11 WCEE
Copyright © 1996 Elsevier Science Ltd
Paper No. 2028. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

EFFECTS OF SITE CONDITIONS ON STRONG GROUND SHAKING IN THE SAN FRANCISCO BAY REGION DURING THE 1989 LOMA PRIETA EARTHQUAKE

ROGER D. BORCHERDT

U.S. Geological Survey, MS 977, 345 Middlefield Road
Menlo Park, CA 94025

ABSTRACT

Strong ground motions recorded at 37 sites in the San Francisco Bay region during the Loma Prieta earthquake suggest that soil amplification and reflected crustal shear energy were major contributors to levels of ground motion sufficient to cause damage to vulnerable structures at distances near 100 km in the cities of San Francisco and Oakland, CA. Peak acceleration, velocity, and displacement values normalized to local rock sites are statistically larger for soil sites than rock sites. Spectral ratios establish the existence of predominant site periods at some, but not all soil sites. Empirical regression curves establish a strong correlation between amplification and mean shear-wave velocity. Regression curves predict amplification for short- and mid-period motion by $F_a = (v_o / v)^{m_a}$ and $F_v = (v_o / v)^{m_v}$, where v is the mean shear-wave velocity to a depth of 30 m (100 ft) at the site, v_o is the average shear-wave velocity for the site class chosen as the reference ground condition, and m_a and m_v are specified at the 0.1g input ground-motion level from the Loma Prieta strong-motion data and at higher levels by numerical modeling results. These strong-motion amplification factors provide rigorous estimates of amplification for site-specific design spectra.

KEYWORDS

Amplification, site-specific design, Loma Prieta earthquake, strong motion, site conditions

INTRODUCTION

Strong-motion recordings of the Loma Prieta, California earthquake of January 17, 1989 have proven to be an important data set for quantifying the response of local geologic deposits for purposes of earthquake-resistant design. Prior to recent data sets collected from the Northridge and Kobe earthquakes, they constituted one of the most extensive sets of *in-situ* measurements of the response of soil deposits to damaging levels of earthquake ground motion. They were obtained at sites on a variety of geologic deposits in close proximity, ranging from very soft clays to hard rock. They were obtained over narrow ranges in azimuth so that influences of local geologic deposits could be isolated from those of the source and crustal-propagation path. The data were recorded in a region for which a large amount of previous geologic, geotechnical, and seismic data existed for use in understanding the results. Measurements of site response derived from the data set have been used to ascribe amplification factors at corresponding input ground motion levels for site classes being adopted recently for earthquake resistant building code provisions.

This paper provides an invited summary of the effects of site conditions on strong ground shaking in the San Francisco Bay region during the 1989 Loma Prieta earthquake. A brief description of the geologic units in the region and their relation to recently proposed site classes for site-specific building code provisions is provided. Comparative strong-motion measurements are summarized for peak levels of ground acceleration, velocity, and displacement and for average spectral ratios for various period bands resolved into vertical, radial, and transverse components of motion. Empirical regression curves predicting short- and mid- period spectral amplification factors as a function of mean shear-wave velocity derived from the Loma Prieta strong-motion data are specified. Estimates of amplification factors for site classes being considered for site specific code provisions are presented.

GEOLOGIC DEPOSITS

San Francisco Bay is located in a basin about 15 km wide bounded by the active San Andreas and Hayward fault zones. The region is characterized by a wide variety of geologic deposits in close proximity. The deposits range in age from more than 100 million years for rocks exposed in the hills to esturine mud and clay deposits still being deposited at present in the flatlands along the margins of the bay.

The flatland deposits in the San Francisco Bay region are classified into two general categories, Quaternary alluvium (Qal) and Quaternary Holocene bay mud (Qhbm). These unconsolidated units are differentiated and mapped according to composition, grain size, texture, and relative age (Helley and Lajoie, 1979). The hillside material units in the region are generalized into six units which appear on geologic maps as Quaternary and Tertiary sedimentary rocks of the Santa Clara and Merced formations (QTs), Tertiary and Mesozoic sedimentary rocks (TMzs), Cretaceous granitic rocks (Kg) and Cretaceous Jurassic Franciscan Complex (KJf). These units are differentiated and mapped according to composition, hardness, fracture spacing and amount of weathering (Wentworth *et al.* , 1985). Seismic, geologic, and physical property logs from boreholes to a depth of 30 meters have been compiled at more than 60 sites distributed throughout these various units (Gibbs *et al.*, 1975, 1976, 1977).

Previous ground-response studies (Borcherdt, 1970; Fumal, 1978; Borcherdt and Gibbs, 1976) show that, in general, average amplification of ground motion increases with decreasing mean shear-wave velocity and increasing softness of the deposits. Detailed studies (Fumal, 1978) have established well-defined correlations between physical properties (predominately grain size and fracture spacing) and shear-wave velocity. These correlations afford delineation in ground response based on regional geologic maps.

The unit of most concern for its potential influence on strong ground shaking is the Holocene bay mud unit (Qhbm). This unit located along the margins and beneath the bay generally overlies the alluvial unit. It is comprised of unconsolidated, water-saturated, dark plastic clay and silty clay with well-sorted silt and sand dunes in some areas. It may contain more than 50 percent water by weight and has characteristically low interval shear-wave velocities (55-115 m/s; Fumal, 1978). It reaches maximum thickness near 35 m along the margins of the bay. In urbanized areas the bay mud is overlain by man-placed fills (Qaf) generally stiffer with slightly higher shear velocities (160-220 m/s).

Recent building code considerations have led to the rigorous specification of new site classes in terms of mean shear velocity to a depth of 30 m (Borcherdt, 1994b). This specification permits unambiguous classification of all sites ranging from the hardest of rocks to the softest of soils. The physical description, range in mean shear velocity, and amplification capability for the four main site classes (SC) designated using both roman numerals and letters are, respectively; 1) *SC-I*, NEHRP A,B Firm to Hard Rock, > 700 m/s; Low to Very Low, 2) *SC-II*, NEHRP C, Soft to Firm Rock and Gravely Soils, 375 to 700 m/s, Low to Intermediate, 3) *SC-III*, NEHRP D, Stiff Clays and Sandy Soils, 200 to 375 m/s, Intermediate to High, and 4) *SC-IV*, NEHRP E, Soft Soils, < 200 m/s, High to Very High. The site class for rock is subdivided into two subclasses; *SC-Ia*, Hard Rock, > 1400 m/s and *SC-Ib*, Firm to Hard Rock, 700 to 1450 m/s. The correspondence between these classes and mapped geologic units is specified in detail (Borcherdt and Glassmoyer, 1994). In general, assuming the units extend to a depth of 30 m a general classification for the units is Holocene Bay mud unit (*SC-IV*), fine and medium grained alluvium (*SC-III*), coarse grained Pleistocene alluvium (*SC-II*), Tertiary and Mesozoic sedimentary rocks (*SC-II*), and Cretaceous and Jurassic rocks of close to very close fracture spacing and/or moderate to fresh weathering (*SC-Ib*).

Short- and mid-period amplification factors for these site classes as adopted in the new building code provisions were initially derived on the basis of the Loma Prieta strong-motion recordings. This derivation corresponding to input ground motion levels near 0.1g is summarized here from Borcherdt (1994b).

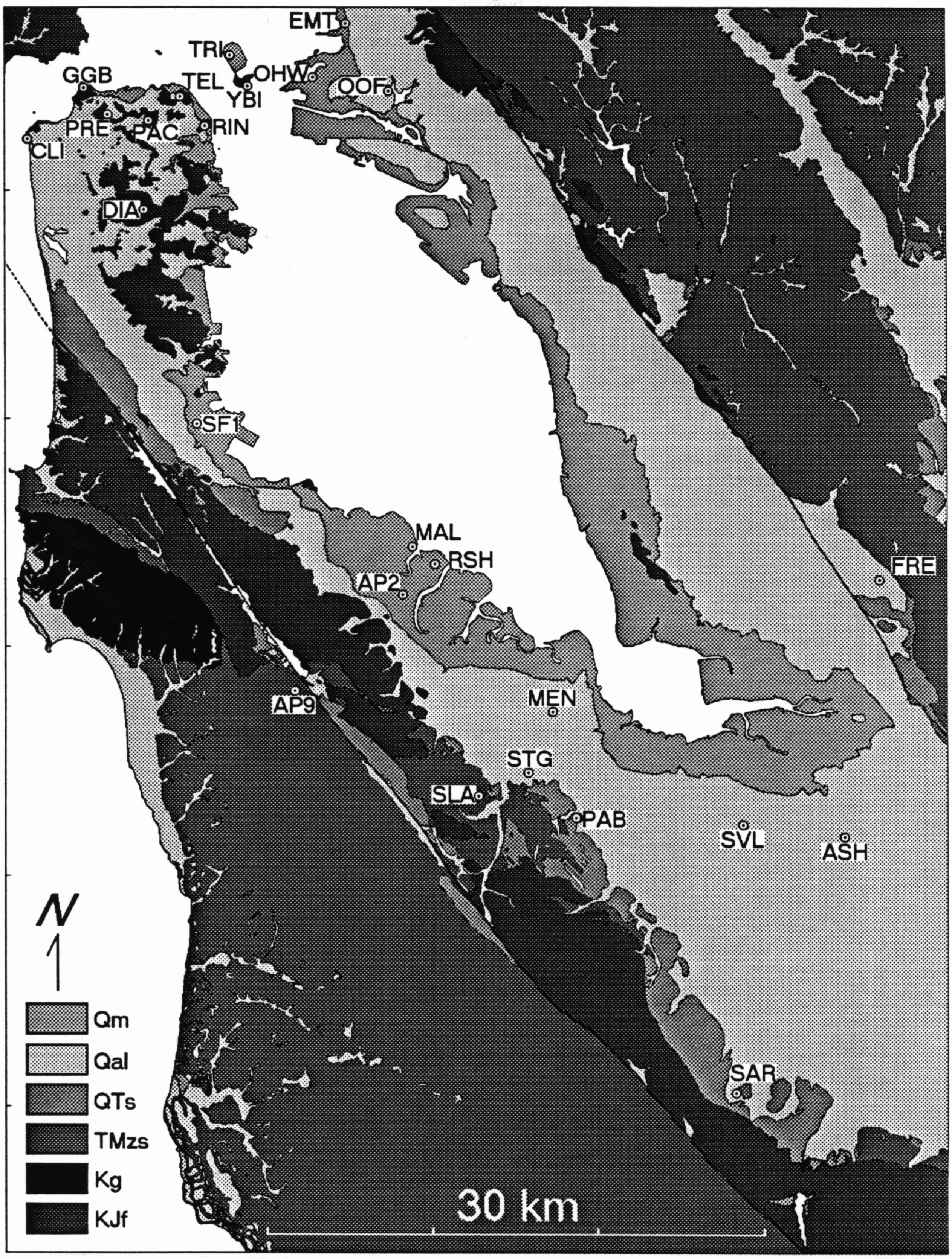

Figure 1 Geologic map of the San Francisco Bay region showing locations of free-field stations which recorded the Loma Prieta earthquake of October 17, 1989 and the generalized geologic units described in the text (from Borcherdt and Glassmoyer, 1992).

STRONG GROUND-MOTION RECORDINGS

The Loma Prieta earthquake provided an especially important strong-motion data set. It provided free-field recordings at 37 sites in the San Francisco Bay region on a variety of geologic deposits in close proximity. These data included ten free-field recordings on "soft" clays which augment those obtained previously in Mexico City. These limited data provided critical in-situ estimates of the response of these deposits at higher strain levels corresponding to damaging levels of motion. The measurements have proven to serve as the basis for site-specific amplification factors recently adopted in earthquake resistant building code provisions.

The strong ground motion recordings from the Loma Prieta earthquake have been presented and analyzed in detail (Borcherdt and Glassmoyer, 1992; 1994; Borcherdt, 1994a; 1994b). Results of these analyses are summarized here.

Comparative Time-Series and Peak-Motion Observations

Ground motions were of short duration, consistent with relatively rapid bilateral (~ 6 secs) rupture inferred for the earthquake faulting process. Consequently, resulting damage from the earthquake probably was less than would have occurred from a similar event with more complex or unilateral rupture.

Equiscaled plots of the three components of motion prepared for each site show that, in general, both the amplitude and duration of shaking were amplified by local soil deposits relative to motions recorded on nearby rock sites. Horizontal motions were amplified more than vertical motions at most "soil" sites; amplification of radial motion exceeded that for transverse motion. The larger amplifications for radial motion were interpreted to be due in part to the influence of earth structure on the propagation of radial energy as SV waves.

Comparison of recorded peak motions at sites underlain by "firm to soft" rocks with those anticipated on the basis of previously recorded strong motion data showed that the peak motions for the Loma Prieta earthquake exceeded previous empirical predictions at most sites. These increased motions were interpreted to be due in part to efficient reflection of seismic energy from the base of a relatively shallow earth's crust (25 km; Somerville and Yoshimura, 1990; Borcherdt and Glassmoyer, 1992; 1994).

Ratios of peak amplitude were computed for each measure of ground motion (acceleration, velocity, and displacement) and each component of motion (vertical, radial, transverse) relative to corresponding motions at a nearby rock site. The ratios show that all three measure of peak ground motion were amplified by local soil deposits, with the amplifications for peak velocity and acceleration exceeding those for peak displacement at most sites.

An important influence of local geology at some sites on recorded ground motions was the development of site resonance resulting in narrow frequency bands being amplified by factors as large as 10-20. These resonances apparent in Fourier amplitude spectral ratios appear as pronounced peaks for horizontal ground motions recorded at some sites located on alluvium and fill over bay mud. These resonances are of special interest for earthquake engineering. The ground-motion recordings of the Loma Prieta earthquake indicate that resonances developed at some but not all soil sites at ground motion levels sufficient to generate damage. The resulting amplifications as large as 10-20 times over narrow period bands are consistent with those observed in Mexico City during the earthquake of 1985. Such site resonances are of special concern in locations where man-made structures exist with natural periods which may lengthen into the resonant period bands of the soil as strong shaking persists.

Comparative Spectral Ratio Measurements

Average spectral amplification factors for 35 free-field sites, as inferred from the strong-motion recordings of the Loma Prieta earthquake are summarized in Table 1. These amplification factors correspond to average Fourier spectral ratios for vertical and average horizontal ground motion (Borcherdt and Glassmoyer, 1992). The ratios summarized in these tables have been computed with respect to nearby sites underlain by rock with peak motions near 0.1g. Each of the ratios has been normalized by hypocentral distance and adjusted to a reference ground condition *Firm to Hard rock (SC-Ib)* of the Franciscan formation (KJf).

The spectral ratios represent averages over the short-period band (0.1-0.5 s), intermediate-period band (0.5-1.5 s), long-period band (1.5 -5.0 s), mid-period band (0.4-2.0 s), and entire-period band (0.1-5.0 s). Mean shear-wave velocity to a depth of 30 m (100 ft) as either measured or estimated for each site by Fumal (1991) are summarized in Table 1.

TABLE 1 -- Average spectral ratios inferred from Loma Prieta strong-motion data with respect to a common, reference ground condition, Firm to Hard rock, KJf (from Borcherdt, 1994b).

Station	Geologic Unit	Site Class	H.Dist. km	S vel.		Vertical period bands (secs)					Horizontal period bands (secs)				
				m/s	ft/s	0.1-0.5	0.5-1.5	1.5-5.0	0.1-5.0	0.4-2.0	0.1-0.5	0.5-1.5	1.5-5.0	0.1-5.0	0.4-2.0
South San Francisco	KJfss	*Ib*	85	910	2985	1.07	1.00	0.69	1.04	0.96	1.12	0.92	0.92	1.09	0.96
Yerba Buena	KJfsh	*Ib*	97	880	2886	0.78	0.98	0.80	0.81	0.90	0.72	0.73	0.98	0.73	0.74
Rincon Hill	KJfsh	*Ib*	96	745	2444	1.13	1.00	1.15	1.11	1.11	1.06	1.11	1.07	1.07	0.98
Pacific Heights	KJfsh	*Ib*	98	745	2444	0.72	0.99	1.67	0.81	1.07	0.59	1.00	1.16	0.67	0.96
Diamond Heights	KJfsh	*Ib*	94	745	2444	1.38	1.44	1.20	1.38	1.39	1.60	1.28	1.04	1.53	1.39
Piedmont Jr. High	KJfss	*Ib*	94	745	2444	0.92	0.61	0.48	0.85	0.56	0.91	0.96	0.83	0.91	0.97
MEAN (KJf norm.; *SC-Ib*)				795	2608	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
STANDARD DEVIATION				78	256	0.25	0.27	0.43	0.23	0.27	0.36	0.18	0.12	0.31	0.21
Cliff House	KJfsh	*Ib*	101	745	2444	1.05	1.91	1.61	1.21	2.06	0.80	1.83	1.79	0.98	1.62
Bonita Point	KJfsh	*Ib*	105	745	2444	0.79	1.28	1.72	0.91	1.28	0.87	1.35	2.30	1.00	1.43
MEAN				745	2444	0.92	1.60	1.66	1.06	1.67	0.83	1.59	2.05	0.99	1.53
CSUH Stadium Grounds	TMzs	*II*	73	525	1722	1.42	1.10	0.52	1.34	1.06	1.44	0.86	0.78	1.34	0.76
Woodside Fire Station	TMzs	*II*	57	440	1443	0.82	0.79	0.87	0.82	0.77	0.66	0.95	1.19	0.72	0.86
APEEL 7 (Pulgas Templ	TMzs	*II*	65	435	1427	1.78	1.00	0.92	1.63	0.97	1.33	1.47	1.37	1.36	1.41
Berkeley (Lawrence Lab.	TMzs	*II*	100	610	2001	0.90	2.90	1.80	1.20	2.60	0.77	2.15	2.08	1.01	1.98
APEEL 10 (Skyline Blvd	TMzs	*II*	65	405	1328	0.70	1.48	1.61	0.86	1.51	0.70	1.69	2.49	0.99	1.68
Presido	sp	*II*	99	594	1948	2.06	2.01	2.46	2.07	2.10	1.58	2.32	1.87	1.69	2.11
Golden Gate Bridge	Qal/sp	*II*	101	515	1689	1.56	1.82	2.88	1.66	2.03	1.44	3.74	3.27	1.83	3.36
APEEL 9 (Crys.Spr. Res.	QTs	*II*	64	450	1476	2.00	2.60	2.30	2.10	2.50	1.84	3.50	1.57	2.06	2.71
SLAC	QTs	*III?*	54	344	1128	2.85	0.82	0.29	2.45	0.83	1.98	1.17	0.59	1.94	1.00
MEAN (QTs, TMzs, sp; *SC-II*)				480	1574	1.57	1.61	1.52	1.57	1.60	1.30	1.98	1.69	1.44	1.76
STANDARD DEVIATION				88	288	0.70	0.77	0.92	0.57	0.73	0.49	1.05	0.84	0.47	0.87
Hayward BART Station	Qpa	*III*	74	365	1197	4.61	1.53	1.13	4.04	2.11	2.70	3.00	1.33	2.98	2.97
Oakland Office Bldg	Qps/Qpa	*III*	93	315	1033	5.20	3.20	2.40	4.80	3.40	2.42	3.81	5.31	2.73	3.83
Fremont	Qpa	*III*	58	285	935	2.42	1.59	2.78	2.33	1.74	1.89	2.73	2.44	2.24	2.89
Mission San Jose	Qpa	*III*	57	285	935	3.18	1.58	2.00	2.92	1.94	1.79	2.38	2.35	2.10	2.39
Muir School (APEEL 2E	Qpa	*III*	73	280	918	4.22	1.62	1.70	3.75	1.62	2.29	3.59	3.50	2.78	3.70
Richmond City Hall	Qhaf	*III*	109	288	945	4.00	3.03	2.51	3.80	2.94	3.23	2.78	2.38	3.44	2.54
Sunnyvale	Qhaf	*III*	46	268	879	3.98	1.68	3.14	3.63	1.88	3.40	2.34	3.85	3.66	2.30
Agnew State Hosp	Qhaf	*III*	44	240	787	3.56	1.87	2.25	3.27	2.00	3.09	1.78	2.22	3.22	1.71
MEAN (Qal: *SC-III*)				291	954	3.90	2.01	2.24	3.57	2.21	2.60	2.80	2.92	2.89	2.79
STANDARD DEVIATION				37	120	0.86	0.69	0.63	0.74	0.63	0.61	0.67	1.24	0.55	0.71
Oakland Harbor Wharf	Qaf/Qhbm	*IV?*	96	251	823	4.10	3.40	5.30	4.00	4.00	2.93	6.68	7.77	3.67	6.12
Emeryville Towers	Qaf/Qhbm	*IV*	98	196	643	3.40	2.50	2.50	3.30	2.60	1.90	5.03	8.62	2.63	5.20
San Francisco Airport	Qaf/Qhbm	*IV*	81	180	590	1.78	1.51	0.88	1.70	1.63	2.86	3.72	2.27	2.95	3.64
Alameda Naval Air Sta.	Qaf/Qhbm	*IV*	92	191	626	2.59	2.71	3.15	2.63	3.18	1.79	4.17	5.07	2.27	3.56
Treasure Island	Qaf/Qhbm	*IV*	99	130	426	0.83	0.31	0.44	0.74	0.45	1.51	3.63	3.58	1.90	3.13
Dumbarton Bridge West	Qaf/Qhbm	*IV*	58	149	489	3.18	1.58	1.50	2.89	1.50	1.38	2.68	2.66	1.78	2.56
Maley Res.(F. City)	Qaf/Qhbm	*IV*	68	150	492	1.91	1.70	1.53	1.87	1.68	0.84	2.05	2.96	1.20	1.87
APEEL 2	Qaf/Qhbm	*IV*	66	130	426	2.68	1.96	1.19	2.52	2.30	0.73	4.24	2.70	1.36	3.57
Larkspur Ferry	Qaf/Qhbm	*IV*	116	130	426	3.56	1.22	1.64	3.13	1.32	1.26	4.19	2.34	1.68	2.92
Redwood Shores	Qaf/Qhbm	*IV*	67	115	377	3.04	2.42	1.51	2.89	2.42	3.16	4.57	5.40	3.79	4.35
MEAN (Qaf/Qhbm; *SC-IV*)				162	532	2.71	1.93	1.97	2.57	2.11	1.84	4.10	4.33	2.32	3.69
STANDARD DEVIATION				42	138	0.97	0.87	1.40	0.92	1.01	0.87	1.26	2.31	0.91	1.25

Regression curves for average horizontal spectral amplification as a function of mean shear-wave velocity for the short-, intermediate-, long-, and mid-period bands were derived (Figures 6a through 6d, Borcherdt, 1994b). The curves show that, in general, average horizontal spectral amplification increases with decreasing mean shear-wave velocity. The increase in amplification with decreasing mean shear-wave velocity is distinctly less for short-period motion than for intermediate-, long- or mid-period motion. This important observation suggests that site response can best be characterized by two factors, one for the short-period component of motion and one for the other period bands. This important result is most apparent for sites underlain by soft soils. It implies that average horizontal response characteristics at the sites can be summarized by amplification factors expressed as continuous functions of mean shear-wave velocity.

The resulting empirical equations represent simple closed form expressions, useful for estimating site-specific amplification factors. The equations together with correlations between shear-wave velocity and physical properties (Fumal, 1978) provide rigorous estimates of amplification factors for sites and site classes based on physical property descriptions. These equations suggest the plausible result that the amplification factors are a function of the seismic impedance for the surficial material at the site with respect to *Firm to Hard rock* (*SC-Ib*) raised to some power. They yield amplification factors in good agreement with those derived independently based on numerical modeling of the Loma Prieta strong-motion data (Seed et al., 1994; Dickenson, 1994) and parametric studies of several hundred soil profiles (Dobry, et al.,1994).

Implications for Site Specific Design Provisions

The short- (0.1-0.5 s) and the mid- (0.4-2.0 s) period amplification factors, F_a and F_v, implied by the Loma Prieta strong-motion data and recently specified for site-specific building code provisions are given as a function of mean input ground-motion level by:

$$F_a = (v_o / v)^{m_a} \tag{1a}$$

and

$$F_v = (v_o / v)^{m_v} \tag{1b}$$

where,

1) v is the mean shear-wave velocity to depth of 30 m (100 ft) at the site,
2) v_o is the average shear-wave velocity for the site class chosen as the reference ground condition,

and

3) m_a and m_v are implied by the amplification factor for the soft-soil site class (*SC-IV*) specified at the 0.1g input ground-motion level from the Loma Prieta strong motion data and at higher levels by numerical modeling results (Borcherdt, 1994b).

These equations are plotted for various input ground motion levels in Figure 2. They yield well-defined estimates of amplification both as discrete functions of shear-wave velocity for the recently adopted site classes as well as continuous functions for sites with more detailed information. The equations, together with estimates of input ground-motion levels for the short and mid period bands provide a well-defined, quantitative framework for estimates of site-dependent response spectra, S_A. They provide a general framework for estimates of seismic coefficients for inclusion in improved building code provisions and average amplification estimates for predictive ground shaking maps (Borcherdt, 1994b). They offer a general framework for estimating site-dependent seismic coefficients that can be modified readily as additional results regarding the response of soft-soil deposits at high strain levels become available.

Site classes and corresponding mean amplification factors (F_a,F_v) implied at the 0.1g level by equation 1 are, respectively: 1) *SC-Ia* (NEHRP A), Hard rock, (0.8, 0.8); *SC-Ib* (NEHRP B), Firm to hard rock, (1.0, 1.0), 2) *SC-II* (NEHRP C), Soft rock and gravely soils (1.3, 1.6) 3) *SC-III* (NEHRP D), stiff clay and sandy soils (1.6, 2.3) 4) *SC-IV* (NEHRP E), soft soils (2.0, 3.5); *SC-IV b* (NEHRP F), special-study soils.

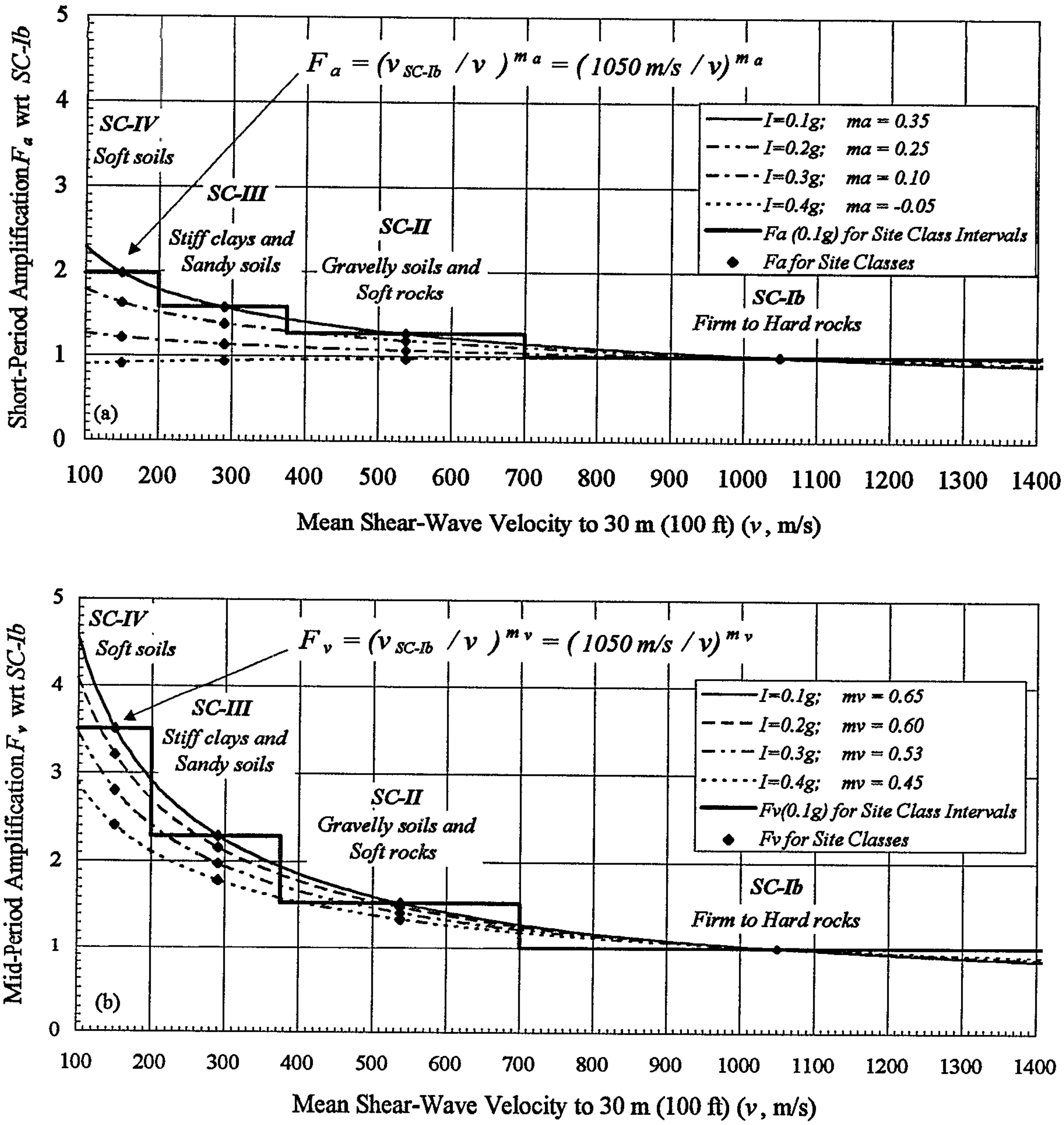

Figure 2. (a) Short-period F_a *and (b) mid-period* F_v *amplification factors with respect to* Firm to Hard rock, *SC-Ib, plotted as a continuous function of mean shear-wave velocity, using the indicated equations for specified levels of input ground motion (equations 2 or 4, see text). Amplification factors with respect to SC-Ib for the simplified site classes also are shown.*

ACKNOWLEDGMENTS

The efforts of F. Sanchez-Sesma and J. Bielak in organizing this special session of the 11WCEEE are appreciated. Interactions with members of the "Working Committee to Draft NEHRP Site-Dependent Response Provisions" (C.B. Crouse, R. Dobry, I.M. Idriss, W. B. Joyner, G.R. Martin, M.S. Power, E.E. Rinne, and R.B. Seed) stimulated the derivation of equation 1. The helpful review comments of M. Celebi and G. Glassmoyer are appreciated.

REFERENCES

Borcherdt, R.D. (1970). Effects of local geology on ground motion near San Francisco Bay, *Bulletin of the Seismological Society of America*, **60**, p.29-61.

Borcherdt, R.D. (1994a). Simplified site classes and empirical amplification factors for site-dependent code provisions, Proceedings NCEER, SEAOC, BSSC workshop on site response during earthquakes and seismic code provisions, University of Southern California, Los Angeles, California, November 18 - 20, 1992.

Borcherdt, R.D. (1994b). Estimates of site-dependent response spectra for design (Methodology and Justification), *Earthquake Spectra*, **10**, p. 617-653.

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, *Bulletin of the Seismological Society of America*, **66**, p. 467-500.

Borcherdt, R.D., Gibbs, J.F., and Fumal, T.E. (1978). Progress on ground-motion predictions for the San Francisco Bay region, California, in *U.S. Geological Survey Circular 807.* Also, *Proceedings Second International Conference on Microzonation Safer Constr. Research*, Appl. 2, **1**, p. 13-25.

Borcherdt, R.D., and Glassmoyer, G. (1992). On the characteristics of local geology and their influence on ground motions generated by the Loma Prieta earthquake in the San Francisco Bay region, California: *Bulletin of the Seismological Society of America*, **82**, p. 603-641.

Borcherdt, R.D. and Glassmoyer, G. (1994). Influences of local geology on strong and weak ground motions in the San Francisco Bay region, California and their implications for site-specific code provisions, *in* The Loma Prieta earthquake of October 17, 1989 -- strong ground motion, R. D. Borcherdt, *ed., U.S. Geological Survey Professional Paper 1551-A,* p. 77-108.

Borcherdt, R.D., Wentworth, C.M., Glassmoyer, G., Fumal, T., Mark, R., and Gibbs, J. (1991). On the observation and predictive GIS mapping of ground response in the San Francisco Bay region, California: *Fourth International Conference on Seismic Zonation, Stanford, California, Proc.*, **III**, p. 545-552.

Dickenson, S.E. (1994). Dynamic response of soft and deep cohesive soils during the Loma Prieta earthquake of October 17, 1989, *Ph.D. Dissertation*, Dept. Civil engineering, Univ. Calif., Berkeley, 331pp.

Dobry, R., Martin, G.M., Parra, E., and Bhattacharyya, A. (1994a). Development of site-dependent ratios of elastic response spectra (RRS) and site categories for building seismic codes, Proceedings NCEER, SEAOC, BSSC workshop on site response during earthquakes and seismic code provisions, University of Southern California, Los Angeles, California, November 18 - 20, 1992.

Fumal, T.E. (1978). Correlations between seismic wave velocities and physical properties of geologic materials in the San Francisco Bay region, California. *U.S. Geological Survey Open-File Report 78-1067.*

Fumal, T.E. (1991). Shear-wave velocity estimates and site geology for strong-motion recordings sites of the Loma Prieta earthquake of October 17, 1989. *U.S. Geological Survey Open-File Report*, 91-311, 163 pp.

Gibbs, J.F., Fumal, T.E., and Borcherdt, R.D. (1975). *In-situ* measurements of seismic velocities at twelve locations in the San Francisco Bay region. *U.S. Geological Survey Open-File Report 75-564.*

Gibbs, J.F., Fumal, T.E., and Borcherdt, R.D. (1976). *In-situ* measurements of seismic velocities in the San Francisco Bay region—Part II. *U.S. Geological Survey Open-File Report 75-731.*

Gibbs, J.F., Fumal, T.E., Borcherdt, R.D., and Roth, E.F. (1977). *In-situ* measurements of seismic velocities in the San Francisco Bay region-Part III. *U.S. Geological Survey Open-File Report 77-850.*

Helley, E.J., and Lajoie, K.R. (1979). Flatland deposits of the San Francisco Bay region, California---their geology and engineering properties, and their importance to comprehensive planning: *U.S. Geological Survey Professional Paper 943*, 88pp.

Seed, R.B., Dickenson, S.E., and Mok, C.M. (1994). Site effects on strong shaking and seismic risk; recent developments for seismic design codes and practice, American Society Civil Engineering Structures Congress 12 , 1, p 573-578.

Seed, R. B. (1994). Proc. NCEER, SEAOC, BSSC Workshop on Site-dependent Code Provisions, University Southern California, Los Angeles, Nov., *in press*.

Somerville, P.G., and Yoshimura, J. (1990). The influence of critical Moho reflections on strong ground motions recorded in San Francisco and Oakland during the 1989 Loma Prieta earthquake: Geophysical Research Letters, 17, 8, p.1203-1206.

Wentworth, C.M., Ellen, S.D., Frizzell, V.A., and Schlocker, J. (1985). Map of hillside materials and description of their engineering character, San Mateo County, California, *U.S. Geological Survey Miscellaneous Investigations Map I--1257D*, map scale 1:62,500.