International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
1995 - Third International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

04 Apr 1995, 1:30 pm -2:30 pm

A New Seismic-Geotechnical Strong Motion Approach

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Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
April 2-7, 1995; Volume III, St. Louis, Missouri

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Paper No. 8.11

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SYNOPSIS We have developed a new approach to estimate site-specific strong motion due to earthquakes on specific faults or source zones. It combines seismologic and geotechnical studies. It entails obtaining records of small earthquakes at the site, both at the surface and downhole in bedrock, as well as performing geotechnical dynamic site characterization. This new approach has the dual result of providing an optimized definition of the dynamic geotechnical site properties and providing calculated free-field, strong motion estimates. The procedure is demonstrated at the Painter Street Bridge site in Rio Dell, CA, for which we provide a range of surface motions corresponding to an earthquake of magnitude 7 on the subducting plate underlying this region. These calculated motions bracket the records of the Petrolia event (M = 7) measured near the site.

THE PAINTER STREET BRIDGE SITE

This site was originally chosen because it is well instrumented for earthquake data acquisition and is in a highly seismic zone. In addition, the bridge structure is representative of several hundred highway crossings in California. The site and the structure are shown in Figure 1. It was fortuitous that the Petrolia event (magnitude 7.0) occurred in April 1992, several months after we had started work at this site. A companion publication (McCallen and Romstad, 1994) discusses the comparison between calculated and observed motions of the bridge during the Petrolia earthquake.

THE LLNL COMBINED SEISMIC-GEOTECHNICAL APPROACH

The LLNL Empirical Green's Function (EGF) Method

In seismology, Green's functions are mathematical representations of how the Earth's geologic structure affects seismic waves generated by small earthquakes. Because the geologic structure is often poorly known, however, these functions cannot generally be constructed accurately. Analytical Green's functions can only be calculated for simple, idealized geologic structures that may not represent the actual geology. Nevertheless, actual recordings of small earthquakes (magnitudes less than about 3) can be used to approximate analytical Green's functions. Such recordings, which are also called empirical Green's functions (EGF's), can be used instead of mathematical forms to more accurately represent the seismic waves that could be expected at any given point on the surface or subsurface to the Earth even when the subsurface structure is unknown.

In the LLNL seismic methodology (Hutchings, 1990, 1991, 1994; Jarpe and Kasameyer, 1993) we collect EGFs from adjacent fault(s) both at the surface and at bedrock underlying the site. Concurrently, we assume that an earthquake of given magnitude may occur, and we develop a family of fault rupture scenarios all constrained to give the same magnitude of event (i.e. energy release). The combination (convolution) of recorded EGFs with these rupture scenarios then provides calculated time-histories of rock motions at the site (syntheses). These syntheses are linear mathematical operations performed on EGF records. Those records can be assumed to reflect linear soil and rock behavior because EGFs typically are obtained for small earthquakes ($M \leq 3.0$) in which strains generally do not exceed a few microstrains. The validation of the physics of the EGF-based syntheses has been demonstrated for strong motions such as those due to the Loma Prieta earthquake (Hutchings, 1991, 1994). Note, however, that the (linear) strong motion syntheses are appropriate for rocks only (i.e. rock incident motions), since rocks can be assumed to stay linear under strong earthquake motion. Such syntheses would not be appropriate for soils, because soils are non-linear under strong motion. Thus, in order to predict strong motion in soils the (linear) seismologic approach must be combined with geotechnical non-linear analysis.

The Geotechnical Component

In the current context, a comprehensive geotechnical site characterization program will include drilling, core sampling, in situ testing such as standard penetration tests (SPT), and/or cone penetration tests (CPT), geophysical logging to determine wave speeds in the soils and maximum dynamic moduli, and laboratory testing for soil index properties and static and dynamic mechanical properties.

The Seismic-Geotechnical Interface

The objective of the ground motion study is to provide calculated estimates of strong motion in the free-field, i.e. at the surface and at appropriate depth(s) if a soil-foundation interaction must be evaluated. The tools we have at hand are: the surface and bedrock EGFs, and the wave propagation geotechnical models, which can be linear, equivalent linear, e.g. SHAKE (Schnable et al., 1972), or non-linear, e.g. DYNAFLOW (Prevost, 1993; Popescu and Prevost, 1993).

Optimization of the low-strain soil profile moduli, using surface and bedrock EGF's

First, we optimize the definition of geotechnical dynamic properties of the soil column making the assumption that shear and compressional waves are propagating vertically. To do so, we use pairs of surface and downhole EGFs. Starting from the surface, we deconvolve the motion down to bedrock with the SHAKE code. This provides the total (i.e. the incident plus reflected and refracted) rock motions. The total motion is compared to the rock EGF, which it should match. Because of the very small strains (10^{-6}) these motions do not involve modulus degradation. Starting from the initial, low-strain geotechnical dynamic properties obtained from laboratory testing and/or field geophysical logging, the profile definition is heuristically adjusted to optimize the match between calculated and measured total rock motion. This process is repeated for as many pairs of up-and-down EGFs as desired, to narrow the range of soil layer maximum shear moduli. The quality of the final result can be further checked by testing the results on EGF pairs which were not part of the optimization process. This will be demonstrated at the Painter Street bridge site.

Integration of the seismic and geotechnical analyses

Then we turn to the matter of predicting free-field and surface strong motions, assuming vertically traveling shear and compressional waves. Using the terminology of Seed and Lysmer (1980), both "control motion" and "control point" must be defined. In our approach, the control point is the top of bedrock under a particular surface location and the control motion is the incident portion of a large earthquake motion defined at that control point.

Now the question is how to define that incident portion. In our methodology, it will be based on a convolution of EGF's measured at the site with rupture scenarios for the fault(s) threatening the site. Should one use the downhole (bedrock) EGF's? The answer is no (Seed and Lysmer, 1980; Safak, 1991; Field et al, 1992). In theory, due to surface reflection effects, clean downhole motion records should show sharp frequency suppressions corresponding to the fixed-based natural frequency of the overlying soil column and its harmonics. Actual records often do not have such sharp deficiencies, and when sent upward in calculations they will create exaggerated surface motions. This also will be demonstrated in the application to the Painter Street site. A more reliable approach is to use the surface EGF's, which generally offer a smooth spectrum, and to deconvolve them in order to obtain, by calculations, the incident wave at bedrock.

Following the soil profile optimization, and with the above constraints in mind, the following approach then has been devised to obtain site-specific strong motion estimates (Figure 2):

- deconvolve each surface EGF to get the corresponding incident downhole motion, using SHAKE
- synthesize the downhole strong motions using these incident small motions and the fault rupture scenarios
- propagate the strong motion upward using a 3-component non-linear and effective stress code, such as DYNAFLOW

This approach satisfies all the constraints discussed earlier.

The process of optimization and free-field calculations that we have outlined constitutes the new integrated seismic-geotechnical approach developed by LLNL. It was demonstrated at the Painter Street bridge site, as discussed next.

APPLICATION TO THE PAINTER STREET SITE

Site Characterization

The following program was completed:

- initial surface seismic refraction measurements to outline the soil profile (Heuze and Swift, 1991)
- new drilling by Caltrans: 2 holes (borings 1 and 2) into the abutments, to a depth of 21 m, and 2 holes (borings 3 and 4) under the bridge to a depth of 30.5 m, reaching 6 m into bedrock; 3.5 cm diameter soil samples were recovered and SPT values were obtained.
- downhole shear-wave velocity measurements, also conducted by Caltrans.
- installation of two seismic measurement packages, one at a depth of 0.3 m and one at 27.5 m, 3 m into bedrock. Each contained a 3-component HS-1 seismometer and a 3-component Wilcoxon 731 accelerometer. They are capable of recording from weak to strong motions (10^{-6} to 0.7 g). Frequency response is flat between 0.1 and 100 Hz. EGFs were recorded over a period of 8 months from aftershocks of the Petrolia event ranging in magnitude from 2.1 to 3.0.
- laboratory cyclic triaxial tests, performed at the University of California at Berkeley on 13 samples, to determine shear modulus and damping variation with strain (Riemer, et al, 1993).

Properties of Painter Street Soils

The optimization of the low-strain shear modulus values was performed using four pairs of EGFs. The result is shown in Figure 3. The laboratory-measured maximum

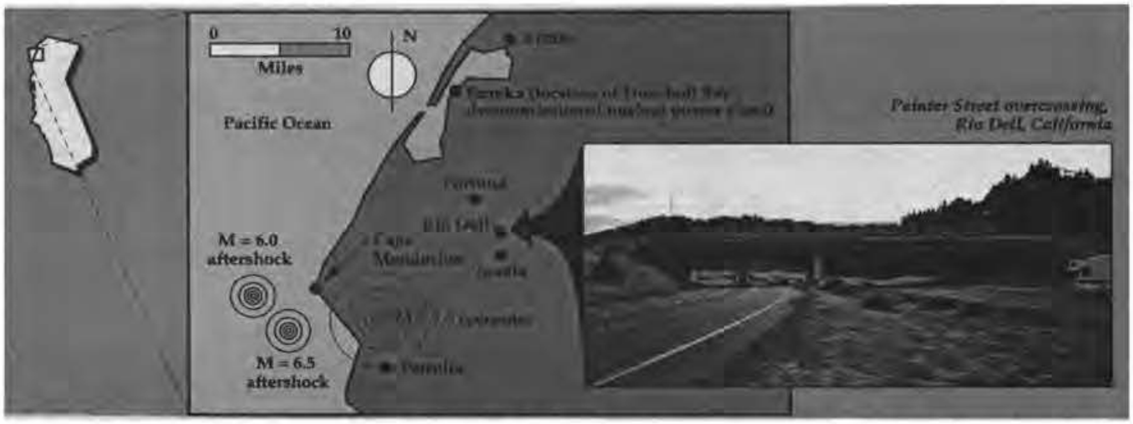

Figure 1: The Painter Street Bridge in Rio Dell, CA, and epicenters of the Petrolia Earthquakes of April 1992.

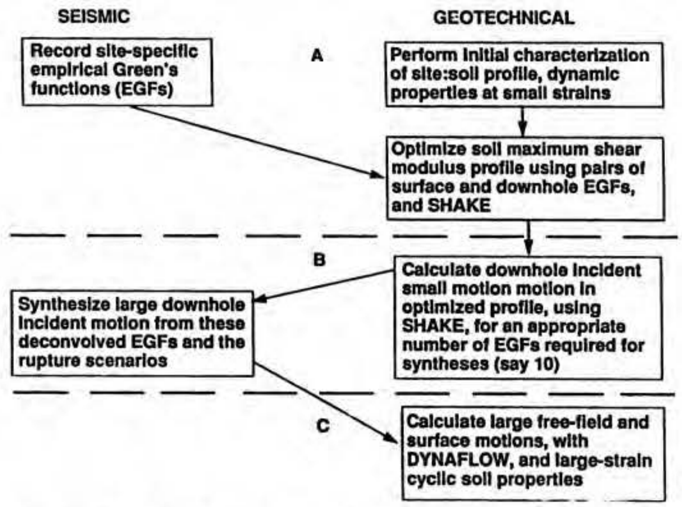

Figure 2: Combined seismic-geotechnical procedure for estimating site-specific strong ground motion.

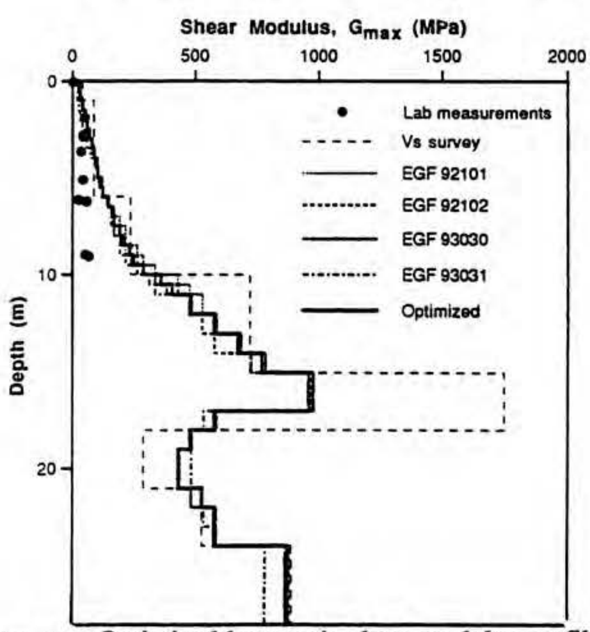

Figure 3: Optimized low-strain shear modulus profile and comparison with values from laboratory tests and downhole tests.

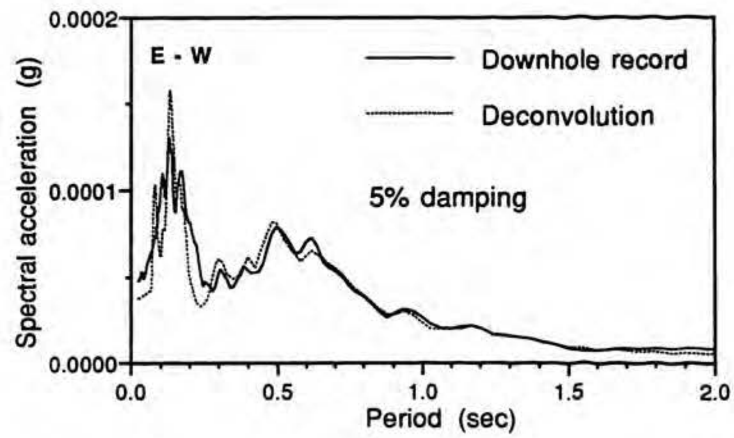

Figure 4: Total motion comparison between downhole record and deconvolution from surface record for E-W acceleration, for EGF pair 93031, which was used in the soil modulus profile optimization.

modulus and the values from downhole S-wave tests also are shown for comparison. Clearly, the shallower samples gave more appropriate values. This is probably related to higher disturbance in the deeper samples. The downhole S-wave measurements are rather coarse. P and S-wave suspension logging likely would provide better accuracy.

The quality of the soil profile optimization can be evaluated by comparing the total rock motion, deconvolved from a surface EGF to the actual rock record. This is shown in Figure 4 for the E-W component of EGF 93031, one of the record pairs used in the optimization. The calculated acceleration spectrum matches the observations well.

Because of the limited range of strains in the laboratory cyclic triaxial tests, the relationships for the shear modulus (G) and damping versus shear strain for the silty sand (depth $\leq$ 11 m) and gravelly soil (depth $\geq$ 11 m) also used data by Seed, et al. (1984). These relationships are input in SHAKE calculations. Since both soils consist of a substantial amount of fines (PI = 5 - 10), relations for shear modulus versus shear strain at the upper bounds of Seed's data were selected, whereas relations near the lower bounds of Seed's data were selected for damping. This is consistent with results for plasticity effects on dynamic properties of soils from Vucetic and Dobry (1991). Because the cyclic triaxial tests did not include gravels, we made a further check on the adopted gravel properties. They are consistent with recent results from Kokusho and Tanaka (1994), Goto et al (1994), and Konno et al (1994).

The constrained modulus, B, was calculated from the shear modulus as $B = 2G(1-\nu)/(1-2\nu)$. For a value of Poisson's ratio, ν, taken to be 0.35, then B = 4.33 G. In the absence of data, it was assumed that the decay of B with compressive strain was at the same rate as the decay of G with shear strain.

Fault Rupture Scenarios

A family of 25 subduction zone rupture scenarios was developed, drawing from the profession's seismic knowledge of the area (Turcotte, et al., 1980; Dengler et al, 1992; Youngs et al, 1993; Perkins and Hanson, 1993; Oppenheimer, et al., 1993), and our experience in such modeling (Hutchings, 1991, 1994). The fault surface is at a depth of 15 km beneath the site. We considered that the earthquake could occur anywhere within a 30 by 55 km area of the fault underneath Rio Dell. For an assumed magnitude, M = 7, three scenarios were adopted to represent the low, middle, and high range of potential site motion. These are respectively labeled MPE10, MPE00 and MPE22, and are shown in Figure 5.

The details of the rupture parameters for these scenarios are provided in Heuze et al (1994). Note that the seismic moment is the same for all three, but that this total energy release occurs in different fashion from one to the other. For example MPE22 (the largest) includes the shearing of large asperities on the rupture surface. MPE10, the weakest, has a relatively low stress drop and a slow rise time compared to the others.

Synthesis from Surface EGF's, and Calculations of Corresponding Incident Rock Motions

As discussed earlier, ground motion syntheses require the combination (convolution) of rupture scenarios with actual records of small earthquakes at the site (EGF's). At Painter Street a set of 8 EGF's obtained in October and November 1992 was combined with the 25 selected rupture scenarios.

An example of the surface syntheses for the E–W direction is shown in Figures 6 and 7 respectively for the intermediate (MPE00) and large (MPE22) scenarios. In turn, our new procedure was applied to provide the corresponding incident rock motions which are shown in Figures 8 and 9. Note the difference in acceleration scales between the figures.

Upward Propagation of the Incident Rock Motion

Both SHAKE and DYNAFLOW were used for upward wave propagations. The purpose was two-fold: to confirm the consistency of results with both codes when strain stayed small such as with scenario MPE00, and to highlight the differences between the results for higher ground motions, such as with scenario MPE22. The first comparison is shown in Figure 10 for E-W acceleration spectra concerning the intermediate scenario. DYNAFLOW and SHAKE gave comparable results. The maximum shear strain in the soil column calculated with DYNAFLOW was 0.030% in the E-W direction. The corresponding value with SHAKE also was 0.030%. For the larger event, the spectral comparison is shown on Figure 11. The maximum E-W shear strain in the soil column calculated with DYNAFLOW was 1.30%. The corresponding value with SHAKE was 2.33%. Note that the maximum shear strains discussed above did not necessarily occur at the same locations in either code, and for either scenario. Even though the maximum shear strains are not very different in the SHAKE and DYNAFLOW calculations for MPE22, the surface accelerations differ widely. This is a reflection of the fact that SHAKE uses a single equivalent (secant) modulus for each soil layer for the entire calculation. At large strains it turns out to be quite stiffer than the tangent modulus used in DYNAFLOW, which can change and soften with every time step. This also gives differences in frequency content.

Earlier, the point was made that total motion bedrock records should not be used as control motion. This is demonstrated using EGF pair 93031 at Painter Street. In Figure 12 we compare the E-W acceleration spectrum of the actual EGF 93031 surface record to the estimate that would be obtained by a SHAKE-based upward propagation of the bedrock record. The lack of the required frequency deficiencies in that bedrock record engenders very large calculated oscillations at the surface and very large spectral peaks which are just not there in the actual surface record.

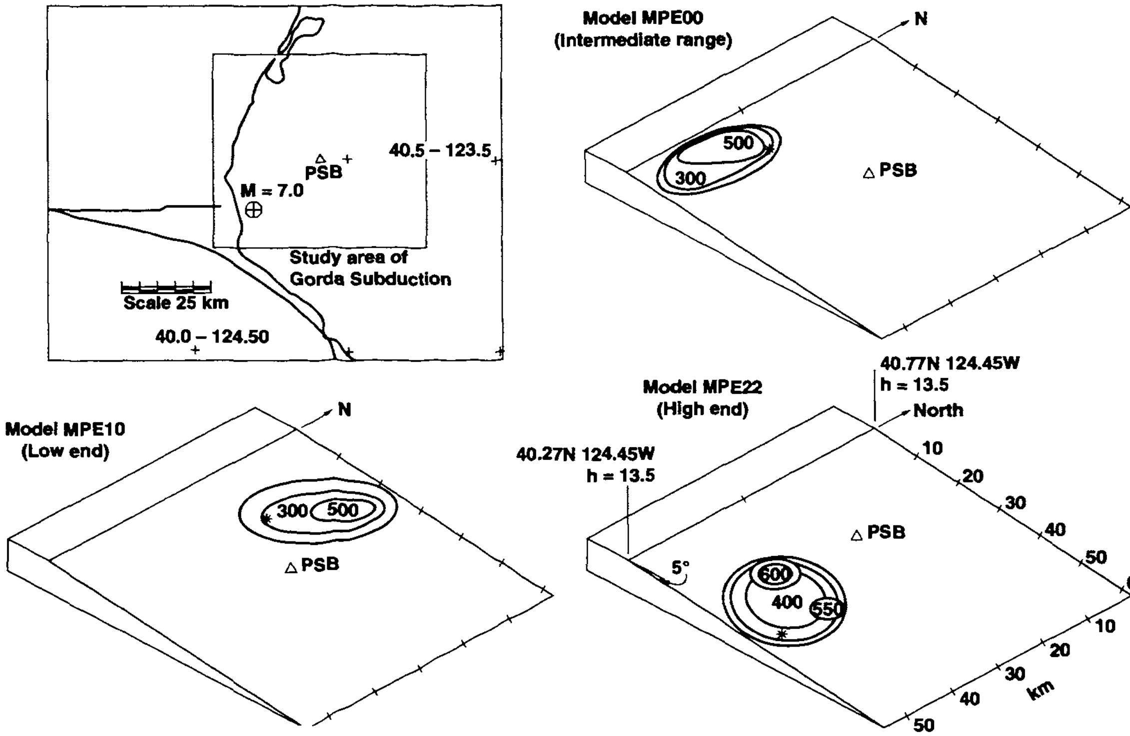

Figure 5: Location of study area, and rupture scenarios for a M=7 event at the Painter Street bridge site (PBS). Contours of fault rupture displacement in cm.

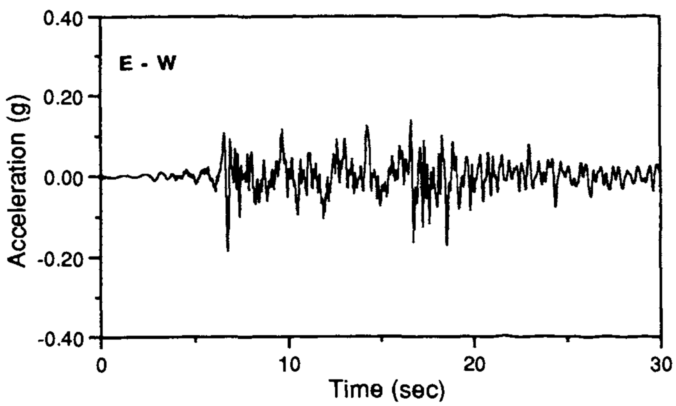

Figure 6: Synthesized surface motions for the intermediate rupture scenario, MPE00, E-W component.

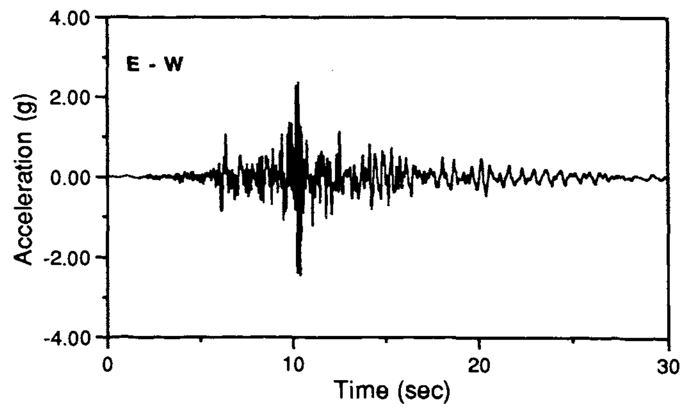

Figure 7: Synthesized surface motions for the large rupture scenario, MPE22, E-W component.

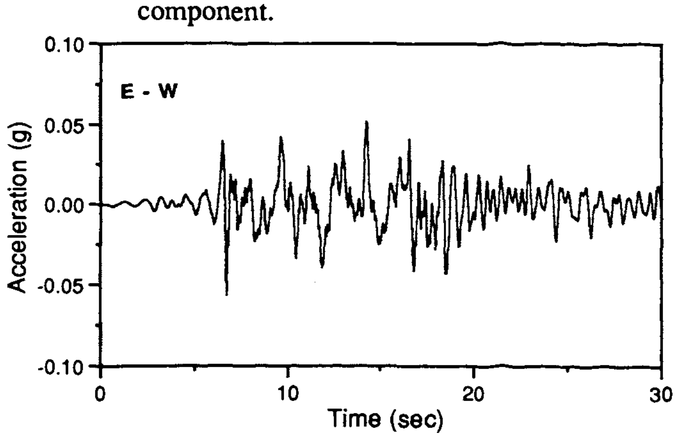

Figure 8: Corresponding incident rock motion at depth of 28 m for the intermediate scenario, MPE00, E-W component.

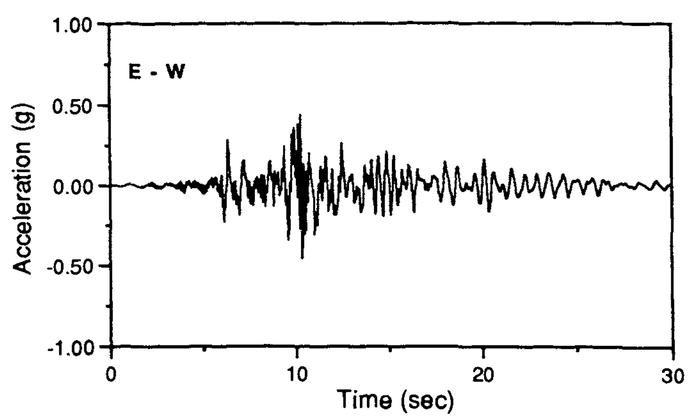

Figure 9: Corresponding incident rock motion at depth of 28 m for the large scenario, MPE22, E-W component.

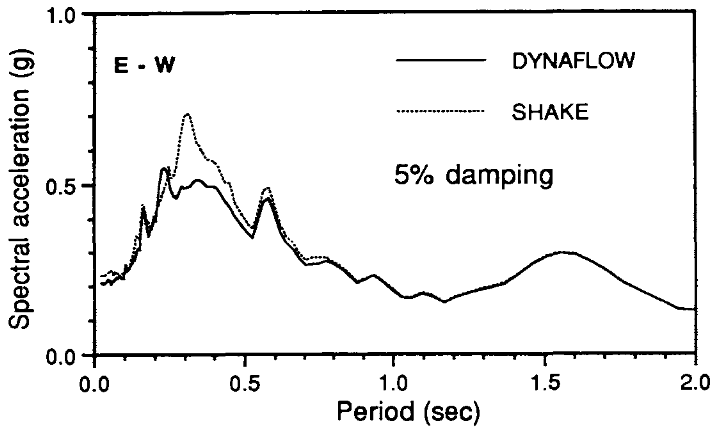

Figure 10: Comparison of SHAKE and DYNAFLOW calculated surface spectral accelerations for the intermediate scenario, MPE00, E-W component.

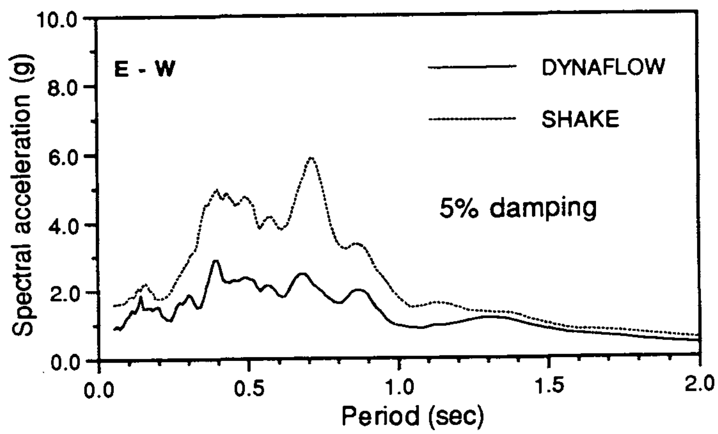

Figure 11: Comparison of SHAKE and DYNAFLOW calculated surface spectral accelerations for the large scenario, MPE22, E-W component.

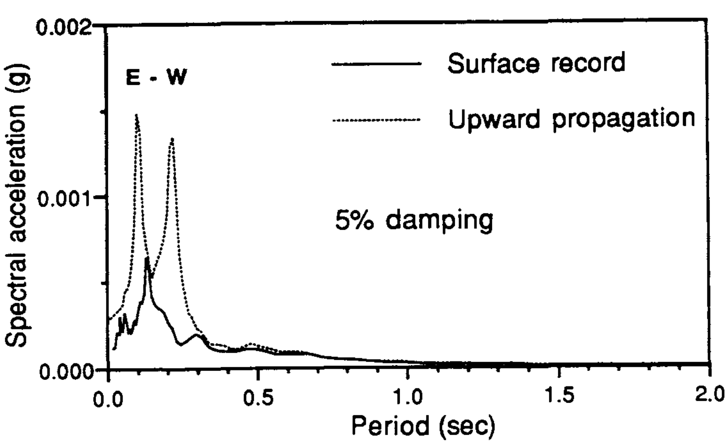

Figure 12: Spectral acceleration comparison between the EGF 93031 surface record and the SHAKE-based estimate of that surface record using as input the total motion record from bedrock.

Comparison of Rupture Scenario Results with an Actual Event

The seismologic part of our procedure is designed to provide a family of rupture scenarios leading to a range of likely site-specific strong motions. This corresponds to the notion that no one can predict how a particular fault will actually rupture, but that given a specified magnitude for an earthquake at a given location one can bracket the range of resulting ground motions.

The Petrolia, CA earthquake of April 25, 1992 provides a basis for calibration of our results. It was a magnitude M=7.1 subduction event, the mechanism of which has been discussed at length (Michael, 1992; Michael et al, 1992; Mueller, 1992; Ammon et al, 1993; Sommerville, 1993; Tanioka et al, 1993; Youngs et al, 1993; Velasco et al, 1994). Although there is no unanimity on the rupture process it is generally thought to have initiated at a depth of 11 to 15 km, 4 km E of and underneath Petrolia, on a 9 to 13° ENE dipping fault, and propagated updip. Clearly no one can predict a particular, detailed rupture before the fact, and our methodology reflects that reality. Conversely, the rupture process of the Petrolia event is consistent with the phenomenology embodied in the range of our 25 rupture scenarios for this site.

Figure 13 shows the spectral acceleration of the Petrolia event's E-W surface records obtained in the vicinity of the bridge, compared to our site-specific low, intermediate, and large estimates for a magnitude 7 earthquake. The predictions do bracket the actual event. Figure 13 also shows that the large scenario accelerations exceed the accelerations measured in the Petrolia earthquake for each component. Conversely, it can be inferred that a magnitude 7 event at Petrolia could have engendered even stronger motions than were recorded. Such an inference is becoming more readily acknowledged, as new earthquakes in California expand our database of magnitude-to-motion relationships. The Northridge earthquake of January 1994 is a case in point.

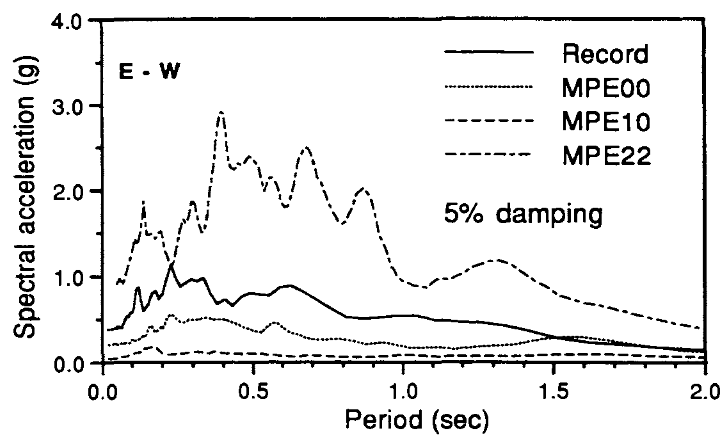

Figure 13: Comparisons of spectral surface accelerations at Painter Street for three scenarios, with E-W near-site records for the Petrolia Event of April 1992.

DISCUSSION AND SUMMARY

Vertical seismic arrays are becoming more and more prevalent. Some of the better known are in California, at Menlo Park (Joyner et al, 1976), Garner Valley (Archuleta et al, 1992; Pecker and Mohammadioun, 1993), Treasure Island (Darragh et al, 1994), and Borrego Valley (Nigbor, 1994). They can also be found in Lotung, Taiwan (Chang et al, 1990, 1994) and Chiba, Japan (Lu et al, 1991). These arrays have been used to evaluate site motion amplification and, occasionally, to optimize the velocity profiles of the soil column. Surface motion deconvolution with SHAKE is common and upward propagation has also been performed. However, in this latter instance one finds that recorded downhole motion frequently is used as input for upward wave propagation. This should be avoided because the downhole records generally are not the true incident motion required for input. Our calculations using rock records at Painter Street offered a clear example of the fact that propagation of rock EGF's would not recover the recorded surface EGF's.

The new contribution of the Painter Street project is to integrate the linear tools of seismology and the non-linear methods of soil dynamics in a procedure which provides estimates of strong motions based on the recording of very small events. Such predictions cannot be performed with simple scalings or extrapolations because of the non-linearity of soil sites under strong motion. Our new procedure has demonstrated how to use a combination of both surface and bedrock EGF's and how to take advantage of linear soil behavior at very low strains while respecting soil non-linearity at large strains.

We are looking foward to a broad utilization of this new methodology at sites where vertical seismic arrays are available, with surface and rock stations.

ACKNOWLEDGEMENTS

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory (LLNL) under contract number W-7405-ENG-48. Funding was provided by the LLNL/LDRD Program.

We thank G. Goudreau for initiating the multi-disciplinary study at Painter Street. We also gratefully acknowledge the field testing performed by Caltrans, and the fine typing of S. Uhlhorn.

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