Title
Site response at Treasure and Yerba Buena Islands, California

Journal
Journal of Geotechnical and Geoenvironmental Engineering, 129(5)

ISSN
1090-0241

Authors
Baise, L G
Glaser, Steven D
Dreger, D

Publication Date
2003-05-01

Peer reviewed

Site Response at Treasure and Yerba Buena Islands, California

Laurie G. Baise, M.ASCE[1]; Steven D. Glaser, M.ASCE[2]; and Douglas Dreger[3]

Abstract: A variety of methods are utilized to reinvestigate the physical relationship between the seismic response of Treasure Island (TI) and Yerba Buena Island (YBI) in California. These islands are a soil (TI) and rock (YBI) site pair separated by 2 km. The site pair has been used previously by researchers to identify soil response to earthquake shaking. Linear regime ground motions ($M_W 4.0$–$M_W 4.6$ and *PGA*: 0.014–0.017 g) recorded in the TI vertical array indicate a coherent wavefield in the sediments and an incoherence between the rock and sediments. Our analyses show that the greatest change in the wavefield occurred between the rock and soil layers, corresponding to a significant impedance contrast. The waveforms change very little as they propagate through the sediments, indicating that the site response is a cumulative effect of the entire soil structure and not a result of wave propagation within individual soil layers. In order to highlight the complexity of the site response, correlation analysis was used to demonstrate that the rock and soil ground motions were not highly coherent between the two sites. YBI was, therefore, shown to be an inappropriate reference site for TI. One-dimensional (1D) vertical wave propagation and inverse techniques were used to differentiate between 1D site response and more complex site behavior. Both 1D methods (vertical wave propagation and inverse transfer functions) proved incapable of capturing the site response at TI beyond the initial four seconds of motion. Finite difference waveform modeling, based on a two-dimensional velocity structure of the northern San Francisco Bay was needed to explain the linear site response at TI as horizontally propagating surface waves trapped in the bay sediments. A simplified velocity structure for the San Francisco Bay including a single 100 m basin layer (constant shear-wave velocity of 400 m/s) over a 1.5 km/s layer of Franciscan bedrock was able to trap energy in the basin and produce surface waveform ringing similar to that observed in the TI data. Due to surface waves propagating in the San Francisco Bay sediments, any 1D model will not fully characterize site response at TI. All 1D models will fail to produce the late arriving energy observed in the ground motions.

DOI: 10.1061/(ASCE)1090-0241(2003)129:6(415)

CE Database subject headings: Surface waves; Finite difference; California; Seismic response; Soils; Rocks; Comparative studies.

Introduction

Earthquake site response at soft soil sites is an important issue along the margins of coastal urban cities, and Treasure Island (TI), California is a prime example (Borcherdt 1970; Borcherdt and Gibbs 1976; Idriss 1990; UCB 1990; Seed et al. 1991). TI, a man-made island in San Francisco Bay between San Francisco and Oakland, consists of several meters of fill overlying marine sediments, a similar soil profile to other filled sites around the San Francisco Bay (de Alba et al. 1994). TI is attached to Yerba Buena Island (YBI), and the two islands are a unique pair for site response studies, since ground motions recorded on the outcropping rock of YBI might provide an estimate of incoming energy at the base of the soil column at TI. The seismic site response at TI and YBI is complicated by regional geologic conditions in the shallow San Francisco Bay sediments. Therefore, a variety of techniques were enlisted to reinvestigate the physical relationship between the seismic response of Treasure and Yerba Buena Islands, focusing on recorded ground motions in the linear range of soil behavior.

Many previous studies have used rock ground motions at YBI (as a reference site) as input to estimate the earthquake site response at TI to subsequently draw conclusions on the nonlinear response at TI (Jarpe et al. 1989; Idriss 1990; Darragh and Shakal 1991; Seed et al. 1991; Rollins et al. 1994). To augment these previous studies we used a more complete set of ground motions recorded in the linear range of soil response for two events ($M_W 4.0$ and $M_W 4.6$) to determine the relationship between TI and YBI, and ultimately the linear site response at TI. Using ground motions recorded at depth in both soil and rock below the TI site, and at the surface and at depth in rock at the YBI site, the assembled data set for this study provided a more complete view of the earthquake site response than others to date. The surface recordings at TI were compared with those in bedrock at TI and at YBI to evaluate the YBI reference site validity and the site response at TI.

Site response studies often rely on Fourier-based spectral ratios to determine site response from a rock and soil site pair of ground motions. Because commonly used Fourier-based site response methods are fundamentally linear and rely on an input/output relationship between a reference rock site and a soil site, a correlated linear relationship between ground motions is required

[1]Assistant Professor, Dept. of Civil and Environmental Engineering, 113 Anderson Hall, Tufts Univ., Medford, MA 02155. E-mail: laurie.baise@tufts.edu

[2]Associate Professor, Dept. of Civil and Environmental Engineering, 440 Davis Hall, Univ. of California, Berkeley, CA 94720.

[3]Associate Professor, Dept. of Earth and Planetary Science, 307 McCone Hall, Univ. of California, Berkeley, CA 94720.

Note. Discussion open until November 1, 2003. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on January 17, 2001; approved on July 15, 2002. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 129, No. 6, June 1, 2003. ©ASCE, ISSN 1090-0241/2003/6-415–426/$18.00.

for reliable site response estimates. The coherency, a frequency domain measure of the linear relationship between input and output records, may deviate from one as a result of one or more of the following (Bendat and Piersol 1993, p. 84): excessive measurement noise in the time series; significant resolution bias in the spectral estimates; the system relating the two time series is nonlinear; or the output is not produced exclusively by the input. Any of these reasons are valid with ground motion input/output pairs. Specifically, an inappropriate reference site, or seismic energy entering the site from multiple directions (surface waves) are potential causes of incoherence and fall under the fourth source of low correlation. If input/output signals are uncorrelated, reliable transfer functions estimates are not possible. Field et al. (1992) looked into this issue for site response estimates for weak-motion and attributed low coherence between rock and soil sites to signal generated noise. Field et al. (1992) found that the signal generated noise caused large uncertainties but no bias in the individual spectral ratios whereas the cross-spectrum estimate was biased as a result of the low coherence. Spectral ratios can be used to estimate a transfer function; however, the resulting estimate can smear a complex response across frequencies. For example, if the site response is due to S waves and surface waves that enter the signal at different times, the spectral ratio taken over the entire signal will smear the effects of each wave arrival across frequencies to give a single site response estimate. In the case of surface waves, wave propagation remains linear but the rock ground motion does not adequately represent the input thereby resulting in low correlation. Low correlation between input and output provides a warning of this or similar cases, alerting us to the fact that output is not a simple linear function of the input.

To evaluate the use of YBI as a reference site for input motions to the TI site, correlation analysis was used to quantify the linear relationship between the input/output signals. In addition, system identification techniques (Glaser 1996; Baise and Glaser 2000) were implemented to investigate the effect of the bay sediments on ground motions. For our studies, the soil system was characterized as a linear filter, with the buried sensor the input, and the sensors above, the outputs. The efficacy of one-dimensional (1D) site response at TI was evaluated with vertical wave propagation (Ching and Glaser 2001) and with system identification techniques to determine an empirical transfer function evaluated from the rock input and surface output ground motions. Evaluation of particle motions at TI provided a better understanding of the physical nature of the wavefield. Finally, the wavefield was modeled for a $M_W4.6$ earthquake using a two-dimensional (2D) velocity structure of the northern San Francisco Bay and a finite difference wave-propagation model (Baise et al. 2003a).

Treasure and Yerba Buena Island Sites

Treasure Island Downhole Array, California

In 1993, a deep instrumentation array through the soil to the bedrock was installed at Treasure Island (TI) to gather information on site response. TI is a hydraulically filled island constructed on an existing sand spit northwest of Yerba Buena Island (YBI) (Lee 1969). The TI site is located 12.8 km from the Hayward fault and 29 km from the San Andreas fault, as shown in Fig. 1. The fill was dredged from the bay and is composed primarily of fine sand, ranging from clayey, to gravelly sand (Lee 1969). As a result, the TI fill is loosely packed and is susceptible to liquefaction under cyclic loading. A representative TI soil profile is shown in Fig. 2. The downhole array initially had one station below the bedrock surface and five stations in the soil (de Alba et al. 1994). A second bedrock station was added at a later date. The stations were placed to record ground motions below the bedrock surface (122 and 104 m), twice in the Pleistocene bay mud (44 and 31 m), near the top of the Holocene bay mud (16 m), and twice in the hydraulic fill (7 and 0 m) (de Alba et al. 1994).

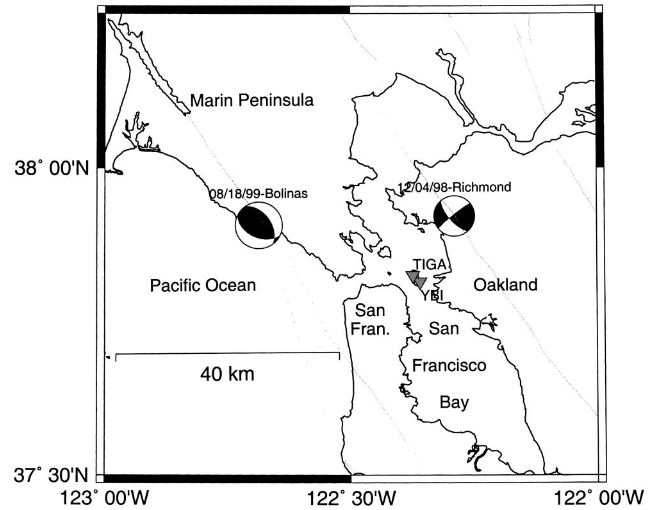

Fig. 1. Map of San Francisco Bay Region. Location of Treasure Island vertical array and Yerba Buena Island shown as triangles. Focal mechanisms for Bolinas (8/18/99) and Richmond (12/04/98) events are shown.

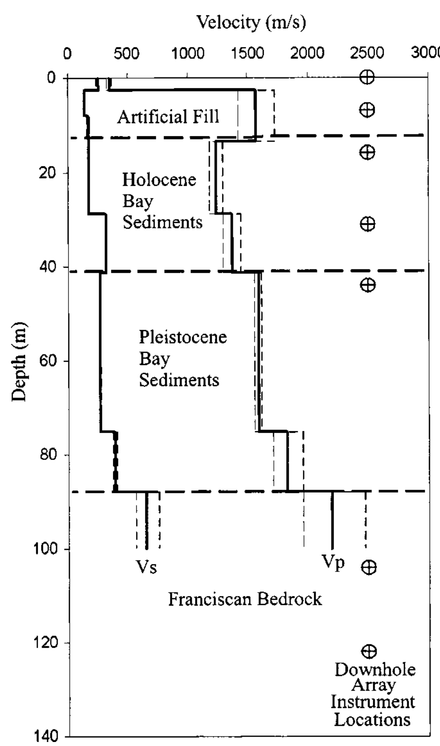

Fig. 2. Simplified soil profile at Treasure Island vertical array site with shear and compressional wave-velocity profiles and instrument locations (after Gibbs et al. 1992)

Table 1. Earthquakes at Treasure Island and Yerba Buena Island

Date	Location	M_W	Latitude	Longitude	Depth (km)	Distance (km)	Azimuth (°)	PGA (g)
12/4/98	Richmond	4.0	37.920	−122.287	6.9	13.0	217	0.014
8/18/99	Bolinas	4.6	37.907	−122.686	6.9	29.0	108	0.017

Yerba Buena Island Downhole Array, California

Yerba Buena Island is a bedrock island also shown in Fig. 1. The YBI downhole site (61 m depth) was installed after the 1989 Loma Prieta event as part of the Berkeley Digital Seismic Network and the Hayward Fault Borehole Network. The uphole YBI site was a temporary site installed as part of the Bridge network above the permanent station (Hutchings et al. 1999). The YBI site (both uphole and downhole), shown in Fig. 1, is located near Pier E2 of the San Francisco-Oakland Bay Bridge on the eastern slope of the island. The rock below the site is composed of the Franciscan melange consisting of sandstone interbedded with siltstone over graywacke interbedded with siltstone and shale.

Data from Treasure Island and Yerba Buena Island

The stations in the TI downhole array have recorded two earthquakes, summarized in Table 1, with companion data for the YBI site: the August 18, 1999 Bolinas event (M_W5.0, M_W4.6) and the December 4, 1998 Richmond event (M_W4.1, M_W4.0). The TI and YBI recording sites are two kilometers apart.

Yerba Buena Island as Reference Site

Most previous TI site response studies have relied on surface ground motions recorded at an additional Yerba Buena site on the southern end of the island as representative input base motion. Idriss (1990), Seed et al. (1991), and Rollins et al. (1994) completed ground response analyses for the Loma Prieta earthquake ground motions at TI using the *SHAKE* equivalent linear wave-propagation program. In addition, Jarpe et al. (1989) and Darragh and Shakal (1991) conducted TI site response studies with spectral ratios using YBI as the reference site to investigate nonlinear site response during the Loma Prieta Earthquake. For both studies, the TI and YBI strong motion spectral ratios exhibited lower amplification than the weak motion spectral ratios, indicating possible soil nonlinearity at TI. In the present study, the assumption of YBI as a reference site for TI site response studies was evaluated by using a correlation analysis to determine if the outcrop ground motions recorded at YBI are a linear mapping of those actually recorded in the rock beneath TI.

Correlation Analysis Methodology

The correlation coefficient (**r**), the normalized maximum value of the cross correlation, is a single-valued statistic which varies from −1 to 1 and describes the validity of an assumed linear relationship. The coherency and the correlation coefficient are directly related; coherency is in the frequency domain whereas the correlation coefficient is measured in the time domain. A correlation coefficient of 1 identifies a perfect linear relationship and −1 is a perfectly inverse linear relationship. We proposed that correlation analysis can be used to help choose an appropriate reference rock site. Recent work shows that some rock sites can have a local site response of their own and therefore introduce a bias into a site response calculation when used as a base motion reference site (Margheriti et al. 1994; Steidl et al. 1996; Boore and Joyner 1997; Archuleta et al. 2000). High correlation between reference rock and soil sites will indicate a linear relationship, and therefore an appropriate system input/output pair. Low correlation between sites, which may result from complexities in the wavefield due to topography, variations in the subsurface geology, surface waves, or other propagation effects, would lead to an inappropriate and inaccurate transfer function estimate no matter what estimator is used. Low correlation does not mean that wave propagation is necessarily nonlinear. Rather, the low correlation specifically indicates that $output \neq f(input)$.

Correlation Analysis at Yerba Buena Island and Treasure Island

Fig. 3 presents a schematic drawing of the YBI/TI site pair with recorded rock motions for the Richmond (12/4/98) event. Evaluating the correlation coefficient between the YBI bedrock motions and those recorded in rock beneath TI quantified the spatial consistency of the incoming wavefield. Fig. 4 compares the ground motions for YBI downhole (YBI↓)-TI downhole (TI↓) rock location, as well as the YBI uphole (YBI↑)-TI downhole (TI↓) rock pair, for the Richmond temblor. The low-correlation coefficients for the two combinations of TI and YBI waveforms—$\mathbf{r}_{(\mathbf{YBI}\downarrow\text{-}\mathbf{TI}\downarrow)} = 0.59$, $\mathbf{r}_{(\mathbf{YBI}\uparrow\text{-}\mathbf{TI}\downarrow)} = 0.41$—indicated that the rock motions at these two nearby locations were only moderately coherent. As a comparison, $r_{(\mathrm{YBI}\downarrow\text{-}\mathrm{YBI}\uparrow)}$ was 0.93. Therefore, caution is advised when using any YBI rock motion as an input to the TI site. The low correlation observed between rock at TI and at YBI is an indication of complexity in the wavefield.

A further analysis, comparing the coherency of the TI surface (output-TI↑) ground motion with the potential input rock motions at TI and YBI provided an estimate of the quality of each reference site as a base motion. When the entire 30 s record was used to estimate the correlation coefficient, both reference sites proved inappropriate—$\mathbf{r}_{(\mathbf{YBI}\uparrow\text{-}\mathbf{TI}\uparrow)} = 0.2$, $\mathbf{r}_{(\mathbf{TI}\downarrow\text{-}\mathbf{TI}\uparrow)} = 0.2$. However, if the record was windowed to the 4 s of initial motion, the TI bedrock motion and the TI surface motion were more coherent than the YBI surface bedrock motion and the TI surface motion—$\mathbf{r}_{(\mathbf{YBI}\uparrow\text{-}\mathbf{TI}\uparrow)} = 0.3$, $\mathbf{r}_{(\mathbf{TI}\downarrow\text{-}\mathbf{TI}\uparrow)} = 0.5$. According to these **r** values, the TI

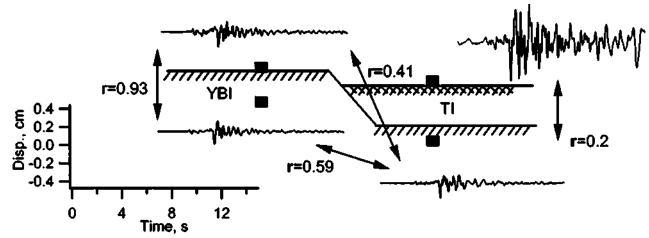

Fig. 3. Schematic drawing of the YBI and TI surface and downhole rock stations for Richmond event. Cross section is not to scale. Correlation coefficients (**r**) for each pair are shown.

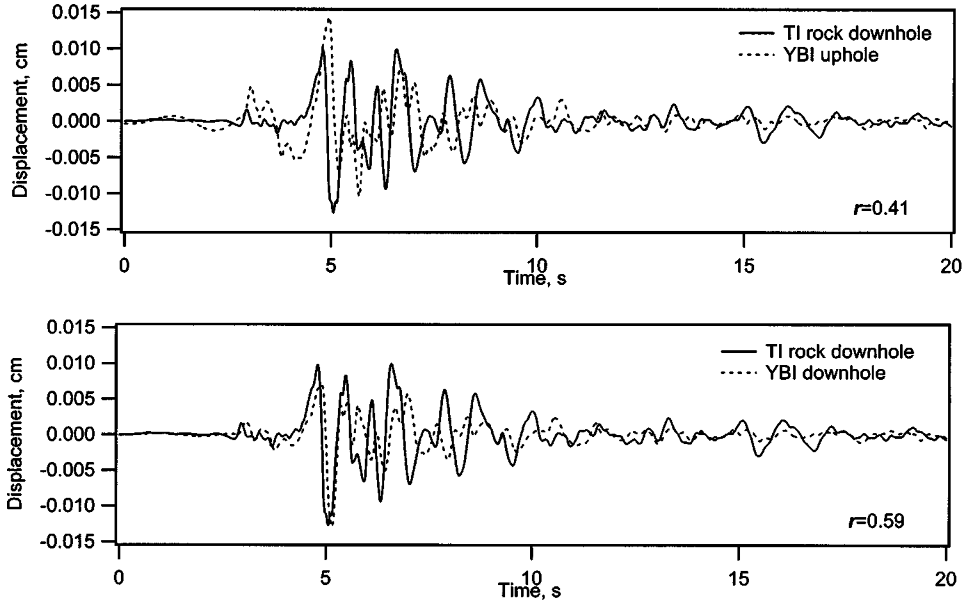

Fig. 4. Comparison of east-west component displacement ground motions recorded during Richmond event at YBI and TI

bedrock motion may provide a better input rock motion for the TI site response; however, the low-**r** values especially for the full 30 s record indicate that a linear transfer function may not be reliable for estimating TI site response no matter which reference site is used.

Yerba Buena Island Site Response

Why are the rock motions at YBI so different from those beneath TI when the sites are within 2 km of each other? Although both rock sites are in the Franciscan bedrock, the bedrock is highly variable possibly resulting in site response effects. The YBI data set provided an opportunity to examine site response with the input-output data pairs.

System Identification

Because the recorded data from vertical arrays are in the form of input/output time series, inverse methods were an obvious choice for investigating the phenomena of earthquake site response. Using system identification, an empirical transfer function (ETF) was developed for the site's seismic behavior. As an inverse method, no assumptions are required about the material properties (stiffness and damping) to produce an estimate of the site transfer function. Rather the assumptions lie in the assumed parametric form and estimation procedure. The system identification (SI) framework was used for these inversions to insure rapid and confident convergence to the best-fit model for the soil system through optimization and validation criteria set out by Ljung (1987) and Bohlin (1987). Previous applications of SI to geotechnical problems include Udwadia (1985), Safak (1989), Glaser (1995, 1996), Elgamal et al. (1996), Zeghal et al. (1996), Stewart and Fenves (1998), Stewart et al. (1999), Baise and Glaser (2000), and Glaser and Baise (2000).

The parametric model used for the empirical transfer function is a complex-valued rational polynomial, referred to as an autoregressive moving-average model with exogenous noise, or ARX model (Glaser 1995; Ljung 1987). The linear SI algorithm used is a least squares-based optimization for fitting the ARX model (Ljung 1987) and results in model parameters that are constant with time. The ARX input/output model accounts for all noise components with an additive white noise term at the output (exogenous). Autoregressive moving average modeling has been used to model waves propagating in layered systems (Robinson and Treital 1978; Hubral et al. 1980) and to characterize earthquake ground motions (Gersch and Kitagawa 1985; Safak 1988; Ellis and Cakmak 1991). Several researchers (Claerbout 1968; Robinson and Treital 1978; Hubral et al. 1980; Dargahi-Noubary 1999) have shown that seismic wave propagation through a layered system (i.e., stratigraphic column) is an autoregressive process.

Given input and output data from borehole instruments, the ETF captures a mapping of particle motion time histories between two points in the soil profile, much like the spectral ratio commonly used in site response studies (Borcherdt 1970). The resulting ETF is interpreted as part of the site response.

Site Response Using Empirical Transfer Functions at Yerba Buena Island

At YBI, the ground motions at the surface and those measured at depth in the borehole are highly coherent, 0.93 and 0.92 for the Richmond and Bolinas events, respectively. This high degree of correlation indicates that the ground motions from the surface and the downhole location should be linearly related and yield a valid ETF.

A rock reference site should ideally have a flat spectral response with an amplitude of 1, in order to not bias the soil site response estimate. An estimated ETF at YBI for the Richmond event is shown in Fig. 5 along with the predicted surface ground motions. The ETF plotted in Fig. 5 has a peak at 8.6 Hz. The 95% confidence intervals shown in the figure indicate the uncertainty in the ETF estimate and in the amplification at 8.6 Hz from 3.5 to 5.5. The peak at 8.6 Hz may correspond to a spectral hole resulting from the interference of upgoing and downgoing waves at 61 m depth. The frequency location of a spectral hole due to interference of upgoing and downgoing waves in homogeneous media

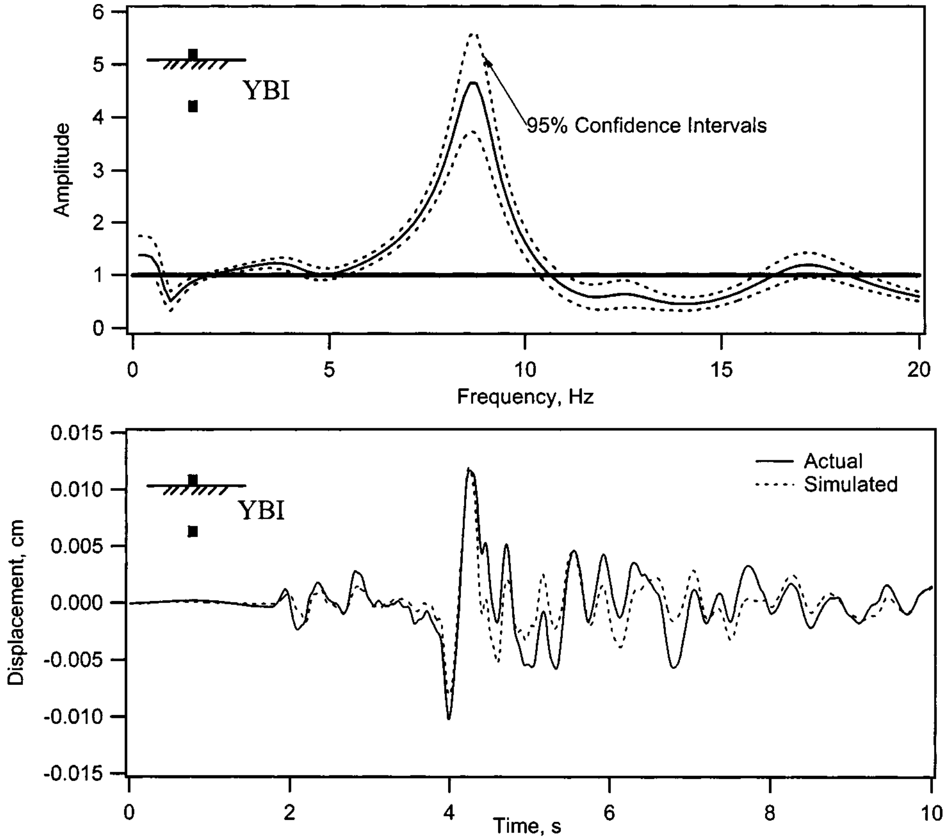

Fig. 5. Estimated empirical transfer function in frequency domain for YBI uphole/downhole pair and the Richmond event (top). Estimated and recorded surface displacement ground motions at YBI for empirical transfer function model (bottom).

can be calculated as the shear-wave velocity divided by four times the depth of the downhole sensor (Safak 1997). Assuming an average shear-wave velocity of 1.7 km/s for the rock (Baise et al. 2003b), the expected spectral hole would occur at 7 Hz. The ETF therefore does not provide clear evidence of site response at the rock site over the 61 m depth interval as the transfer function is possibly influenced by the interference between upgoing and downgoing waves.

Treasure Island Site Response

The location of recording stations at TI provided an excellent opportunity to study how the different sediment layers affect the ground motions. Fig. 6 shows the displacement records from the TI vertical array for the Richmond event. The ground motions are highly correlated through the soil profile with **r** between 0.85 and 0.99, indicating the ground motions at adjacent levels in the soil can be related by a linear filter model. The correlation coefficients for each interval pair are summarized for the two earthquakes in Table 2. The only interval with low correlation spans the bedrock/soil interface ($\mathbf{r}=0.18-0.39$). The breakdown in correlation occurs somewhere between 44 and 104 m depth. Based on our understanding of wave propagation, we assume that the change in ground motion occurred at the bedrock and sediment interface, with ground motions highly amplified by the impedance contrast. The waveforms differed significantly in character on either side of this interface at 44 and 104 m depth (see Fig. 6). The ground motions in the sediments for all recorded earthquakes display a pronounced resonance (near 1 Hz) while the bedrock motion is primarily composed of the initial body waves. This would indicate that the surface reverberations are trapped energy in the San Francisco Bay sediments.

It is helpful to examine the waveform evolution over depth (shown in Fig. 6) for qualitative differences. The ground motions in the Pleistocene bay mud (44 to 31 m) are very consistent in amplitude and shape, indicating that within this soil, the wave train does not change. Comparison of the 16 m (Holocene bay mud) to the 31 m (Pleistocene bay mud) recordings shows a noticeable amplification. The correlation between these two levels drops below 0.9 for both events, indicating a subtle change in the wavefield. The change in waveforms as the motions move from the Holocene bay mud to the fill is less significant but still noticeable. The two signals recorded in fill have a similar shape. Overall, the wavefield was uniform in the sediments with most of the change at the rock/soil boundary. The site response at TI, therefore, was a cumulative response of the soils bounded and/or controlled by the soil/rock interference.

In order to assess the nature of the late arriving energy present in the soil records, the three-dimensional particle motion was examined. Fig. 7 shows the particle motion for two time intervals recorded at the surface of the TI vertical array during the Richmond event. The direction of propagation is indicated on each graph. The early arriving shear waves are polarized in the horizontal plane while the later arriving waves have slightly more elliptical orbits in the vertical plane. The particle motions provide only weak evidence towards the existence of surface waves.

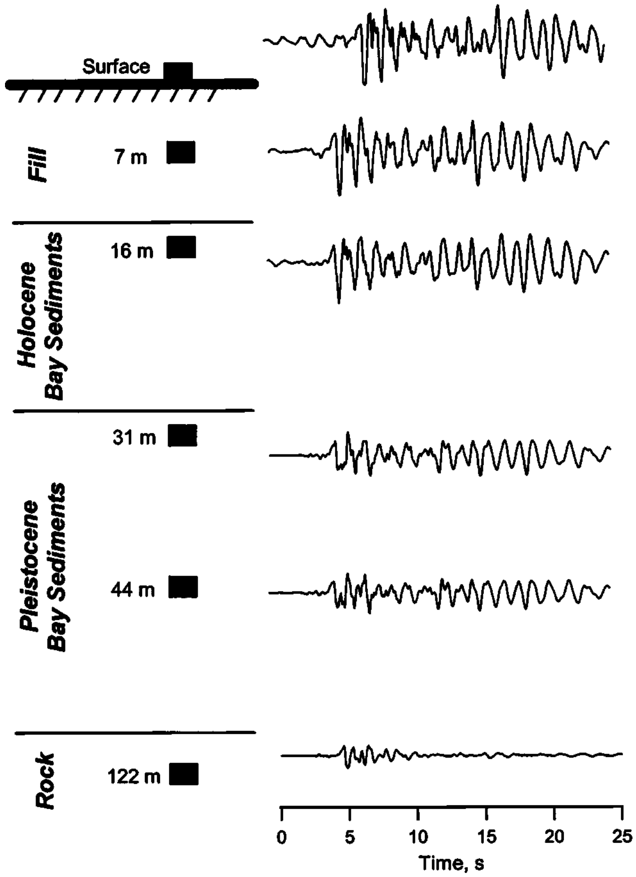

Fig. 6. East-west component displacements for Richmond earthquake recorded at Treasure Island vertical array

Treasure Island Empirical Transfer Function

The TI site response can be estimated using surface soil and nearby rock outcrop sites, or by using borehole reference rock sites either beneath TI or YBI. Based on the results of the correlation analysis of waveforms recorded in rock at YBI and TI, YBI was not considered to be a reliable reference site for TI. The ground motions recorded in rock beneath the TI site were preferred. As observed in Fig. 6 and Table 2, a major change in the wavefield occurred between rock and soil at the TI site. With a low **r** of 0.18 for the full record of the Richmond event, a linear filter will not be able to accurately model the intervening transfer function. To improve the chance of finding a reliable transfer function, we used the Bolinas event (**r**=0.35) to estimate an ETF from rock to surface at TI. From a visual inspection of the waveforms, the early body waves appeared to be more coherent between rock and soil. This was confirmed with the calculated correlation coefficients. We further windowed the ground motions to two seconds directly around the direct S arrival, resulting in an increased **r** of 0.70. The shorter windowed input/output pair would therefore lead to a better estimated transfer function.

Table 2. Correlation Coefficients at Treasure Island

		12/4/98 Richmond	8/18/99 Bolinas
0–7 m	Fill	0.97	0.98
7–16 m	Fill to Young Bay Mud	0.96	0.97
16–31 m	Young Bay Mud to Old Bay Clay	0.85	0.79
31–44 m	Old Bay Clay	0.98	0.98
44–104 m	Old Bay Clay to Rock	0.18	0.35

Fig. 8(a) shows the optimal ETF for downhole rock to surface at TI, estimated using the first two seconds of displacement motions at the bedrock and surface level for the Bolinas event. The first two seconds were chosen to represent the initial shear-wave arrivals. Although only two seconds of record were used, the site response is constant and applicable for the entire record assuming that the site response results from vertically propagating shear waves. A low-model order was required by the optimization and resulted in a single fundamental mode at 1.6 Hz. The data did not support a more complex model. Fig. 8(b) compares the surface motions estimated with this filter to the data. The initial pulse of motion was matched very well in shape and in amplitude. The ground motion was not well estimated after the initial arrivals as indicated by the model residuals shown in Fig. 8(c). Because the rock motion was deficient in energy beyond the direct arrivals and the ETF only mapped the wavefield from the rock to the surface, it can be concluded that the late arriving wave energy was not entering the system from the rock below as vertically propagating shear waves. An ETF estimated from the TI rock input/TI surface output will only be able to account for the amplification of the soil profile, as observed in the initial shear wave arrival but not the surface wave generation. The ETF estimate residuals shown in Fig. 9(c) correspond to the energy trapped in the sediments alone (i.e., surface waves, trapped waves, and interface waves).

To investigate the possibility of site resonance due to the strong rock/soil impedance contrast as an alternative explanation to surface waves, a 1D vertical shear-wave propagation response in the linear regime (Ching and Glaser 2001) was calculated for the TI site. If the late arriving energy was due to 1D resonance caused by the rock-soil impedance contrast rather than more complex wave propagation such as horizontally propagating surface waves, 1D wave propagation would be able to predict it. The shear-wave velocity profile shown in Fig. 2 was simplified to three soil layers over bedrock as shown in Fig. 9. Due to the low-intensity ground motions, low damping was assumed in the sediments (β=0.01). Reduced damping did increase the trapped energy but was not able to replicate the late arriving energy in the observed records. The resulting site response transfer function is plotted in Fig. 9(a), the predicted surface ground motion is plotted against the actual ground motion in Fig. 9(b), and the model residuals are plotted in Fig. 9(c). As shown in the figure, the 1D wave-propagation method matches the first arrivals well but fails to capture the late arriving surface energy. One-dimensional vertical wave propagation may be able to match direct arrivals at TI and therefore intensity measures related to peak acceleration values but cannot capture duration and frequency content measures of intensity.

Figs. 9(a and c) compare the results from the 1D inverse method with the 1D forward method. The transfer functions for the two methods identify the same resonant peak at 1.4 Hz for the forward model and 1.6 Hz in the inverse model although the ETF is significantly lower in amplitude. The residuals are similar in amplitude for the late arriving energy indicating a similar lack of fit. Because surface waves would enter the system horizontally and are not a part of the bedrock ground motions, they cannot be causally captured by any input/output filter mapping.

Surface Waves—3D/2D Wave Propagation Effects

In order to account for surface waves traveling horizontally in the sediments, multi-dimensional waveform modeling is required.

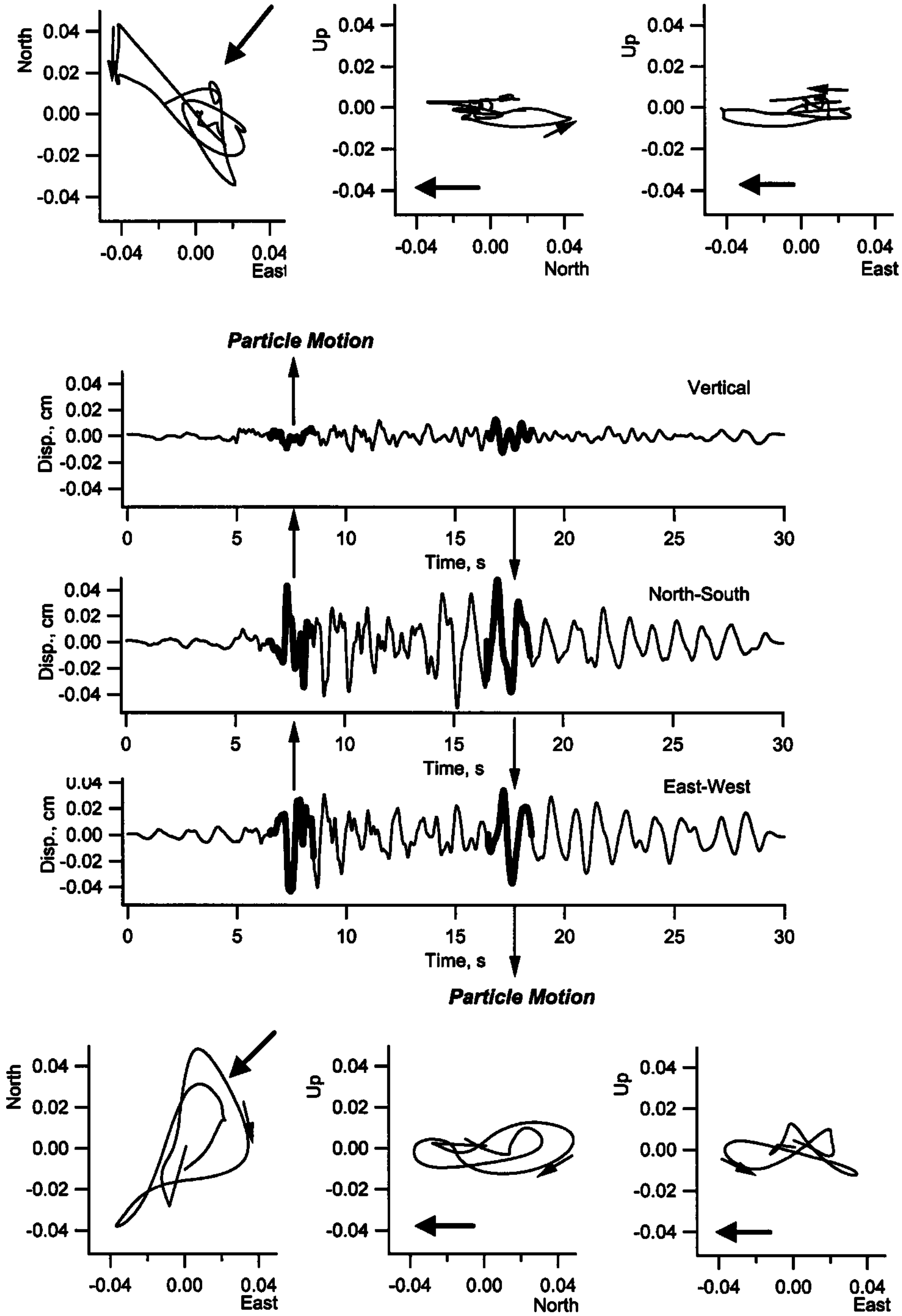

Fig. 7. Surface displacements at Treasure Island for Richmond earthquake showing particle motions for initial shear waves and later arriving surface waves. Bold arrows show direction of propagation and small arrows indicate sense of particle motion.

Surface waves are generally a result of a larger regional feature that cannot be described by a single site and a 1D vertical wave-propagation assumption. Most studies of surface waves therefore use two-dimensional (2D) and three-dimensional (3D) finite difference calculations of the wavefield (e.g., Vidale et al. 1985; Dreger and Helmberger 1990; Graves 1993; Scrivner and Helmberger 1994; Graves 1998; Stidham et al. 1999; Olsen et al. 2000).

Methods of Waveform Modeling

We modeled the waveforms at TI and YBI following Vidale et al. (1985) and Dreger and Helmberger (1990). The forward waveform modeling is discussed in detail in Baise (2000) and Baise et al. (2003a). We began with a simple layered velocity model and drew from the literature to improve the regional velocity model and waveform fits at several stations. In order to constrain the velocity model, we tested the sensitivity of waveforms to variations from the simple model. As an inverse problem, constraining the model space is necessary to prevent model convergence to a physically unrealistic local minima. Matching the absolute timing and amplitude of phases helps to retain realistic models. We realize that trial and error inverse modeling is not an effective methodology for determining velocity structure. We, therefore, used waveform modeling to understand the sensitivity of the wavefield to the basin velocity structure and to estimate a

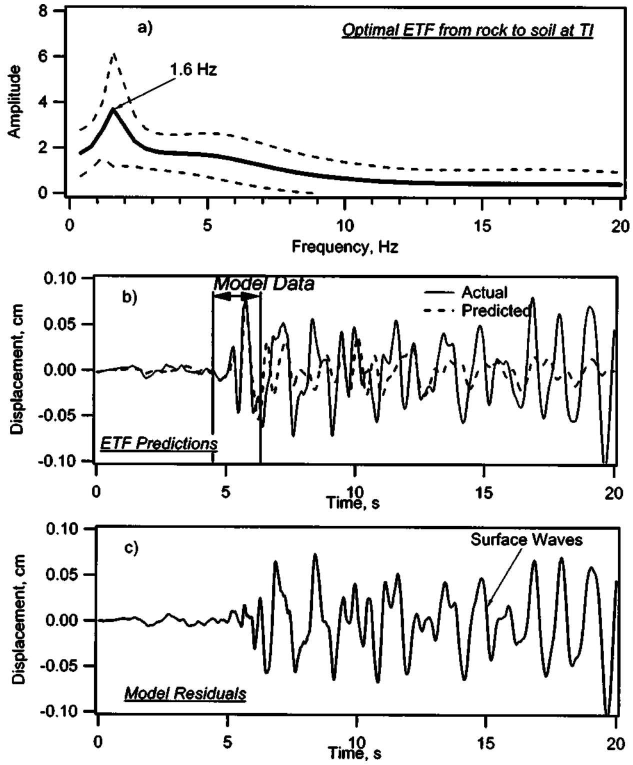

Fig. 8. (a) Frequency domain representation of optimized empirical transfer function for TI site from rock to surface with 95% confidence intervals; (b) Predicted surface motions; and (c) model residuals

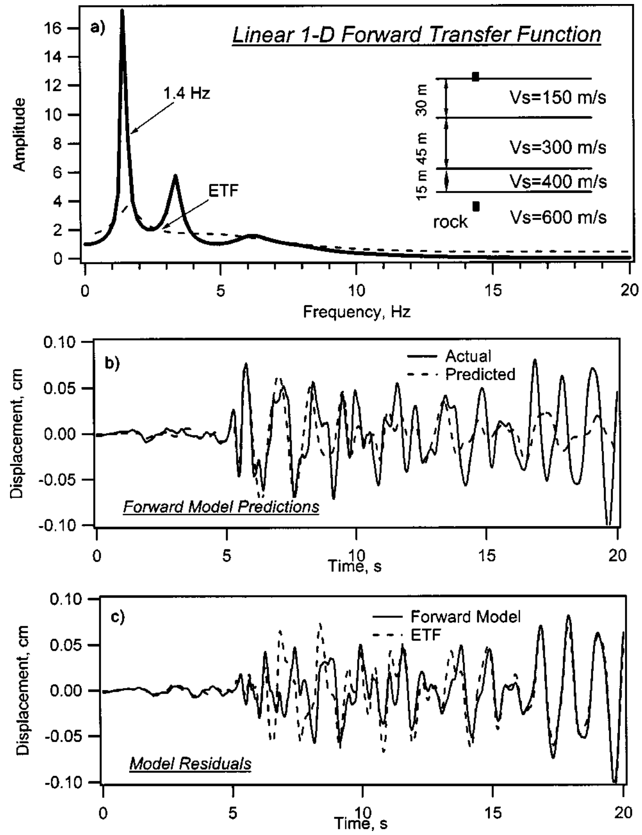

Fig. 9. (a) Frequency domain representation of forward wave propagation model transfer function for TI site from rock to the surface (ETF is shown as dotted line for comparison); (b) predicted surface motions; and (c) model residuals (ETF model residuals are shown as dotted line for comparison)

possible regional response to ground shaking as a result of the San Francisco Bay sediments. Our hypothesis was that a 2D structure in the sediments could explain the late arriving energy in the observed ground motions. The modeling effort used realistic velocity models drawn from the literature, varying parameters within reasonable ranges and was careful when drawing conclusions on the velocity structure of the region.

We modeled the particle displacement time histories at TI and YBI bandpass filtered using a zero-phase Butterworth filter with corner frequencies at 0.02 to 2.0 Hz. The lower frequencies were matched first to constrain the average velocity model. Then higher frequencies were matched by varying the smaller scale basin structure. The 2 Hz bound was controlled by the grid spacing of the finite difference models (20 m) and is a low resolution for engineering interest; therefore, a future study will be required to investigate the TI wavefield at higher frequencies and develop a more complete view of TI site response and seismic hazard.

The tools used for this methodology are waveform modeling using a frequency-wave number integration scheme (FK) for 1D velocity structures and finite different (FD) waveform modeling for 2D velocity structures. A FK computer code by Saikia (1994) was used to generate Green's functions for different 1D velocity models, source locations, and epicentral distances. The component Green's functions were combined according to the specific earthquake focal mechanism to create synthetic seismograms. The synthetic seismograms were also convolved with a source time function to account for the source rise time. Many models were simulated to test the sensitivity of waveforms to layer thicknesses and velocities. All three components of motion were generated, and the modeling focused on first matching the tangential component and secondly the radial component.

The FK method also considers wave-energy dissipation through an elastic wave propagation. The amplitude spectra for the 1D model at epicentral distances of 14 and 30 km (appropriate for the study) using a $Q_\alpha=600$ and $Q_\beta=300$ (appropriate for hard rock) were compared to amplitude spectra in which the upper layer was assigned a $Q_\alpha=Q_\beta=50$ (average value of Johnson and Silva 1981). The results show that consideration of low Q in the upper 200 m damps the modes associated with reverberations in the upper layer at frequencies above 2 Hz. In the 0.02 to 2 Hz passband, the effect of low Q is almost negligible; therefore, damping was ignored in the analysis. Of course when higher frequencies and shallower structures are considered in future studies, Q will have a profound effect.

Once the "best-fit" 1D structure was determined for the region, 2D basin structure was added using a FD waveform modeling procedure described by Vidale et al. (1985). The San Francisco Bay was included as a shallow 2D structure. The amplitudes of the synthetics were determined by application of the source time function and multiplication of the synthetics by the moment of the earthquake. Because of the difficulty of tracking individual phases with this method, it did not account for attenuation. The short paths in this study, however, were not particularly sensitive to the damping in the 0.02 to 2 Hz passband as determined using the FK method and 1D structure.

Waveform Modeling

Although the San Francisco Bay sediments are not deep (91 m at TI) as compared to some of the major sedimentary basins (i.e., Los Angeles Basin), they appear to produce a surface-wave train. Based on the velocities and layer thicknesses reported in other San Francisco Bay studies, the San Francisco basin was modeled as a single 100 m thick layer across the bay, and a range of sediment shear wave velocities from 150 to 500 m/s was tested. The preferred velocity structure was chosen based on the best fit for the absolute timing of the wave packet arrivals and the appropriate phase, shape, duration, and amplitude of the surface waves at TI. Although the fill and Holocene bay mud in the upper 20 m were expected to have lower velocities ($V_s = 150$ to 250 m/s), the regional surface waves (0.02–2 Hz) were adequately modeled by a higher-uniform average velocity ($V_s = 400$ m/s) in a 100 m sediment layer as compared to a more realistic multiple layered model. This unexpected result most likely was caused by the coarse grid spacing of 20 m which could not adequately represent the more realistic upper portions of the layered model. The average uniform layer ($V_s = 400$ m/s) is more heavily influenced by the deeper faster layers. A weighted shear-wave velocity average of the upper 100 m at Treasure Island is 320 m/s.

The modeling exercise indicated that the surface waves observed at TI could be produced by the large impedance contrast between the low-velocity sediments ($V_s = 400$ m/s) and the weathered Franciscan bedrock (1.5 km/s) in a shallow basin. Surface waves initially formed at the basin edges along the east coast of the Marin Peninsula (Fig. 1), resulting in trapped energy at a resonant frequency near 1 Hz, similar to that observed in the data. Fig. 10 compares the best-fit, 2D model, tangential component synthetics, and observed ground motions for several levels in the vertical array at TI. As seen in the figure, the comparisons are consistent for all depths, matching the shape of the first 10 s of motion well. The amplitude of the synthetics overpredict the primary S-wave arrival amplitude by 30% which may result from an overestimate of the earthquake moment or errors in the model. The synthetics at 40 m depth do not match the data at 44 m depth as well as at the surface. The simulated primary S wave is a single pulse whereas the observed primary S wave is separated into upgoing and downgoing waves. These differences indicate that the shear-wave velocity in the model is faster than the actual material in the upper 40 m of sediments, as expected. The upper 40 m of sediments at TI include Holocene deposits and fill with shear-wave velocities between 150 and 250 m/s instead of the 400 m/s in the model.

The sensitivity study of the reported model indicated that the synthetics could be improved with further adjustments to the model; however, the modeling effort was not made since such detail is too fine for the 20 m grid spacing that was used and a detailed velocity model was not the desired product of this study. Rather, this study set out to provide an explanation for the site response (observed resonance) at TI. The important achievement of this model was the production of late arriving 1 Hz energy similar to the data which was not produced in the 1D models. Although the model residuals are still of a similar magnitude to the 1D models as a result of timing errors and phase shifts, the synthetic ground motions produce the duration and frequency content better than the 1D methods. The synthetics at 40 and 120 m depth also match the data (at 44 and 122 m depth) in shape and amplitude. These fits indicated that the model results capture the wave propagation from the rock to the sediments. Specifically, the surface waves in the model were suppressed below 100 m depth (the rock/soil boundary in the model).

The 2D San Francisco Bay model was also verified for the YBI site. The estimated and observed surface displacements at YBI and TI are shown in Fig. 11. The synthetics for both sites are consistent in amplitude and shape to the corresponding observed waveforms. In the model, the bay sediments pinch out at the edge of YBI, 1 km from the site instruments, and this effectively prevented the surface waves from propagating to YBI as observed at the site. The data and synthetics are simplified at YBI as compared to TI indicating that the model produces a similar relative response. Dreger and Helmberger (1990) have shown that a basin margin produces this filtering effect where high frequencies are preferentially removed as energy is converted to diving body waves.

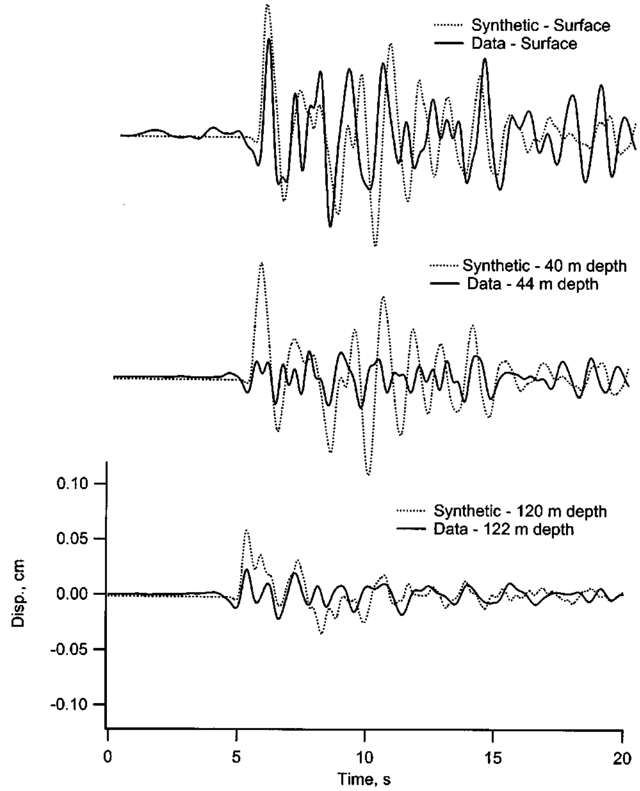

Fig. 10. Synthetic calculations for tangential component of motion during Bolinas earthquake at TI vertical array

Discussion

Many researchers have used coherency of data to statistically assess the linear relationship between different time series. The primary use in site response analyses has been to evaluate the spatial coherence of a wavefield (Menke et al. 1990; Hough and Field 1996). Hough and Field (1996) found that waveform coherence estimates from earthquakes in the San Fernando Valley support the general conclusion that a site response estimate is an adequate representation of expected site response over a region several kilometers in diameter if the local geology is consistent. As compared to work in rock regions (Menke et al. 1990), Hough and Field (1996) concluded that sedimentary basins may possess more coherent wavefields as a result of the resonant behavior of the sediments. Therefore, analysis of the correlation of waveforms is a valuable tool for site response. Specifically, we have used the correlation coefficient to assess the reliability of site response estimates from input/output rock/soil pairs. Correlation coefficients can be used to determine appropriate reference rock sites for site response studies. Our conclusion that YBI is an inappro-

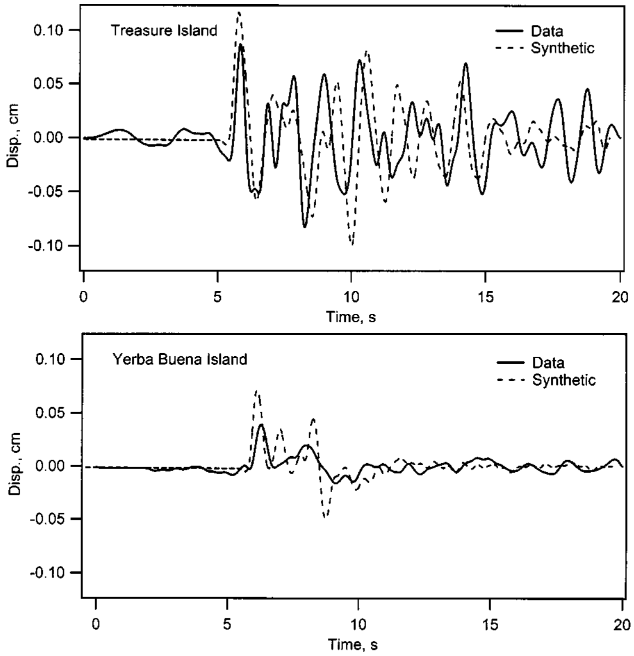

Fig. 11. Tangential displacements at TI and YBI for Bolinas event plotted against synthetics for best-fit 2D model. Waveforms are filtered to a passband below 2 Hz.

priate reference site for TI runs counter to many previous studies which relied on this site pair for site response investigations of the Long Prieta earthquake. As a comparison we calculated the correlation coefficient for the YBI/TI pair during the Loma Prieta earthquake. For 20 s of displacement motion (east/west), **r** was 0.41. When the records were cut to the direct arrivals (4 s) of motion, **r** increased to 0.46. In the Loma Prieta case, the correlation was lower than that observed over the direct arrivals (2 s) during the Bolinas event (**r**=0.70) in the TI vertical array. As a result of low correlation indicating system complexity, both linear estimates of site response transfer functions should be considered unreliable. At best, the estimated site response will characterize the direct shear-wave response but not the complex site response. During Loma Prieta, the TI site liquefied. During the Bolinas event, the TI site experienced upwards of 20 s of surface waves. Neither of these complexities can be captured by linear transfer function site response methods.

The seismic behavior of the San Francisco Bay region has been extensively investigated in the past. The investigations primarily used aftershock and other weak ground motion, and all concluded that bay sediments and the associated locally generated surface waves control the waveforms (Johnson and Silva 1981; Boatwright 1991; Graves 1993). We looked specifically at the Treasure Island site response and identified a surface wave resonance near 1 Hz, similar to the previous studies in the region. During their studies of the Marina district, Graves (1993) and Boatwright (1991) also observed amplification at around 1 Hz in the Loma Prieta aftershock waveforms.

The weak motion surface recordings from the TI vertical array reveal surface waves that are not evident at depth in the bedrock. The question becomes how does this weak motion observation carry over to strong motion, and therefore to regional earthquake hazard assessment? Using ground motions recorded at two rock sites in San Francisco, YBI, TI, and three soil sites in Oakland, Hanks and Brady (1991) found that the ground motions at the rock sites were coherent and of a short duration. The soft soil site ground motions, on the other hand, were longer in duration and higher in amplitude, indicating a strong resonance with a period near 1.5 s. This resonance was not observed at TI during the Loma Prieta earthquake due to the liquefaction of the fill; however, prior to signs of liquefaction in the TI record, the S-wave packet was phase coherent with the recordings at the Oakland sites (Hanks and Brady 1991). If the surface waves were propagating throughout the sediments, they would be felt during strong motion at non-liquefiable sites in the region. Therefore, we believe that the surface waves observed at TI during weak motion earthquakes and documented in the literature at other sites will be a seismic hazard at nonliquefiable sites around the margins of the San Francisco Bay in future large earthquakes.

Conclusion

The site response of TI was extensively studied after the 1989 Loma Prieta earthquake. Most studies used the YBI site as a rock reference site to estimate the incoming energy below TI. The Treasure Island site response was evaluated using 1D equivalent linear vertical wave propagation to conclude that soil nonlinearity had occurred. Since liquefaction was known to have occurred, soil nonlinearity was not a surprise. Due to an improved data set including ground motions recorded at depth beneath TI and YBI, we have reevaluated the site response at TI focusing on the linear range. We found the YBI surface reference site to be an inappropriate site input signal because of low correlation between the rock ground motions at YBI and TI even in the linear range of ground response. TI site response was therefore reevaluated using at-depth ground motions recorded at the TI vertical array as the input reference motion.

The linear site response at TI includes horizontally propagating surface waves trapped in the San Francisco Bay sediments that cannot be captured by 1D wave propagation or inverse methods. The surface waves were identified by examination of particle motions, and subsequently modeled using 2D finite difference (FD) waveform modeling. The FD model including a 100 m depth sedimentary basin with a constant shear-wave velocity of 400 m/s over a 1.5 km/s layer of Franciscan bedrock successfully trapped energy in the basin and produced ringing in the synthetics similar to that observed in the TI data. This coarse model provides both an example of the possible velocity structure that could cause the observed ground motions and an indication of the seismic hazard of surface waves in the San Francisco Bay area, especially at sites in and around the margins of the bay.

As a result of surface waves at TI, any 1D model will not be able to fully characterize the site response, and the optimal empirical transfer function from rock to the surface could only predict the initial two seconds of motion accurately. After two seconds, the empirical transfer function and the forward model fail to produce the resonance observed in the surface ground motions. The greatest change in the wavefield, outside of the rock-to-soil transition, occurred between the Pleistocene and the Holocene sediments. Overall, the waveforms change very little as they propagate through the sediments, indicating that the site response is a cumulative effect of the entire soil structure and not a result of individual soil layers. This is further supported by the FD waveform modeling results which accurately predicted the surface wavetrain at TI with a 100 m thick averaged uniform sedimentary basin.

Acknowledgments

The writers would like to thank David Boore and an anonymous reviewer for their helpful and thorough reviews of the manuscript. Their insights helped improve the paper significantly.

References

Archuleta, R., Steidl, J. H., and Bonilla, L. F. (2000). ''Engineering insights from data recorded on vertical arrays.'' *12th World Conf. in Earthquake Engineering*, Auckland, New Zealand.

Baise, L. G. (2000). ''Modeling of the northern San Francisco bay velocity structure for the 18 August 1999 Bolinas earthquake.'' Masters thesis, Dept. of Geology and Geophysics, Univ. of California, Berkeley, Calif.

Baise, L. G., Dreger, D. S., and Glaser, S. D. (2003a). ''Modeling of the Northern San Francisco Bay velocity structure for the 18 August 1999 Bolinas earthquake.'' *Bull. Seismol. Soc. Am.*, in press.

Baise, L. G., and Glaser, S. D. (2000). ''Consistency of ground-motion estimates made using system identification.'' *Bull. Seismol. Soc. Am.*, 90(4), 993–1009.

Baise L., Hutchings, L., and Glaser, S. (2003b). ''Site response at Yerba Buena Island, San Francisco Bay, California analyzed with weak motion recordings.'' *BOLLETTINO DI GEOFISICA Teorica ed Applicata: Special Issue on "Site response estimation from observed ground motion data,"* Instituto Nazionale di Oceanografia e di Geofisica Sperimentale–OGS, Trieste, Italy, 43(3–4), in press.

Bendat, J. S., and Piersol, A. G. (1993). *Engineering applications of correlation and spectral analysis*, 2nd Ed., Wiley, New York.

Boatwright, J. (1991). ''Ground motion amplification in the Marina district.'' *Bull. Seismol. Soc. Am.*, 81(5), 1980–1997.

Bohlin, T. (1987). ''Model validation.'' *Encyc. of sys. and cont.*, M. Singh, ed. Pergamon, London.

Boore, D. M., and Joyner, W. B. (1997). ''Site amplification of generic rock sites.'' *Bull. Seismol. Soc. Am.*, 87(2), 327–341.

Borcherdt, R. D. (1970). ''Effects of local geology on ground motion near San Francisco Bay.'' *Bull. Seismol. Soc. Am.*, 60(1), 29–61.

Borcherdt, R. D., and Gibbs, J. F. (1976). ''Effects of local geological conditions in the San Francisco Bay region on ground motions and the intensities of the 1906 earthquake.'' *Bull. Seismol. Soc. Am.*, 60(2), 467–500.

Ching, J. Y., and Glaser, S. D. (2001). ''1D time-domain solution for seismic ground motion prediction.'' *J. Geotech. Geoenviron. Eng.*, 127(1), 36–47.

Claerbout, J. (1968). ''Synthesis of a layered medium from its acoustic transmission response.'' *Geophysics*, 33, 264–269.

Dargahi-Noubary, G. R. (1999). *Time series with applications to seismology*, Nova Science, New York.

Darragh, R. B., and Shakal, A. F. (1991). ''The site response of two rock and soil station pairs to strong and weak ground motion.'' *Bull. Seismol. Soc. Am.*, 81(5), 1885–1899.

de Alba, P., Benoit, J., Pass, D. G., Carter, J. J., Youd, T. L., and Shakal, A. F. (1994). ''Deep instrumentation array at the Treasure Island Naval Station.'' *Loma Prieta earthquake of October 17, 1989: Strong ground motion and ground failure*, R. D. Brocherdt, ed., *USGS Prof. Paper P 1551-A, A155-A168*, United States Geological Survey, Denver.

Dreger, D. S., and Helmberger, D. V. (1990). ''Broadband modeling of local earthquakes.'' *Bull. Seismol. Soc. Am.*, 80(5), 1162–1179.

Elgamal, A.-W., Zeghal, M., Parra, E., Gunturi, R., Tang, H. T., and Stepp, J. C. (1996). ''Identification and modeling of earthquake ground response—I. Site amplification.'' *Soil Dyn. Earthquake Eng.*, 15, 499–522.

Ellis, G. W., and Cakmak, A. S. (1991). ''Effect of spatial variability on ARMA modeling of ground motion.'' *Struct. Safety*, 10(N1-3), 181–191.

Field, E. H., Jacob, K. H., and Hough, S. E. (1992). ''Earthquake site response estimation a weak-motion case study.'' *Bull. Seismol. Soc. Am.*, 82(6), 2283–2307.

Gersch, W., and Kitagawa, G. (1985). ''A time varying AR coefficient model for modeling and simulating earthquake ground motion.'' *Earthquake Eng. Struct. Dyn.*, 13, 243–254.

Gibbs, J. F., Fumal, T. E., Boore, D. M., and Joyner, W. B. (1992). ''Seismic velocities and geologic logs from borehole measurements at seven strong-motion stations that recorded the Loma Prieta earthquake.'' *U. S. Geological Survey Open-File Rep. No. 92-287*, Menlo Park, Calif., 139.

Glaser, S. D. (1995). ''System identification and its applications to estimating soil properties.'' *J. Geotech. Eng.*, 121(2), 553–560.

Glaser, S. D. (1996). ''Insight into liquefaction by system identification.'' *Geotechnique*, 46(4), 641–656.

Glaser, S. D., and Baise, L. G. (2000). ''System identification estimation of soil properties at the Lotung site.'' *Soil Dyn. Earthquake Eng.*, 19, 521–531.

Graves, R. W. (1993). ''Modeling three-dimensional site response effects in the Marina district basin, San Francisco, California.'' *Bull. Seismol. Soc. Am.*, 83(4), 1042–1063.

Graves, R. W. (1998). ''Three-dimensional finite-difference modeling of the San Andreas Fault; source parameterization and ground-motion levels.'' *Bull. Seismol. Soc. Am.*, 88(4), 881–897.

Hanks, T. C., and Brady, A. G. (1991). ''The Loma Prieta earthquake, ground motion, and damage in Oakland, Treasure Island, and San Francisco.'' *Bull. Seismol. Soc. Am.*, 81(5), 2019–2047.

Hough, S. E., and Field, E. H. (1996). ''On the coherence of ground motion in the San Fernando Valley.'' *Bull. Seismol. Soc. Am.*, 86(6), 1724–1732.

Hubral, P., Treitel, S., and Gutowski, P. R. (1980). ''A sum autoregressive formula for the reflection response.'' *Geophysics*, 45(11), 1697–1705.

Hutchings, L., Kasameyer, P., Foxall, W., Hollfelder, J., Turpin, C., Hayek, C., McEvilly, T., Clymer, R., Uhrhammer, R., and Jarpe, S. (1999). ''Deep borehole instrumentation along San Francisco Bay Bridges.'' *Rep. No. UCRL-ID-132137*, Lawrence Livermore National Laboratory, Livermore, Calif., March 1, 1999.

Idriss, I. M. (1990). ''Response of soft soils during earthquakes.'' *H. Bolton seed volume 2 memorial symposium proceedings*, J. Michael Duncan, ed., Bitech, Vancouver, B.C.

Jarpe, S. P., Hutchings, L. J., Hauk, T. F., and Shakal, A. F. (1989). ''Selected strong- and weak-motion data from the Loma Prieta Sequence.'' *Seismol. Res. Lett.*, 60, 167–176.

Johnson, L. R., and Silva, W. (1981). ''The effects of unconsolidated sediments upon the ground motion during local earthquakes.'' *Bull. Seismol. Soc. Am.*, 71(1), 127–142.

Lee, C. H. (1969). ''Treasure Island fill.'' *Bay mud developments case histories*, C. Lee and U. Praszker, eds., California Division of Mines and Geology, 69–72.

Ljung, L. (1987). *System identification*, Prentice-Hall, Englewood Cliffs, N.J.

Margheriti, L., Wennerberg, L., and Boatwright, J. (1994). ''A comparison of Coda and S wave spectra ratios as estimates of site response in the Southern San Francisco Bay Area.'' *Bull. Seismol. Soc. Am.*, 84, 1815–1830.

Menke, W., Lerner-Lam, A. L., Dubendorff, B., and Pacheco, J. (1990). ''Polarization and coherence of 5 to 30 Hz seismic wave fields at a hard-rock site and their relevance to velocity heterogeneities in the crust.'' *Bull. Seismol. Soc. Am.*, 80(2), 430–449.

Olsen, K. B., Nigbor, R., and Konno, T. (2000). ''3D viscoelastic wave propagation in the upper Borrego Valley, California, constrained by borehole and surface data.'' *Bull. Seismol. Soc. Am.*, 90(1), 134–150.

Robinson, E. A., and Treitel, S. (1978). ''The fine structure of the normal incidence synthetic seismogram.'' *Geophys. J. R. Astron. Soc.*, 53, 289–309.

Rollins, K. M., McHood, M. D., Hryciw, R. D., Homolka, M., and Shewbridge, S. E. (1994). ''Ground response on Treasure Island.'' *Loma Prieta earthquake of October 17, 1989: Strong ground motion and ground failure*, R. D. Borcherdt, ed., *USGS Prof. Paper P 1551-A, A155-A168.*

Safak, E. (1988). ''Analysis of recordings in structural engineering: adaptive filtering, prediction and control.'' *U. S. Geological Society Open File Rep. No. 88-647*, Menlo Park, Calif.

Safak, E. (1989). ''Optimal-adaptive filters for modelling spectral shape, site amplification, and source scaling.'' *Soil Dyn. Earthquake Eng.* 8(2), 75–95.

Safak, E. (1997). ''Models and methods to characterize site amplification from a pair of records.'' *Earthquake Spectra*, 13(1), 97–129.

Saikia, C. K. (1994). ''Modified frequency-wavenumber algorithm for regional seismograms using Filon's quadrature: Modeling of Lg waves in eastern North America.'' *Geophys. J. Int.*, 118, 142–158.

Scrivner, C. W., and Helmberger, D. V. (1994). ''Seismic waveform modeling in the Los Angeles basin.'' *Bull. Seismol. Soc. Am.*, 84(5), 1310–1326.

Seed, R. B., Dickenson, S. E., and Idriss, I. M. (1991). ''Principal geotechnical aspects of the 1989 Loma Prieta earthquake.'' *Soils Found.*, 31(1), 1 26.

Steidl, J., Tumarkin, A. G., and Archuleta, R. (1996). ''What is a reference site?'' *Bull. Seismol. Soc. Am.*, 86, 1733–1748.

Stewart, J. P., and Fenves, G. L. (1998). ''System identification for evaluating soil-structure interaction effects in buildings from strong motion recordings.'' *Earthquake Eng. Struct. Dyn.*, 27, 869–885.

Stewart, J. P., Fenves, G. L., and Seed, R. B. (1999). ''Seismic soil-structure interaction in buildings. I: Analytical methods.'' *J. Geotech. Geoenviron. Eng.*, 125(1), 26–37.

Stidham, C., Antolik, M., Dreger, D., Larsen, S., and Romanowicz, B. (1999). ''Three-dimensional structure influences on the strong-motiono wavefield of the Loma Prieta earthquake.'' *Bull. Seismol. Soc. Am.*, 89(5), 1184–1202.

Udwadia, F. E. (1985). ''Some uniqueness results related to soil and building structural identification.'' *SIAM (Soc. Ind. Appl. Math.) J. Appl. Math.*, 45(4), 674–685.

University of California at Berkeley/Earthquake Engineering Research Center (UCB/EERC-90/05). (1990). ''Preliminary report on the principal geotechnical aspects of the October 17, 1989 Loma Prieta earthquake.'' Rep., Earthquake Engineering Research Center, Univ. of California, Berkeley, Calif.

Vidale, J. E., Helmberger, D. V., and Clayton, R. W. (1985). ''Finite-difference seismograms for SH waves.'' *Bull. Seismol. Soc. Am.*, 75(6), 1765–1782.

Zeghal, M., Elgamal, A. W., and Parra, E. (1996). ''Identification and modeling of earthquake ground response — II. Site liquefaction.'' *Soil Dyn. Earthquake Eng.*, 15, 523–547.