4^{th} IASPEI / IAEE International Symposium:

Effects of Surface Geology on Seismic Motion

August 23–26, 2011 · University of California Santa Barbara

EFFECTS OF LOCAL GEOLOGY ON EARTHQUAKE GROUND MOTIONS: FROM RESEARCH TO ENGINEERING PRACTICE AND BUILDING CODES

C. B. Crouse
URS Corporation
Seattle, WA 98101
USA

ABSTRACT

A great amount of research has been conducted during the last 40 years on the effects of local geology on earthquake ground motion. During this period analytical methods for computing site response have evolved from simple one-dimensional (1-D) linear or equivalent linear models to 2-D and 3-D nonlinear models. The empirical ground-motion database, consisting of motions recorded at a variety of soil and rock sites, has also grown tremendously. Studies of these data, supplemented with results from numerical modeling, have led to improvements in the way the effects of local geology are included in the seismic provisions of the International Building Code (IBC), which contains site-coefficient tables (F_a and F_v) to account for local geologic effects at short and long natural periods. However, the validity of the F_v table for long periods greater than about 2 sec is questionable because these longer period motions are influenced by the regional geology. One solution is to eliminate the IBC site-coefficient tables altogether and incorporate the effects of the local and regional geologies directly into a new generation of region-specific ground-motion equations for predicting response spectra to 10-sec period. These equations, developed from simulations and available strong motion data, would be inputs to probabilistic and deterministic seismic hazard analysis (PSHA and DSHA) methods presently used to develop the ground-motion maps in the IBC. Alternatively, simulations that directly model the 3-D regional geology could be used exclusively to develop the maps for periods greater than 2 sec. The feasibility of either approach could be tested in a pilot study for the Los Angeles region, where the 3-D geology is well known and where a reasonable amount of ground-motion data has been recorded.

INTRODUCTION

The genesis of the F_a and F_v site-coefficient tables in the IBC and its reference standard, ASCE 7, was a series of studies and workshops in the late 1980's and early 1990's. Details can be found in Dobry et al. (2000) and references cited therein. The primary basis for the F_a and F_v values were statistical studies of ground-motion data recorded during moderate to large magnitude earthquakes. Data recorded during subsequent earthquakes (e.g. 1994 Northridge, California) have confirmed the F_a and F_v values are reasonable, and hence the site-coefficient tables have not been revised in almost 20 years.

However, minor revisions may be introduced during the present code cycle as a result of empirical studies of the Next Generation Attenuation (NGA) ground-motion database, which is available through the Pacific Earthquake Engineering Research (PEER) Center website. This extensive database is impressive not only because of the large number of accelerograms and response spectra that comprise it, but also (and perhaps more importantly) because of the vast metadata associated with each record. This metadata took several years to compile and consists of data corresponding to the causative earthquakes and recording stations.

The ground-motion data and selected parameters from the metadata file were used by several researchers to derive five NGA ground-motion prediction equations (see Earthquake Spectra, v. 24, No. 1, 2008). The US Geological Survey (USGS) used three of the NGA equations in its development of the Western US ground-motion maps in the ASCE 7-10 standard, which will be incorporated by reference in the next (2012) edition of the IBC.

One of the parameters in four of the NGA equations is $V_{s30,}$ defined as the average shear-wave velocity in the upper 30 m at the recording station. This parameter was selected by NGA researchers because it is the primary basis for defining the site classes in the

F_a and F_v site-coefficient tables. These classes (A, B, C, D, and E) represent local geologies ranging from hard rock (A) to soft soil (E)[1]. A PEER-sponsored committee led by Dr. J. Stewart is studying site response through the use of the NGA equations. Preliminary results generally confirm the F_a and F_v values for the stiff soil classes, C and D, but not for the soft soil class (E) (Stewart and Seyhan, 2011; Borcherdt, 2011). However, compared to Site Class C or D, relatively few ground motion accelerograms have been recorded at stations categorized as Site Class E. Thus, the F_a and F_v values for this site class are necessarily more uncertain than those for the stiff soil classes.

The F_a and F_v tables are found in Chapter 11 of the ASCE 7 standard. This chapter is typically used by structural engineers to compute the response spectrum for subsequent determination of the lateral seismic loads for structural design. This spectrum is constructed from the bedrock (Site Class B) ground-motion maps appearing in Chapter 22 of the standard and the site coefficients. The ASCE 7 standard also permits the calculation of the design response spectrum by site-specific studies of ground motion. The procedures for these studies are outlined in Chapter 21 and consist of site-response analysis and PSHA and DSHA methods.

The remainder of this paper first discusses site-specific site-response analysis from the practicing engineers' perspective. Next, comments are offered on the site-response analyses conducted as part of the Turkey Flats blind-prediction experiment and its implications for site-specific procedures per Chapter 21 of the ASCE 7 standard. The paper then examines the issue of long period design ground motions and whether these motions can be reliably predicted by the PSHA/DSHA and site-response methods commonly used in current practice, or whether seismological models can or should be used instead, particularly in large western US urban areas where the regional 3-D geology and seismic velocities are well known.

SITE-RESPONSE ANALYSIS

Chapter 21 of the ASCE 7 standard permits site-specific site-response analyses regardless of the local soil conditions. Site-response analyses is required for Site Class F soils with one exception: if the fundamental period of the structure is less than or equal to 0.5 sec and soil meets the criterion for liquefaction, then an exception in the standard allows the site ground motion to be determined with the F_a and F_v site coefficients under the assumption that the soil does not liquefy.

The question geotechnical engineers must address is whether to perform site-response analysis at sites categorized as Site Class C, D, or E. A case can be made that such analysis is not warranted for stiff soil sites (Site Classes C and D). If site-specific procedures are selected or required (e.g. hospitals in the State of California), then the recommended approach is to account for site response directly in the PSHA/DSHA by selecting the proper V_{s30} or site-response term in the ground-motion prediction equations (GMPEs). This approach avoids the two-step procedure of first determining a bedrock motion from PSHA/DSHA methods and then conducting site-response analysis to obtain the ground-surface motion. There are several reasons why this two-step procedure is generally less attractive in the western US, aside from the fact that it involves an extra time-consuming step:

1. The empirical GMPEs used in PSHA/DSHA were derived from databases consisting of ground-motions recorded mostly at Site Class C and D sites, and therefore the GMPEs are considered more reliable predictors of ground motions at such sites than at bedrock sites;
2. The depth of bedrock beneath a site is often unknown, or known but deeper than the depths of the geotechnical borings and shear-wave velocity surveys. Even if bedrock is encountered during the geotechnical investigation, boreholes usually do not penetrate into the bedrock far enough to obtain representative shear-wave velocities by commonly used downhole surveys. Thus, the soil-rock impedance contrast, which affects the motion amplification, is uncertain.
3. The 1-D linear, equivalent linear, or nonlinear models used for site-response analyses predicted vastly different ground motions during the Turkey Flat blind prediction experiment.

Regarding the first reason, Figure 1 shows the distribution of the V_{s30} values of the ground-motion records in the NGA database used by Chiou and Youngs (2008). Note the vast majority of the data are between V_{s30} of 180 and 760 m/s, the range encompassing Site Classes C and D. Much smaller numbers of records are observed for $V_{s30} < 180$ m/s (Site Class E or F) and $V_{s30} > 760$ m/s (Site Classes A and B, bedrock). Four of the NGA GMPEs contain V_{s30} as an independent parameter and because these equations are now commonly used to estimate ground motion from shallow crustal earthquakes in plate-boundary or active seismic regions, one or more V_{s30} can be assigned based on the site velocity surveys and substituted into the GMPEs selected for PSHA/DSHA.

---

[1] Site Class F is also included in the site-coefficient tables and represents soils prone to failure (e.g. liquefiable soils) or soils with the potential to greatly amplify ground motions (e.g. thick deposits of soft clay). Values of F_a and F_v for this site class are not listed and must be determined by site-specific procedures.

Some geotechnical firms have avoided this direct site-specific PSHA/DSHA approach because they do not have the expertise to conduct it. Instead, they typically use the bedrock response spectrum obtained from the bedrock ground-motion maps in Chapter 22 of the ASCE 7 standard (or from the calculator tool on the USGS website) and conduct a site-specific site-response analysis. In the near future, the USGS calculator tool may be enhanced to incorporate the direct approach and provide response spectra for a user-specified V_{s30} value. In the meantime, geotechnical firms can purchase commercial PSHA software that has the same seismic sources and earthquake recurrence models the USGS used to prepare the ground-motion maps in the ASCE 7 standard. The input would simply consist of the site coordinates, the GMPE selection, and the V_{s30} value.

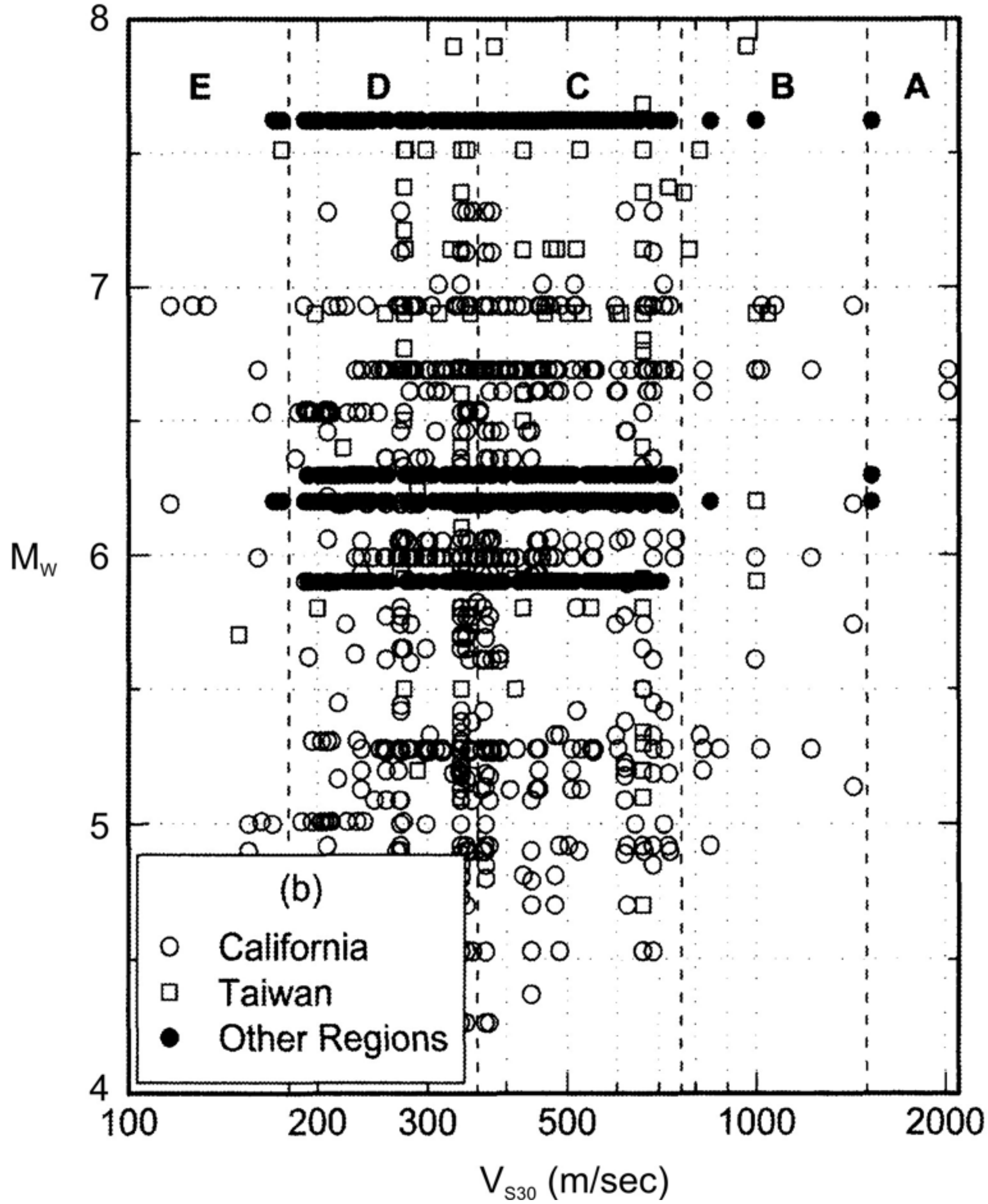

Fig. 1. M-V_{s30} Distribution of NGA Records used by Chiou and Youngs (2008). Vertical dashed lines denote boundaries between site classes listed at top of figure.

The more recent Turkey Flat blind prediction experiment was a true test of the adequacy of site-response analysis. The experiment was conducted by the California Strong Motion Instrumentation Program (CSMIP) of the California Geological Survey (CGS). CSMIP provided volunteers from geotechnical firms and academia with (1) the bedrock motions recorded at the Turkey Flat station during the 2004 M_w 6.0 Parkfield, California earthquake, and (2) the results of numerous shear-wave velocity (V_s) surveys conducted at various locations at the site where the bedrock and surface motions were recorded.

The volunteers were then instructed to predict the recorded soil motions, which CSMIP withheld. A comprehensive report of this experiment (Kramer, 2009) presents rather surprising results for one particular prediction, analogous to the way site-response is conducted in geotechnical practice. A schematic plan and section views of the Turkey Flat instrumentation is shown in Figure 2, where the green color is bedrock, the white color is stiff soil, and the solid red circles denote the locations of the strong motion instruments. The predictions of the motions at V1 from the D3 bedrock motions are more relevant to geotechnical practice, because the site bedrock outcrop motions (i.e. motions recorded at D3 in the absence of the soil column) and the V_s profiles (Figure 3) are given quantities.

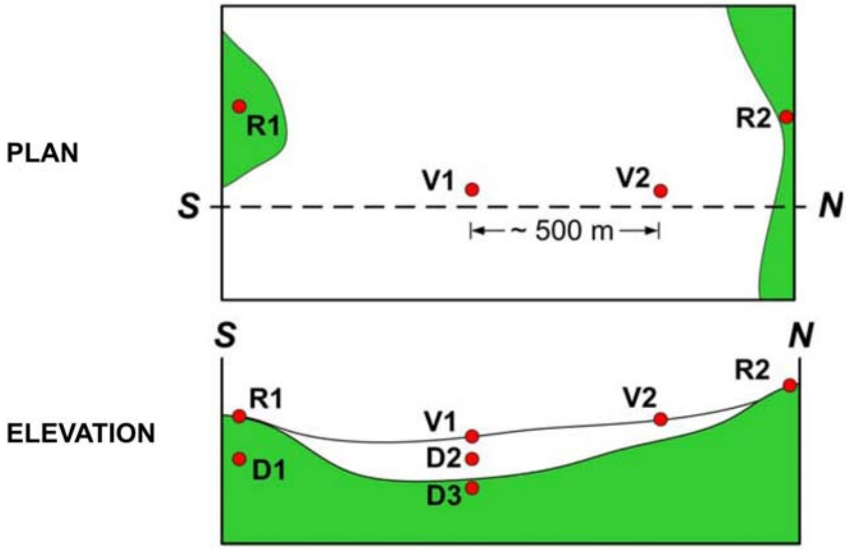

Fig. 2. Schematic illustration of Turkey Flat instrumentation layout (after Tucker and Real, 1986). R=rock; V=valley; D=downhole. Figure from Kramer (2009).

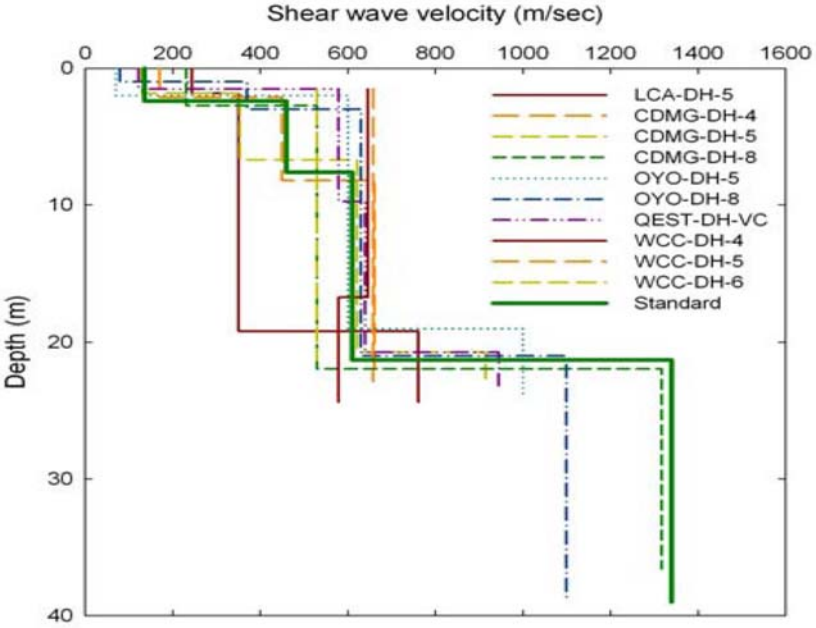

Fig. 3. Interpreted shear wave velocity profiles from individual subsurface explorations and Standard velocity profiles interpreted by Real (1988): (a) Rock South, (b) Valley Center, and (c) Valley North. Figure from Kramer (2009).

The soil profile consists of moderately stiff to stiff alluvial sediments to a depth of approximately 20 m, where bedrock is encountered. Except near the surface, the soil V_s is around 500 to 650 m/s; the bedrock V_s is around 1,200 m/s. The D3 bedrock motions were not exceptionally strong (the NW and EW peak accelerations were less than 0.1 g), so nonlinear response was not significant. Thus, from a prediction standpoint this experiment did not appear to be particularly difficult or challenging.

The results suggest otherwise. Figure 4 presents the 5% damped pseudovelocity response spectra of the various ground motions predicted at V1 for the NS and EW components. The recorded response spectra at V1 are shown as the thick solid red line. The spectra are plotted in the 0.1 to 0.4-sec period band where the dynamic amplification occurred. The predictions in this band vary greatly; for such a simple controlled experiment, one would have expected all predictions to be much closer to the observed response spectra, regardless of the site-response model used. While post-mortem arguments can be advanced for lack of consensus, this experiment is considered a good representation of the state-of-practice in site-response analysis, and it seriously questions the utility of site-response analysis in geotechnical engineering, particularly when alternative direct approaches for determining ground motions at stiff soil sites are available.

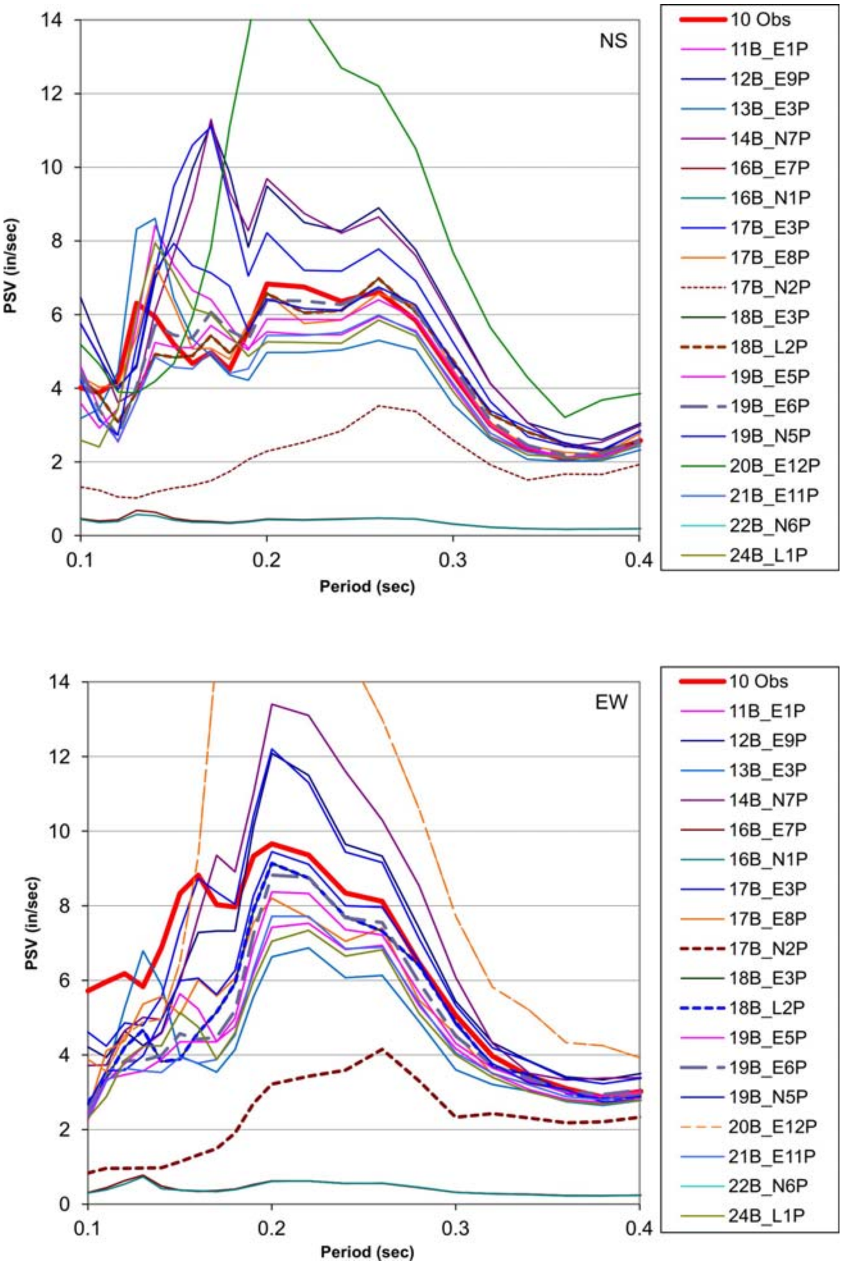

Fig. 4. NS and EW response spectra (thin lines) at V1 from rock time histories recorded at D3. Thick solid red line is response spectrum of motion recorded at V1.

LONG PERIOD GROUND MOTIONS

As the period of motion increases, the regional rather than the local geology has an increasingly greater influence on the motions at a given site. The F_a and F_v site-coefficient tables account for local geologic effects at short and intermediate natural periods to around 2 sec. However, no table has yet been introduced in the ASCE 7 standard for longer period motions; the site-coefficient table for intermediate periods applies to the longer period motions also. Constructing such a table is not feasible because the effects of a 3-D regional geology, which varies significantly from region to region, are difficult, if not impossible, to capture in a simple table suitable for the building code.

One solution is to eliminate the site-coefficient tables altogether and incorporate the effects of the local and regional geologies directly into a new generation of ground-motion prediction equations. These equations would be inputs to PSHA and DSHA methods presently used to develop the ground-motion maps in the ASCE 7 standard. Presently, three of the five NGA equations approximately account for the effect of deep soils, typically found in basin environments, by including a term that is the depth to the top of the subsurface layer with a shear-wave velocity of 1.0 km/sec or 2.5 km/sec. However, this modeling is essentially a 1-D empirical approach and does not account for the effects of the 3-D regional geology.

An approach to account for the regional effects is to perform 3-D simulations of long period ground motions using seismological models of fault rupture and wave propagation. These calculations would be confined to those areas where the 3-D geology is sufficiently well known. A number of such simulations have been performed for urban areas such as Los Angeles, but the challenge is to corroborate and transfer the results into ground-motion prediction equations that can be used by engineers to estimate ground motions at a given site by standard PSHA/DSHA methods, or used by the USGS in its development of future ground motions for the ASCE 7 standard. For the latter, it is envisioned that at some point in the future, engineers would simply enter the site's geographic coordinates and the value of a parameter representing the local geology (presently V_{s30}) into a USGS web look-up tool and obtain ground-motion parameters for seismic design covering the natural period band of interest, which may include periods up to 10 sec or greater.

Alternatively, instead of (or in addition to) developing a new set of GMPE's, the PSHA/DSHA would be performed directly from the simulations of long period motions from those faults in the regional seismic source model that are judged capable of generating significant long period motions. The process would be as follows:

(1) Identify the regional faults and earthquake magnitudes capable of generating significant long period motion.
(2) Perform a sufficient number of simulations for each fault and each magnitude, and compute the acceleration time series from the simulations at each point in a grid of sites in the urban area.
(3) Compute the response spectra of the time series for each magnitude and each fault in the simulations, and compute the median response spectra for each fault/magnitude pair.
(4) Based on the scatter in the response spectra, select a standard deviation for the assumed lognormal distribution of the residuals about the median value.
(5) At each grid point proceed with the PSHA in the usual manner by multiplying the annual earthquake recurrence rate for each fault/magnitude pair by the conditional probability of exceeding a specified response spectral acceleration, which is computed from the lognormal distribution in Step (4). Sum the products from all fault/magnitude pairs to obtain the annual rate of exceeding the specified response spectral acceleration.
(6) At those locations close to an active fault where the response spectra from the PSHA exceed a deterministic lower limit response spectrum, use the simulated results for that fault in a DSHA to establish the response spectrum for the Maximum Considered Earthquake (MCE) according to the rules in Chapter 21 of the ASCE 7 standard.
(7) Use the results at all grid points to generate long period MCE response spectral acceleration maps at specified natural periods.

Presently, this approach can be implemented in a limited number of urban areas. The recommendation would be to first test it in the Los Angeles region, where the 3-D geology is well known and where a large number recorded and simulated ground motions are available for calibration. The outcome of this pilot study will indicate whether simulation methods are ready to progress from their current use in research and loss-estimation exercises (e.g., see Earthquake Spectra, v. 27, no. 2, 2011) to improving ground-motion specifications for long periods in code seismic provisions.

The pilot study would ideally be undertaken jointly by the USGS and the Southern California Earthquake Center (SCEC). SCEC held a ground-motion simulation validation planning workshop on January 10, 2011. The purpose of the workshop was to identify and prioritize studies aimed at testing and validating simulation methods. The studies would be conducted under a SCEC-appointed Technical Activity Group. Results would indicate the methods and procedures that could be used in a computational platform specifically established to perform the fault-specific ground-motion simulations necessary to prepare the regional long period MCE response spectral acceleration maps. Funding and organizing this effort are issues that still need resolution, but if they can be solved during the present code cycle, then the pilot study could conceivably be completed during the next code cycle.

ACKNOWLEDGEMENTS

The author wishes to thank Steve Kramer for providing the Turkey Flat ground-motion data and his report (Kramer, 2009) on the evaluation of these data.

REFERENCES

Borcherdt, R., [2011]. Email communication, June 29.

Chiou, Brian S-J, and Youngs, R., [2008]. "An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra", Earthquake Spectra, Vol. 24, No., 1 pp. 173-215, February.

Dobry, R. and 8 coauthors [2000], "New Site Coefficients and Site Classification System Used in Recent Building Seismic Code Provisions", Earthquake Spectra, Vol. 16, No. 1, February.

Kramer, S., [2009], "Interpretation of Turkey Flat Site Response Experiment Results: Lessons Learned and Recommended Practices", Draft Report to CSMIP, October.

Real, C.R. [1988]. "Turkey Flat, USA site effects test area – Report 2: Site characterization", California Division of Mines and Geology TR 88-2.

Stewart, J., and Seyhan, E., [2011]. "Site Response in NEHRP Provisions and NGA Models", to be submitted to GeoCongress 2012 Conference on State of Art and Practice in Geotechnical Engineering, Oakland, California, March 25-29, 2012.

Tucker, B.E., and Real, C.R., [1986] Turkey Flat, USA Site Effects Test Area – Report 1: Needs, Goals, and Objectives. TR 86-1, California Department of Conservation, Division of Mines and Geology, 16 p.