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STRONG GROUND MOTIONS GENERATED BY THE NORTHRIDGE AND HANSHIN-AWAJI EARTHQUAKES OF JANUARY 17, 1994 AND 1995; IMPLICATIONS FOR SITE-SPECIFIC DESIGN FACTORS

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ABSTRACT

Strong ground shaking generated by the Northridge and Hanshin-Awaji earthquakes of January 17, 1994 and 1995, resulted in combined property losses exceeding 120 billion U.S. dollars, and 5300 deaths, either directly through shaking-induced structural failure or indirectly through shaking-induced liquefaction and landslide failures. The strong-motion instruments, which recorded these earthquakes provided unprecedented sets of ground motion measurements on both stiff- and soft-soil deposits at high input shaking levels near the source to better understand these losses. Implications of these new measurements for site dependent design spectra are examined.

KEYWORDS

Site amplification, strong motion, attenuation, site-specific design.

INTRODUCTION

The extensive losses to property and life from the Northridge and Hanshin-Awaji earthquakes of January 17, 1994 and 1995 were due in large part to strong ground shaking. Consequently, understanding its nature in relation to source rupture characteristics, crustal propagation effects and effects of local site conditions is of special interest for new site-specific building code provisions. Strong-motion stations in the Los Angeles and Kobe-Osaka basin regions provided unprecedented documentation of the nature of strong shaking near the earthquake source. The Northridge earthquake provided forty-two recordings on sites underlain by materials ranging from stiff soil to hard rock within 25 km of the epicenter with ground acceleration exceeding 0.9 g at seven sites. The Hanshin-Awaji earthquake provided more than 26 recordings within 25 km of the extended rupture surface with many of these sites being located on "soft" Holocene soil deposits. These data provide an especially important opportunity to document the nature of strong shaking on "stiff" and "soft" soil sites at high levels of shaking near the source.

SOURCE RUPTURE CHARACTERISTICS

The Northridge earthquake occurred in a region of compressional tectonics associated with a major regional bend in the strike of the San Andreas fault. The earthquake of moment magnitude M_w 6.7 occurred on a thrust fault, dipping 42 degrees to the south with a strike of 122 degrees. Inversion of strong-motion and teleseismic data (Wald and Heaton, 1994), suggest that rupture initiated at a depth of about 18-19 km, extended to within 7-8 km of the earth's surface along a slip vector oriented 109°. Rupture extended updip about 20 km over a surface about 14 x 15 km and lasted about 7 seconds yielding a seismic moment of 1.2 x 10^{26} dyne-cm with the largest slip of nearly 4.0 meters occurring near the deepest portion of the fault (17-18 km). Strong ground motions were significantly larger north of the epicenter due to the directivity associated with updip propagation of the rupture.

The Hanshin-Awaji earthquake occurred in an area of complex faulting about 200 km from the Nankai trough, which forms the boundary between the Philippine Sea and Eurasian plates. The earthquake of magnitude 7.2 (JMA) and M_w 6.9 is the largest and most severe earthquake to affect the region this century. Source rupture characteristics inferred from teleseismic and regional data by Kikuchi (1995) suggest rupture initiated at a depth of about 14.3 km on the Nojima fault. It was comprised of three subevents of moment magnitudes 6.8, 6.3, and 6.4 each with a predominant strike-slip source mechanism. Rupture occurred along a 46 km segment of the fault at an average depth of about 8 km and reached the surface along a 9 km segment with maximum surface displacements of 1.7 m right-lateral, horizontal and 1.0 m vertical (T. Masaharu, pers. commun.,1995). Duration of total rupture lasted about 11 seconds.

Comparison of source characteristics suggests the earthquakes are about the same magnitude (Northridge, M_w 6.7; Hanshin-Awaji, M_w 6.9), with longer rupture duration for the Hanshin-Awaji earthquake (11 seconds as opposed to 8 or 9 seconds). The rupture mechanism is predominantly strike slip or horizontal for the Hanshin-Awaji earthquake compared to relatively larger vertical components of motion associated with thrust faulting for the Northridge earthquake. The average depth of rupture and hypocentral depth for the Hanshin-Awaji earthquake is less than that for the Northridge earthquake. Rupture for the Hanshin-Awaji earthquake reached the surface on Awaji Island and may have come within 4 km of the surface beneath Kobe City. Rupture was inferred not to extend closer than 6 to 7 km of the surface for the Northridge event.

GROUND MOTION ATTENUATION

Locations and peak amplitude information for the strong motion recordings have been compiled from a variety of original data sources for the Northridge earthquake (Borcherdt, 1995) and the Hanshin-Awaji earthquake (Borcherdt, 1995b). Contour maps of peak vertical and horizontal acceleration were derived from the strong motion recordings of both events and superimposed upon available digital geologic maps. (Wentworth, et al.,1994; 1995; Borcherdt and Wentworth, 1995). The contour maps for the Northridge earthquake show a general north-south elongation consistent with the inferred thrust rupture characteristics of the source. The contour maps for the Hanshin-Awaji earthquake suggest a linear zone of intense ground shaking underlain by Holocene soil deposits parallel to the surface projection of the crustal rupture zone. The maps for both earthquakes emphasize that the peak values decrease rapidly away from the immediate epicentral region with local anomalies due to topographic and local site amplification.

Peak horizontal accelerations as reported for the Hanshin-Awaji and Northridge earthquakes are plotted versus the closest distance to seismogenic rupture. Attenuation curves developed by Boore et al. (1994) are superimposed with projected surface rupture distance converted to seismogenic-rupture distance using average depths of 4 and 6 km, respectively (Fig. 1). Curves of Campbell and Borzognia (1994) also are superimposed. The peak values for the Hanshin-Awaji earthquake tend to be less than those for the Northridge earthquake for sites within 4 to 20 km of the seismogenic source, but greater at distances exceeding about 30 km. These differences in amplitude are roughly consistent with differences in source mechanism and types of geologic site conditions. The source mechanism for the Northridge earthquake is predominantly vertical movement on a thrust fault. Such source mechanisms typically generate higher peak accelerations near the source than comparable sized strike-slip mechanisms. The geologic conditions beneath a majority of the recording sites for the Hanshin-Awaji earthquake are soft-soil (Holocene) deposits with higher amplification capabilities for ground motions near one second period than the stiff Pleistocene deposits beneath many of the recording sites for the Northridge earthquake. Consequently, the high frequency motions near the source might be expected to be larger for the Northridge earthquake, but the longer period motions at some distance from the source might be expected to be larger for the Hanshin-earthquake. Attenuation curves derived by Boore, et al, 1994 when extrapolated to soft soils using an average shear-wave velocity of 200m/s fit the data quite well.

INFLUENCE OF LOCAL SITE CONDITIONS

The relatively large accelerations recorded at several of the sites for both earthquakes raise important questions concerning the influence of local site conditions on high levels of incoming high-level bedrock motions near the source. To examine the influence of local site conditions, the peak motions and amplitude spectra (Northridge) for each component were normalized by the corresponding value determined for a nearby station on firm to hard rock. Each ratio was also normalized by the corresponding reciprocal ratio of distances to the zone of largest energy release. Groups of stations for normalization were determined from

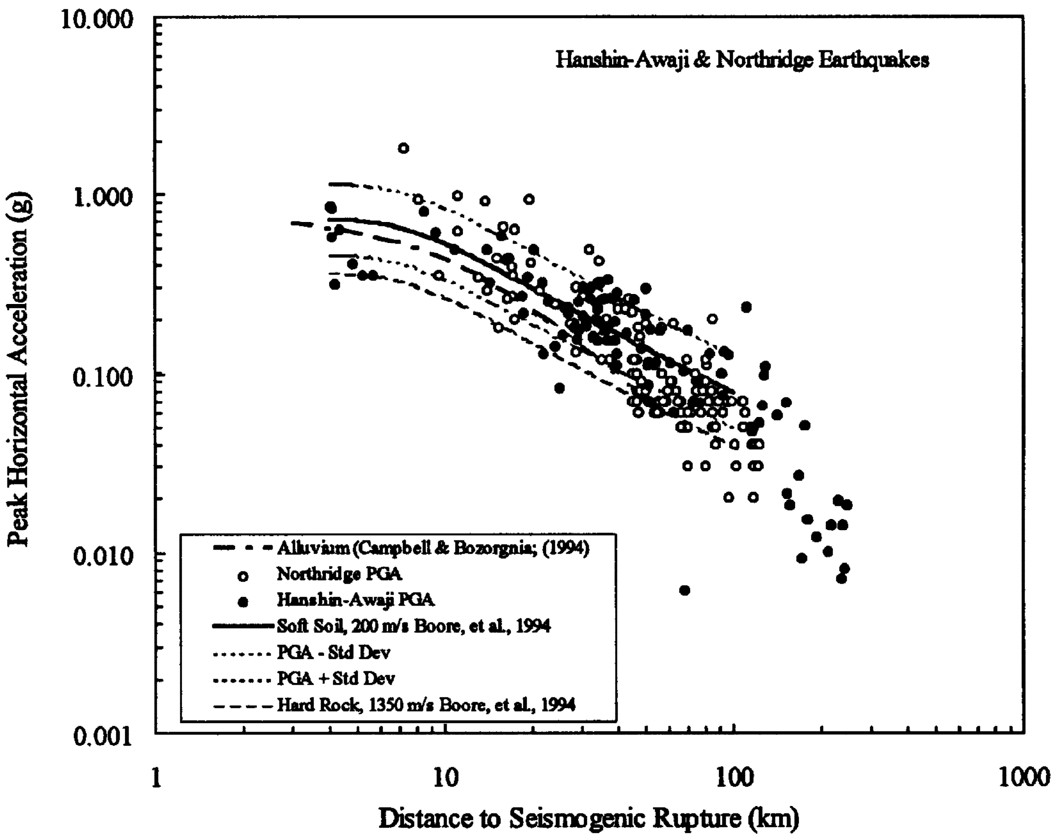


Fig. 1. Preliminary compilation of peak horizontal acceleration as a function of closest distance to seismogenic rupture for the Northridge and Hanshin-Awaji earthquakes.

22.5 (Northridge) and 45 (Hanshin-Awaji) degree azimuthal windows measured with respect to polar coordinate systems oriented parallel to the strike of the faults and segmented into 25 km distance intervals with origin at the epicenter. If no normalization station occurred in the window, then the closest normalization station in the azimuthal window was chosen (see Borcherdt, 1994 and 1995 for detailed discussion).

Amplification vs. Input Ground Motion Level for "Stiff" Soil Sites (Northridge Earthquake)

To quantify the dependence of the measured amplifications on input ground motion level for the Northridge earthquake, the acceleration ratios and the average spectral amplifications are plotted as a function of the "input" or base acceleration inferred at each site (Figs. 2a, 2b, and 2c). The "base" acceleration is defined as the value recorded at the surface normalized by the inferred acceleration ratio. Plots are shown for ratios of average peak horizontal (radial-transverse) acceleration (Fig. 2a) and average spectral ratio, Fa ,for the short-period (0.1 - 0.5 s;) band (Fig. 2b) and the average spectral ratio, Fv ,for mid-period (0.4 - 2.0 s) band (Fig. 2c).

Geologic classifications for the sites were determined from recent digital GIS compilations of the surficial geology for the Los Angeles basin (Wentworth, et al., 1995). The sites are classified according to recently defined site classes (Borcherdt, 1994) into a combined "stiff" soil to "soft" rock site class, designated *SC*

II+III or using NEHRP designations C+D and a "firm-hard" rock site class, designated *SC-Ib* or NEHRP B. Use of the combined site class reduces uncertainty in the site classification, until ongoing detailed investigations are completed at each site. Shear-wave velocities for *SC II+III* range from 200 to 700 m/s with an average velocity inferred to be about 363 m/s. Shear-wave velocities for the *SC Ib* exceed 700 m/s with an average velocity of about 867 m/s. Rigorous definitions of the site classes are provided by Borcherdt, 1994.

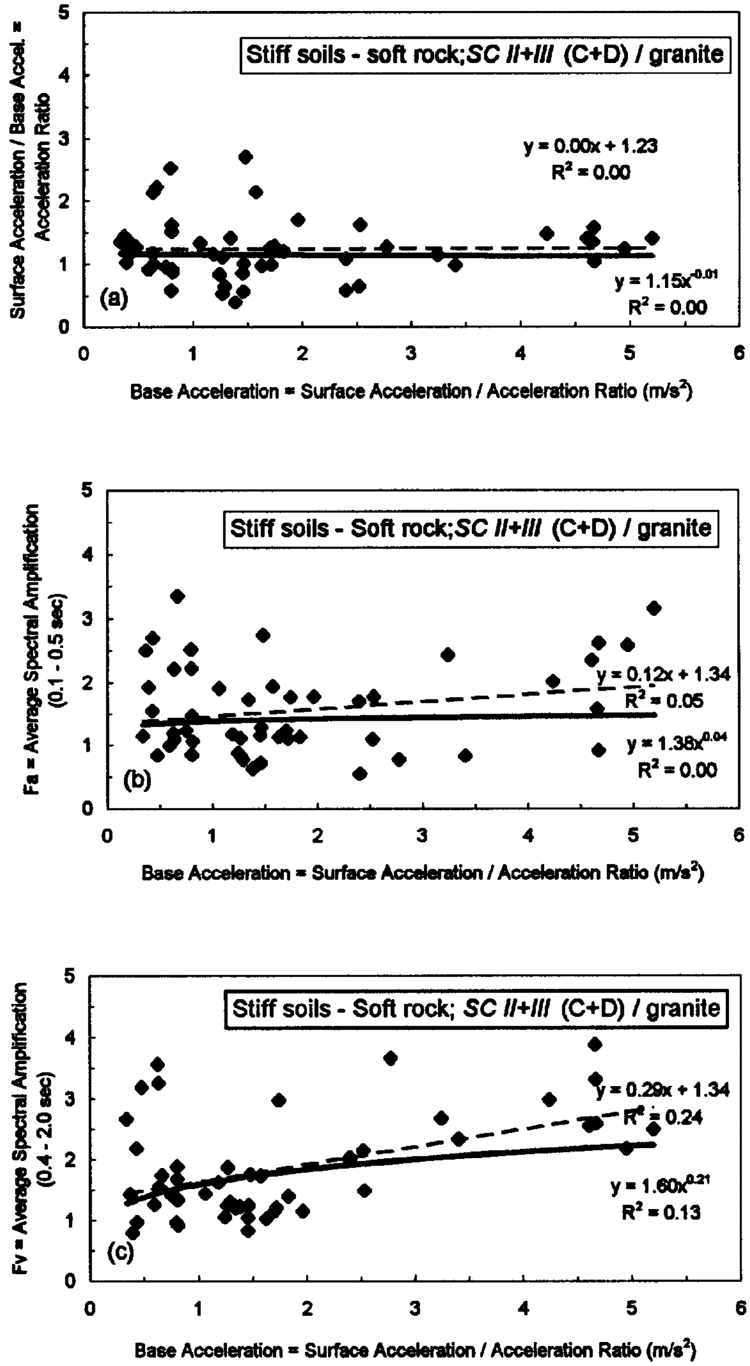


Fig. 2. Acceleration ratio (a), average spectral amplification ratio for the short-period (0.1 - 0.5 s) band (b), and average spectral amplification ratio for the mid-period (0.4 - 2.0 s) band (c) versus base acceleration for "stiff soil - soft rock sites" (SC II+III; NEHRP C+D) determined from strong-motion recordings of the Northridge earthquake. Power law and linear regression curves fit to the data are superimposed.

The acceleration ratios show a slight trend to decrease with increasing "base" acceleration level (Fig. 2a) as evident in the small negative exponent of the power-law regression curve. The zero slope of the linear regression curve suggests no dependency on base acceleration level.

The average spectral ratios for the short-period (0.1 - 0.5 s;) band (Fig. 2b) suggest a slight tendency to increase with increasing base acceleration level as evident in the positive exponent and slopes for the regression curves. However, scatter in the data suggests that this trend is probably, not meaningful. The average spectral ratio for the mid-period band (0.4 - 2.0 s) band (Fig. 2c) tends to increase with increasing base acceleration level. These preliminary observations are consistent with more detailed observations for the entire data set (Borcherdt, 1995).

Preliminary Amplification Estimates vs. Input Ground Motion Level for "Soft" Soil Sites (Hanshin-Awaji Earthquake)

As a preliminary attempt to quantify the response characteristics of "soft" soil deposits (Holocene deposits) at high input-ground motion levels for the Hanshin-Awaji earthquake, ratios of average peak horizontal acceleration were computed with respect to the Kobe University (KC-KUN) site for which an average peak acceleration of 270 cm/s^2 g was recorded at a distance of about 1.3 km from the surface projection of the crustal rupture zone. The site is underlain by hard rock (Sugito, 1995). Geologic classifications for the other sites were obtained from the GIS superposition of station locations on the digital Geologic Map of Japan (1:1,000,000 scale, Geological Survey of Japan, 1992, Borcherdt and Wentworth, 1995). The resultant classification is preliminary as it is dependent on both the accuracy of the station coordinates and the published map scale.

The average of the acceleration ratios, normalized by the reciprocal ratio of the seismogenic-rupture distance, are plotted versus "base" or input acceleration levels. The ratios are plotted only for sites underlain by Holocene soils that are located along strike at distances less than 22 km (Fig. 3). The mean and standard deviation for these acceleration ratios are 2.6 and 1.3, respectively.

The ratios of average peak acceleration show a well defined trend to decrease with increasing "base" acceleration level (Fig. 3). This trend is evident in both the negative slope of the linear regression curve and the negative exponent of the power law regression curve. These results must be considered as preliminary. Further evaluation, based on detailed site evaluations are needed to improve quantification of these results.

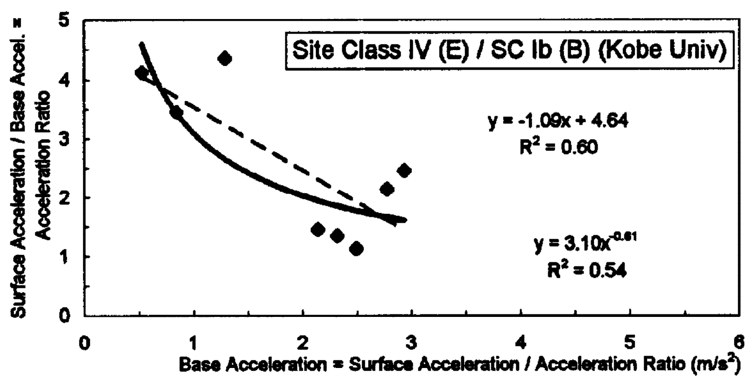


Fig. 3. Preliminary acceleration ratios versus base acceleration for "soft" Holocene soil deposits (SC IV; NEHRP E) determined from peak acceleration reported for the Hanshin-Awaji earthquake. Power law and linear regression curves fit to the data are superimposed.

PRELIMINARY IMPLICATIONS FOR SEISMIC DESIGN PROVISIONS

Improvements in estimates of site-dependent, earthquake-resistant design spectra are under review for incorporation into United States building code provisions (NEHRP and UBC). These new developments better account for the amplification effects of local geological deposits in earthquake resistant design. They are based on new unambiguous definitions of site classes and amplification factors derived from empirical and numerical modeling results. Values for the amplification factors as a function of input ground motion level and site class are specified by Borcherdt (1994).

The amplification factors Fa and Fv for short- and mid- period motion 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:

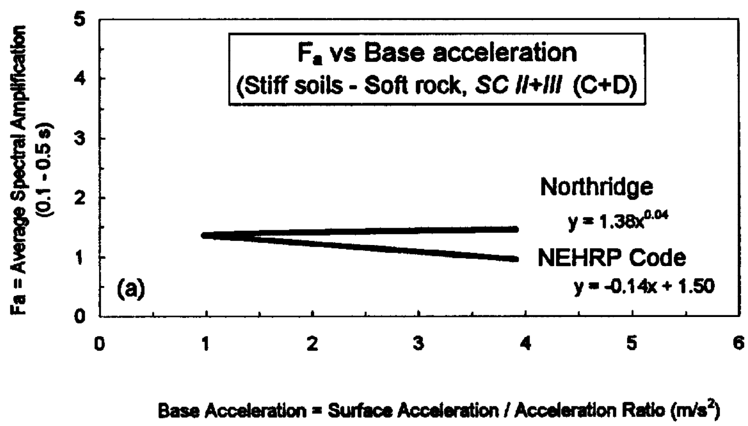
$$F_a(v,I\ )=(v_o\ /\ v)^{m_a},\qquad (1a)$$

and

$$F_v(v,I\ )=(v_o\ /\ v)^{m_v},\qquad (1b)$$

where, m_a and m_v are exponents which depend on the level of base input motion. These equations can be used to rigorously compare results derived here.

Results derived from the Northridge earthquake for sites on "stiff soils - soft rock" suggest that the amplification factors Fa and Fv do not show a strong tendency to decrease with increasing "base" acceleration. This trend as specified in Figs. 2b and 2c by the power law regression curves is replotted in Figs. 4a and 4b. Superimposed on these trends are the trends implied by recent NEHRP code provisions. (The code trends are specified by equations 1a and 1b with v = 363 m/s for SC - II+III, v_0 = 867 m/s, m_a = 0.35 and -0.05 and m_v = 0.65 and 0.45 for input acceleration levels of 0.1 and 0.4g ;Borcherdt, 1994.)



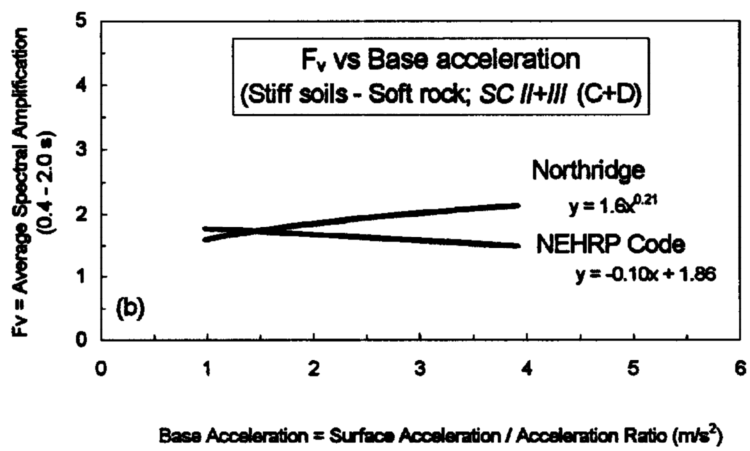


Fig. 4 Site-specific amplification factors versus base acceleration level for sites on stiff soils to soft rock (SC II+III; *C+D) implied by the Northridge earthquake and the NEHRP code provisions for the short-period band, (a) and the mid-period band, (b).*

The amplification factors implied by the Northridge earthquake are in good agreement with those suggested for the code provisions at the 1 m/s^2 base acceleration level. For higher levels of acceleration the factors implied by Northridge become increasingly greater than those proposed for the NEHRP code provisions. However, for the "stiff soil -soft rock" sites being considered the absolute amounts of amplification are not large in comparison with those for soft soils and hence, may not be of significance for many applications. These preliminary Northridge results suggest that for "stiff soil - soft rock" sites similar to those in the Los Angeles basin that Fa and Fv values of (1.4, 1.8) as predicted by equation 1 for base ground acceleration levels near 1 m/s^2 base provide simple and conservative estimates for site-specific design.

The preliminary results from the Hanshin-Awaji earthquake for "soft" soil sites suggest that the acceleration ratios and hence the Fa factors do show a well defined decrease with increasing base acceleration level. This trend as specified in Fig. 3 by the power law regression curve is replotted in Fig. 5. Superimnposed on this trend is the trend implied by recent NEHRP code provisions for "soft soils". (The code trend is specified by equations 1a with v = 150 m/s for *SC IV* (E), v_0 = 1050 m/s for *SC Ib* (B), m_a = 0.35 and -0.05 for input acceleration levels of 0.1 and 0.4g ;Borcherdt, 1994.)

The very preliminary results reported here for the Hanshin-Awaji earthquake for "soft" soils appear to be in relatively good agreement with those suggested for the code provisions in that the general trend and amounts of amplification suggested by the power law regression curve are similar to those in the proposed code provisions. These preliminary results suggest that the values of amplification observed in the Kobe City area may be larger than those currently specified for Fa in the current NEHRP provisions. Additional information on seismic velocity profiles at each site are needed for a definitive conclusion.

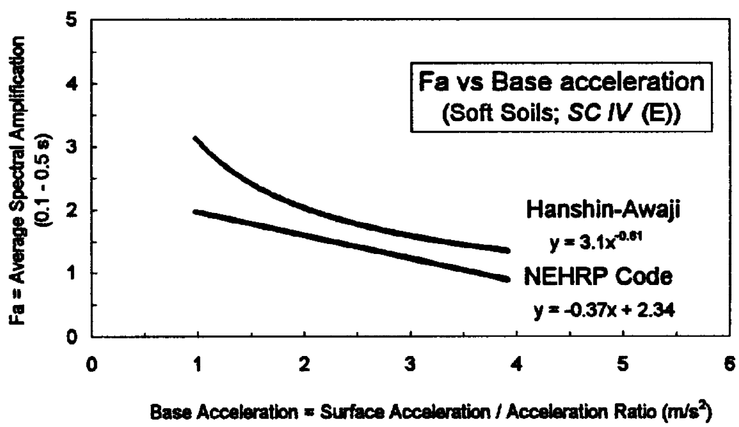


Fig. 5 Site-specific amplification factors versus base acceleration level for sites on soft soils (SC IV; NEHRP E) implied by the strong ground motion recordings of the Hanshin-Awaji earthquake and the NEHRP code provisions for the short-period band band.

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