A Review of Empirical Evidence For Site Coefficients in Building-Code Provisions

by

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ABSTRACT

Site-response coefficients, F_a and F_v, used in U.S. building code provisions are based on empirical data for motions up to 0.1g. For larger motions they are based on theoretical and laboratory results. The Northridge earthquake of 17 January 1994 and other recent earthquakes have provided significant new sets of empirical data up to 0.5g. These data together with recent site characterizations based on shear-wave velocity measurements provide empirical estimates of the site coefficients at base accelerations up to 0.5g for Site Classes C and D. These empirical estimates of F_a and F_v as well as their decrease with increasing base acceleration level are consistent at the 95 percent confidence level with those in present building code provisions, with the exception of estimates for F_a at levels of 0.1 and 0.2 g, which are less than the than the lower confidence bound by amounts up to 13 percent. The site-coefficient estimates are consistent at the 95 percent confidence level with those of several other investigators for base accelerations greater than 0.3 g. These consistencies and present code procedures indicate that changes in the site coefficients are not warranted.

KEYWORDS: Amplification, Building Codes, Design Spectra, Ground-motion, International Building Code, NEHRP Provisions, Northridge Earthquake, Shear-Wave Velocity, Site Coefficients, Site Classes, Uniform Building Code

1.0 INTRODUCTION

Present US building codes are based on empirical estimates of site coefficients, F_a and F_v, derived from recordings of the Loma Prieta earthquake at the 0.1g level (Borcherdt 1993, 1994) and derived at higher levels using numerical modeling and laboratory results (Seed, et al., 1994). The Northridge earthquake of 17 January 1994 and other recent earthquakes have provided sets of ground-motion recordings with peak ground accelerations at levels up to 0.5g. These new data provide an opportunity to further evaluate site coefficients as currently specified in US building codes.

This paper provides a review of the empirical evidence for site coefficients as derived by analyses of Northridge earthquake recordings (Borcherdt, 2002) and those derived by a number of other investigators using other databases and procedures.

2.0 COMPARISON OF SITE COEFFICIENTS DERIVED USING VARIOUS METHODS

Estimates of the short-period F_a and mid-period F_v site coefficients have been derived relatively recently by a number of investigators using a variety of databases and procedures. Results of these investigations are compared herein with those derived from Northridge by Borcherdt (2002). Estimates of F_a and F_v together with corresponding 95 percent confidence intervals for each site class as derived by Borcherdt (2002) are plotted in Figures 1 and 2. Corresponding code values ($F_{a_{code Table}}$, $F_{v_{code Table}}$) and results derived by Crouse and McGuire (1996), Dobry et al. (1999), Joyner and Boore (2000), Rodriguez-Marek et al. (1999), Silva et al. (2000), and Stewart et al. (2001, 2002) are provided for comparison.

Crouse and McGuire (1996) derived estimates of site coefficients using a set of empirically based attenuation curves based on strong-motion recordings from a select group of 16 U.S. earthquakes, which included the Landers earthquake, but was completed before the Northridge data could be incorporated. Site classifications were based on a separately

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compiled database. The site coefficients were derived from empirical predictions at various magnitude and acceleration levels. Ratios of spectral levels at specific periods were computed from averages for the magnitude acceleration pairs, from which averages for the short and mid period band were computed.

Dobry et al. (1999) derived amplification ratios using the Northridge strong-motion data from ratios of response spectral ordinates for nearby soil-rock pairs. Their database is a subset of that used by Borcherdt (2002). They derived estimates from ratios computed using a hypocentral distance norm (method 1) and from ratios computed by normalizing the response spectra for various soil sites to the corresponding value predicted by Silva using the Abrahamson and Silva (1997) attenuation relation for rock (method 2). Estimates of the short and mid-period site coefficients were derived from averages of the response spectral ratios over the short- (0.1 - 0.5 s) and mid- (0.4 – 2.0 s) period bands. Estimates of the mean and standard deviation were derived for Site Classes C and D from a subset of sites for which the ratios were considered most reliable. Averages of their ratios for base acceleration intervals of 0.04 - 0.14 g, 0.15 - 0.24 g, and 0.25 - 0.35 g are plotted (Figures 1 and 2).

Joyner and Boore (2000) derived estimates of F_a and F_v by adding a new term to their regression relation of the form

$$(a_6 + a_7 PSV_{ref}) \log(V / V_{ref}) , \tag{3}$$

where V is the average V_{30} for the site class, V_{ref} is the average V_{30} for the reference site condition, PSV_{ref} is the predicted pseudo spectral velocity for the reference site condition, a_6 and a_7 are coefficients determined by regression, and distance is measured as closest distance to projected rupture surface. Their estimates are based on a database, which does not include the Northridge, Landers, or Loma Prieta data sets. Their estimates are not averaged over a period band, but correspond to spectral ratios at 0.2 and 1.0 seconds. Their estimates of F_a and F_v as derived with respect to a reference site velocity of 1068 m/s are plotted (Figures 1 and 2).

Rodriguez-Marek et al. (1999) used the strong-motion recordings from the Loma Prieta and Northridge earthquakes. They classified the sites based on general geologic and geotechnical information, but did not consider shear-velocity measurements essential to their classification scheme. They developed attenuation relations for each earthquake and site class from which they developed amplification factors with respect to an attenuation relation for site class B.

Silva et al. (2000) developed generic shear-wave velocity profiles for the surficial geologic units in California. Silva used these profiles and a random vibration theory equivalent linear model to estimate amplification factors as a function of frequency. He developed estimates based on both Peninsular Ranges and EPRI models of randomized material profiles. He also developed curves for conditions considered most appropriate for both the western and eastern U.S. Estimates inferred from figures in Silva et al. (2000) for the Peninsular Ranges model are plotted (Figures 1 and 2).

Stewart et al. (2001) used a large database recently compiled by Silva (PEER, http://peer.berkeley.edu/smcat/). It includes recordings from the Northridge, and other earthquakes that have occurred up until 1999. Recording sites were classified using mapped surface geology. Their estimates of F_a and F_v were derived from ratios of response spectral acceleration as computed from the recordings at the site and a reference peak acceleration as predicted by the attenuation functions of Abrahamson and Silva, 1997. Their estimates of F_a and F_v are derived from averages over the appropriate period band. They used linear regressions of the logarithm of estimates for F_a and F_v on the logarithm of predicted reference peak ground acceleration to derive the estimates of the amplification factors as a function of input acceleration level.

The procedures and database used by Borcherdt (2002) differs in two important respects from those of other investigators. The amplification factors are computed with respect to that for a nearby reference site to minimize effects of variations in source radiation pattern and crustal propagation path. The estimates are based only on the data recorded from the Northridge earthquake. The sites are classified using shear velocity as either measured or estimated for each recording site. Classification of the sites using shear velocity is preferred because seismic response correlates better with shear velocity than with geologic age. In addition, shear velocity is preferred because the actual site characteristics at several recording sites were found to differ from those shown on the geologic maps. The reason for this difference is that several of the sites are located near a geologic boundary that may have been generalized or the geology mapped at the surface is not the same as that within a few feet of the surface.

The estimates of site coefficients by various investigators (Figures 1 and 2) vary depending on the database, the reference ground motion, the site-classification method, and the procedure used to infer the resultant site factors. In addition to previously stated differences in procedures to develop reference motions and resultant estimates of the site coefficients, the site classification method is thought to be a significant contributor to uncertainty in the various estimates. Limited shear-wave velocity data at most of the strong-motion recording sites necessitates the use of mapped geology to classify the sites. Unfortunately, units on most geologic maps have been mapped for purposes of inferring geologic history and not seismic response. For example, in the San Francisco Bay region (Borcherdt, 1994) soil units mapped as quaternary alluvium (Qal) excluding the Holocene units may contain deposits ranging from fine-grained clays and sands with $v_{s_{30}}$ near 250 m/s to over consolidated, very dense course-grained sandy gravels with $v_{s_{30}}$ near 600 m/s. Similarly, rock units mapped as Tertiary in age may vary from firm to soft sandstones and siltstones with $v_{s_{30}}$ near 300 m/s to hard to firm rhyolites with little or no weathering and $v_{s_{30}}$ near 1000 m/s. Without shear-velocity information, sites with rocks of Tertiary and Mesozoic age tend to be classified as class B sites resulting in higher average reference motions and hence lower estimates for the site coefficients than would be obtained were sites correctly classified using shear-velocity information. The uncertainties induced by geologic classifications are expected to be a significant contributor to the differences in the estimates derived by the various investigators using the different databases from different geologic and tectonic regions. As a further explanation of some of the uncertainties in estimates derived by various investigators, results not based on Northridge strong-motion data are necessarily derived from data sets with fewer data with base acceleration levels above 0.2g, and hence, would not be expected to show as large a dependencies on peak acceleration. In addition, estimates derived at individual periods of 0.2 and 1.0 seconds are expected to be less and greater than those, respectively, computed as averages over the short (0.1-0.5 s) and mid-period (0.4-2.0 s) bands.

Results derived by Stewart et al. (2001) are consistently less than those derived by other investigators and only within the 95 percent confidence band for peak accelerations greater than about 0.35 g to 0.42 g depending on site class. Stewart et al. (2001) attributes this difference to the fact that their estimates are referenced to "soft rock" as opposed to "firm to hard" rock used for the code, however uncertainties caused by the necessity to classify sites using geologic age may also be a contributor. Results of Stewart (2002) referenced to a velocity of 1050 m/s are also shown. These estimates compare better with those in the code. Further discussion will be limited to the estimates derived from averages by Crouse and McGuire (1996), Dobry et al. (1999), Rodriguez-Marek et al. (1999), Silva et al. (2000) for the Peninsular Ranges, and Stewart (2002).

Comparison of the short-period F_a estimates

derived from averages for Site Classes C and D shows that the estimates of Silva et al. (2000) for the Peninsular Ranges and Rodriguez-Marek et al. (1999) are near or within the 95 percent confidence band for the sample estimates of the ordinates to the true population regression line derived by Borcherdt (2002) for each base acceleration level. Their estimates and those of Crouse and McGuire (1996) and Borcherdt (2002) exceed the code values for each base acceleration level. Estimates by Crouse and McGuire (1996) and Stewart (2002) are below the 95 percent confidence bound for base acceleration levels near 0.2 g and less. The value of Dobry et al. (1999) for Site Class D at the 0.1 g is significantly less than the code value. Their values for Site Class C at 0.1g and 0.3 g are within the 95 percent confidence band, but their value at 0.2 g is not. With the exception of the estimates by Crouse and McGuire (1996) for Site Class C estimates derived by each investigator decrease with increasing base acceleration.

Comparison of the mid-period F_v estimates for Site Class C shows that the estimates of Crouse and McGuire (1996) and Silva et al. (2000) exceed the code values and are within the confidence band derived by Borcherdt (2002) for each base acceleration level. The estimates of Rodriguez-Marek et al. (1999) are significantly less than the code values and outside the 95 percent confidence band except for base acceleration of 0.4g. The Dobry et al. (1999) values do not show a well-defined dependence on peak acceleration and are within the confidence band only at 0.3 g. Estimates derived for Site Class C by Crouse and McGuire (1996) and Silva et al. (2000) do not show a dependence on base acceleration.

Comparison of the mid-period F_v estimates for Site Class D shows that the estimates of Silva et al. (2000) exceed the code values and are within the confidence band for each base acceleration level. Estimates derived by Crouse and McGuire (1996) and Rodriguez-Marek et al. (1999) are within the confidence band for base accelerations 0.3 g and greater, but below the band for accelerations 0.2g and less. Each of these estimates shows a dependence on base acceleration.

3.0 CONCLUSIONS

Recent estimates of site coefficients derived by various investigators vary depending on the database, the reference ground motion, the site-classification method, and the procedure used to infer the resultant site factors. These variations tend to suggest the lack of a consensus for modifying the code factors. However, the consistent tendency for the estimates of F_a derived by Crouse and McGuire (1996), and Rodriguez-Marek (1999), Silva et al. (2000), and those herein to exceed the code values at each base acceleration suggests that some increase in the F_a factors might be appropriate for Site Classes C and D. Similarly, the tendency for the estimates of F_v by Crouse and McGuire (1996), Silva et al. (2000), and Borcherdt (2002) to exceed those of the code for Site Class C might be used to argue that some increase in F_v for Site Class C is appropriate. An increase in estimates of F_v for Site Class D can be argued on the basis of the consistency between the Silva et al. (2000) results, the results of Borcherdt (2002), and the Joyner and Boore result at 1 second, but not the results of the other investigators. In summary, variation in the estimates derived by various investigators and the uncertainty associated with the various estimates does not support a significant change in the site coefficients F_a and F_v as currently specified in US building codes.

4.0 ACKNOWLEDGMENTS

Discussions during the initial research with two special colleagues, the late W. B. Joyner and the late H.P. Liu, were helpful.

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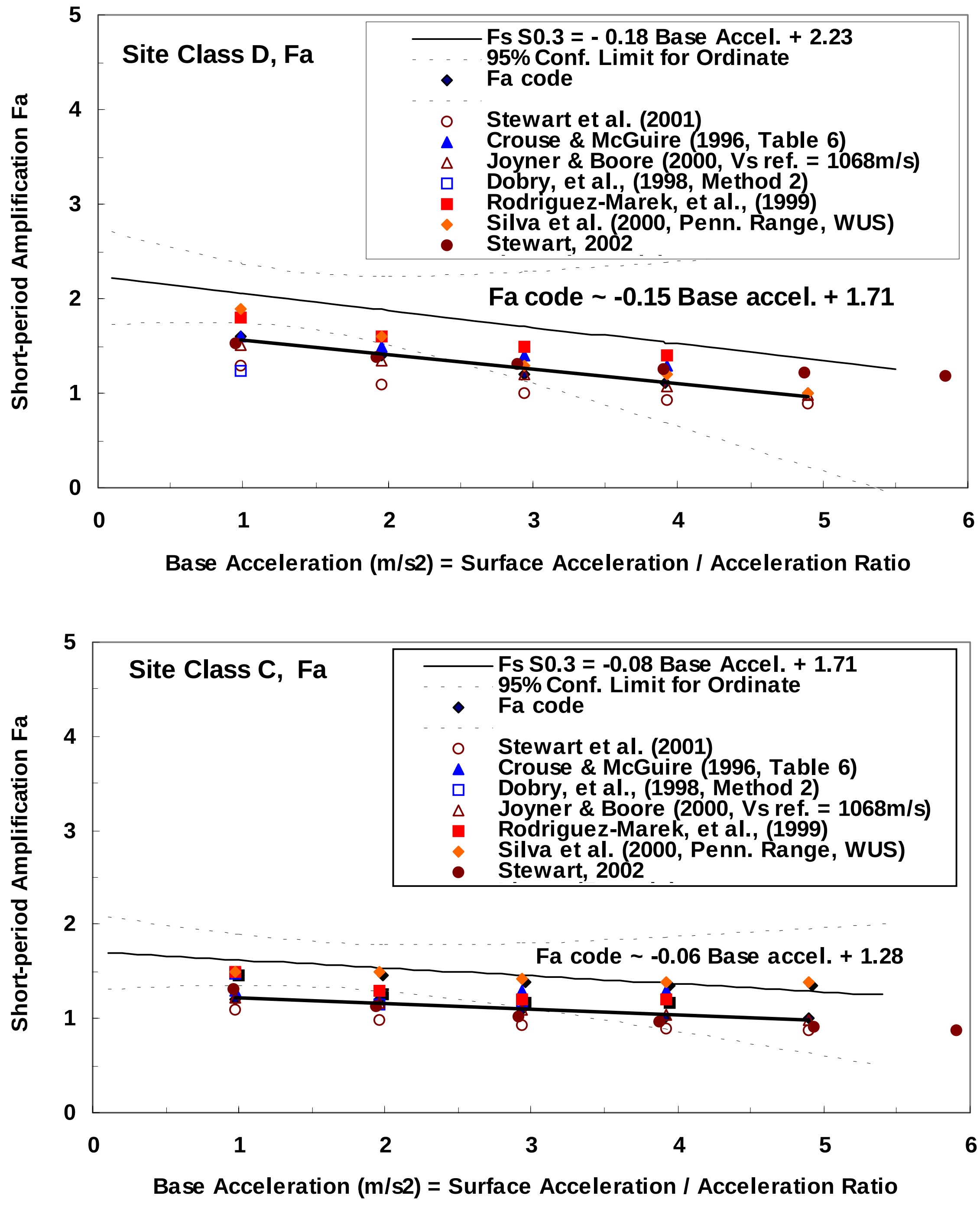

Figure 1. Empirical estimates of the short-period site coefficient F_a for site classes D and C as derived by several investigators.

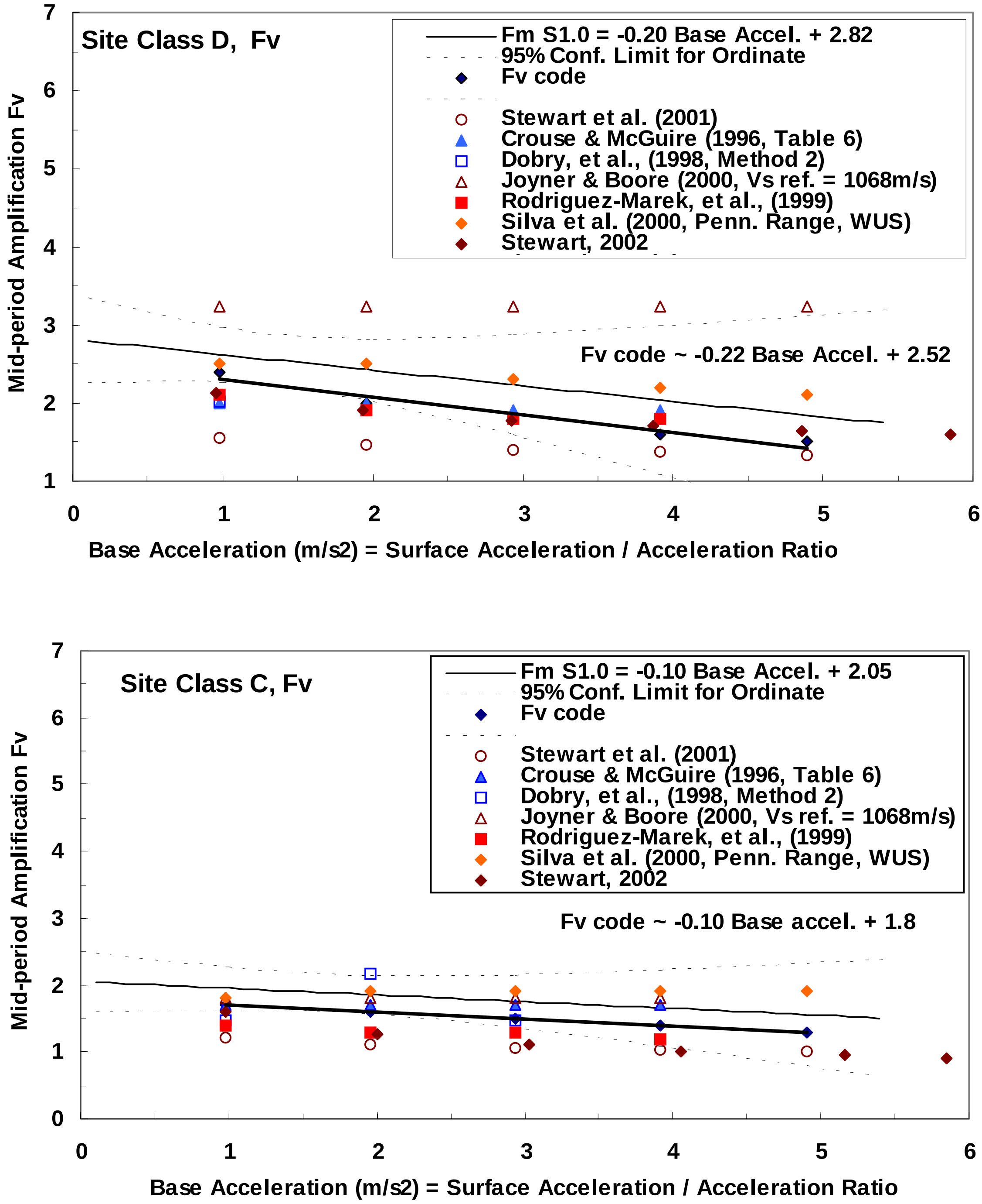

Figure 2. Empirical estimates of the mid-period site coefficient F_v for site classes D and C as derived by several investigators.