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State-of-the Art Report
ENGINEERING MODELING OF GROUND MOTION

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SUMMARY

An overview of the engineering approach in modeling strong ground motion is presented. A brief historical review of the stochastic modeling of earthquake strong motion is attempted, followed by a classification of the existing models. The subject of spatial variability of ground motion is also addressed. An effort to point out the merits as well as weaknesses of the engineering approach is made vis a vis seismological methods of synthesis.

INTRODUCTION

Recordings of earthquake strong motions were obtained for the first time during the Long Beach, California earthquake of March 10, 1933, and since then the database of strong motion records has expanded considerably. A common feature of all the recordings was their erratic appearance. The first engineering interpretation of strong-motion accelerograms was made by Housner (Refs. 1 and 2) who explained their appearance by reasoning that high-frequency seismic waves are generated by irregular slippage along faults and subsequently are subjected to numerous random reflections, refractions and attenuations as they propagate through the heterogeneous crustal structure of the earth. Since then, many researchers followed Housner's paradigm in interpreting and modeling strong-motion accelerograms as random processes for aseismic design.

The stochastic nature of high-frequency ground motions is recognized by both engineers and seismologists. However, the approaches they use in modeling ground motions differ fundamentally. The engineer relies on an expedient approach in which earthquake motions are simulated so as to agree in essential (for engineering design) ways (such as amplitude, frequency content and duration) with existing data. The intent of this approach is to capture the essential characteristics of high-frequency motion at an average site from an average earthquake of specified size. Phrasing this differently, the accelerograms artificially generated by engineers do not duplicate any specific earthquake but embody certain average properties of past earthquakes of a given magnitude. On the other hand, the approach adopted by seismologists involves the prediction of motions from a fault that was identified by geologists and which has specific dimensions and orientation in a specific geologic setting. This latter approach is useful for site-specific simulations.

Stochastic modeling of earthquake motions and the ability to efficiently generate "realistic" artificial accelerograms are necessary for the study of the inelastic seismic response of structures which is of considerable importance for design. Inelastic response is accompanied by degradation of the structure's stiffness or strength or both. The location of yielding and extent of structural degradation which may result, may vary considerably from excitation to excitation corresponding to the same earthquake magnitude. Given the difficulty of obtaining analytical solutions for the seismic response of inelastic and degrading structural systems, the most tractable - although computationally expensive - approach to the problem is Monte Carlo simulation using a deterministic structural model (e.g., Refs. 3 and 4). But even for classes of inelastic systems for which approximate analytical approaches can be devised, Monte Carlo simulations using artificial accelerograms as input are necessary in order to assess the validity of the approximations.

As will be mentioned in the present paper, various stochastic models, stationary and nonstationary in intensity and/or frequency content, have been proposed for the simulation of high-frequency earthquake strong motion. The choice of statistical model depends on aspects of the structural response which are important for the problem at hand. A brief historical overview of the stochastic modeling of earthquake strong motion is attempted followed by classification of existing models.

In addition to the temporal variation of ground motion of a single point of the ground surface, dynamic analyses of extended structures such as pipelines, tunnels, bridges and dams, require description of the spatial variability of the ground motion as well. Therefore, we will also address the issue of the spatial variability of earthquake ground motion, and we will discuss some attempts which were recently made by engineers to model its stochastic component.

STATISTICAL MODELS OF STRONG-GROUND MOTION

Historical Overview It is instructive to attempt a brief overview of the historical development of the statistical modeling of strong ground motion. We will primarily concentrate on early original contributions, and no exhaustive literature survey will be attempted.

As stated in the introduction, Housner (Ref. 1) made the first engineering interpretation of strong-motion accelerograms. He proposed that the extreme irregularity of recorded ground acceleration could be explained by a large number of waves which are generated by a swarm of shear dislocations on the fault plane. Housner (Ref. 2) then proceeded to show that an accelerogram formed by adding a large number of uni-cycle acceleration sine-waves occurring randomly in time has a response spectrum that is in good agreement with spectra derived from recorded accelerograms. Following Housner's paradigm, various investigators modeled strong motion as a stochastic process composed of a series of pulses distributed randomly in time (Refs. 5-8). It is well known that many important characteristics of the response of linear damped structures to earthquake motions can be modeled by the response to white noise even though the frequency content of this model is known to be unrealistic.

As a step toward improving the simulation, white noise has been passed through a single-degree-of-freedom linear filter. Housner and Jennings (Ref. 9) modeled the "primary phase" or "strong motion" part of accelerograms as a stationary Gaussian random process to study the response of hysteretic structures. The average response spectrum proposed by Housner (Ref. 37) was used to derive the power spectral density (PSD) function of the process which was expressed in closed form by a mathematical expression of the Kanai-Tajimi type widely used in engineering literature (Refs. 10-11).

The stationary artificial acceleration time histories generated by the above process have proved to be satisfactory in many studies. However, when modeling ground motions of smaller events or for use in studies where damage accumulation is of primary concern (e.g., soil liquefaction under cyclic loading), the assumption of stationarity is not appropriate.

The simplest way to introduce nonstationarity is to make the intensity of motion per unit time a time function. This is accomplished by multiplying a segment of a stationary process by a deterministic time-dependent envelope. (The multiplication can be done at the white noise stage or after filtering the white noise process [Ref. 12]). Thus, the PSD function describes the frequency content of the motion, while the slowly varying envelope is used to model the initial build-up of motion, the strong (almost stationary) central phase and slowly diminishing coda. Bolotin (Ref. 13) appears to be the first to have suggested the use of a deterministic envelope function. The form of the envelope does not have a significant effect on the spectra of the simulated accelerograms as long as it varies slowly with time. Various researchers modeled accelerograms as random processes with time-varying intensity (Refs. 8, 12, 14-17, 19). Such a representation of earthquake strong ground motions was used in connection with random vibration theory to determine the expected maximum response of structures (e.g., Refs. 20-23).

The assumption of stationary spectral characteristics seems satisfactory in analyzing the earthquake response of linear structures in which only spectral components in the vicinity of natural periods are important. However, as has been demonstrated by several investigators (e.g., Ref. 24), when the mechanical properties of a structure deteriorate during an earthquake and its natural period is prolonged, later arrivals of relatively longer prevailing periods may cause a large response which would not otherwise occur in response to motions with stationary spectral shape.

Among several concepts proposed to represent nonstationary spectral characteristics is Priestley's (Ref. 25) evolutionary spectrum. This concept offers the most palatable transition from the power spectra associated with stationary stochastic processes to those associated with nonstationary stochastic processes, and makes it feasible to generate a mathematical description which accounts for the evolution of both the intensity and temporally local frequency content of the process. Several studies have been made on the time dependency of the spectral content of earthquake accelerograms (e.g., Refs. 26-27). The evolutionary power spectrum may be estimated either by the "Moving Window Fourier Transform Method" (e.g., Refs. 28-29) or more accurately by the "multifilter technique" (Refs. 30-33). Attempts have been made to parametrize and analytically describe the observed evolutionary power spectra (e.g., Refs. 29 and 31). However, all such descriptions are phenomenological and it is not clear how they can be related to the physics of wave propagation and how (if at all) they can be generalized. For a stochastic process with prescribed evolutionary power spectrum, the method for generating sample time histories was established by Shinozuka and Jan (Ref. 34).

Using a different approach, Trifunac (Refs. 35-36) proposed a method for generating artificial accelerograms which accounts for many aspects of the physics of seismic wave propagation in a layered medium. The synthetic motions generated by this method incorporate the properties of wave propagation by making use of theoretical group dispersion data for a given site, and thus have time variations in frequency content as well as in amplitude due to surface wave dispersion. The stochastic nature of motion is captured by random phasing of the various frequency components.

Finally, it should be pointed out that in the early years of earthquake engineering, the spectral content of the simulated accelerograms was derived from empirical spectra such as those of Housner (Ref. 37) or Trifunac (Ref. 38). Recent advances in the field of engineering seismology (Refs. 39-43) have made it possible to describe earthquake spectra and their associated scaling law (i.e., the law that describes how spectra change with earthquake size), in terms of physical parameters of the earthquake source and the attenuation characteristics of the tectonic zone of interest. This constitutes a development in the right direction and we will discuss it in a later section.

Analytical Representation of Earthquake Strong Motion as White Noise Process and Filtered Poisson Process   Having traced the historical development of stochastic modeling of earthquake strong motion, let us present and discuss the analytical models used in the simulation of accelerograms (for a more comprehensive presentation see Ref. 44).

The ground acceleration $f(t)$ caused by strong-motion earthquakes can be simulated by either the filtered white noise process model which is described by either of the following two equations:

$$f_1(t) = \int_{-\infty}^{\infty} h(t-\tau)\Psi(t)n(\tau)d\tau = \Psi(t)X_1(t); \qquad f_2(t) = \int_{-\infty}^{\infty} h(t-\tau)\Psi(\tau)n(\tau)d\tau \quad (1);\ (2)$$

or by the filtered Poisson process model which is described by either one of the following two equations:

$$f_3(t) = \sum_{n=-\infty}^{\infty} A_n\Psi(t)h(t-t_n) = \Psi(t)X_2(t); \qquad f_4(t) = \sum_{n=-\infty}^{\infty} A_n\Psi(t_n)h(t-t_n) \quad (3);\ (4)$$

In Eqs. 1 and 2, $n(t)$ is a Gaussian white noise with spectral density equal to S, $h(t)$ is the impulse response function of a linear, time-invariant filter whose Fourier transform $H(\omega)$ specifies the form of the spectral density function ($= S|H(\omega)|^2$) of a stationary stochastic process given by:

$$X_1(t) = \int_{-\infty}^{\infty} h(t-\tau)n(\tau)d\tau \tag{5}$$

and $\Psi(t)$ is a deterministic function of time serving as the envelope to the stationary process $X_1(t)$ in the model shown in Eq. 1 and to the white noise $n(t)$ in Eq. 2, thus making both processes $f_1(t)$ and $f_2(t)$ nonstationary. The difference in the response of a linear structure when subjected to the ground acceleration $f_1(t)$ in Eq. 1 and to $f_2(t)$ in Eq. 2 appears to be insignificant, if any at all. Both models approximately retain the shape of the spectral density function of the underlying stationary process if $\Psi(t)$ is chosen to be a slowly varying function of time.

In Eqs. 3 and 4, the sequence of time instants $\{\ldots, t_{-1}, t_0, t_1, \ldots\}$ indicates Poisson arrival times with arrival rate λ and $\{\ldots, A_{-1}, A_0, A_1, \ldots\}$ is a sequence of mutually independent and identically distributed random variables A_n with mean zero and variance σ^2:

$$E\{A_n\} = 0 \qquad\qquad E\{A_n^2\} = \sigma^2 \tag{6}$$

where $E\{\cdot\}$ indicates the expectation. Defining now

$$Z_1(t) = \sum_{n=-\infty}^{\infty} A_n\delta(t-t_n) \tag{7}$$

as a series of Poisson impulses with arrival rate λ and random amplitude A_n, the stationary stochastic process given by

$$X_2(t) = \sum_{n=-\infty}^{\infty} A_n h(t-t_n) \tag{8}$$

can be considered the output of a linear filter with impulse response function $h(t)$ to $Z_1(t)$. Obviously then, if we consider the series of Poisson impulses $Z_3(t)$ and $Z_4(t)$ with arrival rate λ and random amplitudes in the form of either $A_n\Psi(t)$ or $A_n\Psi(t_n)$:

$$Z_3(t) = \sum_{n=-\infty}^{\infty} A_n \Psi(t)\delta(t-t_n); \quad Z_4(t) = \sum_{n=-\infty}^{\infty} A_n \Psi(t_n)\delta(t-t_n) \qquad (9);\ (10)$$

the (nonstationary) filtered Poisson processes $f_3(t)$ and $f_4(t)$ are obtained respectively as the outputs of the same linear filter to $Z_3(t)$ and $Z_4(t)$. As in Eq. 1, $f_3(t)$ can be interpreted as a nonstationary filtered Poisson process obtained by multiplying a stationary filtered Poisson process $X_2(t)$ by a deterministic function of time $\Psi(t)$, whereas $\Psi(t)$ in Eqs. 4 and 10 introduces a physically more plausible nonstationarity into the random amplitudes of the underlying Poisson impulses.

It can be shown that

$$E\{f_i(t)\} = 0 \qquad i=1,2,3,4 \qquad (11)$$

and that if the following relation holds

$$\lambda\sigma^2 = 2\pi S \qquad (12)$$

then the autocovariance functions of $f_i(t)$ (i=1,2) are such that

$$E\{f_1(t)f_1(s)\} = E\{f_3(t)f_3(s)\} = 2\pi S\Psi(t)\Psi(s) \int_{-\infty}^{\infty} h(t-\tau)h(s-\tau)d\tau \qquad (13)$$

$$E\{f_2(t)f_2(s)\} = E\{f_4(t)f_4(s)\} = 2\pi S \int_{-\infty}^{\infty} h(t-\tau)h(s-\tau)\psi^2(\tau)d\tau \qquad (14)$$

Equations 13 and 14 indicate that the filtered Poisson processes and filtered white noise processes as defined above can be made identical up to the second moment by imposing the condition given in Eq. 12. It can further be shown that (a) the processes $f_1(t)$ and $f_2(t)$ are Gaussian and (b) although $f_3(t)$ and $f_4(t)$ are in general non-Gaussian, they are asymptotically Gaussian as $\lambda \to \infty$ with $\lambda\sigma^{24}$kept constant.

Finally, it can be shown (Ref. 12) that $f_4(t)$ in Eq. 4 is equivalent to

$$f_4^*(t) = \sum_{n=-\infty}^{\infty} A_n h(t-t_n) \qquad (15)$$

if the underlying Poisson process has nonstationary arrival rate $\lambda\Psi^2(t)$. This fact has been directly used by Lin (Ref. 45) to produce nonstationarity in his model for ground acceleration. Furthermore, Lin (Ref. 46) demonstrated that if $E[A_n] = 0$, the filtered Poisson process given in Eq. 15 is equivalent, at least up to the second moment, to an evolutionary process with evolutionary power.

Digital Generation of Sample Functions As alluded to earlier, the filtered Poisson process model is more amenable to plausible physical interpretation when compared to the filtered white noise process model. In terms of efficiency of digital simulation of sample functions, however, direct use of the filtered Poisson process model as indicated in Eqs. 3 and 4 requires digital generation of Poisson arrival times and random amplitudes, as well as summation, and is usually more costly when compared to use of Eqs. 1 and 2 that requires digital generation of independent Gaussian random numbers and integration (or equivalently summation). Therefore, even though the filtered Poisson process model appears more preferable in terms of physical interpretation, sample functions of the stochastic process simulating the ground acceleration are usually generated with the aid of the filtered white noise model. This generation is performed under the assumption that the condition shown in Eq. 12 is satisfied or under the premise that it is good enough for the purpose of engineering analysis to use the filtered white noise model in place of the filtered Poisson model since their first two moments are identical. From the viewpoint of applications to structural analysis problems, it is important to note that, as far as linear responses are concerned, these two families of models for the simulation of ground acceleration produce structural responses which are identical asymptotically as $\lambda \to \infty$ (and hence both are Gaussian) and if Eq. 12 is satisfied. Otherwise, they are identical up to the second moment.

A method which is general and easy to implement for the digital simulation of seimograms is the "spectral representation method" introduced by Shinozuka and his associates (Refs. 34, 47-49). If a nonstationary process $y_0(t)$ has an evolutionary power spectrum of the form $|A(t,\omega)|^2 f(\omega)$, then the process can be simulated by the following expression, as $N \to \infty$:

$$y(t) = \sqrt{2} \sum_{j=1}^{N} \sqrt{2|A(t,\omega_j)|^2 f(\omega_j)\Delta\omega} \cos(\omega_j t+\phi_j) \tag{16}$$

where $\omega_j = j\Delta\omega$, $(j=1,2,\ldots,N)$. An upper bound of the frequency $\omega_u = N\cdot\Delta\omega$ is implicit in Eq. 16 and ϕ_j are independent random phase angles uniformly distributed over the range $(0,2\pi)$. Note that the simulated process y(t) is asymptotically Gaussian as N becomes large due to the central limit theorem. (The Gaussian nature of real accelerograms has been verified by Ref. 39 for the 1971 San Fernando records.) It can be shown that the simulated process y(t) possesses the target evolutionary power spectrum as $N \to \infty$.

Thus, with the spectral representation method, we can obtain sample accelerograms if we know the spectrum of the earthquake source and the attenuation characteristics of the tectonic region of interest. The earthquake source spectrum may be estimated either empirically, using regression analysis on the data (e.g., Ref. 38) or may be based on a seismological model of the source (e.g., Refs. 40 and 43).

Physical Basis of Stochastic Models of Earthquake Accelerograms It is evident that the original work of Housner (Refs. 1 and 2) provide a physical basis for stochastic modeling of earthquake accelerograms. As already stated, Housner's hypothesis is that strong-motion accelerograms are formed by superposition of waves which are generated by a swarm of dislocations on the fault plane. The random timing of the rupture of the dislocations and subsequent scattering that may occur along the propagation path, justify the random arrival time of the waves at an observation point. At the time Housner formed the above hypothesis, earthquake source theory and methods for evaluating Green functions for realistic earth media were not well developed. Thus Housner proceeded by considering simple - yet effective for earthquake engineering purposes - functional forms for radiated waves. We now know that high frequency waves emanate from the rupture front as it interacts with heterogeneous (i.e., barriers or asperities) of the fault plane (Refs. 41, 42 and 50). The recorded motion may be computed by convolving the slip function (i.e., the function which describes the evolution of slippage at a point on the fault plane) with the Green tensor of the earth (Ref. 51).

Housner's original idea on modeling high frequency seismic radiation has obtained a more concrete expression with the "specific barrier model" proposed recently by Papageorgiou and Aki (Refs. 41 and 42). According to this model, the earthquake source is represented by circular cracks distributed on the fault plane and the high frequency radiation of the model is controlled by "stopping phases" which are emitted as crack ruptures are arrested by barriers. What is particularly important to mention about this model is that its key physical parameter, the local stress drop, may be also estimated by geological exploration methods (paleoseismology) and thus the model is potentially useful in predicting strong ground motion even for tectonic areas for which there are no recordings (Ref. 52).

Spatial Variation of Earthquake Strong Ground Motion Let us now discuss the spatial characteristics of earthquake motions. The spatial variability of strong ground motion, as observed in recordings obtained in dense arrays, was found to be rather high even over short distances (Refs. 53-58). The spatial variation of freefield motion is an important consideration for the seismic design of elongated structures supported on extended foundations or multiple supports (e.g., elongated buildings on mat foundations or footings, dams, long-span bridges, buried lifelines such as tunnels and pipelines), and consequently, engineers need to measure the variations of earthquake motions over distances comparable to the dimensions of large structures (i.e., 50-1,000 m).

The spatial variability of earthquake motions may be due to: (1) nonvertical incidence of body-wave energy, (2) surface-wave propagation, (3) waves arriving from different points of an extended source, (4) amplitude changes and time delays due to hetergeneities along the propagation path which act as scatterers.

The effects of nonvertical incidence of body wave energy and surface-wave propagation on the response of structures have been studied by various investigators (e.g., Refs. 59-61) and are well documented. The spatial variation of ground motions due to wave passage in general causes a reduction in the translational response of the foundation and an increase in the rocking and torsional response. For structures supported on flexible foundations or multiple supports and for buried lifelines (e.g., pipelines and tunnels), the spatial variation of the ground motion may cause increased localized deformations and strains.

The two factors of spatial variability of ground motion discussed above, i.e., nonvertical incidence of body waves and surface-wave propagation are associated with the coherent component of seismic radiation. However, the spatial variability of ground motion resulting from the incoherent component of seismic radiation (i.e., seismic waves scattered by heterogeneities along the propagation path and which arrive at an observation point from various directions) has been shown to be equally significant. Analytical studies of the response of a rigid square foundation subjected to spatially random ground motion conducted by Luco and Wong (Ref. 62) have shown that the spatial randomness of ground motion produces effects similar to the effects of wave passage, including reduction of the translational components of the response at high frequencies and creation of rocking and torsional response components.

A major source of data for improving our understanding of the spatial variability of strong ground motion is the SMART-1 array. This is the first dense multiple-element array of digital strong-motion seismographs which to provide measurements of seismic waves of strong earthquakes near their sources. As discussed by Bolt et al. (Ref. 56), a pioneering work of this kind, for, however, small ground motions, was carried out in Japan by Aki and Tsujiura (Ref. 63) using a small array of seismographs and correlational analysis. Analyses of data recorded so far by the array have been reported by various investigators (for a review, see Ref. 57). The major conclusion derived from these analyses is that the coherency of ground motion is a decreasing function of distance and frequency, for frequencies above approximately 1 Hz. More specifically, comparison of seismograms and wave number-frequency spectral plots shows that coherent seismic energy is associated with low and intermediate frequency components (< 1 Hz). This coherent component of ground motion corresponds to the expected body and surface waves which can be modeled using deterministic methods developed by seismologists. As the frequency increases, however, the percentage of incoherent energy increases. At high frequencies (above 3 Hz for S-waves at the SMART-1 array site), the recorded motion is dominated by incoherent energy. These observations are consistent with the hypothesis that the lithosphere is a strongly heterogeneous medium causing scattering of high-frequency waves (Ref. 64). This lack of spatial coherence at high frequencies also explains why wave form modeling of strong ground motion does not closely match observed high-frequency waves.

Given the above observations, it is not practical (although in principle possible) to model this incoherent component of ground motion deterministically because even small variations in the velocity structure can produce significant phase shifts in high-frequency energy. Thus, as suggested by Abrahamson and Bolt (Ref. 65), a practical approach to modeling would be to generate a suite of synthetic ground motions in which the Fourier phase of the incoherent energy is varied in a statistical manner while the Fourier phase of the coherent energy remains unchanged.

In modeling the effects on engineering structures of the coherent component of ground motion (i.e., wave passage effects), the spatial variation of ground motion is typically represented in the form of plane waves. On the other hand, in modeling the spatial variability of the incoherent component of ground motion, the cross-correlation or coherence function between the motion of two points is typically used. A major difficulty in the statistical characterization of the incoherent component of motion is that the functional dependence of the coherence function on distance and frequency has not been fully established. Various empirical functional forms have been proposed by researchers who have analyzed the SMART-1 array data primarily for the purpose of evaluating the seismic risk of lifelines (pipelines) (Ref. 66) while Luco and Wong (Ref. 62) used a functional form resulting from theoretical models of scalar shear wave propagation through a random medium. Clearly, a better understanding of the scattering phenomena of high-frequency waves is needed in order to establish the functional form(s) of the coherence function and its dependence on physical phenomena on physical parameters of the crustal structures through which the seismic waves propagate.

Concluding, we should point out that as for the temporal variability of ground motion, the spectral representation method can be used for the digital simulation (in space and time) of wave fields with given power spectra. A two-dimensional wave field $y_0(\underline{x},t)$ with spectral content $|A(\underline{x},t;\underline{k},\omega)|^2 \cdot f(\underline{\kappa},\omega)$ can be simulated as follows:

$$y(\underline{x},t) = \sqrt{2} \sum_{m=1}^{N_t} \sum_{\ell_x=1}^{N_x} \sum_{\ell_y=1}^{N_y} \sqrt{2A^2(t,x,y,\omega_m \kappa_{x\ell_x},\kappa_{y\ell_y})}$$

$$\cdot \sqrt{f(\kappa_{x\ell_x},\kappa_{y\ell_y},\omega_m)\Delta\omega\Delta\kappa_x\Delta\kappa_y} \cdot \cos[\omega_m t \pm \kappa_{x\ell_x} x \pm \kappa_{y\ell_y} y + \phi_{m\ell_x\ell_y}] \tag{17}$$

where

$$(\Delta\omega,\Delta\kappa_x,\Delta\kappa_y) = (\frac{\omega_u}{N_t},\frac{\kappa_{xu}}{N_x},\frac{\kappa_{yu}}{N_y})$$

$$\omega_m = m \cdot \Delta\omega; \quad \kappa_{i\ell_i} = \ell_i \cdot \Delta\kappa_i \qquad m=1,2,\ldots,N_t; \quad \ell_i=1,2,\ldots,N_i; \quad i=x,y$$

with $\phi_{m\ell_x\ell_y}$ = independent random phase angles uniformly distributed in $(0,2\pi)$.

Shinozuka et al. (Ref. 67) have used the method in connection with power spectra inferred from analysis of SMART-1 array data to generate multiple realizations with the same statistical characteristics as those of the recorded wave field. A topic that merits further attention is the possibility of combining the spectral representation method for generating wave fields with the discrete wave number method for representing seismic sources (Refs. 68-69). The discrete wave number method could be used to evaluate the power spectrum of the motion at a site and subsequently the spectral representation method could be used to simulate realizations of the wave field by randomly varying the phase of the spectral components. Such a procedure could be used, for example, to simulate the spatial variability of ground motion at a site in the vicinity of an extended source.

CONCLUSION

Having reviewed the engineering approach in modeling strong ground motion, the following question arises. Where does such an approach stand in comparison with seismological methods of strong ground motion synthesis? This question is particularly critical in view of the fact that developments in the last two decades in strong motion seismology make it possible for seismologists to synthesize ground motions generated by a given fault using Green functions (synthetic or empirical) of very realistic earth models. Part of the answer to the above question was given in the introduction where we pointed out that the intent of the engineering approach is to capture in an expedient way the essential characteristics of high-frequency motion at an average rock site from an average earthquake of specified size. This is particularly convenient from an engineering point of view because many times the only information available to the designer about the earthquake loading is a measure of the magnitude/size and epicentral distance. With such limited information, the engineering approach makes it possible to capture the gross characteristics of the expected ground motions (assuming proper earthquake source spectra and attenuation curves are used). Furthermore, the engineering approach makes it easy (and inexpensive) to supplement the conventional peak ground acceleration (PGA)-based seismic hazard curve (i.e., the curve which describes the annual exceedance probability as a function of PGA) with uniform risk spectra, thus incorporating more information into the probabilistic risk assessment (PRA). To mention an example, such an approach has been adopted by the Tokyo Electric Power Services Corporation (TEPSCO) for a seismic PRA study involving nuclear power plant structures (Ref. 70).

However, it is important to realize the limitations of the engineering approach. For instance, the engineering approach may be inappropriate for modeling near-fault ground motions. An important characteristic of such motions are long-duration acceleration pulses which have important implications for the dynamic response of buildings located near faults (Refs. 71-72). The methods we discussed in modeling ground motion are not tailored to model such pulses. Furthermore, radiation patterns and directivity effects shich influence the amplitude and duration characteristics of records are not accounted for in the engineering approach. This was clearly demonstrated in a simulation study (Ref. 73) of the long-period ground motions of the Fort Tejon, California, 1857 earthquake in which the synthetic seismograms obtained using empirical Green functions were compared with the artificial time histories generated by Jennings et al. (Ref. 68).

Summarizing, despite the various limitations associated with the engineering approach for modeling ground motions, it is still appealing and useful in engineering practice, especially given the limited resources and data usually available to design engineers.

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