Paper No. 1073. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

A DUAL APPROACH TO GROUND MOTION PREDICTION

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ABSTRACT

Observations of small earthquakes at a site can be successfully used to predict time histories from a future large earthquake. If these events are co-located and have focal mechanisms consistent with the large earthquake's anticipated rupture, then approaches by Tumarkin and Archuleta (1994) or Hutchings (1994) can be applied. In most practical cases, however, high-quality seismic data are limited to a few events. We propose a way of improving ground motion simulations obtained by the kinematic modeling of an earthquake rupture with 1-D synthetic Green's functions (SGFs). The common SGF approach has two major problems: strong dependence of predictions on assumed slip distribution (which is a priori unknown), and great uncertainty in accounting for site response except for the rare cases when a complete geotechnical description is available. First we show that by fixing the ratio of the slip and the rise time everywhere on the fault, the resulting synthetics are weakly dependent on the slip distribution even in the near-field. Then by comparing any observation with the corresponding synthetics we get an empirical site-specific transfer function which represents the inaccuracy of the theoretical path and site models (as well as the small event's source model). After applying this transfer function to SGF predictions of the large earthquake we get a considerable improvement in both the amplitude and duration of predictions. Variability of transfer functions obtained from different small earthquakes' recordings at a site depicts the uncertainty of modeling small earthquakes using the SGFs, and thus can be used to estimate the uncertainty of forward predictions.

KEYWORDS

Empirical Green's functions; strong motion synthetics; kinematic modeling; site response.

INTRODUCTION

We develop a dual approach to the problem of prediction of ground motions from future large earthquakes. Simulations of the scenario earthquakes are performed by an Empirical Green's Functions (EGF) method and a hybrid method, which utilizes observations of earthquakes at a site to correct predictions from kinematic modeling using Synthetic Green's Functions (SGF). Our EGF method is based on a specific non-uniform distribution of rupture times of subevents, which eliminates the deficit of energy of predictions based on a constant rupture velocity. In the SGF approach we assume a constant stress drop over the rupture area. Thus we achieve an excellent stability of waveforms regardless of the distribution of slip even in the proximity of the fault. In the hybrid method we deconvolve synthetics from an observation at a site to obtain an empirical site transfer function. This transfer function, which accounts for inconsistency of our theoretical path and site models, can be applied to SGF results to improve the quality of predictions.

A simultaneous application of these two different techniques has the following advantages: by comparing results we have means to estimate the variability of the forward predictions; we can separate the source from the path and site effects, and can thus estimate the contribution of the local site geology; we can fully utilize the information contained in the available earthquake recordings at a given site. In each of these methods we try to confine ourselves to the smallest number of free parameters, such as rupture geometry, location of the hypocenter, and seismic moment. Other important features of these methods are: a simultaneous prediction of all three components of motion at a site; phasing is preserved both between components and different seismic waves arrivals; directivity effects are taken into account.

SUMMATION OF EMPIRICAL GREEN'S FUNCTIONS

The idea of EGF methods (Hartzell, 1978; Joyner and Boore, 1988; Aki and Irikura, 1991; Hutchings, 1994) is to utilize the observed small earthquakes originating within the rupture area of the simulated large earthquake as its subsources, representing the complexity of propagation of seismic waves through the crust and near-surface media. In this approach all subevents should have focal mechanisms similar to that of the simulated main event. Then one can simulate the large earthquake as a subsequent rupture of properly scaled and lagged subevents, especially if we have a good coverage of the anticipated main event rupture area by small earthquakes.

Any method of adding subevents in the time domain requires knowledge (or determination) of rupture times of subevents. The common methods that provide a satisfactory simultaneous fit to the lowest and highest frequencies of the target spectrum (Irikura, 1983; Joyner and Boore, 1986; Boatwright, 1988; Archuleta and Tumarkin, 1993; Tumarkin *et al.*, 1994) are based on a uniform distribution of subevent rupture times, i.e., a constant rupture velocity over the fault. However this natural assumption leads to a significant underestimation of the main event's spectrum in the vicinity of the target corner frequency (Joyner and Boore, 1988). As the corner frequency acts as a source resonant frequency (due to the fact that the source velocity amplitude spectrum is peaked at the corner frequency), the resulting predictions underestimate the total energy by as much as a factor of 3 (Tumarkin and Archuleta, 1994). A decrease in sizes of subevents results in a greater energy deficit of predictions. This problem can be overcome by adjusting rupture times of identical subevents in a special manner (Wennerberg, 1990), but not by allowing for different size subevents. However Wennerberg used a non-causal subevent-to-main event transfer function that resulted in unrealistic negative rupture times on the fault (see also Ordaz *et al.*, 1995).

Recently we have developed new empirical methods of ground motion prediction based on a specific non-uniform distribution of subevents' rupture times (Tumarkin and Archuleta, 1994; 1995; 1996). Directivity effects are taken into consideration by adjusting the apparent source duration according to the azimuth between the site and the direction of rupture propagation. The algorithm requires only seismic moment, size of rupture, hypocentral location and direction of propagation as input parameters. Figure 1 shows EGF predictions (dotted) of acceleration and velocity time histories of the Northridge earthquake (solid lines) at the Jensen Filtration Plant of the Los Angeles MWD (USGS station #0655 - 13100 Balboa Blvd.). This site is located at a distance of about 7 km directly above the North-Eastern edge of the rupture surface (Wald and Heaton, 1995). We used 4 aftershocks with magnitudes 3.2-3.4 as EGFs (Table 1). We see that even using such small subevents we are able to achieve a satisfactory prediction of both acceleration and velocity time-histories. As one can expect predictions obtained from the method which utilizes small earthquakes are overestimating high-frequency response. This fact is an inherent limitation of all linear ground motion prediction algorithms. On the other hand, except for the factor of about 1.5 in peak values, predicted waveforms are remarkably similar to observations both in amplitude and duration.

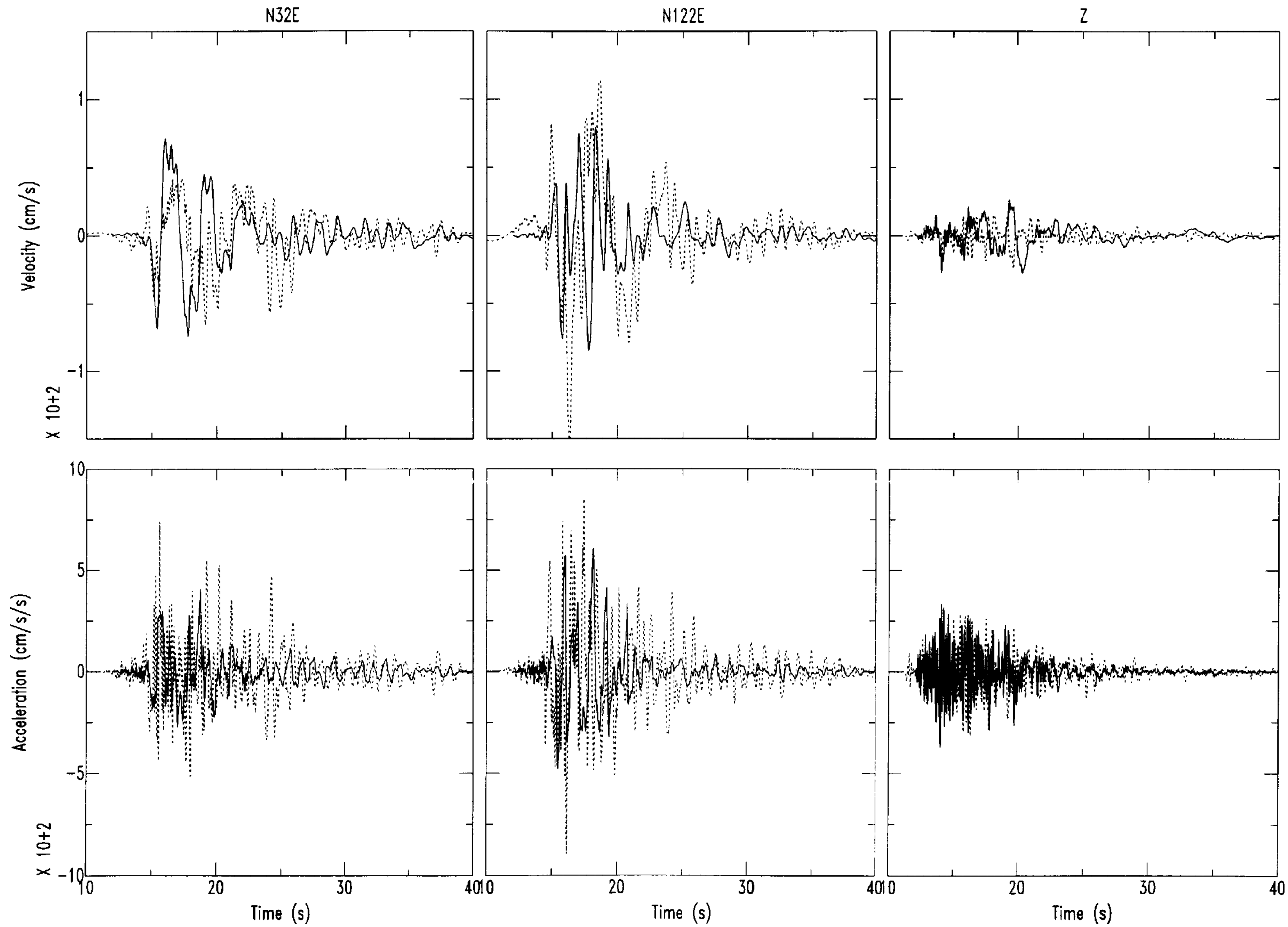

Fig. 1. Empirical Green's function prediction (dotted) and observed velocity and acceleration (solid) at Jensen Filtration Plant

Table 1. Source parameters of the Northridge earthquake sequence from the Caltech catalog and Hauksson *et al.* (1995) for M>4.0. Listed are the main event and 5 aftershocks, used in the present study.

Earthquake time	Latitude N (degrees)	Longitude W (degrees)	Depth (km)	M_L	Strike (degrees)	Dip	Rake
1/17 12:30:55	34.209	118.541	18.7	6.7	105	35	100
1/27 14:31:11	34.250	118.589	14.5	3.3	-	-	-
1/27 17:19:59	34.272	118.569	16.3	4.6	140	10	110
1/28 07:44:46	34.233	118.614	19.9	3.4	-	-	-
1/29 14:03:07	34.298	118.567	2.9	3.4	-	-	-
2/01 09:59:11	34.330	118.696	3.1	3.2	-	-	-

HYBRID APPROACH

A commonly used theoretical approach to ground motion prediction is a kinematic modeling of earthquake sources (Aki and Irikura, 1991). We calculate synthetic Green's functions using a full-waveform reflectivity code written by O. Coutant (Bouchon, 1981; Coutant, 1989). If we denote by $G_i(t)$ the ground displacement caused by a unit dislocation on the i-th subfault, then the resulting kinematic SGF prediction is: $U(t) = \sum_i \dot{S}_i(t) * G_i(t - t_i)$. Rupture times t_i are determined using a fixed rupture velocity of 3 km/s (which in most cases roughly corresponds to 85% of the shear-wave velocity). We assume the polynomial slip-rate functional form: $\dot{S}(t) = \frac{30}{T^5} s \cdot t \cdot (T-t)^4$, $0<t<T$, where t is time, T - rise time, s - final slip. This function's amplitude spectrum is practically identical to the Aki-Brune ω-squared model (Aki, 1967; Brune, 1970), while the function itself has an advantage of smoothly tapering to 0 at the time moment T. Our major assumption is that the average slip-rate s_i/T_i is 50 cm/s at each subfault. Essentially that means a constant stress drop distribution over the rupture area. This results in an impressive stability of velocity and displacement waveforms regardless of the slip distribution on the fault. The maximum slip-rate at each subfault is 123 cm/s and occurs at $\tau_i = T_i/5$. Thus effectively the only free parameters for a forward modeling are the total seismic moment, fault geometry and hypocenter location, as our predictions are insensitive to the assumed slip distribution.

We show predictions of the Northridge mainshock at the Jensen Filtration Plant (JFP). We used the rock velocity structure with lowest shear-wave velocity of 1 km/s at the surface (Wald and Heaton, 1994). Simulations using a completely random distribution of the slip on the fault (Fig. 2; top traces) and using the slip distribution of Wald and Heaton (1994) (Fig. 2; middle traces) produce very similar results even for such near-fault site as JFP. The stability of waveforms is especially notable in lower frequencies as shown by the velocity time histories (Fig. 2). At the same time, comparing predictions to data (Fig. 2; bottom traces) it is apparent that we are underestimating duration, overestimating high frequencies by predicting accelerations exceeding 2 g, and underestimating low frequencies. This is a result of the assumptions of rock velocity structure, low near-surface attenuation and disregard of scattering. The quality of predictions can be improved by using either available geotechnical data or seismological observations.

During the last year we developed a new technique which allows one to overcome shortcomings of the purely theoretical SGF approach by utilizing observations of earthquakes at a site. We were motivated by the problem of accounting for site response at soil sites. The idea, which we submitted in an abstract for this conference, and presented at the General Assembly of IUGG (Boulder, Colorado, July 2-14) and 5ICSZ (Nice, France, October 17-19) is to use an observation of *any* earthquake at a given site to improve the

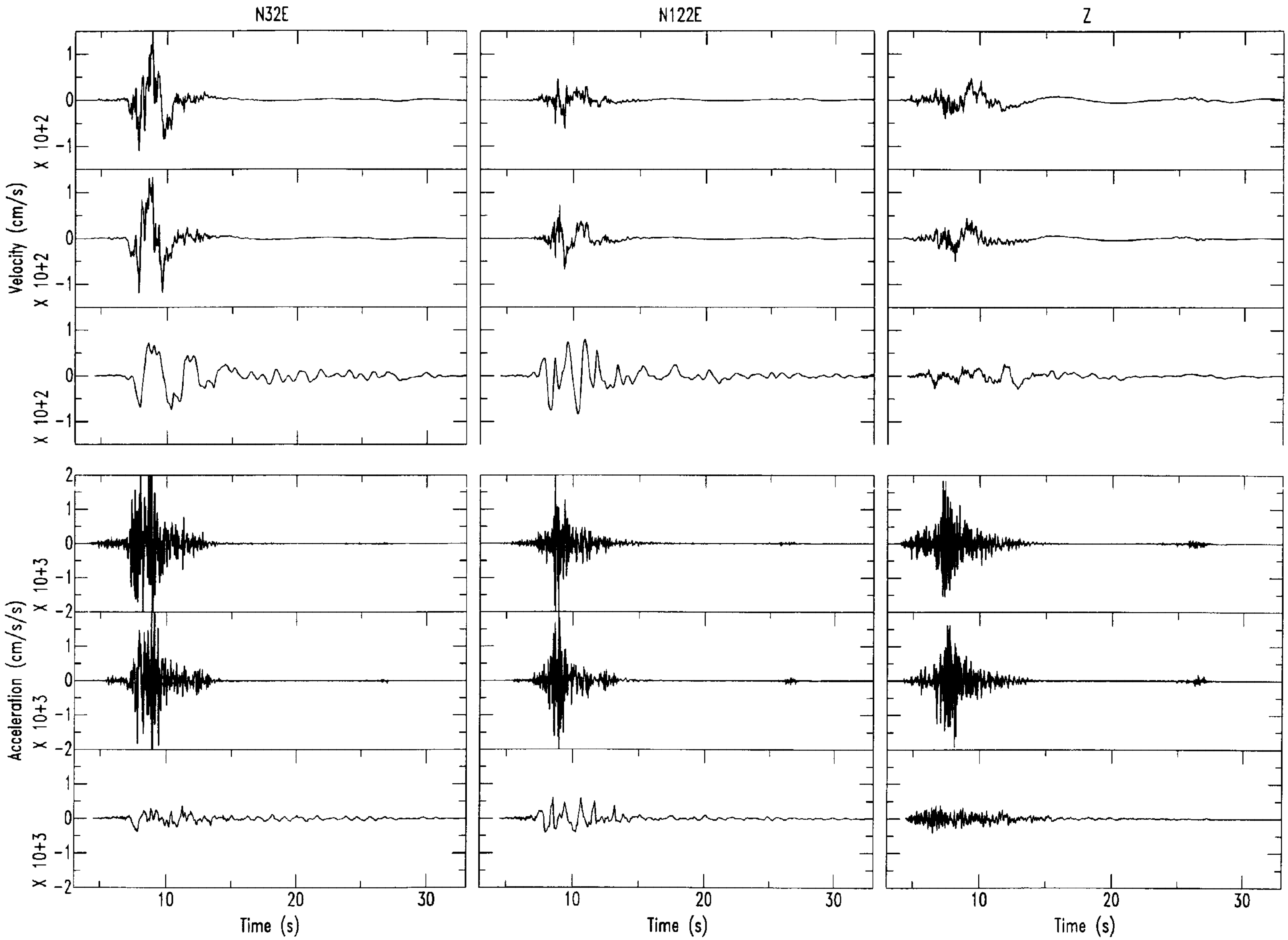

Fig. 2. SGF predictions: random distribution of slip (top), Wald–Heaton model (middle); and observation (bottom) at Jensen Filtration Plant

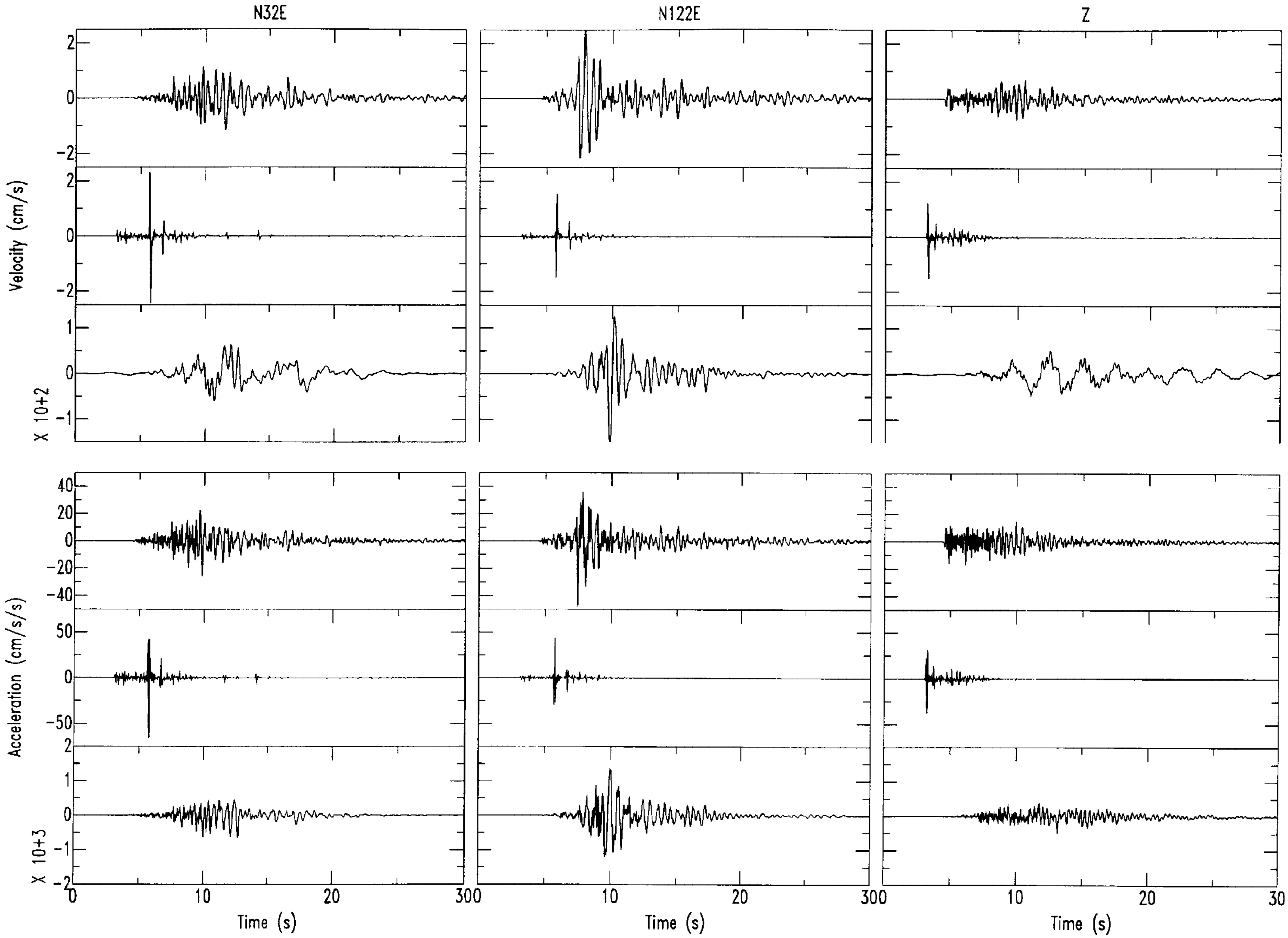

Fig. 3. M 4.6 aftershock (top), corresponding synthetics (middle); and result of application of ETF (bottom) at Jensen Filtration Plant

quality of theoretical predictions (Tumarkin *et al.*, 1995). A similar approach was independently and simultaneously proposed by Su *et al.* (1995).

In practice it is not uncommon to have a limited set of recordings (sometimes a single on-scale observation with a sufficient signal-to-noise level) available for site-specific ground motion prediction. Moreover these events might not necessarily originate within the anticipated large earthquake rupture area or might have different focal mechanisms. In this case we cannot apply the EGF methods (Tumarkin and Archuleta, 1994; Hutchings, 1994). Nonetheless by predicting a small earthquake's response $u(t)$ with the SGF approach we get an empirical site transfer function (ESTF) $H(t)$ between the predicted and observed waveforms: $u(t) = H(t) * \dot{s}(t) * G(t)$, where $G(t)$ is the synthetic Green's function calculated using the focal mechanism of the small earthquake and $\dot{s}(t)$ is its source slip-rate function. This transfer function represents the inaccuracy of the theoretical path and site models, as well as the small event's source model $\dot{s}(t)$. Variability of ESTFs for different small earthquakes' recordings at a site represents the uncertainty of modeling small earthquakes using the SGFs and thus can serve as an estimate of the uncertainty of our predictions. Ordaz *et al.* (1993) applied an empirical transfer function between a soil site and a rock site to their predictions, accounting for site effects. In our approach, however, we do not need a reference site, and our transfer function is directly related to the theoretical model inaccuracies. Figure 3 illustrates that even a single event's ESTF can be used to adjust SGF predictions to the local site conditions. We used the recordings (Fig. 3; top traces) of the M 4.6 aftershock on 01/27/94 (Table 1) from the site co-located with JFP during the SCEC portable deployment (Edelman *et al.*, 1994). To obtain the synthetics for the aftershock we assumed that its source time function $\dot{s}(t)$ is a Brune's pulse with a corner frequency 1 Hz (Brune, 1970). Exactly the same result is obtained if we use the polynomial functional form. The ESTF for each component of motion, resulting from deconvolution of synthetic Green's functions (Fig. 3; middle traces) and the Brune's pulse from the observed aftershock time series, was applied to the initial mainshock predictions with a random slip distribution (Fig. 2; top traces). The corresponding hybrid simulations are plotted in Fig. 3 (bottom traces). We see that after application of the ESTFs we get realistically looking acceleration and velocity time histories, much more consistent with observations both in amplitude and duration than the initial purely theoretical predictions.

CONCLUSIONS

We have arrived at a flexible, dual approach for forward modeling of ground motion from earthquakes. If there is sufficient coverage of the assumed fault plane by small events, we may use the empirical Green's function (EGF) approach with a non-uniform distribution of subevent rupture times to well model both the amplitude and duration of records from a large event. However, if the coverage of the fault plane by small events is poor, the hybrid approach is preferable: First we kinematically model the large earthquake by calculating synthetic Green's functions for the whole fault, and then we convolve resulting time histories with an empirical site transfer function (ESTF) based on one or more small events. This process provides a good compromise between coverage of the fault plane with Green's functions, and taking into account the empirical effects of site and path. In both cases the assumption of constant stress drop over the rupture area leads to robust synthetics that are insensitive to the distribution of slip on the fault, thus minimizing the number of free parameters in the model. Simultaneous application of these two methods provides valuable insight into the uncertainties associated with the forward prediction of ground motion from large events.

ACKNOWLEDGMENTS

We are grateful to Fabian Bonilla and Jamie Steidl for providing us with corrected data from the SCEC Northridge aftershock deployment. The work was supported by the National Science Foundation through Cooperative Agreement EAR-8920136 and USGS Cooperative Agreement 14-08-0001-A0899 to the Southern California Earthquake Center (SCEC), and by the USGS grant 1434-94-G-2461. ICS contribution #0237-51EQ.

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