival and including most of the coda. The data time window was tapered with a whole-cosine bell (Hanning window) before being transformed by a standardized Fast Fourier Transform (FFT) computer program. Spectral amplitudes and ratios were smoothed using a moving-average window with a Hanning taper and with a width of 0.15 Hz. The earthquake smoothed spectra were then compared with the preevent smoothed spectra to determine the signal-to-noise ratio. All of the data used in this report had a signal-to-preevent noise ratio of at least 1.5. The GRF was calculated using smoothed spectra by the following equations:

$$GRF_{ia} = 0.5(R_{i,2,a} + R_{i,3,a})$$

$$R_{i,j,a} = (S_{i,j,a})/(S_{o,j,a})$$

where:

i	=	recording site on unconsolidated sediments
o	=	standard recording site
j	=	horizontal component; 2 = North-South, 3 = East-West
R	=	spectral ratio
S	=	smoothed Fourier amplitude spectrum
a	=	frequency band (.5-1 Hz; 1-2 Hz; 2-4 Hz; 4-8 Hz).

The standard recording site used for these calculations was SEW (fig. 2). The seismometer at SEW was placed directly on Tertiary fine-grained sandstone.

Figures 3, 4, and 5 show the process of deriving the GRF. Figure 3 shows typical seismograms with amplitudes normalized so that all components are displayed at the same scale. Figure 4 shows smoothed Fourier amplitude spectra on the left and on the right the GRF or spectral ratio between the sites on unconsolidated sediments and the standard rock site, SEW. Figure 5 and Table 2 summarize the GRF's at each site, the surficial geology and seismic velocity structure at the site, and the MM intensity observed from the 1965 earthquake.

Earthquakes A and C were recorded at LIN and the standard site at SEW. Figure 6 shows the derived spectral ratio for both of these earthquakes plotted together. The similarity of the two plots indicates a high degree of repeatability of GRF values for different shaking sources.

Building Studies

Immediately following the 1965 earthquake, Algermissen and Harding (1965) conducted a block-by-block survey of West Seattle in which they calculated the ratio of damaged to undamaged chimneys during the earthquake. One possible explanation for the large number of damaged chimneys is that they were tuned to the same frequency as the earthquake shaking of the site. We selected 10 houses within two blocks of HIA in the area of maximum chimney damage and installed seismometers on chimneys, roof tops, and at the midpoint of the bearing walls. Several minutes of ambient seismic background noise and several man-induced vibration events were recorded. The natural frequency (first mode) was determined by calculating an FFT on the time series data (examples are shown in fig. 7). The damping ratio was obtained by using:

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

where D is the percent of critical damping and X_n is the velocity amplitude of the nth cycle of motion (Dowding, 1980). The results of these tests are shown in table 3.

Site Investigations Using Seismic Refraction

High-resolution P-wave seismic-refraction profiles were acquired at the six sites to characterize the near-surface velocity structure of the sites. A 12-gauge shotgun or gasoline-powered earth tamper (Wacker) was the seismic source and the signal was recorded by a 24-channel digital seismograph with 100-Hz geophones spaced 1.5 to 3.05 m apart. The slope-intercept method of analysis was used to interpret the recordings. The results of the interpretation provide information on the compressional-wave seismic-velocity structure of a site at the depth range of 0 to 10 m for the shorter profiles and up to 90-m depth for longer profiles. Because surface-wave velocity is only a few percent slower than shear wave velocity (Aki and Richards, 1980), we used the surface waves generated by the 12-gauge and Wacker sources at some of the sites to estimate the near-surface S-wave velocity. The surface wave was identified on the vertical component refraction records as a high-amplitude dispersed wavetrain on each record. Then we determined the surface wave velocity from the slope of the highest velocity (first arrival group) surface wave on a time distance seismogram. For the S-wave velocity calculations, we assumed that the surface wave velocity was 10 percent slower than the S-wave velocity. We also assumed that this surface wave velocity applies to a depth of about one wavelength of the surface wave (Sheriff and Geldart, 1982). Because we only have vertical component refraction data, it's possible that we could be measuring the S-wave direct arrival and not the highest velocity surface wave. Therefore, we could be overestimating the S-wave velocity by about 10 percent; however, the relative differences in S-wave velocity between the sites would remain the same. Results of the refraction profiles are summarized in table 2.

The standard site for this study (SEW), in Seward Park on Bailey Peninsula, was underlain by a fine-grained sandstone with a compressional-wave velocity of approximately 2,600 m/s to at least 15-m depth. This is the highest P-wave velocity observed at any of the recording sites.

Site HAR was located on fill material in the Duwamish River waterway with a uniform 1,371 m/s P-wave seismic velocity to a minimum depth of 90 m. The surface-wave data translates to a very slow 150 m/s S-wave velocity in the upper 6 m of fill at HAR.

Sites JEF and LIN were located on Vashon till, which in this area is a graded mixture of clay to gravel. The seismic-velocity data indicate that these two sites are located on relatively firm ground with P-wave seismic velocities increasing from 1,470 m/s at about 2-m depth up to 2,220 m/s at 30-55-m depth. The S-wave velocity at LIN was about 300 m/s at 5-m depth and at JEF it was about 740 m/s at about 15-m depth. Site HIG was located on a well-sorted and poorly graded gravel that has a P-wave seismic velocity structure similar to LIN. Site HIA was located on older uncemented sand of Quaternary age with a P-wave seismic-velocity structure also similar to LIN.

DISCUSSION AND CONCLUSIONS

The low velocities at HAR confirmed that the fill material is unconsolidated, saturated, and probably forms a high impedance contrast at the base of the fill which would influence seismic-wave amplification. Not surprisingly, site HAR had a GRF value 5-12 times greater than at the standard rock site, SEW. This result is in accordance with the MM intensity VIII damage experienced at Harbor Island from the 1965 earthquake. Similar sites in Olympia (King and others, 1990), underlain by artificial fill and unconsolidated saturated sediments, also have very low seismic velocities, high GRF values, and experienced MM intensity VIII damage from the 1965 earthquake.

There has been considerable interest in explaining why West Seattle experienced MM intensity VIII shaking in the 1965 earthquake. Some investigators (Langston and Lee, 1983; Inhen and Hadley, 1986) have used velocity models and ray tracing to create synthetic accelerograms for the Puget Sound region. They conclude that the shaking was enhanced in both West Seattle and Harbor Island by basin-geometry wave focusing as well as by near-surface ground response.

We located HIA in West Seattle in the center of the MM intensity VIII damage from the 1965 earthquake. The GRF's recorded at HIA are not significantly higher than those at the other West and South Seattle sites that experienced MM intensity V and VI shaking. Compared to HAR, all of the other sites had relatively low GRF values, and their P-wave seismic velocity structures were also similar. Furthermore, no sites in Olympia experienced MM intensity VII or greater without having a GRF of at least 5.7 (King and others, 1990). Thus, the near-surface geophysical data we have collected indicates that ground response was probably not a factor in producing higher intensities near HIA in West Seattle compared with those in the surrounding neighborhoods.

The natural frequencies of the residential structures in West Seattle show that the frequencies at which the buildings and chimneys are most sensitive to damage range from 5 to 15 Hz (table 3). The frequency range of the building resonance only marginally overlaps with our earthquake data frequency band. However, the GRF for site HIA suggests that the houses are subjected to ground motion amplifications of about 2.5 near their resonance frequencies (table 2). Again, our data from Olympia indicates that this GRF would not be high enough to explain the MM intensity VIII reported for this neighborhood.

A possible explanation for the high MM intensity became apparent as we talked with home owners during the building vibration phase of our fieldwork. We asked people who experienced the 1965 earthquake what other effects they had observed. None of them, even those whose houses had chimney damage, said that they had experienced any other damage. One man we talked to, who had been a building contractor in the area, stated that a poor grade of mortar containing salty sand had originally been used in many of the chimneys of West Seattle. Of 15 houses on which we tried to measure chimney vibration, 5 were in such poor condition that we deemed it unsafe to place a small single component seismometer on the top. Of the 10 houses we did test, one-half of the chimneys had significant deterioration of the mortar. Two of the 10 chimneys we tested exhibited loose bricks when we placed the seismometer. We believe that the original intensity rating could have been biased because many chimneys were in very poor condition. The MM intensity VII (Richter, 1958) includes "...damage to masonry D (weak materials, poor mortar) including cracks. Weak chimneys broken off at roof line". The true intensity of shaking at West Seattle might be better characterized by a MM intensity VII.

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FIGURE CAPTIONS

Figure 1.Map showing the locations A, B, and C of the earthquakes used as seismic shaking sources for computation of ground response functions. Locations were calculated by the University of Washington using their permanent seismograph network and are listed in table 2. Stars indicate the locations of the 1946, 1949, and 1965 earthquakes.

Figure 2.Surficial geologic map of the west and south Seattle area, adapted from Waldron and others, 1962. Location and name of ground response recording sites is shown by the bullet and three-letter code. Roman numerals indicate the Modified Mercalli intensity observed at the recording sites during the 1965 earthquake.

Figure 3.Representative seismograms recorded at the west and south Seattle recording sites for earthquakes B and C (locations are given in table 1). Three components of motion are shown for each recording site, vert is vertical, N-S is North-South, and E-W is East-West.

Figure 4.Representative example of velocity spectra for two station pairs which recorded earthquake B. The spectral ratios are the result of computing this ratio of the spectra of an site on unconsolidated sediments (HAR or HIA) to the standard site at SEW on rock.

Figure 5.Ground-response functions (GRF's) calculated, using earthquakes A, B, and C, from seismograms recorded at stations JEF, HIA, LIN, and HIG (all on unconsolidated sediments) relative to the standard station located on rock at SEW. Station LIN recorded 2 earthquakes so we have shown 2 sets of GRF's.

Figure 6.Velocity spectral ratios of two earthquakes recorded at station LIN relative to the standard site to SEW. This shows the reproducibility of the spectral ratio from different shaking sources.

Figure 7.Seismograms (time histories) and velocity spectra which were used to derive natural frequencies and damping coefficient of representative houses in west Seattle. Results of this testing is shown in table 3.

Table 1 EARTHQUAKE SOURCE LOCATION

EARTHQUAKE CODE	LATITUDE NORTH	LONGITUDE WEST	DEPTH KM	MAG. M_L	GENERAL LOCATION
A	47°49.04′	−122°21.76′	50	2.8	Edmonds, Wa.
B	46°40.49′	−122°41.03′	18	4.1	Yakima, Wa.
C	47°32.94′	−122°44.59′	19	2.8	Bremerton, Wa.

Earthquake and event code locations are shown on figure 1.
Locations from the University of Washington computer hypocenter data file.

Table 2 GROUND RESPONSE FUNCTION COMPARISONS

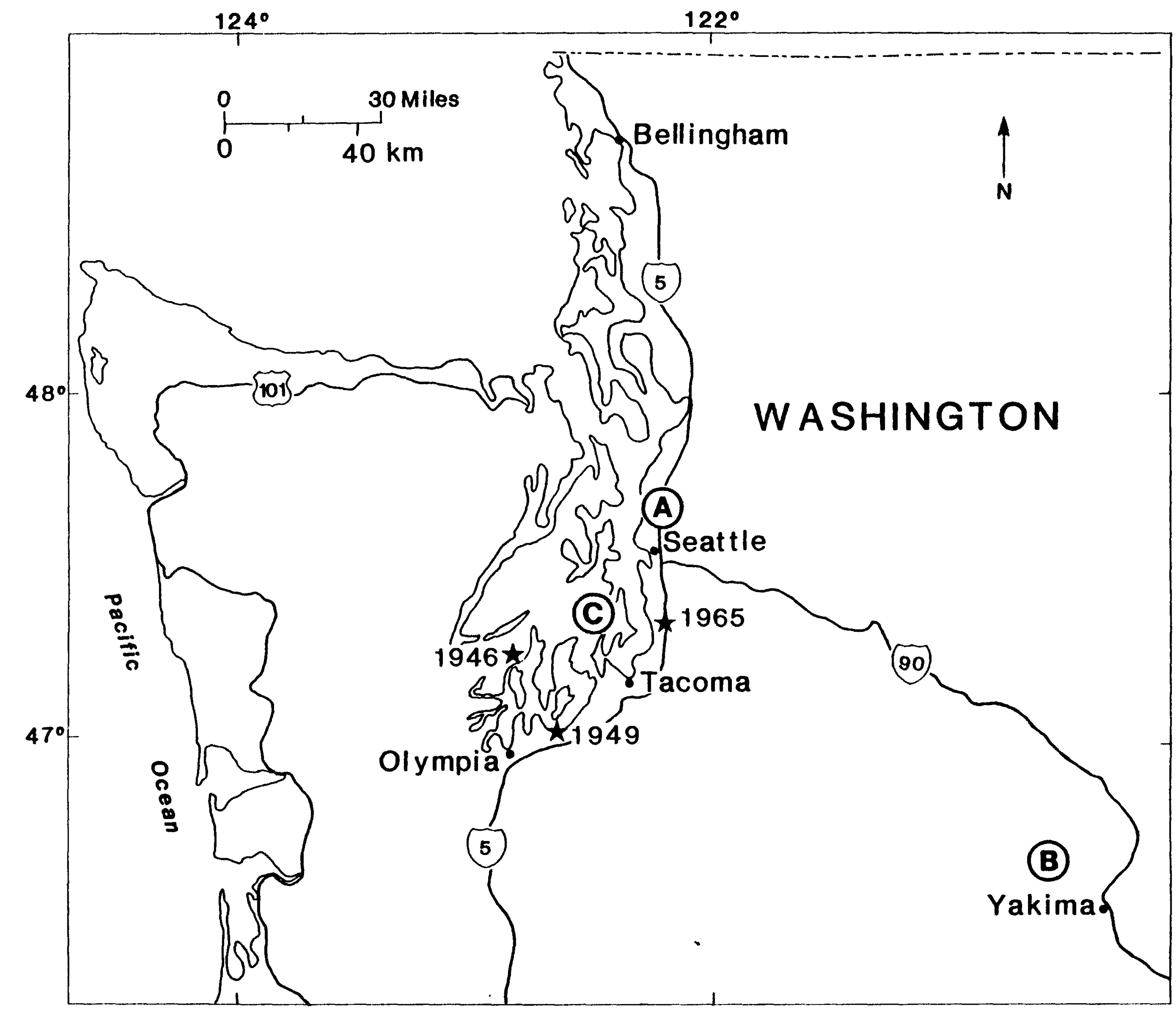
Station	Event	Average Horizontal Ground Response Function Hz. 0.5–1	1–2	2–4	4–8	Geology[1]	Intensity[2]	Average P–Wave velocity m/s	Depth Interval m
SEW	ABC	1	1	1	1	Tb	IV	2600	1–15
JEF	A	3.7	3.5	2.8	2.3	Qt	V	2200	1–55
HIG	C	3.3	2.9	2.1	2.2	Qt	VI	1470	1–10
LIN	A	3.8	3.2	2.3	2.3	Qt	V	1460	1–14
LIN	C	3.5	3.0	3.2	2.4	Qt	V	1460	1–14
HIA	B	4.4	3.9	4.0	2.5	Qos	VIII	1520	1–10
HAR	B	11.7	8.8	4.9	4.8	af	VIII	1370	1–90

Tb = Tertiary sedimentary rocks, sandstone. Qt = Vashon till, compact silt, sand, gravel. Qos = Vashon outwash, older sand, medium sand loose. af = artificial fill. (1) Waldron and others, 1962. (2) Hopper, personal communications.

Table 3 BUILDING TESTING
(Height – 1 story)

Building	Natural freq. long axis Hz.	Natural freq. short axis Hz.	Damping %critical	Natural chimney Hz.
01	7.2	11.4	3.5	7.0
02	8.2	8.6	1.4	6.2
03	5.5	5.4	3.0	8.6
04	6.8	7.0	2.5	10.0
05	8.6	11.1	1.8	13.7
06	10.2	13.6	2.2	12.5
07	7.0	14.0	2.5	7.8–11.7
08	9.8	10.6	3.8	9.4
09	10.5	14.8	2.4	9.0–10.2
010	5.3	11.7	2.9	6.1–9.8

All buildings are located within 2 blocks of site "HIA" shown on figure 2.



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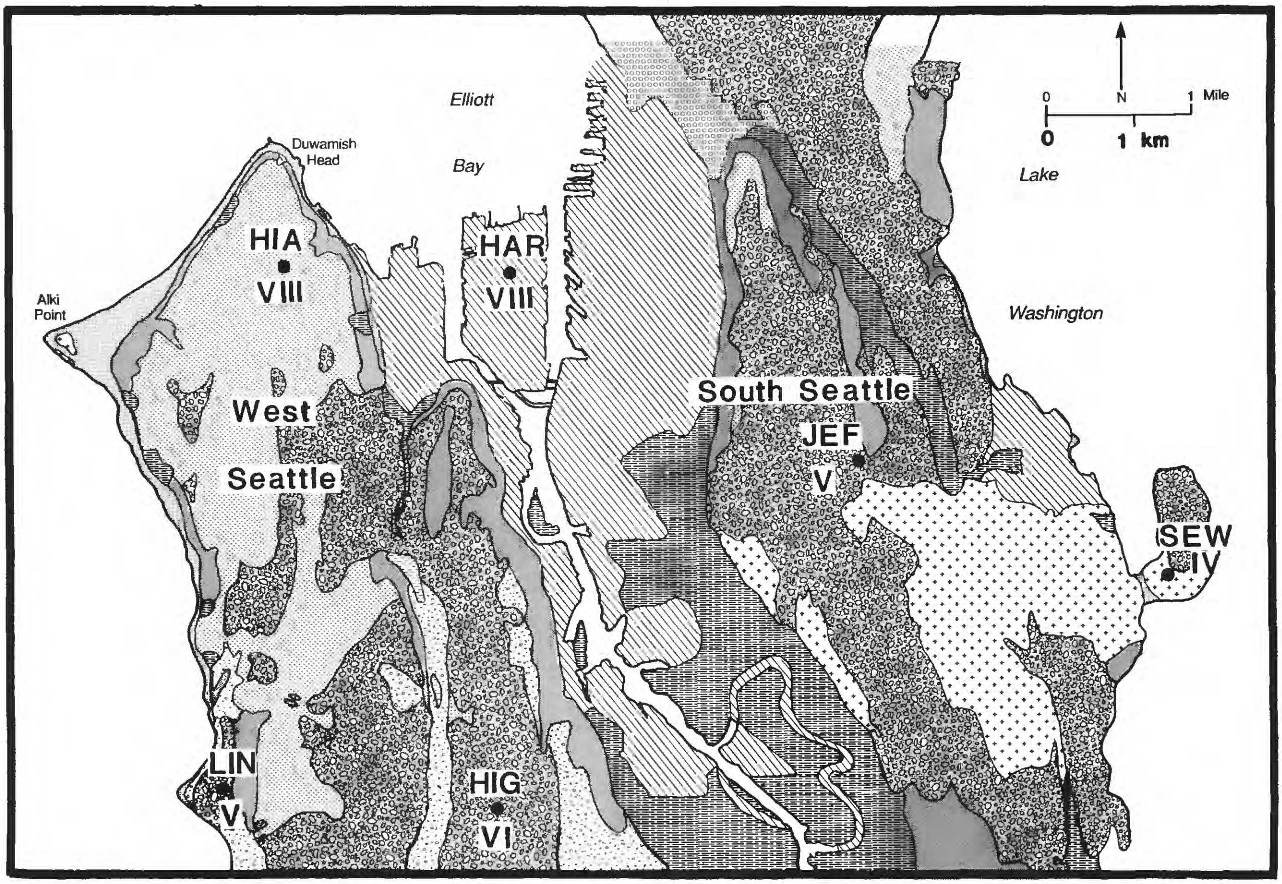


EXPLANATION

f m

Artificial fill, f and modified land, m
Modified land:areas leveled by cut and fill & fill frequency

Qa

Alluvium
Chiefly sand and silt but includes clay and peat. South of Renton and Tukwila these sediments are 15 to 25 feet thick and overlie sand and gravel. Mostly sand and gravel in Cedar River valley

Qb

Beach deposits
Chiefly sand; may include interbedded organic material. Deposits in places are veneers of sand and gravel less than 2 feet thick on older deposits

Qsc

Lacustrine sediments
Chiefly unconsolidated silt, clay, and fine sand generally less than 10 feet thick

Qys

Younger gravel
Chiefly sand and pebble gravel. Commonly overlies Qt. As much as 100 feet thick

Qt

Vashon till
Compact, concrete-like mixture of silt, sand, gravel and clay. As much as 150 feet thick, but generally less than 50 feet. Upper 2 to 5 feet generally a loose, silty sand and gravel

Qog

Older gravel
Chiefly sand and pebble gravel. Lies beneath Qt. As much as 200 feet thick

Qos

Older sand
Chielfly medium sand; loose. As much as 300 feet thick

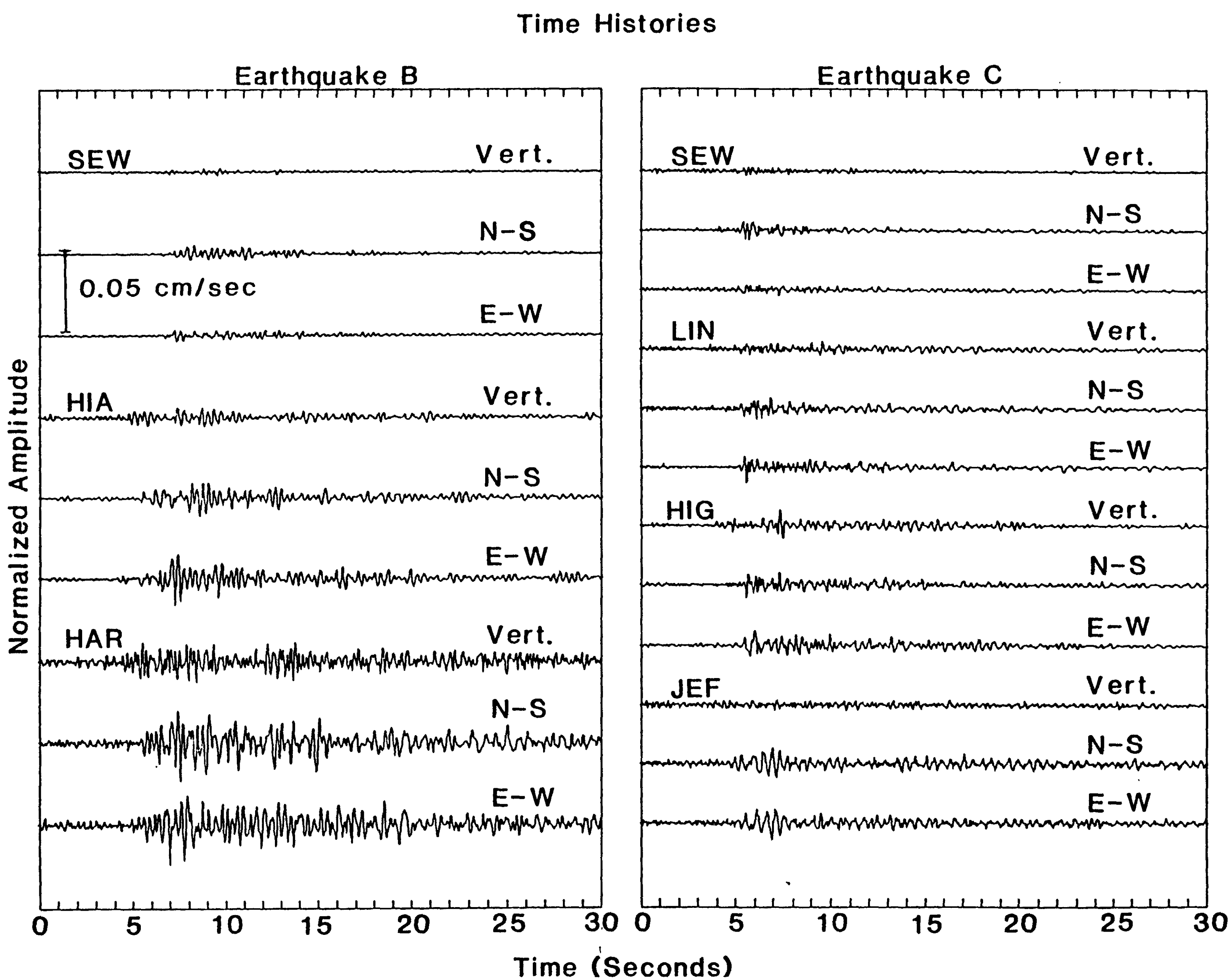
Qc

Older clay, till, and gravel
Silt, clay, fine sand, and till, very compact; locally includes lenticular sand and gravel shown as Ocg where mappable

Tb

Sedimentary rocks of Oligocene age
Chiefly tuffaceous sandstone and conglomerate; compact but poorly cemented. At least 2500 feet thick

Figure 2. Surficial geologic map of the west and south Seattle area, adapted from Waldron and others, 1962. Location and name of ground response recording sites is shown by the bullet and three–letter code. Roman numerals indicate the Modified Mercalli intensity observed at the recording sites during the 1965 earthquake.



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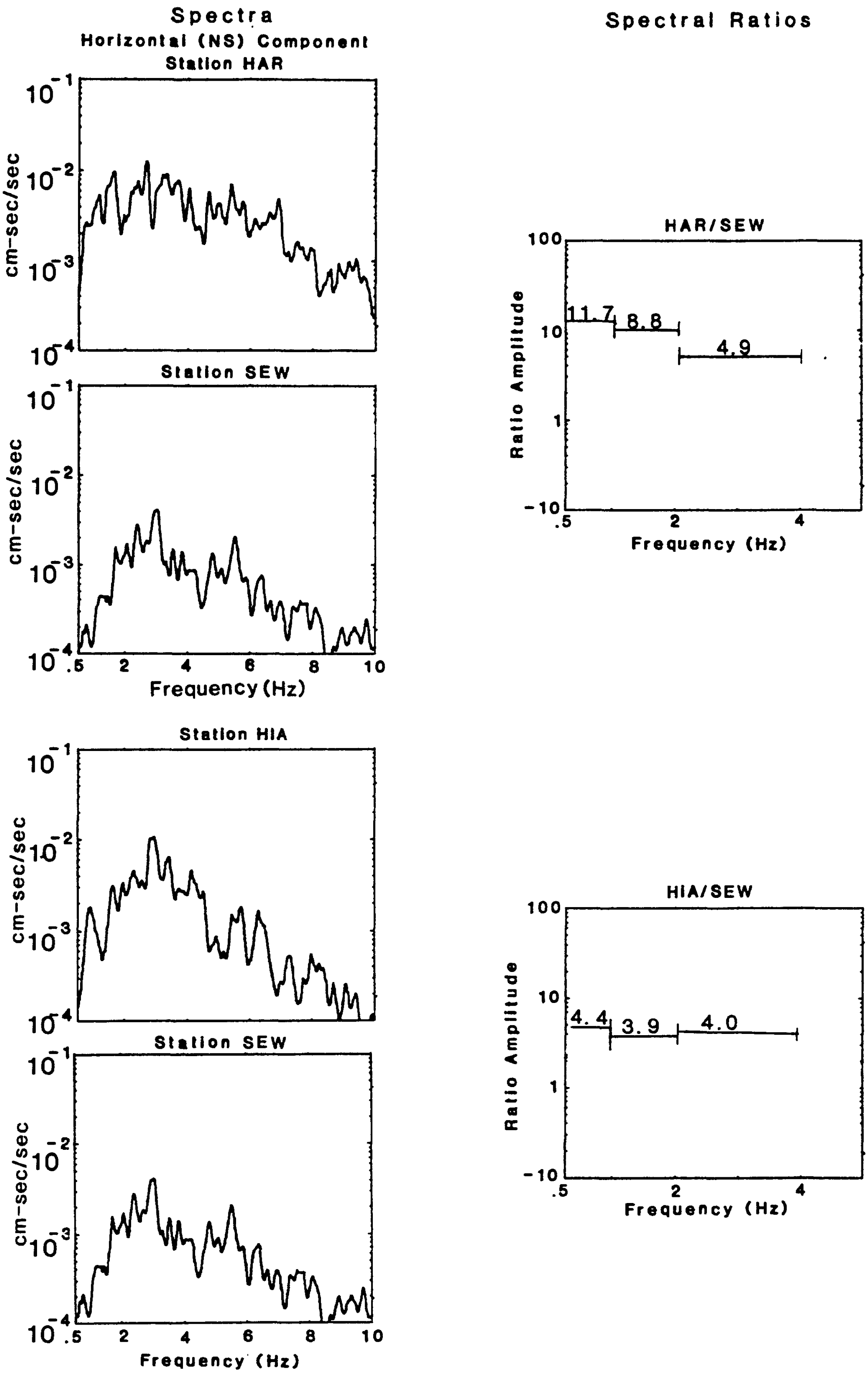

Figure 4. Representative example of velocity spectra for two station pairs which recorded earthquake B. The spectral ratios are the result of computing this ratio of the spectra of an site on unconsolidated sediments (HAR or HIA) to the standard site at SEW on rock.

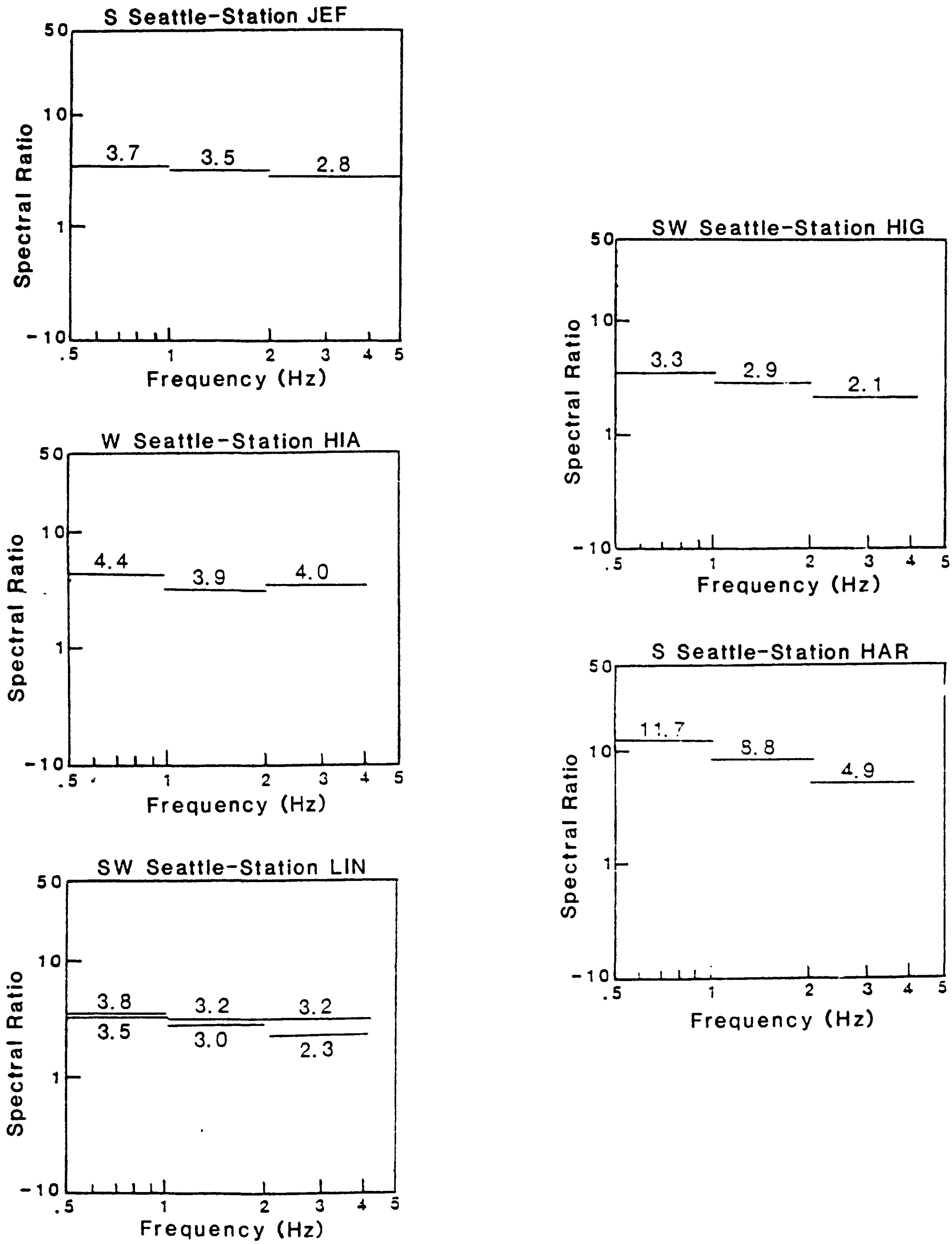

Figure 5. Ground–response functions (GRF's) calculated, using earthquakes A, B, and C, from seismograms recorded at stations JEF, HIA, LIN, and HIG (all on unconsolidated sediments) relative to the standard station located on rock at SEW. Station LIN recorded 2 earthquakes so we have shown 2 sets of GRF's.

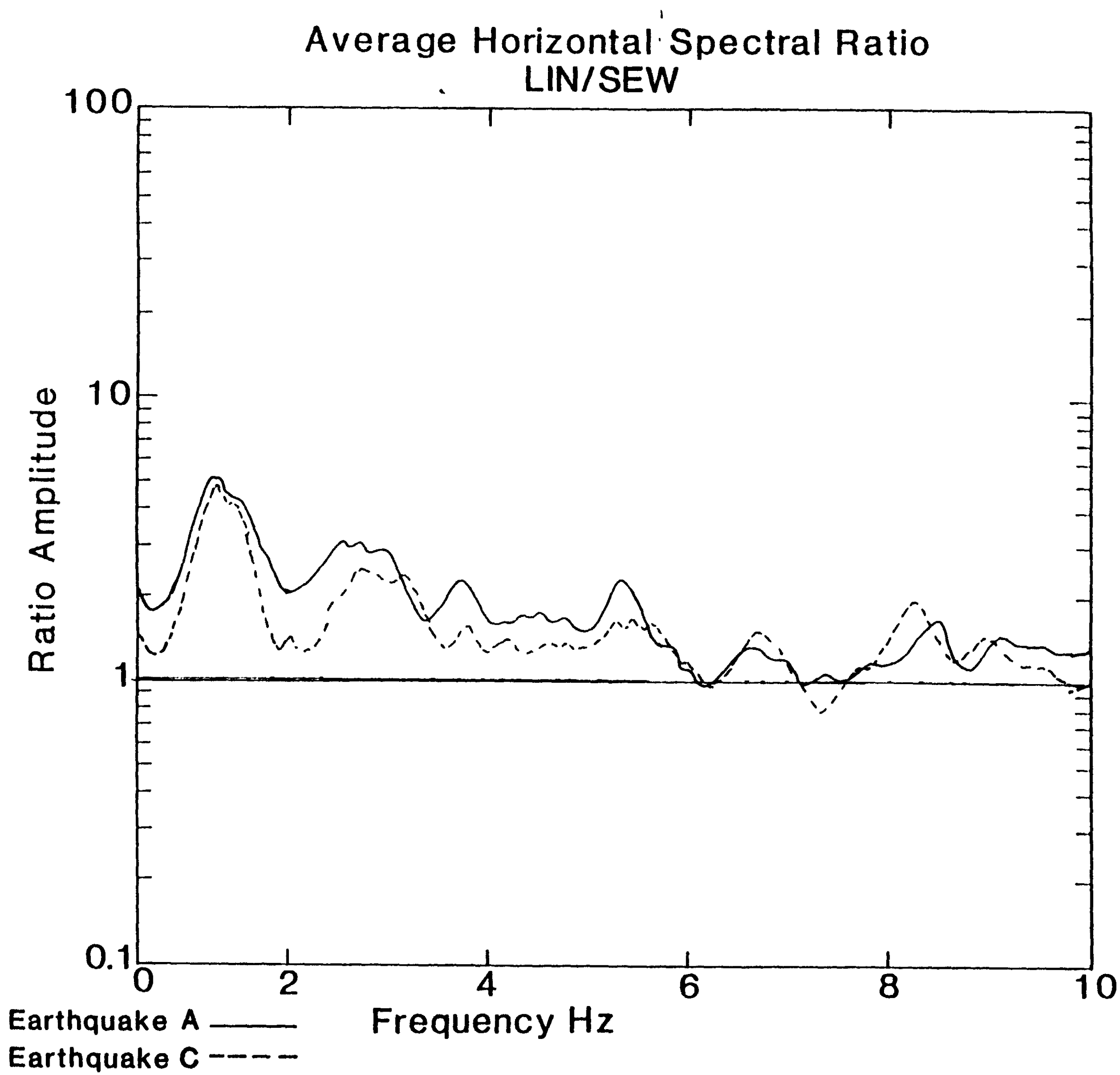

Figure 6. Velocity spectral ratios of two earthquakes recorded at station LIN relative to the standard site to SEW. This shows the reproducibility of the spectral ratio from different shaking sources.

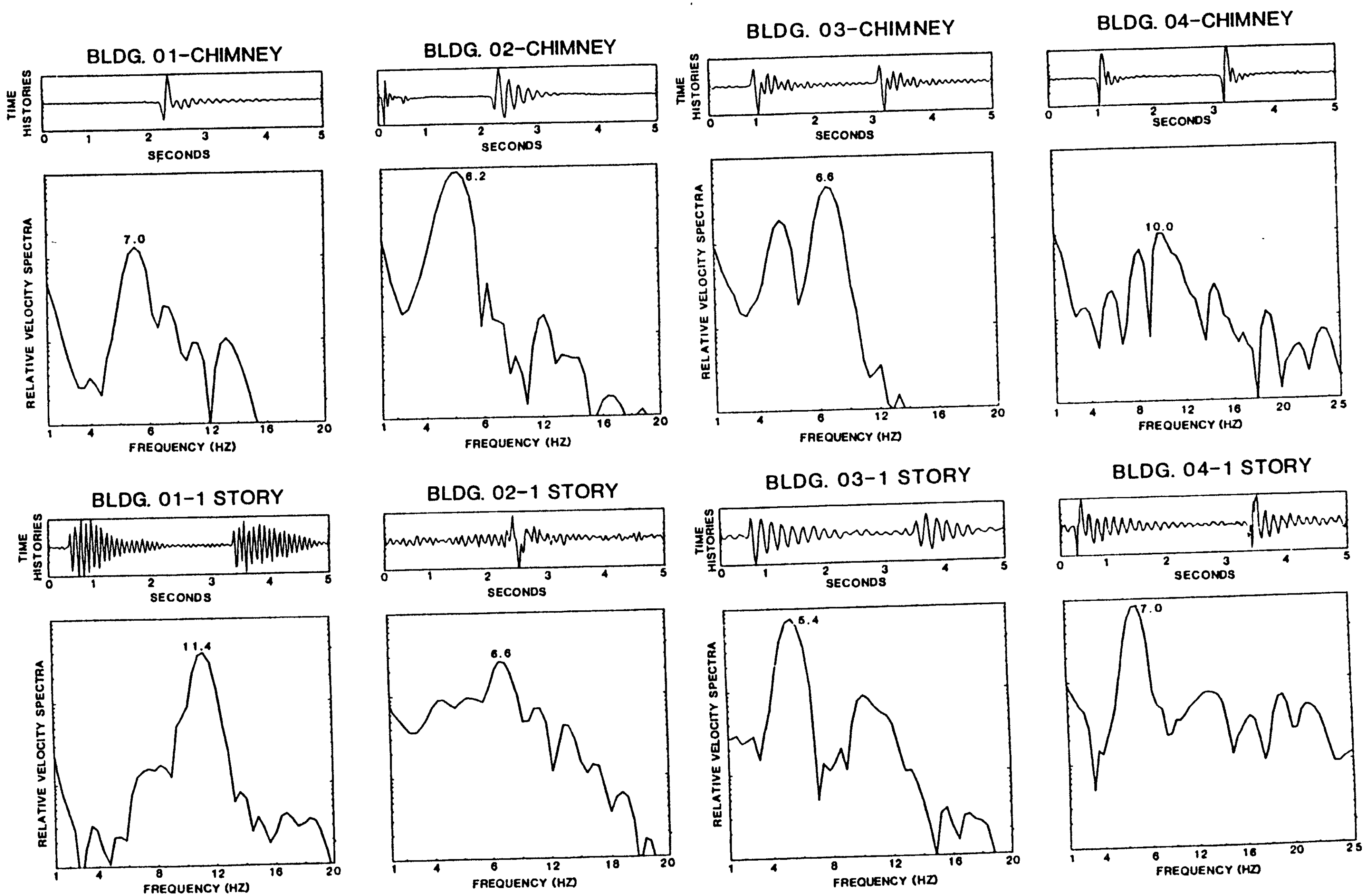

Figure 7. Seismograms (time histories) and velocity spectra which were used to derive natural frequencies and damping coefficient of representative houses in west Seattle. Results of this testing is shown in table 3.