SUMMARY

We present a hybrid finite-difference technique capable of modeling non-linear soil amplification from the 3-D finite-fault radiation pattern for earthquakes in arbitrary earth models. The method is applied to model non-linear effects in the soils of the San Fernando Valley (SFV) from the 17 January 1994 M 6.7 Northridge earthquake. 0-7 Hz particle velocities are computed for an area of 17 km by 19 km immediately above the causative fault and 5 km below the surface where peak strike-parallel, strike-perpendicular, vertical, and total velocities reach values of 71 cm/s, 145 cm/s, 152 cm/s, and 180 cm/s, respectively. Selected Green's functions and a soil model for the SFV are used to compute the approximate stress level during the earthquake, and comparison to the values for near-surface alluvium at the U.S. Nevada Test Site suggests that the non-linear regime may have been entered. We use selected values from the simulated particle velocity distribution at 5 km depth to compute the non-linear response in a soil column below a site within the Van Norman Complex in SFV, where the strongest ground motion was recorded. Since site-specific non-linear material parameters from the SFV are currently unavailable, values are taken from analyses of observed Test Site ground motions. Preliminary results show significant reduction of spectral velocities at the surface normalized to the peak source velocity due to non-linear effects when the peak velocity increases from 32 cm/s (approximately linear case) to 64 cm/s (30-92%), 93 cm/s (7-83%), and 124 cm/s (2-70%). The largest reduction occurs for frequencies above 1 Hz.

INTRODUCTION

Currently used ground motion modeling techniques are limited to either finite-source, linear simulation of the full 2-D or 3-D wavefield in arbitrary earth models (e.g., finite-difference methods), or strongly simplified non-linear simulation in layered earth models (e.g., vertically-incident plane SH waves in the code SHAKE). However, in the near-field of the earthquake the source is typically not accurately described as a plane vertically-incident SH wave. Moreover, the lateral variation of the elastic and inelastic material properties of the near-surface layers can be significant. In such cases, the existing simulation methods may not be sufficient to accurately model the ground motion. This study is a step toward a full 3-D non-linear model of earthquake ground motion by combining the advantages of existing linear and non-linear ground motion finite-difference modeling codes.

MODELING TECHNIQUE

Our modeling techniques proceed in two steps: 1) a linear kinematic computation of the 3-D finite-fault radiation pattern to a datum below the region affected by non-linearity, followed by 2)
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Figure 1: Map of the Los Angeles area. The dashed rectangle shows the projection of the Oak Ridge fault that ruptured during the Northridge earthquake and the solid rectangle shows the area where Greens functions have been computed (see Figure 2). The thick line depicts the strike-perpendicular profile used to compute the stress level in a soil column taken at the site "*". The thin solid lines depict major freeways in the area.

non-linear wave propagation to the ground surface using the Green's functions computed in (1). The linear modeling is carried out by a 4th-order staggered-grid finite-difference method which is proven to be an efficient and flexible for large-scale wave propagation (Olsen et al., 1995) allowing a variety of propagating kinematic sources (e.g., Olsen and Archuleta, 1996). The linear code includes absorbing boundary conditions at the edges of the grid (Clayton and Engquist, 1977) as well as a sponge zone to minimize artificial reflections (Cerjan et al., 1985).

The non-linear modeling is carried out by the Los Alamos stress-wave modeling code SMC123 (Dey and Kamm, 1994). SMC123 can be run in one, two or three dimensions and utilizes material constitutive rules very similar to the ones used by App and Brunish (1991) to produce accurate simulations of ground motions observed at the surface and in deep satellite holes in the vicinity of underground nuclear tests at the Nevada Test Site.

3D COMPUTATION OF NORTHRIDGE GREENS FUNCTIONS

We use the 17 January 1994 Northridge earthquake to test our hybrid finite-difference approach. The earthquake rupture is simulated as propagating radially outward from the hypocenter with a rupture velocity of 3 km/s using the combined (variable) slip and rake model by Wald et al. (1996). The linear 3-D finite-fault wavefield (0-7 Hz) is simulated to a datum 5 km below the San Fernando Valley within an area of 17 km by 19 km immediately above the fault plane (see Figure 1). The slip rate on the fault plane is calculated by

\[ \text{sliprate}(t) = \frac{1-t}{\sqrt(t)} \]
Figure 2: 0-7 Hz peak velocities for the Northridge earthquake simulated to a datum 5 km below the San Fernando Valley within the area shown in Figure 1. The maps are scaled with a constant value for comparison. The maximum values are listed in Table 1. Note that the strike-perpendicular and vertical velocities are the largest due to the predominantly thrust rupture mechanism, and that the northern (top) part of the area experienced the largest motion due to directivity effects.

and lowpass-filtered to 7 Hz. Peak particles velocities on the 5 km-deep datum are shown in Figure 2, and maximum values are listed in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAXIMUM PEAK VELOCITIES AT 5 KM BELOW SURFACE</td>
</tr>
<tr>
<td>Strike parallel component (cm/s)</td>
</tr>
<tr>
<td>Strike perpendicular component (cm/s)</td>
</tr>
<tr>
<td>Vertical component (cm/s)</td>
</tr>
<tr>
<td>Total vector (cm/s)</td>
</tr>
</tbody>
</table>

The largest velocities occur towards the northern edge of the fault due to source directivity, in agreement with the low-frequency results by Olsen and Archuleta (1996).

LINEAR NEAR-SURFACE STRESS LEVEL

To obtain an estimate of the elastic stress levels in the San Fernando Valley we propagate the simulated Northridge P-SV waves along a strike-perpendicular profile (Figure 1) into a 1-D model
Figure 3: Parameters used to simulate the elastic stress level at a site within the Van Norman Complex ("*" in Figure 1). The velocities and densities are taken from Magistrale et al. (1996) of the soil using a 2-D visco-elastic finite-difference method. The P- and S-wave velocities and densities for the soil profile are taken from the geology-based 3-D Los Angeles basin model generated by used Magistrale et al. (1996) at a site within the Van Norman Complex ("*" in Figure 1) where some of the strongest ground motions were recorded during the earthquake. The seismic velocities, densities and Q values used for the simulation are shown in Figure 3. The results show peak shear and normal stresses exceeding 10 bars in the near-surface layers (< 300 m) of the valley (see Figure 4).

With relatively little information on in-situ rock strength properties in the region, it is uncertain whether or not failure of the rocks occurs at these stress levels. However, in comparing the peak stresses from the San Fernando Valley simulation with those for near-surface alluvium at the U.S. Nevada Test Site, where non-linear behavior at similarly low stress levels is well documented (App and Brunish, 1991), we infer that sites in the San Fernando Valley may have entered the non-linear regime during the Northridge earthquake. This study addresses that possibility and the attendant effects on ground motion.

NON-LINEAR EFFECTS

We will now examine the non-linear effects in the soils of the San Fernando Valley from the Northridge earthquake. As a first step, we propagate a planar gaussian SH-wave into a 1-D soil column. Lacking specific material parameters for the area, we use seismic velocities, densities, and non-linear parameters of the soil column from well-studies materials at the U.S. Nevada Test Site, where non-linear behavior at similarly low stress levels is well documented (App and Brunish, 1991). (see Table 2).
Figure 4: Peak normal and shear stress in the upper 300 m computed using a 2-D visco-elastic finite-difference method and the Greens functions computed for the Northridge earthquake at a site within the Van Norman Complex in the SFV. The peak stress level can exceed 10 bars which is used as an approximate threshold for initiating non-linear behavior within near-surface alluvium at the U.S. Nevada Test Site (App and Brunish, 1991).

<table>
<thead>
<tr>
<th>Material</th>
<th>Alluvium</th>
<th>Tuff 1</th>
<th>Tuff 2</th>
<th>Hard Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer Bottom (km)</td>
<td>0.72</td>
<td>1.35</td>
<td>3.6</td>
<td>-</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>1.0</td>
<td>2.0</td>
<td>2.4</td>
<td>2.7</td>
</tr>
<tr>
<td>P-wave speed (km/s)</td>
<td>1.0</td>
<td>2.0</td>
<td>4.0</td>
<td>6.0</td>
</tr>
<tr>
<td>S-wave Speed (km/s)</td>
<td>0.53</td>
<td>1.07</td>
<td>2.13</td>
<td>3.20</td>
</tr>
<tr>
<td>P1 (bars)</td>
<td>330.0</td>
<td>200.0</td>
<td>900.0</td>
<td>900.0</td>
</tr>
<tr>
<td>P2 (bars)</td>
<td>319.9</td>
<td>140.0</td>
<td>800.0</td>
<td>800.0</td>
</tr>
<tr>
<td>P3 (bars)</td>
<td>475.0</td>
<td>480.0</td>
<td>3500.0</td>
<td>3500.0</td>
</tr>
<tr>
<td>P-crush (bars)</td>
<td>12.0</td>
<td>30.0</td>
<td>900.0</td>
<td>inf</td>
</tr>
</tbody>
</table>
Figure 5: Comparison of stress-strain hysteresis paths for the surface SH velocities computed using the four different peak source velocities. Note that the ground motion for peak source velocity of 31 cm/s is practically linear.

Specifically, we model the soil column with 720 meters of alluvium overlying two tuff layers and a hard-rock layer. Shear strength, S, in these materials is modeled with an exponential law

\[ S = P1 - P2 \cdot \exp(-P/P3) \]

where \( P \) is the mean overpressure, \( P1 \) is the shear strength at infinite mean stress, \( P1 - P2 \) is the unconfined shear strength, and \( P3 \) is a characteristic pressure. At these stress levels, the compressive response, relating mean stress to compression, is characterized by the threshold crush pressure, \( P\text{-crush} \), at which pore crush begins.

SMC123 can utilize variable cell sizes. To prevent the introduction of non-physical signal reflections, the sizes of cells on either side of a material interface are chosen so that they have equal mass. The smallest cell size in the simulations is 2.5 m in the alluvium. The source signal is a gaussian SH-wave pulse with a half width of 0.2 seconds and a peak at 1.0 seconds of simulation time. The source is placed at 4 km depth in the hard-rock layer. No linear anelastic attenuation is included in the simulations.

Figure 5 shows the stress-strain hysteresis paths for the surface SH velocities computed using the four different peak source velocities. It is clear that the surface ground motion for the peak source velocity of 31 cm/s is practically linear, while that for the peak source velocities of 64 cm/s, 93 cm/s and 124 cm/s are all in the non-linear regime.

Figure 6 compares source-normalized surface spectra for peak source velocities of 64 cm/s, 97 cm/s,
Figure 6: Comparison of source-normalized surface spectra peak source velocities of 64 cm/s (solid), 93 cm/s (dash-dot), and 124 cm/s (dashed), relative to those for a peak source velocity of 32 cm/s.

and 139 cm/s, relative to those for a peak source velocity of 32 cm/s. Since the reference case of 31 cm/s is approximately linear (see Figure 5) and the source spectrum has been removed, Figure 5 shows the reduction in surface spectral velocity due to non-linear effects in the soil column (30-92% for 64 cm/s, 7-83% for 93 cm/s, and 2-70% for 124 cm/s). All cases show an expected increased reduction with frequency.

FUTURE WORK

We plan to simulate the 0-7 Hz non-linear response within the entire area covered by the linear Greens functions functions from the Northridge earthquake (see Figure 1). The seismic velocities, densities, and non-linear parameters will be refined by the results currently being estimated within the project "Resolution of Site Response Issues from the Northridge Earthquake (ROSRINE). Corrections for anelastic attenuation (Q) will be made in order to compare the simulations to data recorded in the San Fernando Valley. In particular, we plan to compare simulations to data recorded within the Van Norman Complex where the largest velocity ever was recorded instrumentally (177 cm/s) (Bardet and Davis, 1996). We will among other parameters use horizontal/vertical spectral ratios as a function of both frequency and depth to estimate the extent of non-linear effects.
REFERENCES


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