1.

Estimates of Site-Dependent Response Spectra for Design (Methodology and Justification)

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Recent borehole-geotechnical data and strong-motion measurements constitute a new empirical basis to account for local geological conditions in earthquake-resistant design and site-dependent, building-code provisions. They provide new unambiguous definitions of site classes and rigorous empirical estimates of site-dependent amplification factors in terms of mean shear-wave velocity. A simple four-step methodology for estimating site-dependent response spectra is specified herein. Alternative techniques and commentary are presented for each step to facilitate application of the methodology for different purposes. Justification for the methodology is provided in terms of definitions for the new site classes and derivations of simple empirical equations for amplification as a function of mean shear-wave velocity and input ground-motion level. These new results provide a rigorous framework for improving estimates of site-dependent response spectra for design, site-dependent building-code provisions, and predictive maps of strong ground shaking for purposes of earthquake hazard mitigation.

INTRODUCTION

Earthquakes of the last decade, especially those affecting Mexico City, Leninakan, Armenia, and the San Francisco Bay region, have reemphasized the important influence of local geologic deposits on amounts of damage and resultant loss of life. In general, damage and loss of life in each of these earthquakes was concentrated in areas underlain by deposits of soft soil. These concentrations of damage have emphasized the need to modify design provisions to better account for the amplification effects of local geologic deposits.

The strong-motion recordings of the Loma Prieta, California earthquake of January 17, 1989 are an important data set for quantifying the response of local geologic deposits for purposes of earthquake-resistant design. They constitute one of the most extensive sets of *in-situ* measurements of amplification of 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 source characteristics and wave propagation were minimal or could be isolated in analyses of the data from those of local geologic deposits. The data were recorded in a region for which a large amount of previous geologic, geotechnical, and seismic data existed for use in

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understanding the results. As a result, they constitute an important set of empirical measurements of ground-motion amplification useful for improving earthquake resistant design procedures.

Extensive sets of borehole geologic, geotechnical and shear-wave velocity data, collected since the definition of soil-profile types S_1 - S_4, form an important new basis upon which to improve definitions of site classes for design provisions. Large data sets have been collected and analyzed in the San Francisco and Los Angeles regions and smaller data sets in other urbanized regions of the United States such as Salt Lake City, Seattle, and Memphis. These analyses have established important correlations between seismic response, mappable physical properties, and seismic shear-wave velocity of various geologic units. These correlations provide a rigorous framework for improvements in the definitions of site classes used in earthquake-resistant design.

This paper provides a general methodology for developing estimates of site-dependent response spectra based on these new data sets. The methodology is summarized as a step-by-step procedure with alternative techniques presented for each step. Commentary is provided to facilitate evaluation and selection of techniques appropriate for the desired application. Definitions and derivations, based on borehole-geotechnical data, strong-motion data, and numerical modeling results, are provided as justification for the methodology. An application of the methodology is provided in the appendix in the form of a proposed update to the NEHRP recommended building code provisions (1991 edition).

METHODOLOGY

Definitions and step-by-step procedures for estimating site-dependent response spectra are given below. Commentary and justification for the methodology are presented in subsequent sections.

Free-field, site-specific response spectra with 5% damping, S_A, are defined as:

$$S_A = Minimum\,for\,each\,period\,T\,of \begin{cases} I_a F_a \\ I_v F_v / T^x \end{cases} \qquad (1)$$

where

I_a and I_v are input ground-motion spectral levels for the short-period (acceleration) and mid-period (velocity) bands, respectively for an implied reference ground condition,

F_a and F_v are average short- and mid-period amplification factors with respect to the reference ground condition used for determination of I_a and I_v,

T represents period in seconds, and

x is the spectral decay exponent for the mid-period band.

Parameters in equation 1 are illustrated in Figure (1). Steps required to estimate the spectra are given below. Alternative techniques are provided for each step to facilitate selection of appropriate estimates for design and code revision purposes.

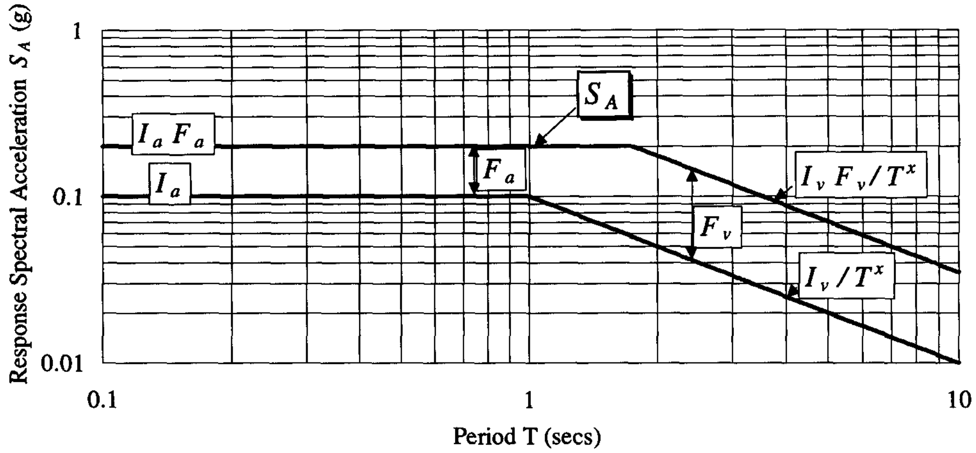


Figure 1. Site-dependent response spectra, S_A defined in equation 1 (see text) in terms of short- and mid-period ground motion spectral levels, I_a and I_v, and amplification factors, F_a and F_v.

Step 1 --- Determine input ground-motion spectral levels, I_a and I_v for the short- and mid-period bands, respectively from either:

a) maps showing effective peak ground-motion values, A_a and A_v (Algermissen et al., 1982), with $I_a = 2.5 A_a$, $I_v = 1.2 A_v$, $x = 2/3$, and reference ground condition *Firm to Hard rock, SC-Ib,*

or

b) maps showing spectral ordinates, $S_{(0.3)}$ and $S_{(1.0)}$ (Algermissen, et al., 1991), with either:

i) $I_a = S_{(0.3)}$, $I_v = S_{(1.0)}$, $x = 1$, and reference ground condition S_2, represented as a combination of site classes *SC-II* and *SC-III* designated here as *SC-(II+III)*),

or

ii) $I_a = S_{(0.3)} / F_a\ (v_{SC\text{-}(II+III)}, I)$, $I_v = S_{(1.0)} / F_v\ (v_{SC\text{-}(II+III)}, I)$, $x = 1$ and reference ground condition *Firm to Hard rock, SC-Ib,* where $F_a\ (v_{SC\text{-}(II+III)}, I)$ and $F_v\ (v_{SC\text{-}(II+III)}, I)$ represent amplification factors for S_2 (*SC-(II+III)*) with respect to *SC-Ib, as* specified by equation 2 for input ground motion level $I = S_{(0.3)} \,/\, F_a\ (v_{SC-(II+III)}, S_{(0.3)})$,

or

c) a preferred ground-motion estimation model.

Step 2 --- Characterize local site conditions in terms of mean shear-wave velocity v to a depth of 30 m (100 ft) by either:

a) site classification using physical descriptions of the near-surface materials as specified in Table 1,

or

b) inferred mean shear-wave velocity, using information on thickness and physical properties for each of the underlying layers and established correlations as shown in Figures 2 and 3,

or

c) measured mean shear-wave velocity v to a depth of 30 m (100 ft) below the surface, defined as v = *30 m / shear-wave travel time to 30 m in secs.*

Step 3 --- Infer site-dependent amplification factors, F_a and F_v specified with respect to reference ground condition for input ground motion level I defined by $I = A_a$ (Step 1a) or $I = S_{(0.3)} \,/\, F_a\ (v_{SC-(II+III)}, S_{(0.3)})$ (Step 1b) from either:

a) site classification (Step 2a) and corresponding amplification factor for appropriate reference ground condition tabulated in Table 2,

or

b) mean shear-wave velocity estimate (Step 2b or 2c) and corresponding amplification factor for appropriate reference ground condition plotted in Figure 4 or 5.

Amplification factors tabulated in Tables 2a and 2b and plotted in Figures 4 and 5 are predicted as a function of mean shear-wave velocity v for various input ground-motion levels, I, with respect to a reference ground condition by the following equations:

$$F_a(v, I) = (v_o \,/\, v)^{m_a}, \tag{2a}$$

and

$$F_v(v, I) = (v_o \,/\, v)^{m_v}, \tag{2b}$$

where,

$$m_a = Log[F_a(v_{SC-IV}, I)] \,/\, Log[v_o \,/\, v_{SC-IV}], \tag{2c}$$

$$m_v = Log[F_v(v_{SC-IV}, I)] \,/\, Log[v_o \,/\, v_{SC-IV}], \tag{2d}$$

v_o is mean shear-wave velocity for the site class used as the reference ground condition,

$v_{SC\text{-}IV}$ is mean shear-wave velocity for the *Soft-soil* site class *(SC-IV)*,

and

$F_a(v_{SC-IV}, I)$ and $F_v(v_{SC-IV}, I)$ are short- and mid-period amplification factors respectively, for site class *SC-IV* specified with respect to reference ground condition *Firm to Hard rock* (*SC-Ib*) and with respect to S_2 or combined site class *SC-(II+III)* at input ground-motion level *I* in Table 2.

Step 4 --- Calculate free-field, site-dependent, response spectra, S_A, as defined in equation 1, using input ground-motion spectral levels I_a and I_v derived in Step 1, mean shear wave-velocity estimate v inferred in Step 2, and the amplification factors F_a and F_v derived in Step 3.

COMMENTS ON METHODOLOGY

The procedures specified in Steps 1-4 constitute a flexible and general methodology for estimating free-field, site-dependent, response spectra. The methodology affords the flexibility of selecting different techniques for estimating both input ground-motion spectral levels and amplification factors, depending on specific site requirements and available information. The methodology forms a framework to incorporate new information and new procedures as they become available. It provides a general framework for estimates of design spectra for inclusion in building code revisions. As an example, a possible update of section 4.2.1 of the *NEHRP Recommended Provisions for Development of Seismic Regulations for New Building* (1991 edition) is provided in the Appendix. Commentary on the techniques specified at each step are provided below.

ESTIMATION OF INPUT GROUND-MOTION LEVELS (STEP 1)

Three main options are suggested for inferring short- (I_a) and mid- (I_v) period input ground-motion spectral levels (Step 1). The first two options are based on published maps and the third on a ground-motion prediction model of choice. The first option requires effective peak ground-motion maps used widely in current building code provisions. The second option uses recent spectral-ordinate maps and offers two alternatives. The first of these alternatives uses input ground-motion levels and amplification factors estimated with respect to reference ground condition S_2 (*SC-(II+III)*), while the second converts these to reference ground condition *Firm to Hard rock, SC-Ib*. The wide range in materials included in site class S_2 and ongoing revisions in spectral attenuation relations currently argue that option 1 is preferred for estimating input ground-motion levels based on published maps.

The value for the spectral decay exponent "x" is under review. The value currently used to estimate seismic coefficients for code provision purposes is 2/3. This value is based in part on building response considerations. The value, based only on ground-motion considerations and currently being suggested for code revision purposes, is unity. For consistency with

TABLE 1 -- Site classes for site-dependent design spectra, building-code provisions, and regional earthquake hazard analyses.

SITE CLASS: Name		General Description	Mean Shear-Wave Velocity^ minimum ft/s	minimum m/s	average ft/s	average m/s	maximum ft/s	maximum m/s	Thickness minimum ft	minimum m
SC-I		FIRM and HARD ROCKS								
SC-Ia	Ao*	HARD ROCKS (e.g. metamorphic rocks with very widely spaced fractures).	**4600**	1400	5300	1620				
SC-Ib	A	FIRM to HARD ROCKS (e.g. granites, igneous rocks, conglomerates, sandstones, and shales with close to widely spaced fractures).	**2300**	700	3500	1050	**4600**	1400		
SC-II	B	GRAVELLY SOILS and SOFT to FIRM ROCKS (e.g. soft igneous sedimentary rocks, sandstones, and shales, gravels, and soils with > 20% gravel).	**1230**	375	1800	540	**2300**	700	**30**	10
SC-III	C	STIFF CLAYS and SANDY SOILS (e.g. loose to v. dense sands, silt loams and sandy clays, and medium stiff to hard clays and silty clays (N>5 blows/ft)).	**660**	200	950	290	**1230**	375	**20**	5
SC-IV	D	SOFT SOILS	**330**	100	500	150	**660**	200		
SC-IVa	D1	NON SPECIAL-STUDY SOFT SOILS (e.g. loose submerged fills and very soft to soft (N<5 blows/ft) clays and silty clays < 37 m (120 ft) thick).							**10**	3
SC-IVb	E	SPECIAL-STUDY SOFT SOILS^^ (e.g. liquefiable soils, quick and highly sensitive clays, peats, highly organic clays, very high plasticity clays (PI>75%), and soft soils more than 37 m (120ft) thick).							**10**	3

(^) Mean shear velocity to a depth of 30 m (100 ft). (^^) Site-specific geotechnical investigations recommended for this class.
(*) Initial site class designation (Martin, 1994) not recommended for use in code revisions due to confusion with letter designations for seismic performance categories.

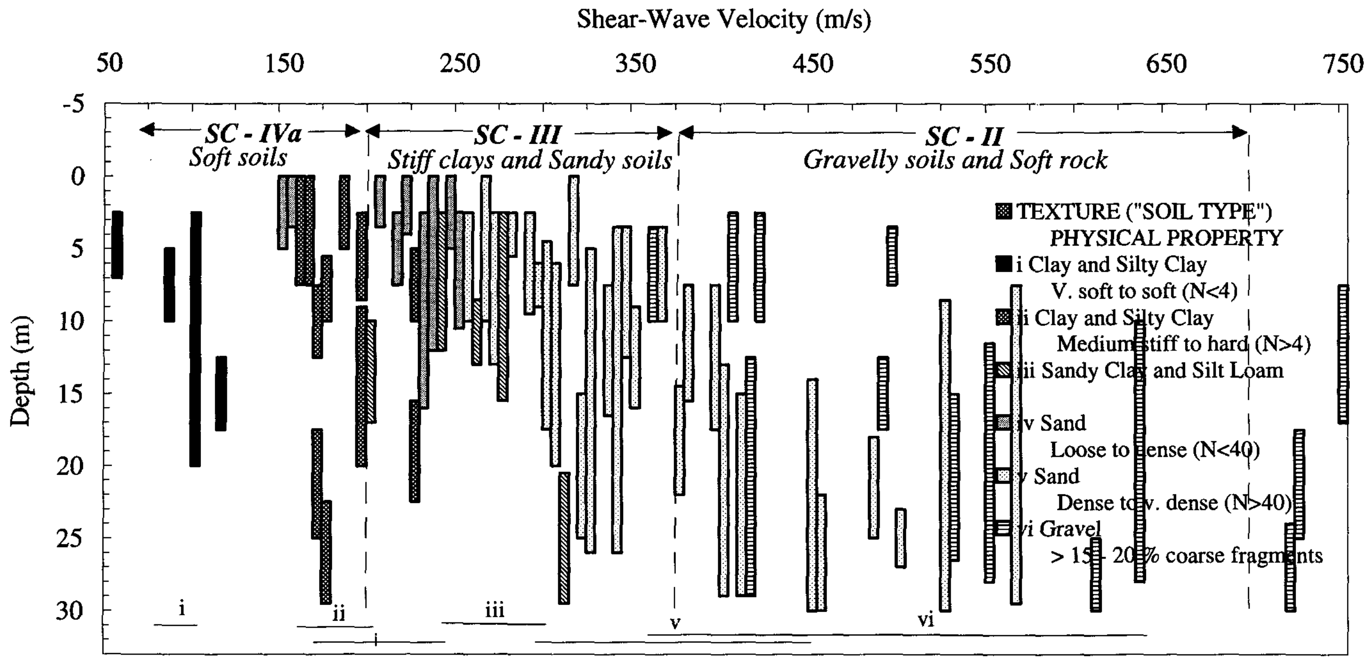


Figure 2a. Shear-wave velocities for depth intervals determined in unconsolidated to moderately consolidated deposits (*Soils*) in the San Francisco Bay region (from Fumal, 1978). The deposits are divided into groups according to texture and standard penetration resistance N (blows per foot). Shear-wave velocity intervals for each group are shown as bars parallel to abscissa. Shear-wave velocity intervals for corresponding new site classes as defined in Table 1 are indicated.

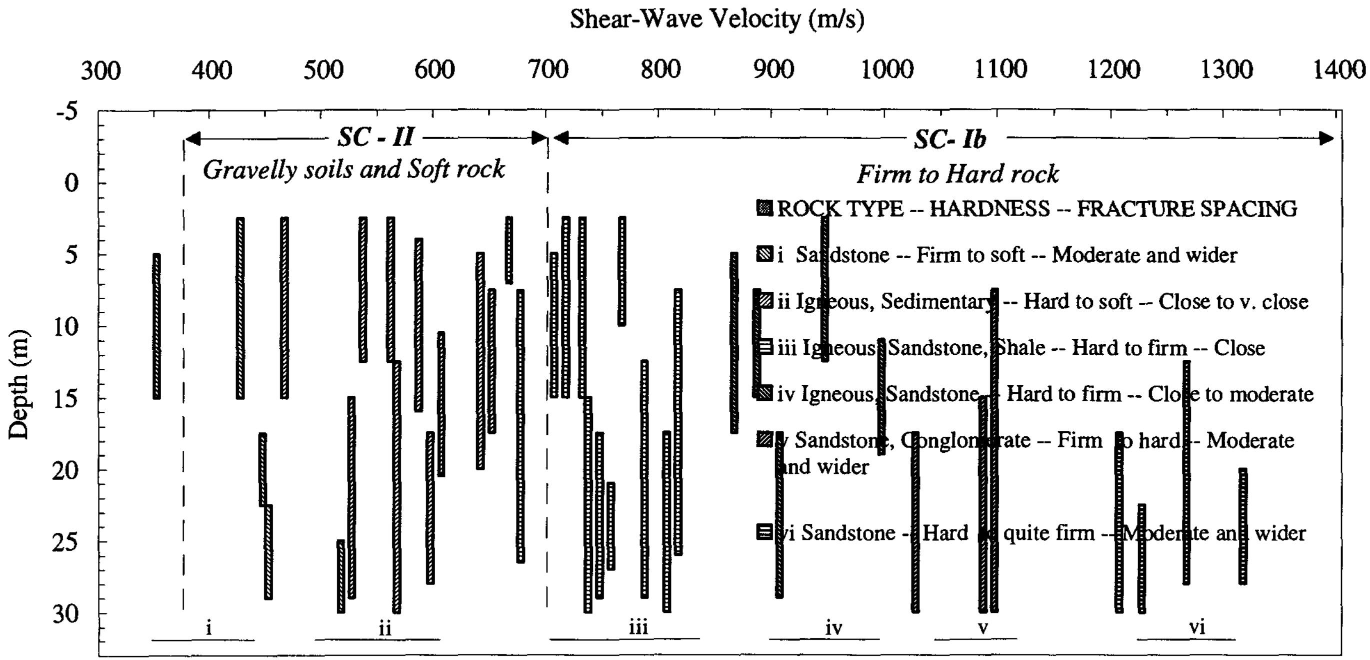


Figure 2b. Shear-wave velocities for depth intervals determined in bedrock materials in the San Francisco Bay region (from Fumal, 1978). The materials are divided into groups according to fracture spacing, hardness, and lithology. Fracture spacing is defined as: very close 0 to 1 cm, close 1 to 5 cm, moderate 5 to 30 cm, and very wide more than 100 cm. Shear-wave velocity intervals for each group are shown as bars parallel to abscissa. Shear-wave velocity intervals for corresponding new site classes as defined in Table 1 are indicated.

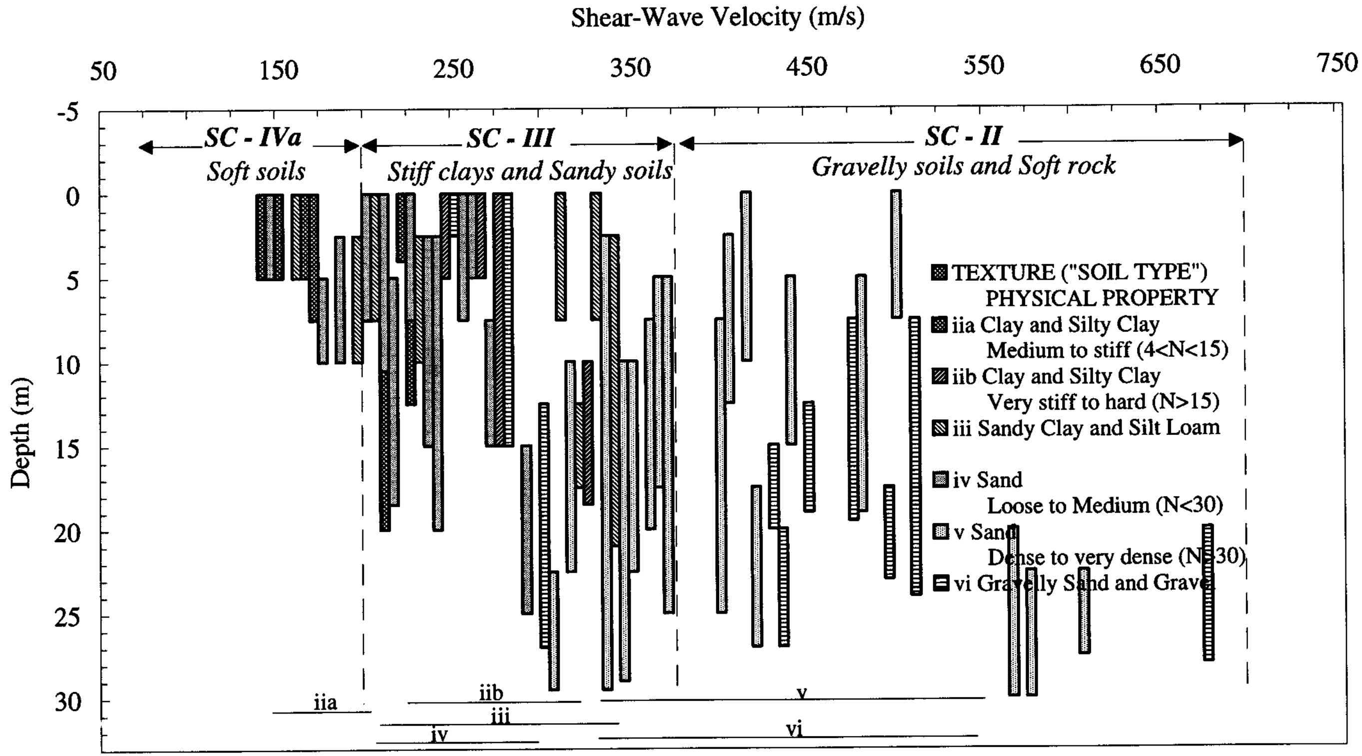


Figure 3a. Shear-wave velocities for depth intervals determined in unconsolidated to moderately consolidated deposits (*Soils*) in the Los Angeles region (from Fumal and Tinsley, p. 132, 1985). The deposits are divided into groups according to texture and standard penetration resistance N (blows per foot). Shear-wave velocity intervals for each group are shown as bars parallel to abscissa. Shear-wave velocity intervals for corresponding new site classes as defined in Table 1 are indicated.

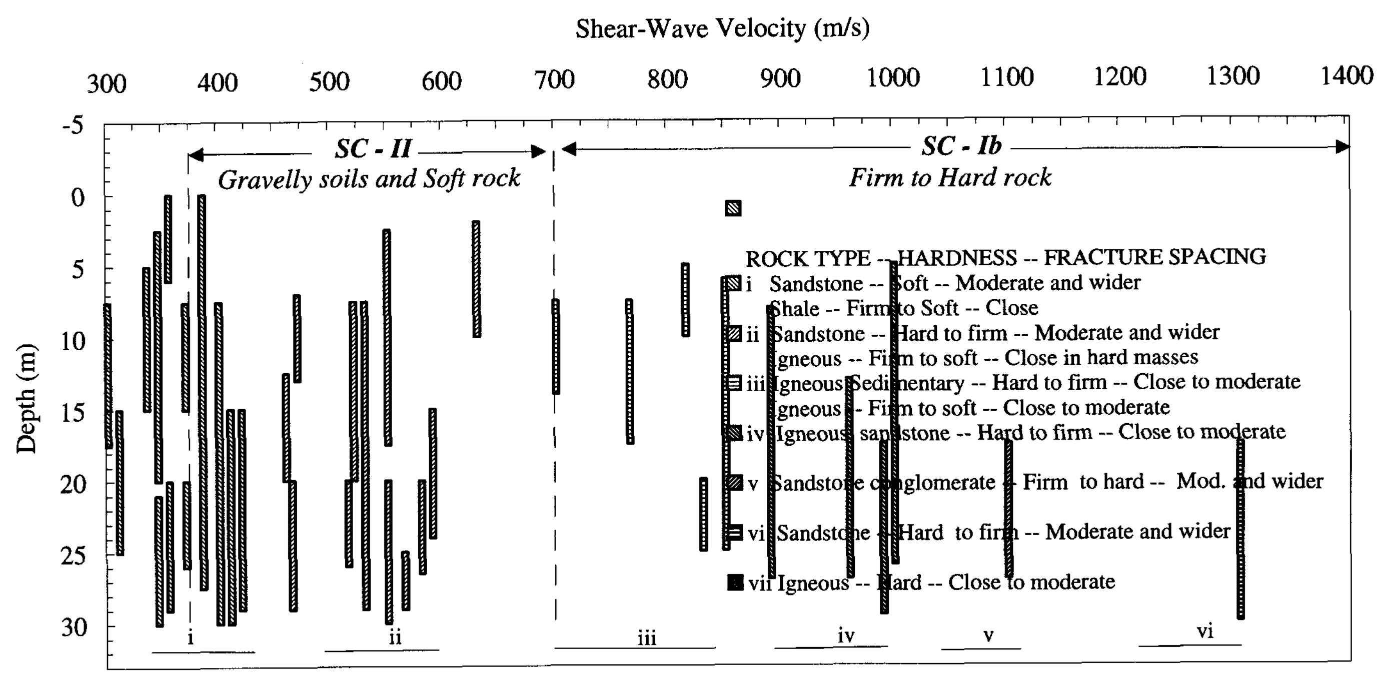


Figure 3b. Shear-wave velocities for depth intervals determined in bedrock materials in the Los Angeles region (from Fumal and Tinsley, p. 140, 1985). The materials are divided into groups according to fracture spacing, hardness, and lithology (see figure caption 2b for definitions). Shear-wave velocity intervals for each group are shown as bars parallel to abscissa. Shear-wave velocity intervals for corresponding new site classes as defined in Table 1 are indicated.

TABLE 2 -- Short- and mid-period amplification factors, F_a and F_v, with respect to reference ground conditions *Firm to Hard rock*, *SC-Ib*, and *SC-(II+III)* (S_2) for the site classes defined in Table 1.

Input Ground Motion		Amplification with respect to *SC-Ib** (Site Class --- shear-wave velocity, m/s)					Amplification with respect to *SC-(II+III)*** (Site Class --- shear-wave velocity, m/s)			
		SC-Ia 1620	*SC-Ib* 1050	*SC-II* 540	*SC-III* 290	*SC-IV* 150	*SC-Ia* 1620	*SC-Ib* 1050	*SC-(II+III)* 450	*SC-IV* 150
I (g)	m_a	Short-period Amplification Factor F_a					Short-period Amplification Factor F_a			
0.1	0.35	0.9	1.0	1.3	1.6	**2.0**	0.6	0.7	1.0	**1.5**
0.2	0.25	0.9	1.0	1.2	1.4	**1.6**	0.7	0.8	1.0	**1.3**
0.3	0.10	1.0	1.0	1.1	1.1	**1.2**	0.9	0.9	1.0	**1.1**
0.4	-0.05	1.0	1.0	1.0	0.9	**0.9**	1.1	1.0	1.0	**0.9**
0.5										
I (g)	m_v	Mid-period Amplification Factor F_v					Mid-period Amplification Factor F_v			
0.1	0.65	0.8	1.0	1.5	2.3	**3.5**	0.4	0.6	1.0	**2.0**
0.2	0.60	0.8	1.0	1.5	2.2	**3.2**	0.5	0.6	1.0	**1.9**
0.3	0.53	0.8	1.0	1.4	2.0	**2.8**	0.5	0.6	1.0	**1.8**
0.4	0.45	0.8	1.0	1.4	1.8	**2.4**	0.6	0.7	1.0	**1.6**
0.5										

* Amplification with respect to *SC-Ib* is predicted by $F_a = (1050\ m/s / v)^{m_a}$ and $F_v = (1050\ m/s / v)^{m_v}$ (see text, equations 2 or 4) with factors for *SC-IV* inferred at the 0.1g level from the Loma Prieta strong-motion data (see Tables 3a and 3b) and for higher levels from numerical modeling results (R. Seed and R. Dobry, pers. commun., 1992; Martin, 1994).

** Amplification with respect to *SC-(II+III)* is predicted by $F_a = (450m/s / v)^{m_a}$ and $F_v = (450m/s / v)^{m_v}$ (see text, equations 2 or 5) with factors for *SC-IV* scaled from those inferred with respect to *SC-Ib*.

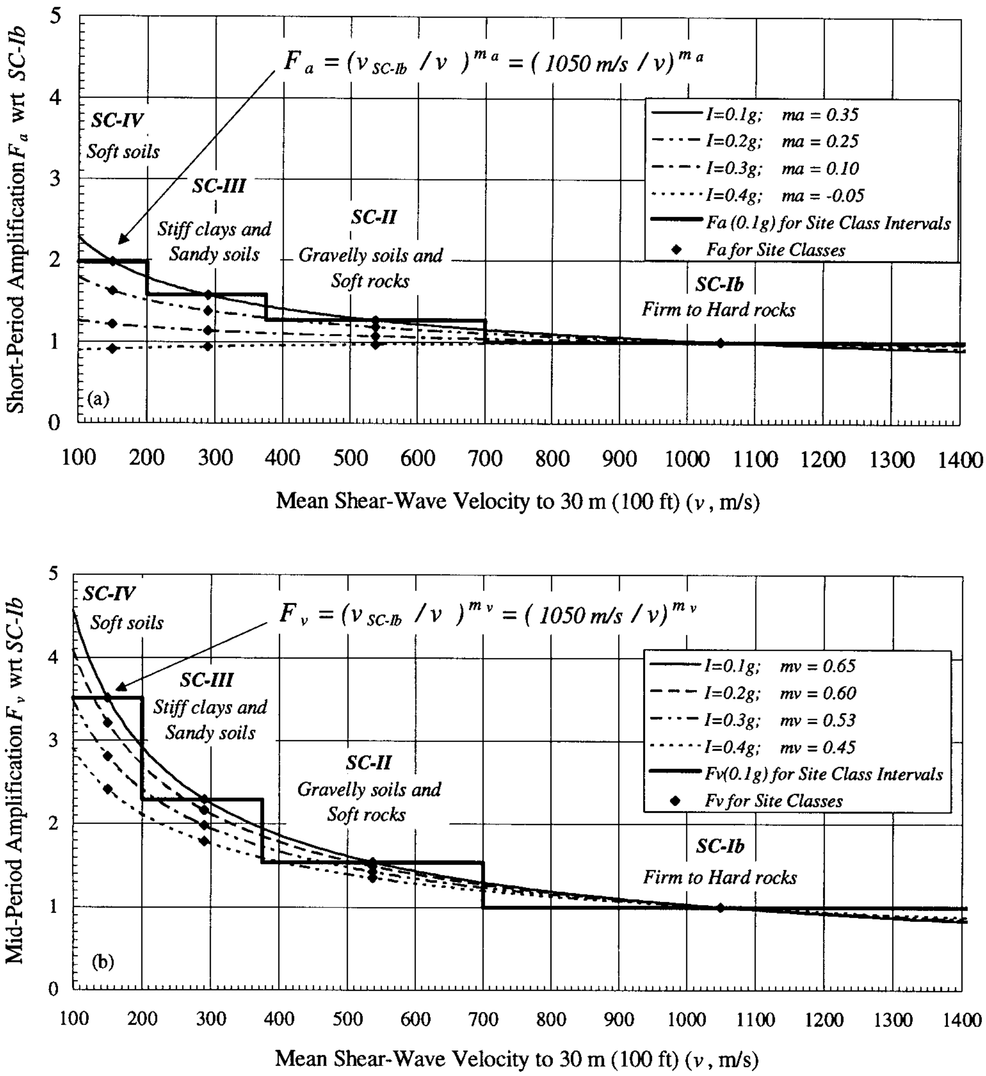


Figure 4. (a) Short-period F_a and (b) mid-period F_v amplification factors with respect to *Firm to Hard rock, SC-Ib,* plotted as a continuous function of mean shear-wave velocity, using the indicated equations for specified levels of input ground motion (equations 2 or 4, see text). Amplification factors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

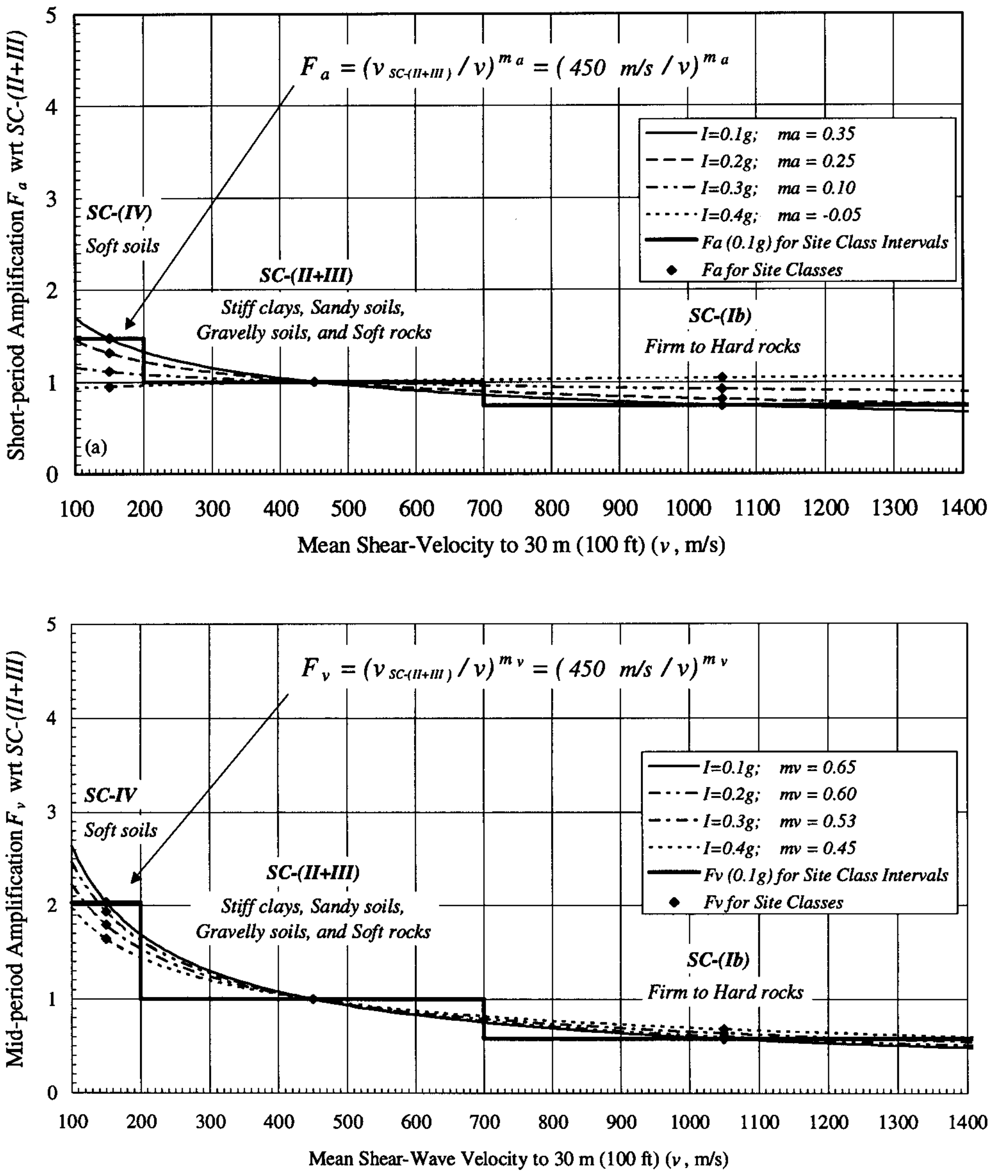


Figure 5. (a) Short-period F_a and (b) mid-period F_v amplification factors with respect to combined site class *SC-(II+III)* as a continuous function of mean shear-wave velocity, using the indicated equations for specified levels of input ground motion (equations 2 or 5, see text). Amplification factors with respect to *SC-(II+III)* for the simplified site classes also are shown.

present convention, if input ground motion spectral levels are specified from the effective peak-motion maps (Step 1a), then $x = 2/3$; if they are specified using spectral-ordinate maps or a ground-motion model of choice (Steps 1b or 1c), then $x = 1$ is recommended.

CHARACTERIZATION OF LOCAL SITE CONDITIONS (STEP 2)

Three options are suggested for characterizing the local site conditions in terms of mean shear wave velocity for purposes of estimating ground response or amplification factors. The first option allows the site conditions to be characterized by classification of the site using a description of the physical properties of the near-surface materials. This classification in turn allows the mean shear-wave velocity for the corresponding simplified site class to be assigned to the site. The second and third options afford more quantitative characterizations in terms of either inferred or measured estimates of mean shear-wave velocity to a depth of 30 m (100 ft). These estimates of shear-wave velocity permit more accurate classification of the sites using the shear-wave velocity criteria specified in Table 1. They also permit estimates of amplification as a continuous function of shear-wave velocity using equations 2a-2d. Choice of technique depends on information available and intended site usage.

Physical Property Classification (Step 2a) Classification of a site using the physical property criteria specified in Table 1 may be accomplished using only a description of the near-surface materials. As such, this option affords a simple and straightforward procedure for classifying the site and in turn assigning a mean shear-wave velocity. It is a procedure that should allow most sites to be classified readily based on primarily near-surface information easily acquired at the site. The amplification characteristics of geologic deposits tend to decrease with depth, consequently a site classification based only on the near-surface materials will tend to over estimate the amplification characteristics of the site. Site classifications may be improved with additional information on the physical properties and distribution of materials at depth. Any uncertainties in classifications based on physical property descriptions can be resolved by assignment of the more conservative site class.

Estimates of Mean Shear-Wave Velocity (Steps 2b and 2c) Improved classifications of a site can be derived from estimates of mean shear-wave velocity. Estimates may be either inferred (Step 2b) or measured directly (Step 2c), where mean shear-wave velocity v to a depth of 30 m is defined as v = *30 m / shear-wave travel time to 30 m in secs.*

The second technique for characterizing the local site conditions (Step 2b) is based on inferences of mean shear-wave velocity to a depth of 30 m (100 ft), using information on thickness and physical properties of the underlying layers. If this information is available from borehole logs or other sources, then shear-wave travel-times and corresponding velocities for each layer may be inferred from velocity measurements derived in other boreholes with similar materials at comparable depths. At most sites this technique should yield estimates of shear-wave velocity more accurate than those inferred in Step 2a. Information on other geotechnical parameters such as standard penetration resistance, undrained shear strength, or void ratio also can be used to further refine estimates of shear-wave velocity (e.g., Fumal and Tinsley, 1985, pp 134-135).

Such inferences, based on the correlations between shear-wave velocity and physical properties used for the definitions of the simplified site classes (Figures 2 and 3), permit relatively reliable inferences of mean shear-wave velocity to a depth of 30 m (100 ft) at a site (Fumal, 1978, 1991). The data permit inferences of interval velocities and, in turn, travel times for each depth interval. These interval travel times can then be summed to determine the total travel time to 30 m (100 ft) and, in turn, the desired estimate of mean shear-wave velocity. Similar correlations for other materials in other regions can be established readily using a limited number of borehole logs for principal geologic units in the region. The correlations provide a framework to which additional data may be easily added as it is collected.

The third technique for characterizing the local site conditions (Step 2c) is direct measurement of mean shear-wave velocity using shear-wave travel times through the top 30 m (100 ft) of material. Procedures for such measurements in boreholes, as provided here for the San Francisco and Los Angeles regions (Figures 2 and 3) are described (e.g. Gibbs et al., 1975, 1976, 1977, 1980). This technique provides the most accurate characterization of a site for purposes of estimating amplification factors. It permits a site to be classified unambiguously. It permits quantitative estimates of amplification using either equations derived from the Loma Prieta strong-motion data or results derived from numerical models. Direct measurements of shear-wave velocity should be needed primarily for special projects.

ESTIMATION OF SITE-DEPENDENT AMPLIFICATION FACTORS, F_a AND F_v (STEP 3)

Quantitative estimates of site-specific amplification factors F_a and F_v are implied by the mean shear-wave velocity estimates used to characterize the local site conditions in Step 2. Two options are suggested in Step 3 for determining these factors with respect to a specified reference ground condition for a given input ground-motion level. The input ground motion level can be determined from $I = A_a$ (Step 1a) or $I = S_{(0.3)} / F_a\ (v_{SC-(II+III)}, S_{(0.3)})$ (Step 1b).

The first option (Step 3a) suggests that the amplification factors be derived as a discrete function of site characteristics based on classification of the site into one of the four major site classes or associated subclasses (Step 3a). The corresponding discrete amplification values are given in Table 2.

The second option (Step 3b) suggests that the amplification factors may be estimated as a continuous function of shear-wave velocity using equation 2 or the corresponding plots in Figures 4 and 5. Values of the exponents m_a and m_v, needed to evaluate equations 2a-2d are given in Table 2. This approach yields more accurate estimates of amplification factors than might be derived from discrete estimates for the simplified site classes. This option is useful for sites that can not be readily classified or for sites with projects which warrant special study.

JUSTIFICATION

Justification for the procedures to estimate site-dependent response spectra is based on results derived from recent borehole-geotechnical and strong-motion data. The geotechnical data afford quantitative definitions of new simplified site classes in terms of mean shear-wave velocity. The strong-motion data yield simple equations, which predict amplification as a function of mean shear-wave velocity both for the new simplified site classes and for individual sites. Simple assumptions and numerical model results permit extrapolation of these equations to higher levels of input ground motions. Derivation of these results provides the desired justification.

EMPIRICAL JUSTIFICATION FOR SIMPLIFIED SITE CLASSES

Extensive sets of geologic, geotechnical and seismic data collected within the last two decades yield new results for simplifying the definitions of site classes used for earthquake-resistant design purposes. New correlations have been established between parameters known to characterize the response of near-surface deposits, such as shear-wave velocity and parameters describing physical properties that can be mapped on a regional scale. These correlations, together with recent strong-motion amplification observations, allow mappable site classes to be defined with distinct seismic-response characteristics that simplify and reduce ambiguity in the classification of sites for seismic design purposes.

Definitions of the simplified site classes are given in Table 1. These definitions are based on recent comprehensive sets of in-situ data collected to determine relationships between mappable properties of near-surface materials, shear-wave velocity, and ground-motion amplification (Borcherdt et al., 1978, Fumal, 1978; Fumal and Tinsley, 1985; Borcherdt, et al., 1991). These in-situ data derived from detailed borehole logs are published for about 130 sites in the San Francisco and Los Angeles regions (Fumal, 1978; Borcherdt et al., 1978; Gibbs et al., 1975; 1976; 1977; 1980; Fumal, et al. 1981, 1982, 1984, Fumal and Tinsley, 1985; Gibbs et al., 1992, and Fumal, 1991).

Shear-wave velocity and physical-property correlations as published for about 130 sites in the San Francisco and Los Angeles regions are replotted in Figures 2 and 3, from Borcherdt, et al., 1978, Fumal, 1978, and Fumal and Tinsley, 1985. These figures show that the soil and rock units in the regions can be subdivided for mapping purposes into about thirteen groups distinguishable on the basis of shear-wave velocity and mappable physical properties (Fumal, 1978; Borcherdt et al., 1978). Inspection shows that of these thirteen groups, four major classes can be distinguished on the basis of physical properties and mean shear-wave velocity. These four classes are defined in Table 1.

The three criteria specified to distinguish the site classes are physical properties, mean shear-wave velocity to 30 m (100 ft) and minimum thickness. The minimum thickness criteria was selected to ensure that sufficient material is present for resonant amplification to occur in the period band of engineering interest (>0.1 s). These criteria define classes with distinguishable amplification characteristics (Borcherdt, 1991; Borcherdt, et al., 1991; Borcherdt, 1994a, 1994b) that also are useful for mapping purposes.

Roman numeral designations are suggested for the site classes (that is, *SC-I* through *SC-IV*) in order to distinguish them from site class designations S_1 through S_4 and seismic performance categories A through D currently used in code provisions (see *e.g.* Section 3.3 and 3.4 of the NEHRP recommended provisions). (Unfortunately, as this manuscript goes to press, at least two letter designations have been used by different investigators to refer to the site classes described here. In one case letters A_o, A, B, C, D, and E and in another case letters A through F have been used to correspond to *SC-Ia*, *SC-Ib*, *SC-II*, *SC- III*, *SC-IVa*, and *SC-IVb*).

The four main site classes (Table 1), as described in terms of simple physical properties, are *SC-I*, *Firm to Hard rock*; *SC-II*, *Soft to Firm rock and Gravelly soils*; *SC-III*, *Stiff clay and Sandy soils*; and *SC-IV*, *Soft soils*. Subdivisions of these major site classes are provided for site classes *I* and *IV*. Site class *I* (*SC-I*) for *Rock* is subdivided in order to distinguish sites underlain by *Very hard rock*, (*SC-Ia*), for example some sites in the eastern United States, from more prevalent sites in the western United States underlain by *Firm to Hard rock*, (*SC-Ib*). Site class *IV* (*SC-IV*) for *Soft soils* is subdivided in order to distinguish soft soils less than 37 m (120 ft) thick that do not present special stability problems (*SC-IVa*) from those that do present special problems or are especially thick (*SC-IVb*). Subclass IVb (*SC-IVb*) is defined on the basis of geotechnical studies, foundation investigations, and numerical modeling results (R. Dobry and R. Seed, pers. commun. 1992). Soft soils in subclass *SC-IVb* present seismic stability problems that require special studies prior to site development and/or construction.

Comparison of these definitions with those for the original classes S_1-S_4 shows that in general, S_1 corresponds to *SC-I*, S_2 is included in, but not equivalent to *SC-II* and *SC-III*, and S_3 and S_4 are included in *SC-IV*. Definitions for the new site classes *SC-I* through *SC-IV* are independent of thickness except for a minimal thickness. The new definitions should help simplify and reduce ambiguity in the classification process.

The shear-wave velocity intervals, as specified for each site class in Table 1, are implied by the correlations between physical properties and shear-wave velocity summarized in Figures 2 and 3. Some flexibility exists in the choice of these endpoints, however, choice not based on empirical data can lead to significant discrepancies between physical properties and mean shear-wave velocity, especially for soft soils. For example, if the upper limit for seismic shear-wave velocity were restricted to 180 m/s (600 ft/s) for the *Soft-soil* site class, then some sites underlain by more than 3 m (10 ft) of Bay mud in the San Francisco Bay region (e.g. the strong-motion station at the San Francisco airport, see Table 3b) could be improperly classified as *Stiff clays and Sandy soils*. Similarly, if the range for shear-wave velocity for *Gravelly soils and Soft to Firm rock* was extended to 750 m/s (2460 ft/s), then a number of sites on *Firm to Hard rock* of the Franciscan Complex would be classified incorrectly. Consequently, definitions of the site classes must be consistent with correlations between amplification, mean shear-wave velocity to 30 m (100 ft), geotechnical parameters, and physical descriptions of the materials, otherwise inconsistent classifications of sites and biases in strong-motion attenuation relationships can result.

Reductions in the number of site classes might also be considered as a possible means to simplify the classification process. For example, site class *SC-II* might be combined with *SC-III* to form a single site class. However, inspection of amplification curves (Borcherdt, et al., 1991) shows that the scatter in the data for such a combined class is sufficiently large to suggest no statistical difference between the amplification factors for the remaining site classes. Consequently, such a reduction is not supported by present empirical data.

The criteria used to define the site classes in Table 1 are intended to be universally applicable. They are based on physical property descriptions used for standard mapping purposes consistent with other standard classification systems (e.g. Unified Soil Classification, U.S. Corps of Engineers). They are rigorously defined in terms of a large and published data set. They are intended to permit the unambiguous classification of essentially all sites ranging from the softest soils to the hardest rocks. Upon review of this manuscript, M. Celebi (pers. commun.) pointed out that the shear-wave velocity intervals derived here for the site classes are nearly identical to intervals that had been previously developed for building codes in Turkey (Earthquake Research Institute, 1975). The only endpoint that is different from those in Table 1 is that separating *SC-II* from *SC-III*. It is 400 m/s in the Turkish code instead of 375 m/s as derived here from the seismic borehole data.

Extensive and well documented data sets such as that summarized in Figures 2 and 3 provide a rigorous basis on which to differentiate sites according to the simple criteria specified. The resulting site classes provide a rigorous basis for inferring special study zones for strong ground shaking in response to California Seismic Hazards Mapping Act (California Law AB-3897) as well as development of site-specific code provisions (see appendix and Borcherdt, 1994a, 1994b). The site classes as defined have been ascribed amplification capabilities ranging from *Low to Very low* for *SC-I* to *High to Very high* for *SC-IV* (Borcherdt and others, 1991; Borcherdt, 1994b; Borcherdt and Glassmoyer, 1994). These amplification capabilities are ascribed on the basis of correlations presented here between shear-wave velocity and measured strong-motion amplification.

EMPIRICAL JUSTIFICATION FOR SITE-DEPENDENT AMPLIFICATION FACTORS

The strong-motion recordings obtained from the Loma Prieta Earthquake of October 17, 1989 are an important data set for characterizing the response of various geologic deposits to damaging levels of ground shaking (Borcherdt and Glassmoyer, 1992; 1994). They provide quantitative measures of the *in-situ* response of a wide variety of geologic deposits in close proximity to damaging levels of shaking. As such, the measurements provide a new empirical basis from which to infer average amplification factors for construction of site-specific response spectra. Peak input ground-motion levels for most of the measurements were near 0.1 g for sites underlain by rock in the San Francisco Bay region. Consequently, the inferred amplification factors are most relevant for input ground-motion values near or less than these values. For larger input ground-motion levels as might occur closer to the epicenter or for larger earthquakes, these empirical amplification factors constitute a base from which to extrapolate amplification factors using numerical modeling results. Derivation of the strong-motion amplification factors and general predictive equations for amplification as a function of input ground-motion level follow.

Amplification Factors Implied By The Loma Prieta Strong-motion Data Average amplification factors for 35 free-field sites, as inferred from the strong-motion recordings of the Loma Prieta earthquake are given in Tables 3a and 3b. 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). Corresponding ratios of peak acceleration, velocity, and displacement and average spectral ratios for the individual radial and transverse components of motion are given elsewhere (Borcherdt and Glassmoyer, 1992: Borcherdt and Glassmoyer, 1994). Mean shear-wave velocity to a depth of 30 m (100 ft) as either measured or estimated for each site by Fumal (1992) are summarized in Tables 3a and 3b.

Regression curves for average horizontal spectral amplification as a function of mean shear-wave velocity for the short-, intermediate-, long- and mid-period bands are provided in Figures 6a through 6d. 95% confidence limits for the observed values and for the ordinate to the true population regression line also are shown. These curves show that, in general, average horizontal spectral amplification increases with decreasing mean shear-wave velocity. Replotting the curves with linear scales (Figure 7) emphasizes that 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 curves for the short- (0.1-0.5 s) and the mid- (0.4-2.0 s) period bands provide empirical estimates of the short-period (F_a) and the mid- or long-period (F_v) site-specific amplification factors. These amplification factors derived from the Loma Prieta strong-motion data are appropriate for input ground-motion levels less than or near 0.1g for sites on *Firm to Hard rock* (*SC-Ib*). The corresponding regression curves are described by

$$F_a = (997 m/s \; / \; v)^{0.36} \tag{3a}$$

TABLE 3a -- Average spectral ratios inferred from Loma Prieta strong-motion data for specified period bands for *Rock* sites normalized to local rock stations and adjusted to a common, reference ground condition, *Firm to Hard rock*, KJf (from Borcherdt and Glassmoyer, 1992).

Station	Geologic Unit	Site Class	H.Dist. km	S vel. m/s	S vel. ft/s	KJf Norm. Factors Vert.	KJf Norm. Factors Horizontal 0.1-0.5	KJf Norm. Factors Horizontal other	Vertical period bands (secs) 0.1-0.5	Vertical 0.5-1.5	Vertical 1.5-5.0	Vertical 0.1-5.0	Vertical 0.4-2.0	Horizontal period bands (secs) 0.1-0.5	Horizontal 0.5-1.5	Horizontal 1.5-5.0	Horizontal 0.1-5.0	Horizontal 0.4-2.0
South San Francisco	KJfss	*Ib*	85	910	2985	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	0.82	0.79	0.87	0.82	0.77	0.66	0.95	1.19	0.72	0.86
APEEL 7 (Pulgas Temple	TMzs	*II*	65	435	1427	1.00	1.00	1.00	1.78	1.00	0.92	1.63	0.97	1.33	1.47	1.37	1.36	1.41
MEAN (TMzs; norm. south)				467	1531				1.34	0.97	0.77	1.26	0.94	1.14	1.09	1.12	1.14	1.01
STANDARD DEVIATION				51	166				0.48	0.16	0.22	0.41	0.15	0.43	0.33	0.30	0.36	0.35
Berkeley (Lawrence Lab.)	TMzs	*II*	100	610	2001	1.00	1.00	1.00	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	1.53	1.25	1.42	0.70	1.48	1.61	0.86	1.51	0.70	1.69	2.49	0.99	1.68
MEAN (TMzs)				508	1665				0.80	2.19	1.70	1.03	2.06	0.73	1.92	2.28	1.00	1.83
Presido	sp	*II*	99	594	1948	1.00	1.00	1.00	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	1.00	1.00	1.00	1.56	1.82	2.88	1.66	2.03	1.44	3.74	3.27	1.83	3.36
MEAN (sp)				555	1819				1.81	1.92	2.67	1.87	2.06	1.51	3.03	2.57	1.76	2.73
MEAN (TMzs, sp)				503	1651	1.53	1.25	1.42	1.32	1.59	1.58	1.37	1.58	1.13	1.88	1.86	1.28	1.74
STANDARD DEVIATION				80	263	1.53	1.25	1.42	0.52	0.73	0.87	0.45	0.68	0.40	0.98	0.84	0.40	0.88
APEEL 9 (Crys.Spr. Res.)	QTs	*II*	64	450	1476	1.00	1.00	1.00	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	1.53	1.25	1.42	2.85	0.82	0.29	2.45	0.83	1.98	1.17	0.59	1.94	1.00
MEAN (QTs)				397	1302				2.42	1.71	1.30	2.28	1.66	1.91	2.33	1.08	2.00	1.86
STANDARD DEVIATION				75	246				0.60	1.26	1.42	0.25	1.18	0.10	1.64	0.69	0.09	1.21
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
MEAN (*ROCK*; *SC-Ib*, *SC-II*)				622	2041				1.29	1.40	1.35	1.31	1.40	1.14	1.59	1.49	1.23	1.47
STANDARD DEVIATION				183	601				0.59	0.66	0.59	0.49	0.62	0.45	0.70	0.58	0.42	0.54

TABLE 3b -- Average spectral ratios inferred from Loma Prieta strong-motion data for specified period bands for *Soil* sites normalized to local rock stations and adjusted to a common, reference ground condition, *Firm to Hard rock*, KJf (from Borcherdt and Glassmoyer, 1992)

Station	Geologic	Site	H.Dist.	S vel.		KJf Norm. Factors			Vertical					Horizontal				
	Unit	Class	km	m/s	ft/s	Vert.	Horizontal		period bands (secs)					period bands (secs)				
							0.1-0.5	other	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
Hayward BART Station	Qpa	*III*	74	365	1197	1.53	1.25	1.42	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	1.00	1.00	1.00	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	1.53	1.25	1.42	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	1.53	1.25	1.42	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	1.53	1.25	1.42	4.22	1.62	1.70	3.75	1.62	2.29	3.59	3.50	2.78	3.70
MEAN (Qpa)				306	1004				3.93	1.90	2.00	3.57	2.16	2.22	3.10	2.99	2.57	3.15
STANDARD DEVIATION				36	117				1.12	0.73	0.64	0.97	0.72	0.38	0.59	1.51	0.38	0.60
Richmond City Hall	Qhaf	*III*	109	288	944.6	1.00	1.00	1.00	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	1.53	1.25	1.42	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	1.53	1.25	1.42	3.56	1.87	2.25	3.27	2.00	3.09	1.78	2.22	3.22	1.71
MEAN (Qhaf)				265	870				3.85	2.19	2.63	3.57	2.28	3.24	2.30	2.82	3.44	2.19
STANDARD DEVIATION				24	79				0.25	0.73	0.46	0.27	0.58	0.15	0.50	0.90	0.22	0.43
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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.00	1.00	1.00	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	1.53	1.25	1.42	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	1.53	1.25	1.42	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	1.53	1.25	1.42	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	1.00	1.00	1.00	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	1.53	1.25	1.42	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
MEAN (*SOIL*; *SC-IV*, *SC-III*)				219	719				3.24	1.97	2.09	3.01	2.15	2.18	3.52	3.71	2.58	3.29
STANDARD DEVIATION				76	250				1.08	0.77	1.10	0.97	0.84	0.84	1.21	1.99	0.81	1.12

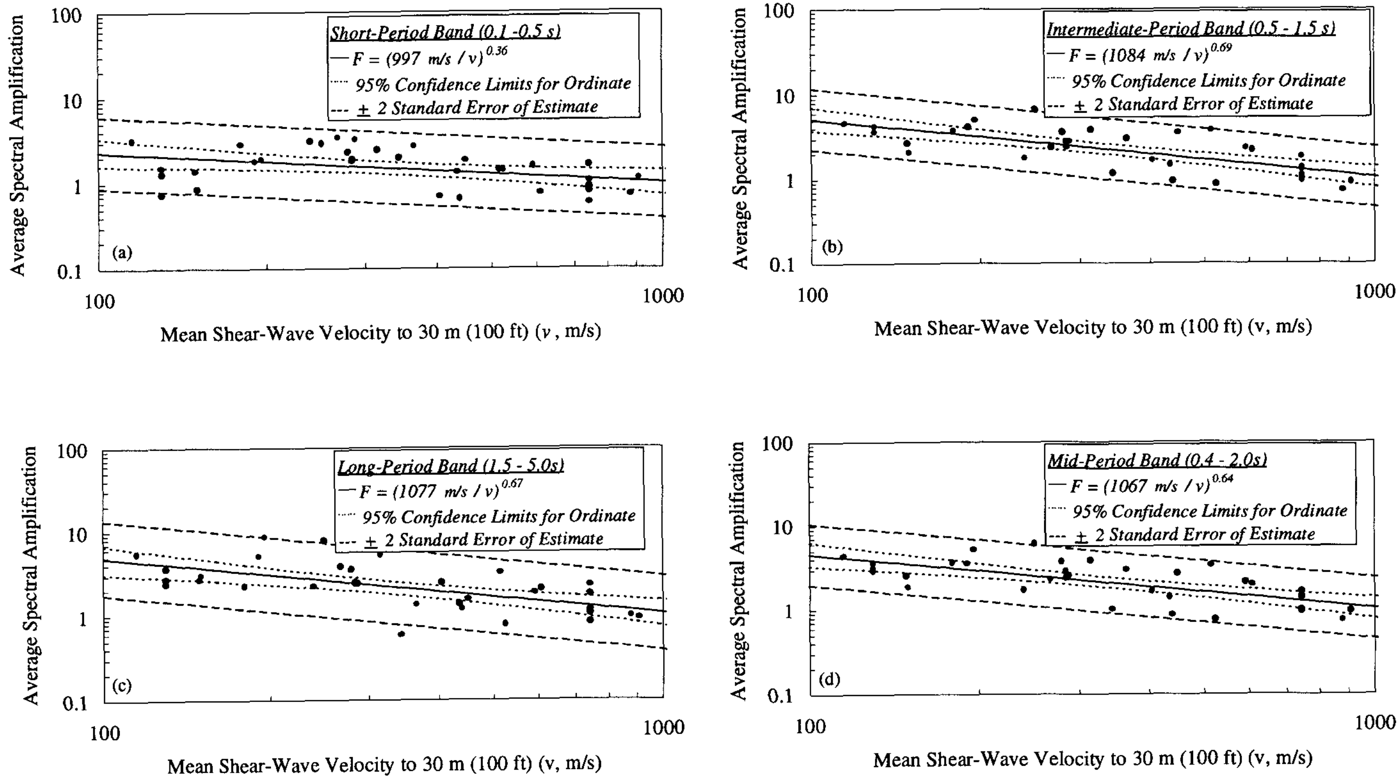


Figure 6. Average horizontal amplification factors, regression curves, and confidence intervals inferred from the free-field strong-motion recordings of the Loma Prieta earthquake of October 17, 1989 for the (a) short- (0.1-0.5 s), (b) intermediate- (0.5-1.5 s), (c) long- (1.5-5.0 s) and (d) mid- (0.4-2.0 s) period bands. The 95% confidence intervals for the ordinate to the true population regression line and the limits for ± 2 standard error of estimate are shown.

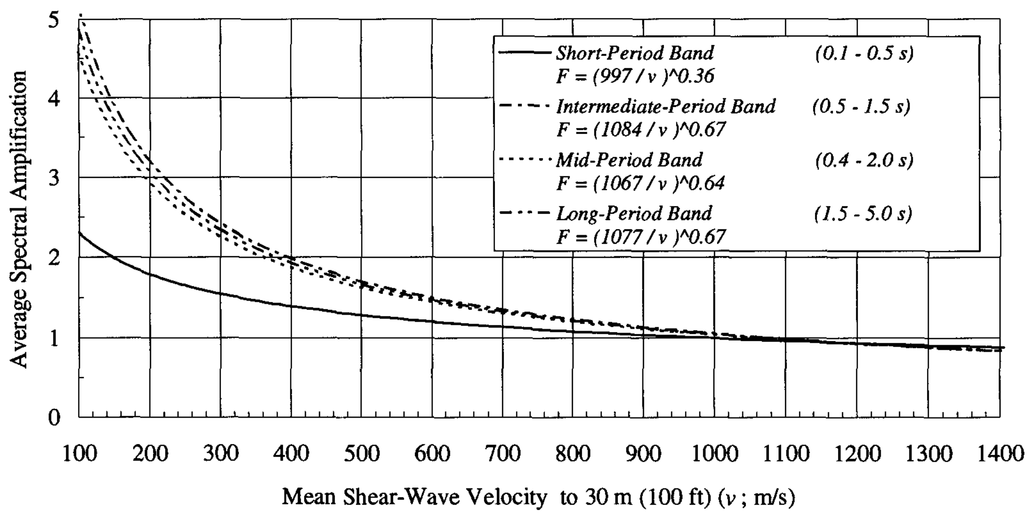


Figure 7. Average horizontal spectral amplification factor, F, computed with respect to *Firm to Hard rock*, (*SC-Ib*) and plotted as linear function of mean shear-wave velocity for the short-, mid-, intermediate-, and long-period bands as inferred from the Loma Prieta strong-motion data (see Figure 6 for plots with logarithmic scales). The plots emphasize that both short-period and mid- or long-period amplification factors are required to account for the response characteristics of near-surface deposits.

and

$$F_v = (1067 m/s \,/\, v)^{0.64} \tag{3b}$$

where v is the mean shear-wave velocity to 30 m (100 ft) measured in m/s.

These 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; Fumal and Tinsley, 1985) 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.

Amplification factors for the 0.1g input ground-motion level as predicted by equations 3a and 3b are plotted both continuously and discretely for the simplified site classes in Figure 8. They are tabulated for the 0.1g level and the simplified site classes in Table 2. These empirical amplification factors are in good agreement with those derived independently based on numerical modeling of the Loma Prieta strong-motion response (Seed, 1994) and those derived based on parametric studies of several hundred soil profiles (Dobry, et al., 1994). The Loma Prieta amplification factors at the 0.1g level provide a new empirical basis for estimates

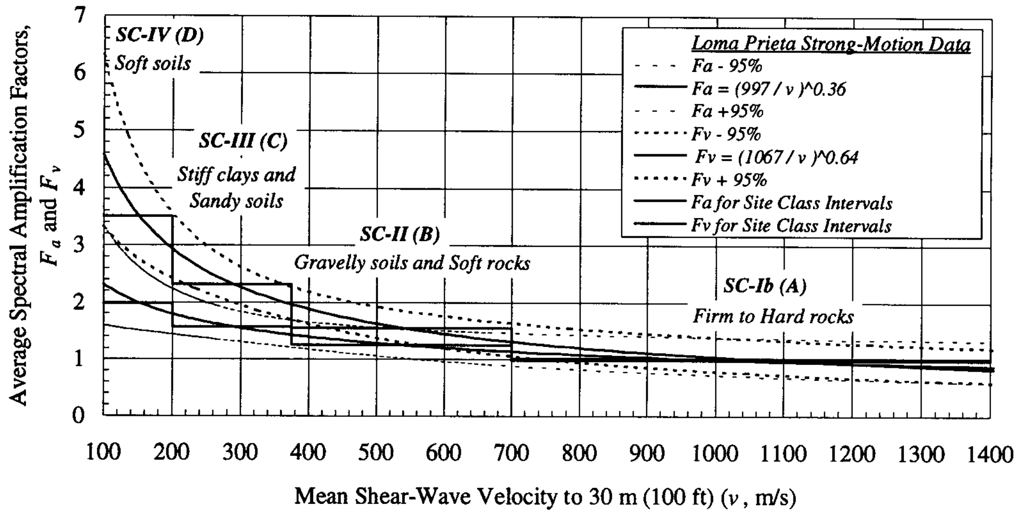


Figure 8. Short-period F_a and mid-period F_v amplification factors with respect to *Firm to Hard rock* (*SC-Ib*) plotted as a continuous function of mean shear-wave velocity using the regression equations derived from the Loma Prieta earthquake. The 95% confidence intervals for the ordinate to the true population regression line and the limits for $\pm$ 2 standard error of estimate are shown. Corresponding amplification factors predicted for the simplified site classes with respect to *Firm to Hard rock* also are shown.

of site-dependent response spectra and possible code revisions (see appendix and Borcherdt, 1994b).

Amplification Factors Extrapolated From Loma Prieta Strong-Motion Data The amplification factors implied by the Loma Prieta strong-motion data were derived from input ground-motion levels on *Firm to Hard rock* near 0.1g. For input ground-motion levels greater than this level, little or no empirical data exist on site response for soft soils. Consequently, as of this writing amplification estimates at these higher levels of motion must necessarily be based on laboratory and theoretical modeling considerations. An important issue in this regard concerns the extent to which the average amplification factors as inferred from *in-situ* strong-motion recordings extrapolate linearly to larger input ground-motion levels.

In general, laboratory and theoretical results suggest that damping increases and shear modulus or velocity decreases for large strain levels as might occur near soil failure (Seed, et al., 1974; Idriss, 1990). These nonlinear characteristics of soil response can serve to increase impedance ratios and therefore increase amplification effects. They also can increase the intrinsic attenuation of the soil layer or the damping of seismic waves and therefore reduce the amplification effects. They can result in decreased shear modulus and seismic velocity and thereby lengthen the fundamental response period of a soil layer. As strain levels in general increase with increasing "softness" of the soil deposits and increasing frequency of the wave, laboratory and theoretical results suggest that these nonlinear effects should be more apparent for the softer soil deposits and for input ground motions in the shorter period or higher frequency range. Consequently, nonlinear effects should be greater for F_a than F_v and increase with "softness" or decreasing shear-wave velocity of the deposit. Strong-motion data on soft-soil deposits at high input ground-motion levels (>0.3 g) are needed to quantify non-linear effects in an *in-situ* environment. The linear form of the regression curve in Figure 6 suggests a simple and well-defined procedure for extrapolation. Specifically, it suggests that the strong-motion amplification factors derived from the Loma Prieta earthquake may be extrapolated based on the simple assumptions that

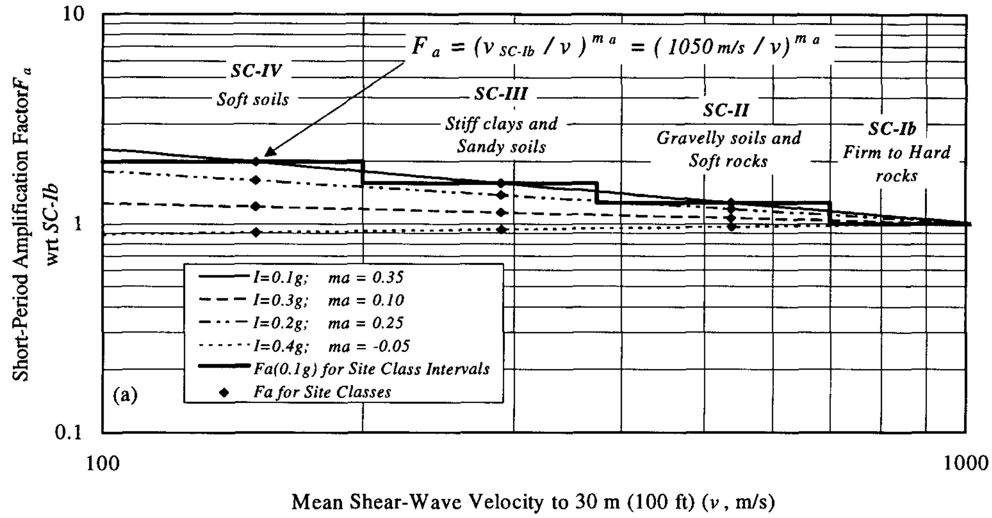
1) the functional relation between the logarithms of amplification and mean shear-wave velocity remains a straight line at higher levels of motion, and

2) the effect of nonlinearity on the response of the reference ground condition is negligible.

These two simple assumptions imply that the straight lines for each level of input motion intersect the two points defined by the mean amplification and shear-wave velocity of the *Soft-soil* site class (*SC-IV*) and that for the reference site class. Consequently, as the amplification factors for the reference ground condition are necessarily unity, the extrapolation problem is completely determined by specification of the amplification factors at successively higher levels of motion for the *Soft-soil* site class (*SC-IV*). For input ground-motion levels near 0.1g these amplification levels are specified by the empirical regression curves (equations 3a and 3b) for the Loma Prieta strong-motion data. For higher levels of motion, they are inferable currently from laboratory and numerical modeling results (Seed, et al., 1994; Dobry, et al., 1994) and eventually from *in-situ* data as other large earthquakes are recorded at higher levels of input motion.

The short-period (F_a) and mid-period (F_v) amplification factors derived on the basis of the extrapolation assumptions are given by equations 2a-2d. These equations express the amplification factors as a function of mean shear-wave velocity (v) and input ground-motion level I specified with respect to a particular reference ground condition. These equations provide a rigorous framework for extrapolation based on well-defined data and assumptions. They can be modified readily to incorporate new results simply by replacing the amplification factors for the *Soft-soil* site class (*SC-IV*) at high levels of motion (>0.3g) with better values that might be inferred from future strong-motion data.

Amplification factors predicted by equation 2 for the simplified site classes (Table 1) are given in Tables 2a and 2b for reference ground conditions corresponding to *SC-Ib* and *SC-(II+III)*, respectively. Corresponding site-specific amplification factors predicted continuously as a function of mean shear-wave velocity are plotted with linear scales in Figures 4 and 5. Equation 2 is replotted in Figure 9 with logarithmic scales. Plots of equation 2 with logarithmic scales readily illustrates the procedure for derivation of equation 2. The plots show that the equations represent simple straight lines that pass through the points determined



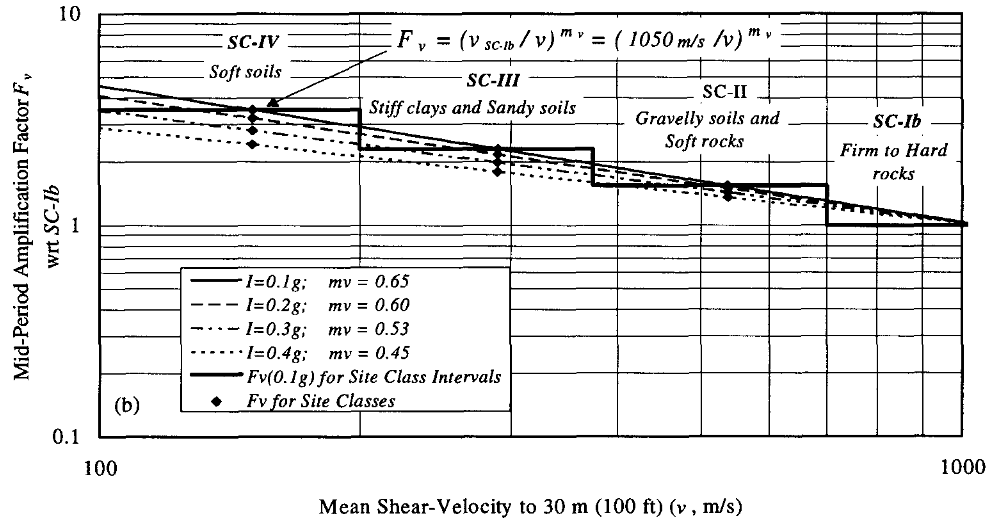


Figure 9. (a) Short-period F_a and (b) mid-period F_v amplification factors with respect to *Firm to Hard rock* (*SC-Ib*) plotted with logarithmic scales as a continuous function of mean shear-wave velocity v, using the indicated equations with exponents m_a and m_v for the appropriate level of input ground motion (equations 2 or 4, see text). Amplification factors with respect to *SC-Ib* for the simplified site classes also are indicated. The plots show that the equations represent straight lines through the points determined by the logarithms of the amplification factors and shear velocities for the *Soft-soil* (*SC-IV*) and *Firm to Hard rock* (*SC-Ib*) site classes. The exponents m_a and m_v represent the slope of the straight lines and can be modified easily as new information on the amplification characteristics of *Soft-soil* deposits becomes available.

by the logarithms of the shear velocities and the amplification factors for the *Soft-soil* site class (*SC-IV*) and the chosen reference ground condition at the specified input ground-motion level. The equations also show that the average amplification at a site is proportional to the impedance ratio with respect to the reference ground condition raised to an exponent, whose magnitude is the slope of the straight lines.

Equation 2 can be written more simply, if expressed only with respect to a single reference ground condition. The resulting equations specified with respect *Firm to Hard rock* (*SC-Ib*) with mean shear-wave velocity v in m/s are

$$F_a = (1050\, m/s\, /\, v)^{m_a} \tag{4a}$$

and

$$F_v = (1050\, m/s\, /\, v)^{m_v}, \tag{4b}$$

where, m_a and m_v for various input ground-motion levels, I, are specified in Table 2 from the simple expressions

$$m_a = Log[F_{a_{SC-Ib}}(v_{SC-IV}, I)] / 0.845, \tag{4c}$$

and

$$m_v = Log[F_{v_{SC-Ib}}(v_{SC-IV}, I)] / 0.845, \tag{4d}$$

where the factors for amplification of the *Soft-soil* site class (*SC-IV*) with respect to the *Firm to Hard rock* site class (*SC-Ib*) are designated by $F_{a_{SC-Ib}}(v_{SC-IV}, I)$ and $F_{v_{SC-Ib}}(v_{SC-IV}, I)$. The values for these factors are given at the 0.1g level by equations 3a and 3b evaluated at the midpoint of the shear-wave velocity interval (150 m/s) and at higher levels of motion by values specified for *SC-IV* in Table 2 by numerical modeling results (Seed et al., 1994) and consensus (Martin et al., 1994). The amplification factors predicted by equation 4 with respect *SC-Ib* for each of the site classes for various input ground-motion levels, I, are given in Table 2.

Equations 4a and 4b together with values for m_a and m_v implied by 4c and 4d provide an especially simple basis for estimating amplification with respect to reference ground condition *Firm to Hard rock* (*SC-Ib*). These equations are recommended for purposes of earthquake-resistant design and code provisions.

Similar equations predicting amplification factors with respect to reference ground condition *SC-(II+III)* can be written as

$$F_a = (450\, m/s\, /\, v)^{m_a} \tag{5a}$$

and

$$F_v = (450\, m/s\, /\, v)^{m_v}, \tag{5b}$$

where, m_a and m_v for various input ground-motion levels are specified in Table 2 with respect to the combination of site classes II and III (*SC-(II+III)*) from the simple expressions

$$m_a = Log[F_{a_{SC-(II+III)}}(v_{SC-IV}, I)]/0.452, \quad (5c)$$

and

$$m_v = Log[F_{v_{SC-(II+III)}}(v_{SC-IV}, I)]/0.452. \quad (5d).$$

The values for the amplification factors for *SC-IV* with respect to *SC-(II+III)*, that is $F_{a_{SC-(II+III)}}(v_{SC-IV}, I)$ and $F_{v_{SC-(II+III)}}(v_{SC-IV}, I)$ can be inferred readily from equations 3a and 3b. With a little algebra expressions 5c and 5d for m_a and m_v simplify to 4c and 4d implying that the slope of corresponding straight lines is the same for the two reference ground conditions. The amplification factors predicted by equation 5 with respect *SC-(II+III)* for each of the site classes for various input ground-motion levels are given in Table 2, plotted with linear scales in Figure 5, and with logarithmic scales in Figure 10.

Values for the exponents m_a and m_v for the equations based on the simple extrapolation assumptions, (4a-4d) at the 0.1g level agree to within one unit in the second decimal place with those derived by regression analysis (3a and 3b). This agreement shows that the amplification factors derived from the simple extrapolation assumptions are well within the uncertainty indicated by the regression analysis. This agreement further suggests that the shear-velocity intervals for the site classes, the extrapolation equations, and the empirical regression curves as derived are consistent.

The amplification factors predicted with respect to *Firm to Hard rock* by equations 2 and 4 (Table 2) are in good agreement with those derived by consensus based on agreement between Loma Prieta strong-motion data (Borcherdt and Glassmoyer, 1992, 1994), numerical modeling results (Seed, et al., 1994), parametric studies (Dobry, et al., 1994), and subsequent modifications based on expert opinion (Martin, 1994). The amplification factors predicted with respect to *Firm to Hard rock* (*SC-Ib*; Table 2) agree exactly within the accuracy specified for most of the site classes. For those predictions that do differ the difference generally is less than 10 percent.

These general equations constitute a rigorous framework for estimating site-dependent spectra for earthquake-resistant design. They permit various techniques to be compared for purposes of developing site-dependent code provisions. They afford simple and straightforward estimates of site-specific amplification factors as a continuous function of site characteristics, as well as discrete estimates for the various site classes. They yield amplification factors that can be readily refined in a self consistent fashion as additional empirical and theoretical results become available regarding the response of *Soft-soil* deposits (*SC-IV*).

The extensive set of strong-motion recordings from the Northridge, California earthquake of January 17, 1994 is an important new set of *in-situ* measurements of the response of local geologic deposits at high levels of input ground motion. This set of

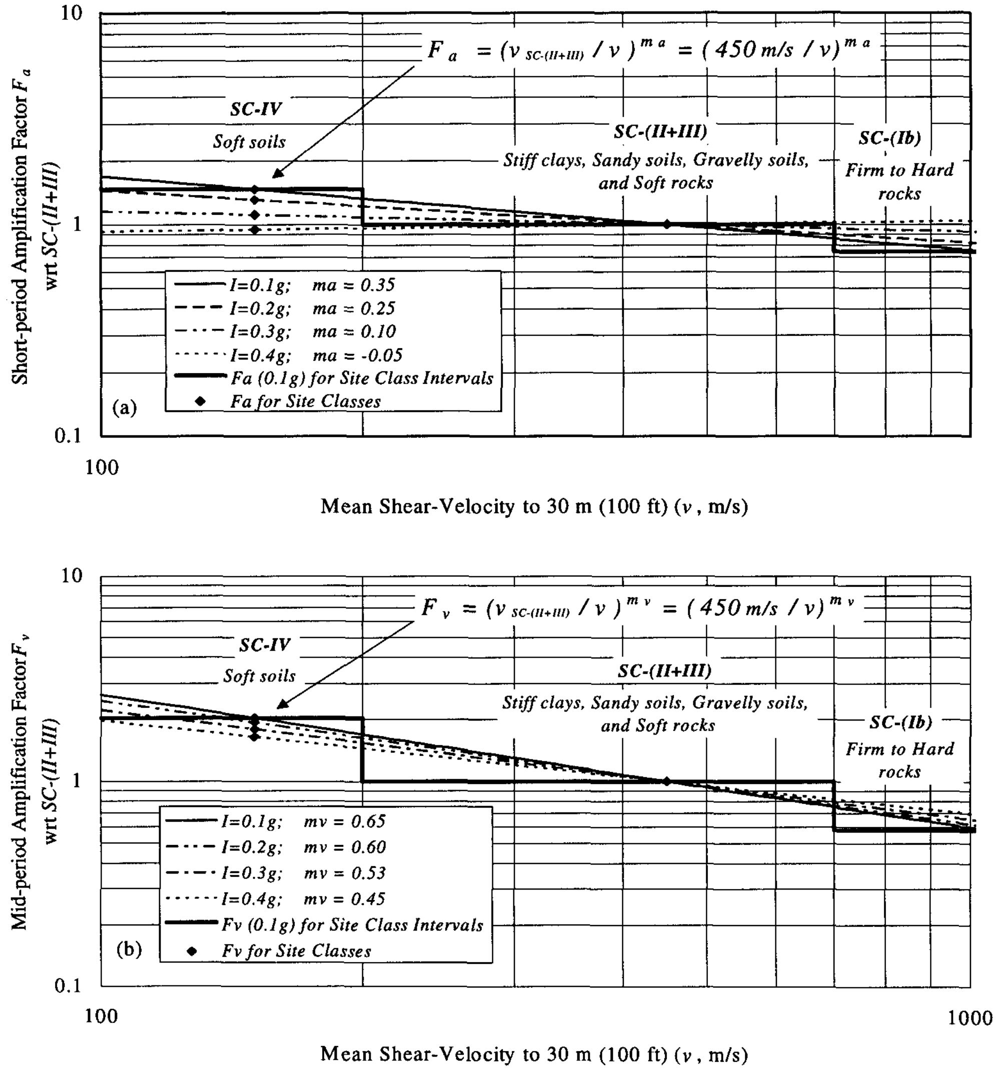


Figure 10. (a) Short-period F_a and (b) mid-period F_v amplification factors inferred with respect to combined site class *SC-(II+III)* and plotted with logarithmic scales as a continuous function of mean shear-wave velocity *v*, using equations 2 or 5, see text for specified levels of input ground motion. Amplification factors with respect to *SC-(II+III)* for the simplified site classes also are shown. See text and caption Figure 9 for discussion.

measurements differs from that recorded from the Loma Prieta earthquake in that several of the recordings were obtained at significantly higher levels of input ground motion on stiff-soil and rock deposits (*SC-III*, *SC-II*, and *SC-Ib*), but none on *Soft-soil* deposits (*SC-IV*). Preliminary amplification factors for peak ground acceleration inferred from these data suggest that the amplification factors for the *Stiff clays and Sandy soils* (*SC-III*) and *Gravelly soils* *and Soft rock* (*SC-II*) inferred at input ground-motion levels up to about 0.5 to 0.6 g agree with those derived at lower levels of about 0.1g from the Loma Prieta earthquake (Borcherdt, 1994c). This preliminary agreement suggests that soil non-linearity was not a dominate influence on the ground motions recorded on these types of sites and that extrapolation based on numerical modeling results may need to be modified. If further analyses confirm these conclusions, then the amplification factors F_a and F_v for *SC-III* and *SC-II* at the higher levels of motion (>0.1g) can be easily modified within the framework presented here. As a first approximation the new results can be incorporated using the factors inferred at 0.1g from the Loma Prieta earthquake at higher levels of input motion. As an improved approximation, F_a and F_v may be predicted readily from equation 2 with the exponents m_a and m_v determined as slopes of the linear regression lines required to predict the empirical amplification factors inferred for *SC-III* from the Northridge data at appropriate input ground-motion levels.

CONCLUSIONS

Strong-motion data, borehole-geotechnical data, and numerical modeling results provide a new basis to account for local geological conditions in earthquake-resistant design. They provide unambiguous definitions of site classes and rigorous empirical estimates of site-dependent amplification factors, both for specific sites and for the new site classes. These new results offer several different, but comparable techniques for estimating free-field, site-dependent response spectra for design. The new results provide an integrated methodology for estimates of site-dependent response spectra, seismic coefficients for site-dependent building code provisions, predictive seismic hazard maps, and special study-zone maps for strong ground shaking in conformance with California Law AB-3897 (Borcherdt, et al., 1991; Borcherdt, 1994b). They provide a rigorous framework for estimates of site-dependent amplification that can be readily refined as new data and results are acquired regarding the *in-situ* response of soil deposits.

A simple four-step methodology for estimating free-field, site-dependent response spectra,

$$S_A = Minimum\ for\ each\ period\ T\ of \begin{cases} I_a F_a \\ I_v F_v / T^x \end{cases} \tag{6}$$

is summarized as follows.

Step 1 -- Determine input ground-motion spectral levels I_a and I_v from either:

a) effective peak ground-motion maps with $I_a = 2.5\ A_a$, $I_v = 1.2\ A_v$, $x = 2/3$, and reference ground condition *Firm to Hard rock* (*SC-Ib*),

or

b) spectral ordinate maps with;

i) $I_a = S_{(0.3)}$, $I_v = S_{(1.0)}$, $x = 1$, and reference ground condition S_2 (*SC-(II+III)*),

or

ii) $I_a = S_{(0.3)} / F_a\ (v_{SC-(II+III)}, I)$, $I_v = S_{(1.0)} / F_v\ (v_{SC-(II+III)}, I)$, $x = 1$ and reference ground condition *Firm to Hard rock*, *SC-Ib*, where $F_a\ (v_{SC-(II+III)}, I)$ and $F_v\ (v_{SC-(II+III)}, I)$ represent amplification factors for S_2 (*SC-(II+III)*) with respect to *SC-Ib* as specified by equation 2 for input ground motion level $I = S_{(0.3)} / F_a\ (v_{SC-(II+III)}, S_{(0.3)})$,

or

c) ground-motion estimation model of choice.

Step 2 -- Characterize the local site conditions by either:

a) site classification using physical descriptions of near-surface materials (Table 1),

or

b) mean shear-wave velocity v inferred from physical property logs (e.g. Figures 2 and 3),

or

c) mean shear-wave velocity v to 30 m (100 ft) measured at the site.

Step 3 -- Infer site-dependent amplification factors F_a and F_v for appropriate reference ground condition and input ground-motion level from either:

a) site classification (Step 2a) and Table 2,

or

b) mean shear-wave velocity estimate v (Step 2b or 2c) and amplification curve in Figure 4 or 5, predicted by equation 2.

Step 4 -- Calculate free-field, site-dependent, response spectra, S_A.

Designations, general physical descriptions, and intervals for mean shear-wave velocity for the simplified site classes as specified in Step 2a are, in summary:

Site Class	Physical Description	Shear-Wave Velocity Interval m/s	Shear-Wave Velocity Interval ft/s
SC-I	*Hard and Firm rock*		
SC-Ia (A_0)	*Hard rock,*	> 1400	> 4600
SC-Ib (A)	*Firm to Hard rock*	700-1400	2300-4600
SC-II (B)	*Gravelly soils and Soft rock*	375-700	1230-2300
SC-III (C)	*Stiff clays and Sandy soils*	200-375	660-1230
SC-IV	*Soft soils,*	< 200	< 660
SC-IVa (D)	*Non special study;* $\leq$ *37 m thick (120 ft)*		
SC-IVb (E)	*Special study; > 37 m thick (120 ft)*		

These classes permit rapid and unambiguous classification of sites. They provide a rigorous basis for estimates of site-dependent design spectra, as well as predictive ground shaking maps for various purposes of seismic hazard analyses and improved building code provisions. Minimum thickness for each site class is given in Table 1.

The short- and mid-period amplification factors, F_a and F_v, specified in Step 3, tabulated in Table 2, and plotted in Figures 4 and 5, are given as a function of mean shear-wave velocity and input ground-motion level by:

$$F_a = (v_o / v)^{m_a} \quad (7a)$$

and

$$F_v = (v_o / v)^{m_v} \quad (7b)$$

where,

1) v is the mean shear-wave velocity to 30 m (100 ft) and may be either inferred from physical properties (Steps 2a and 2b) or measured directly (Step 2c) 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 by the Loma Prieta strong-motion data and at higher levels by extrapolation using numerical modeling results (the exponents m_a and m_v, as tabulated (Table 2) represent the slope of linear regression lines and are specified explicitly by equations 2c and 2d).

These equations yield well-defined estimates of amplification at various input ground-motion levels both as discrete functions of shear-wave velocity for the simplified 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 improved 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 as illustrated in the appendix. They provide average amplification estimates for purposes of 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.

ACKNOWLEDGMENTS

This manuscript was stimulated by the author's participation as a member of the "Working Committee to Draft NEHRP Site-Dependent Response Provisions". A part of this manuscript was presented at the national workshop of similar title, organized by the Working Committee at the University of Southern California, Los Angeles, November, 1992. Interactions with other members of the Committee (C.B. Crouse, R. Dobry, I.M. Idriss, W. B. Joyner, G.R. Martin, M.S. Power, E.E. Rinne, and R.B. Seed) helped shape several of the concepts presented here. Conversations and exchange of results, initially with Professor R. Seed and later with Professor R. Dobry, were especially helpful. T. Fumal independently derived shear-wave velocity intervals for the simplified site classes in agreement with those shown here. His conscientious efforts and those of J. Gibbs in analysis and collection of the borehole seismic and geologic data are appreciated. The helpful review comments of M. Celebi, R. Dobry, H.P. Liu, R. Scholl, W. Silva, and two anonymous reviewers are appreciated.

APPENDIX

This section includes a proposed update to section 4.2.1 of the *NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings* (1991 edition). The proposed update incorporates the new short- and mid-period amplification factors F_a and F_v, specified from either the values for the new simplified site classes or the values implied by the mean shear-wave velocity at the site predicted by equations 2 or 4.

The seismic coefficient C_S computed in the following provision corresponds to the site-dependent response spectra, S_A, normalized by the building response modification factor, R, that is $C_S = S_A / R$. S_A is computed with respect to input ground-motion levels and amplification factors determined with respect to *Firm to Hard rock, SC-Ib,* as specified in Steps 1a, 2, 3, and 4. The proposed revisions to section 4.2.1 are shown with additions indicated in bold-italic font and deletions with strike-through font.

4.2.1 CALCULATION OF SEISMIC COEFFICIENT: When the fundamental period of the building is computed, the seismic design coefficient (C_S) shall be determined in accordance with the following equations:

$$C_S = 1.2\, A_v\, \boldsymbol{F_v}\, \cancel{S} / (R\, T^{2/3}) \qquad (4\text{-}2)$$

where

A_v = *the coefficient representing effective peak velocity-related acceleration from Sec.1.4.1* ***determined with respect to sites on Firm to Hard rock, SC-Ib,***

F_v = ***the mid-period amplification factor specified for various levels of*** A_a ***either by Table 2 for the simplified site classes or by equations 2a through 2d as plotted in Figure 4b.***

~~S = the coefficient for the soil profile characteristics of the site in Table 3.2,~~

R = *the response modification factor in Table 3.3, and*

T = *the fundamental period of the building determined in Sec. 4.2.2.*

A soil-structure interaction reduction is permitted when determined using the "Appendix to Chapter 6", or other generally accepted procedures approved by the regulatory agency.

Alternatively, the seismic design coefficient (C_S) need not be greater than the following equation:

$$C_S = 2.5\, A_a F_a \,/ R, \qquad (4\text{-}3)$$

where:

A_a = *the seismic coefficient representing the effective peak acceleration* ***as determined in Sec. 1.4.1 with respect to sites on Firm to Hard rock, SC-Ib,***

F_a = ***the short-period amplification factor specified for various levels of*** A_a ***either by Table 2 for the simplified site classes or by equations 2a through 2d plotted in Figure 4a,***

R = *the response modification factor in Table 3.3.*

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