Ambient microtremors were measured to obtain estimates of site amplification effects for soils to determine what sites would experience the most significant amplification of earth shaking.

An understanding of ground motion amplification due to the effects of local site conditions has been a research goal since J. Milne published his first study on this topic. Since then, there has been a quest for more knowledge of the parameters and mechanisms responsible for the widespread destruction caused by this phenomenon. Some well-known recent examples of amplification of seismic motions caused by local soil conditions include the earthquakes in Michoacan, Mexico, in 1985; Armenia in 1988; Loma Prieta, California, in 1989; Northridge, California, in 1994; and Kobe, Japan, in 1995. Some of the destruction might have been avoided if more information regarding the engineering properties and dynamic response of the soils at urban sites had been available. A better knowledge of the fundamental periods and level of amplification of in-situ soils and their relationship to buildings and infrastructure will lead to improved earthquake-resistant engineering design.

Areas of high seismicity, such as California and Japan, present opportunities for determining amplification and fundamental periods of soils through the analysis of strong-motion data. The frequency of high-magnitude events and the large number of seismic instruments in operation provide direct observations for obtaining these site factors.
However, on the east coast of the United States, seismic activity is less frequent and seismic stations are widely spaced. In this region, other methods must be employed to estimate ground-motion modifications and resonant periods due to site conditions. First proposed by Kanai, the use of ambient noise measurements to study the ground-motion response at individual sites has become increasingly common. Two methods have been developed to process the ambient noise measurements for site-response information:

- **The sed/rk method**: The response of the soils at a site is estimated using the Fourier spectral ratio of the sediment-to-bedrock ground motions, in which the seismograms from the soil site and from a nearby bedrock outcrop site are processed together to estimate the fundamental period of the soil and the amplification due to the soil.

- **The H/V method**: The H/V method utilizes a measurement of the ambient noise solely on the soil itself and the Fourier spectral ratio of the horizontal-to-vertical component seismograms to estimate the fundamental period and amplification of the ground motions in the soil.

Each of these methods has advantages and disadvantages. The sed/rk method assumes that seismic energy received at both the soil and hardrock sites comes from the same source and follows the same path, and it also assumes that the source of the microtremors has a white spectrum. A spectral ratio of the ambient noise from the soil site and from the rock site is assumed to give the response of the soil. Because microseisms in a city are produced primarily by noise due to machinery, buildings, etc., and since the receivers are placed at separate hard-rock and sedimentary sites, the assumption that there is a common source of the ambient noise may be violated. Even so, the sed/rk method has provided reliable and reproducible information on resonant soil periods in a number of studies, probably due to the dominance of the site effects over dissimilarities in the microtremor sources between sites and to the fact that the spectrum of ambient microtremors is not far from being a white spectrum in many cases.

The H/V technique was proposed in order to satisfy the similar source and path effect problem, which is the main source of uncertainty in the sed/rk method. The H/V method uses the ratio of the horizontal-to-vertical component of the ground motion at the soil site. This technique assumes that ambient noise microtremors are Rayleigh waves propagating through a single soil layer overlying a half-space of relatively higher velocity than the soil. The method is based on the premise that the horizontal component of the Rayleigh waves is amplified by the soil at the surface, while amplification of the vertical component is negligible. This assumption may not be true at all soil sites. A comprehensive explanation of the H/V method, along with numerical modeling to test its reliability, has been published by Lermo and Chavez-Garcia. Bard also provides an extensive analysis of the applicability of the H/V method.

Both the sed/rk and H/V methods have been applied to study the response of soils in the northeastern United States. Field et al. performed a study in Flushing Meadows, New York City, taking both ambient noise measurements and recordings from a pile-driver source to assess potential soil response. Fischer et al. applied the H/V method to estimate the resonant periods of the soils in Providence, Rhode Island.

The non-linear behavior of soils must be accounted for when attempting to draw inferences about strong-motion response from weak-motion data such as those analyzed in ambient noise studies. The resonant period of a soil tends to increase and the amount of amplification of the ground motions tends to decrease when stress-to-strain ratios become non-linear during strong earthquake ground motion. However, once the linear response for a soil is determined, correction factors can be used to estimate the non-linear soil response during strong ground shaking.

Some comparison studies between earthquake and ambient microtremor data show similarities between site response deter-
mined using each type of data. Other results suggest that ambient noise may not always accurately predict earthquake response.

The Boston area is a prime candidate for a study of microtremor measurements to predict earthquake response. It is an area of moderate seismicity, though it has experienced strong earthquakes in the past. The most damaging earthquake on record for Boston was the 1755 earthquake, which had an epicenter probably off the coast of Cape Ann. Written accounts describe liquefaction in some areas south of Boston and partial collapse of structures in Boston, where a modified Mercalli intensity of VII has been assigned. A large portion of the present city of Boston consists of fill that was deposited around the shores of the city in the eighteenth and nineteenth centuries. Since then, buildings and infrastructure have been built on this fill, most of them erected prior to the 1975 enactment of earthquake-resistant standards for buildings. Several engineering and geotechnical firms have calculated soil response based on measured or inferred dynamic soil properties for many areas in and around Boston, but as yet there are no surface strong ground-motion measurements with which to make a comparison. The only observed earthquake data showing possible soil amplification effects in Boston are those of Ebel and Hart, who analyzed modified Mercalli intensity data in the Boston area for a number of twentieth-century earthquakes.

Basement & Surficial Geology of Boston and Vicinity
The basement and surficial geology of the greater Boston area has been thoroughly summarized. Bedrock for most of the Boston area is the Cambridge argillite, which is typically hard and thinly laminated to massive (however, it is severely weathered to kaolinite at several sites). The bedrock surface is highly undulatory, varying from 220 feet deep just west of Back Bay to nearly outcropping at Beacon Hill. The Roxbury conglomerate is the bedrock in the areas of Roxbury, Brookline and Newton. In comparison to the argillite, this conglomerate is strong, resists weathering and does not possess natural jointing and fractures.

Overlying the bedrock in the Boston area are several types of soils. In most places, glacial till sits atop the bedrock. Above the glacial materials, there are typically found marine deposits, particularly clays, from the advance of the sea that immediately followed the retreat of the glacial ice from the region. A unit commonly known as the Boston Blue Clay comprises these deposits in many areas. The deposits above the Boston Blue Clay are alternating layers of sands, silts and clay-sized particles, the result of a complex marine depositional environment during glacial retreat. A glacial readvance provided another layer of outwash deposits above the marine deposits. Organic deposits can be found on top of the outwash in most low-lying areas. Fill materials have been emplaced by man at several locations around Boston. Beginning in the eighteenth century, a growing population and a quest for more land in Boston resulted in the filling of tidal flats and stagnant waters. Material from Needham (a nearby town southwest of Boston), from other highland areas such as Beacon Hill and Fort Hill in Boston, and from demolition rubble was used to create the new land around the Boston area. The fill appears to be deepest beneath the downtown area of Back Bay.

General Methodology
Ambient noise (microtremor) measurements were used to estimate the fundamental soil periods and amplification of ground motions in the soils in and around Boston. The fundamental soil period is the lowest resonant frequency of the soil — in other words, the lowest frequency maximum of the frequency-dependent amplification function of the horizontal component of surface ground motion relative to the horizontal motion of the bedrock. In interpreting these measurements it is also necessary to assess the viability of using the sed/rk and H/V methods to estimate soil response properties for the Boston area. Soil response properties computed from both observational and theoretical (computer modeled) analyses for several of the study sites are determined in order to compare pre-
dicted and measured fundamental soil periods and site amplification effects.

**Microtremor Monitoring for Local Soil Amplification Effects**

Ambient noise microtremors are low-amplitude motions of the ground caused by man-made (also called cultural), oceanic and atmospheric disturbances. Microtremors above 10 hertz are usually caused by the wind and by cultural sources, while lower frequency microtremors are generally caused by near-shore oceanic waves and by ocean currents. In this study, cultural sources are the primary cause of ambient noise since the study area is predominantly in an urban setting. There is disagreement as to the type of seismic waves that comprise ambient noise microtremors. Udwadia and Trifunac concluded that compressional, shear and surface waves can all be found in microtremor data. Others have determined that Rayleigh waves are the primary component. However, surface waves have been known to act like body waves that internally reflect in a single layer above a half-space and, thus, may be modeled as such. Drake used a finite-element model to show that a shear wave propagating vertically through a half-space correctly predicted Rayleigh and Love wave amplification. Drake used this evidence to argue that Love and Rayleigh waves show amplification effects in soils similar to those for vertically propagating shear waves.

Soil resonance is the term used to describe the fact that soils will vibrate strongly at certain periods due to seismic energy reverberating within the soils. Seismic energy can become trapped in a soil layer above a high impedance boundary such as the bedrock and reflect within the layer at a period twice the travel time through the soil layer. At the same time, some of the energy transmitted across the high impedance boundary can travel up to the surface and constructively or destructively interfere with the energy already reverberating in the soil layer. Heterogeneities in the soil also scatter the waves, resulting in more constructive and destructive interference. All of these factors contribute to the resonance of seismic waves in a particular soil column. There can be resonances at many different frequencies depending on the vertical heterogeneity of the soil column. However, layer thickness and seismic wave velocity control which periods of seismic energy will be most amplified by the soil resonances. For a single homogeneous soil layer over bedrock, this equation estimates the fundamental period for which resonant amplification of shear waves takes place in the layer:

$$T = \frac{4H}{V_s}$$

where

- $T$ = the period
- $H$ = layer thickness
- $V_s$ = the shear-wave velocity

For other distributions of shear-wave velocity with depth (i.e., in the soil column), the fundamental period can be estimated using the procedures of Doby et al.

**Microtremor Field Investigations in the Boston Area**

The microtremor observations were carried out using portable instrumentation that consisted of a seismograph connected by an electrical cable to a seismometer. The seismometer — a device to transform ground motions to electrical signals — was placed on the ground at the site where the ground motion measurement was to be made. The electrical cable connected the seismometer to a digital seismograph, which was the device that recorded the signals from the seismometer. Two kinds of portable digital seismographs were used. The seismometer used with each type of seismograph had a flat response in the period range from 30 seconds to 0.03 second. (In addition, data from a permanent seismograph connected to a personal computer-based data acquisition system at Weston Observatory in Weston, Massachusetts, were used for this research.)

To determine the variation of the Fourier spectra of the ambient noise at various times of the day and night, a set of initial measurements were taken at Massachusetts Institute of Technology (MIT) University Park (see Figure 1). MIT University Park was a construction
FIGURE 1. Base map for this study. Numbers indicate those sites where microtremors were measured.

2. Bunker Hill Community College, Charlestown
3. Airport Park, East Boston
4. North End Playground
5. Massachusetts General Hospital "Brown" Parking Lot
6. Columbus Park
7. MIT University Park, Cambridge
8. Old West Church
9. Boston Common
10. Tang Hall, MIT, Cambridge
11. 330 Commonwealth Avenue
12. Prudential Center (bottom floor garage)
13. Back Bay Garage (bottom floor)
14. Fenway Park
15. Massachusetts Highway Dept., D Street

FIGURE 1. Base map for this study. Numbers indicate those sites where microtremors were measured.

site and, therefore, experienced high levels of cultural noise during the day and occasional traffic during the late evening and early morning hours. The seismometer was placed on a concrete slab at the site and operated from 7:00 PM, July 30, 1997, to 3:00 PM, the next day. The seismograph recorded for four minutes each hour. Each four-minute window was divided into six 40-second subwindows that were Fourier transformed, stacked and filtered (using a five-point averaging filter) to provide smoother spectra before the ratios were taken. Figure 2 shows the east-west to vertical (E-W/V) H/V Fourier spectral ratios obtained at this site. Each line represents a different time window, and the time windows are separated by at least one hour. Since each plotted function represents a different time of day, the Fourier spectral ratio has the same shape and the same resonant frequency. The mean spectral ratio amplitude at the maximum value of the spectrum is 6.4 with a standard deviation of 1.3.

In the first stage of routine data collection, seismometers and seismographs were placed at each of two different locations of the Boston Basin. One set of instrumentation remained at St. Francis Rectory on Bunker Hill in Charlestown for all measurements. Although Bunker Hill is a drumlin, it was used as a reference hard rock site for the sediment spectral ratio calculations due to the lack of outcropping bedrock near downtown Boston. The other seismometer-seismograph set was placed on different days at Bunker Hill Community College in Charlestown, Old West Church in Boston, Commonwealth Avenue in the Back Bay, MIT University Park, etc.
FIGURE 2. H/V spectral ratios computed from the east-west and vertical components of the ground motion recorded July 30-31, 1997, at MIT University Park in Cambridge.

in Cambridge, and D Street in South Boston (see Figure 1).

The seismographs recorded four minutes of continuous data each hour from the afternoon or evening on one day until daylight the next day. At each location, the seismometer was placed on pavement, if available, or on a concrete slab atop sand and was covered with a plastic bin with heavy bricks placed on top to avoid wind or other surficial noise. The seismograph at each site was placed on a 1-inch foam pad and was covered, along with the battery, by another plastic bin with bricks placed on top. High-amplitude cultural noise was edited out of each record prior to analysis, and then H/V spectral ratios were computed along with sed/rk ratios referenced to Bunker Hill.

In a second stage of data collection, measurements at eleven more sites in Boston and Cambridge (see Figure 1) were obtained over the course of two days. Two of the sites from the first stage of data collection were revisited in order to determine the repeatability of the results. In the second stage of the experiment, data were collected for approximately 20 minutes at each location, and a 4-minute window containing relatively low cultural noise was chosen for analysis. H/V ratios were determined at each site, along with sed/rk spectral ratios using the Weston Observatory as a reference site. Since the Weston Observatory is a bedrock site that permanently monitors ground motions, the purpose of these sed/rk estimations was to test the suitability of the Weston Observatory as a reference rock site. (Weston Observatory is located approximately 19 kilometers from downtown Boston.)

Data Analysis

A standard set of data processing steps was followed to reduce the data. Sample data time series are shown in Figure 3. All time series were baseline corrected, and a 5-percent taper was applied prior to application of the fast Fourier transform (FFT) in order to smooth the spectrum somewhat. Data recorded on the seismographs at MIT University Park and St. Francis Rectory were not filtered. The Weston Observatory data were filtered by a sixth-order 0.1 to 7 hertz Butterworth bandpass filter to eliminate the spectral contribution of
FIGURE 3. Representative time series at three different locations where microtremors were recorded. The vertical component of motion is shown for all three sites. For each seismogram, the amplitude scale is digital counts.

Some periodic spikes from the instrument timing system that contaminated the time series.

For the first stage of the experiment, a 40-second segment of the seismogram with low cultural noise for each site was chosen for analysis. Seismogram segments with high amplitudes due to vehicular traffic passing near the site were avoided. No stacking was

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performed on these data, but a seven-point smoothing filter was applied to all computed spectra. In the second stage of the experiment, stacking was performed. A 120-second portion of the seismogram with relatively low local cultural noise was chosen. It was filtered, tapered and then split into three 40-second subwindows. The subwindows were Fourier transformed, then averaged together and multiplied by a seven-point spectral smoothing filter. The last step was dividing the spectrum from one component of motion by the spectrum from the other component.

Examples of H/V and sed/rk Fourier spectral ratios are shown in Figure 4 for D Street in South Boston using Bunker Hill as a reference hard-rock site. Figure 5 shows ratios for the same location one month later, but the reference site is Weston Observatory. Comparing the H/V spectra from Figures 4 and 5, it is evident that, on the two different dates, similar frequencies of the highest spectral peak (called here the fundamental soil frequency or the fundamental resonant frequency), similar spectral shapes and similar amplitudes at the fundamental soil frequency appear in the spectral ratios. The similarities in the H/V spectra taken one month apart indicate that the fundamental soil frequencies, amplitudes and general shapes do not vary significantly with
Comparison of the sed/ rk spectra on Figures 4 and 5 shows similar fundamental soil frequencies but different amplitudes. The peaks of the N-S sed/ rk spectra for both days have the same width, but the E-W sed/ rk spectral shapes differ. The differences between the sed/ rk spectra on the different days are due to the difference in reference site and the very low level of cultural noise at Weston Observatory.

Figure 6 shows spectral ratios for the East Boston site, with Weston Observatory as a reference. The H/ V and sed/ rk methods do not give similar fundamental soil frequencies, spectral shapes or amplitudes, and the vertical (or Z) component sed/ rk spectra shows high amplification (which peaks near 8 hertz). The individual spectra at both sites indicate that the increase in the Z component ratio is due to increased high-frequency noise in East Boston relative to the Weston Observatory site. This increase in high-frequency noise at East Boston must also be present in the horizontal seismograms since it affects the horizontal sed/ rk spectra. A relatively small peak is also observed at 3 hertz in the sed/ rk N-S spectra in Figure 6. This peak is at approximately the same frequency where the fundamental resonant frequency occurs in the H/ V spectra from this site. However, it is apparent in
Figure 6 that the strong high-frequency microtremors in the city dominate the 3-hertz spectral peak in the plotted sed/rk data.

Taken together, Figures 4, 5 and 6 indicate that the Bunker Hill site is a much better reference site for sed/rk analyses than Weston Observatory. In some cases for downtown Boston (i.e., Figure 5) the fundamental soil period can be accurately found using Weston Observatory as the reference rock site. In other cases (i.e., Figure 6), however, the ambient microtremor noise spectrum at Weston Observatory is so different from that in downtown Boston that the fundamental soil period is not readily apparent in the sed/rk ratios.

The large sed/rk ratio values in Figures 5 and 6 (up to 800+) are indications that the excitation of ambient microtremors in suburban Weston is much less than in downtown Boston. Figure 7 shows the fundamental soil periods and spectral ratios computed from the ambient noise measurements using the H/V method. (The fundamental soil period map shows the period where there is the greatest peak in the H/V spectral ratio.) The values shown on the maps represent average values from the individual N-S and E-W H/V spectra for each site. Larger resonant periods from 0.63 to 1.0 second are in the Back Bay, MIT and Fenway areas, where bedrock is relatively
deep. The fundamental soil period values reduce to 0.24 to 0.43 second as bedrock nears the surface around the Boston Common, Beacon Hill and the North End. The lowest fundamental soil period of 0.20 second found on the map is in South Boston, where bedrock is a relatively shallow 33 feet below the surface. The one significant inconsistency between fundamental soil period and bedrock depth is in East Boston, where the fundamental resonant period of the soil on Figure 7 is 0.32 second but where the bedrock surface is at a relatively deep 174 feet, comparable to that in the Back Bay. The H/V ratio map shows the lowest spectral ratio values at the fundamental resonant periods in the Back Bay and at MIT. The sites where the bedrock is relatively shallow seem to have higher amplitudes in these spectral ratios.

An estimate of the absolute amplification for each study site cannot be easily obtained using the spectral ratio methods described here. Lachet et al. found that H/V spectral ratios underestimated amplification when compared to classical reference station spectral ratios of earthquake motions. Field et al. also found that sed/\(r\bar{k}\) spectral ratios from ambient noise measurements did not accurately predict the amount of amplification a site can experience. Lachet and Bard found no correlation between the H/V spectral amplitude ratio and the computer-modeled transfer function of a site.

Around Boston, the variation in the spectral amplitude ratios at a single site is most evident in the sed/\(r\bar{k}\) method. For example, at MIT University Park, 20 different measurements of the sed/\(r\bar{k}\) amplitude ratio (using Bunker Hill as a reference site) fluctuate between values of 19.5 and 62.9, with most between 19.5 and 28.2. The distribution of H/V spectral ratios at MIT University Park calculated from data recorded on a different
### TABLE 1

Soil Models Used for the One-Dimensional Linear Soil Response Calculations

<table>
<thead>
<tr>
<th></th>
<th>Bunker Hill Community College</th>
<th>Boston Common</th>
<th>Columbus Park</th>
<th>Commonwealth Avenue</th>
<th>D Street</th>
<th>East Boston</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_s (1)*</td>
<td>1,000</td>
<td>750</td>
<td>655</td>
<td>540</td>
<td>370</td>
<td>370</td>
</tr>
<tr>
<td>γ (1)</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>110</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Depth (2)</td>
<td>5</td>
<td>40</td>
<td>18</td>
<td>70</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>V_s (2)</td>
<td>370</td>
<td>750</td>
<td>700</td>
<td>400</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>γ (2)</td>
<td>111</td>
<td>115</td>
<td>120</td>
<td>100</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>Depth (3)</td>
<td>13.5</td>
<td>65</td>
<td>50.5</td>
<td>24</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>V_s (3)</td>
<td>450</td>
<td>1,256</td>
<td>1,100</td>
<td>936</td>
<td>800</td>
<td>450</td>
</tr>
<tr>
<td>γ (3)</td>
<td>114</td>
<td>135</td>
<td>120</td>
<td>120</td>
<td>111</td>
<td>87</td>
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<td>Depth (4)</td>
<td>18</td>
<td>85</td>
<td>69</td>
<td>29</td>
<td>14</td>
<td></td>
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<tr>
<td>V_s (4)</td>
<td>650</td>
<td>1,500</td>
<td>871</td>
<td>974</td>
<td>638</td>
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</tr>
<tr>
<td>γ (4)</td>
<td>111</td>
<td>135</td>
<td>120</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (5)</td>
<td>27</td>
<td>74</td>
<td>74</td>
<td>34</td>
<td>123.5</td>
<td></td>
</tr>
<tr>
<td>V_s (5)</td>
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<td>1,900</td>
<td>575</td>
<td>1,250</td>
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<td></td>
</tr>
<tr>
<td>γ (5)</td>
<td>111</td>
<td>135</td>
<td>120</td>
<td>120</td>
<td></td>
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<tr>
<td>Depth (6)</td>
<td>42</td>
<td>197</td>
<td>197</td>
<td>139</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V_s (6)</td>
<td>800</td>
<td>2,143</td>
<td>1,500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>γ (6)</td>
<td>111</td>
<td>135</td>
<td>135</td>
<td></td>
<td></td>
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<tr>
<td>Depth (7)</td>
<td>64</td>
<td>146.5</td>
<td></td>
<td></td>
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</tr>
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<td>V_s (7)</td>
<td>2,205</td>
<td>1,460</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>γ (7)</td>
<td>315</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (Rock)</td>
<td>88</td>
<td>10,000</td>
<td>3,200</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>V_s (Rock)</td>
<td>2,000</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>γ (Rock)</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
</tbody>
</table>

* Notes: V_s = Shear-wave velocity in feet per second, γ = Total unit weight in pcf, Depth = Depth to the top of this layer in feet, * Layer numbers are in parentheses.

Day shows a smaller variation than the sed/rk data. The N-S and the E-W distributions vary from 4.1 to 7.1 and from 4.2 to 9.5, respectively. In terms of amplitude ratios, the H/V values are more stable and repeatable than the sed/rk measurements.

**One-Dimensional Soil Response Analyses**

For all of the study sites, one-dimensional frequency-domain response analyses were performed using the software program UFSHAKE. This program is a user-friendly version of SHAKE91, originally developed at the University of California, Berkeley. The program computes the response of a semi-infinite, horizontally layered soil column overlying a uniform half-space subjected to vertically propagating shear waves. The soil layers are characterized by thickness, shear-wave velocity or shear modulus, damping ratio, unit weight and other index soil properties. Non-linear soil response is approximated through an iterative process where both damping and shear modulus are recomputed based on the level of effective cyclic shear strain. This process continues until either the user-specified maximum number of iterations is exceeded or the desired level of convergence is reached.

It was assumed that the site effects determined in this study through measuring microtremors were not influenced by non-linear effects in the soils because the energy level of the ambient noise microtremors was too low. To form a comparison between the site responses from the microtremor measurements and from the UFSHAKE calculations,
only one iteration was performed in UFSHAKE in order to obtain the linear modeled response. Motions at the top of the soil layer were calculated for each site, and then the Fourier spectral ratio of the soil layer to the bedrock ground motions was obtained. For most of the study sites, geotechnical logs near the site were obtained, and the shear-wave velocities and total unit weights were determined. Table 1 summarizes the soil models for each of the sites for which a one-dimensional linear soil response was performed.

Figure 8 shows an example of the results of the one-dimensional soil response analysis. An estimated soil column and the modeled one-dimensional soil response for the site at D Street in South Boston are illustrated. Soil properties for this site were obtained from a boring for the Central Artery/Third Harbor Tunnel (CAT) Project that was drilled very near to the site. Shear-wave velocities at the D Street site were obtained by converting standard penetration test (SPT) blow counts to shear-wave velocities using empirical correlations determined from a site in East Boston where both a cross-hole geophysical survey and downhole geotechnical logging were carried out. Total unit weights for the D Street soil column were estimated from the geotechnical log. The source of the input ground motion was an acceleration time series synthesized for the New England area, with a maximum acceleration of 0.05 g. The highest spectral peak found in the one-dimensional soil response analysis (see Figure 8) occurs at the approximately same frequency as the fundamental soil frequency determined from the ambient microtremor data from the D Street.
Table 2 compares fundamental soil periods computed from the ratio of the bedrock and surface ground motions in the one-dimensional soil response analysis with the fundamental soil periods measured from the ambient noise data using the H/V method for those sites for which geotechnical logs were obtained. In many cases in Table 2, the fundamental period determined from the observed microtremors corresponds fairly well with that calculated from the one-dimensional response analysis. At Boston Common, East Boston, Massachusetts General Hospital and the North End, the fundamental periods computed in the one-dimensional amplification studies are significantly greater than those found in the H/V measurements; while at Tang Hall the opposite is observed. For the Boston Common and East Boston sites, the fundamental soil periods determined using UPSHAKE reflect the relatively deep bedrock below those sites. For the Massachusetts General Hospital and the North End sites, the fundamental soil periods found using UPSHAKE are influenced strongly by relatively thick, low-velocity layers in the soil models. For these five sites, it is not clear whether the notable differences between the fundamental soil periods determined from the observed microtremors and from the one-dimensional soil models are due to problems in the ambient microtremor measurements or to uncertainties in the soil models used in the one-dimensional soil response analysis.

A comparison can be made in Table 2 between the H/V ratios and the amplitude ratios from the one-dimensional response runs. There appears to be some correspondence between the H/V spectral amplitude ratios and the rock/surface spectral amplitude ratios computed using the UPSHAKE results for several of the sites. However, in other cases the observed and model amplitude ratios from the observed data and from the one-dimensional model calculations differ by as much as a factor of 3.

The one-dimensional linear soil response analyses also were used to investigate how much variation from site to site there might be in the time-domain amplitudes of earthquake ground motions across the study area.
Table 2.
Summary of Observed & Modeled Fundamental Soil Periods & Spectral Amplitudes at Those Periods

<table>
<thead>
<tr>
<th>Location</th>
<th>H/V Period (sec)*</th>
<th>UFSHAKE Period (sec)</th>
<th>H/V Amplification Ratio*</th>
<th>UFSHAKE Amplification Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Bay Garage</td>
<td>0.83</td>
<td>0.63</td>
<td>2.2</td>
<td>12.0</td>
</tr>
<tr>
<td>Bunker Hill</td>
<td>0.29</td>
<td>0.34</td>
<td>9.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Community College</td>
<td>0.23</td>
<td>0.48</td>
<td>7.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Boston Common</td>
<td>0.43</td>
<td>0.33</td>
<td>11.4</td>
<td>4.1</td>
</tr>
<tr>
<td>Columbus Park</td>
<td>0.91</td>
<td>1.14</td>
<td>6.8</td>
<td>6.8</td>
</tr>
<tr>
<td>Commonwealth Avenue</td>
<td>0.20</td>
<td>0.19</td>
<td>13.3</td>
<td>13.3</td>
</tr>
<tr>
<td>D Street</td>
<td>0.32</td>
<td>0.71</td>
<td>7.6</td>
<td>9.5</td>
</tr>
<tr>
<td>East Boston</td>
<td>0.38</td>
<td>0.71</td>
<td>22.0</td>
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</tr>
<tr>
<td>Fenway</td>
<td>0.63</td>
<td>0.63</td>
<td>12.9</td>
<td>8.1</td>
</tr>
<tr>
<td>Massachusetts General Hospital</td>
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<td>0.63</td>
<td>8.3</td>
<td>7.1</td>
</tr>
<tr>
<td>North End</td>
<td>0.29</td>
<td>0.20</td>
<td>10.1</td>
<td>10.0</td>
</tr>
<tr>
<td>Old West Church</td>
<td>0.77</td>
<td>0.71</td>
<td>3.6</td>
<td>9.9</td>
</tr>
<tr>
<td>Prudential Center</td>
<td>0.34</td>
<td>0.67</td>
<td>5.6</td>
<td>7.6</td>
</tr>
<tr>
<td>St. Francis Rectory, Charlestown</td>
<td>1.00</td>
<td>0.67</td>
<td>5.6</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Note: *Average of all values determined for each site.

Figure 9 shows the ratio of the calculated peak ground acceleration (PGA) on the soil surface to the input PGA for each site for which a one-dimensional soil response analysis was carried out. The acceleration time series from which the PGA values are found are the linear response to the synthetic New England earthquake with maximum acceleration of 0.05 g. Figure 9 indicates that the greatest amplification of PGA occurs at those sites with the shortest fundamental soil period and that the amplification of PGA due to the soils tends to decrease with increasing fundamental soil period. At fundamental soil periods of 0.6 to 0.8 second the surface amplification of the bedrock PGA values varies widely among these sites. From the results in Figure 9, it is evident that the stiffness (or lack thereof) of local soils along with the acoustic impedance contrast at the soil-rock interface is rather important in determining the potential for ground shaking amplification than the depth to the bedrock in the Boston area.

A test was made to see if the pattern of surface amplification among the sites shown in Figure 9 might be seen in the time domain amplitudes of the ambient noise measurements from the second stage of data collection. The same instrument was used to collect all of the data in this part of the experiment. Thus, if the level of excitation of the ambient seismic noise is roughly the same at all the sites, higher seismogram amplitudes should be recorded at sites with greater soil amplification. For each location where ambient microtremor
FIGURE 9. Plot of the ratio of the PGA values computed on the soil surface in the one-dimen-
sional linear soil response analysis to the PGA of the input bedrock ground motion.

FIGURE 10. Plot of the ratio of the average horizontal time-domain ambient microtremor
amplitudes to the average vertical ambient microtremor amplitudes.
measurements were taken on September 15 and 16, 1997, the time series were filtered by a sixth-order 0.5 to 10 hertz Butterworth band-pass filter. Then the average time domain amplitude of the filtered microtremor records in digital counts was calculated for each component, and the average horizontal time-domain amplitude was divided by the average vertical time-domain amplitude. This horizontal-to-vertical time-domain amplitude ratio was calculated under the assumption that the soils amplify the horizontal but not the vertical ground motions relative to the bedrock ground motions. This assumption was also made by Nakamura.

The time-domain average H/V amplitude ratios are plotted in Figure 10. Similar to the pattern in Figure 9, there is a tendency in Figure 10 for the time-domain H/V amplitude ratios from the microtremor observations to decrease with increasing fundamental soil period. Furthermore, at the sites with the largest resonant periods in Figure 10, the vertical component amplitudes are all comparable to or larger than the horizontal amplitudes. This finding suggests significant amplification of the vertical ground motions in the ambient noise at these sites, and it explains the low H/V spectral ratio values at these sites in Table 2 and Figure 7. The similarity of the trends of the data points in Figures 9 and 10 suggest that the time-domain ambient microtremor amplitudes give some qualitative indication of how much amplification the local soils might impart to the bedrock ground motions.

Conclusions
This study used ambient noise microtremor measurements to establish site amplification effects in areas of the Boston Basin and to test the viability of using ambient microtremor observations for microzonation of the Boston area. The study provides a comparison of both the sediment-to-bedrock and horizontal-to-vertical Fourier spectral ratio techniques and compares them with computer-generated models of transfer functions for one-dimensional soil columns representing different areas around Boston. The following are the primary results:

- The fundamental soil period and the overall spectral shape obtained using both the H/V and sediment/rock techniques are site-specific and do not depend on the time of the measurement. The H/V method appears to be more reliable for establishing the fundamental soil period since results with this method are more repeatable.
- A reference site on Bunker Hill, composed of glacial till, proved to be a better approximation of a rock site for the sediment/rock analyses. Weston Observatory, located about 19 kilometers from downtown Boston, did not give consistently accurate results as a rock reference site.
- The H/V Fourier spectral amplification provided estimates of the fundamental soil periods for the study sites. These periods ranged between 0.65 and 1.0 second at MIT in Cambridge and in the Back Bay area of Boston. The periods were between 0.29 and 0.43 second at the Boston Common, on Beacon Hill, in the North End, in Charlestown, and in East Boston. The smallest fundamental period of 0.20 second was at D Street in South Boston, where the shallowest bedrock of the study sites is located.
- Transfer functions of soil-to-bedrock response at individual sites calculated by one-dimensional soil response analyses generally correlate with H/V spectra determined from the observed microtremors in amplitude ratio, Fourier spectral shape and fundamental soil period for rock sites. These calculations show that the stiffness of local soils along with the acoustic impedance contrast at the soil-rock interface appear to be more important in determining the potential for ground-shaking amplification than the depth to the bedrock in the Boston area.
- Qualitative estimates of the amplification of earthquake ground motions due to the soils at individual sites can be made from the ratio of the average horizontal to vertical time-domain amplitudes from the ambient microtremors.
- At the sites with the thickest soil deposits in this study, there appears to be signifi-

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cant amplification of the vertical time-domain microtremor amplitudes.

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REFERENCES


