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Seismic Response of a Linear, 2-D Model of the Marina District

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SYNOPSIS The recorded response of the Marina District of the City of San Francisco to an aftershock of the 1989 Loma Prieta earthquake is simulated using a two-dimensional model of the sedimentary deposits. Even though the response of the Marina is truly three-dimensional, the two-dimensional model successfully captures some important aspects of the response and consequently may be useful for predicting strong ground motion in the Marina District for engineering applications.

INTRODUCTION

Four years after the destruction caused in Mexico City by the Michoacan earthquake more than 300 km away, the 1989 Loma Prieta earthquake came as a reminder of the effects of ground motion amplification in soft soils and ground failure in non-engineered fills (Hanks and Krawinkler, 1991). To acquire perspective on the matter it is relevant to point out that approximately 98% of the $5.9 billion in property damage from the 1989 Loma Prieta earthquake was caused directly by ground shaking; amplified ground motion by local site conditions was directly responsible for approximately permanent ground deformation accounted for about 2% of the damage (Holzer, 1994).

In particular, the destruction inflicted on the Marina District of the City of San Francisco is a significant part of the Loma Prieta earthquake experience because of the complex interplay between strong ground motion, permanent ground deformation and structural damage. During the Loma Prieta earthquake and its aftershocks, ground motion in the Marina District was amplified in comparison to sites on bedrock. Amplification occurred both at natural deposits and artificial fills, and a majority of damage to structures was caused by strong shaking. Effects such as settlement, ground failure/liquefaction, and attendant damage were essentially limited to areas of artificial fill (Bonilla, 1991; Hanks and Brady, 1991; Boatwright et al., 1991; O'Rourke et al, 1992; Seed et al., 1991).

Because there was no ground motion recording instrument existing in the Marina District at the time of the Loma Prieta earthquake, considerable uncertainty surrounds estimates of the amplitude, frequency content, and duration of the mainshock ground motion there (Hanks and Brady, 1991; Boatwright et al., 1991). The present work investigates aspects of the dynamic response of the sediments underlying the Marina District, and thus it is a first step of an attempt to address the problem stated above. Such a study is timely given the fact that the potential for one or more large earthquakes (of Magnitude M7) on faults of the San Andreas system has been assessed—by the Working Group of California Earthquake Probabilities—to be equal to 67% for the next 30-year period (U.S.G.S., 1990).

PREVIOUS INVESTIGATIONS OF THE SEISMIC RESPONSE OF THE MARINA DISTRICT

The Marina District sits atop a northwest-trending valley that is filled with natural and artificial sediments. The bedrock consists of Franciscan assemblage and serpentine. The sediments, moving upwards from the bedrock-sediment interface, consist of Pleistocene bay clay, a dense Pleistocene sand layer (described also as silty sand, or clayey sand), soft Holocene bay sediments, loose to dense Holocene beach and dune sands, and artificial fill that have an aggregate maximum thickness of about 90 m.

As pointed out above, no accelerographs existed in the Marina District prior to the Loma Prieta earthquake, so the mainshock was not recorded there. Following the mainshock, triggered seismographs were deployed by Boatwright et al. (1991) in and around the Marina District to investigate site amplification (Figure 1). Analyses of aftershock recordings showed that the Fourier spectral amplitude at the basin sites is amplified by factors of 6 to 10 at the 1 Hz and 2 to 4 at 3 Hz, relative to a station located on Franciscan sandstone at Fort Mason (Figure 1) irrespective of whether they are sited on artificial fill or beach sand. For frequencies above 2.5 Hz, a 1-D model (i.e., plane-layered model), which accounts for impedance amplification and anelastic absorption (Q), can

Marina Basin Model

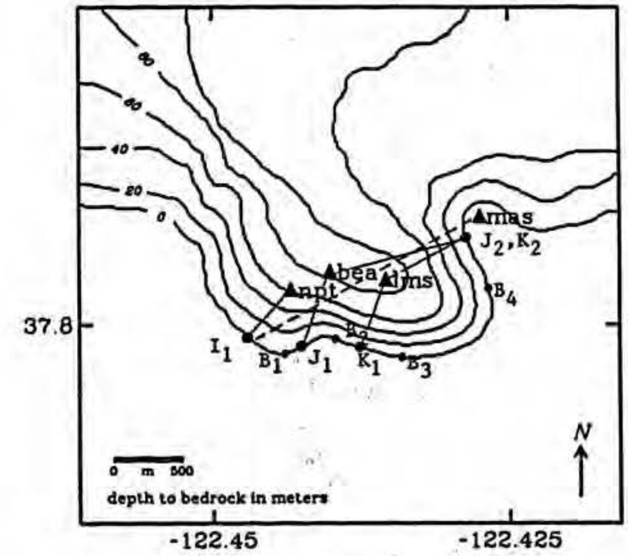

Figure 1: Structural model of the Marina District basin (modified from Graves, 1993)

provide reasonably good estimates of the relative amplification. However, as Boatwright et al. (1991) point out, such a 1-D model markedly underestimates the amplification observed near 1 Hz. Boatwright et al. (1991) also point out that the amplification is common to all the basin sites (especially for frequencies below 2.5 Hz), and they speculate that the "additional" observed amplification (as compared to the 1-D model predictions) for frequencies below 2.5 Hz may be associated with the *focusing* of shear waves derived from the three-dimensional shape of the sedimentary basin underlying the Marina District.

Liu et al. (1992) used aftershock data recorded by a downhole array (in the vicinity of station NPT) to estimate spectral rations for surface and basement rock motions. They observed that except for the lowest frequency spectral-ratio peak at ~ 1 Hz, frequency of other peaks depends on the azimuthal position of the earthquake source relative to the Marina District. Furthermore, Liu et al. (1992) observed that the particle-motion polarization becomes complex shortly after the P-wave and S-wave onset. They interpret this as an indication that the wavefield in the basin is three-dimensional and they attribute such effects to the three-dimensional topography underlying the site.

A 3-D elastic response analysis of the Marina District has been reported in the literature by Graves (1993), who, due to computational limitations, modeled only the *scalar shear waves* as opposed to the full elastic wavefield. This study is important and informative in that it shows clearly the overall response characteristics of the Marina District and thus reveals the limitations of the 2-D model that we use in our analysis.

Finally, Bardet et al. (1992) used a 2-D finite element model to complement the 1-D response analyses of the Marina District. The 2-D model analyses were approximate in that wave propagation effects at the basement rock-interface were considered only in an empirical/approximate way and no consideration was given to the radiation condition. They concluded that two-dimensional effects are important in modeling the site response of the Marina District although, they note, material nonlinearity was observed to decrease these effects.

MODEL OF THE MARINA DISTRICT

In our analyses we use a 2-D model which represents a cross-section of the basin indicated by the intermittent line in Figure 1. The azimuthal direction of the incoming wave is perfectly normal to the selected cross-section. Thus, for the 2-D model shown in Figure 2, the azimuthal angle $\varphi = 90°$. The selected material properties of the sediments as well as the two-dimensional cross-section are very similar to those selected by Bardet et al. (1992).

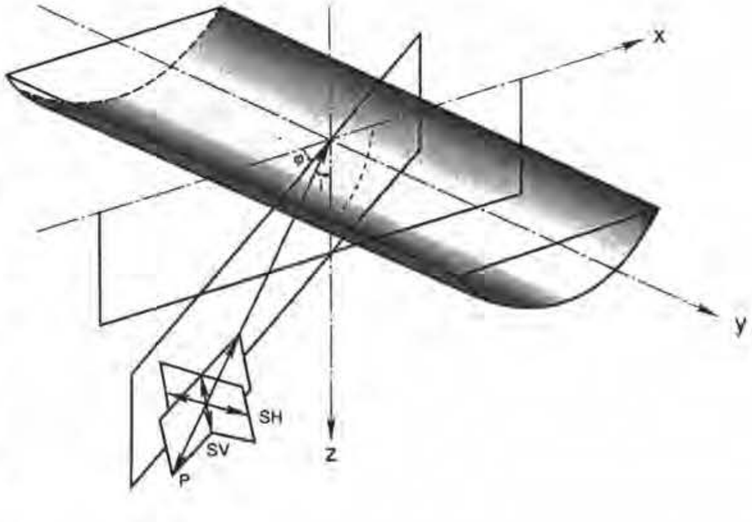

Figure 2: 2-D model of a valley/scatterer excited by incident plane body waves

We state at the outset that the topography of the basement rock-sediment interface underlying the Marina District is really three-dimensional. For irregularly shaped basins, such as this one, S-to-surface-wave conversion could occur along several portions of the border of the basin, producing surface waves traveling in different directions across the basin, as observed by Frankel and Vidale (1992) for the region of the Santa Clara Valley just south of the San Francisco Bay. It is evident, then, that a 3-D model would be necessary to capture all important wave phenomena induced by the incident seismic excitation.

The obvious question then, is how useful, if at all, are the simulations with a 2-D model for the case of the Marina District. Clearly, any diffractions and any surface waves originating over the segments B_1B_2 and B_3B_4 cannot be represented with a 2-D model. To answer the question, we investigate the wavefield observed in the simulations performed by Graves (1993) and in particular the points of origin, along the basin boundary, of the surface waves observed passing stations NPT, BEA and LMS (Figure 1). These points are marked in Figure 1. It appears that all the surface waves that originate at the eastern edge of the basin and affect the above three stations can be represented reasonably well by the 2-D model. On the other hand, of the surface waves that originate on the southwestern margin of the basin, only the wave which originates in the vicinity of point I1 (and affects station NPT) may be modeled reasonably well with a 2-D model. Regarding the other surface waves which originate at points J1, K1 (and affect stations BEA and LMS, respectively), we can hope that they are simulated in a qualitative sense by the 2-D model.

It is interesting to note that most of the "bright spots" (i.e., regions of the basin where amplitude of shaking is larger) observed in the simulations of Graves (see Figure 7 of Graves, 1993) appear to be aligned in the vicinity of the cross-section shown in Figure 1, and appear to correlate well with the depth to the underlying basement. All of these "bright spots" appear also in the 2-D simulations and agree, at least in a qualitative sense, with the 3-D results. It should be noted, though, that the 3-D simulations reveal a few other "bright spots" at sites away from the cross-section that obviously cannot be represented by a 2-D model.

However, as Graves (1993) points out, the location of these "bright spots," as well as several other characteristics of the basin response, are quite sensitive to the degree of accuracy of the geometry of the basement rock-sediment interface and the material properties of the sediments. Given that all these factors are only approximately known, and taking all the above facts into account, it is not unreasonable to expect that a 2-D model may still provide some useful information and insight about the response of the Marina District to the Loma Prieta earthquake.

PRELIMINARY RESULTS

For the location of the Marina District relative to the earthquake source, the excitation consists primarily of SH-waves (which explains also the relative strength of the EW component of the recorded motions as compared to the NS component). Therefore, we consider a plane SH wave with an angle of incidence $i = 11°$ appropriate for critical reflections from the lower crust (Figure 2).

The method of analysis is a hybrid numerical technique which combines the Finite Element Method (FEM) with the Boundary Integral Equation Method (BIEM). The main advantage of such a numerical 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.

Figure 3 shows the amplification ratio along the profile of the Marina District considered for analysis. Two observations can be made with regard to the results presented in this Figure:

1. The "bright spots" of the 3-D simulations which were observed in the neighborhoods of stations BEA and LMS (Graves, 1993) are also evident in this Figure (see the high amplifications in the neighborhood of BEA and LMS in the vicinity of 1 Hz).

2. The frequency bands that are more strongly amplified in the central region of the 2-D profile (i.e., from -0.5 km to +0.5 km) are centered at 1, 2.3 and 4 Hz. This is in very good agreement with observed amplification ratios in the Marina District which exhibit a broad peak at 1 Hz and a "side lobe" at 2.3 Hz (Boatwright et al., 1992).

Figure 4 compares the synthetic ground motions with the recorded ones. From an engineering perspective, the amplitude, frequency content and duration of the synthetics resemble the recorded motions reasonably well.

CONCLUSION

The response of the Marina District, as revealed by recorded aftershock data of the 1989 Loma Prieta earthquake and by numerical simulations, is truly three-dimensional. Nevertheless, a 2-D model, despite its shortcomings, may still be useful for estimating strong ground motion in the Marina District for engineering applications.

ACKNOWLEDGMENTS

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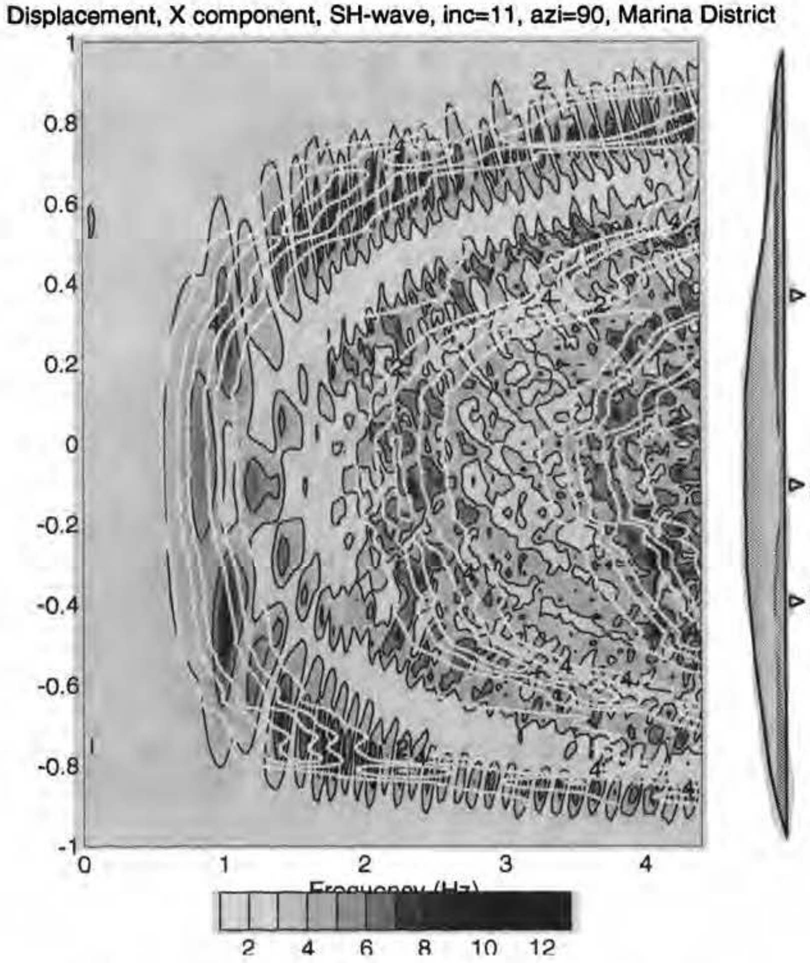

Figure 3: Frequency response characteristics of a 2-D model of the Marina District.

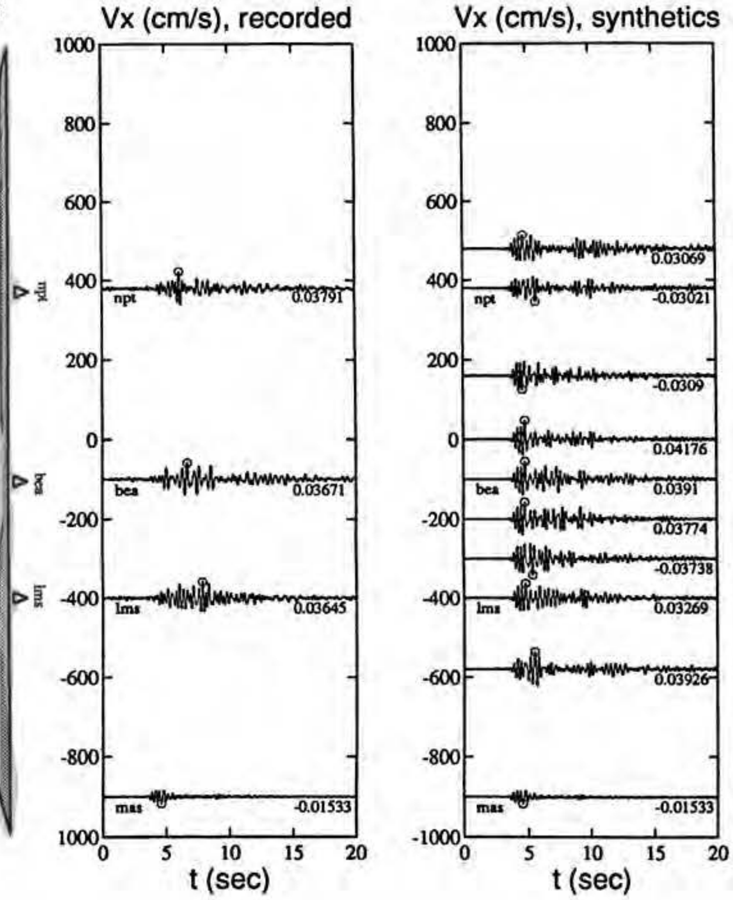

Figure 4: (a) recorded and (b) synthetic motions of a Loma Prieta aftershock ($M_L = 3.6$) across the Marina District.

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