# Practical Use of Geotechnical Site Response Models

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**Abstract:** Tools and techniques for geotechnical site response analyses have developed significantly over the past 30 years. This paper reviews the basic types of site response analyses that can be performed, identifies the main computer programs used for such analyses in practice, and presents the results of an informal survey of practitioners regarding site response analysis practice. The survey provides insight into the manner in which site response analyses are performed and their results interpreted in contemporary geotechnical engineering practice.

## Introduction

Site response analyses have been conducted by practicing geotechnical engineers for over 30 years. Certain elements of this practice have undergone dramatic changes during this period, while others remain very much the same. This paper reviews the development of site response analysis tools, describes the basic approaches to site response analysis that are available to practicing engineers, and presents the results of an informal survey of site response models used in contemporary geotechnical engineering practice.

## Historical Development

Site response analyses began making their way into geotechnical engineering practice in the early 1970s with the development of SHAKE (Schnabel et al., 1972). Within a few years, additional site response programs such as QUAD-4 (Idriss et al., 1973) and FLUSH (Lysmer et al., 1975), were available. Nonlinear site response analyses became available shortly after SHAKE with codes such as CHARSOIL (Streeter et al., 1974), DESRA (Lee and Finn., 1978), and MASH (Martin and Seed, 1978). The use of these codes must be considered in the context of computer facilities that were available at the time – the codes were developed and compiled on mainframe computers, input was typically via punch cards, and output consisted of printed numbers on large sheets of folded paper. Running an analysis usually involved driving to a computer center, typing the input files (with perfect formatting) on punch cards, running the input through a card reader, waiting several hours (if not overnight) for the job to be executed, and manually plotting the results on graph paper.

Site response analyses became easier with the advent of improved input/output devices, easier again with the introduction of the personal computer, and easier yet with the development of graphical user interfaces. Fortran compilers allowed at least one-dimensional site response programs to be ported from mainframe computers to PCs in the early 1980s, with multi-dimensional analysis programs following somewhat later. Windows-based site response codes are now available with built-in menus of soil models and extensive graphics capabilities for plotting both input and output quantities.

## Classes of Site Response Models

Equivalent linear and nonlinear models can be used to estimate ground response at a soil site due to earthquake shaking. Verification studies have shown that the two model types produce similar results when shear strains in the soil are low, which typically occurs when the ground motions are weak or the site consists of stiff soils. Nonlinear models can more accurately capture response for sites that experience higher strains (i.e. soft soil sites, liquefiable sites, and/or strong motions) by using advanced constitutive models. Higher dimensions can be used for each of the models, depending on the complexity and importance of the problem.

### Equivalent Linear Models

Equivalent linear models use an iterative approach to approximate the nonlinear, inelastic behavior of soils. An average shear modulus, $G_{sec}$, is used over an entire cycle of loading to approximate the hysteresis loop. While equivalent linear material parameters that are iteratively adjusted to be consistent with an effective level of shear strain can be found, the analysis is nevertheless linear.

The method is computationally efficient and provides reasonable results for many cases, especially for those where small strains (< 1-2%) and modest accelerations (<0.3-0.4 g) develop. The linear approach allows computation of the bedrock motion from a given free surface motion, or deconvolution. The reliability of deconvolved motions should be carefully evaluated on a case by case basis.

There are a few limitations to the using the equivalent linear model. Because the model is linear, it cannot be used to calculate permanent displacements since the shear strain returns to zero after loading is complete. The inherent linearity of the soil can also lead to spurious resonances that would not occur in the field. Moreover, the equivalent linear model is not capable of modeling pore pressures because a total stress approach is used in the analysis. Proper selection of an effective shear strain is required to prevent over- or under-softening of the response.

### Nonlinear Models

The response of nonlinear models is determined through direct numerical integration of the equation of motion in small time steps (e.g. explicit finite difference technique). Nonlinear models can account for the nonlinear behavior of soil using various constitutive soil models. The constitutive models implemented in various nonlinear model programs have different features that can include using updated stress-strain relationships, pore-pressure generation, and/or cyclic modulus degradation. These features, unavailable in the equivalent linear model, allow more accurate calculations of soil behavior.

Because they may be formulated in terms of effective stresses, unlike equivalent linear models, nonlinear models can account for the build up of porewater pressure that can cause the soil to soften. An important application of nonlinear soil models is in liquefaction hazard analysis. The wave equation solution can be combined with the numerical solution of the diffusion equation to compute the redistribution and dissipation of excess porewater pressures. Nonlinear models can also predict permanent deformations since the strain does not return to zero following cyclic loading.

The accuracy of a nonlinear site response model depends on the constitutive model it uses; good constitutive models require numerous parameters which must be determined through lab tests and/or field tests. This amount of effort required to develop the required parameters for accurate models often limits their frequency of use. Nonlinear models tend to be necessary for analyses where large strains or displacements are expected.

### Dimensions

Both model types can be used for one-, two-, and three-dimensional problems. One-dimensional analyses assume that the ground surface and soil layers below the ground surface extend infinitely in all lateral directions. Based on these assumptions, one-dimensional analyses are computationally efficient for level or gently sloping sites with parallel material boundaries.

Two-and three-dimensional analyses require considerably more computation time, due to the increased complexity in the model, compared to their one-dimensional counterparts. Dynamic finite-element analyses are used to compute the responses. The computational efficiency and the assumptions of the models, whether equivalent linear or nonlinear, are similar to those in one-dimension.

Anisotropy, irregular soil stratigraphy, and inclined material boundaries may be taken into account in multi-dimensional analyses. Two-dimensional analyses are commonly used for geotechnical structures that can be idealized as plane strain problems, e.g. retaining walls, earth dams, tunnels, etc. Moreover, 2-D nonlinear analyses can be used to estimate permanent displacements as well as dynamic ground motions, and can be extended to evaluate soil-structure interaction problems. Three-dimensional analyses add additional degrees of freedom to the model, but are useful when the boundary conditions of the problem or the motions vary significantly in three dimensions.

## Available Codes

A significant number of computer programs are now available for site response analyses. These programs can be divided in different ways, but it is useful to distinguish them on the basis of general soil model (equivalent linear vs. nonlinear), dimensions (1-D, 2-D, or 3-D), and interface (DOS- or Windows-based). Any listing of such programs is likely to be incomplete, but an attempt is made in Table 1 below.

Table 1 shows that geotechnical engineers have a variety of equivalent linear and nonlinear codes to choose from for one- and multi-dimensional site response analyses. Some of the codes are very widely used, for example SHAKE and its numerous DOS- and Windows-based derivatives. Some of the Windows-based equivalent linear codes operate essentially as pre-processors and post-processors for SHAKE91, while other were written completely from scratch. The Windows-based codes generally offer convenient plotting of input data (soil profile and ground motions) and resulting output. FLUSH and QUAD4 are well established and widely used two-dimensional, DOS-based, equivalent linear codes; QUAKE/W is similar to QUAD4, but has a Windows GUI. Nonlinear codes are somewhat less well established with DESRA remaining popular for one-dimensional analyses and a variety of DOS-based programs for nonlinear 2-D and 3-D analyses. General purpose geotechnical analysis codes such as FLAC and PLAXIS now have dynamic analysis capabilities and are becoming increasingly popular for such applications.

**Table 1. Geotechnical computer codes used in practice for site response analysis.**

| Dimensions | OS | Equivalent Linear | Nonlinear |
|---|---|---|---|
| 1-D | DOS | Dyneq, Shake91 | AMPLE, DESRA, DMOD, FLIP, SUMDES, TESS |
| | Windows | ShakeEdit, ProShake, Shake2000, EERA | CyberQuake, DeepSoil, NERA, FLAC, ShearBeam |
| 2-D / 3-D | DOS | FLUSH, QUAD4/QUAD4M, TLUSH | DYNAFLOW, TARA-3, FLIP, VERSAT, DYSAC2, LIQCA |
| | Windows | QUAKE/W, SASSI2000 | FLAC, PLAXIS |

## Current Practice

In order to obtain a better understanding of which geotechnical site response models are actually being used in practice, a brief and informal survey was developed and sent to a number of individuals that practice in the area of geotechnical earthquake engineering. The survey, reproduced in Appendix A, was sent to two groups: (1) attendees at the recent ICSDEE/ICEGE conference in Berkeley, and (2) members of EERI working for geotechnical engineering firms and agencies with email addresses listed in the 2003 EERI Membership Roster. The list of people to whom the survey was sent included private firms and public agencies in the United States and other countries; it should be emphasized, however, that the list was not developed with any explicit consideration of statistical concepts – the results of the survey, therefore, may be biased and unrepresentative of the distributions of site response models and practices that are actually used. Nevertheless, the survey fulfilled its original goal of identifying geotechnical site response models used in practice, and provided additional insights into the manner in which engineers use those models.

## Background

The survey, which consisted of 10 questions, was emailed to a list of 204 individuals, 55 of whom responded. The questions were generally multiple choice, but a few requested that respondents assign percentages to various choices and others requested that users indicate multiple selections where appropriate. In several cases, these instructions appeared to have caused some confusion (for example, sums of percentages from individuals that added up to values well over 100), which complicated interpretation of some of the responses. Several of the questions requested that the respondents provide other information if the listed choices were not representative of their practice. Finally, the respondents were encouraged to provide additional comments on the general subject matter and on issues that they felt were important to advancing the practice of seismic site response analysis.

## Survey Respondents

The majority of the survey respondents (35 of 55) were from private firms in western North America (WNA). Smaller numbers were from private firms (6) in eastern North America (ENA) and from overseas firms (5). A number of responses came from public agencies in WNA (3), ENA (1), and overseas (5).

The respondents represented firms/agencies with a wide variety of sizes; some were describing their own practices and others the practices of their firm or agency. Some indicated that their responses represented their own views and practices, and others indicated that their responses were representative of the practice of firms with many engineers. An attempt to consider these factors was made in the interpretation process.

## Methods of Analysis

The responses clearly showed that one-dimensional, equivalent linear analyses are far and away the most commonly used method in contemporary geotechnical engineering practice in North America. When asked to estimate the percentages of different types of analyses (relative to the total number of site response analyses performed), both private firms and public agencies in WNA and ENA indicated that they used one-dimensional equivalent linear analyses much more frequently than other types of analyses (Table 2). Interestingly, the small number of overseas respondents indicated that they use other methods, particularly nonlinear methods, more frequently than equivalent linear methods. Some North American respondents pointed out that site response efforts are usually controlled by budget and time constraints; others expressed concern that equivalent linear analyses were frequently being used for soft clay and liquefiable sites and for very strong levels of shaking where their inherent assumptions about material behavior are least valid.

The computer codes used to perform these analyses were the ones listed in Table 1. Determination of the percentages of use of each program proved difficult because many respondents responded generically (e.g. listing SHAKE for any of the suite of DOS- and Window-based one-dimensional equivalent linear analysis programs). Several respondents also listed large, general purpose, finite element codes (e.g. ADINA) without any description of how they were used for geotechnical site response analysis.

**Table 2.** **Distribution of methods of site response analysis used in practice (in percent). Actual number of respondents indicated in parentheses; percentages are not weighted by size of firm/agency.**

| Method of Analysis | WNA | | ENA | | Overseas | |
|---|---|---|---|---|---|---|
| | Private (35) | Public (3) | Private (6) | Public (6) | Private (5) | Public (5) |
| 1-D Equivalent Linear | 68 | 52 | 86 | 50 | 24 | 5 |
| 1-D Nonlinear | 11 | 17 | 12 | 0 | 48 | 5 |
| 2-D/3-D Equiv. Linear | 9 | 28 | 1 | 25 | 6 | 0 |
| 2-D/3-D Nonlinear | 12 | 3 | 1 | 25 | 23 | 90 |

Equivalent linear analyses require characterization of soil properties by modulus reduction and damping curves, and a number of relationships for such curves have been presented in the literature. In the 1970s, separate curves were presented for sands and for clays before the effects of soil plasticity and effective confining pressure on soil behavior were well understood. The responses to the informal survey showed, however, that the original sand and clay curves are still widely used in contemporary practice (Table 3). It should be noted, however, that the respondents were asked to check boxes of the models they “usually use” for equivalent linear site response analyses; the fact that a particular box was checked does not indicate the relative frequency with which it is used. The “other” models reported included linear models, Schnabel’s rock model, Seed’s gravel model, Darendeli’s model, Sun et al.’s model, and in-house curves for specific soils.

**Table 3.** **Distribution of equivalent linear soil models used in practice (in percent). Percentages are not weighted by size of firm/agency, and should be interpreted as the percentage of respondents reporting common use of a particular model.**

| Equivalent Linear Soil Model | WNA | | ENA | | Overseas | |
|---|---|---|---|---|---|---|
| | Private (35) | Public (3) | Private (6) | Public (6) | Private (5) | Public (5) |
| EPRI | 48 | 33 | 17 | 0 | 0 | 0 |
| Ishibashi-Zhang | 12 | 0 | 0 | 0 | 20 | 0 |
| Iwasaki | 9 | 0 | 0 | 0 | 0 | 0 |
| Seed-Idriss Clay | 91 | 100 | 100 | 17 | 40 | 60 |
| Seed-Idriss Sand | 76 | 67 | 50 | 17 | 20 | 20 |
| Vucetic-Dobry | 82 | 67 | 83 | 0 | 20 | 0 |
| Other | 44 | 33 | 33 | 0 | 40 | 20 |

Nonlinear site response analyses also require soil models, though the manner in which the model is parameterized varies with the model – as a result, comparison is much more difficult than for equivalent linear site response analyses. The responses to the survey indicate that the choice of nonlinear soil model was closely tied to the choice of nonlinear site response code since most nonlinear codes do not offer multiple soil models. Hyperbolic models with Masing rules and Mohr-Coulomb models were the most widely reported nonlinear soil models.

The survey included one question about how soil properties were "typically obtained" for use in site response analyses. Almost all respondents (Table 4) indicated that they obtain properties by correlation to field test results; again, the survey does not indicate how often this approach is used. Field testing was listed by most respondents, as was empirical correlation to index test results. The use of laboratory testing was reported by a minority of North American firms and agencies, but by a large majority of overseas respondents.

**Table 4. Methods for obtaining soil properties for use in site response analyses (in percent). Percentages are not weighted by size of firm/agency, and should be interpreted as the percentage of respondents using a particular method.**

| Method for obtaining soil properties for site response analysis | WNA | | ENA | | Overseas | |
|---|---|---|---|---|---|---|
| | Private (35) | Public (3) | Private (6) | Public (6) | Private (5) | Public (5) |
| Laboratory testing | 43 | 33 | 33 | 17 | 100 | 80 |
| Field testing | 83 | 100 | 100 | 17 | 80 | 60 |
| Empirical correlation to field test results | 100 | 67 | 83 | 17 | 80 | 60 |
| Empirical correlation to index test results | 71 | 100 | 17 | 0 | 40 | 20 |
| Empirical correlation to depth | 26 | 33 | 0 | 0 | 0 | 20 |
| Other | 11 | 0 | 0 | 0 | 40 | 0 |

### Consideration of Uncertainties

The results of site response analyses, like those of all other analyses, are influenced by uncertainties in input parameters. The survey attempted to determine the users' perceptions of the parameters for which uncertainties influenced the results of site response analyses most strongly, and how uncertainties were accounted for in the design process.

The survey listed a series of input parameters to typical site response analyses and asked which were considered most important – respondents could (and did) indicate more than one parameter. The North American respondents consistently indicated (Table 5) that uncertainties in input motions were most important, with one user expressing particular concern in ENA where few recorded ground motions are available. Uncertainties in material properties (stiffness and damping at low and high strain levels) were also considered to be very important. Uncertainties in geometry and bedrock properties were considered to be among the most important uncertainties by a small percentage of respondents. The small sample of overseas respondents put more emphasis on material properties than on input motions.

A number of different methods for accounting for uncertainties in design were reported (Table 6). The most common method listed by North American respondents was the use of sensitivity analysis; details on how the results of sensitivity analyses were interpreted were not requested. About one-third of the total number of respondents based their analyses on best-estimate values of input parameters and then applied some degree of conservatism to the results. The use of sensitivity analyses was not reported by any of the overseas respondents. Other respondents reported using suites of input motions to "bracket" response, and using attenuation relationships to check results. One user stated that the best way to account for uncertainty is to use "experience and judgment with regard to the computed response."

**Table 5.** **Distribution of most important uncertainties in site response analysis input parameters (in percent). Percentages are not weighted by size of firm/agency, and should be interpreted as the percentage of respondents describing a particular input parameter as most important.**

| Most important uncertainties in site response input | WNA | | ENA | | Overseas | |
|---|---|---|---|---|---|---|
| | Private (35) | Public (3) | Private (6) | Public (6) | Private (5) | Public (5) |
| Low-strain stiffness (i.e., $G_{max}$ or $V_s$) | 43 | 33 | 67 | 0 | 40 | 20 |
| Higher strain stiffness (i.e. $G/G_{max}$) | 51 | 67 | 17 | 17 | 60 | 20 |
| Damping behavior | 57 | 0 | 33 | 0 | 40 | 20 |
| Soil layer thicknesses | 17 | 33 | 17 | 0 | 0 | 0 |
| Depth to bedrock | 20 | 0 | 0 | 0 | 20 | 0 |
| Character of bedrock | 14 | 0 | 0 | 0 | 0 | 0 |
| Input motions | 83 | 100 | 67 | 0 | 20 | 20 |
| Other | 26 | 67 | 0 | 0 | 40 | 40 |

**Table 6.** **Methods of accounting for uncertainties in site response analysis input parameters (in percent). Percentages are not weighted by size of firm/agency, and should be interpreted as the percentage of respondents describing a particular method.**

| Method of accounting for uncertainties in design | WNA | | ENA | | Overseas | |
|---|---|---|---|---|---|---|
| | Private (35) | Public (3) | Private (6) | Public (6) | Private (5) | Public (5) |
| Select reasonably conservative values of input parameters | 20 | 0 | 0 | 0 | 20 | 20 |
| Use "best estimate" values of input parameters, then apply conservatism to results | 34 | 67 | 50 | 0 | 20 | 20 |
| Perform sensitivity analyses | 74 | 100 | 67 | 100 | 0 | 0 |
| Perform probabilistic analyses (e.g. FOSM, Monte Carlo) | 11 | 33 | 0 | 0 | 20 | 0 |
| Don't address uncertainties explicitly | 0 | 0 | 0 | 0 | 0 | 20 |
| Other | 17 | 0 | 17 | 0 | 20 | 20 |

## Summary and Conclusions

Tools and techniques for site response analysis have developed considerably over the past 30 years. Some of the improvements have resulted from advancements in computer hardware and software, which have greatly improved the ease-of-use of various site response procedures. This improved ease-of-use is significant in practice because it allows analyses to be performed more easily and more quickly – as a result, practitioners can afford to perform sensitivity analyses and to use larger suites of input motions. The use of automated graphics capabilities allow error-checking of input data and evaluation of the reasonableness of analytical results. Ground response animation, available in some Windows-based codes, can provide extremely useful insight into site response.

Other improvements have resulted from the development of more advanced analytical models, particularly for nonlinear, effective stress modeling of site response. Multi-dimensional nonlinear analysis codes employing advanced, plasticity-based constitutive models are now available. The use of nonlinear models for one-dimensional analyses is becoming more common, but multi-dimensional nonlinear analyses are not frequently used. Part of the reason for this is the increased engineering time they require, but part is also due to the fact that the analytical procedures have developed much more quickly than practical procedures for developing the input parameters those analytical procedures require.

An informal survey of geotechnical earthquake engineering practitioners yielded useful information on the tools and procedures currently used in practice. The survey was not developed with formal statistical sampling concepts in mind, so its results should not be interpreted as though it was. Nevertheless, it provides insight into contemporary practice, particularly in WNA. The survey indicates that one-dimensional, equivalent linear analyses are by far the most commonly used in North American, but not among the overseas respondents to the survey. For these analyses, a number of equivalent linear soil models are used, with the relatively old Seed-Idriss sand and clay curves retaining a striking level of popularity. Dynamic soil properties appear to be most commonly determined by field testing and empirical correlation in North America; the use of laboratory testing was much more commonly reported by overseas respondents. North American respondents considered uncertainties in input motions to have the greatest influence on site response analyses, while overseas respondents appeared to be more concerned about uncertainties in material properties. Finally, sensitivity analyses appeared to be the most common tool for evaluating the effects of uncertainties on computes site response.

In summary, it appears that one-dimensional, equivalent linear analyses have become the *de facto* standard for site response prediction in North American practice. It also appears that users have concerns about the applicability of equivalent linear analyses for the cases for which site-specific response analyses are most useful – soft sites, liquefiable sites, and sites subjected to very strong shaking. Their adoption of nonlinear analyses, however, appears to be restrained by uncertainty in how to develop the input parameters required for available nonlinear models, and by the lack of well-documented validation studies for those models. These limitations must be overcome for nonlinear site response analysis to become accepted in geotechnical earthquake engineering practice.

### References

Idriss, I.M. (1973) “QUAD-4: a computer program for evaluating the seismic response of soil structures by variable damping finite element procedures,” July 1973

Lee M.K.W. and Finn W.D.L. (1978). “DESRA-2, dynamic effective stress response analysis of soil deposits with energy transmitting boundary including assessment of liquefaction potential’, Soil Mech. Series No. 38, Dept. of Civil Eng., Univ. of British Columbia, Vancouver B.C.

Lysmer, J., Udaka, T., Tsai, C.F., and Seed, H.B. (1975). "FLUSH - A computer program for approximate 3-D analysis of soil-structure interaction problems," *Report No. EERC 75-30*, Earthquake Engineering Research Center, University of California, Berkeley, California, 83 pp.

Martin, P.P. and Seed, H.B. (1978). “MASH – A computer program for the nonlinear analysis of vertically propagating shear waves in horizontally layered deposits,” Report No. UCB/EERC-8/23, University of California, Berkeley.

Schnabel, P.B., Lysmer, J., and Seed, H.B. (1972). “SHAKE – A computer program for earthquake response analysis of horizontally layered soils,” Report No. EERC-72/12, University of California, Berkeley.

Streeter, V.L., Wylie, E.B. and Richart, F.E. (1973). "Soil motion computations by characteristics methods," *Proceedings*, ASCE National Structural Engineering Conference, San Francisco, California.

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## Appendix A - Email Survey

Please respond to each question by inserting an X or a numerical/text response in the square brackets provided for each question.

1. Do your following responses apply to:

[ ] a. your own individual practice?
[ ] b. the practice of your office? If so, please indicate # of engineers [ ]
[ ] c. the practice of your firm/agency? If so, please indicate # of engineers [ ]

2. Approximately how many of your projects involve site response analyses in a given year?

[ ] a. 1-2
[ ] b. 3-6
[ ] c. 7-12
[ ] d. 12-25
[ ] e. 26-50
[ ] f. >50

3. Of the total number of site response analyses you perform, indicate the approximate percentages that fall within each of the following categories:

[ ] a. One-dimensional equivalent linear
[ ] b. One-dimensional nonlinear
[ ] c. Two- or three-dimensional equivalent linear
[ ] d. Two- or three-dimensional nonlinear

4. What computer program(s) do you use for each of the following types of analyses (list more than one if appropriate; leave blank if you do not perform one of these types of analyses)?

One-dimensional equivalent linear: [ ]
One-dimensional nonlinear: [ ]
Two- or three-dimensional equivalent linear: [ ]
Two- or three-dimensional nonlinear: [ ]

5. What soil models do you usually use for equivalent linear site response analyses (mark each with an X)?

[ ] a. EPRI
[ ] b. Ishibashi-Zhang
[ ] c. Iwasaki
[ ] d. Seed-Idriss sand
[ ] e. Seed-Idriss clay
[ ] f. Vucetic-Dobry
[ ] g. Other (please describe): [ ]

6. What soil models do you usually use for nonlinear site response analyses (mark each with an X)?

[ ] a. Hyperbolic with Masing criteria
[ ] b. Mohr-Coulomb
[ ] c. Whatever model is included with my nonlinear analysis program
[ ] d. Other (please describe): [ ]

7. When you evaluate cyclic stress ratio (CSR) for liquefaction analyses, how often do you do so by means of site response analyses (as opposed to using the simplified method)? [ %] What criteria do you use for deciding when to do so? [ ]

8. What do you consider to be the most important uncertainties in the input to a typical seismic site response analysis?

[ ] a. Low-strain stiffness (represented by Gmax or Vs)
[ ] b. Higher strain stiffness (represented by modulus reduction or backbone curve)
[ ] c. Damping behavior (represented by damping curve or unloading-reloading model)
[ ] d. Soil layer thicknesses
[ ] e. Depth to bedrock
[ ] f. Character of bedrock (Vs, modulus reduction and damping behavior)
[ ] g. Input motions
[ ] h. Other (please describe): [ ]

9. How do you typically account for such uncertainties in design?

[ ] a. Select reasonably conservative values of input parameters
[ ] b. Use "best estimate" input parameters, then apply conservatism to results
[ ] c. Perform sensitivity analyses
[ ] d. Perform probabilistic analyses (e.g. FOSM, Monte Carlo)
[ ] e. We don't address uncertainties explicitly
[ ] f. Other (please describe): [ ]

10. How do you typically obtain soil properties (stiffness and damping characteristics) for input into your site response analyses (please list approximate percentages)?

[ ] a. Laboratory tests (cyclic triaxial, resonant column, etc.)
[ ] b. Measurement using field tests (downhole, seismic cone, SASW)
[ ] c. Empirical correlation to field test results (SPT, CPT, etc.)
[ ] d. Empirical correlation to index tests (e.g. to PI via Vucetic-Dobry model)
[ ] e. Empirical correlation to depth (e.g. as in EPRI model)
[ ] f. Other (please describe): [ ]

Please feel free to list any comments you have on any of the questions or on the general subject matter, particularly issues you feel are important to advancing the practice of seismic site response analysis.