Two- and Three-Dimensional Effects on Ground Motion

by Apostolos Papageorgiou

Abstract

Geologic conditions and topography at, or near, a site are known to exert a very significant influence on the nature of ground shaking, and their importance on seismic hazard has long been recognized. In particular, sedimentary deposits in the form of sediment-filled valleys or basins very often have a pronounced effect on the intensity of strong ground motion. The finite lateral extent of the sedimentary deposit introduces complex effects through the generation of surface waves (referred to as *locally generated (or valley induced) surface waves*) at the edges and resonance in the lateral direction, and tends to increase both the *amplitude* and the *duration* of the ground motion. Therefore, for the correct interpretation and/or reliable prediction of strong ground motion, as much insight as possible must be gained about the response of these geologic structures. This can be accomplished by theoretical modeling and by comparing/validating the predictions of theoretical models with recorded data.

Collaboration

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Objectives and Approach

Numerical simulation techniques which have been used in the past are being further developed, (Papageorgiou and Kim, 1991, 1993), and applied with the following objectives: to perform parameter sensitivity studies of realistic 2-D and 3-D models; to study the pattern of shaking during particular target earthquakes; to bridge the gap between the engineering approach which is based on 1-D *"local"* models which emphasize on detailed modeling of the layering and constitutive behavior of the soil profile, and the seismological approach which addresses the problem of site effects by analyzing 2-D and 3-D *"regional"* models at the expense of detail modeling of the soil deposits; and to provide guidelines for the selection of values of important parameters, such as *phase velocities* and *apparent horizontal velocities*, to be used for the design of extended structures such as bridges and pipelines.

To accomplish these objectives, a hybrid numerical technique was developed which combines the *Boundary Integral Equation Method (BiIEM)* with the *Finite Element Method (FEM)*. The advantage of this technique is that it utilizes the versatility of the FEM to model in detail the valley/scatterer while the BIEM is used to account analytically for the radiation condition.

This research task is part of NCEER's program in Seismic Hazards and Ground Motion. Task numbers are 92-2002 and 93-2001.

Accomplishments

Observations during past and recent earthquakes, notably the San Fernando earthquake of February 7, 1971, the Loma Prieta earthquake of October 17, 1989 and the Northridge earthquake of January 17, 1994, have clearly demonstrated the importance of local site effects on strong ground motion. In particular, the devastating effect that ground motions, strongly amplified by local soil and topographic conditions, may have on bridges and utility pipelines systems, have been amply demonstrated in all three of the aforementioned earthquake events. While protection of life obviously is the first concern, the devastating economic consequences of prolonged closure of one or more key transportation arteries may now be visualized clearly (Housner, 1990).

According to a recent study by Holzer (1994), approximately 98% of the $5.9 billion in property damage from the 1989 Loma Prieta earthquake was caused directly by ground shaking; amplified (i.e. enhanced) ground shaking was directly responsible for approximately two-thirds, $4.1 billion, of the total property loss, while permanent ground deformation accounted for about 2% of the damage.

As Holzer (1994) points out, these observations indicate that local shaking and motion amplification must be understood. Research into amplified ground shaking and its effects on manmade facilities as well as mapping of urban areas susceptible to enhanced shaking would improve any hazard mitigation effort, from insurance programs to mandatory construction requirements.

Sedimentary deposits in the form of valleys or basins have a pronounced effect on the intensity of strong ground motion. One of the most important effects of sedimentary valleys on earthquake ground motions is the generation of surface waves - referred to as *locally generated* (or *valley induced*) *surface waves* - which propagate back and forth within the sediments, prolonging the signal duration and inducing the development of significant differential motions (for a recent state-of-the-art review see Aki, 1988).

In the earthquake engineering literature, surface waves and nonvertically incident body waves are loosely referred to as *traveling seismic waves* because they cause a traveling disturbance on the free surface of a half-space (as opposed to vertically incident body waves which cause every point of the free surface of a half-space to move in phase). The influence of traveling seismic waves has been studied (e.g. Newmark, 1969; Luco and Wong, 1982) as well as for bridges (e g. Abdel-Ghaffar and Trifunac, 1977; Werner et al., 1979). Specifically, Love waves and non-vertically incident SH waves induce a torsional component of response even in the case of symmetric structures and foundations, while Rayleigh waves and nonvertically incident P and SV waves induce additional contributions to the rocking response.

In particular for bridges, phase differences in the input ground motions applied to the bridge foundations can have significant effects on the bridge response Therefore, it is important to consider such traveling wave effects when designing earthquake-resistant structures of this type. Furthermore, the nature of the structural response to traveling seismic waves is strongly dependent on the azimuthal direction of incidence as well as on the excitation frequency of the seismic waves.

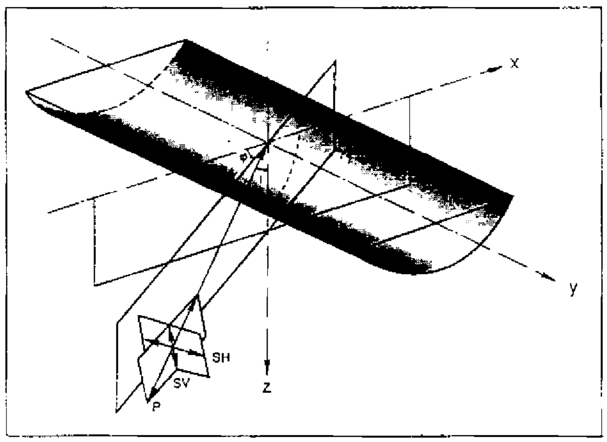
The magnitude of the effects associated with traveling seismic waves - on bridges as well as on buildings - depends on the assumed characterization of the seismic excitation and, in particular, on the values of ***phase velocities*** (for surface waves) or *apparent horizontal velocities* (for body waves). The lower the phase velocities or apparent horizontal velocities, the more important the rotational effects on structures.

Therefore, one of the objectives of the research project is to provide guidelines for the selection of values of important parameters, such as phase velocities and apparent horizontal velocities, to be used for the design of extended structures such as bridges and pipelines.

Almost all previous theoretical studies of scattering of elastic waves in two-dimensional space —including the studies of Papageorgiou and Kim (1991, 1993)—have assumed that: (1) the scatterer (e.g. valley) has the shape of a cylinder (i.e infinitely long in one direction) with arbitrary cross section, and (2) the incident waves act perpendicularly to the long (major) axis of the valley.

The above formulation will be modified and extended as follows: the scatterer (e g valley) again is assumed to be in the form of an infinite cylinder. However, the incident wave field is assumed to be three-dimensional (i.e the incident waves act at arbitrary angles with respect to the vertical and horizontal axes of the valley) (figure 1).

The above stated task has been successfully

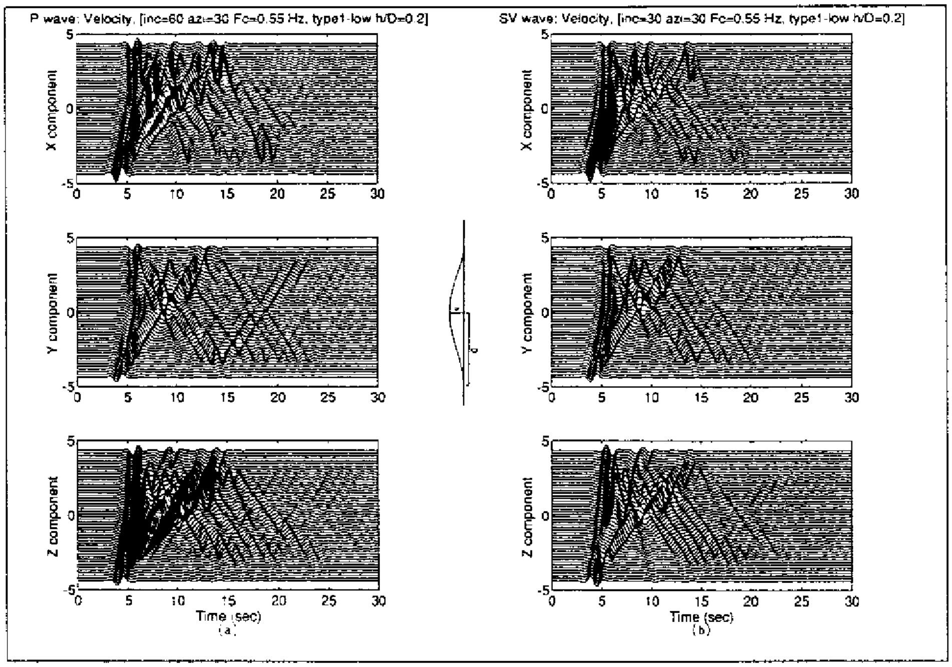


■ **Figure 1**

2-D model of a valley/scatterer excited by incident plane body waves.

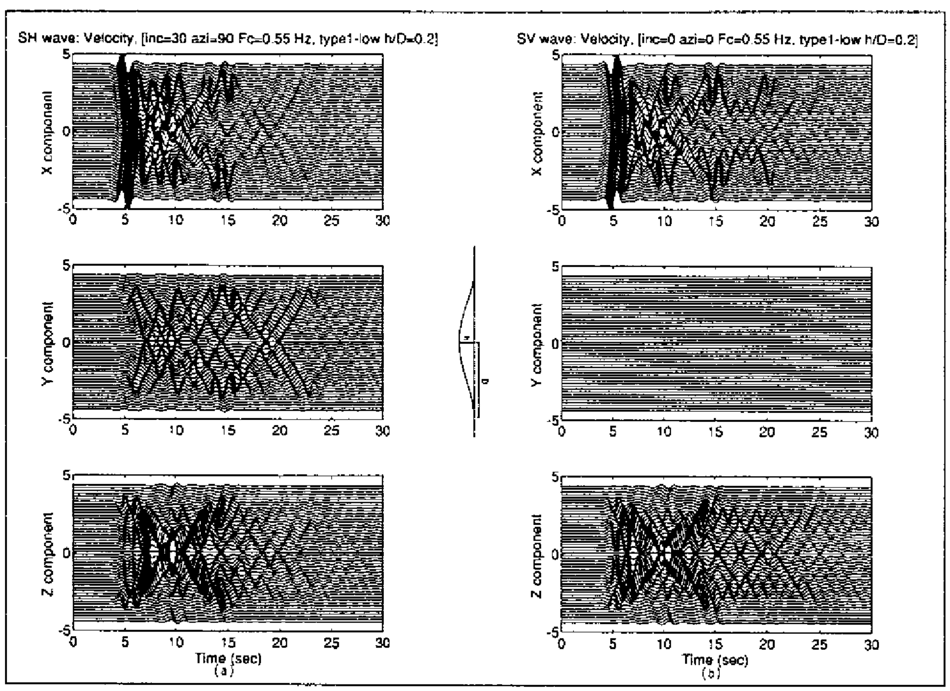
accomplished, and the mathematical formulation has been implemented in a computer code.

Using numerical simulations, a parameter sensitivity study was performed for idealized models of basin structures (Pei and Papageorgiou, 1993; Papageorgiou and Pei, 1994) The simulations reveal the existence of strong coupling between P/SV and SH modes of wave propagation, while many important features of the valley response appear to be sensitive to the *polarization* of the particle motion of the incident wave. For instance, figure 2 shows the great similarity in the valley responses for the cases of incident *P(i=60°,*



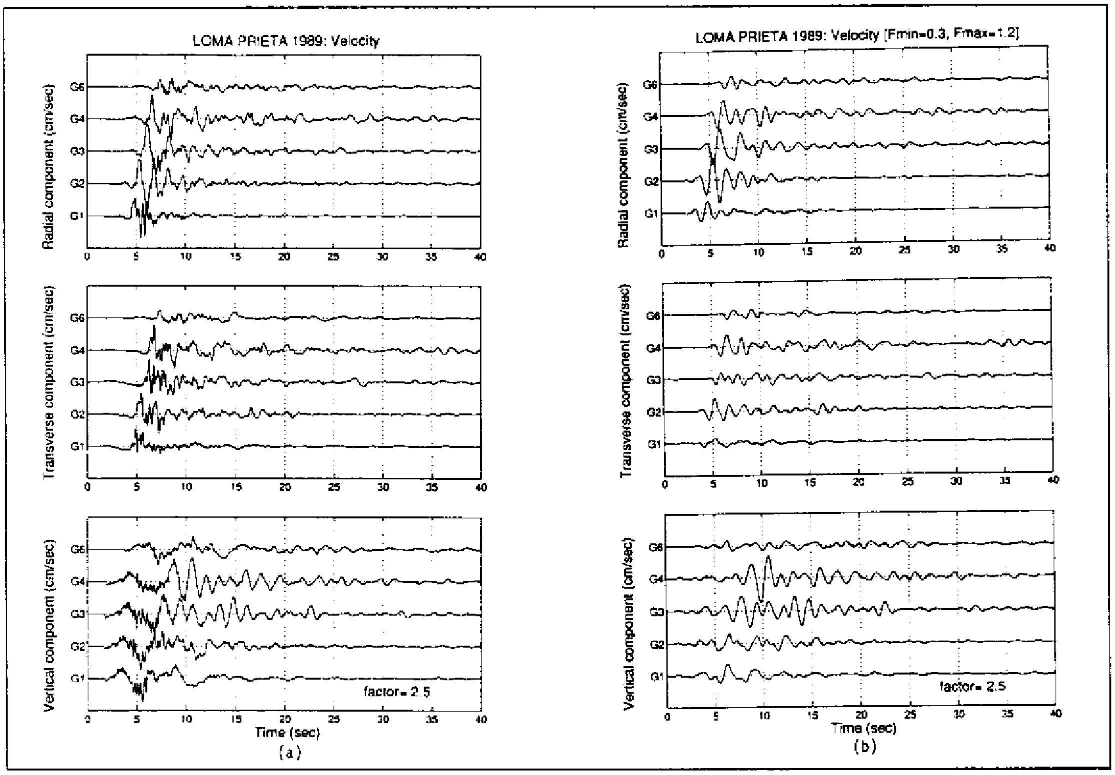
■ Figure 2

Displacement response of a 2-D valley model to incident (a) *P(i=60°, φ=30°)* and (b) *SV(i=30°, φ=30°)*.



■ Figure 3

Displacement response of a 2-D valley model to incident (a) *SH(i=30°, φ=90°)* and (b) *SV(i=0°, φ=0°)*.



■ **Figure 4**

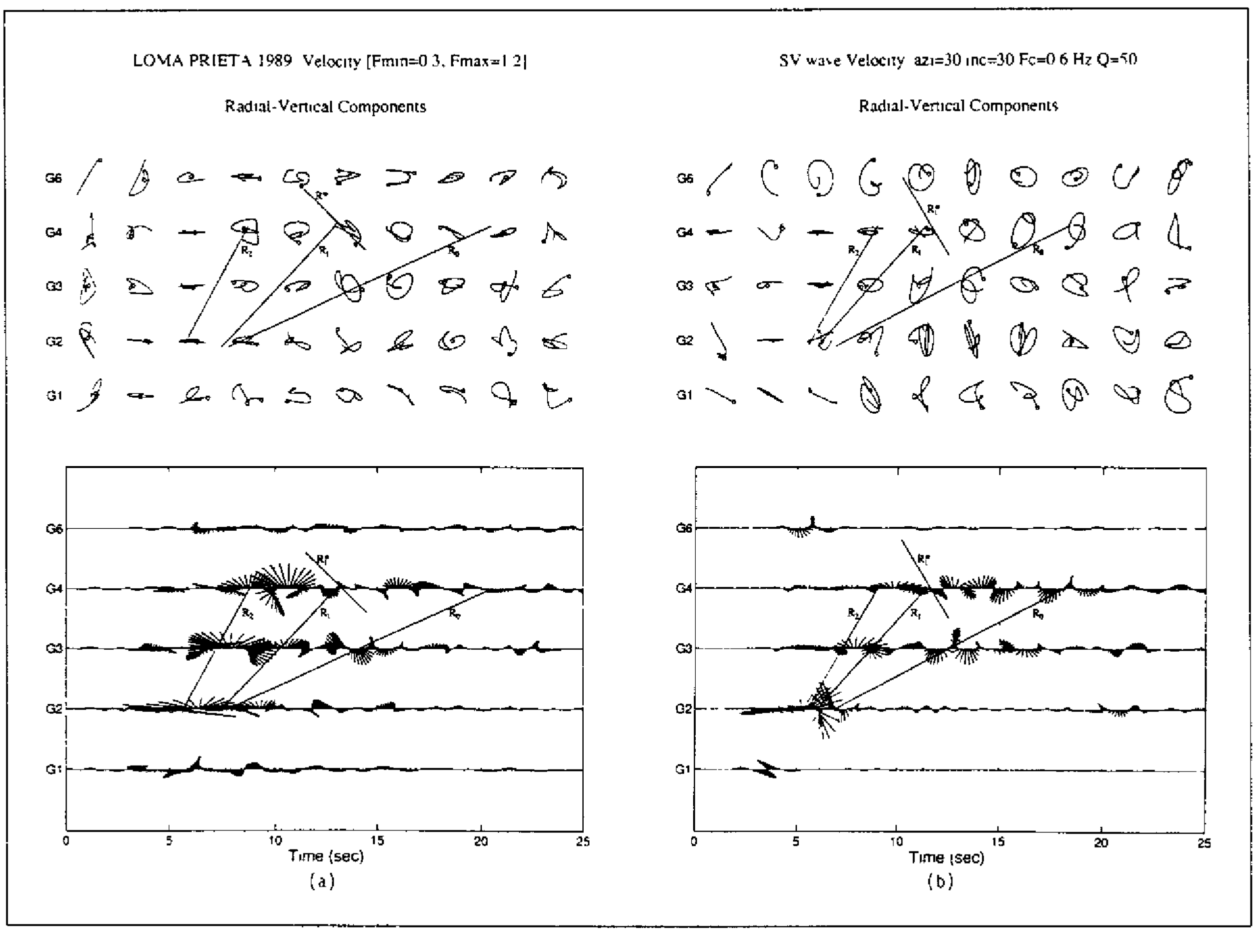
The radial, transverse, and vertical components of velocity of the 1989 Loma Prieta earthquake recorded across the Gilroy array: (a) original recorded data; (b) filtered recorded data.

ϕ=30°) and *SV (i=30°, ϕ=30°)* waves where *i* = *incidence angle* and *ϕ* = *azimuthal angle* (figure 1). In both cases the polarization of particle motion is closer to the horizontal direction than to the vertical one. In the same vein, figure 3 shows the great similarity in the valley responses for incident *SH (i=30°, ϕ=90°)* and *SV(i=0°, ϕ=0°)* waves; in both cases the direction of particle motion is horizontal and parallel to the transverse direction of the valley.

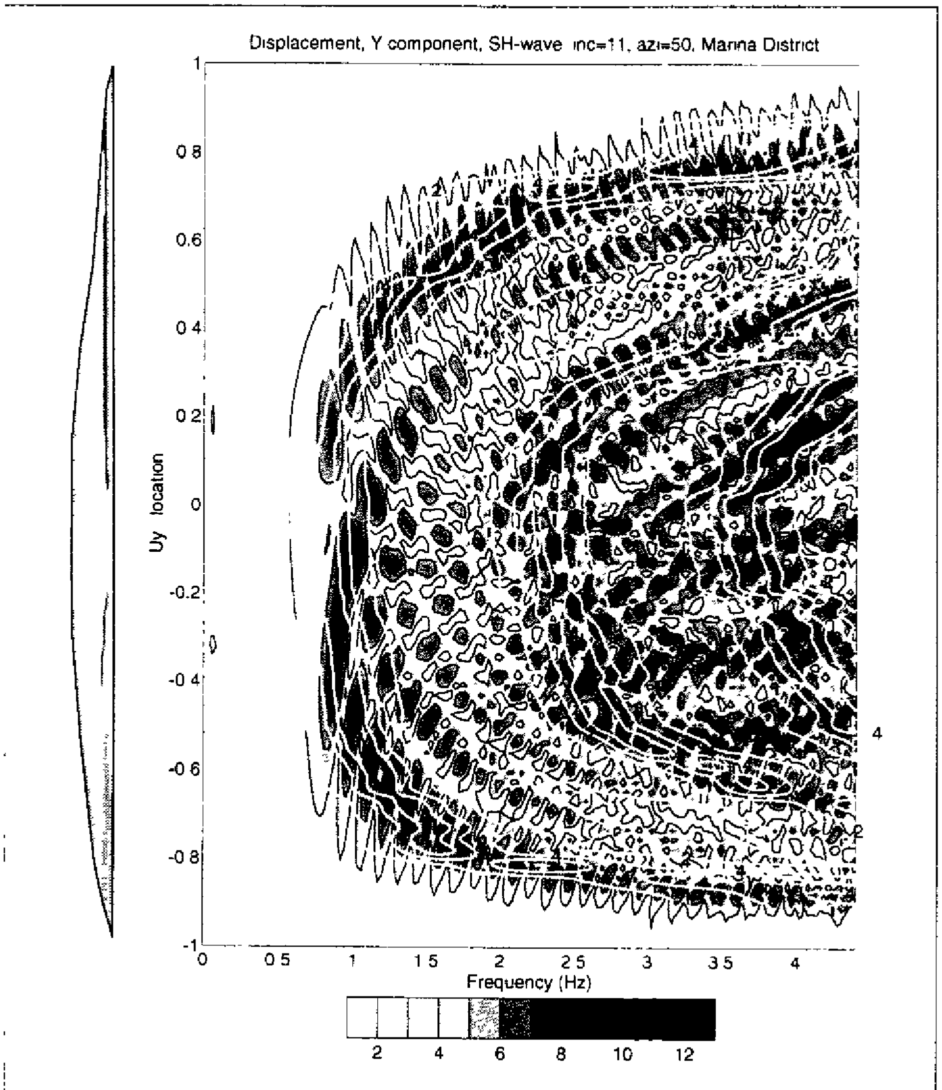
Furthermore, the type of surface wave (i.e. Love or Rayleigh) and the particular mode (i.e. first higher versus fundamental Rayleigh mode) that is more strongly excited depends on the polarization of the particle motion. For example, as the direction of particle motion of the incident waves approaches the horizontal, the first higher Rayleigh mode (for which the horizontal component of motion is dominant as compared to the vertical one) is more strongly excited at the detriment of the fundamental Rayleigh mode (for which the vertical component of motion is dominant).

In order to validate the numerical model, the earthquake data recorded by the Gilroy array was analyzed, which is an east-west alignment of stations crossing the Santa Clara Valley. The array, extending from rock on the east across the alluvial Santa Clara Valley to rock on the west, provided significant records of the 1979 Coyote Lake earthquake, the 1984 Morgan Hill earthquake and the 1989 Loma Prieta earthquake. In our analysis of the recorded strong ground motions, the polarization of particle motion on horizontal and vertical planes (*"polarigrams"*) were studied to identify the type of surface waves and their direction of propagation (Pei and Papageorgiou, 1994). Figure 4 shows the velocity data (original and filtered versions) recorded by the array in the 1989 Loma Prieta earthquake. Stations G1 and G6 are sited on firm ground (i.e. rock) while stations G2, G3 and G4 are sited on sediments. The type of the surface waves, which are evident on figure 4, is revealed on the polarigrams shown in figure 5a. Various Rayleigh modes originate at the two edges of the valley and propagate in opposite directions Figure 5b shows polarigrams of the synthetic motions which agree, at least qualitatively (i e. in terms of phase type and timing of arrival), with the recorded data.

Finally, in consultation with other NCEER researchers, an effort to estimate the intensity of ground motion that the Marina District of the City of San Francisco sustained in the Loma Prieta earthquake was undertaken No accelerograms were located in the Marina when the earthquake struck. However, based on the damage distribution pattern, it is well established that the area underlain by the 1912 hydraulic fill, which sustained extensive liquefaction, was less severely damaged than the blocks to the west and south. In order to simulate the response in the Marina, the complex stratification of the sediments had to be taken into account. This was easily taken care of with the hybrid numerical technique that was developed by the author The model was calibrated by studying the response of the sediments of the Marina to an aftershock (local mag-



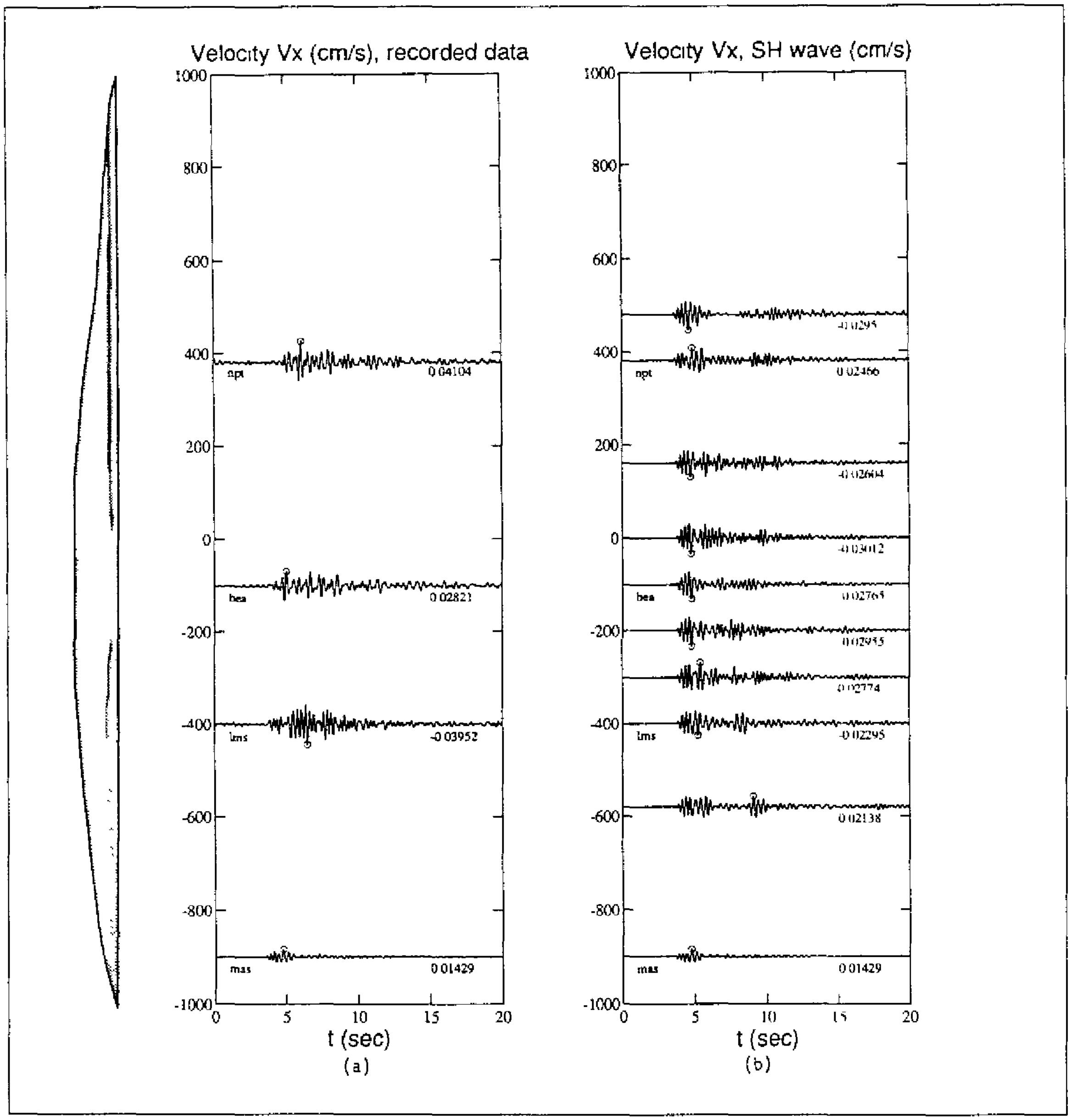
■ **Figure 5**
***"Polarigrams"* of the particle motion on a vertical plane in the radial (i.e. epicenter-station) direction: (a) recorded data and (b) synthetic motions.**



■ Figure 6

Frequency response characteristics of a 2-D model of the Marina District. On the *amplification ratios (AR)* of 2-D model are superimposed the ARs of the corresponding 1-D model of each site across the valley.

nitude $M_L = 3.6$) that was well recorded on the sediments as well as on an adjacent rock outcrop. For such weak motions, the sediment response may safely be assumed to be linear Figure 6 shows the frequency response characteristics of the valley, while in figure 7, the synthetic motions may be compared to the recorded motions at three stations (Zhang and Papageorgiou 1994, 1995) Simulation of the response of the Marina District to the Loma Prieta earthquake as well as to other potentially destructive events in the vicinity of San Francisco, are currently under way and near completion The soil nonlinearities for such intense motions are currently accounted for by the *"equivalent linear approach"* (Kausel et al., 1976), while liquefaction, which occurred in the upper 10 m of the fill, is not modeled One of our long term objectives is to extend the 2-D math-



■ **Figure 7**
(a) Recorded and (b) synthetic motions of a Loma Prieta aftershock (M_L = 3.6) across the Marina District.

ematical formulation so as to model the true non-linear behavior of the soil deposit.

At present, the authors are embarking on a study of the response of a 2-D model of the San Fernando and Los Angeles Valleys to the 1994 Northridge earthquake for which valley effects were very prominent (EERI, 1994) as one would anticipate on the basis of the response of these valleys to the 1971 San Fernando earthquake (Dobry et al., 1978,Vidale and Helmberger, 1988)

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