RECENT ADVANCES IN FINITE DIFFERENCE METHODOLOGIES FOR THE SIMULATION OF STRONG GROUND MOTIONS

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SUMMARY

Over the last decade, advances in computational resources and numerical simulation algorithms have made possible the routine application of large scale two- and three-dimensional finite difference (FD) calculations of seismic wave propagation for a wide variety of problems. Recent major advances in the FD methodology include the use of memory optimization procedures and the development of variable grid schemes, both of which have greatly expanded the availability of this technique by allowing for code implementations on common desktop workstations (i.e., non-supercomputers). Furthermore, these enhancements have also allowed the use of FD modeling to progress from primarily academic applications to more practical applications directly related to seismic hazard analyses. The FD method is attractive because of the tremendous flexibility for incorporating both complex geologic structural heterogeneity as well as complex, finite-fault rupture processes. Current simulation studies demonstrate that the FD method is capable of reproducing ground motion waveforms down to periods of 1 or 2 seconds. These capabilities are demonstrated by application of the FD technique to model recorded ground motions from damaging earthquakes. These studies demonstrate that detailed knowledge of both the subsurface structure and the source rupture process are necessary in order to accurately reproduce the recorded ground motions, especially for periods approaching 1 second.

INTRODUCTION

The dramatic improvement in computational resources, along with the continued development of efficient numerical algorithms have allowed elastic wave field simulation techniques to be applied to large scale three-dimensional (3D) problems. The results of these studies demonstrate the important influence that variable 3D subsurface structure can have on the propagation and amplification of seismic waves, particularly in regions containing deep sedimentary basins. These propagation effects include the generation of surface waves at basin margins, basin-edge amplification, and focusing-type amplification. In this paper, we will concentrate on the application of the 3D finite difference (FD) method to model strong ground motions from large earthquakes.

A wide variety of computational algorithms exist which provide different formulations of the FD method. The most popular implementations are the conventional displacement formulation (e.g., Frankel and Vidale, 1992) and the staggered-grid formulation in velocity and stress (e.g., Virieux, 1986) or displacement (e.g., Xu and McMechan, 1995). While each type of formulation has its advantages and disadvantages, we have found no clear distinction that would dictate the choice of one technique over another for the application to a general class of wave propagation problems.

The primary drawback to all of the FD formulations is the tremendous computational requirements needed for 3D problems. For realistic models, grid discretization requirements are on the order of at least 10 million nodes, which translates into a gigabyte or more of memory. Additionally, the large number of computations necessitates the use of very fast and efficient CPU processors. Several researchers have addressed these issues through the use of multi-processor supercomputers. While these types of machines can certainly handle the computational demands, they are very expensive and their inaccessibility to the general seismological community relegates their use to primarily academic applications.

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Recently, several types of optimization techniques have been applied to the FD method with the goal of developing more efficient computational algorithms. These include the memory optimization algorithm (Graves, 1996b) and the use of variable grid schemes (Pitarka, 1998; Aoi and Fujiwara, 1999). The use of these types of formulations along with recent advances in computational technology have allowed the 3D FD method to be implemented on commonly available desktop workstations.

In the following sections, we outline the current capabilities and limitations of the FD technique with examples of recent 3D wave propagation simulation studies, concentrating on the modeling of strong ground motions that have been recorded near large earthquakes in California (Wald and Graves, 1998) and Japan (Sato et al., 1999).

1992 LANDERS EARTHQUAKE

The 1992 Landers earthquake provides an excellent strong motion data set for the analysis of the long period (T > 2 sec) response of the Los Angeles basin region. Since the Landers event occurred about 160 km from the Los Angeles region (Figure 1), the recordings within the metropolitan area can be directly interpreted in terms of the geographic distribution of the long period site response.

The FD grid area used in this study is shown in Figure 1. The model is 232 km long, 112 km wide, and 44 km deep. This area encompasses the Landers source, as well as the entire path up to and including the Los Angeles and San Fernando basins. With a uniform grid spacing of 0.4 km, the frequency resolution limit is 0.5 Hz within the lowest velocity regions of the models (Vs = 1.0 km/s). This limit was chosen based on computational demands and the fact that the Landers source model is only strictly valid for frequencies less than 0.5 Hz. In addition, the resolution of the 3D velocity models decreases at higher frequencies.

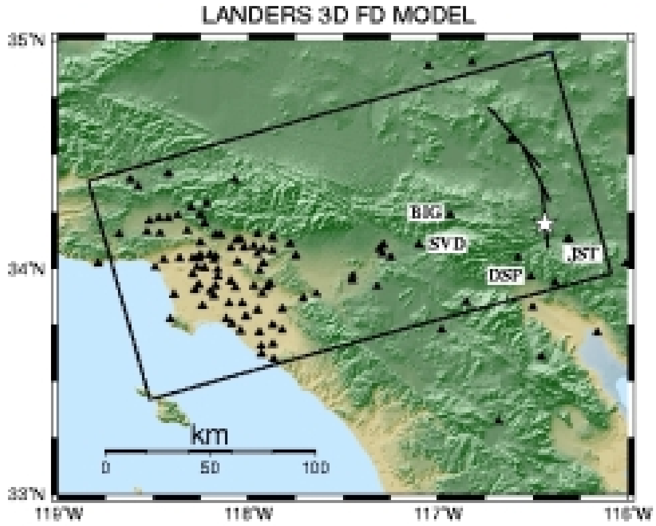

Figure 1: Map of the Landers simulation model region.

The details of the rupture process can have a significant influence on ground motions, even at long periods, thus it is important to preserve the complexity of the Wald and Heaton (1994) rupture model in its entirety when doing the simulations. This includes the use of the same fault segmentation, number of point sources and subfaults, slip-time history, and rupture velocity as determined from the inversion (Figure 2).

A series of 3D velocity models for the Los Angeles region, taken from Magistrale et al. (1996), Graves (1996a), and Magistrale et al. (1998) are analyzed in this study. These models are similar in terms of many of the large-scale features, but they do contain some noticeable differences. The models use geologic constraints to represent subsurface horizons (e.g., depth to basement), but differ where these data are sparse, such as in the San Fernando basin. In addition, the Graves model uses discrete, homogeneous layering to represent the velocity structure of the basin sediments, while the Magistrale models have a smoother vertical distribution of velocity, generally increasing with depth in the basins. Outside of the 3D basins, the models merge into a prescribed 1D background velocity structure.

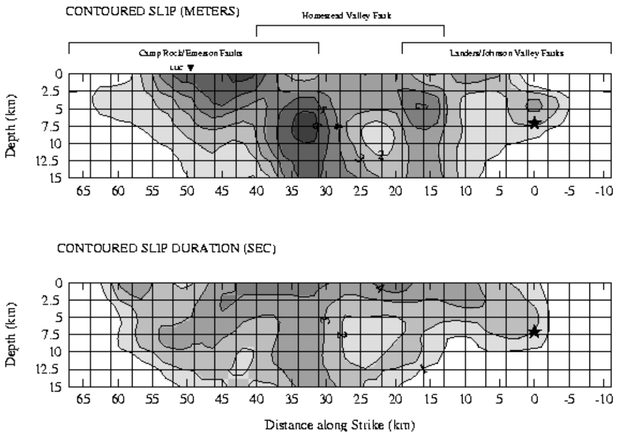

Figure 2: Landers slip distribution (top) and duration (bottom) from Wald and Heaton (1994).

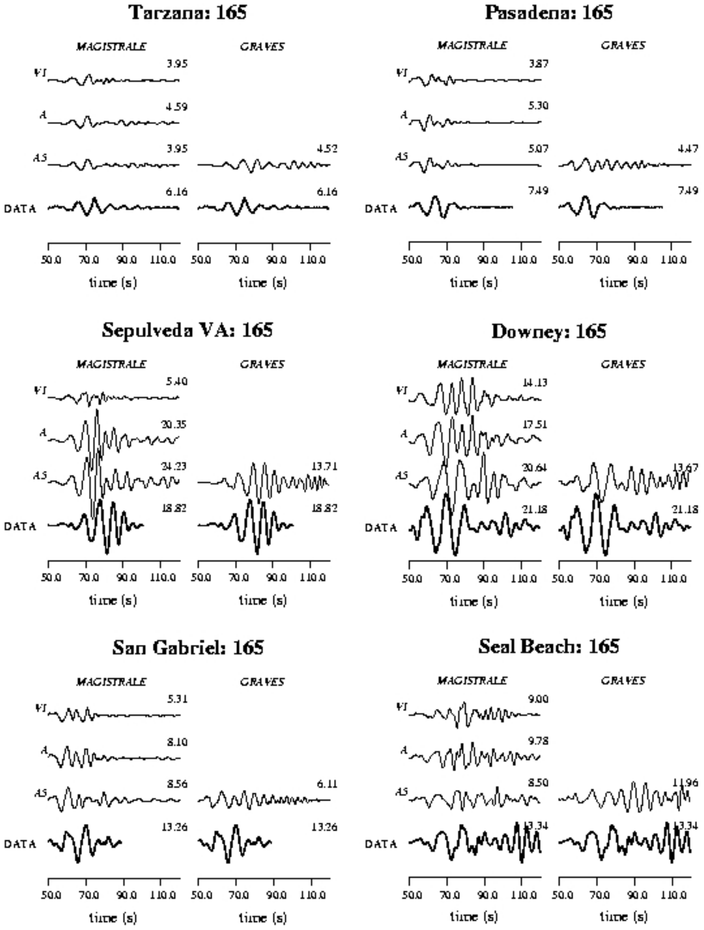

Figure 3: Observed and simulated displacement time histories for LA region sites.

Figure 3 shows a comparison of simulated and observed displacement (165 comp.) time histories (T > 2 sec) for sites in the San Fernando and LA basin regions. Pasadena and Tarzana are non-basin sites, and the remaining sites all indicate substantial basin amplification of the recorded motions. Thin traces are simulated time histories and heavy traces at bottom of each column are data. Left column in each set shows results from three versions of the Magistrale model and right column shows the results for the Graves model. The evolution of the Magistrale model (original to A5) indicates a general improvement for all sites, particularly in terms of matching the peak amplitude of the observed motions.

Another way to view the overall amplification patterns predicted by these models with respect to the observations is to compare the observed and predicted peak ground displacements contoured in map view (Figure 4). The peak displacements within the Los Angeles basin are over 20 cm, substantial motions for sites 160 km from the causative faults. The largest recorded displacements occurred over the deepest portion of the Los Angeles basin, and are about three to four times larger than at sites outside of the basins. The amplification within the San Fernando valley is also relatively large compared to its surroundings, nearly a factor of 3, while a slightly lower amplification is seen in the San Gabriel basin.

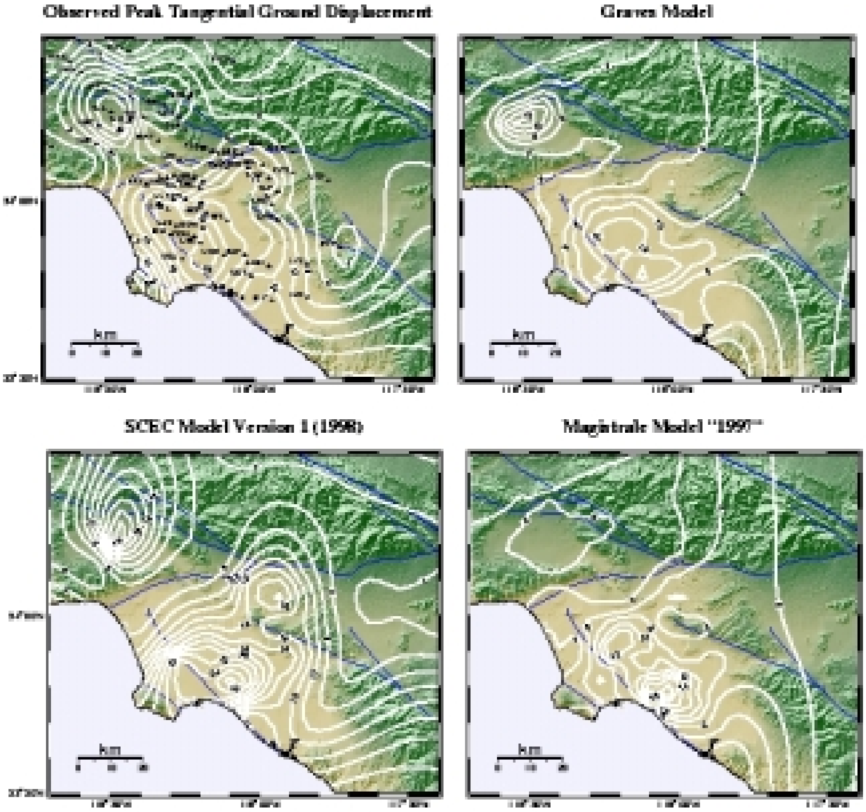

Figure 4: Contours of observed and simulated peak ground displacement for Landers.

The most dramatic differences in the response of the models is seen in the San Fernando valley. The Graves model (upper right) recovers the overall pattern and nearly the amount of amplification, while the original Magistrale model (lower right) does not. However, the updated Magistrale model (SCEC Model Version 1) does significantly better in this region. These differences are due to large variation (and uncertainty) in the structure of the San Fernando basin in the models, particularly in variations of the effective depth extent as a function of lateral position. In general, all of the models predict amplification patterns that mimic that observed over the Los Angeles basin, and the Magistrale model best reproduces the amount of amplification. However, the predicted peaks in these models are shifted substantially south and eastward relative to the observations.

Obviously, more work is needed to reconcile the differences between these proposed models. Furthermore, since the Los Angles basin region has a very complex geologic makeup, the model development process requires a multi-disciplinary approach in order to adequately image, constrain, and test the 3D velocity. However, it is quite encouraging that noticeable improvement is seen in the predicted ground motion pattern for the recently released SCEC V1 model compared to both the original Graves or Magistrale models.

1923 KANTO EARTHQUAKE

The Kanto earthquake of 1923 (Ms 8.1) was one of the most devastating earthquakes ever to occur, killing many thousands of people in the Tokyo metropolitan region and damaging or destroying a great deal of property. This event still has tremendous importance because present day engineering design practices and emergency preparedness in Tokyo are based in a large part on a repeat of the 1923 earthquake. To help facilitate these activities, it is imperative that we develop a more complete understanding of the rupture process and ground motion characteristics of the 1923 event.

As with many other earthquakes, the ground motion response from the Kanto event represents a complex combination of source processes and wave propagation effects within the Kanto basin. Due to the lack of complete near fault ground motion recordings from the Kanto event, there still exists some uncertainty as to the exact nature of the rupture history of this event. This lack of strong motion data also makes it difficult to adequately characterize the ground motion response that occurred in the Tokyo area during the Kanto earthquake. Another major concern in the Tokyo region is that basin amplification effects due to the structure of the deep Kanto basin may significantly affect the ground motion response. Previous studies have shown that in order to accurately interpret the observed long period strong ground motions in the Kanto basin, a wave propagation analysis that includes the 3D heterogeneity of the subsurface structure is required.

To represent the basin velocity structure of the Kanto region, a 3D model was constructed, which covers an area of 170 km by 210 km, and extends to a depth of 44 km (Figure 5). This model encompasses the fault plane of the 1923 event and most of the Kanto basin, including the entire path from the source region to the Tokyo metropolitan area. The model area is roughly characterized by the following three regions: the mountain region (MTN), the large sized sediment filled region of the Kanto basin (KNT), and the small sized region of the Sagami basin (SGM), as indicated in Figure 5.

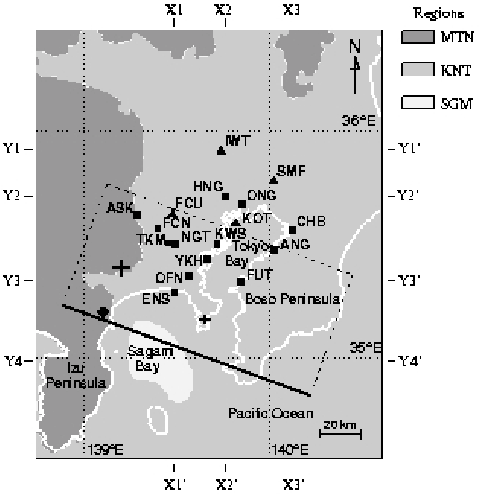

Figure 5: Map of the Kanto study area.

For the MTN region, and the areas below the basins, a 1D background velocity model is used. Within the Kanto basin, numerous studies have been conducted to delineate the nature of the 3D structure (e.g., Koketsu and Higashi, 1992). The velocity of the basin sediments gradually increases with depth, and the basin reaches a maximum depth of just over 3 km in the area west of Tokyo Bay.

Due to computational limitations, the minimum shear velocity is set to 0.6 km/s in the FD model. The grid spacing used in the calculations is 0.4 km, which gives a maximum frequency resolution of 0.3 Hz within the lowest velocity regions of the model. To account for the long durations expected for the basin motions, the computations were run for over 10,000 time steps. Nonetheless, despite the large model size (24 million grid points) and the large number of time steps, the computations were easily handled using the workstation FD algorithm of Graves (1996b).

In order to examine the validity of the 3D model of the Kanto region for predicting ground motions, simulations were performed for the 1990 (Mj 5.1) Odawara earthquake. A comparison between the observed three component displacement time histories and those simulated with the 3D model at four selected sites is shown in Figure 6. In order to illustrate the adequacy of the 3D model, simulations were also performed at each site using a flat layer (1D) velocity model. For the rock site station, ASK, the 1D model was taken from the MTN region, and for the basin stations, CHB, KWS, and HNG, the 1D model was taken from the KNT region.

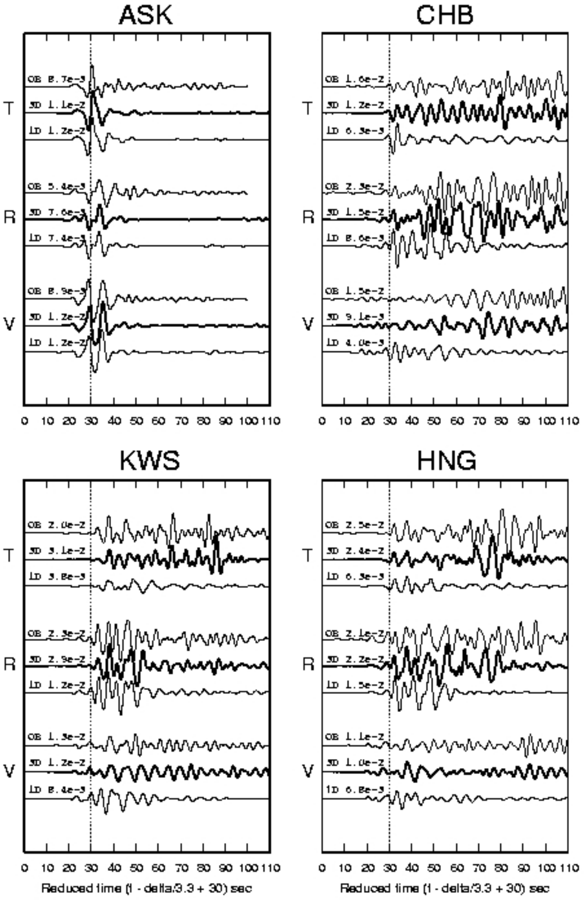

Figure 6: Comparison of data, 1D, and 3D synthetics for the Odawara earthquake.

For station ASK, since the paths to the station are almost entirely within the 1D (MTN) region of the model, the 3D and 1D simulations are very similar. In addition, both of these simulations accurately reproduce the observed waveforms. For stations CHB, KWS, and HNG, the 1D simulations fit the earliest part of the observed waveforms, but fail to reproduce the complexity of the later arriving energy. In contrast, the 3D simulation results do much better at matching not only the early parts of the waveforms, but also the well developed later arrivals that are very strong in the observed waveforms. These results indicate that the general long period wave propagation aspects of the Kanto basin are modeled reasonably well with the proposed 3D velocity model.

Sato et al. (1999) provides a detailed discussion of the source and 3D wave propagation aspects for the 1923 Kanto earthquake rupture simulation throughout the entire Tokyo metropolitan region. Here, we concentrate our discussion on the simulation of the motions at Hongo station where the only available strong motion recordings of the 1923 earthquake were obtained.

The restored Ewing and Imamura time histories at Hongo are compared with the 3D and 1D simulation results in Figure 7. Both the data and the synthetics have been bandpass filtered at 0.067 - 0.25 Hz and are aligned in time with the initial P wave arrival. It is thought that the peak amplitude of the restored Imamura seismogram may be underestimated by at least 10% to 15%, so a scaled-up version of this record is also plotted in the figure.

Both the 1D and 3D simulations produce similar waveforms for the first 40 sec of the time histories, and these results are generally compatible with the recorded motions. It is interesting to note that even though this portion of the records is controlled by the direct source arrivals and surface waves, the 3D simulation predicts larger amplitudes than the 1D simulation, despite the fact that both models have the same surface velocity (0.6 km/s). This indicates that 3D basin response in addition to simple 1D impedance effects is important even for the direct wave energy.

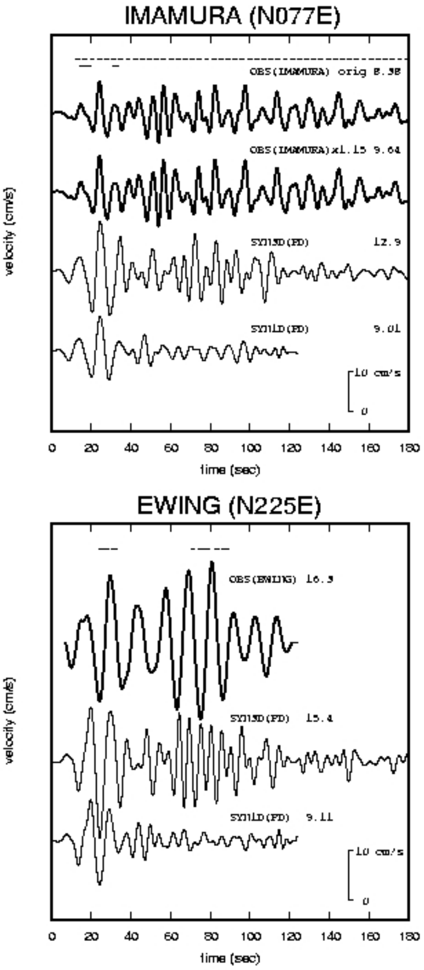

Figure 7: Comparison of 1D and 3D synthetics with the Imamura and Ewing motions at Hongo.

Clearly, the 3D simulation does much better than the 1D simulation at reproducing the large amplitude later arrivals that are seen in the data. Obviously, the fit to the waveforms with the 3D model is not perfect, indicating the need for improvements to the 3D model, but the general nature of the later arrivals is matched quite well by the 3D synthetics.

The 3D simulations of the 1923 Kanto earthquake using the Wald and Somerville (1995) slip model and a 3D model of the Kanto basin structure provide important insights to understanding the ground motions that occurred in the Tokyo region during this event. The results of this study suggest that the motions at Hongo were characterized by significant basin response effects, which led to amplification of the motions and the generation of strong, late arriving surface wave energy

CONCLUSIONS

The studies described in this paper demonstrate that large scale 3D FD ground motion simulations, including complex finite fault source representations, are feasible for realistic earth models down to periods approaching 1 or 2 seconds. The continued development of more efficient computational algorithms (e.g., variable grid spacing), in combination with advances in computational hardware should push this bandwidth threshold to below 1 second period in the next few years.

However, we must keep in mind that computational needs are not the only restrictions which may limit the successful application of these types of analyses. In fact, for many situations, the main limitations for these large scale long period 3D ground motion simulations are no longer related to computational issues, but rather reflect our lack of sufficient knowledge of earthquake source processes and 3D earth structure, particularly those which contribute to the ground motion response at periods around 1 sec. This stresses the need for 1) independent analyses to develop a better understanding of fault rupture and earthquake source characterization, integrating both kinematic and dynamic representations of the source processes and 2) comprehensive, multidisciplinary studies including geologic, seismological, and geophysical observations to develop and validate 3D velocity models for regions of complex geology. By improving our knowledge on these fronts, we will reduce the uncertainty in our numerical simulation models, and this will provide us with a more reliable predictive capability of the ground motion response expected for future earthquakes.

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