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Nonlinear soil amplification inferred from downhole strong seismic motion data

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Abstract. Nonlinear seismic response of soil is studied by comparison of the frequency-dependent soil amplification functions calculated on weak and strong motion. Amplifications are obtained by dividing Fourier amplitude spectra of acceleration at the ground surface by the spectra at the depths of 11 and 47 m in a borehole. Observed weak and strong motion spectral ratios are compared with those theoretically deduced from the one of the nonlinear soil models adopted in geotechnical engineering. Significant deamplification of the strong motion having PGA (peak ground acceleration) greater than 0.16 *g*, relative to the weak motion, is exhibited by the experimental ratios in the frequency range that is consistent with the model prediction. Existence of the different frequency bands, in which specific features of the nonlinear soil response are recognized in the theory, is also confirmed. These results give evidence of that nonlinear response can be observed at soft sedimentary sites from the real strong motion data.

Introduction

Nonlinear soil response in strong ground motion has long been a controversial subject in seismology and earthquake engineering. It has been known theoretically [e.g., *Idriss and Seed*, 1968] that nonlinear effects in near-surface deposits can be manifested in increased damping and reduced shear wave velocities, both occurring as the excitation strength increases from low to high. These effects are caused by the hysteretic nature of the soil shearing deformation, as revealed from cycling loading tests performed on soil samples under laboratory conditions.

It is well known that low-impedance surface layers amplify the upcoming seismic waves [e.g., *Shearer and Orcutt*, 1987]. The fundamental resonance frequency of a layer is $f = V / 4H$, where V is the wave velocity and H is the layer thickness. Reduction in shear wave velocity is thus associated with the decrease in the fundamental frequency [*Chang et al.*, 1989; *Johnson et al.*, 1993]. Because nonlinearity also increases damping, it works against ground motion amplification. Hence, the seismologically observable symptom of the nonlinear ground behavior is deamplification of the strong motion with respect to the weak motion, accompanied by the downward shift in resonance frequencies.

Reliable seismological demonstrations of the nonlinear ground response are nevertheless scarce. That is why nonlinearity was never taken into account in routine seismological practice such as microzonation, while being recognized by geotechnical engineers at the same time [*Finn*, 1991; *Aki*, 1993]. This controversy emphasizes the necessity of direct seismological substantiation of the nonlinear site effects. Several such observations appeared recently. Indication on the deamplification of strong ground motion was reported by *Jarpe et al.* [1988] for aftershocks of the 1983 Coalinga earthquake and by *Chin and Aki* [1991] and *Darragh and Shakal* [1991] for the 1989 Loma Prieta earthquake.

A main obstacle to identifying nonlinear site effect is that observed spectra are always contaminated by source and path contributions. A straightforward way to isolate a site amplification function is to take the ratio of Fourier amplitude spectrum at one site to that at a reference site. As a rule, a station installed on a nearby hard rock outcrop is chosen as a reference one [*Jarpe et al.*, 1988; *Darragh and Shakal*, 1991]. However, this procedure never eliminates source and path spectral contributions altogether because of the finite distance between the stations. This problem is efficiently overcome when the site amplification is assessed using the uphole/downhole data [*Archuleta et al.*, 1992]. The site response can be almost ideally isolated by taking the spectral ratio of the surface to downhole accelerometers.

Nonlinear site effects in the upward vertically propagating transverse wave have been theoretically modeled recently by *Yu et al.* [1993] using the public-domain geotechnical code DESRA2. The model postulates a hysteretic constitutive law with a hyperbolic skeleton curve. Predicted spectral ratios of accelerations between the surface and the center of a sedimentary stratum in the linear and nonlinear cases are reproduced in Figure 1. The layer has a thickness of 20 m, and its shear wave velocity gradually increases from about 100 to 320 m/s from the top to the bottom.

Figure 1 shows that the discrimination between the linear and nonlinear responses is frequency-dependent. The theoretical response can be separated into three frequency bands. Ratios are not affected by nonlinearity at the low frequencies, because the wavelength becomes sufficiently long and the waves do not really "see" the layer. In the central frequency range, nonlinear deamplification occurs and the resonance shifts downwards. Finally, spectral ratios in the strong motion are, conversely, amplified over those in weak motion in the high-frequency band. This nonlinear "overamplification" is a result of the competitive effects of increased damping and higher harmonics generation. Generation of high frequencies is typical for the wave propagation in a material with a nonlinear relationship between stress and strain. Recent seismic and ultrasonic experiments carried out by *Beresnev and Nikolaev* [1988] and *Johnson and McCall* [1994] show that it can be detected in the earth materials.

Note that the peculiarities of the nonlinear site response illustrated in Figure 1 are not inherent to the particular stress-strain model implemented in DESRA2. The existence of all three fre-

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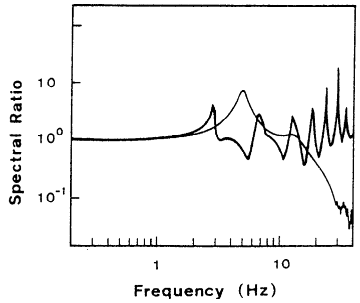

Figure 1. Theoretical spectral ratios of accelerations at the surface to the center of a soil layer in linear (thin line) and nonlinear (thick line) responses [after *Yu et al.*, 1993].

quency bands has a general physical rationale behind it. We verify this prediction using the borehole weak and strong motion data observed in Taiwan.

Data and Method

Our data consist of the recordings from a downhole accelerograph array which was deployed as part of the LSST (Lotung Large-Scale Seismic Test) project in the south-west quadrant of the SMART1 array in Taiwan [*Chang et al.*, 1989; *Wen*, 1994]. The borehole was drilled to a depth of 47 m in alluvial deposits. Figure 2 gives its shear wave velocities. Accelerographs were installed at the surface and the depths of 6, 11, 17, and 47 m. Digital data were recorded as 12-bit words at the rate of 200 samples per second. We present the surface to 11 m and surface to 47 m spectral ratios in this paper.

Events selected for the analysis are listed in Table 1. Earthquakes with peak horizontal acceleration at the surface less than 50 Gal are provisionally attributed to the "weak motion". Events having PGA over 160 Gal (roughly 0.16 *g*) are considered "strong motion". We compare the spectral ratios of weak and strong motion, as well as the ratios calculated for two strong events and their weaker foreshocks and aftershocks. We are primarily interested in the amplitude-dependent soil amplification study in this paper. Shear wave velocity reduction effect derived from the same database is discussed elsewhere [*Wen*, 1994].

All spectral ratios are calculated as follows: (1) an 8-s window containing the shear wave is identified; (2) the window is tapered; (3) the Fourier amplitude spectrum is calculated; (4) the spectrum is smoothed using a 3-point running Hanning average; (5) the ratio of two smoothed spectra is then calculated. Eighty consecutive smoothings were applied to the raw spectra. This number was chosen empirically considering its visual effect on the spectral shape. All final ratios used in this analysis are calculated by summing the squares of the ones for EW- and NS-components, dividing by two, and taking the square root.

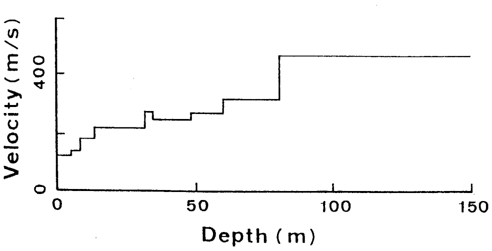

Figure 2. Low-strain shear wave velocity structure at the LSST site.

A signal-to-noise ratio was estimated from the seismograms having sufficiently long pre-event noise time history by dividing the smoothed amplitude spectra of the S-wave and the pre-event noise. All the results are plotted in the frequency band where the signal-to-noise ratio is greater than five.

Safak [1991] points to some problems in applying spectral ratio method to the real records. In our application, we use a uniform-length time window with a fixed number of spectral smoothings and present only those parts of spectral ratios where the signal-to-noise ratio is sufficiently large. This effectively reduces the possible uncertainties in the results.

Results

Figure 3 compares the average spectral ratio calculated for 11 weak events (thin line) with the individual ratios for three strong events (thick lines). The shaded band around the average curve represents ± 1 standard deviation. Ratios of spectra at surface to 11 m and 47 m are shown in Figures 3a and 3b, respectively. The strong motion ratio is given only for event 7 in Figure 3b, because the corresponding borehole instrument has been out of operation since event 11 was recorded.

It can be seen, first, that the soil column amplifies the weak motion at all frequencies. The fundamental frequency of the upper 11 m-thick stratum is approximately 3.5 Hz (Figure 3a). The weak motion transfer functions are estimated rather precisely, which is confirmed by the low values of standard deviation.

Secondly, reduction in strong motion ratios is clearly seen in the intervals from approximately 2.5 to 5 and 7.5 to 10 Hz in Figure 3a, and from 1 to 7 and 8.5 to 10 Hz in Figure 3b, sug-

Table 1. Selected LSST Events

Event	Date	Depth (km)	M_L	Δ* (km)	$A_0/A_{11}/A_{47}$† (Gal)
		Weak Motion			
5	29/03/86	10	4.7	8	41.4/17.8/15.4
6	08/04/86	11	5.4	31	35.4/15.2/13.0
8	20/05/86	22	6.2	69	34.3/21.5/14.2
10	16/07/86	1	4.5	6	39.3/26.3/19.2
14	30/07/86	2	4.9	5	49.4/31.2
20	10/12/86	98	5.8	42	23.8/11.4
21	06/01/87	28	6.2	77	31.8/16.8
22	04/02/87	70	5.8	16	43.8/20.4
23	24/06/87	31	5.7	52	31.7/11.5
24	27/06/87	1	5.3	40	23.7/13.1
27	18/09/88	63	5.6	68	22.3/11.1
		Strong Motion			
7	20/05/86	16	6.5	66	223.6/113.7/96.9
12	30/07/86	2	6.2	5	186.7/192.8
16	14/11/86	15	7.0	74	167.2/94.6
		Stronger Foreshock to Event 12			
9	11/07/86	1	4.5	5	70.5/34.1/28.4

* Epicentral distance.

† Peak horizontal acceleration at the surface, 11 m, and 47 m, respectively. Recordings at 47 m were not made for the earthquakes subsequent to no.10.

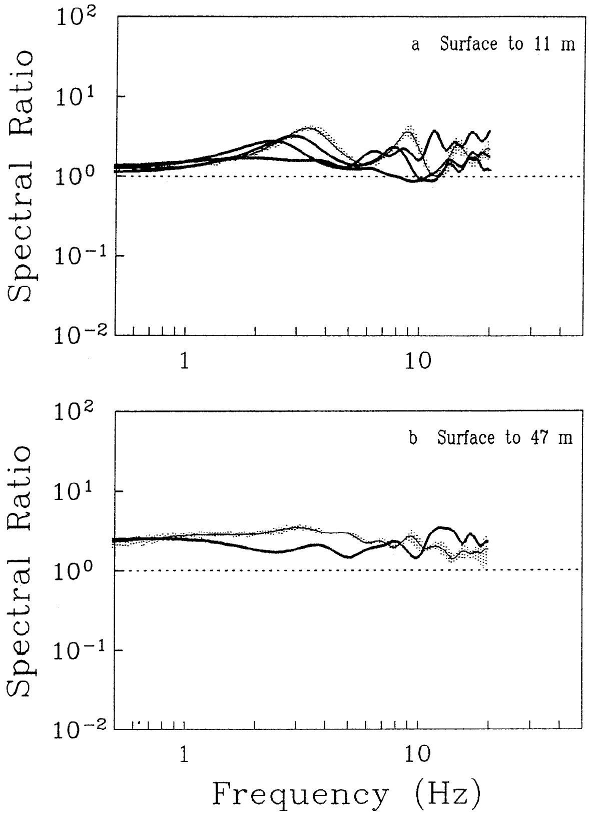

Figure 3. Average weak motion and individual strong motion spectral ratios between the surface and 11 m (a), and surface and 47 m (b).

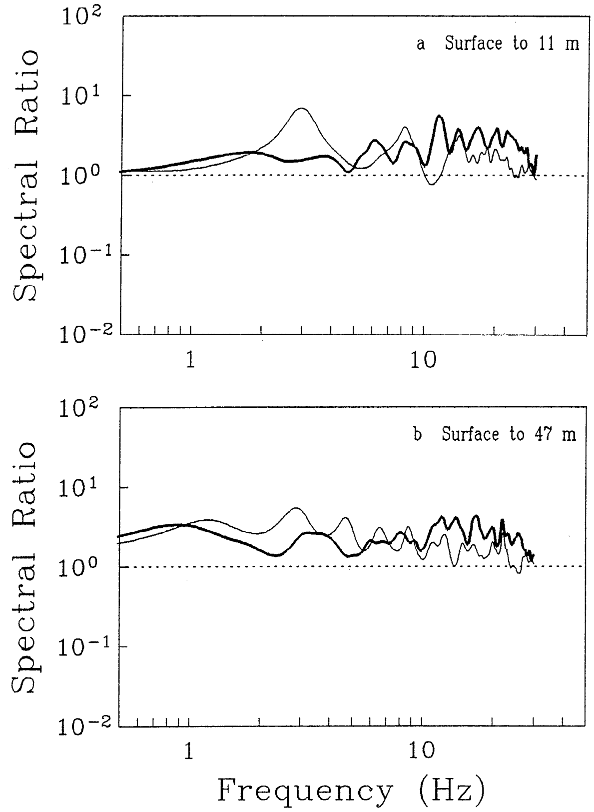

Figure 4. Spectral ratios between the surface and borehole instruments for the strong shock 7 and its aftershock 8.

gesting a nonlinear response in agreement with the theoretical prediction. A downward shift in the fundamental frequencies of the strong motion responses for the upper 11 m is also clear from Figure 3a. The deamplification effect well exceeds the error margin. Amplifications in weak and strong motions converge at the low-frequency limit. Predicted overamplification of the strong motion in the high-frequency range appears only in one strong event 7, both in Figures 3a and 3b. We address this discrepancy in more detail below.

Figure 4 presents spectral ratios for the same pairs of instruments taken individually for the strong earthquake 7 (thick line) and its aftershock 8 (thin line). Peak horizontal accelerations at the surface were 224 and 34 Gal for the main shock and the aftershock, respectively. We reduced the number of smoothings from eighty to twenty in the calculation of spectra here to illustrate its effect on spectral ratios. Strong motion deamplification occurs in the same frequency range as in Figure 3. A high-frequency interval with a relative amplification of the strong motion clearly appears in both Figures 4a and 4b above a cross-over of approximately 10 Hz. Behavior of overall curves in Figure 4 compares well with the calculation in Figure 1.

Figure 5 compares spectral ratios calculated for the strong earthquake 12 with those of its foreshocks and aftershocks (events 9, 10, and 14). Also plotted in Figure 5 is a weak motion ratio obtained from the eight-second coda window starting at 17 s after the S-wave arrival in the event 12 time history. All four spectral ratios calculated from foreshocks, aftershocks, and coda are close to each other (thin lines). The strong motion ratio (thick line) is notably reduced between approximately 2.6 and 11 Hz. However, high-frequency nonlinear amplification is not manifested in Figure 5. As inferred from the previous analysis, only earthquake 7 exhibited this effect. The tentative explanation for such an inconsistency may be as follows. Firstly, the event 7 produced a largest horizontal acceleration of about 0.22 *g*, that may have resulted in a more significant nonlinear response than in the other strong earthquakes. Secondly, as seen from Figure 1, the high-frequency difference between the linear and nonlinear responses increases with increasing frequency; however, we generally could not address the frequencies beyond 20 Hz because of the poor signal-to-noise ratio (Figure 4 is the only exception). This virtually prevents us from the identification of the high-frequency generation effect.

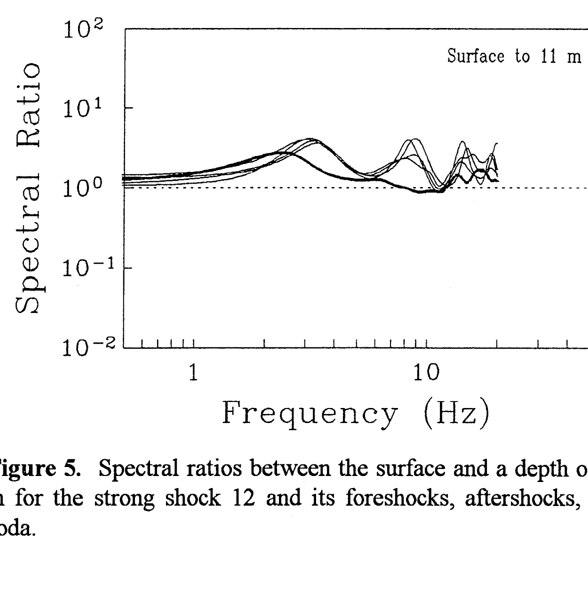

Figure 5. Spectral ratios between the surface and a depth of 11 m for the strong shock 12 and its foreshocks, aftershocks, and coda.

One corollary drawn from Figure 5 is that the amplification function calculated from the coda of the strong shear wave is a good approximation of the weak motion amplification function.

Discussion and Conclusions

We compare theoretical and observed soil responses to weak and strong earthquake loading, using uphole/downhole acceleration data. Results clearly identify the effect of the nonlinear deamplification occurring in soil when the weak motion with a surface PGA of less than 0.05 *g* is compared with the strong motion having PGA exceeding 0.16 *g*. Low-frequency and intermediate-frequency linear and nonlinear behavior of the experimental spectral ratios is in good agreement with that deduced from a hysteretic constitutive relationship of soil. The existence of numerically predicted high-frequency overamplification of strong motion relative to weak motion is noted for the strongest event. The observed differences between the weak and strong motion spectral ratios are systematic and thus cannot be attributed to the random interference effects. The interference would not tell between the weak and strong fields and could never create a systematic difference between them.

Note that the frequency-dependent difference between the linear and nonlinear amplifications implies that characterizing nonlinear site response by the uphole-to-downhole PGA ratio may be misleading. Deamplification, overamplification, or equal amplification of the strong motion relative to the weak motion may occur for the strong events in terms of their PGA, depending on which of three frequency bands their predominant energy falls to.

One of the conclusions of this analysis is that spectral ratio derived from coda following the strong shear wave is identical to the ratio calculated from independent weak earthquakes. Our results show that the nonlinear soil response characteristics are experimentally detectable from the available strong ground motion records.

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