Earthquake Site Response and Seismic Code Provisions

by Geoffrey Martin and Ricardo Dobry

Abstract

In current versions of guidelines or buildings codes for seismic design, site effects are accounted for through four soil factors which modify the shape of normalized acceleration response spectra recommended for use in design. This basic format was developed as part of an Applied Technology Council study in the early 1970's, and is the basis for the current versions of most seismic design codes. Over the past 20 years, numerous concerns have been expressed about both the limitations and code language dealing with site effects including the lack of a precise definition of site categories.

In October 1991, a workshop on the effects of site soil conditions on earthquake ground motions (supported by the National Center for Earthquake Engineering Research and chaired by Robert Whitman) was held at the State University of New York at Buffalo (Whitman, 1991). The timing of this workshop was considered particularly appropriate in that the Structural Engineers Association of California (SEAOC) had recently made plans for a major effort to review earthquake ground motion parameters for design and the Building Seismic Safety Council (BSSC) was beginning a cycle of effort leading to the 1994 revision of the NEHRP recommended provisions on seismic design. Conclusions reached at this workshop included the need for more quantitative descriptions of site and soil types, together with soil factors which take into account the intensity of ground shaking and variations in site effects with spectral ordinate period. A committee was formed at the workshop conclusion to organize a further workshop to resolve these issues, and to make recommendations for changes in code provisions to BSSC committees reviewing the NEHRP provisions.

The workshop held at the University of Southern California in November 1992, (Martin, 1994) was the outcome of extensive planning by the above workshop committee. The workshop was supported by NCEER, SEAOC and BSSC and was funded by the National Science Foundation, NCEER and the U.S. Geological Survey. The workshop was attended by over 65 invited geoscientists, geotechnical engineers and structural engineers. Formal presentations included results of recent research studies and draft proposals for new site coefficients. Breakout discussion sessions led to a merged consensus proposal providing recommendations for new site response coefficients. Site coefficients applicable to response spectra at 0.3 seconds (F_a) and 1 second (F_v) were developed as a function of input rock acceleration for six site categories. The recommendations were subsequently adopted by the BSSC for inclusion in the 1994 NEHRP provisions on the seismic design of buildings.

Collaboration

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Geoffrey R. Martin
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Objectives and Approach

The objective of the *Workshop on Site Response During Earthquakes and Seismic Code Provisions* [held at the University of Southern California on November 18-20, 1992], was to develop specific recommendations for modifications to existing seismic design guidelines and codes in relation to the effects of site response on earthquake ground motions. In particular, the recommendations were tc focus on the definitions, descriptions and number of site factors [S factors] used in building code provisions for design acceleration response spectra.

The approach to the three-day workshop was to focus the first day on defining objectives, issues and general background through a series of presentations. Further presentations followed which described the state of knowledge on the effects of site response and the results of recent research. Draft proposals for new site response factors, together with the first day's presentations, formed the building blocks of second day breakout group discussions. The third day plenary session commenced with group summary presentations and led to final workshop recommendations for the approach to revised site factors.

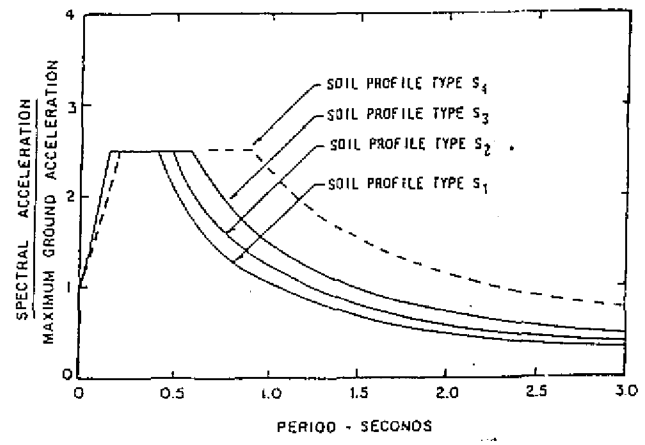
This research is part of NCEER's program in Geotechnical Engineering. Task numbers are 88-6005, 90-6002, 91-2011, 91-2511, 92-2001, and 92-2003.

Background

In current versions of design guidelines or codes for the seismic design of buildings, such as the 1991 NEHRP Provisions and the Uniform Building Code, a site or soil factors is incorporated in equivalent lateral force equations based on standardized elastic response spectra. This format, which uses four soil factors in most codes, is illustrated in figure 1

The need to re-examine the soil categories and site factors (S factors) used in building code site response provisions arose because of new research data developed since current building code provisions were formulated in the mid-1970 s as part of an Applied Technology Council study (soil categories S_1 through S_4 except for S_4 provisions, which were added following the 1985 Mexico City earthquake) Research by Seed et al (1976) formed the basis for the site categories S_1, S_2 and S_3. In addition, many concerns were being expressed in relation to the appropriateness of existing definitions of site classes for site factors Concerns included difficulties or ambiguities in classifying sites using the given definitions, the lack of inclusion of non-linear or earthquake intensity effects on the S factors and the need to include factors reflecting variations in short period response Extensive research data and new knowledge on site response effects gained in recent years further highlight the need for revisions.

In October 1991, a workshop on the effects of site soil conditions on earthquake ground motions (supported by the National Center for Earthquake Engineering Research and chaired by Robert V Whitman) was held a the State University of New York at Buffalo (Whitman, 1991) The timing of this workshop was considered particularly appropriate, in that the Structural Engineers Association of California (SEAOC) had recently made plans for a major effort to review earthquake ground motion parameters for design and the Building Seismic Safety Council (BSSC) was beginning a cycle of effort leading to the 1994 revisions of the NEHRP recommended provisions on



Site Coefficient

Soil Profile Type	Description	Site Coefficient, S
S_1	A soil profile with either: (1) rock of any characteristic, either shale-like or crystalline in nature, that has a shear wave velocity greater than 2,500 feet per second or (2) stiff soil conditions where the soil depth is less than 200 feet and the soil types overlying the rock are stable deposits of sands, gravels, or stiff clays.	1.0
S_2	A soil profile with deep cohesionless or stiff clay conditions where the soil depth exceeds 200 feet and the soil types overlying rock are stable deposits of sands, gravels, or stiff clays.	1.2
S_3	A soil profile containing 20 to 40 feet in thickness of soft- to medium-stiff clays with or without intervening layers of cohesionless soils.	1.5
S_4	A soil profile characterized by a shear wave velocity of less than 500 feet per second containing more than 40 feet of soft clays or silts.	2.0

■ Figure 1
Soil Factor Format Used in Existing Building Codes

seismic design. During the 1991 workshop, efforts were made to produce specific recommendations for changes to site effects provisions in current codes and additional related research to address the concerns expressed above. Questions considered included:

■ Do we now have the proper standard site categories?

■ Should there be more or different categories described in a different manner?

These questions were seen as fundamental to short term revisions to code guidelines planned for 1994.

The workshop favored an approach that retained a small number of categories (no more than five), but with a matrix of soil factors for each category. This matrix could provide for factors such as the impedance contrast between the soil profile and the underlying rock, intensity of ground motion (non-linearity problem), nature of the ground motion (influence of possible source effects) and variation of site effects with spectral ordinate periods of interest. It was felt that this scheme permitted a reasonable and workable balance between over-simplicity and undue complexity. The matrix of soil factors for each site category could have two (or possibly three) columns corresponding to different periods on a response spectrum plot. Horizontal rows in the matrix would then give "corrections" for additional factors.

The 1991 workshop concluded that there was a need for major studies to develop specific recommendations concerning soil factors. These studies should investigate the influence of a number of important parameters, so as to determine whether or not they have significant influence upon site effects. Significant factors could then be quantified for code-based design calculations.

Several research efforts related to the above needs were noted to be in progress at the time, including:

■ A U.S. Geological Survey study (Joyner), redoing regression analyses of spectral ordinates using a larger data base.

■ University of California at Davis research (Idriss), checking the validity of the SHAKE computer codes for predicting amplification effects for pairs of sites where recordings are available.

■ University of California at Berkeley research (Ray Seed), analyzing pairs of records (rock and soft sites) obtained during the Loma Prieta earthquake.

■ A theoretical study to evaluate appropriate values for soil factors for site response effects funded by NCEER (Dobry, Martin and Papageorgiou). This parametric study was examining the influence of the most important factors including source effects, intensity of ground shaking, impedance contrast, and soil strength.

■ Other similar studies being conducted by private consultants and industry (e.g. Geomatrix and the Electric Power Research Institute).

■ A major effort undertaken to revise the New York City and New York State building code to incorporate upgraded site factors and categories (Jacob 1990).

To effectively coordinate on-going research studies and to ensure that maximum use was made of available results in the code-updating efforts of SEAOC and BSSC, it was recommended at the 1991 workshop and at the urging of Robert Whitman, that a coordinating committee be formed. The following workshop attendees were designed members of this committee: Drs. Crouse, Dobry, Idriss, Joyner, Martin and Power. The committee met at the end of the workshop to plan its future activities, which included subsequent meetings and a further workshop to address critical issues and to develop consensus recommendations to the BSSC. The November 1992 workshop was the outcome of the committee activities.

Accomplishments

The *NCEER/SEAOC/BSSC Workshop on Site Response During Earthquakes and Seismic Code Provisions* program, documenting the agenda and speakers, is shown in figure 2. Background material was mailed to all participants prior to the workshop, including:

■ the Proceedings from the Site Effects Workshop held in October 1991, chaired by Robert Whitman;

■ publications related to recent research results on the topic of site response effects; and

■ preliminary recommendations for modifications to code provisions prepared by committee members during planning meetings.

The workshop was attended by a wide representation of 65 geoscientists, geotechnical engineers and structural engineers. In compiling a list of participants to invite to the workshop, the committee recognized the need to have representatives covering a broad range of disciplines and interests including:

■ Members of SEAOC and BSSC committees associated with recommending code revisions related to site effects;

■ geotechnical engineers and seismologists presently engaged in research on site effects; and

■ practicing geotechnical and structural engineers or "users" of code guidelines.

Draft proposals for new site coefficients were presented at the workshop by R.D, Borchert, R Dobry and R.B. Seed, and although somewhat independent, showed similarities in many areas. With strong direction from breakout session moderators, a general consensus was developed during the final plenary session as to the direction in

NCEER/SEAOC/BSSC WORKSHOP ON SITE RESPONSE DURING EARTHQUAKES AND SEISMIC CODE PROVISIONS, NOVEMBER 18, 19, AND 20, 1992 UNIVERSITY OF SOUTHERN CALIFORNIA, LOS ANGELES

AGENDA

Wednesday, November 18, 1992***

Registration, Coffee

Welcome and Introductory Remarks
- G.R. Martin, University of Southern California/SCEC
- I.G. Buckle, National Center for Earthquake Engineering Research
- C. Astill, National Science Foundation
- E.V. Leyendecker, U.S. Geological Survey

Session #1 - Objectives, Issues and Background
- M.S. Power, Moderator

R.V. Whitman - Objectives, Issues, and Background for Developing Site Response Provisions for Seismic Codes - Geotechnical Perspective

N. Youssef - Objectives, Issues, and Background for Developing Site Response Provisions for Seismic Codes - Structural Perspective

Coffee Break

N. Donovan, How do others do it? Review of Worldwide Code Approaches

Session #2 - The State of Knowledge of Earthquake Site Response
- R.V. Whitman, Moderator

K. Aki, Local Site Effects on Weak and Strong Ground Motions

R.D. Borcherdt, Characteristics of Site Response as Implied by Loma Prieta Strong Motion Data and Viscoelastic Wave Propagation Models.

Lunch

W.B. Joyner, Empirical Spectral Response Ratios for Loma Prieta Strong Motion Data

R.B. Seed, Seismic Response of Soft and Deep Clay Sites

R. Dobry, Effect of Impedance Ratio and Other Factors on Site Response

Coffee Break

I.M. Idriss, Factors Affecting Site Response Analyses and Evaluations

D.G. Anderson, EPRI/DOE Site Response Research Program

T.L. Youd, Evaluating Potential for Earthquake-induced Ground Failure

Reception with No-host Bar

Thursday, November 19, 1992***

Discussion of Proposals for Codes and Practice

Plenary Session
- G.R. Martin, Moderator

Breakout Sessions
1. Site Response - Code Provisions
   - E.E. Rinne and R. Dobry, Moderators

2. Site Response - Analytical Approaches
   - I.M. Idriss, Moderator

3. Ground Failure Code Provisions, Analytical Approaches, and Mitigation
   - R.B. Seed, Moderator

Lunch

Breakout Sessions (continued)

Coffee Break

Plenary Session - Informal Summaries by Breakout Session Moderators and Discussion
- C.B. Crouse, Moderator

Buffet Dinner, University Upstairs Cafe

Friday, November 20, 1992**

Summary, Conclusions and Recommendations
R.L. Sharpe, Moderator

Group Reports and Discussions
- E.E. Rinne and R. Dobry: Site Response - Code Provisions
- I.M. Idriss: Site Response - Analytical Approaches
- R.B. Seed: Ground Failure Code Provisions, Analytical Approaches, and Mitigation

Closure
R.L. Sharpe and G.R. Martin

■ Figure 2
Workshop Agenda and Speakers

which modifications to existing code provisions should take.

The subsequent workshop recommendations are summarized in a memorandum prepared by Rinne and Dobry (1992) to a BSSC technical subcommittee. Extracts from this memorandum are used below in summarizing the workshop recommendations.

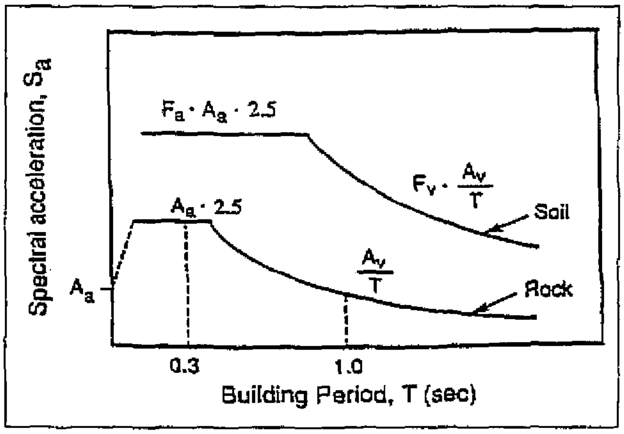
The recommended site categories were determined in terms of the average shear wave velocity in the upper 100 feet of a soil profile, as shown in table 1. Exceptions included soils with greater than 10 feet thickness of soft clay and specific site conditions where site specific studies were recommended.

Site Class	Site Class Name/ Generic Description[5]	Site Class Definition[1 3 4 5]
A_0	Hard Rock	$\bar{V}_s$ > 5,000 ft/sec
A	Rock	2,500 ft/sec < $\bar{V}_s$ < 5,000 ft/sec
B	Hard and/or stiff/very stiff soils; most gravels	1,200 ft/sec < $\bar{V}_s$ < 2,500 ft/sec
C	Sands, silts and/or stiff/very stiff clays, some gravels	600 ft/sec < $\bar{V}_s$ < 1,200 ft/sec
D	Profile containing a small-to-moderate total thickness H of soft/medium stiff clay	$\bar{V}_s$ < 600 ft/sec and/or 10 ft < H < 50 ft
D_2	Profile containing a large total thickness H of soft/medium stiff clay	$\bar{V}_s$ < 600 ft/sec and/or 50 ft < H < 120 ft
(E)[2 5]	(E_1) - Soils Vulnerable to Potential Failure or Collapse Under Seismic Loading: [Liquefiable Soils, Quick and Highly Sensitive Clays, Collapsible Weakly-Cemented Soils, etc.] (E_2) - Peats and/or Highly Organic Clays: [H > 10 ft of peat and/or highly organic clay] (E_3) - Very High Plasticity Clays: [H > 25 ft with PI > 75%] (E_4) - Very Thick "Soft/Medium Stiff Clays" [H > 120 ft]	

■ **Table 1**
Preliminary site classification for seismic site response

The proposed methodology for constructing response spectra is based on the current acceleration and velocity-based effective peak accelerations (A_a and A_v) presented in maps 3 and 4 of the 1991 NEHRP Provisions (for rock, assumed class B). However, the method could be easily modified for other spectral maps which may eventually be adopted in the provisions. The two factor approach for constructing free-field acceleration response spectra is shown in figure 3. The anchor spectrum corresponding to the current S_1 spectrum from rock (class B) is modified by site coefficients applicable to short period motion F_a and long period motion F_v. It should be noted that these spectra are intended to cover the period range of about 0.2 seconds to 3.0 seconds, or the portion of the spectra controlled by nearly constant spectral acceleration and velocity in the classic Newmark-Hall method. The method does not address the period range between 0 and about 0.2 seconds, and thus cannot be used to amplify peak acceleration or other high frequency spectral values. The factors F_a and F_v are a function of A_a and A_v, respectively, and of site classification as shown in tables 2 and 3.

The methodology, site classes, and spectral site coefficients F_a and F_v were based on draft proposals submitted to the workshop by three in-



■ **Figure 3**
Two Factor Approach to Defining Design Spectra

vestigators: R.D. Borcherdt, R. Dobry, and R.B. Seed. These three draft proposals, developed independently but using the same general ground rules, took advantage of extensive research efforts by a number of researchers on the subject of site response, which intensified after the 1989 Loma Prieta earthquake and in preparation for the workshop. Analytical and empirical studies by K. Aki, R.D. Borcherdt, W.B. Joyner, W. Silva, M. Ordaz, R. Dobry, G.R. Martin, R.V. Whitman, J. Taylor, R B. Seed, and I.M. Idriss played especially important roles in the preparation of the three draft proposals and in the discussions at the workshop.

It is appropriate to briefly review some of the above studies and the role they played in defining the site classes and values of F_a and F_v:

W. Silva: Study of response of rocks of different stiffnesses. This study helped define site class A_0 and the corresponding F_a and F_v.

K. Aki: Empirical studies of earthquake records, and especially the coda wave arrivals, which helped bound the F_a and F_v values at low levels of shaking for various site conditions.

R. D. Borcherdt: Empirical studies from nuclear explosions and Loma Prieta records obtained on a variety of site conditions up to about 0.10 g peak acceleration on rock. These studies showed a consistent, although widely scattered relationship between low and high-period site response and average shear wave velocity in the top 100 feet of the soil profile, which greatly influenced the recommended site classes.

M. Ordaz. Empirical studies of records at more than 30 stations on soft clay obtained in Mexico City in recent years, which confirmed the influence of average shear wave velocity on site amplification.

W. B. Joyner: Empirical studies of Loma Prieta records, which supplemented Borcherdt's results and added useful information about the influence

Shaking Intensity → / Site Class ⇓	A_a = 0.1 g	A_a = 0.2 g	A_a = 0.3 g	A_a = 0.4 g	A_a = 0.5 g
(A_0)	0.8	0.8	0.8	0.8	0.8
A	1.0	1.0	1.0	1.0	1.0
B	1.2	1.2	1.1	1.0	1.0
C	1.6	1.4	1.2	1.1	1.0
D_1	2.5	1.7	1.2	0.9	(--)[1]
D_2	2.0	1.6	1.2	0.9	(--)[1]
(E)	(--)[1]	(--)[1]	(--)[1]	(--)[1]	(--)[1]

[1] Site-specific geotechnical investigations and dynamic site response analyses should be performed.

■ **Table 2**

Values of F_a as a Function of Site Conditions and Shaking Intensity

Shaking Intensity → / Site Class ⇓	A_v = 0.1 g	A_v = 0.2 g	A_v = 0.3 g	A_v = 0.4 g	A_v = 0.5 g
(A_0)	0.8	0.8	0.8	0.8	0.8
A	1.0	1.0	1.0	1.0	1.0
B	1.7	1.6	1.5	1.4	1.3
C	2.4	2.0	1.8	1.6	1.5
D_1	3.5	3.2	2.8	2.4	(--)[2]
D_2	3.5	3.2	2.8	2.4	(--)[2]
(E)	(--)[2]	(--)[2]	(--)[2]	(--)[2]	(--)[2]

[2] Site-specific geotechnical investigations and dynamic site response analyses should be performed

■ **Table 3**

Values of F_v as a Function of Site Conditions and Shaking Intensity

of a soft clay layer thickness on low- and high-period site amplification.

R. B. Seed and I. M. Idriss: Very comprehensive analytical and empirical studies of site response of a number of site conditions. The analytical methods were empirically calibrated to the Loma Prieta strong motion records prior to their use for higher levels of shaking

R. Dobry and G. R. Martin: A large number of analytical studies of site response for a wide range of site conditions. These parametric studies were especially helpful in the evaluation of thickness boundaries for soft soils and exceptions needing site specific analytical studies.

R. V. Whitman and J. Taylor: Analytical site response studies, including parametric calculations and analyses of response of soil profiles representative for several U.S. cities.

These and other studies resulted in the three draft proposals presented by Borcherdt, Dobry and Seed at the workshop, which—after verifying that there were no substantial differences between them—were merged during the workshop into the consensus proposal described in figure 3 and tables 2 and 3. It is emphasized that the proposed values of F_a and F_v in tables 2 and 3 for low A_a ª 0.1 g and A_v ª 0.1 g are firmly grounded in empirical results, especially from the Loma Prieta earthquake. At these low levels of rock acceleration, the values of F_a and F_v obtained from the empirical and analytical studies agree well, and this provided a calibration point for the analytical techniques used (mostly one-dimensional equivalent linear and nonlinear codes). On the other hand, the values of F_a and F_v at high A_a and A_v such as 0.4 g are mostly based on these calibrated analytical techniques.

While the F_a and F_v values of tables 2 and 3 appear to represent a significant increase in the current S factors, this increase in less significant when compared to the relative spectral values for various conditions presently in the UBC and the NEHRP Commentary.

Some comment on the risk levels and uncertainties relative to the recommended method is appropriate. The method generally applies to the 90% probability of non-exceedance in 50 years that forms the basis for present codes. It does not, however, incorporate the uniform risk approach used in the spectral maps. The areas of uncertainty and the method used in dealing with it can be summarized as follows:

■ Use of the current A_a and A_v map values should recognize that these maps were prepared over 20 years ago, using historical data available at the time and mean attenuation relationships that do not account for variability. In addition, the values are truncated to 0 40 g maximum. These effects may lead to unconservative results particularly in high seismicity zones near active faults. Site specific studies are recommended within 10 km of an active fault to better evaluate near fault conditions.

■ The F_a values in table 2 generally represent mean values based on the limitations of the studies. There is considerable uncertainty at higher rock input motions due to limited empirical data and analyses of same. In addition, the degree of uncertainty in these values is not incorporated into the method which could have either over or under conservative implications depending on the site.

■ The F_v values in table 3 generally represent mean plus about one sigma because the actual value is highly variable depending on the specific period being considered, site conditions and input motion. In the period range of highest site amplification (typically associated with resonance near the site period), the proposed F_v values are well below the mean, while at periods of relatively low amplification, they are much higher than the mean. The selection of mean plus sigma was made to provide better protection for the high amplification period range although it is still below the mean based on both analytical and empirical results near the site period.

Conclusions

The recommendations described in this paper, with some refinements, have been recommended by the BSSC Council for inclusion in the 1994 NEHRP seismic design provisions. (Refinements included complementary site category definitions based on standard penetration blowcounts and undrained shear strengths.) The site categories are now more clearly defined, and reflect the effects of non-linear soil behavior as well as observational data from recent earthquakes. The site factor modifications clearly provide improvement to the shortcomings of the existing factors.

In commenting on the effects of the new provisions, Rinne (1994) noted that the main impact of the new site factors is the dramatic increase in soft soil amplification in lower seismicity portions of the country. The inclusion of the short period F_a factor will affect designs in all areas since the current code uses $F_a = 1$. However, the effect is particularly significant in low to moderate seismicity areas. Rinne (1994) cites the example of the eastern part of the country characterized on NEHRP maps with A_a and A_v less than or equal to 0.10 g. For this case, the equivalent static force with the new coefficients may increase 20 to 250 percent for short period structures and 20 to 60 percent for long period structures depending on the soil conditions. On the other hand, the increase for structures in the highest seismicity zone in the west is less than 10 percent. The reason for this is the nonlinearity of soil modulus and damping properties which decreases soil amplification at higher input motion.

Personnel and Institutions

The Workshop organizing committee formed at the 1991 NCEER Workshop convened by Robert Whitman and included the following members: R.D. Borchert (USGS Menlo Park), C.B. Crouse (Dames and Moore, Seattle), R. Dobry (RPI/NCEER), I.M. Idriss (UC-Davis), W. Joyner (USGS Menlo Park), G.R. Martin, (USC/NCEER-Workshop convener), and M.S. Power (Geomatrix, San Francisco-Chairman). E.E. Rinne (Kleinfelder Inc., Walnut Creek - BSSC representative), R.B. Seed (UC-Berkeley), W. Silva (Consultant), and J. Schneider (EPRI) also participated in several committee meetings. The financial support of the National Science Foundation (Clifford Astill-program coordinator), the U.S. Geological Survey and NCEER ensured the success of the Workshop.

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