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Quantification of nonlinear soil response for the Loma Prieta, Northridge, and Imperial Valley California earthquakes

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ABSTRACT: A validated source, path, and equivalent-linear site model is used to evaluate nonlinear response at soil sites that recorded the **M** 6.5 1979 Imperial Valley, **M** 6.9 1989 Loma Prieta, and **M** 6.7 1994 Northridge earthquakes using regionally dependent generic soil profiles. Evidence for soil nonlinearity is evaluated by examining the model fit to average horizontal component response spectra over all sites using linear and equivalent-linear analyses with initial depth dependent G/G_{max} and hyteretic damping curves. Site-to-rupture distances ranged from about 1 to over 100 km. Clear evidence of nonlinearity is seen and the conditions where the effects of nonlinearity are strong are resolved: **M** ≥ 6.5, distances within about 30 km (expected rock outcrop PGA exceeds about 0.3g) and frequencies exceeding about 3 Hz. G/G_{max}, and hysteretic damping curves are varied at sites within about 30 km of the sources to improve the model predictions. Differences in material nonlinearity between Northern and Southern California cohesionless soils as well as for the cohesive soils of the Imperial Valley, California are clearly seen and quantified.

1. INTRODUCTION

The issue of nonlinear site response is currently a topic of intense interst. It is well known from laboratory testing that soils exhibit pronounced nonlinear behavior under shear loading conditions. Shear modulus decreases with increasing strain with an accompanying increase in material damping (Drnevich et al., 1966; Seed and Idriss, 1970; Hardin and Drnevich, 1972).

The strain dependence of soil modulus and material damping has been well documented in numerous laboratory studies for sands and clays (Drnevich et al., 1967; Seed and Idriss, 1970; Hardin and Drnevich, 1972; Silver and Seed, 1971; Seed et al., 1984). Various parametric relationships have been proposed to determine values of maximum shear modulus (at small strain levels) and variations of shear modulus and material damping with strain (Hardin and Drnevich, 1971; Martin, 1975). Strain dependency of material properties from laboratory data is universally observed, reproducible, and becomes significant for high levels of earthquake loading, i.e. shearing strains > 10^{-2}% (EPRI, 1993).

1.1 Early field evidence of soil nonlinearity

It has long been recognized that there may be problems associated with laboratory testing of soil samples (Woods, 1968; Seed and Idriss, 1970). Accurate determination of shear moduli is complicated by the effects of sample disturbance. Additionally, resonant column and cyclic triaxial tests do not exactly simulate the dynamic stress paths caused by the passage of shear-waves in the frequency range of several seconds to over 20 Hz. In-situ measurements with stress waves representative of earthquake loading would eliminate these problems, but it is very difficult to induce large strains with controlled amplitudes in natural deposits.

To investigate this problem, two approaches have been utilized: 1) controlled sources employing large-strain-inducing generators; and 2) site response analysis utilizing earthquake or explosion data recorded by horizontal and vertical arrays. The controlled source approach, utilizing soil boring pressureometers, torsional borehole devices, and even controlled explosions, has demonstrated soil nonlinearities (Dobry, 1991). The soil nonlinearity that was observed was either in strain dependent shear-wave velocity or load-deformation relations. Laboratory and field derived curves were in reasonable agreement. Japanese investigators (Tokimatsu and Midorikawa, 1981) have utilized the change in predominant period of site resonances (as observed in response spectra) for different levels of seismic excitation to infer strain dependent velocity changes. The modulus reduction curves obtained in this manner agree in substance with laboratory derived curves for the same sites. Early analyses of transfer functions and amplification factors computed from strong motion data found evidence of nonlinear soil response (Silva et al., 1986; Silva et al., 1989; Chang et al., 1990; Silva, 1991; Su et al., 1992; Silva and Stark, 1992). Silva et al. (1986), based on analyses of direct S-waves and code-waves recorded rock and soil site pairs, quantified the onset of nonlinearity at about 30%g and strains exceeding about 2 x 10^{-2} %. These analyses also demonstrated the potential inadequacy of the standard cohesionless soil G/G_{max} and hysteretic damping curves which were based on early laboratory dynamic testing.

The consistency of the transfer function between a soil site and a rock site has been examined for various levels of shaking (Murphy and Lahoud, 1969; Rogers et al., 1974; Hays et al., 1979; Joyner et al., 1981; Rogers et al., 1984; Tucker et al., 1984; Jarpe et al., 1988). In all of these analyses, the authors did not indicate significant evidence of nonlinear soil response. However, it should be emphasized, that in the majority of cases analyzed, average shear strains in the top 50 to 100 ft of the soil column were probably less than 10^{-2}%. At this strain level, curves such as those shown in Figure 2 predict a shear-wave velocity decrease of only about 10% and a damping level of about 3 to 4%, not within the resolution of these analyses. Prior to the 1989 **M** 6.9 Loma Prieta earthquake, the lack of easily accessible strong motion data significantly curtailed the "discovery" of nonlinear site response. Interestingly enough, even in the late 1980's several empirical attenuation relations for crustal earthquakes showed nonlinear site response in that the ratio of response spectral estimates (soil/rock) showed a dependence on expected rock motion levels.

With the recent dramatic increase in strong motion recordings at close distances (≤ 30 km) to large earthquakes, the evidence of nonlinear site response has become the subject of a large number of studies and the results generally confirm stable features of nonlinearity.

2. ANALYSIS PROCEDURE

In an effort to quantify the degree of in-situ nonlinearity at a large number of sites, average horizontal component response spectra were modeled using a ground motion model which includes source-path and an equivalent-linear site. This study was part of a larger validation effort of both the point- and finite-source stochastic models (Schneider et al., 1993). In this validation effort, response spectra were modeled for 17 earthquakes at over 500 sites and for periods ranging from about 3.0 to 0.01 sec in the distance range of about 1 to 500 km (Silva et al., 1997). The ground motion model uses either a single Aki-Brune omega^2 point-source or distributed (**M** 5) point-sources for a finite-fault. Wave propagation is modeled using either 1/R ($1/\sqrt{R}$) for the single point-source model or through raytracing using the method of Ou and Hermann (1990) for the finite-source. Random vibration theory (RVT) equivalent-linear (total stress) site response assumes vertically propagating shear-waves to approximate nonlinear site response. Extensive comparison of the RVT equivalent-linear approach with three different nonlinear (effective stress) formulations and with recorded motions showed very close agreement with each other and with the recorded motions (EPRI, 1993). For each earthquake modeled in the validation exercise, point-source stress drops and regional Q(f) models were determined by inversions of the Fourier amplitude spectra. Small strain kappa (Anderson and Hough, 1984)values were set to 0.04 sec. Earthquake specific crustal models were used along with published slip models and nucleation points.

Results of the comprehensive validation effort were very encouraging and showed that both models performed well with generally good fits to the recorded motions. These results were in general agreement with more limited validation exercises over the last several years (Schneider et al., 1993; EPRI, 1993) suggesting that the model provides simulations of sufficient accuracy to resolve nonlinear site response. The advantage of the RVT approach is that time histories are not required to estimate peak time domain values (Boore, 1983) resulting in very rapid and cost effective stimulations. For a **M** 7 finite fault and 50 layer site analysis, a complete response spectrum may be simulated in about 30 sec on a Pentinum. Time histories may be produced (for applications to nonlinear structural analyses) by simply adding a phase spectrum from a recorded motion to the point source amplitude spectrum (Silva and Lee, 1987).

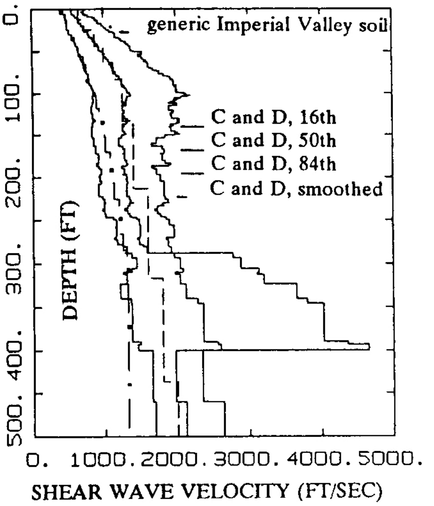

Figure 1. Median and ± 1σ shear-wave velocity profiles for deep soil (Geomatrix C & D) (solid lines) and smooth base case deep soil profile (dashed line). Imperial Valley base case profile (dash-dotted line).

2.1 *Profiles*

For the Northridge and Loma Prieta earthquakes, the soil sites modeled were those classified as either intermediate or deep firm soil (Geomatrix B or C, Youngs et al., 1997). Using the PE&A profile database, a generic shear-wave velocity profile was developed for these site (Figure 1). It extends to a depth of 500 ft where it is placed on top of the regional crustal models. For the Imperial Valley earthquake analyses, a profile was developed based on downhole measurements at the old El Centro strong motion site (Bycroft, 1980). This profile was smoothed and placed on top of the Liu and Helmberger (1985) crustal model. The generic Imperial Valley profile is shown in Figure 1 and is near the -1σ profile for the deep stiff sites. Interestingly, the Imperial Valley profile is similar to the Kobe area Holocene profile suggesting a potential similarity in nonlinear response.

2.2 *Initial G/G_{max} and hysteretic damping curves*

As part of a recent EPRI project, generic modulus reduction and damping curves appropriate for cohesionless soils were developed (EPRI, 1993). The curves accommodate the effects of confirming pressure and were based on laboratory testing, recent literature, and comparisons of simulations to recorded motions in Northern California. The curves are shown in Figure 2 and reflect significantly less nonlinearity than the conventional curves which were based on early laboratory testing. The EPRI curves accommodate the trends seen in the early analyses which suggested onset of nonlinearity around 30%g with conventional mid-range curves generally predicting significantly more nonlinearity than observed at firm sites (Silva et al., 1986). For the validation exercise, these curves provided the initial estimates of nonlinearity at all the firm soil sites and performed well at all but Northridge earthquake soil sites within about 30 km of the source. Imperial Valley sites, due to the presence of clays, were initially modeled with the Vucetic and Dorby (1991) curves for a PI of 15% and 30%.

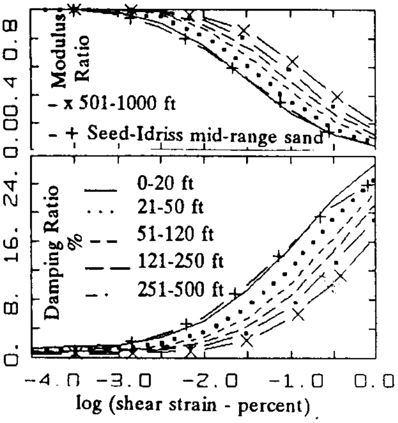

Figure 2. Generic G/G_{max} and hysteretic damping curves for cohesionless soils (EPRI, 1993) and Seed-Idriss mid-range.

2.3 *Median response*

A significant issue arises in evaluating the response of a generic smooth profile in the context of nonlinear analyses and applying the results to actual sites. In general, a site specific soil profile does not display a largely monotomic velocity increase with depth (except perhaps for till and loess sites) and the presence of these variations or notches (low velocity zones) has the effect of reducing the short period motions (particularly as the level of loading increases) compared to a smooth profile with equivalent travel times. As a result, the median response spectra computed over a number of analyses of analyses using random profiles (generally 30 to 50; EPRI, 1993) is generally lower than the spectrum computed using the base case (or median) profile. To illustrate this, Figure 3 shows the spectra computed for a **M** 6.5 earthquake at a distance of 15 km using a 500 ft deep base case soil profile (Figure 1) as well as the median and ± 1σ spectra using 30 random profiles varying in depth from 100 to 1000 ft. Figure 3 shows a difference of about 10 to 20% between the median and base case responses at short periods.

This difference is an important issue and an undesirable limitation in the analyses since only the base case profiles are used. This suggests that the short period motions from the simulations should overpredict on average, resulting in a stable negative bias.

3. RESULTS

Figure 4 shows an example of the model variability and bias (Abrahamson et al., 1990) computed for the Northridge earthquake over 36 soil sites. In general the variability (Chisquare over response spectra at all sites) averages about 0.5 (ln) and the bias (average misfit over all sites) is near zero from 0.1 to 100 Hz. To determine whether the model can discern nonlinear site effects, bias estimates were computed assuming linear and nonlinear response for sites both within and outside the fault distance of 30 km (Figure 5). Although sites outside 30 km (35 sites out to 150 km) do show some evidence of nonlinearity (negative bias = overprediction for linear analyses), the degree is small and likely not outside the 90% confidence limits.

To evaluate the most appropriate set of G/G_{max} and hysteretic damping curves, Figure 6 compares bias estimates using the EPRI curves (Figure 2) and the best fitting curves. The EPRI curves result in a near zero bias which, accommodating for profile variation, would give about a 20% underprediction for frequencies exceeding about 3 Hz. The revised curves (EPRI 0 to 50 ft and 50 to 1000 ft, Figure 9) result in the desired overprediction of about 20% above about 3 Hz.

For the Loma Prieta earthquake results of a similar analysis are shown in Figure 7. In this case only 17 soil sites were available out to 30 km and the EPRI curves result in about the appropriate amount of overprediction.

For the Imperial Valley earthquake, Figure 8 shows bias estimates using three sets of curves as well as a linear analysis. In all analyses, the small strain kappa value is set at 0.03 sec based on inversions of the **M**

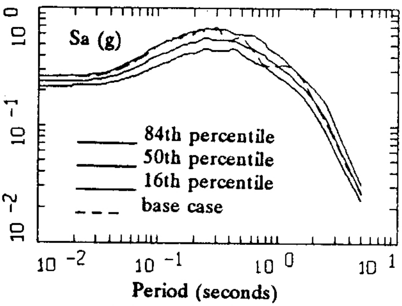

Figure 3. Median and ± 1σ 5% damped pseudo absolute acceleration response spectra computed from 30 randomly generated deep soil profiles with depth varying from 100 to 1000 ft (solid line). The dashed line is the response spectrum computed using the base case deep soil profile (Fig. 1).

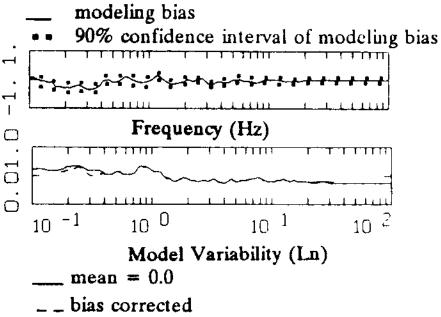

Figure 4. Model bias and variability estimates for the Northridge earthquake computed over all 36 soil sites within 30 km for the finite-source model. EPRI G/G_{max} hysteretic damping curves.

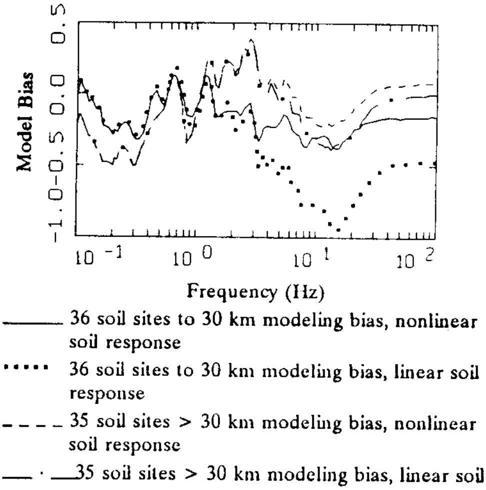

Figure 5. Comparison of bias estimates for the Northridge earthquake computed over soil sites within 30 km and beyond 30 km.

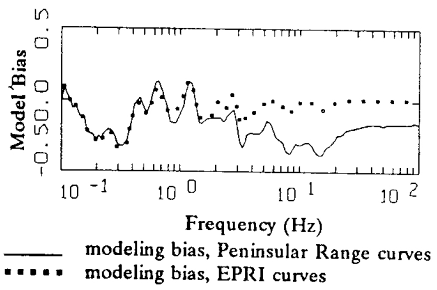

Figure 6. Comparison of bias estimates for the Northridge earthquake computed over all 36 soil sites within 30 km: Solid lines, Peninsular Range G/G_{max} and hysteretic damping curves. Dotted lines, EPRI G/G_{max} and hysteretic damping curves.

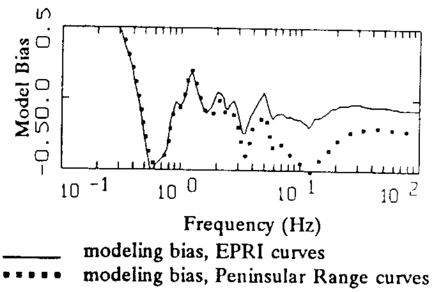

Figure 7. Comparison of bias estimates for the Loma Prieta earthquake computed over all 17 soil sites within 30 km: Solid lines, EPRI soil G/G_{max} and hysteretic damping curves. Dotted lines, Peninsular Range G/G_{max} and hysteretic damping curves.

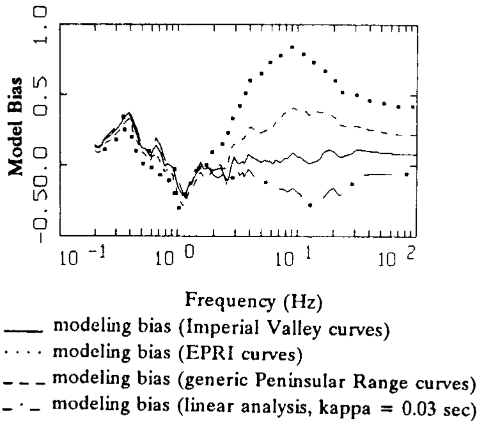

Figure 8. Comparison of bias estimates for the Imperial Valley mainshock earthquake computed over all 15 sites located the El Centro area within 15 km using 3 suites of G/G_{max} and hysteretic damping curves as well as linear site response analyses using fixed small strain material properties.

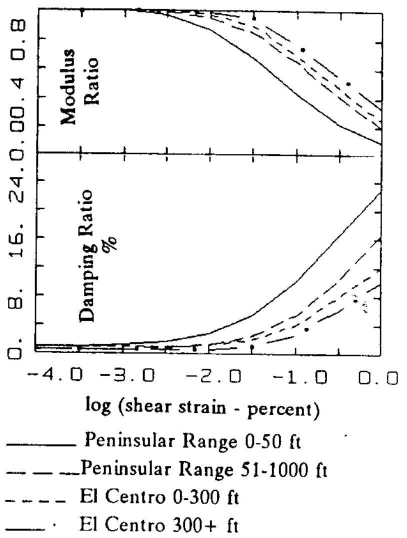

Figure 9. Generic G/G_{max} and hysteretic damping curves for Peninsular Range deep cohesionless soils and Imperial Valley, El Centro soils.

5.2 aftershock. These results suggest that even the highly linear Imperial Valley curves (Figure 9) may be too nonlinear for these sites as they result in a slightly positive bias. Although these sites are expected to be generally more uniform than those comprising the other analyses, all being deep soft soil and within a much smaller area, these results are perplexing and suggest the possibility of highly linear response with recorded motions up to 40 to 50%g. This warrants further study and several sites are being drilled, sampled, and tested as part of the ongoing ROSRINE project.

4. CONCLUSIONS

For three earthquakes, ground motions were sufficiently high and bias estimates were sufficiently small and well determined to permit resolution of nonlinear site response as well as the development of region specific G/G_{max} and hysteretic damping curves. For the cohesionless soils of the North Coast Province, the Loma Prieta analyses demonstrated the appropriateness of the EPRI (1993) curves. For similar cohesionless soil conditions in the Peninsular Ranges Province, the Northridge analyses showed the EPRI (1993) curves resulted in too high a degree of nonlinear soil response and a more linear set of curves was developed. It should be pointed out that these results are relative to the generic soil profile used at all soil sites and any significant differences in median soil profiles between Peninsular Range and North Coast Soils would be reflected in the requirement of distinct G/G_{max} and hysteretic damping curves. Providing the generic soil site profile is appropriate for both regions, the differences in nonlinear dynamic material properties may reflect average differences in age and/or grain size. For the soils of the Imperial Valley, comprised of silts, clays, and silty clays, the analyses of the 1979 mainshock showed very little nonlinear response and a third set of curves was developed for these soils using a generic Imperial Valley soil profile.

These separate analyses suggested an envelope of clear detectability for nonlinear site response: $\mathbf{M} \geq 6.5$, distances within about 30 km, frequencies above 3 Hz, and, for statistical stability, at least 15 stations is desirable.

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