SELECTION OF EARTHQUAKE DESIGN MOTIONS FOR IMPORTANT ENGINEERING STRUCTURES

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SUMMARY

This paper reviews selected recent publications[44] on physical and observational bases for quantitative description of earthquake occurrence rates, on selection of maximum earthquake and on the concept of uniform risk spectrum.[2,21,24] It reviews the empirical description of strong ground motion for generating artificial accelerograms for use in engineering design.[24,34] Using the computer program SYNACC an artificial accelerogram[22,23] can be derived, starting from the uniform risk spectrum computed by the NEQRISK program,[21] or by using independently determined Fourier amplitude spectra[25] of the postulated strong ground motion.

When the seismic risk at a site is dominated by the presence of an active fault nearby, the analyst may wish to compute the waves in terms of a physical model which produces ground motion in terms of the assumed slip and faulting characteristics at the earthquake source.[26] References are cited which summarize the state of the art in forward modeling procedures of ground motion from kinematic description of earthquake sources.

For long structures,[20,30-32] which are sensitive to relative motions of different multiple supports, the local soil and geologic conditions call for detailed modeling of the wave scattering and diffraction.[28,29] For input ground motions computed either in terms of synthetic accelerograms via empirical scaling and uniform risk spectra[21,24] or in terms of deterministic physical modeling[26] the cited papers on wave scattering show, how by using transfer function approach and Fourier analysis and synthesis one can derive motions at multiple support points of long structures.

I. INTRODUCTION

Since 1933, March 10, in Long Beach, California, when the first strong motion accelerogram was recorded, many important advances in earthquake engineering design have been accomplished. From 1940's, when the first earthquake resistant design codes were introduced, to the present, almost every country situated in a seismically active region has adopted some form of earthquake design provisions. In this sense the earthquake resistant design is now entering a "mature" state in which it is performed routinely and according to some specifically defined design codes.

The methodology, and the computer programs which are outlined here, have been calibrated in terms of specific empirical equations, to work in the Western United States, from where most of the data we use comes from. While we have extended some of these empirical equations to other parts of the world,[44] it should be noted that the methodology we present is general, while the examples of scaling equations are not. Thus, for example, to use our approach for estimation of the ground motion characteristics in Europe or in Japan, a sequence of regionally specific empirical scaling equations must be developed.

Most of the available literature on strong ground motion is scattered in many reports which, if available may not represent systematically arranged material for easy study. Therefore, we have selected here sample sections of the available material, and arranged it into a sequence, as outlined in the flow chart of Fig. I. In this form, so grouped and cited material will provide an earthquake engineer with basic introduction on the steps that are required for selection of the design ground motion, and with the starting background for further study.

Section II will briefly summarize the methods for empirical scaling of ground motion, and will end with a response or Fourier spectrum of the representative ground motion, or with a synthetic accelerogram characterizing the expected future ground motion. No detailed site specific wave propagation analyses will be considered, but only the overall site specific spectral considerations.

In contrast, Section III (Fig. I) will cite literature[26] on physical modeling approach for computing the ground motion, in those instances, when the causative fault is very close to the site of the structure being analyzed. Here, it will be assumed that the geometry and the motions on the fault have been specified, so that the task to be accomplished involves only the forward computation of ground motion at desired locations near by.

In Section IV we cite selected papers which deal with the procedures for calculation of the site specific effects.[28,29] The input for these calculations will come from either empirical (Section II) or physical (Section III) modeling of ground motion. The need for this work comes from the requirement to select proper ground motion input for long structures,[30-32] which may be sensitive to the propagating wave effects.

Recently, there were some attempts to reconcile the old, essentially linear, approach for earthquake resistant design, with more realistic non-linear analyses. The outcome of these attempts consisted of some "equivalent," "effective" and "anchoring" "design" ground motion parameters, providing for the required "conversion" between simplified analyses and the reality. To avoid any confusion, in this work, even though the word DESIGN is used in the title, we will address only the problem of estimating the "actual" ground motion that may take place at the site during future earthquakes. Of course, we cannot predict the true details of the motion before it occurs. By "actual" we mean that no reductions, modifications, or changes will be imposed on the ground motion estimates which result from our knowledge and experience with specific features of the structure which is to be analyzed.[10-14]

II. EMPIRICAL ESTIMATION OF DESIGN EARTHQUAKE MOTIONS

Detailed seismic risk analyses begin with description of the seismic environment of the site and characterization of the levels of earthquake activity, distance of the activity from the site and selection of the procedures for introducing the identified sources into the method of analysis.[1,2,24,44] Once the seismic sources have been specified, the second important step involves description of the attenuation equations.[33,38,42] This work has the objective of translating the description of the nature and of the size of the earthquake into the preferred mode of presenting the ground motion at the site where the analysis is to be carried out. The third important step in the analysis combines all contributions from different sources into one joint presentation, for example, involving distribution of spectral amplitudes, so that one can select the final amplitudes on the basis of some desired level of confidence that those will not be exceeded. In some instances, this may be the end result of the analysis representing the spectrum of the "design" motions. In other instances it may also be necessary to produce artificial time histories,[22,23] so that non-linear response analyses can also be carried out.

To organize the tasks that have to be performed in the above steps, one may divide this work into three different parts addressing: sources of earthquakes, uniform risk spectra and synthesizing realistic strong motion accelerograms.

Sources of Earthquakes

This part is concerned with describing the physical and observational bases for a quantitative relationship between earthquake occurrence rates and geological deformation rates.[1] Such relationships are founded on the principles of the elastic rebound theory,[26] and are supported by observations[44]. The role of a seismic creep, the width of the seismogenic zone, the shape of the earthquake magnitude – occurrence rate curve (including maximum earthquake), and the limitations of geological observations to define deformation rates are the most important sources of uncertainty in the process.[44]

Uniform Risk Spectra

First methods to determined the seismic risk at a site were discussed by Cornell.[9] The results are often presented in terms of one ground motion parameter, such as peak acceleration, and the return period may be calculated versus that parameter. Other ground motion parameters like magnitude, some peak amplitude of ground shaking, and Modified Mercalli Intensity at the site have also been used. In such studies, the spectral nature of ground motion is not considered. The probability that a spectral amplitude will be exceeded during future earthquakes does depend on wave frequency[27,36] and so must be considered in all modern analyses.[44]

The concept of uniform seismic risk[2,21,24,44] generalized this work to a functional of shaking, $S(\omega)$, which can represent any functional of strong ground motion at frequency ω (like Fourier amplitude, response spectral amplitude, peak response amplitude, or duration of strong shaking). This work[21] also incorporated a realistic model for describing the seismicity and proposed two independent methods to obtain uniform risk functionals: one assuming that the seismicity, which is the input to the model, is treated as the mean of a Poisson sequence, and the other one assuming that it can be taken literally.

There are several ways of describing seismicity. Depending on the method used, the outcome of a seismic risk analysis may be very sensitive to this description. In a large region, the occurrence rate of earthquakes is often known. The analysis for a specific site is more difficult and depends on the conditions near the site, particularly within 25 to 50 km.[21] For small regions, "historical seismicity" based on felt reports is often incomplete and may not represent the true seismicity of the region. In such cases, the knowledge of fault slip rates or regional strain rates[1] from plate tectonics theory may be used to estimate "geological seismicity." This helps to increase the reliability of the description of seismicity in a region.[21]

The steps in the derivation of a uniform frequency dependent risk functional can be summarized as follows:[21,24]

(1) Specify the geometry of earthquake zones by point, line, areal, dipping plane and volume sources. For each of these source zones, the estimated number of events of each earthquake size, $N(M_j)$, is defined. The uncertainties in the estimation of seismicity and maximum allowed earthquake sizes are also defined. This is done by studying previous seismicity, by insights obtained from geological studies and plate tectonics, and by statistical inference and scientific judgement.[21]

(2) Divide each source zone into small source elements, and assuming the epicenter of each event of some magnitude M_j is equally likely to occur any place in the source zone, distribute the seismicity to each element accordingly.

(3) Specify a frequency-dependent description of the attenuation of strong-motion amplitudes in the region,[42] plus a description of the distribution of the observed amplitudes[33-43] $S(\omega)$ about he mean estimate $\hat{S}(\omega)$. From this, define the function $Q_{ij}[S(\omega)]$ which gives the probability that $S(\omega)$, will be exceeded at the site for an event of size M_j in the i-th element of the source zone.

(4) Calculate $N_E[S(\omega)]$, the expected number of times that $S(\omega)$ will be exceeded at the site from all source elements in all source zones and all allowed earthquake sizes. Then calculate $P[S(\omega)]$, the probability that $S(\omega)$ will be exceeded at least once at the site in the given period.

(5) Derive the frequency dependent uniform risk functional from the functions $P[S(\omega)]$.

Synthesizing Strong Motion Accelerograms

The Majority of proposed methods for generation of synthetic accelerograms fall into two categories:[22,23] (1) methods that utilize random functions, and (2) methods that involve source mechanism and wave propagation models. Using the former methods, the resulting accelerograms do not always have a correct frequency content for engineering applications and the frequency characteristics of the time record are often uniform from the beginning to the end of the record. For a recorded accelerogram, the frequency contained in the earlier part is generally higher. Using the latter methods, a more physically consistent record can be generated, but it is impossible to model all the details of the source, as well as the wave path, for the complete frequency range of interest (e.g., 0.05 Hz to 30Hz). Because of the simplifications, the records generated often lack proper high frequency characteristics when compared with recorded accelerograms.

Trifunac and Todorovska[44] present a brief review and a summary of a method based on computer program SYNACC[22,23,34] for constructing synthetic accelerograms which have a given Fourier amplitude spectrum,[36-39] $F(\omega)$, and a given duration.[41] The Fourier amplitude spectrum and the duration can be obtained from correlation with the earthquake parameters. The times of arrival of the waves are derived from the dispersive properties of the site; i.e., the phase and group velocities for the lowest modes of surface waves. This method thus introduces the characteristics of each site into the resulting artificial accelerogram. The strong motion amplitudes are determined[35-43] in terms of (1) earthquake magnitude and epicentral distance, or (2) Modified Mercalli Intensity at the recording station.

III. PHYSICAL MODELING OF NEAR EARTHQUAKE SOURCES

The computed strong ground motion near dislocation models of earthquakes in a uniform, elastic, layered half-space has been the subject of many investigations.[26] The models include a fault surface, consisting of one or more planes,[16,17] and involve distributions of slip and rupture velocity over the fault.[45] The surrounding medium is represented as a multilayered elastic or viscoelastic half-space. The simplest three-dimensional dislocation model in an infinite space corresponds to constant dislocation moving with constant rupture velocity over a rectangular fault. For simple dislocation time functions, the time convolutions can be obtained analytically. The integrations over the fault plane are conducted numerically.[19] Haskell[16] calculated and plotted displacement, velocity and acceleration time histories for the motion in the vicinity of a vertical strike-slip fault. He also presented contours of maximum range, in the vicinity of the fault, for the parallel and normal components of displacement, velocity and acceleration.

More recently three-dimensional dislocation models of extended faults in a layered half-space have been utilized in the study of recorded near-source ground motion from a number of earthquakes.[4-8,26,45] One of the methods to synthesize ground motion is based on the frequency domain representation as a double integral over two horizontal wave numbers. Another approach is based on the use of the representation theorem in which the response of the medium is expressed in terms of spatial and temporal convolutions of Green's functions with the slip function. The use of this approach is made possible by the recent development of effective methods to evaluate Green's functions for layered media.[3,7,26] The required discretization of the spatial convolution involving the Green's functions and the slip on the fault limits the application of this approach to low frequencies.[19]

IV. GENERATION OF SITE SPECIFIC MOTIONS

In many areas of earthquake engineering analysis the ground amplification effects caused by surface and subsurface irregularities can be an important factor. Therefore, a detailed understanding of these effects is of obvious value to earthquake engineering work. Models with simple geometries are usually employed to study the wave amplification problems. For studies of inhomogeneities smaller than the wavelengths of the incident waves and waves with long periods, these models seem to be satisfactory. However, there are many cases in earthquake engineering where near field ground motions should be included, in which the waves with shorter periods become important.

In earthquake damage studies for example, evidence of wave amplification has been observed. The influence of irregular geological structure or topography may overshadow the effects of local site conditions.[18] The sites with softer alluvium yield higher amplitudes and longer durations than the "stiffer" sites and the intensity of ground shaking can vary within a short distance.[15,28,29] The importance of the amplification caused by soil deposits has been recognized in microzontation studies.[44] Due to such effects of surface and subsurface irregularities, many models have been proposed and studied by different researchers for better understanding of the amplification phenomena.[39,44]

In reviewing the methods of analysis in this subject area, one finds discrete methods and continuous methods. The discrete methods include finite elements and finite differences. Each of these methods have limitations. Due to large dimensions in geophysical problems, the application of discrete methods may be limited. On the other hand, the applicability of continuous methods is mainly restricted to linear, isotopic and homogeneous materials and simple geometries.

Moeen-Vaziri and Trifunac[28,29] have illustrated the methods of solution and the effects of subsurface inhomogeneities and irregularities of arbitrary shape on the ground motion amplification. Their method can be applied to analyze cross sections along profiles of irregular geologic basins, to investigate the effects of subsurface inhomogeneities on scattering and diffraction of incident waves. The surface displacement amplitudes or displacement amplitudes along buried horizontal lines (tunnels) can also be considered.

This type of analysis can also include computation of transient motions. This can be carried out using the transfer functions obtained from harmonic analysis. The accelerograms from the 1971 San Fernando earthquake have been used,[28,29] for example, to illustrate the effects of subsurface inhomogeneities upon transient motions along different profiles of the Los Angeles basin. The results can be presented in terms of amplitude spectra and/or accelerograms at several points on the surface of the inhomogeneity.

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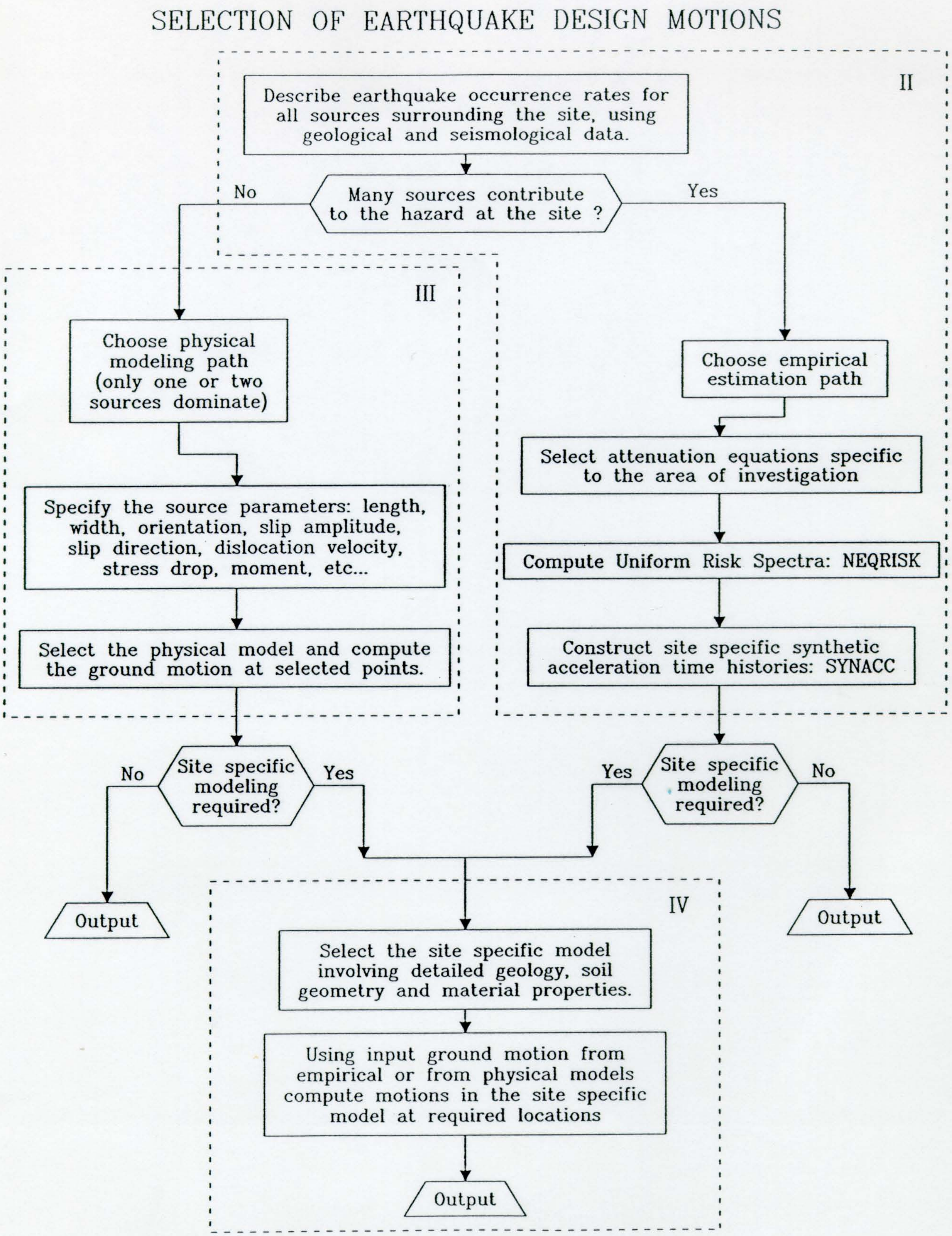
SELECTION OF EARTHQUAKE DESIGN MOTIONS
II
Describe earthquake occurrence rates for all sources surrounding the site, using geological and seismological data.
Many sources contribute to the hazard at the site ?
No
Yes
III
Choose physical modeling path (only one or two sources dominate)
Specify the source parameters: length, width, orientation, slip amplitude, slip direction, dislocation velocity, stress drop, moment, etc...
Select the physical model and compute the ground motion at selected points.
Choose empirical estimation path
Select attenuation equations specific to the area of investigation
Compute Uniform Risk Spectra: NEQRISK
Construct site specific synthetic acceleration time histories: SYNACC
Site specific modeling required?
No
Yes
Site specific modeling required?
Yes
No
Output
Output
IV
Select the site specific model involving detailed geology, soil geometry and material properties.
Using input ground motion from empirical or from physical models compute motions in the site specific model at required locations
Output

Figure I