VARIABILITY IN SITE-SPECIFIC SEISMIC GROUND-MOTION DESIGN PREDICTIONS

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Abstract

Variability in computed site-specific seismic ground motion is examined over a wide range of periods using a stochastic model which incorporates both a finite source and an equivalent-linear formulation for non-linear site effects. A suite of examples involving a single scenario earthquake and a range of site conditions, source-to-site distances, and depths of characterization are used to illustrate how parametric variability can be systematically examined on a case-specific basis. Emphasis is placed on the relative contributions of geotechnical site parameters including the shear-wave velocity (Vs) profile and both modulus reduction (G/Gmax) and hysteretic damping (D) curves. It is shown that the parameters which control variability in ground-motion predictions are a case-specific function of site type, amplitude of motion, and period range of interest to the designer. The impact of site effects is shown to be the predominant source of parametric response-spectra variability for periods of up to several seconds for soil sites experiencing strong to moderate levels of ground motion. All results are described within the framework of parametric and modeling components of total variability in design predictions, and general trends are developed regarding conditions where extensive geotechnical site characterization efforts provide maximum benefit.

Introduction

Earthquakes pose one of nature's greatest engineering-design challenges due, in part, to the wide variability of possible motions which a particular site may experience. Empirical observations show that variations in spectral ordinates (e.g. peak ground acceleration) can span an order of magnitude for sites located at the same distance from a given earthquake. "Attenuation relationships", which provide a functional relationship of site response for a given combination of distance and magnitude, can be used to characterize median response as well as a range of possible motions. However, such relationships are quite generic in that they are developed from instrumental recordings obtained from sites overlying a wide range of subsurface conditions. Furthermore, these relationships are poorly constrained at

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close distances to large magnitude events, an area of great concern to the design of many important facilities.

A variety of modeling approaches can be applied to develop ground-motion estimates for a particular site and earthquake scenario. For the design of important facilities, seismologists are often charged with developing scenario motions appropriate for "rock", and geotechnical engineers typically modify the "rock motion" on the basis of a local site profile to obtain a "site-specific" estimate of ground motion. Unfortunately, meaningful characterization of variability (often called "uncertainty"; see next section) is often lost in this chain-of-design approach. Recently, more comprehensive modeling approaches have become available which allow consistent treatment of parametric variabilities in source, path, and site parameters which contribute to overall ground motion estimates. Such approaches can be used either for site-specific estimation of ground motion, or as a means to extend existing empirically-based attenuation relationships into poorly constrained regions of magnitude-distance-site space. One such technique will be used herein to examine the role which geotechnical site characterization offers in terms of reducing variability in ground-motion estimation.

No discussion of ground-motion variability would be complete without noting that, in many cases, the greatest unknown in ground-motion estimation centers on the likelihood of occurrence of an event which has a potentially damaging combination of magnitude and distance within the "design life" of a facility. Such time-dependent considerations are the realm of probabilistic seismic hazard analysis [NRC, 1988], which is beyond the scope of this paper. However, even probabilistic hazard analyses are strongly influenced by variability in attenuation relations, and for highly active regions, the range of motion for a particular event may dominate the overall variability in hazard.

Nomenclature on Variability, Uncertainty, and Randomness

Modeling of physical phenomena, such as earthquake ground motions, generally yields a range of possible estimates which depend on model form, assumptions, and parameter values. In many disciplines, such a range in estimates is termed "uncertainty", however, this term is used quite generally and can have a variety of interpretations. An alternative nomenclature is used in the field of seismic hazard analysis which allows partitioning of the causes of a range of estimates into various components [Toro, et. al., 1994, Abrahamson, et. al., 1990]. This paper adopts this alternative nomenclature in which "variability" is the generic term used to denote the range of estimates (i.e. ground response), and variability is viewed as having components of both "uncertainty" and "randomness". Furthermore, for purposes of modeling ground motions, total variability is also partitioned into "modeling variability" and "parametric variability", each having components of uncertainty and randomness.

Table 1 outlines the four components of total variability identified by this nomenclature in the context of ground-response predictions. Generally, modeling variability is a measure of how well a model works when parameter values are known, while parametric variability is the sensitivity of a model to a viable range of values for model parameters. Viewing Table 1 from the other direction, uncertainty is that portion of both modeling and parametric variability which, in principle, can be reduced as additional information becomes available, whereas randomness represents the intrinsic or irreducible component of variability for a given model or parameter.

Table 1. Contributions to Total Variability in Ground-Response Estimates

	Modeling Variability	**Parametric Variability**
Uncertainty *(also Epistemic Uncertainty)*	Modeling Uncertainty: Variability in predicted response resulting from particular model assumptions, simplifications and/or fixed parameter values. *Can be reduced by adjusting or "calibrating" model to better fit observed earthquake response.*	Parametric Uncertainty: Variability in predicted response resulting from incomplete data needed to characterize parameters. *Can be reduced by collection of additional information which better constrains parameters*
Randomness *(also Aleatory Uncertainty)*	Modeling Randomness: Variability in predicted response resulting from discrepancies between model and actual complex physical processes. *Cannot be reduced for a given model form.*	Parametric Randomness: Variability in predicted response resulting from inherent randomness of parameter values. *Cannot be reduced a priori* by collection of additional information.*

* Some parameters (e.g. source characteristics) may be well defined after an earthquake.

In the context of earthquakes, modeling variability represents differences between the actual complex physical processes which generate and propagate a strong earthquake and a particular model used to predict ground motions. It is measured in terms of the residual, or misfit, between observations and predictions when model parameters are known. The topic of non-linear soil behavior can be used to illustrate both the distinction between modeling randomness and modeling uncertainty as well as the essential point that this distinction is model dependent. Say that a particular model 'A' considers soil behavior to be linear elastic (i.e. showed no change in stiffness or damping as a function of strain), and assume that soil behavior is indeed strain-dependent. Non-linear soil effects would then contribute to the scatter, or modeling variability, in the residuals between measured ground response and model 'A' predictions, and this scatter would be considered randomness (inherently unresolvable). However, if one examines the scatter as a function of ground-motion amplitude, one might find a systematic trend or "bias" to the scatter, say to overpredict high-amplitude motions and/or underpredict low-amplitude motions. This bias can be viewed as modeling uncertainty, and one could choose to "calibrate" or bias correct the linear-soil model (A*) in some fashion so as to eliminate this consistent trend for the strain levels represented in the data set, thus leaving only the randomness components to the scatter. As an alternative means to remove the amplitude-dependent bias, one might adopt a new model (B) which explicitly accounts for non-linear soil behavior. In this case, some modeling uncertainty would be eliminated, but only at the expense of introducing additional parametric variability associated with establishing the new non-linear parameters. Such a trade-off may, or may not, prove beneficial in terms of reducing total variability. However, the more "correct" model (B) should provide more accurate predictions (median values) for cases outside the empirical data base.

Using the same topic, an example of parametric variability is the range in predicted response associated with a range of possible functions (or "curves") describing non-linear material curves for the soil layers. The parametric uncertainty is that portion of response variability that could be reduced by better definition of the curves, say by using high-quality laboratory testing. However, such curves can never be perfectly defined due to both measurement errors and natural spatial variations within the soil deposit for a particular site. That portion of response variability associated with the undefinable range would be considered part of the parametric randomness. Another important example of parametric randomness stems from processes which cannot be foreseen in future events such as the distribution of slip along a fault plane or the location of the hypocenter.

It is important to emphasize that the distinction between modeling and parametric variability is model dependent. More complex models typically seek to reduce modeling randomness by more closely modeling physical phenomena. However, such models often require more comprehensive sets of observed data to constrain additional model parameters, and generally lead to increased parametric variability. If the increased parametric variability is primarily in the form of uncertainty, it is possible to reduce total variability, but only at the additional expense of constraining the additional parameters. Therefore, existing knowledge and/or available resources may limit the ability of more complex models to reduce total variability.

A central task in design is to select a model that strikes an appropriate balance between increased costs and reduction in total variability. This paper uses a limited set of examples to illustrate how a design engineer might investigate conditions where various levels of geotechnical site characterization may provide meaningful reduction in variability of ground-motion estimates.

Stochastic Finite-Fault Model

Figure 1 depicts central features of the simple, but comprehensive, stochastic finite-fault ground-motion model used herein to examine source, path, and site contributions to parametric variability. Detailed description of the model can be found in Silva [1992], Schneider et.al. [1993], and Silva et.al. [1990]. Generally, the method is based on an extension of a point-source model [Boore, 1983; Hanks and McGuire, 1981] which uses band-limited white noise (BLWN) and random vibration theory (RVT) to estimate site-specific response spectra. Major extensions include incorporation of a "finite fault" to approximate effects of a nearby extended source, and an RVT-based equivalent-linear site model to accommodate effects of strain-dependent soil behavior. A brief overview of the source, path, and site components of the stochastic model are outlined in separate paragraphs below.

The earthquake "source" is characterized as a plane rectangular fault, having specified strike and dip, located within the "seismogenic zone" or the depth range considered capable of significant seismic-energy release (typically >2 km). The fault plane is divided into a grid of subfaults, and each is assigned a different value of slip to simulate regions of high energy emission (i.e. "asperties"). For each subfault, a number of small-magnitude (M5) point sources are "fired" at random locations within the subfault at irregularly staggered time intervals to build up a heterogeneous energy release appropriate for the particular slip value assigned to the subfault. The rupture is initiated at a selected "nucleation point" (or "focus"), and the rupture propagates outward into adjacent subfaults at a rupture velocity, typically taken as about 80% of the shear-wave velocity for the host rock. The rupture velocity is

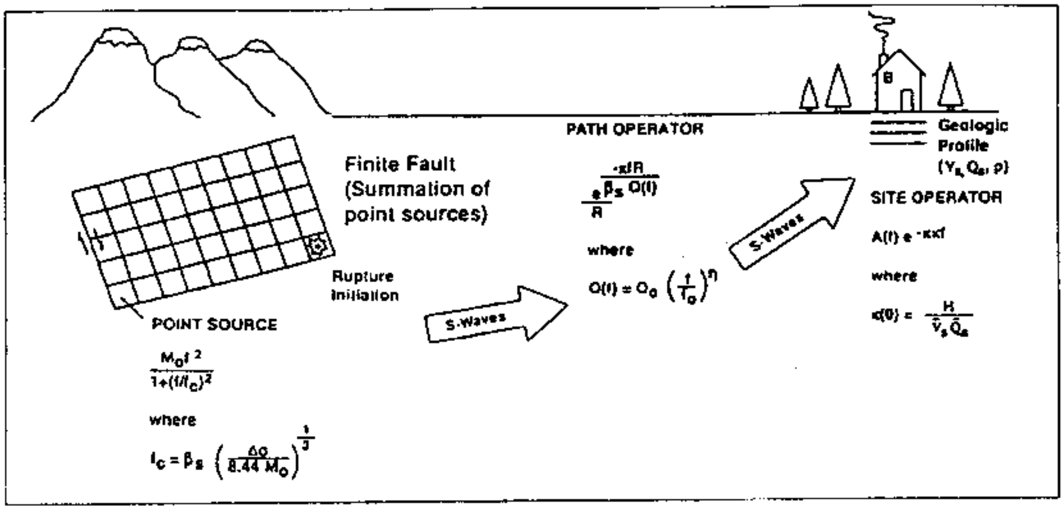


Figure 1. Schematic of Ground Motion Model

randomized within ±20% bounds to simulate an uneven rupture front propagating across the fault releasing spatially-dependent energy.

"Path" effects, which account for wave propagation from source to site, are modeled using simple relationships for geometrical spreading (typically 1/distance) and frequency-dependent crustal attenuation ($Q\{f\}$). Radiation-pattern effects are accommodated using an average over all the subfaults. Crustal amplification ($A\{f\}$) is modeled using one-dimensional inclined or vertically-propagating shear-waves through a specified regional crustal-velocity model, along with a near-surface (<2 km) exponential-decay parameter called "kappa" (κ) [Anderson and Hough, 1984]. Conventionally, seismologists consider both crustal amplification and the kappa term to be "site" effects, however for purposes of this paper (aimed primarily to an engineering audience), the term "site" is reserved for the very-near-surface region (say <300 m) which is accessible for purposes of geotechnical characterization.

"Site" effects, within the context of this paper, pertain only to the impact which both the velocity profile and non-linear (strain-dependent) soil behavior have on shear-wave propagation through the very-near-surface region. The stochastic model uses an RVT-based equivalent-linear approach to propagate outcrop power spectral density through a one-dimensional soil column, and can be viewed as a frequency-domain analog to time-domain analyses (e.g. SHAKE [Schnabel, et al., 1972]) familiar to most geotechnical engineers. Note that an advantage of the frequency-domain approach is that a single run provides a stable estimate of response without the need for a suite of control motions as would be required using a time-domain method.

The comprehensive nature of the stochastic finite-fault ground-motion model makes it well suited for evaluating the relative contributions of various components of parametric variability. Distributions for model parameters can be assigned and considered in various combinations using a Monte Carlo approach to yield both median relationships and statistics on parametric variability. Approximately 30 to 50 combinations of independently-varied parameters are typically required to provide stable estimates of median and one-sigma response over a wide frequency range.

This paper seeks to illuminate the impact of site-effects parametric variability in ground response by presenting median and one-sigma response spectra results for a single scenario earthquake using over 60 combinations of: 1) "known" model-parameter groups, 2) fault-to-site distances, 3) representative soil profiles, and 4) depth-of-characterization zones.

Scenario Earthquake

Figure 2 illustrates the geometry of the scenario earthquake modeled herein, in which a M7 event occurs on a simple vertical strike-slip fault. The top of the seismogenic region of the fault is located 2 km beneath the surface. The seismogenic region is given dimensions of 90 km along strike, and 12 km down dip (vertical). These values are based on both geologic constraints (for the western U.S.) and established correlations of fault area to moment magnitude [e.g. Wells and Coppersmith, 1994]. The sites considered are positioned at up to 4 separate perpendicular distances (3, 10, 30, and 100 km) from the one-third point along the fault trace. The purpose for selecting the third point of the fault rather than the middle is to allow some consideration of the variability associated with "rupture directivity" which can modify spectral shape and durations in a manner similar to a doppler effect depending upon whether a rupture front moves primarily toward or away from a site.

While all results presented herein must be interpreted in light of the particular nature of this selected scenario, the source/site geometry is not unusual, and is believed to provide sufficient generality to illuminate major trends regarding the impact of site effects on overall ground-motion variability.

Model Parameters and Distributions

The stochastic finite-fault model used herein allows randomization of several scalar and non-scalar parameters to capture major components of parametric variability associated with source, path, and site mechanisms contributing to ground response. Table 2 outlines the major parameters along with typical median values, standard deviations (σ), and distributions for those parameters which were not fixed. Figure 3 illustrates how the non-scalar parameter sets are distributed.

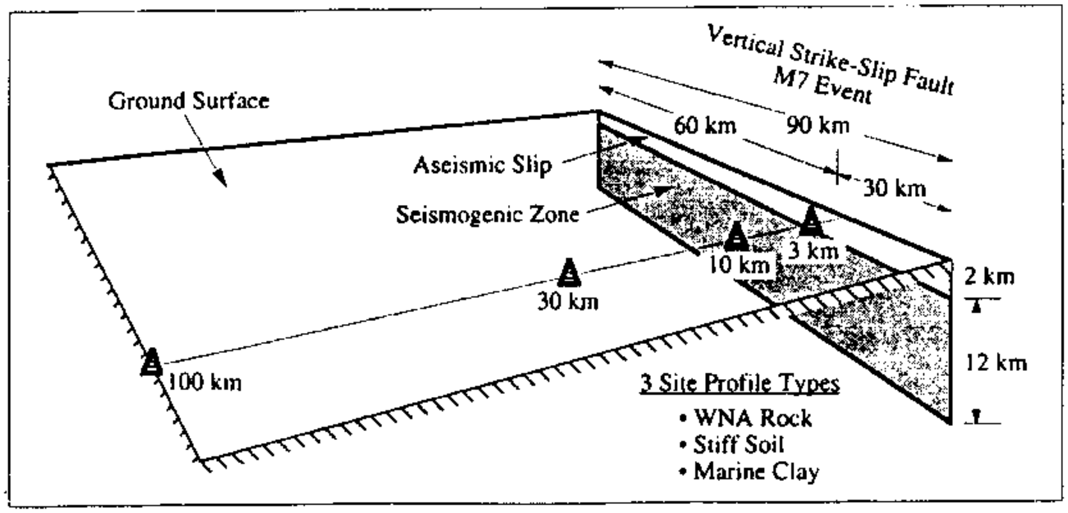


Figure 2. Scenario Earthquake Geometry and Recording Station Locations

Table 2. Model Parameters and Distributions

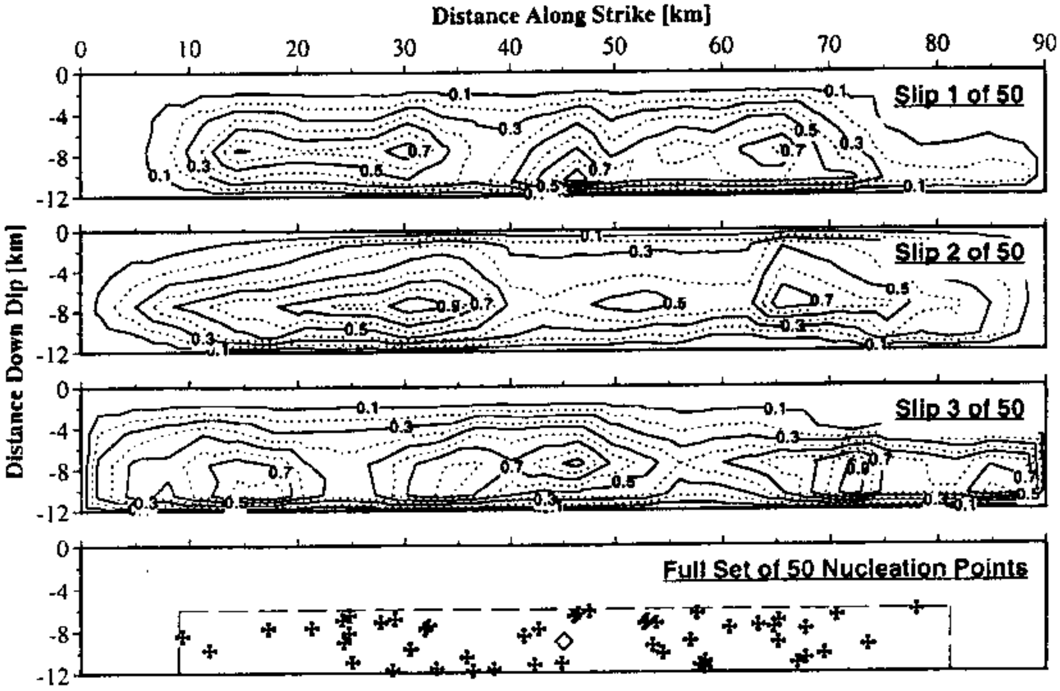
	Median	Std Dev (σ)	Distribution
Source Parameters			
Magnitude (M)	7.0	--	Fixed
Slip Distribution (See Fig. 3a)	--	--	[Silva, 1993]
Nucleation Point (See Fig. 3b)	Geometric Center	--	[Silva, 1993]
Source-Region Density (ρ)	2.7 g/cc	--	Fixed
Source-Region Velocity (β)	3.2 km/sec	--	Fixed
Path Parameters			
Fault-Site Distance (R)	3, 10, 30, 100 km	--	Fixed
Crustal Attenuation Coef. (Q_o)	150	0.18*	Log-Normal
Crustal Attenuation Coef. (η)	0.60	0.05	Normal
Near-Surface Attenuation** (κ)	0.04	0.30*	Log-Normal
Crustal Velocity Structure	[Boore, 1986]	--	Fixed
Site Parameters			
Near-Surface Velocity Profile (V_s)	3 Median Profiles	(See Fig. 4)	[Toro, 1993]
Material Model (G/G_{max} & D)	3 Curve Sets	(See Fig. 4)	[Silva, 1993]

* σ for log-normal distributions is based on the natural log (ln) of the parameter.
** Near-surface attenuation is often considered a "site" term.

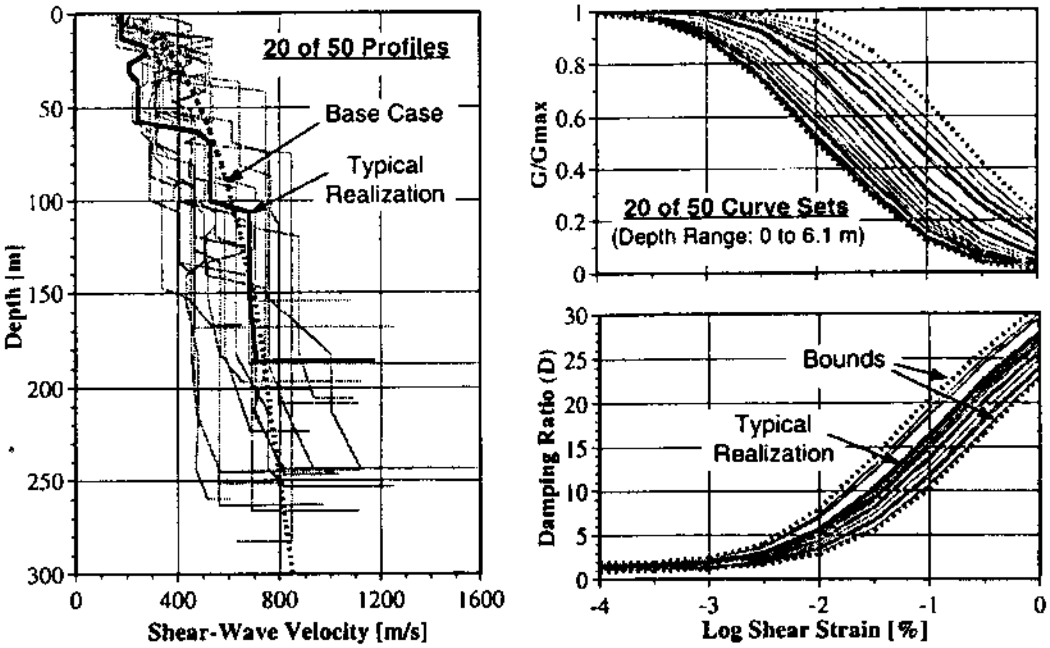
The source modeling parameters include the geometric considerations described in the scenario earthquake section (fault dimensions, fault orientation, and site location) as well as both the distribution of slip on the fault and the nucleation point (focus) for initiation of rupture. For purposes of modeling future events, both slip and focus are varied randomly within empirically-derived constraints. Figure 3a shows three realizations of normalized slip generated using a procedure implemented by Silva [1993] which yields spatial variations of both the number, size, and "height" (amount of slip) of asperities having statistics which match those of observed events. Figure 3a also shows a typical set of 50 randomized nucleation points. Note that the nucleation point is constrained to both the lower half and to within 10% of the edges of the fault plane, also to be consistent with observed events (in California).

Path modeling parameters include the crustal velocity model, and both the frequency-dependent crustal damping function (Q{f}) and the frequency-independent attenuation factor kappa (κ). A single fixed regional crustal-velocity structure [Boore, 1986] is considered herein. The crustal damping function (Q{f}) is represented by a two-parameter function involving parameters Q_o and η. Therefore, the randomized path parameters include Q_o, η, and κ. Median values and distributions for these parameters are presented in Table 2, and were selected to be representative of California.

The fundamental parameters required for implementation of the equivalent-linear site model are the shear-wave velocity profile, and the strain-dependent values of both normalized secant modulus (G/Gmax) and hysteretic material damping (D) as illustrated in Fig. 3b. For purposes of estimating parametric variability, each of these functions are randomized within constraints of observed behavior. The left-hand chart of Fig. 3b shows a representative suite of randomized velocity profiles which includes a randomized depth to "bedrock". Profiles such as these are



a) Source Parameters: Slip Distribution and Nucleation Point



b) Site Parameters: Velocity Profile and Equivalent-Linear Material Curves

Figure 3. Examples of Randomized Non-Scalar Model Parameters

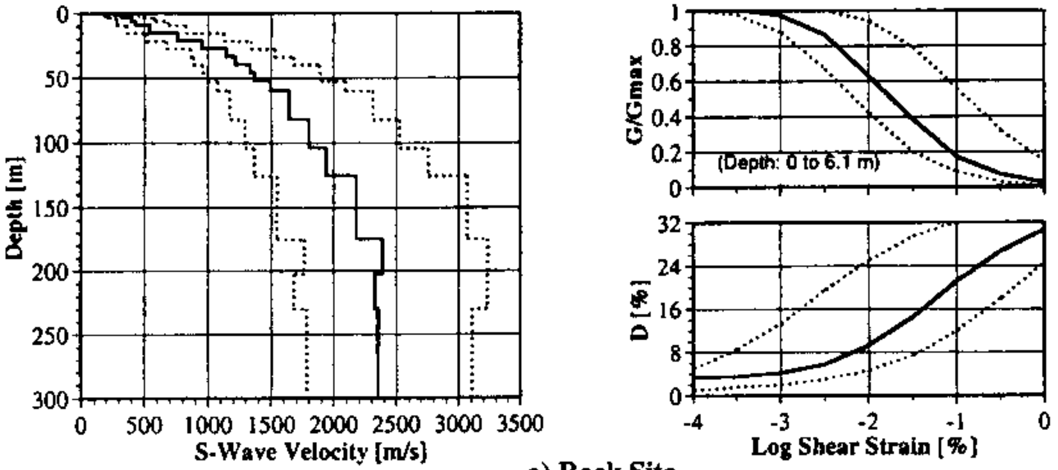
generated using a probabilistic model based on statistical analysis of approximately 650 measured profiles taken from locations throughout the U.S. [Toro, 1993]. In a similar fashion, randomized sets of material-properties curves, such as those shown in the right-hand charts of Fig. 3b, are generated using a routine implemented by Silva [1993]. Specific attributes of the site parameters considered herein are presented below.

Site Profiles and Non-Linear Material Models

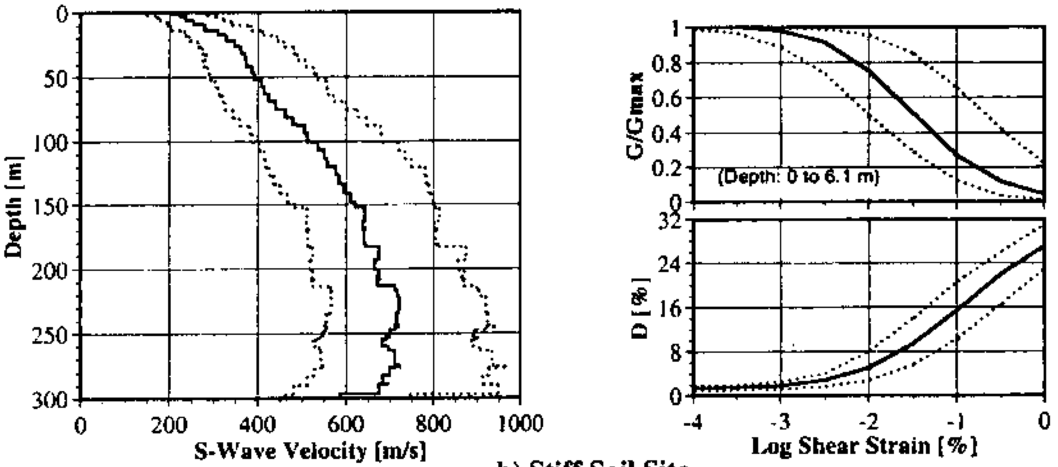
Figure 4 shows both the median and plus-or-minus one standard deviation (±σ) of the set of randomized velocity profiles used for each of three different "base case" site types considered herein. The site types are identified as "rock", "stiff soil", and "marine clay", and sample a wide range in site conditions. The base-case velocity profiles for both the rock and stiff soil sites were developed from measured data where available, and on generic models beyond that depth. The rock site used measured data for the upper 25 m, and transitions to a generic regional rock model for Western North America (WNA) [Boore, 1986] for the remainder of the profile. In a similar fashion, the upper 150 m of the stiff-soil profile was constrained by measured data, while a generic soil model for WNA was adopted beyond that depth. Finally, the "marine clay" profile is a more specialized case involving a 15-m thick layer of marine clay underlying a 5-m thick fill. The base-case velocities for the marine-clay layer were based on a correlation for San Francisco Bay Mud [Dickenson, 1994]. A fixed 10-m-thick transitional layer of stiff clay was placed beneath the marine clay, and the WNA stiff-soil profile was used beyond that depth.

Note, for both the rock and stiff soil sites, the velocity profile was randomized to a depth of 300 m. For the stiff soil site, the depth to the crustal half-space was also randomized between 150 m and 300 m, resulting in an average value of 225 m. For the rock site, the "top of crust" was fixed at 225 m. Both the velocity profile and depth were randomized for the marine clay site. Velocities were varied to a depth of 75 m, and the half space was varied between 45 and 75 m with an average value of 60 m. All profiles shown in Fig. 4 reflect the median and ±σ velocity values for the entire depth of velocity randomization.

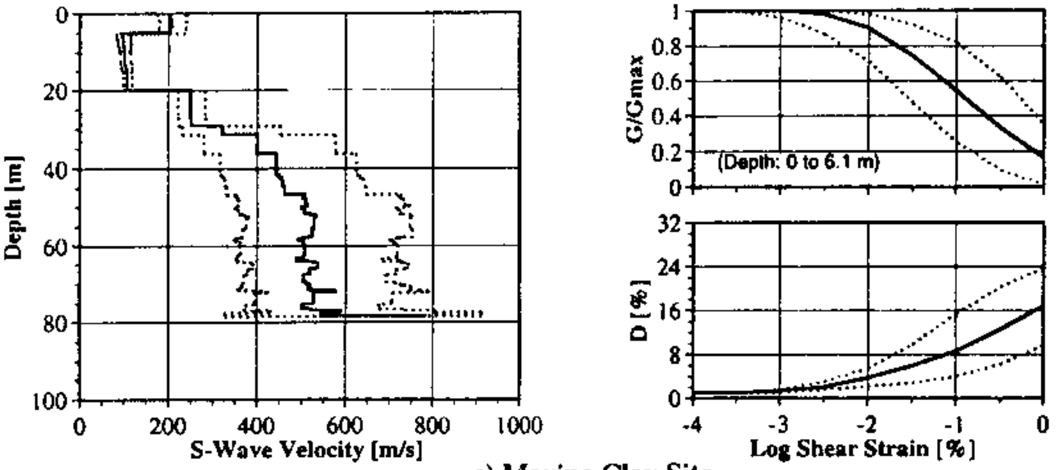
Figure 4 also presents typical median and bounding sets of non-linear material curves for key layers of each site profile. The randomization routine [Silva, 1993] for evaluating a single realization of both curves uses a normal distribution about base-case values at 0.03% strain, with the standard deviation value set at 0.10 and 0.04 for the modulus reduction and damping curves, respectively. A standard scaling relationship is used to establish values and preserve curve shape for the remainder of the strain range. The fixed bounds shown in Fig. 4 are used to eliminate non-physical statistical fluctuations. Note that the current routine does not incorporate coupling between modulus reduction and damping, and therefore has potential to misestimate parametric variability associated with accepted non-linear material behavior. The base-case curves identified as "rock" are one typical pair of the generic set of depth-dependent material properties developed for rock sites [Pyke, 1993], where this and other members of the set are used for all layers in the rock profile. The bounding rock curves were generally set to allow a factor of approximately ±2 of the base-case value. A similar set of depth-dependent generic curves were used for the entire stiff-soil profile as well as for those portions of the marine clay profile where the WNA stiff soil was used. Finally, the base-case and bounding curves labeled "clay" are taken from an empirical relationship for clays having a plasticity index (PI) of 30, 0, and 100, respectively [Vucetic and Dobry,



a) Rock Site



b) Stiff Soil Site



c) Marine Clay Site

Figure 4. Site Properties for Parametric Analysis: Median and ±σ Velocity Profiles and Typical Median and Bounding Nonlinear Material Curves

1991]. These curves are used for both the marine-clay and the stiff-clay layers of the marine clay profile.

Impact of Site Effects

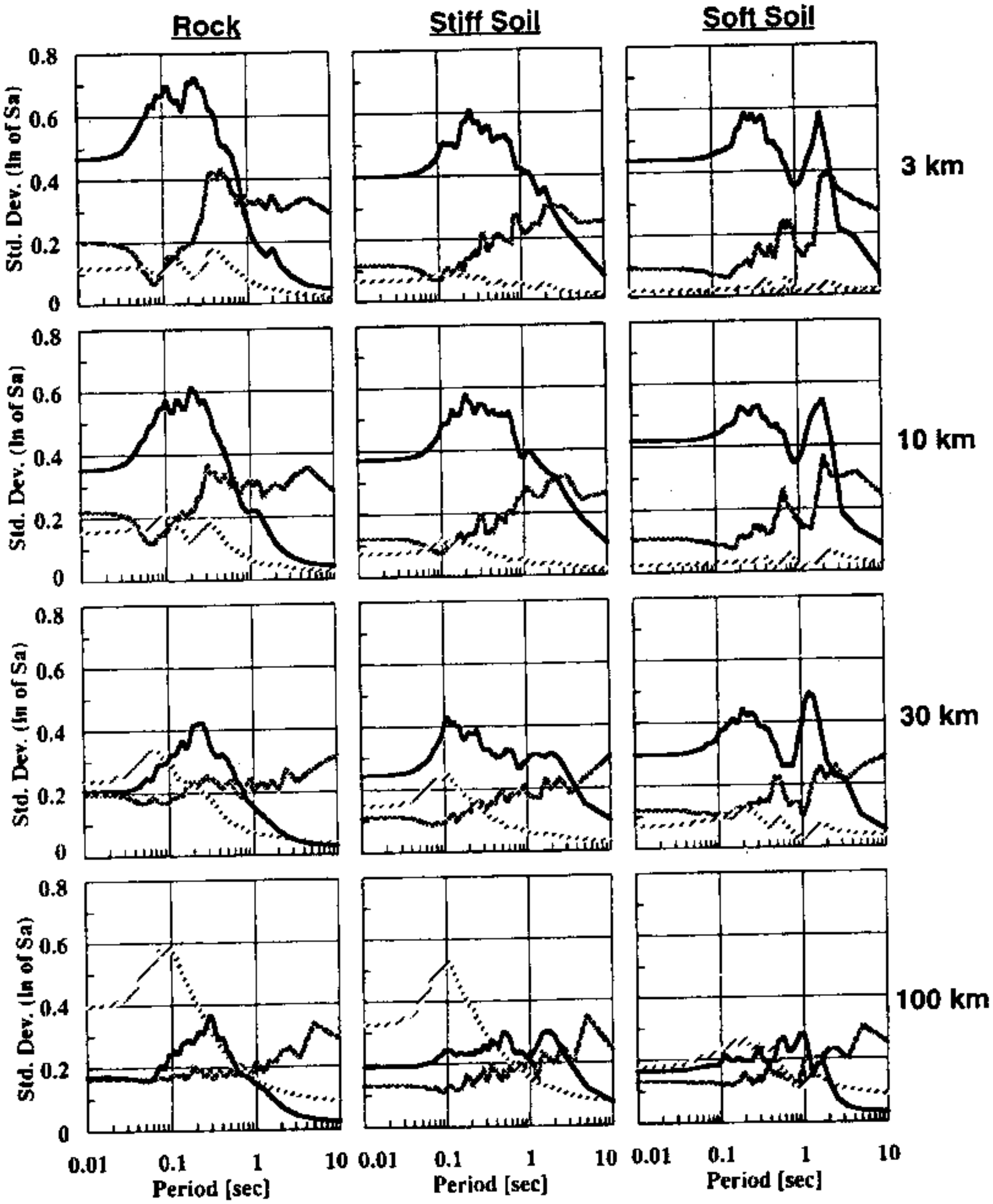
The impact on ground-response parametric variability attributable to site effects can be assessed using the stochastic model by examining the effect on estimates of both σ and median spectral response caused by alternatively varying and fixing different parameter groups. This is done here in two ways, first by comparing individually varied groups of parameters while holding the remaining ones to fixed "base-case" (near median) values, and second by examining the change in response variability associated with holding only the site parameters fixed relative to that where all parameters are simultaneously varied.

Figures 5a and 5b present plots of standard deviation and median values, respectively, of 5%-damped spectral acceleration for distances of 3, 10, 30, and 100 km for each of the rock, stiff soil, and marine clay soil profiles described above. Each chart in both figures show 3 spectra, where each spectrum was generated holding one of the three parameter groups (source, path, and site) fixed to base case values while the remaining two parameter groups were randomly varied. For a linear system, this approach allows direct examination of the contribution to variability of each parameter group.

Figure 5a shows that the significance of each parameter group to parametric variability is a function of period, fault-to-site distance, and site type. Generally, site effects are shown to contribute greatly to parametric variability across most of the spectrum, with a peak in the short-to-intermediate period range (0.1 to 1.0 sec) and a distinct fall-off towards longer periods. The long-period fall-off occurs as wavelengths become significantly longer than the depth of the soil profile. Figure 5a also shows that site-effects variability is clearly a function of distance. For both the soft and stiff soil profiles, site-effects are important contributors to parametric variability to distances of at least 30 km for periods up to several seconds, and overwhelm other factors in this period range for soil sites within 10 km of the fault. For the stiffer rock profile, site effects are the primary contributor to variability from very-short periods to nearly 1 second for distances within 10 km. For 30 km and beyond, site-effects variability for the rock site are comparable or below those for source and path.

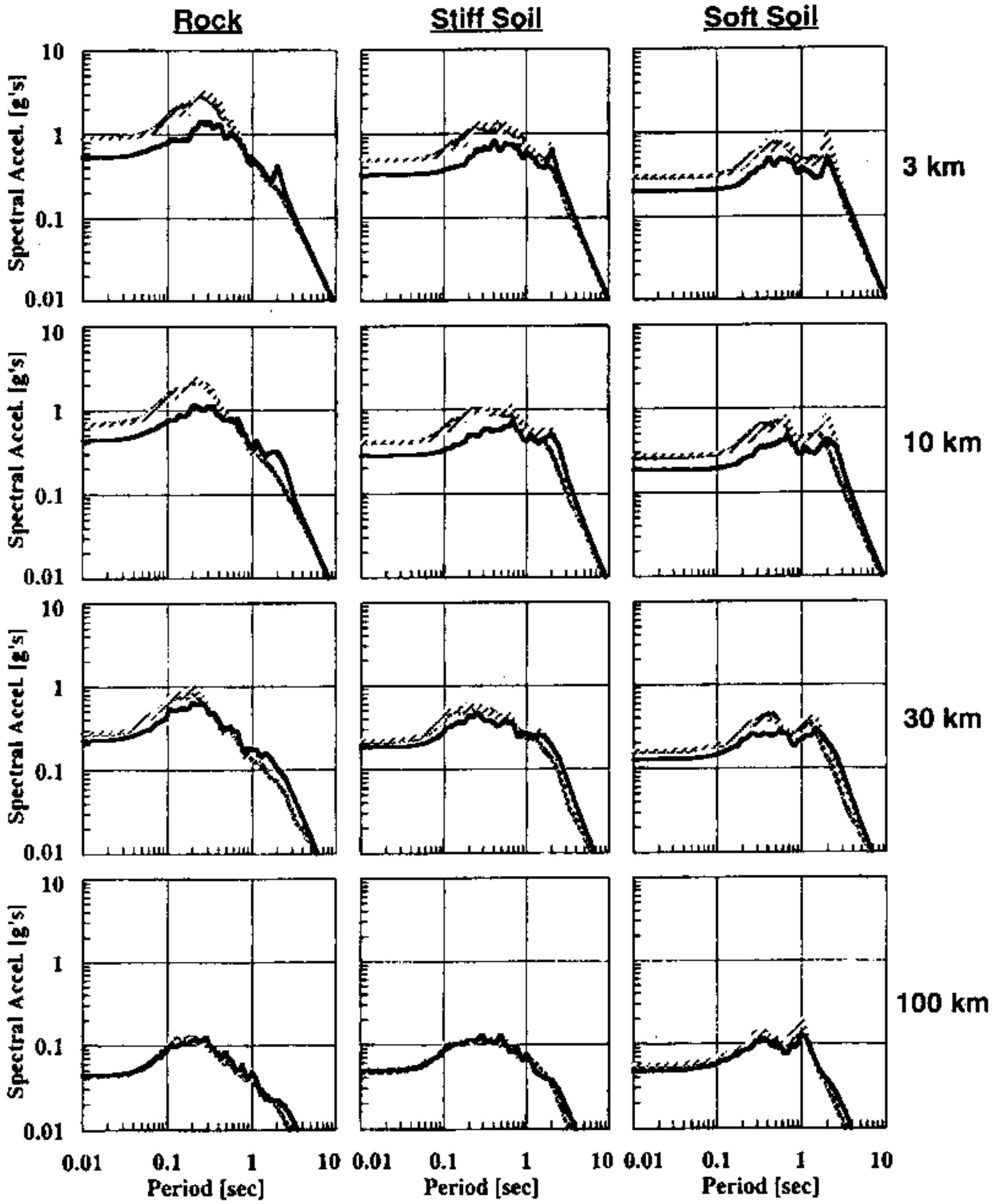
Figure 5a also shows that source effects contribute most to parametric variability at long periods, and are relatively insensitive to both site type and distance. As one would expect, path-effects are shown to have little impact on response variability near fault, but become much more pronounced as fault-to-site distance increases. Additionally, path effects have greater influence on both the stiffer profiles and the short-period end of the spectrum.

Figure 5b presents median spectral-response results for the same conditions presented in Fig. 5a. A very interesting trend pertaining to non-linear soil behavior is evident in these results. Note that the median spectra for the "vary site" case is below those of both the "vary source" and "vary path" cases (which nearly overlap), especially for the larger motions at close distances. This is because the "base case" velocity profile used when the site parameters are fixed is a smooth function of depth with values near the median of the randomized profiles. Under linear conditions, the median response of a randomly-varied velocity profile should nearly equal the response of the smooth base-case profile with only minor losses due to scattering at the layer contrasts. This behavior is observed in Fig. 5b for sites at large distance



Key	**Source** (Slip, Focus)	**Path** (Q_o, η, κ)	**Site** (Profile, Material)
▒▒▒▒▒▒ Vary Source	Randomized	Fixed	Fixed
············ Vary Path	Fixed	Randomized	Fixed
———— Vary Site	Fixed	Fixed	Randomized

Figure 5a. Spectral-Response Parametric Variability for Individually Randomized Source, Path, and Site Parameter Groups



Key	Source (Slip, Focus)	Path (Q_o, η, κ)	Site (Profile, Material)
—— Vary Source	Randomized	Fixed	Fixed
⋯⋯ Vary Path	Fixed	Randomized	Fixed
━━ Vary Site	Fixed	Fixed	Randomized

Figure 5b. Median Spectral-Response for Individually Randomized Source, Path, and Site Parameter Groups

(100 km) where site response is nearly linear. However, as the level of motion increases (e.g. at closer distances), a randomized profile containing low-velocity layers, or "notches", will tend to accumulate high levels of strain at these notches. This, in turn, tends to both increase scattering due to higher velocity contrasts (lower modulus-reduction values) as well as increase the value of hysteretic damping (D) for the layers undergoing higher strain, thus reducing output motion. Therefore, since randomized profiles will include a certain number of realizations having low-velocity notches, the median output should be lower than the median response of the smooth base-case site profile. An interesting converse to this observation is that the output for a smooth median profile tends to approach the one-sigma motion of the randomized set for strong levels of motion.

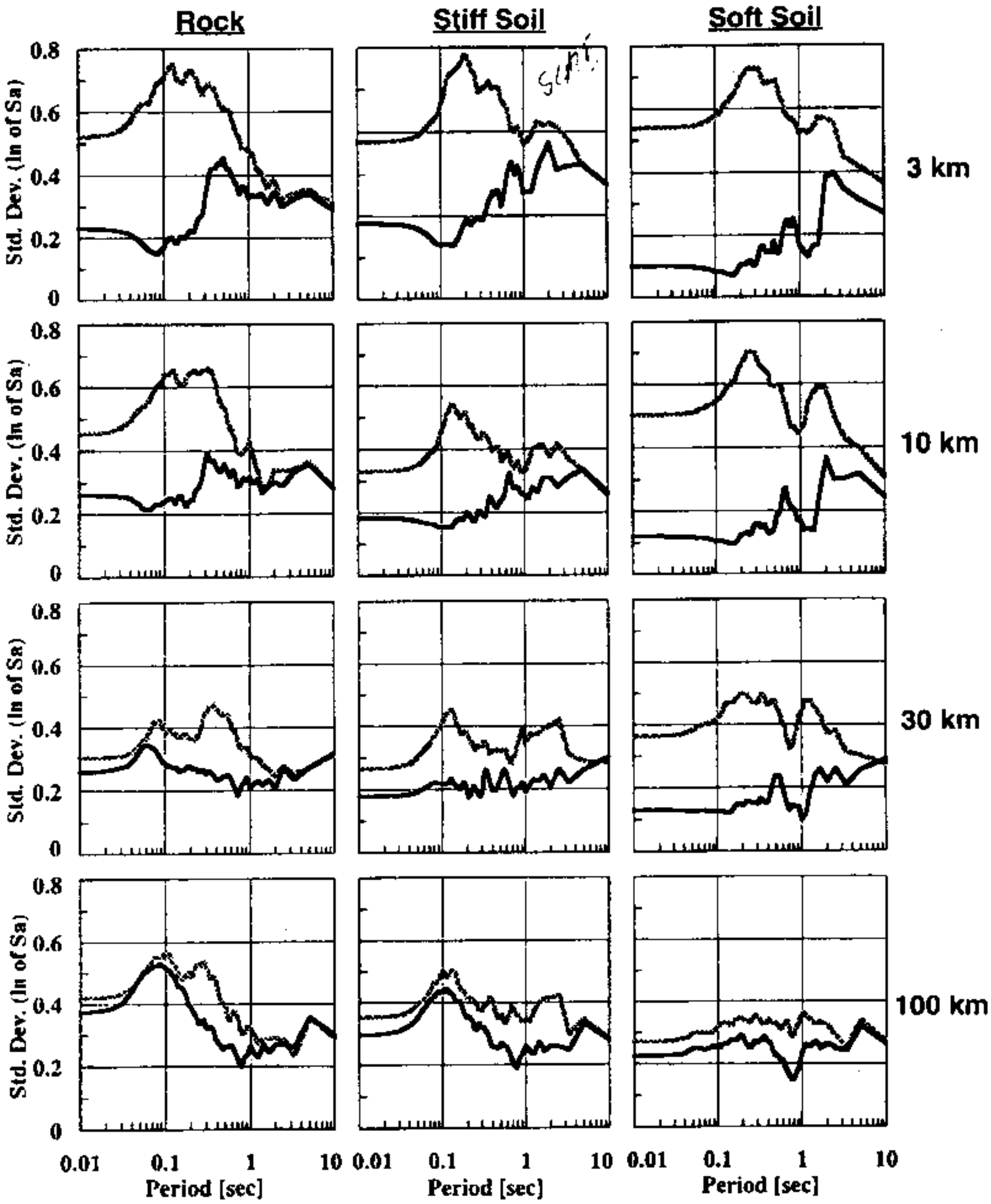
Also notable in the median results of Fig. 5b is the somewhat peculiar dual-peak spectral shape for the marine-clay profile. This response is a result of the very particular nature of the specified velocity profile which leads to a site resonance near 1 to 2 seconds. Note that the resonsance peak shifts toward longer period as the level of motion increases and the materials soften.

An alternative approach for evaluation of the variability contribution of a particular parameter group is to examine the reduction in spectral-response variability associated with fixing that parameter group relative to the case where all parameters are varied simultaneously. Figure 6 presents such results for the case where the site parameters are fixed, which is analogous to having "perfect knowledge" (no uncertainty or randomness) of site conditions. The "vary all" baseline case can similarly be viewed as analogous to having "no knowledge" of site conditions. Note, due to both soil non-linearity and coupling between parameter variabilities, the "vary all" case may not be the sum of individual parametric contributions shown in Fig. 5a (as illustrated for the rock site at 100 km). The results shown in Fig. 6 are fully complimentary to those presented in Fig. 5a, and perhaps provide a clearer picture of the potential impact of site characterization. Very pronounced benefits for reducing parametric variability are shown to be possible for periods ranging upwards to several seconds for soil sites at distances to 30 km. Similar benefits could be achieved for rock sites through at least 10 km, however, the period range is somewhat more restricted.

Finally, one must note that while the results of Fig. 6 clearly illustrates the potential for reducing parametric variability through site characterization, it would be unrealistic to expect that the full extent of this reduction is attainable since site data will always be both imperfect and have a certain random component. Using the nomenclature of Table 1, the difference between the "vary all" and "site known" cases in Fig. 6 represents the total parametric variability which includes both a reducible uncertainty component and an irreducible randomness component.

Reduction in Variability with Increased Depth of Site Characterization

The focus of this paper now shifts from establishing the broad impact of site effects to the more narrow issue of examining the potential benefit of characterizing different parameters of a site profile to increasing depths. This exercise considers only the single case of the stiff-soil profile at a fault-site distance of 10 km. Individual and combined site parameters are considered "known" (fixed) within three separate "characterization zones" of progressively increasing depth. Zones 1, 2, and 3, are defined to extend from the ground surface to depths of 30, 100, and 300 m, respectively, and are intended to be representative of typical, extensive, and research-quality depths for geotechnical site characterization. For each zone, the



Key	Source (Slip, Focus)	Path (Q_o, η, κ)	Site (Profile, Material)
┈┈┈┈ Vary All	Randomized	Randomized	Randomized
──── Site Known	Randomized	Randomized	Fixed

Figure 6. Change in Spectral-Response Parametric Variability Due To Fixing Only Site Parameters Group

parametric variability in spectral response is calculated for a fixed velocity profile, a fixed material model, and for the combination of both a fixed profile and fixed material model.

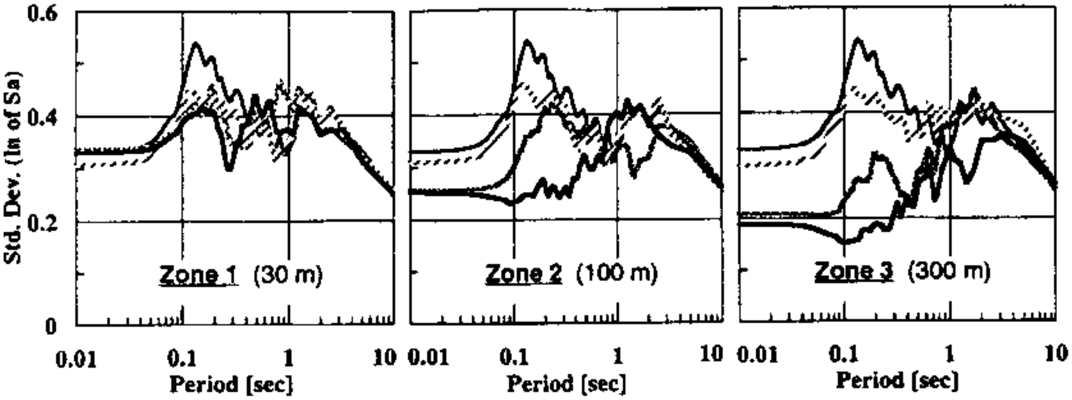
Figure 7 presents results of the characterization-zone analyses in each of two formats. A common baseline case where all parameters are varied is presented in all charts and is alternatively labeled "nothing fixed" and "zone 0". This baseline case serves as a reference from which to measure improvement or reduction in variability. Each chart in the upper row involves a single characterization zone, and shows variability results as site parameters are alternatively fixed both individually and in combination. For example, the cross-hatched line in the upper middle chart corresponds to having the velocity profile fixed and the material properties randomized for the upper 100 m of the profile, and both the velocity and the material model randomized below 100 m. The reduction in variability from the baseline case then corresponds to the benefit achieved by having perfect knowledge of only the velocity profile for the upper 100 m. The same results are rearranged and presented again in the lower row of charts. Here, each chart presents variability results as progressively deeper characterization zones are employed for a fixed single parameter or combination. For example, the cross-hatched line in the lower left chart shows results of fixing velocity only over the upper 100 m (same as above), while the heavy solid line represents velocity fixed over 300 m.

The results in Fig. 7 clearly show the well-anticipated trend toward reduced parametric variability as the depth of characterization progresses deeper. Furthermore, for this particular combination of ground-motion amplitude and site, fixing the velocity profile has a more substantial impact on reducing variability than fixing material properties alone, but fixing the combination of both profile and material properties provides a clear benefit for periods in the 0.1 to 1 second range. Note that one would expect the impact of the material curves to increase as strain amplitudes increase. The results in Fig. 7 also provide information regarding the incremental benefit of characterizing the profile to increased depths. These results suggest a very significant reduction in parametric uncertainty can be achieved for periods of up to approximately one second by extending the characterization zone to 100 m, while the marginal benefit of increasing the characterization depth to 300 m appears more limited.

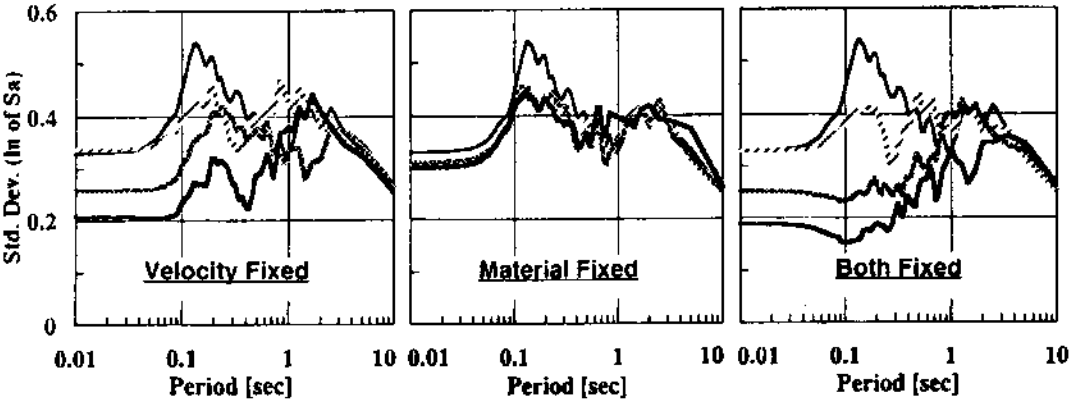
The suite of examples presented in Figs. 5 through 7 are intended to provide some insight into general trends in site-response variability. Clearly, logical extensions of this work include examination of the impact of "realistic" rather than "perfect" site characterization, as well as performing characterization-zone analyses for a wider range of ground-motion amplitudes and site profiles. However, the more general purpose here has been to simply outline procedures whereby one can systematically examine the contribution of a particular parameter set to overall parametric variability in site response.

Modeling Variability

The primary focus thus far has been an examination of parametric variability in ground response, with particular emphasis placed on the role of geotechnical site effects. Modeling variability, as described in Table 1, represents the other component of variability in design ground-motion prediction. Detailed discussions of modeling variability for the stochastic finite-fault ground-motion model can be found in Silva [1992] and Schneider et. al. [1993]. A cursory review is presented here in the context of one of the case examples to provide a broader perspective of



Key	Source (Slip, Focus)	Path (Q_o, η, κ)	Site (Profile)	 (Material)
——— Nothing Fixed	Randomized	Randomized	Randomized	Randomized
……… Material Fixed	Randomized	Randomized	Randomized	Fixed in Zone
——— Velocity Fixed	Randomized	Randomized	Fixed in Zone	Randomized
——— Both Fixed	Randomized	Randomized	Fixed in Zone	Fixed in Zone



Key	Source (Slip, Focus)	Path (Q_o, η, κ)	Site (Profile or/and Material)
——— Zone 0 (0 m)	Randomized	Randomized	Randomized
……… Zone 1 (30 m)	Randomized	Randomized	Randomized Below 30 m
——— Zone 2 (100 m)	Randomized	Randomized	Randomized Below 100 m
——— Zone 3 (300 m)	Randomized	Randomized	Randomized Below 300 m

Figure 7. Change in Spectral-Response Parametric Variability Due To Fixing Individual and Combined Site Parameters Over 3 Depth Ranges for a Stiff Soil Profile Located 10 km from Fault.

the relative contributions of both modeling and parametric components to total variability.

Estimates of modeling variability are typically developed through a "calibration" exercise where model "predictions" are compared and optimized against a suite of strong-motion recordings. Quantitative assessment of modeling variability is typically calculated as the average squared residual for each period for a collection of sites and events, where the residual is defined as the difference between the logarithms of the observed and predicted 5%-damped spectral acceleration [Abrahamson et. al., 1990]. To assure the general applicability of the results of such a calibration exercise to future design predictions, it is important to sample as wide a suite of earthquakes, site conditions, and ground-motion-amplitude levels as possible using model parameters which are fixed by a consistent set of rules. A level of confidence can then be assigned to ground-motion predictions for future earthquake scenarios.

One estimate of modeling variability for the stochastic finite-fault model is shown in Fig. 8 (dotted line), and was developed from calibrations against the 1989 Loma Prieta and the 1987 Whittier Narrows earthquakes [Silva 1992]. Other validation exercises for the 1992 Landers and the 1994 Northridge events yielded similar results, and also showed that the site-specific estimates of ground motion produced by this stochastic model fit measured data as well as any comprehensive model currently available [Aki et.al., 1996]. Furthermore, Schneider et. al. [1993] show that modeling uncertainty for the stochastic model is comparable to the variance in attenuation relations developed from earthquake recordings, thus indicating a comparable level of predictive capability.

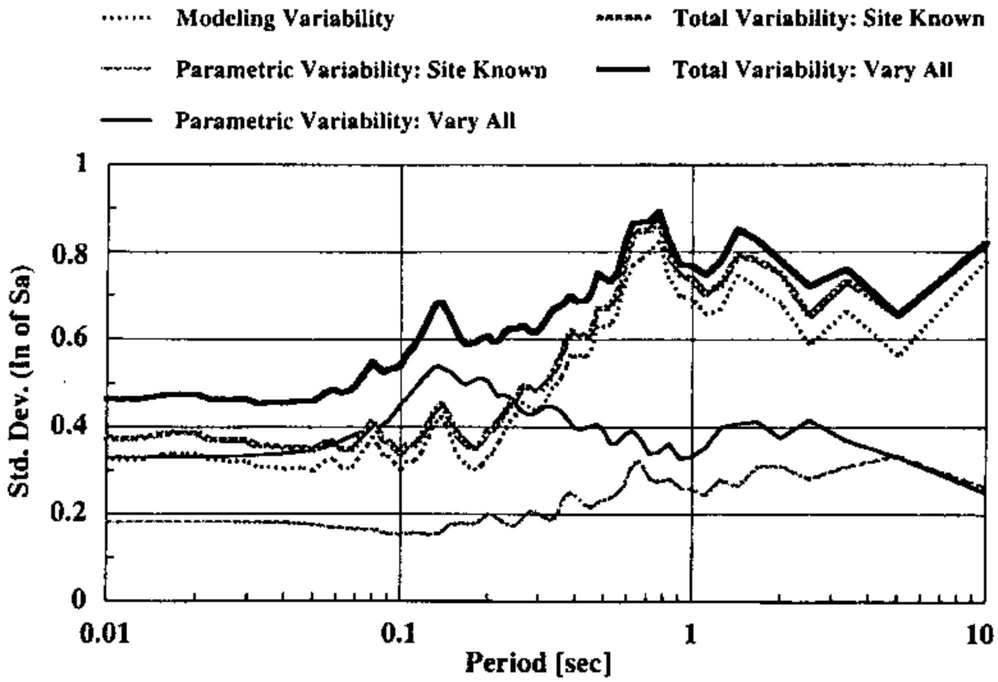


Figure 8. Comparison of Components of Variability for the Scenario Event and the Stiff-Soil Site at a Fault-Site Distance of 10 km.

In addition to modeling variability, Figure 8 also presents a comparison of two estimates each of both parametric variability and total variability for the stiff soil site at 10 km from the previous examples. The upper and lower estimates of parametric variability are based on the "vary all" and "site known" analyses, respectively, shown in Fig. 6. The total variability values are then computed as the vector sum of the modeling and parametric variabilities.

The comparison in Fig. 8 shows that for periods up to several tenths of a second, site-effects components of parametric variability comprise a significant proportion of total variability. For longer periods, modeling variability overshadows all sources of parametric variability including site-effects contributions. Therefore, for scenario conditions similar to those considered here, there is considerable value in extensive site characterization in terms of reducing variability in design predictions up to several tenths of a second. For longer oscillator periods, extensive site characterization is unlikely to provide meaningful reduction in the variability of predictions given the capabilities of current ground-motion models. Note that similar levels of variability exist for current empirical attenuation relationships, so target-spectra design approaches are constrained by the same lack of predictive capability for long-period motions. However, it is critical to keep in mind that even though total variability at long periods is little affected by knowledge of site properties, such information can have a very significant impact on predictions of median response.

Finally, it is important to note that the calibration exercises used to estimate modeling variability inherently include a considerable component of parametric uncertainty regarding site effects. This stems from using very simple generic rock and/or soil profiles during the calibration since little site-specific data are currently available for most strong-motion recording stations. Therefore the estimates of total variability shown in Fig. 8 are somewhat misleading in that they may "double count" site-effects variability to some extent. Therefore, significant improvements in modeling may become possible as more information from recording sites becomes available.

Summary and Conclusions

Variability in computed earthquake ground response has been examined using a stochastic finite-fault model which allows even treatment of source, path, and site components of ground-motion variability. A suite of examples were presented which illustrate how parametric variability can be systematically examined on a site-specific basis, and it was shown that the parameters which control ground-motion predictions are a function of the site-profile type, the amplitude of motion, and the period range of interest to the designer. The impact of site effects, as characterized by the near-surface velocity profile and non-linear material parameters, was shown to be the predominant source of parametric response-spectra variability up to several seconds for soil sites experiencing strong to moderate levels of motion. The example of varying drilling depth for a single scenario was used to illustrate how specific parameters controlling response variability can be isolated. A comparison of parametric and modeling variability for the same scenario showed clear benefits of performing detailed site characterization in terms of reducing variability of design predictions for response periods through several tenths of a second, but for longer periods, the benefit of extensive site characterization is primarily related to median response rather than reduction in variability due to the poorly-constrained nature of current ground-motion models at these periods. While the suite of examples presented herein are insufficient to comprehensively evaluate either the role of site effects or the impact of geotechnical characterization on ground-response predictions, the results presented do illustrate major trends in behavior, and most importantly, provide a clear road map for treatment of such issues on a case-specific basis within the broader framework of total ground-motion variability.

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