RAYLEIGH WAVE INVERSION FOR SHALLOW AND DEEP S-WAVE VELOCITY STRUCTURES IN THE SAN FERNANDO VALLEY BY USING AN ARRAY MEASUREMENT OF MICROTREMORS

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Abstract

The effects of a sub-surface structure on strong ground motion and hence the seismic damage potential is now recognized as one of the most influential factors so that we need detailed information of the sub-surface structure from the surface to a underlying intact bedrock for quantitative simulation of strong motion in a wide frequency range. The Rayleigh wave inversion method by using an array measurement of microtremors has been very successful in Japan, in which S-wave velocities are inverted from the dispersion carve of Rayleigh wave evaluated from microtremors. In this project we use this Rayleigh wave inversion technique to investigate S-wave velocity structures in the San Fernando Valley and Santa Monica. Its purpose is a) to verify the applicability of the technique in the United States, and b) to obtain quantitative estimation of S-wave velocities in the Valley. We have conducted field measurement of microtremors by arrays during July and August in 1995. Total numbers of sites and arrays are seven and fifteen, respectively. We found that the data quality is good enough to do the f-k analysis to find Rayleigh wave propagation velocity in a wide frequency range. Once Rayleigh wave dispersion curves are obtained from the f-k analyses, then we invert S-wave velocity structures to match the observed dispersion curves with models. We focus our attention to two most important sites, namely, California State University, Northridge in the center of the San Fernando Valley and the Santa Monica City Hall where anomalously high acceleration was observed during the Northridge earthquake of 1994. The S-wave velocity structures at these sites can be used for a quantitative simulation of the strong motions in the San Fernando Valley observed during the Northridge earthquake of 1994.

Results

The original plan does not have candidate sites in Santa Monica, but we added four sites there because a strong motion station showed very high acceleration during the 1994 Northridge

earthquake and anomalous damage to the buildings there was also found in the area. We think that it is very important to clarify the cause of these anomalies from the view point of site amplification since this area is potentially very vulnerable to future thrust events below the Santa Monica Mountains.

During about three weeks we have measured microtremors at seven sites with fifteen arrays. Maximum number of arrays at one site is three. Typical size of three different arrays, denoted here as S-, M-, and L-arrays are 100m, 400m, and 1.6km in radius, respectively. Table 1 lists type of arrays for each site. Three major sites, namely, California State University Northridge, V. A. Hospital Westwood, and Santa Monica City Hall have three arrays to cover wider frequency ranges, i.e., deeper depths. Two Sherman Oaks sites are selected to compare relatively shallow structures at these sites, which showed quite different ratios of damaged buildings during the Northridge earthquake. Two sites between V. A. Hospital Westwood and Santa Monica City Hall in Santa Monica are added to find differences in the shallower structures, if any, so we can also compare them to the damage ratios in the region. Figure 1 shows locations of these seven sites on a map of the distribution of damaged buildings made by OES.

We deployed ten stations for each array using cross-shaped configuration for S-array and combined triangular configuration for M- and L-arrays. Each station is composed of one portable digital recorder using IC memory card as a recording medium, one three-component velocity sensor, and a transceiver to receive radio signals from a controller. A controller which is also connected to a transceiver broadcasts signals for synchronization of recorders' internal clocks and start/stop recording. The relative coordinates of each station are measured by measuring tapes for S-array and by a differential GPS system for M- and L-arrays.

Table 1 Site of microtremor measurement

Site	Arrays
Cal. State University, Northridge	S, M, L
Sherman Oaks Park	S, M
Sherman Oaks Elementary School	S, M
V. A. Hospital, Westwood	S, M, L
Santa Monica City Hall	S, M, L
Franklin Elementary School	S
Santa Monica College	S

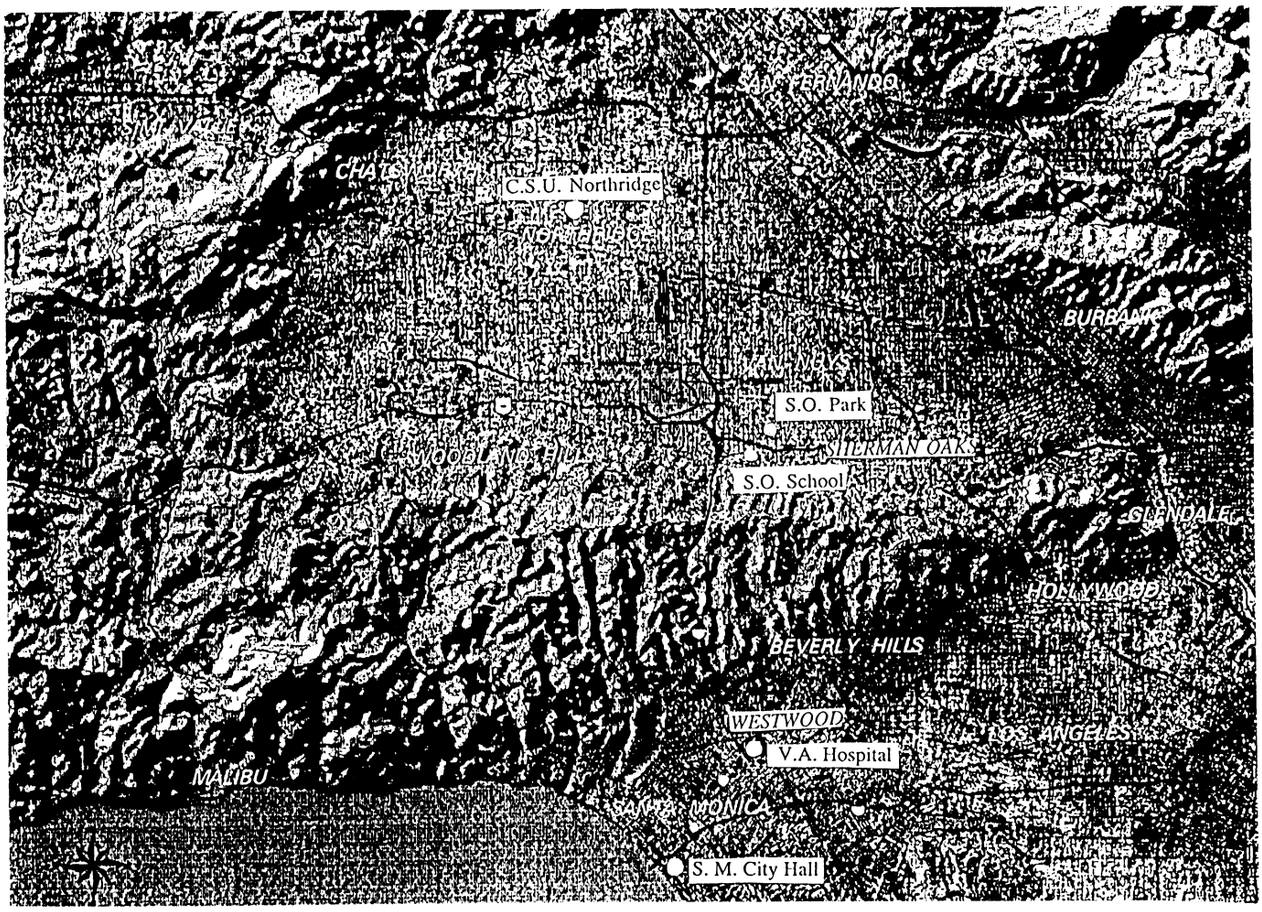

Figure 1 Locations of sites with the distribution of damaged buildings (made by OES).

We have obtained very good data throughout the field measurement in this project, although we measured microtremors in the morning, not in the midnight as we usually do in Japan. Figure 2 shows examples of observed data, that is, the vertical components at ten stations in the S-arrays deployed at Santa Monica City Hall. We apply frequency domain filtering in the valid frequency range, namely, from 2.0 Hz to 6.0 Hz. Note that we measured ground velocity for S-array and ground displacement for M- and L-arrays because we can expect larger amplitude in the frequency range of interest for each array. It is apparent that their waveforms are very similar to each other and we can trace wave propagation within an array for some of the characteristic pulses.

Figure 3 shows power spectra of the microtremors in Figure 2 from 0.1 Hz to 20 Hz. They are also similar to each other. Peaks exist commonly at 0.4 Hz, 3 Hz, and 10 Hz. Figure 4 shows examples of our f-k analyses by using the so-called high resolution technique of Capon. The horizontal axis shows the x-direction wavenumber and the vertical axis the y-direction wavenumber. The wavenumber spectra are plotted on this x- and y-wavenumber field as contour maps for different frequencies of interest and then the highest peaks are taken to calculate apparent velocities and propagation directions for those frequencies.

The upper bound of the frequency range is determined by the Nyquest wavenumber of the minimum station distance, while the lower bound is controlled by the resolution limit related to the maximum station distance. The rule of thumb for the lower bound is that the wavelength of the surface wave should be less than 2 to 4 times of the maximum station separation. Here we use 3 times as the practical limit and check the obtained velocities with those by the larger array whenever possible.

After we have checked the phase velocities from different-sized arrays, we decide to use as representative values the estimated velocities taken from the larger-sized array if we have two estimates from different-sized arrays. We also restrict ourselves to use only those with the coefficient of variance smaller than 50%. The resultant representative values are plotted in Figure 5. In case of Santa Monica City Hall we also plot the values lower than 0.3 Hz in Figure 5 even though they have large deviations. Otherwise we loose information completely in this important lower frequency end. From Figure 5 it is quite obvious that in the high frequency range two sites have similar phase velocities, however, in the lower frequency range Cal. State Univ. Northridge has significantly higher phase velocities than Santa Monica City Hall. This implies that the shallow velocity structures at both sites are similar to each other but deeper ones are different. To quantify how different they are we need to invert S-wave velocity structure by using the dispersion characteristics shown in Figure 5 as a target.

Once we have obtained target phase-velocity curves, then we can invert S-wave velocity structures by matching the theoretical Rayleigh wave dispersion with the target curves. Since we do not have much constraint on the geological structures below the two sites analysed and we do not have enough experience on the effects of each velocity value of layers in this area, we try here a human-controled forward inversion to match the model curves with the target curves under intensive sensitivity studies. Thus the resultant velocity structures will be somewhat arbitrary in detail but basically reflect the real velocity structures below the two sites.

For the Santa Monica site we mainly depend on the velocity structure used by Graves (1995) which is a kind of an average velocity structure of the western Los Angeles basin according to Graves (1995). For the shallow part we refer to Duke et al. (1971) and Fumal and Tinsley (1985). Below the bedrock of the S-wave velocity more than 3.0 km/sec we use the velocity model of the crust used by Zeng and Anderson (1996) for both sites. Note that below this level our frequency range of the target curves does not allow us to resolve the S-wave velocity. Since Davis et al. (1989) suggest that the basement depth in the downtown Santa Monica may be in the range from 2 km to 3 km, we constrain the thickness of the sedimentary formation to be in this range. The contour map shown by Sen (1991), which is derived from Yerkes et al. (1965), also suggests the bedrock depth of around 2 km. After several tens of try-and-error type model search we finally obtained the best solution which yields the model curve shown in Figure 6. The matching is remarkably good except for the lower freqency end where anyway we do not have much confidence

on the target.

For Cal. State Univ., Northridge we start with a model proposed by Anderson and Yu (1996) which is essentially a reconstructed model from Vidale and Helmberger (1988). For the basement depth we assume about 4 km based on the model used by Wald et al. (1996). The contour map of Sen (1991) also suggests the depth of 4 to 4.5 km. The velocity structure below the bedrock is fixed as that by Zeng and Anderson (1996). For the shallow structure we refer to the S-wave velocity from a boring logging (SCEC, 1994), which suggests S-wave velocity to be 343 m/sec for upper 30 m of soils. After several tries we finally get a beautiful matching as shown in Figure 7. The velocity structures obtained here are shown in Figure 8 to compare those at Santa Monica and Northridge, which should be considered as viable representatives among other possibilities. When we look at Figure 8 we can easily notice that the main difference between the two sites is in the velocities of the sedimentary rock layers, that is, Northridge has always higher values than Santa Monica in quite a propotional manner up to 3 km in depth.

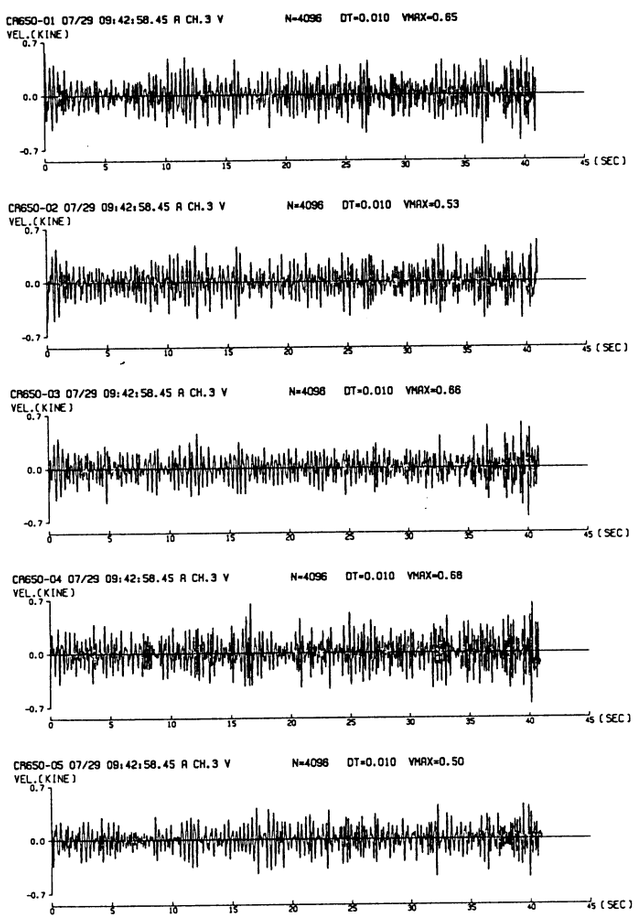

Figure 2 Filtered velocity time histories of observed microtremors at Santa Monica City Hall S-array, vertical components at 10 stations (top: array center).

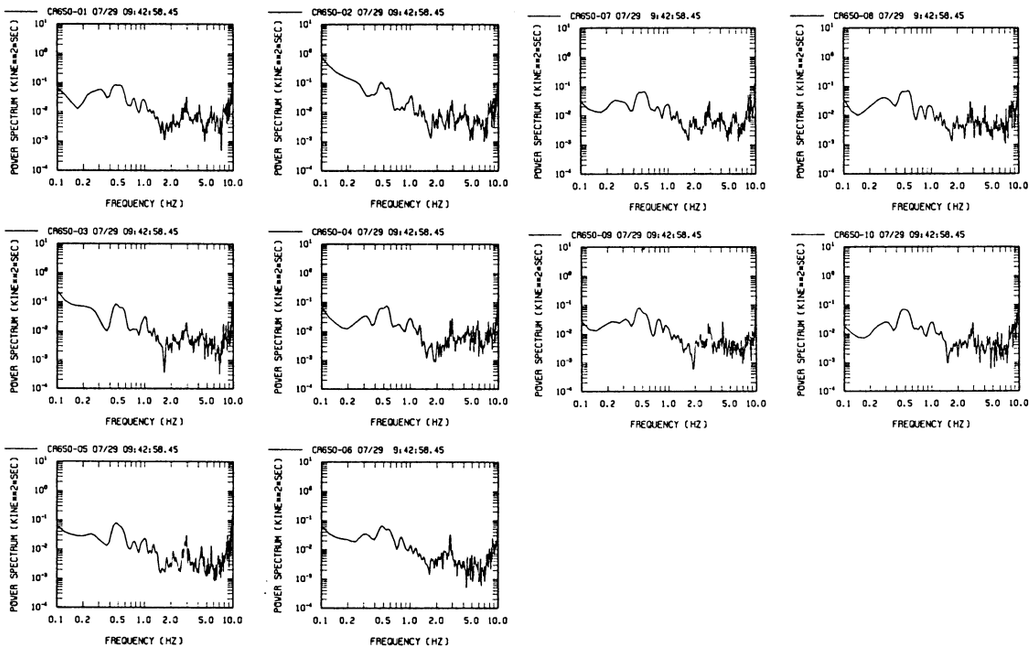

Figure 3 Power spectra of observed microtremors at Santa Monica City Hall. S-array, vertical components at 10 stations (top left: array center).

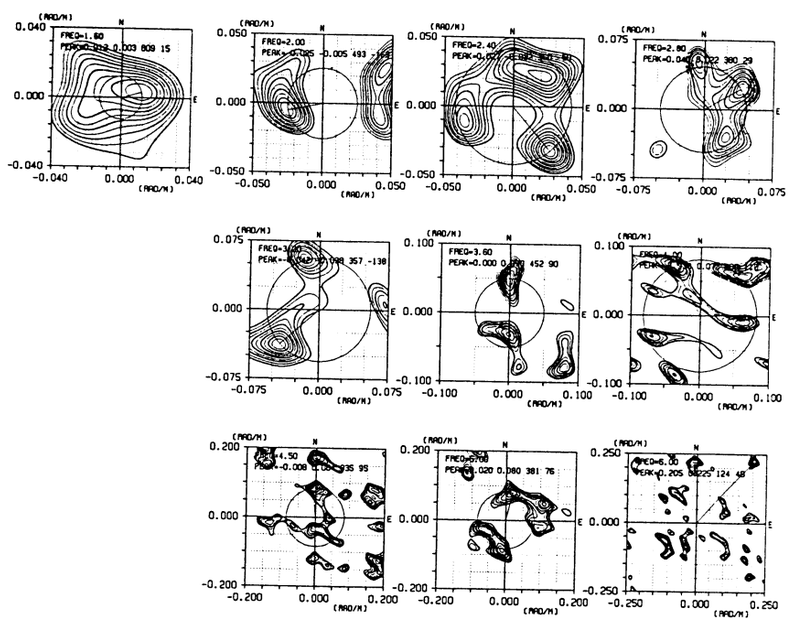

Figure 4 Spectral Contours of the f-k analyses of vertical components for S-array at Santa Monica City Hall (time segment 1-10; 1.6 Hz - 6.0 Hz).

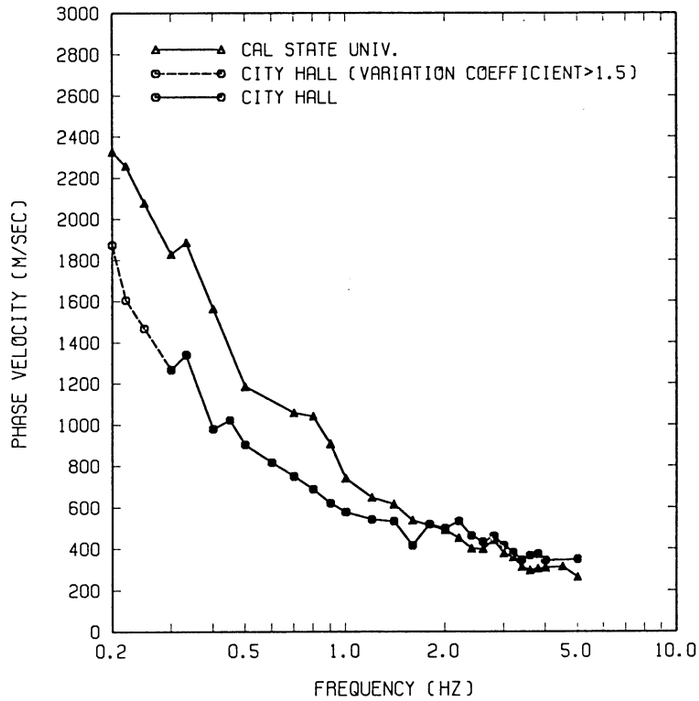

Figure 5 Estimated phase velocities at Santa Monica City Hall and Cal. State Univ. Northridge as final representative values.

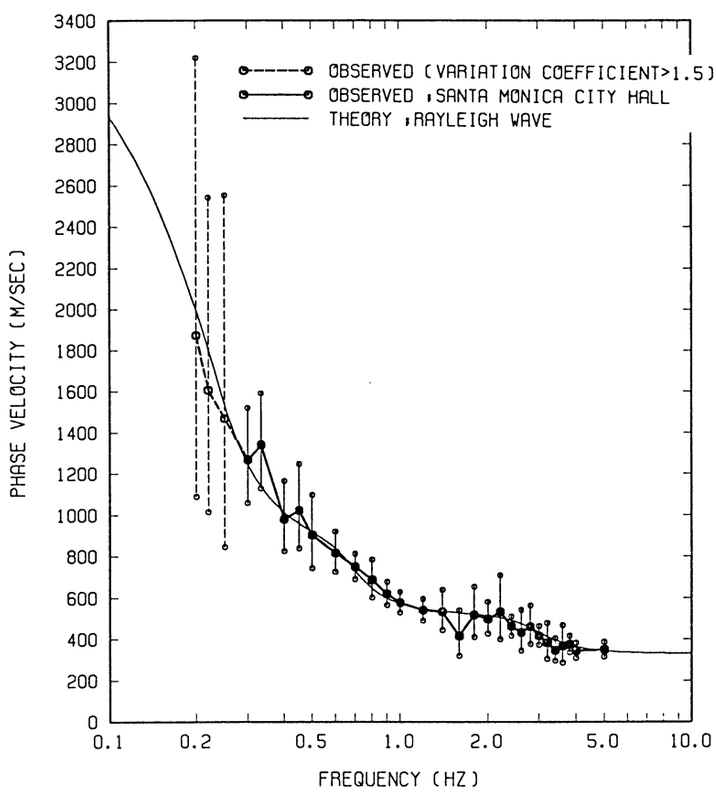

Figure 6 Estimated phase velocities at Santa Monica City Hall and the theoretical dispersion curve of our inverted velocity model in this study.

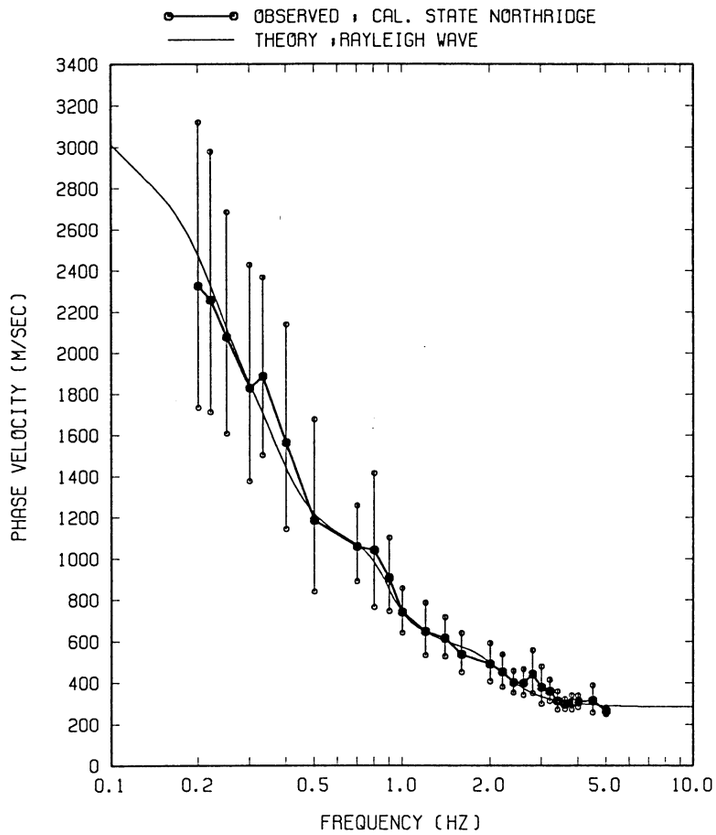

Figure 7 Estimated phase velocities at Cal. State Univ. Northridge and the theoretical dispersion curve of our inverted velocity model in this study.

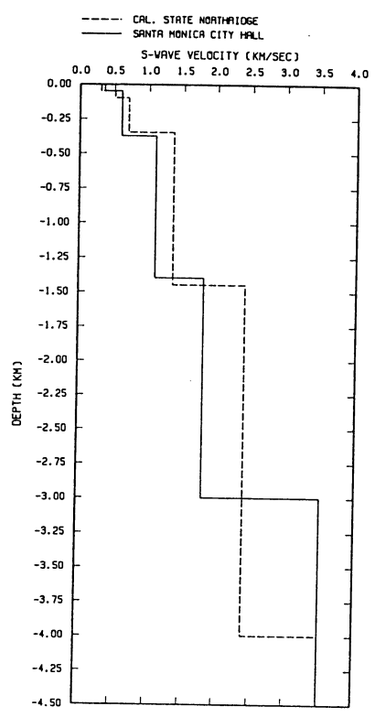

Figure 8 The S-wave velocity structures inverted in this study for Santa Monica City Hall and Cal. State Univ. Northridge

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Non-technical Abstract

We use the Rayleigh wave inversion technique of microtremors to investigate S-wave velocity structures in the San Fernando Valley and Santa Monica. We have conducted field measurement of microtremors by fifteen arrays deployed at seven sites during July and August in 1995. The quality of the observed microtremors is quite good and we verify the applicability of the technique in the US. We obtain S-wave velocity structures at the center of the San Fernando Valley and at the Santa Monica City Hall, which are different from those previously assumed for these sites. Based on the obetined velocity models from the surface down to the bedrock we can simulatie strong motions in these areas.