THE INTEGRATED SURFACE AND BOREHOLE, GEOTECHNICAL STRONG-MOTION, SOIL-RESPONSE ARRAYS IN SAN FRANCISCO, CALIFORNIA

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ABSTRACT

An integrated set of four borehole arrays and ten surface installations is installed in the city of San Francisco, California to measure the response of soft-soil deposits to strong earthquake ground motions. The borehole arrays extend through thick layers of soft water-saturated soils of Holocene age and older more consolidated soils of Pleistocene age into bedrock at depths up to 90 m. The surface installations are configured in pairs to provide simultaneous comparative surface measurements of soft soils and nearby rock. The rock locations also permit comparative measurements of rock motion as observed at the surface and in nearby boreholes. The arrays are designed to address a wide variety of scientific and engineering issues, and especially the issue of anelastic and nonlinear soil response at high strain levels as might be recorded during a large regional earthquake. Recordings of ground motions on the borehole and surface arrays from the largest regional earthquakes that have occurred since the installation of the arrays show marked evidence of amplification as a function of soil type and depth.

INTRODUCTION

Structural damage and consequent loss of life from earthquakes is often concentrated in areas underlain by soft soils. In the city of San Francisco, damage from both the great California earthquake of 1906 and the Loma Prieta earthquake of 1989 was concentrated in areas underlain by soft soil deposits. Many of these areas are along the margins of San Francisco Bay and are densely urbanized. However, no *in-situ* borehole measurements of the amplification characteristics of these deposits in the SF Bay region have yet been obtained at damaging levels of motion. Such measurements are of special importance for quantifying the response of the built environment in a major metropolitan area for improving earthquake resistant design.

Several important questions exist concerning the *in-situ* response of soft soil deposits at damaging levels of shaking. A question of particular interest concerns the role of non linearity in modifying the *in-situ* amplification characteristics of soft soil deposits as a function of shaking amplitude. This is a major issue yet to be resolved with *in-situ* evidence. Other important issues concern 1) empirical estimates of site coefficients as a function of maximum strain and material constitutive properties, 2) changes in constitutive properties with duration, ground motion characteristics necessary for the onset of liquefaction, and 3) the influence of basin geometry.

This extended abstract describes a set of integrated borehole arrays and surface installations in the city of San Francisco designed to address these issues. It describes the design and purpose of the arrays. It provides examples and a summary of recordings obtained on the arrays since their installation. A similar description of the arrays and estimates of low-strain site coefficients for U.S. building codes as derived from the recordings are provided by Borcherdt, *et al.* (2004b).

DESIGN AND PURPOSE OF ARRAYS

The integrated strong-motion soil response arrays in San Francisco operated by the U.S. Geological Survey are designed to provide comprehensive strong-motion data not yet obtained on the *in-situ* response of soft soils. These data are to be collected using four borehole arrays at locations underlain by thick sections of soft water saturated clays, sands, and silts, and at ten surface locations selected as soil-rock pairs to provide ground-response measurements for comparison. Locations of the borehole arrays and surface installations are shown on maps of the city (Figures 1a and 1b). The map shows the location of the sites in relation to the geographic distribution of site classes as defined in present versions of U.S. building codes. The arrays also were designed to augment data recorded on dense arrays of strong-motion instrumentation in nearby buildings as installed by the Strong Motion Instrumentation Programs of the California Geological Survey and the United States Geological Survey (Figure 1b).

The borehole arrays are located in the vicinity of Embarcadero Plaza (EMB) near lower market street, in Levi Strauss Plaza near the base of Telegraph Hill (LP), at Winfield Scott School in the Marina district (WSS), and at Bessie Charmichael School (BCS) in an area south of Market Street in the city of San Francisco. Each of the borehole array locations is underlain by a thin compacted layer of man-made fill overlying deposits of soft clay, silty clay, and silts termed the Younger Bay Mud , which in turn is underlain by stiff older more consolidated soils, termed the Older Bay Sediments, overlying rock of the Franciscan Formation. Detailed geotechnical and seismic velocity logs for each of the borehole locations are described by Borcherdt, *et al.* (1999). In general, the shear wave velocities range from greater than 150 m/s for the Younger Bay Mud to 350 m/s for the Older Bay Sediments to over 800 m/s for the underlying rock. Seismic, geologic, and sensor configurations are shown for each borehole array site (Figure 2).

Measurements in these areas of San Francisco are particularly relevant for evaluation of performance of major man-made facilities during the next damaging earthquake. Major concentrations of damage occurred in each of these areas during both the 1906 and 1989 earthquakes. Evidence for liquefaction during the earthquakes exists at three of the borehole sites (EMB, WSS, and BCS). Important facilities in the areas include high-rise buildings, apartment buildings, rapid transit facilities, bridges, and underground utilities.

The arrays are designed to provide an integrated set of data pertinent to addressing a wide variety of scientific and engineering issues. The borehole arrays are designed to provide *in-situ* data not previously available on the non-linear response of soft soils as a function of strain amplitude, with and without liquefaction-induced failure. Three of the borehole arrays include four three-component forced-balance accelerometers (FBA), two co-located wide dynamic-range pore-pressure transducers, and at least one vertical velocity transducer installed in rock at the base. The co-located *in-situ* measurements of acceleration and pore pressure are designed to provide estimates of the constitutive properties as a function of time and strain amplitude that cannot be inferred from either measurement alone (Borcherdt, *et al*. 1988 and 1989). A separate borehole array of velocity transducers co-located with three FBAs is installed at one of the sites (WSS). These collated velocity and acceleration sensors provide high-resolution recordings of signals ranging in amplitude from seismic background noise levels to damaging levels of shaking up to 2g. These signals ranging in amplitude over more than 150 dB are useful for studies of nonlinearity. The WSS array, initially installed with velocity transducers, has provided an extensive data set interpreted by Liu, *et al.* (1992).

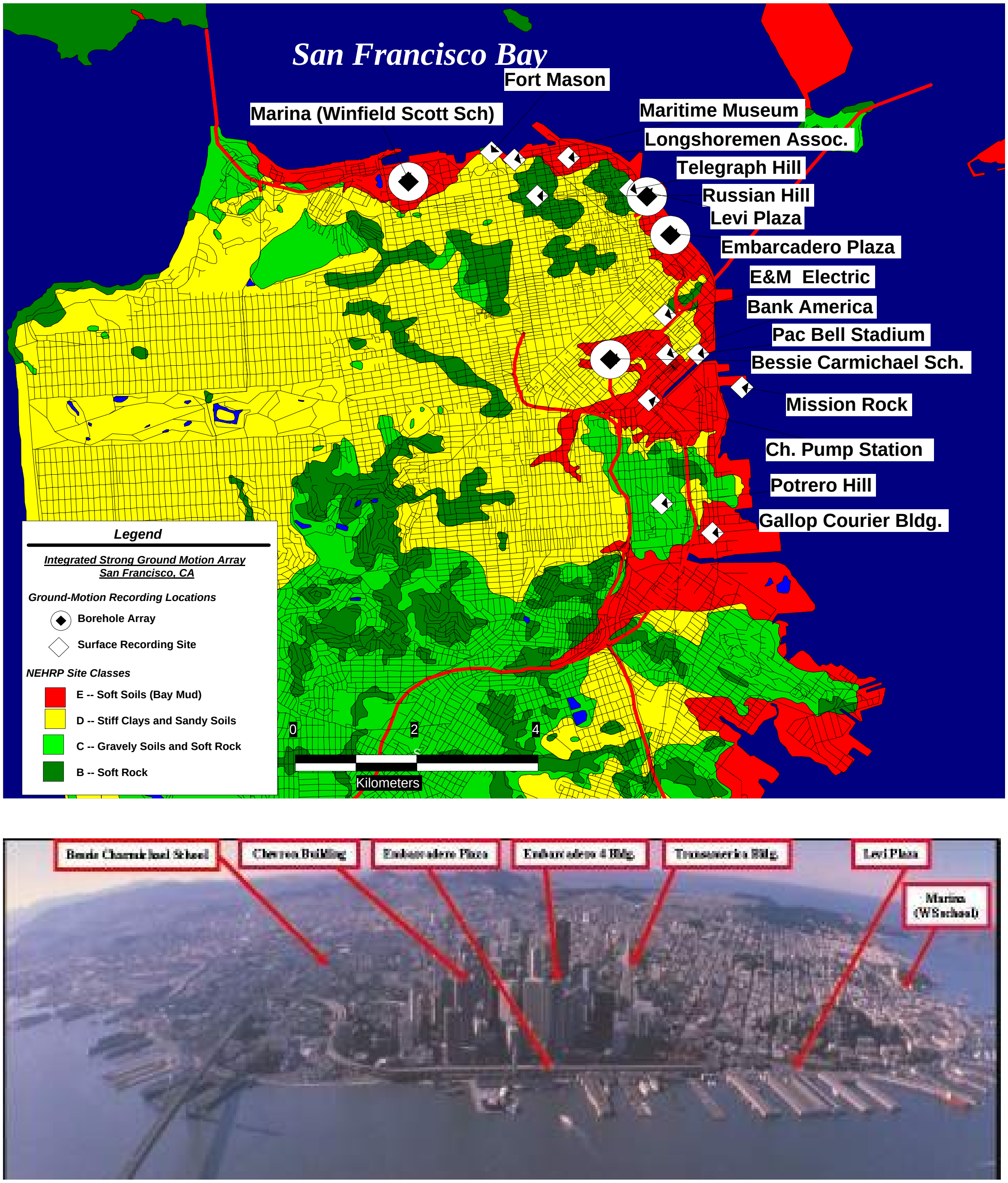

Figure 1. Maps showing location of borehole arrays and surface installations in the Integrated San Francisco Array superimposed on a map showing streets and the site classes adopted in US building code provisions and location of borehole arrays and nearby structural response arrays superimposed on aerial view of San Francisco.

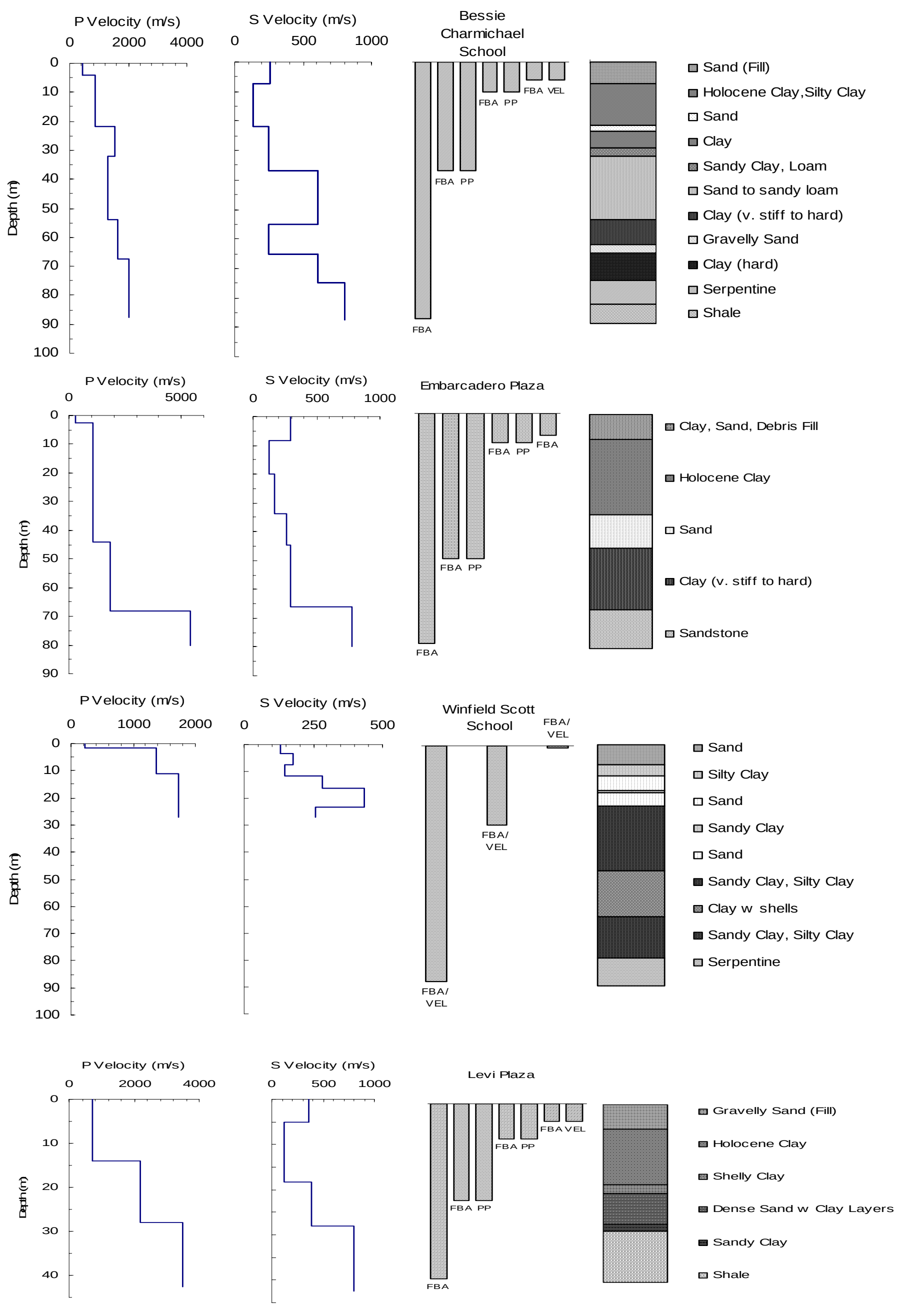

Figure 2. Seismic log (P and S), geologic log, and sensor borehole configuration for the Bessie Charmichael School (BCS), Embarcadero Plaza (EMB), Winfield Scott School (WSS) and Levi Plaza (LP).

The surface array is designed to provide comparative measurements of response at pairs of sites on rock and soil. These instruments provide additional response measurements of soft soil sites in San Francisco. The surface rock locations also permit comparative studies of motions as observed at the surface and in the boreholes at the soil-rock interface. These measurements are useful for quantifying the response of nearby surface rock sites.

The sensors deployed for direct measurement of acceleration are three component borehole force-balance accelerometers with full scale at $\pm$ 1 or $\pm$ 2 g, and frequency response from DC to 100 Hz, models FBA 13 and FBA 23 DH produced by Kinemetrics, Inc. The velocity transducers with a natural frequency of 2 Hz have been developed for borehole deployment (Liu, *et al*. 1991). The pore-pressure transducers are wide dynamic range (~140 dB) transducers with digital output proportional to pressure applied to a quartz crystal resonator, model 8DP depth sensor produced by Parascientific, Inc.

Signals from each of the sensors at each location are recorded on site using broadband digital recorders (General Earthquake Observation Systems, GEOS, Borcherdt, *et al*. 1985) with the capability for event derived parameters transmitted and recorded in near real time via GOES satellite (Mueller, *et al*. 1995). Signals from the various sensors are recorded at various gain levels depending on depth and type of sensor. Gains up to 84dB selectable in 6dB steps are available to permit signals over a dynamic range near 180 dB at frequencies near 1 Hz to be resolved from a variety of sensor types. In general, gains for similar sensors in a single borehole array vary between 6 and 18 dB.

Events are recorded in event-triggered mode at 200 samples per second per channel using 16-bit linear analog to digital conversion. Absolute time and recording parameters are recorded simultaneously. Event and instrument parameters can be transmitted at a selectable time interval usually chosen to be less than 10 minutes via GOES satellite. Parameters such as trigger time, peak amplitude, time of peak amplitude and duration together with a variety of instrument status parameters are transmitted. The satellite transmissions can permit the retrieval of critical event and instrument data in near real time (Mueller, *et al*. 1995). Sensor and recording system calibrations are recorded before and after each storage media change.

EARTHQUAKE RECORDINGS ON THE ARRAYS

Twenty-five earthquakes with magnitudes in the range M 2.9 - 5.1 have been recorded on the arrays since completion of installation of the borehole arrays in 1992. The three of these events that have created the largest ground motions at the array locations are earthquakes near Yountville (M 5.1, Sept. 3, 2000), Gilroy (M 4.9, May 13, 2002), and Orinda (M 4.1, Sept. 4, 2003). These earthquakes occurred north, southeast, and east of the arrays, respectively at epicentral distances of 60 to 70 km, 110 to 120 km, and 15.8 to 19.4 km.

An example of the recordings from the borehole array of accelerometers at the Embarcadero Plaza site is shown for the Yountville earthquake (Figure 3). The three-component recordings of acceleration show that the motions recorded at the surface and at a depth of 10 meters are significantly larger in amplitude and richer in lower frequencies than those recorded at larger depths in the stiffer and more consolidated soil deposits at 49 m and in rock at 79 m.

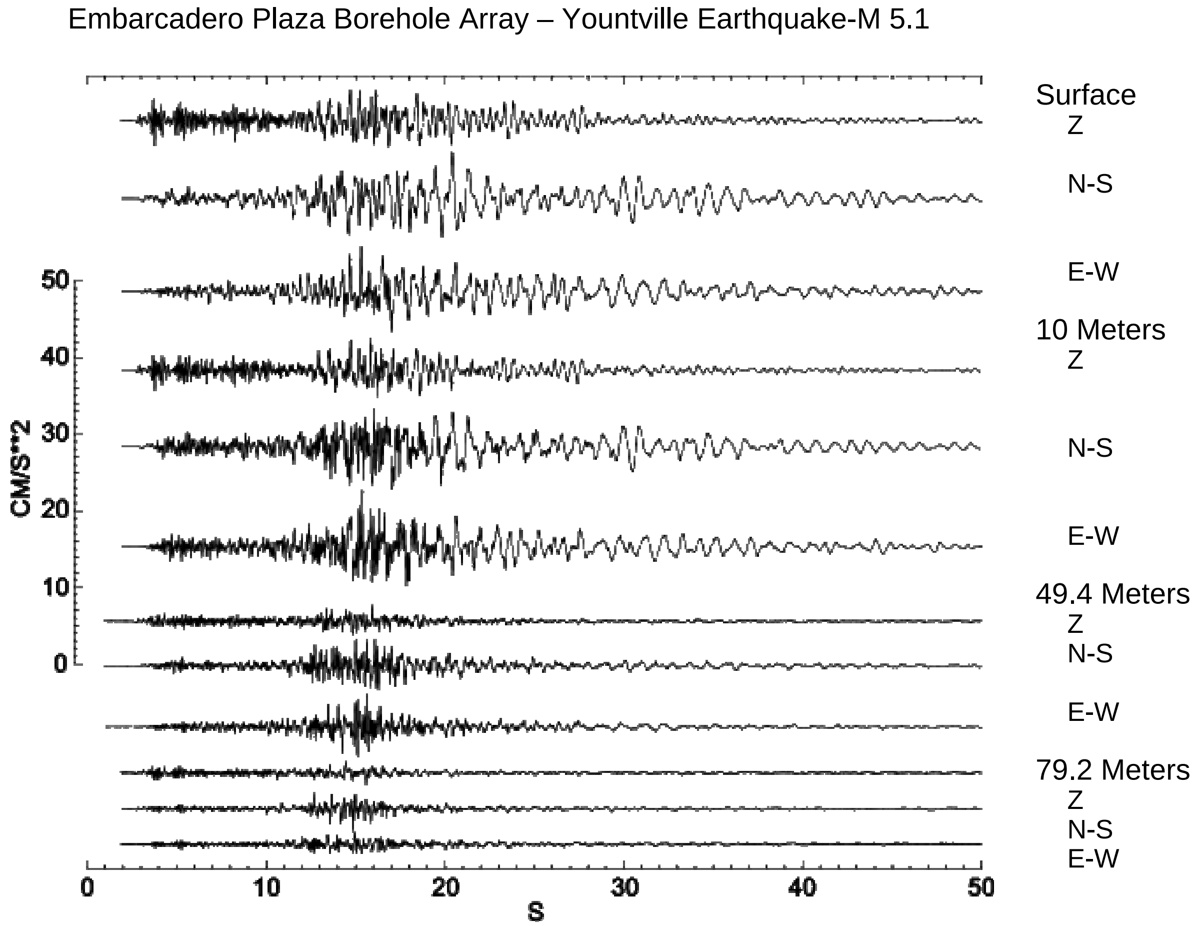

Figure 3. Vertical (Z), North-South (N-S; Radial), and East-West (E-W; Transverse) recordings of the Yountville earthquake (M 5.1) on the Embarcadero Plaza Borehole Array at the surface and depths of 10 m, 49.4 m, and 79.2 m.

As another example, recordings from the borehole array of velocity transducers at the San Francisco Marina site are shown for the Orinda earthquake (Figure 4). These three component recordings of velocity show that the signals from the small relatively close event are rich in higher frequencies. They show that the largest amplification of the dominant frequencies on the seismogram occurs between the depth of 30 meters and the surface. Similar observations are apparent from plots of the recordings obtained on the other borehole arrays (not shown).

The north-south component of velocity plotted at the same scale for the Yountville earthquake as recorded from sensors on the surface are shown in Figure 5. As an additional example, a similar plot of acceleration as recorded for the Gilroy earthquake is shown in Figure 6. The equiscaled plots show that the motions at the surface of the soft soil sites are significantly larger than those recorded at the surface of sites underlain by firm to hard rock.

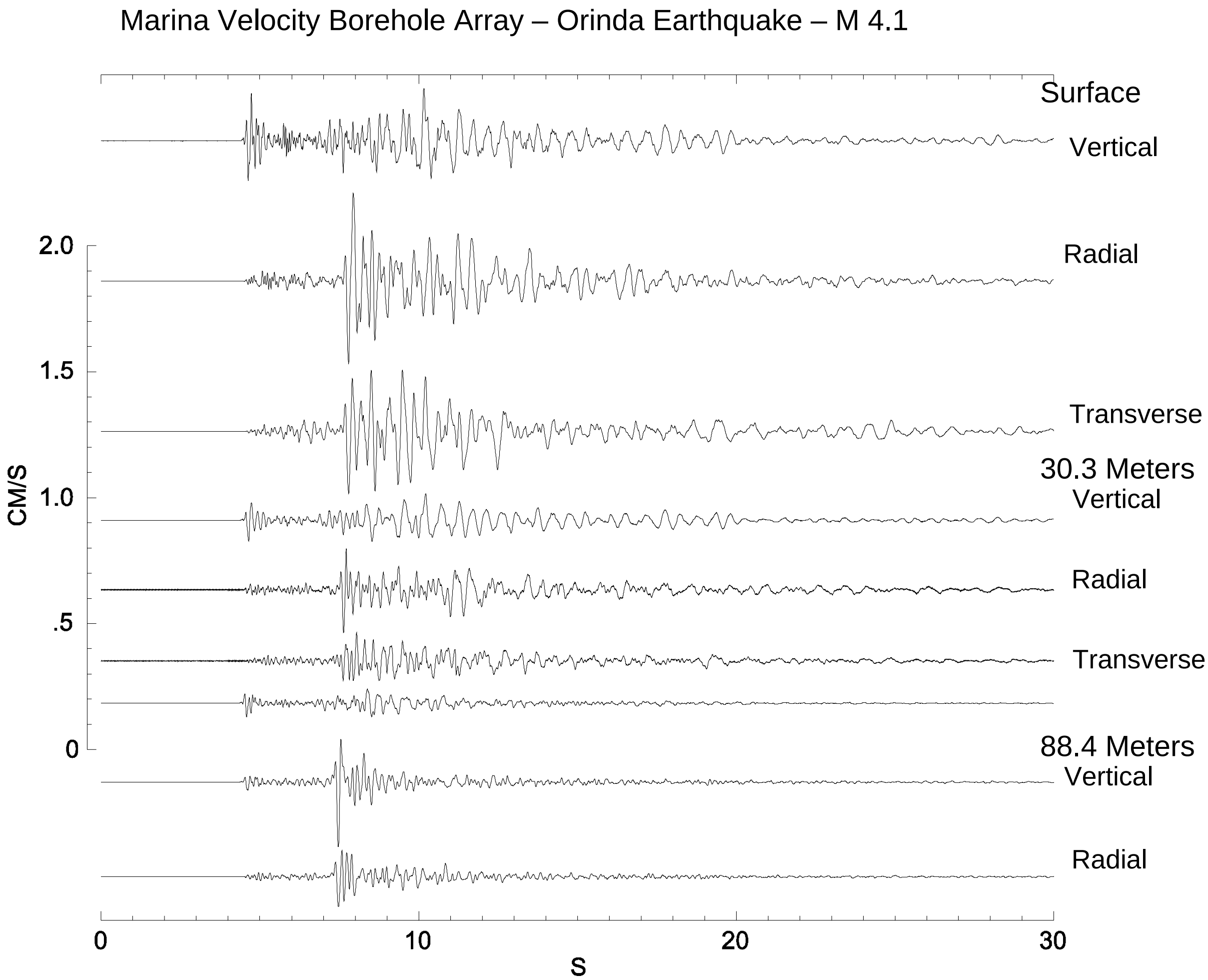

Figure 4. Vertical, Radial, and Transverse recordings of the Orinda earthquake (M 4.1) on the SF Marina Borehole Velocity Transducer Array at the surface and depths of 30.3 m and 88.4 m.

Amplitude spectral ratios for the radial component of motion are shown for thirteen sites that recorded the Yountville earthquake (Figure 7). The spectral ratios show that the amplitude response is strongly frequency dependent especially for sites underlain by soft soils. Several of the softer sites indicate dominant periods of amplification in the period band 0.5 to 2 seconds. The well-defined peaks in some of the spectral ratios suggest that resonance plays a major role in determining the final surface motion.

Amplitude spectral ratios for the recordings obtained at stations underlain by rock (PBS, P50, RHL, M9A C9A, and E8A) also show significant variations. Those computed for the PBS and P50 sites show evidence of dominant periods, which are suspected of being associated with structural response and topographic amplification, respectively. The RHL site on Russian Hill is similar in response to that of FM3. The base motion of the Marina (WSS) site (M9) is consistently larger than that recorded at the other borehole locations in rock at their base. The ratio computed for the recordings at the base of the borehole arrays at the Embarcadero Plaza site and the Charmichael school site provide an estimate of the response of the near-surface rock layers beneath the FM3 site.

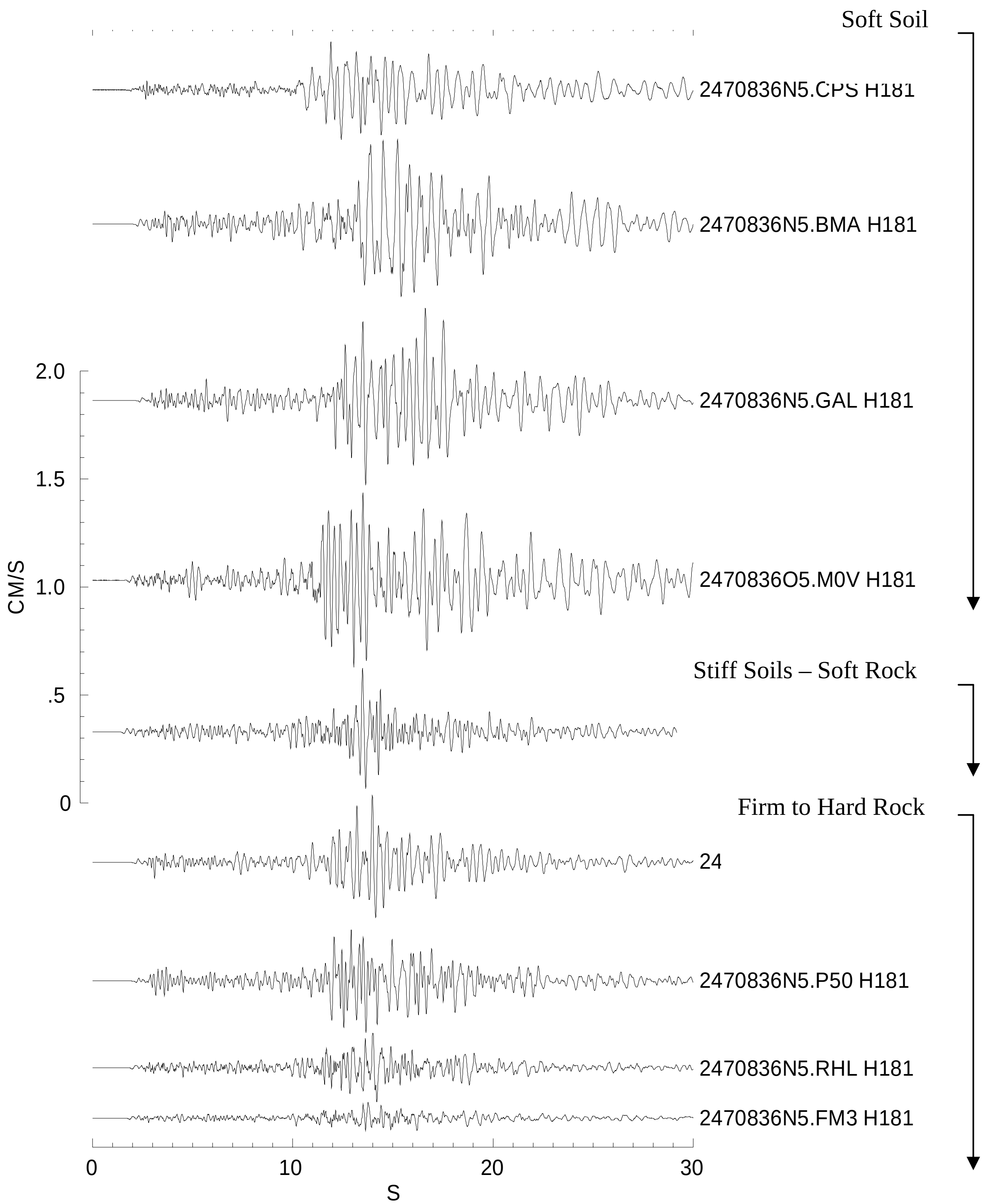

Figure 5. North-South (radial) component of velocity for the Yountville earthquake (M 5.1) as recorded at the surface at nine sites in the San Francisco Integrated Array. The equiscaled recordings show that the velocities recorded at the surface of sites underlain by soft soil are significantly greater than those recorded at the surface of firm to hard rock sites.

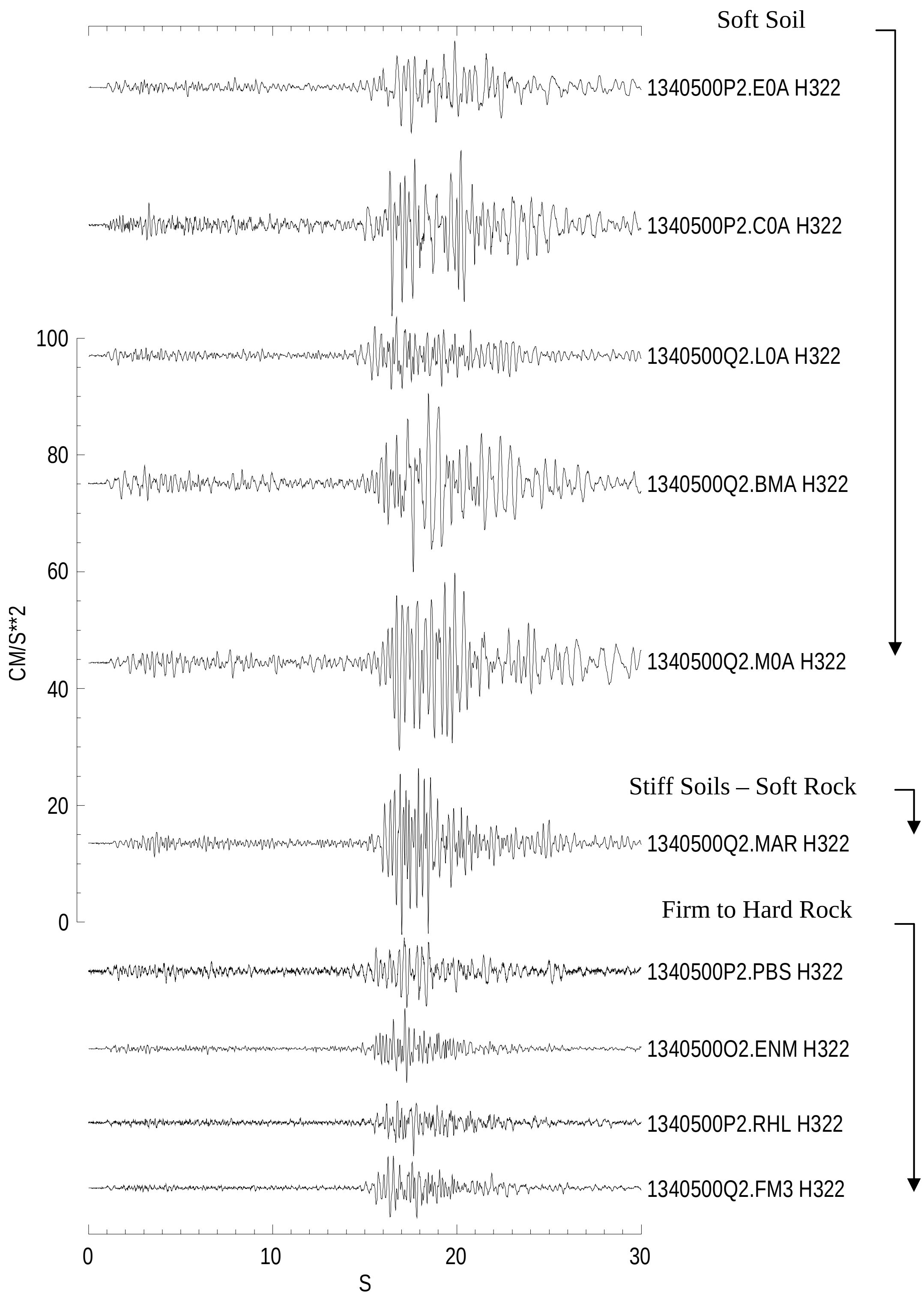

Figure 6. North-South component of acceleration for the Gilroy earthquake (M 4.9) as recorded at the surface at ten sites in the San Francisco Integrated Array. The recordings show that the accelerations recorded at the surface of sites underlain by soft soil are significantly greater than those recorded at the surface of firm to hard rock sites.

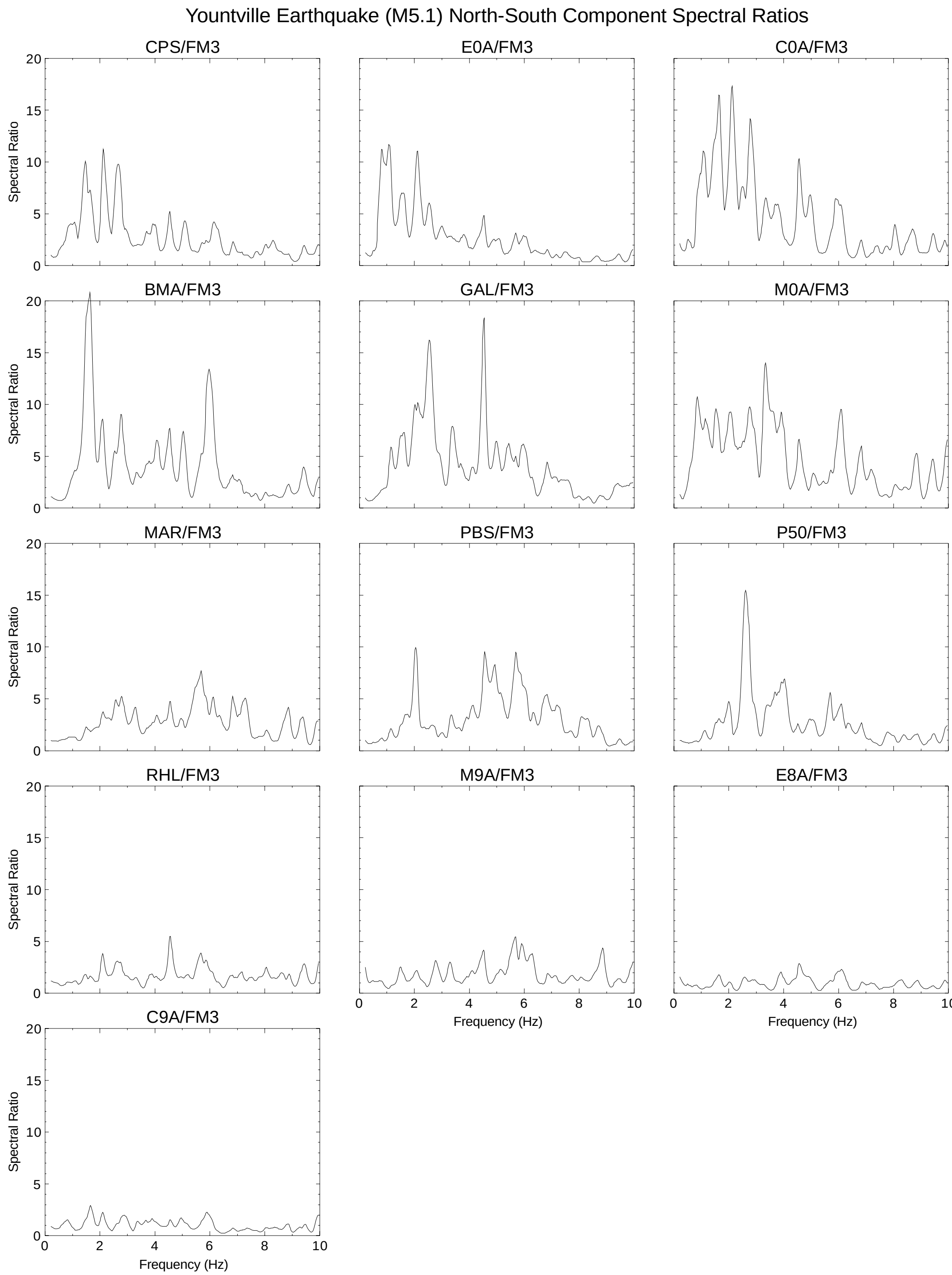

Figure 7. Amplitude spectral ratios for the north-south (radial) component of acceleration as recorded from the Yountville earthquake at 13 sites in the San Francisco Array and computed with respect to the hard-rock, surface recording at the FM3 (Fort Mason) site.

Fourier amplitude spectral ratios for the radial component of motion recorded at the Embarcadero site (not shown) computed with respect to the corresponding component of motion recorded in rock at the base of the borehole array show a well-defined fundamental period and successively higher modes decreasing in amplitude. The well-defined modes provide strong evidence of resonance motion in the surface layer with the amount of damping in the soil increasing with increasing frequency. This type of response is explained well using a simple one-dimensional model of vertically propagating homogenous S waves and a viscoelastic soil layer over a viscoelastic half space (Borcherdt, 2004a).

CONCLUSIONS

The borehole arrays, designed to provide *in-situ* data not previously available on the non-linear response of soft soils as a function of strain amplitude with and without liquefaction-induced failure, have yielded several low-strain recordings of small to moderate earthquakes since their installation. These recordings provide useful measurements of low-strain site response and constitutive parameters for consideration in developing a better understanding of the response of soft soil deposits in the city of San Francisco. Critically needed recordings of the moderate- to high-strain response of the deposits must await the occurrence of a significantly larger earthquake on one of the nearby faults.

Twenty-five earthquakes in the magnitude range M 2.9 to 5.1 have been recorded on the San Francisco Array since its installation. Three of these events have been well recorded above urban background noise levels on the borehole arrays and at several of the surface installations. These *in-situ* recordings of the response of the near-surface deposits at the various sites show significant variations associated with variations in geotechnical characteristics of the sites.

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