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Magnitude of Nonlinear Sediment Response in Los Angeles Basin during the 1994 Northridge, California, Earthquake

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Abstract The study of nonlinear site response has practical difficulties due to large ambiguities in isolating local response from other competing effects. We chose a sedimentary site LF6 in Los Angeles basin that (1) has the closest reference rock sites available, compared to other stations, allowing an accurate estimation of local amplification, and (2) illustrates clear resonance in the near surface. In our opinion, this case represents the least ambiguity in the identification of possible nonlinearity. The site responses during the Northridge, the 1987 Whittier Narrows events and the Northridge aftershocks are compared. The station shows a fundamental resonance–frequency change between the higher- and lower-amplitude motions in the entire ensemble of 17 events used. The net shear-modulus reduction during the Northridge event is a factor of 1.3 to 1.4 compared to the Whittier Narrows event and is a factor of 1.7 compared to the aftershocks. This result provides guidance of what to expect at other sites in the basin, where the nonlinear response is less easy to characterize.

Introduction

The 17 January 1994, *M* 6.7 Northridge, California, earthquake produced ground accelerations that exceeded 1 *g*, or nearly the highest levels ever recorded in an earthquake (Trifunac *et al.,* 1994). Ground deformations at this level of accelerations are expected to be highly nonlinear (Hardin and Drnevich, 1972; Yu *et al.,* 1993; Aguirre and Irikura, 1995; Beresnev *et al.,* 1995; Beresnev and Wen, 1996a; Johnson and Rasolofosaon, 1996).

The soil typically exhibits a ''softening'' nonlinearity, or the decrease in effective modulus and effective shear-wave velocity as strain increases. Increasing strains may also cause progressively larger hysteresis, leading to a higher attenuation at higher strain (Hardin and Drnevich, 1972; Beresnev and Wen, 1996a).

It is well known that the seismic waves recorded at the free surface are significantly amplified by low-velocity soil layers (Shearer and Orcutt, 1987), especially when a low-velocity layer is present leading to resonance response. For a single layer over a half-space, the fundamental resonance frequency is

$$f = V/4H, \tag{1}$$

where V is the shear-wave velocity and H is the layer thickness. It turns out that because nonlinearity reduces the wave velocity, the resonance frequency will be decreased too.

Most estimates of the site amplification for the purposes of microzonation are obtained through weak-motion studies (Phillips and Aki, 1986; Field *et al.,* 1990). For the Los Angeles area, mapping of local response has been conducted by Rogers *et al.* (1984), using the weak motions from the Nevada nuclear tests, and by Hartzell *et al.* (1996), from the aftershocks of the Northridge earthquake. A comparison of weak- and strong-motion amplification factors, derived from remote nuclear blasts and the 1971 San Fernando, California, earthquake (Rogers *et al.,* 1984), led to inconclusive results as to the significance of nonlinear site effects in the Los Angeles basin. However, recent work by Field *et al.* (1997) and Beresnev *et al.* (1998) indicates that the Northridge event produced pervasive nonlinear response at the sedimentary sites, estimated on average. Thus, at the present time, it becomes clear that nonlinear ground behavior has to be seriously considered in local seismic-hazard analyses, at least for the Los Angeles basin. If nonlinearity is pervasive, the microzonation based on weak motions may be misleading in predicting the motions for large events.

Field *et al.* (1997) and Beresnev *et al.* (1998) focused on the basin-average characteristics of nonlinear ground behavior. However, an examination of the response at individual sites provides the necessary clue to the nature of constitutive laws controlling soil response to strong ground motion. Many of the basin's permanent strong-motion instruments that recorded the Northridge event also recorded the 1 October 1987 *M* 6.1 Whittier Narrows earthquake (Fig. 1). The purpose of this study is to compare the site amplification during the Northridge, Whittier Narrows events, and the Northridge aftershocks, which, taken together, provide a wide range in the level of ground shaking. Due to a large uncertainty in isolating the local response from the other

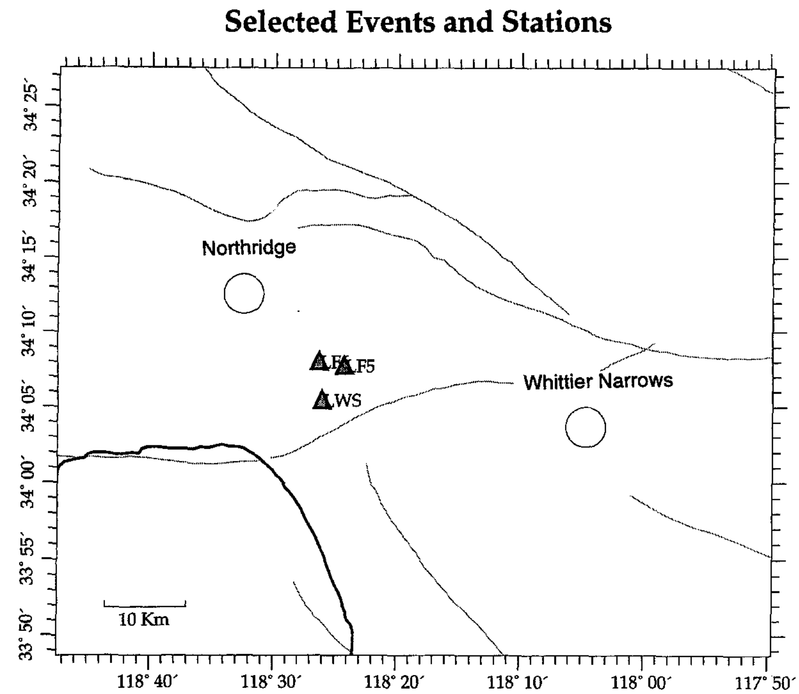

Figure 1. Stations used in this study and epicenters of the Northridge and Whittier Narrows events. The map was drawn using the online software at the Institute of Crustal Studies, University of California, Santa Barbara.

factors contributing to the recorded motions, we limit the analysis to one extreme case that we consider most favorable for characterizing nonlinearity. Based on study of all strong-motion records available, we select the soil station LF6 (Los Angeles Fire Station 99), which has the closest rock sites available and thus allows an accurate estimation of local response (Fig. 1). This station also demonstrates clear resonance response. It is our assumption that if nonlinearity was significant during the Northridge event, it can be most unambiguously identified at this station.

We calculate the site responses using the spectral-ratio technique. The Southern California Earthquake Center (SCEC) abbreviations for station names are used. Stations LF6 and LWS have records of the Northridge aftershocks from the colocated temporary instruments, which are used in our analysis.

The locations of station LF6, as well as rock stations LF5 and LWS used to obtain reference motions, are presented in Figure 1. The stations are categorized as "soil" and "rock" following the classification of Chang *et al.* (1996, Table 1). All of the Northridge and Whittier Narrows mainshock records were obtained through the SCEC strong-motion database (Tumarkin *et al.*, 1996; http://smdb.crustal.ucsb.edu). The aftershock data for station LF6 were obtained from the SCEC data center (http://www.scecdc.scec.org); for station LWS, from the U.S. Geological Survey (Meremonte *et al.*, 1996). The site characteristics are summarized in Table 1. Table 1 also categorizes the stations according to the parameter s used by the University of Southern California, the owner of strong-motion instruments (Trifunac *et al.*, 1994). According to the original definition, $s = 0$, 1, or 2 corresponds to shallow and deep alluvium, sedimentary rock, and igneous or metamorphic rock, respectively (Trifunac and Brady, 1975, p. 150). According to the authors, this grouping is made on the basis of the hardness of the material at the instrument location together with a general knowledge about the site but remains purely qualitative. The classification is apparently not based on the measurements of shear-wave velocities; at least, these velocities are not provided.

Table 1
Soil and Rock Site Characteristics

Station	Latitude (deg)	Longitude (deg)	Site Classification Parameter s*	Peak Horizontal Acceleration† Whittier Narrows (cm/sec^2)	Peak Horizontal Acceleration† Northridge (cm/sec^2)
			Soil		
LF6	34.132	−118.439	$s = 0$	113.9	475.0
			Rock		
LF5	34.127	−118.405	$s = 1$	106.7	530.0
LWS	34.089	−118.435	$s = 2$	51.7	270.0

*After Trifunac *et al.* (1994). $s = 0$, 1, and 2 corresponds to alluvium, sedimentary rock, and basement rock, respectively.

†Average of two horizontal components. Peak values are taken from decimated traces (see text).

Calculation of Spectral Ratios

All records were low-pass filtered with a cut-off frequency of 12.5 Hz and decimated to a common sampling interval of 0.02 sec. The amplitude Fourier spectra of the cosine-tapered 10-sec windows of shear wave were calculated and smoothed using a running three-point weighted (0.25–0.5–0.25) sum. The raw spectra were sampled at 0.0061 Hz. We used visual judgment to determine the number of runs needed to achieve the optimum smoothing. We used 170 runs for all the ratios considered in this article. The spectra of the two horizontal components were geometrically averaged. The ratios between the spectra at two stations were corrected for the difference in hypocentral distance using the expression of Jarpe *et al.* (1988, p. 426). The crustal shear-wave velocity of 3.25 km/sec (Hartzell *et al.*, 1996, p. S169) and attenuation $Q(f) = 150 f^{0.9}$ (Chin and Aki, 1991, p. 1874) were assumed. Estimation of signal-to-noise ratio was obtained from digital recordings of aftershocks. All spectral ratios are shown in the frequency range where the aftershock signal is a factor of 5 or more greater than the pre-event noise, as determined at station LWS.

Comparison of Site Responses

The distances between station LF6 and the rock sites LF5 and LWS are 3.2 and 4.8 km, respectively. Figure 2a presents the amplification at station LF6 calculated with respect to these two sites for Whittier Narrows and Northridge mainshocks (thin and thick lines, respectively). The spectral ratios computed between LF6 and the reference stations were averaged for each earthquake and combined in one curve. Stations LF6 and LWS also jointly recorded 15 Northridge aftershocks. Figure 3 presents the average LF6/LWS aftershock spectral ratio (thick line), with a band showing 95% confidence limits of the mean.

All the ratios resolve the same prominent peak between approximately 1.9 and 2.5 Hz. A useful means to identify the fundamental resonance of a soil layer is to use the spectral ratio between the horizontal and vertical components of ground motion (Field and Jacob, 1995). The average horizontal-to-vertical ratio for the same 15 aftershocks is shown as a thin line in Figure 3. It reveals the same low-frequency peak, suggesting that this is the fundamental resonance at site LF6.

We point out that the resonance frequency in Figures 2a and 3 is amplitude dependent. The largest frequency corresponds to the small-event aftershock data, equal to approximately 2.5 Hz in the soil-to-rock ratio in Figure 3. The frequency is 1.9 Hz for the Northridge mainshock (Fig. 2a), and the Whittier Narrows peak lies in between. Figure 2b depicts the linear correlation coefficient between the shifted Whittier Narrows and Northridge spectral ratios. It has a positive maximum at the frequency shift of −0.32 Hz, the negative sign corresponding to the Whittier Narrows ratio moving to the left. The correlation coefficient was calculated in the frequency band of 0.5 to 4 Hz, surrounding the resonance peak.

The correlation analysis also allows one to directly estimate a net reduction in shear modulus from the observed spectral ratios. Using $V = (\mu/\rho)^{1/2}$ in equation (1), where μ is the shear modulus and ρ is the density, the resonance frequency shift can be related to a modulus change as

$$\Delta f = f_w [1 - (\mu_s/\mu_w)^{1/2}], \quad (2)$$

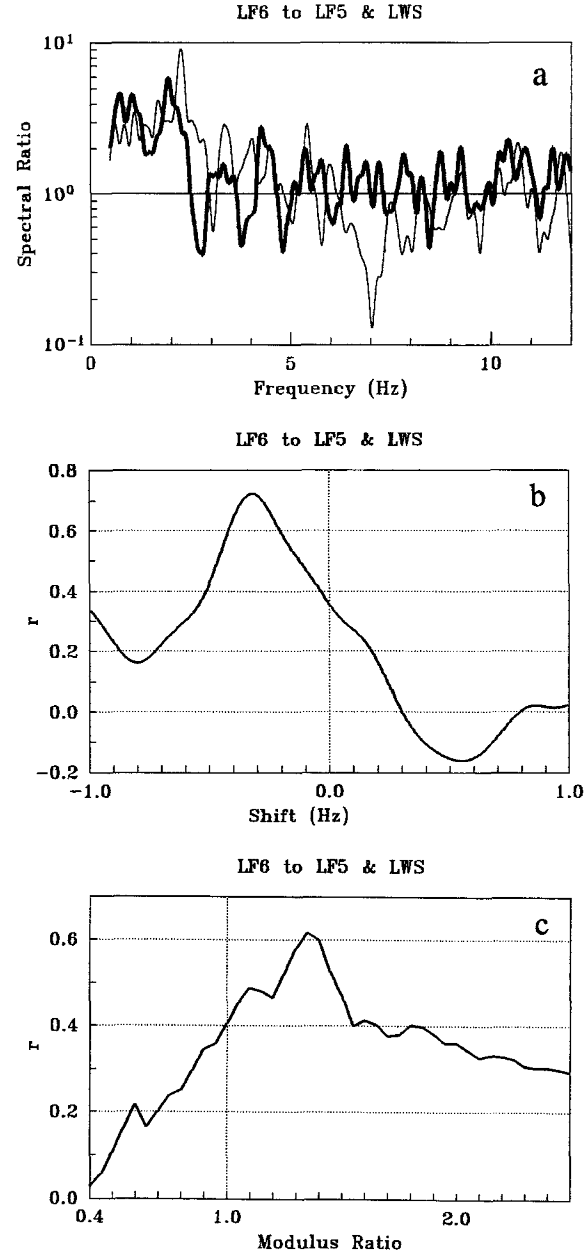

Figure 2. (a) Average ratios of Fourier acceleration spectra between soil site LF6 and rock sites LF5 and LWS in the Whittier Narrows (thin line) and Northridge (thick line) mainshocks. (b) The linear correlation coefficient (r) between the Whittier Narrows and Northridge ratios, calculated in the band of 0.5 to 4 Hz, as a function of frequency shift. (c) The linear correlation coefficient (r) between the strong-motion ratio and the weak-motion ratio "contracted" ("expanded") at all frequencies according to equation (2). r is plotted as a function of μ_w/μ_s.

where Δf is the difference in the resonance locations between the weak and strong motions, f_w is the weak-motion resonance frequency, and μ_w and μ_s are the shear moduli in weak and strong motions, respectively. To assess the modulus change from (2), we shift all the ordinates of a weak-motion ratio along the frequency axis by the corresponding Δf's and correlate the result with the strong-motion ratio, for fixed values of μ_s/μ_w. The maximum correlation then indicates the actual modulus change. Figure 2c presents the result of this calculation for the Whittier Narrows and Northridge spectral ratios. The correlation is the highest at μ_w/μ_s between approximately 1.3 and 1.4, which is the inferred modulus reduction during the Northridge mainshock compared to the Whittier Narrows mainshock.

The obtained value of modulus reduction can be checked for consistency with the nonlinear soil properties measured under laboratory conditions. Figure 4 shows the dependence of the shear modulus on strain in moderately stiff soil characteristic of the Los Angeles basin (Silva *et al.*, 1995). The peak strains during the Whittier Narrows and Northridge events can be estimated from observed peak accelerations, predominant periods, and near-surface velocities in the assumption of a harmonic wave train, as discussed by Beresnev and Wen (1996b, equation 15). For the average shear-wave velocity of 600 m/sec (Silva *et al.*, 1995), the peak strain at station LF6 is approximately 1×10^{-4} and 7×10^{-4} for the Whittier Narrows and Northridge events, respectively. To evaluate nonlinear behavior of soil during dynamic deformation, the value of effective shear strain, which is 65% of the maximum strain, is normally used (Schnabel *et al.*, 1972; Satoh *et al.*, 1995, p. 1829). For the corresponding difference in effective strain, a modulus ratio of 1.8 follows from Figure 4, which agrees satisfactorily with the reduction of 1.3 to 1.4 obtained from field observations, taking into account a non-site-specific character of the laboratory curve used.

Finally, we plot the frequencies of fundamental resonance at station LF6 as a function of peak ground velocity at rock station LWS for all available data, including 15 aftershocks and the Whittier Narrows and Northridge mainshocks (Fig. 5). The resonance frequencies were picked at the abscissas of the maxima of the LF6/LWS spectral ratios in the frequency range from 1.5 to 3 Hz. To estimate the possible error, we used 20, 30, 50, 90, and 170 applications of three-point running average to smooth the raw ratios and calculated the resonance frequency as the mean of the five resulting values. The 95% confidence limits of the mean, estimated from t distribution, are indicated where they exceed the size of the circle. The correlation coefficient between the variables in Figure 5 is -0.74, indicating a probability of more than 99.9% that they are negatively correlated (Bevington and Robinson, 1992, Table C.3).

It may be tempting to draw a least-squares fit in Figure 5 showing a gradual decrease in resonance frequency with increasing velocity; there is, however, much scatter in the

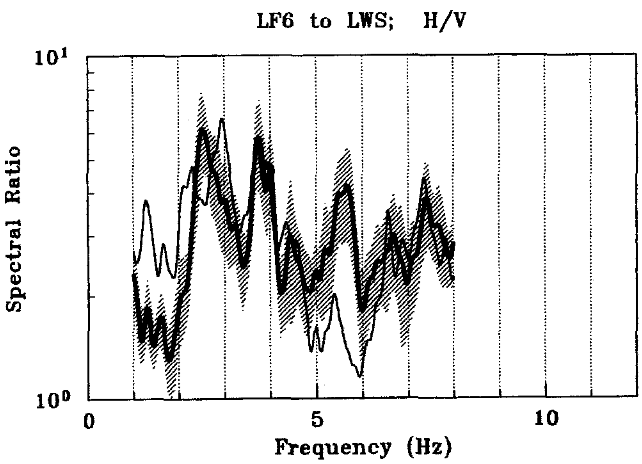

Figure 3. Average spectral ratio between stations LF6 and LWS for 15 Northridge aftershocks (thick line). The shaded band indicates 95% confidence limits of the mean, calculated from t distribution. Thin line shows the average horizontal-to-vertical spectral ratio for the same events.

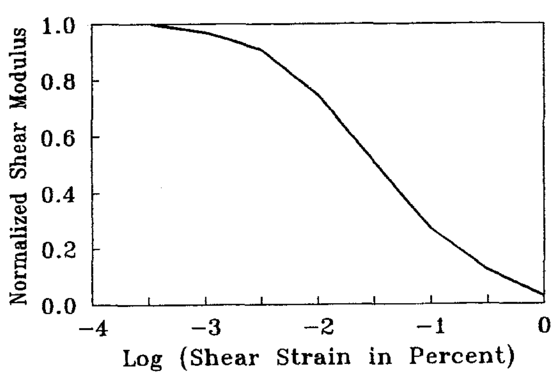

Figure 4. Generalized shear-modulus reduction curve for moderately stiff soil at depths of 0 to 6 m in the Los Angeles basin (after Silva *et al.*, 1995). Shear modulus is normalized to its value at strain of 10^{-4}%.

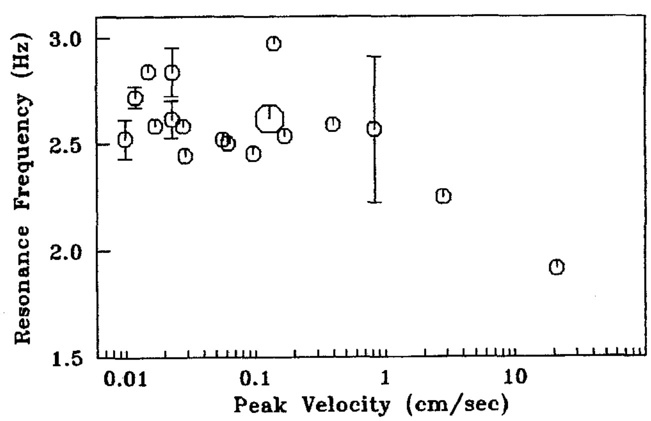

Figure 5. The average fundamental resonance frequency at site LF6 as a function of peak ground velocity at rock site LWS. Data points correspond to 15 Northridge aftershocks and Whittier Narrows and Northridge mainshocks. Error bars indicate 95% confidence limits of the mean. The large circle is the average resonance-frequency value for all aftershocks.

aftershock data, and this could be a misleading interpretation. We opted for adding an additional data point showing the average frequency for all aftershocks (large circle in Fig. 5). Together with the two points indicating Whittier Narrows and Northridge data (extreme right in Fig. 5), this shows a clear trend for the fundamental resonance frequency to decrease with the increasing velocity level.

Note that, excluding the Whittier Narrows mainshock, the distribution is nearly bimodal in frequency. Our recent numerical modeling of nonlinear amplification using hysteretic constitutive law, by the method of Joyner (1977), indicated that the resonant frequency may jump discontinuously, rather than progressively shift (work in progress). Clearly, the frequency diminishes for the large events. Exactly how is still an open question requiring more model and observational data.

The overall resonance frequency change between the Northridge mainshock and its aftershocks is about 0.6 Hz, as seen from Figure 5. Using this value in formula (2), where f_w is approximately 2.5 Hz, gives a total shear-modulus reduction of 1.7 between the aftershock motions and the Northridge mainshock.

Conclusions

The Northridge earthquake produced ground accelerations that lie in a nonlinear range. Some stations show clear resonance effects making nonlinear response easier to observe. Unlike all other recording sites in the Los Angeles basin, the soil station LF6 has two rock stations in the close vicinity, allowing an accurate estimation of site response. In our opinion, the characteristics of nonlinearity in this case can be characterized with most confidence. We compare site response calculated during the Northridge event with the responses calculated from the weaker Whittier Narrows event and a number of Northridge aftershocks.

Nonlinear soil response is known to transiently alter the effective shear modulus resulting in changes in the resonance frequency of the near-surface layer, in addition to reducing amplification in larger-amplitude motions. At site LF6, a clear change of the fundamental resonance has been observed, depending on the amplitude of upcoming motions. The change is consistent with the nonlinear soil properties derived from standardized geotechnical data. We do not notice a significant reduction in amplification at the resonance frequency during the Northridge mainshock. This may be indicative that the near-surface material at site LF6 has not experienced significant hysteretic damping. It remains to be seen what it could imply for the prevailing constitutive laws used in theoretical modeling of soil response. We are currently conducting model studies from Northridge strong-motion sites in order to address this issue.

We conclude that there has been a significant shear-modulus reduction at the sedimentary site LF6 during the Northridge earthquake, caused by soil nonlinearity. The nonlinear response at the other locations may be pronounced as well but may be more difficult to observe because of a lack of nearby rock stations.

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