USING REAL EARTHQUAKE ACCELEROGRAMS FOR DYNAMIC ANALYSIS OF NUCLEAR FACILITIES: DEFINING SPECTRAL TARGETS, SELECTING RECORDS AND ADJUSTING FOR CONSISTENCY

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ABSTRACT

Earthquake-resistant design and seismic risk assessment of nuclear power plants require dynamic analyses for which the input is needed in the form of acceleration time-histories, which need to be consistent with the elastic response spectrum used for the preliminary design. There is now a very extensive literature offering guidance on preparation of appropriate suites of accelerograms, which is frequently ambiguous, and generally difficult to navigate for the structural engineer. The confusion that exists around this topic is not the result of poor research but rather the lack of a clear framework to guide the decision-making process, which needs to work backwards from the definition of the structural analyses to be performed and the required output from these calculations. This in turn defines how many records will be required and how closely they are required to match the target response spectrum, which needs to be defined in a way that is consistent with both the requirements of the structural engineers and the probabilistic seismic hazard analysis that should be the starting point for the definition of the earthquake loading. Clearly defining the questions that are being addressed and the criteria that need to be met by the records, will both assist the process of preparing suites of time-histories for structural analyses and avoid conclusions and guidelines being erroneously transported from one situation to another where they may not be applicable.

INTRODUCTION

For the seismic design and assessment of safety-critical facilities such as nuclear power plants, fully dynamic structural analyses will generally be required beyond simpler approaches in which the earthquake-induced ground shaking is represented in the form of a response spectrum. Since dynamic analysis will generally follow preliminary design based on the response spectrum, the acceleration time-histories used for the former are usually required to be consistent with the latter. The simplest solution to this issue is to generate artificial accelerograms from filtered white noise which can be calibrated to have spectral ordinates that match almost exactly the design basis response spectrum [1]. Although such records have been widely used in the nuclear industry, they generally do not possess the characteristics of real earthquake ground motions in terms of phase content, number of cycles, and energy. The growth of the global databank of recorded earthquake accelerograms (and the ease of access to such data through the Internet) and the development of techniques to modify these ground-motion recordings to improve their match to a target response spectrum, have together rendered recourse to artificial acceleration time-histories difficult to justify [2]. This is reflected in ASCE 43-05 [3], which permits the use of both artificial and modified real records for linear analyses but prohibits the former for non-linear analyses.

The provision of appropriate suites of acceleration records as input to dynamic analyses occurs at the interface between Engineering Seismology and Structural Earthquake Engineering, and may be hampered in many cases by lack of a common language between practitioners in these two disciplines and possibly also some lack of appreciation of the technical details associated with the preparation of the records (by seismologists) and their application (by structural engineers). A specific point on which the interface between seismologists and engineers is essential is in ensuring consistent consideration of the influence of the ground-motion variability [4]. The prediction of ground-motion parameters is unavoidably associated with a high degree of random or aleatory variability [5], which is—or at least should be—fully incorporated into the calculations of probabilistic seismic hazard analysis (PSHA) [6]. The ground-motion variability must be accounted for according to its influence on structural response, but only once in the entire process. This means that the structural analysis should only account for the components of variability influencing the structural response other than the randomness associated with the prediction of the spectral acceleration at the fundamental frequency, which is integrated in the PSHA calculations. Stafford and Bommer [4] examine various widely-used approaches to preparing suites of accelerograms for structural analysis in terms of their consistency in terms of treatment of ground-motion variability.

The guidance on selecting and adjusting real earthquake accelerograms for input to dynamic structural analysis provided in seismic design codes for conventional buildings and bridges is generally poor, ranging from vague indications of how the engineer should proceed to lists of requirements for the records that are almost impossible to satisfy with real earthquake recordings [7]. In some ways this is not surprising since it is a serious challenge to provide useful guidance when all that is provided to the engineer regarding the seismic hazard in many cases is a value of peak ground acceleration (PGA) used to scale a response spectral shape to obtain a crude approximation to a uniform hazard spectrum (UHS) at the site. One remedy that has been proposed for this situation is to intentionally specify the code-based UHS conservatively to encourage site-specific PSHA, which is a much more useful starting point for record selection; the argument being that any structure sufficiently important to warrant dynamic structural analysis should also warrant a site-specific assessment of earthquake loading [8].

Seismic design guidelines specifically for nuclear facilities are not much better in this respect than codes for conventional structures, in part again reflecting the difficulty of outlining the required steps without adequate information regarding either the seismic hazard or the treatment of variability in the calculated structural response. Some of the specifications, such as the stipulation in the most recent IAEA Safety Guide [9] that records should not be scaled by more than a factor of 2, reflect the ‗folklore' that permeates practice in this field. Early studies proposed such limits of scaling factors [2] but whether their technical bases still hold and whether for many applications such limits are unnecessarily restrictive seems not to have been duly considered. This is just one example of an ever-increasing gap between code specifications and the state-of-the-art in this subject, as represented by the technical literature addressing the issues of selection and scaling of accelerograms for structural analysis. This body of literature, published in various forums, has become almost overwhelming and continues to expand rapidly; it would be a bold endeavor to attempt to present a review of this literature, and the reference list alone would exceed the page limit for this paper. Many of these research papers and reports contain very valuable information, but for the structural engineer seeking to prepare a suite of acceleration time-histories for conducting dynamic analyses, it is very challenging to distill the essential lessons from this research in a way that is applicable to the particular design or analysis issue at hand. One fundamental reason for this is that the studies often fail to clearly identify the specific objectives of the structural analyses on which they are based, including all attendant assumptions. There is a certain parallel with the issue of the degree of influence of strong-motion duration on structural response, on which many papers have been published that make strong assertions in favor of or against duration being a significant parameter, without qualifying these claims for the specific circumstances to which they refer and in particular the parameters used to characterize the structural response and whether these measure peak response or cumulative effects [10-11]. Apart from the need to specify which of the many definitions of strong-motion duration is being used [12], the conclusions will logically be quite different if the analyses are based, for example, on the response of a steel frame structure [13] or masonry buildings with degrading stiffness and strength [14]. Consequently, there has been a tendency to transport conclusions and inferences from one situation to another where they may not apply. Given the much greater complexity of defining input to dynamic structural analyses (as a result of the larger number of variables), the need to clearly lay out the framework of each study is even greater.

With this in mind, the purpose of this paper is not to provide conclusive and universally-applicable guidelines but rather to present a possible framework for the decision-making process, illustrated for a specific set of assumptions regarding the application, and highlighting some of the more serious potential pitfalls.

DEFINING TARGET RESPONSE SPECTRA

A target response spectrum needs to be defined both for selecting and subsequently for adjusting the natural accelerograms to be used in structural analyses. For this it is necessary to know the nature of the structural models to be analyzed, in terms of the fundamental frequency of vibration and the assumed structural damping level, as well as whether the seismic excitation will be represented by a single horizontal component of motion or some combination of vertical and horizontal accelerations. In this paper, it is assumed that a 3D structural model is to be analyzed, requiring three (two horizontal and one vertical) components of motion as the input. Fig.1 gives an overview of the steps involved in defining the target response spectra, which are narrated in the following sections.

Horizontal Response Spectrum

The starting point should be a site-specific PSHA to construct a UHS at the specified annual exceedance frequency relevant to design [*e.g.*, 15]. Such an approach is to be preferred over the use of standard design spectra or spectral shapes anchored to site-specific PGA [16]. For nuclear applications, it is also important that the response spectrum is adequately defined at the high frequencies relevant to structures and components of nuclear power plants, which are often considerably greater than those considered in the design of conventional buildings. Recent work has shown that the high-frequency response spectral ordinates are generally generated by much lower-frequency components of the motion [17-18], which allows ground-motion prediction equations (GMPEs) to be derived for spectral accelerations at 50-100 Hz whereas many GMPEs have been unnecessarily limited to lower maximum response frequencies [19]. These insights could obviate the rather dubious recommendation in ASCE 43-05 [3] to increase the Nyquist frequency of records above 50 Hz, if needed, by simply interpolating to a reduced time interval.

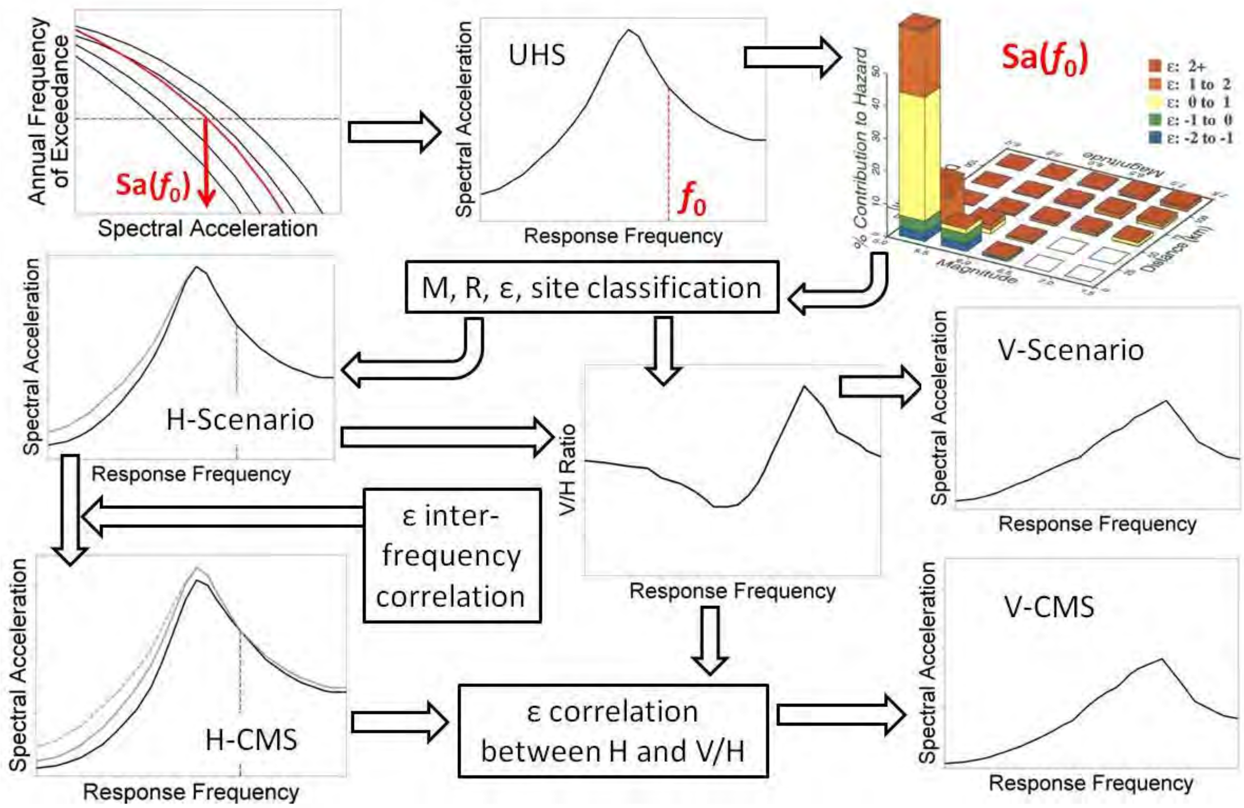

Fig.1: Schematic flowchart for generating horizontal and vertical target response spectra for 5% damping; the disaggregation plot in the top right-hand corner is from McGuire [26]

Attention also needs to be paid to definition of the horizontal component of motion, since there are several definitions based on different treatments of the two horizontal components of the accelerogram, and if several GMPEs are combined in a logic-tree for the PSHA [20], it may be necessary to apply conversions to a common horizontal component definition [21]. The most widely used definition in modern GMPEs is the geometric mean of the two horizontal components. Clearly it is important that whichever definition is adopted, the selected time-histories and their application in structural analysis must be treated in a manner that is consistent with this definition [22-23].

Although a UHS is necessary starting point, it is not a suitable target for selecting or adjusting accelerograms since it envelopes contributions from various seismic sources at different response frequencies [24-25]. Therefore, the next step in the process is to perform a disaggregation of the seismic hazard at the response frequency of the structure to be analyzed, in order to identify the dominant earthquake scenarios underlying the estimate of the hazard [26-27]. These scenarios will be defined by magnitude, M, the distance, R, from the site, and ε, the number of logarithmic standard deviations above the logarithmic mean of the spectral acceleration, as well as the site classification and, possibly, the style-of-faulting. These parameters are then all used to generate a horizontal response spectrum for this earthquake scenario. In this illustrative case, it is assumed that the controlling earthquake scenario is not associated with a clearly-identified active fault in close proximity to the site, in which case the effects of near-source rupture directivity [28] would need to be accounted for in the specification of the earthquake loads.

This construction of the scenario response spectrum as described in the preceding paragraph could be conservative since it assumes that the high positive value of ε that will generally be found at the selected response frequency, f_0, applies across the entire spectrum, which is unlikely to be the case in practice. Rather, the disaggregated scenario is better represented by a record with a spectrum that is locally peaked at that frequency; the exceedances of the spectral ordinates will not be perfectly correlated at all frequencies, and the frequency-to-frequency correlation of ε will decrease with increasing separation of the response frequencies [29]. If the structural response is expected to be dominated by a single mode and if the frequency of vibration is known with confidence, then such correlation functions can be applied to transform the scenario spectrum into what is referred to as a conditional mean spectrum, or CMS [30]. The CMS concept can also be applied conditioned to the spectral acceleration averaged over a range of response frequencies [30].

Vertical Response Spectrum

In most seismic design codes, with the notable exception of Eurocode 8 [31], the vertical response spectrum is obtained by simply scaling the horizontal spectral ordinates by a factor of 2/3. ASCE 4-98 [32] specifies the same approach except for situations where the hazard is dominated by earthquakes at short distances (<15km), in which case the vertical-to-horizontal (V/H) ratio should be at least unity for frequencies greater than 5 Hz. This reflects two important features of the V/H ratio, these being a variation with response frequency (with peak values at high frequencies) and a marked dependence on distance; the ratio is more weakly dependent on other parameters such as magnitude and site classification [33]. The distance dependence of V/H is represented by specifying different ratios depending on the value of PGA in rock in NUREG/CR-6728 [34].

For site-specific analysis, one option for obtaining the vertical response spectrum is to conduct PSHA directly in terms of the vertical ordinates of acceleration, which is the favored approach in the current IAEA Safety Guide [9]. The problem with such an approach is that disaggregation of the hazard at a given response frequency could identify a different dominant earthquake scenario from that controlling the horizontal ordinate, which would create an incompatibility for generating three-dimensional acceleration time-histories. The preferred approach is therefore to input the M-R pair used to generate the horizontal scenario spectrum or CMS to equations for the prediction of the V/H ratio at different response frequencies [*e.g.*, 35-36] and then apply the median ratios to the horizontal spectral ordinates. This assumes that the variability associated with prediction of the horizontal and vertical components is essentially the same, which is broadly supported by those models providing independent equations for the two components. Using correlations between the exceedances of the horizontal component and of the V/H ratios, a vertical CMS can be constructed [36].

Alternative Damping Ratios

All GMPEs for spectral accelerations predict the ordinates with 5% of critical damping, and only a small number provide coefficients for predicting the spectral ordinates at other damping levels [37]. However, the ubiquitous 5% damping level may not be applicable to all structures and components of a nuclear power plant, requiring that the target spectrum be adjusted to other damping levels. Additionally, some studies have proposed adjusting accelerograms so that they match spectral ordinates at several damping levels either to reduce the number of structural analyses required [38] or to overcome deficiencies in the records prepared following some code guidelines [39].

Scaling factors provided in seismic design codes to adjust the 5%-damped ordinates to other damping values show a surprising variation, which has been interpreted as being the result of the fact that these ratios depend on the duration of the strong motion [40]. Duration-dependent scaling factors have been presented [34,41], and their application requires that the M-R pair of the disaggregated scenario first be used to estimate the duration from predictive equations [*e.g.*, 42].

SELECTING AND ADJUSTING ACCELEROGRAMS

In the remaining space available in this paper, only a brief overview of the issues of selecting and adjusting accelerograms can be given; there is little point, however, discussing procedures that aim to meet a target (the spectra discussed previously) if the target is poorly or even erroneously defined.

Selecting Records

The first step is to compile a databank of accelerograms together with a database of associated information related to the generating earthquakes and the nature of the recording sites. For reasons explained below, it is also helpful to generate the response spectral ordinates at various frequencies for all of the records.

In order to avoid missing any aspect of the structural response, a limit of 0.3 on the correlation coefficient between two components is imposed in ASCE 4-98 [32] and ASCE 43-05 [3], which is considered sufficient to render the motions statistically independent. One way to address this issue is to rotate all of the horizontal component pairs into their principal axes, where they are uncorrelated; this assumes that uncorrelated acceleration time-histories will lead to uncorrelated response at all frequencies, which almost definitely not the case but possibly acceptable for the high frequencies of greatest relevance in nuclear plants. Some researchers have proposed rotating all three components into principal axes [43] but there are clearly additional challenges in applying accelerograms that do not coincide with the horizontal and vertical planes.

If the selection of records is based on an exact match with the magnitude, distance and site classification of the controlling earthquake scenario, very few records, if any, are likely to be retrieved. If records are selected on the basis of an M-R bin (centered on the scenario) then the variability in spectral ordinates, even if adjusted to the M-R pair of the scenario, will be very large due to the inherent randomness in ground motions. The consequence is that a very large number of structural analyses will be needed to obtain stable estimates of the response. For this reason, it is strongly recommended that records be selected on the basis of their spectral shape (not amplitude) being comparable to that of the target spectrum. This will involve minimizing the residuals between the target spectrum and the scaled record spectrum over a specified frequency range, which will usually be centered on the fundamental frequency and covering both high mode contributions and potential softening. Whichever particular technique and criteria are used, the objective is to find records without large deviations (peaks and troughs) from the target shape; in other words, a limit is being imposed on inherent variability. Selecting those records for which both horizontal components individually approximate the shape of the target spectrum will clearly be more effective in reducing large excursions than selecting records on the basis of the shape of the geometric mean spectrum. Earthquake magnitude should be considered in the search (because of its dominant influence on duration) but the initial window should not be too constrictive; distance need not be closely matched, other than to avoid near-source pulse-like records if these are not part of the design scenario. Site classification also need not be included as a selection criterion. The shape of the vertical spectrum may also be considered but greater importance should be given to the horizontal components.

All of these additional selection considerations need to be reconciled with the number of records required, which cannot be separated from how the records will be adjusted before application in the structural analyses, and the output required from those analyses.

Adjusting Records

If the median structural response is the focus, then the treatment applied to the records can be selected on the basis of how many dynamic analyses will be conducted. Fig. 2 illustrates three basic options, which result in decreasing levels of variability and consequently fewer records are required to obtain a stable estimate of the median response [38]. The first option is to scale the records to match the target response spectral ordinate at the fundamental frequency of the structure, which is entirely consistent in terms of treatment of the ground-motion variability throughout. This can, however, lead to biased estimates of the response by neglecting the variability at other response frequencies [44]. This can be overcome by instead scaling the records by linear factors so that their ordinates match the target, in an average sense, over a range of frequencies about the fundamental value. This is most appropriate if the target is a CMS, although then there is an element of inconsistency since the variability of the spectral ordinate at the fundamental frequency is non-zero [4].

With either of these two approaches based on linear scaling of the records, fewer records will be required if the records are scaled individually to the target spectrum; the criteria specified in codes [3,32] of scaling the records so that their mean ordinates do not fall below the target by more than a small fraction could lead to suites of records with large variability as well as appreciable double-counting of the variability at the fundamental frequency of the structure. In the case of two horizontal components from each record, several options exist but the most straightforward is probably to scale both components by the same factor to match their geometric mean to the target ordinates, while maintaining the component-to-component variability. Obviously, the vertical component should be separately scaled to target vertical spectrum. Options for scaling of the two horizontal components are discussed in more detail by Beyer and Bommer [23].

Suites of linearly scaled records will always retain appreciable peak-to-trough variability, which leads to many analyses being required to obtain stable response estimates. ASCE 43-05 [3] notes that as many as 30 scaled records may be needed, and permits frequency-domain adjustments [*e.g.*, 45] to be made to improve the match with the target spectrum. In recent years, alternative time-domain procedures using wavelets have been developed that allow an equally good spectral match to obtained with a smaller degree of modification to the time history [46-47]. Hancock et al. [38] found that matching the records to the spectral ordinates at multiple damping levels can reduce even further the number of analyses required. Several studies have concluded that if the spectral shapes match the target spectrum, scaling factors as large as 10 may be applied without leading to biased estimates of structural response. Whether using spectrally-matched records leads to biased estimates of response is an issue of ongoing debate [38,48].

For the case of two horizontal components of motions, rather than matching both to the geometric mean target spectrum it is more correct to create two target spectra by scaling the original ordinates up and down by appropriate factors and matching one component to each. One approach for doing this has been proposed by Grant [49] in which the two target spectra match the major and minor axes. Little attention has been paid to spectral matching of vertical components but this presumably could be done in the same way as for a single horizontal component.

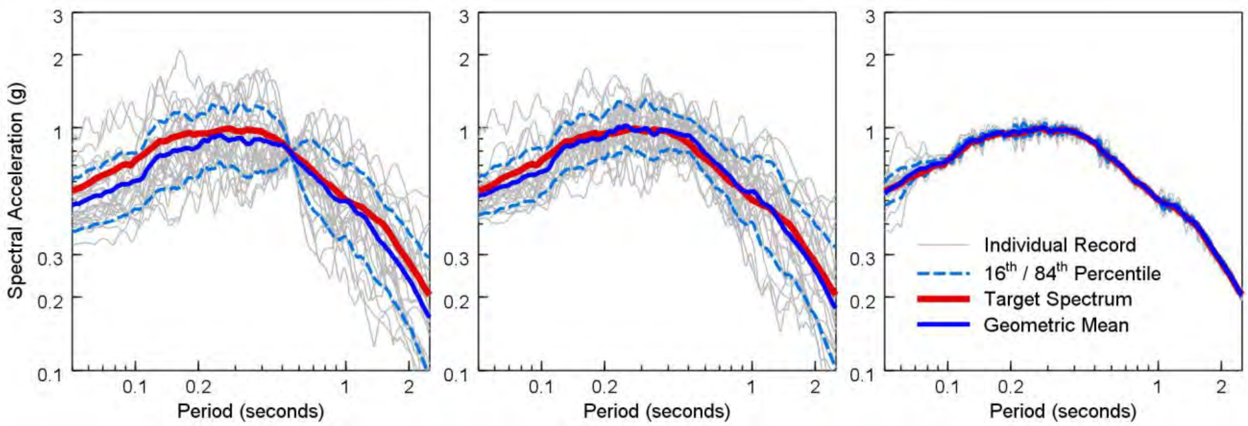

Fig.2: Records scaled to the target ordinate at the fundamental structural period (*left*) and to the average target over a range about this period (*middle*); records match the target spectrum (*right*) [4]

When the objective of the structural analyses is to estimate the full (conditional) distribution of responses, as will be needed in fragility analyses for probabilistic risk assessments, the complete suppression of the peak-to-trough variability through spectral matching is not an option. Stafford and Bommer [4] discuss options for selecting numbers of scaled records with a defined degree of peak-to-trough variability averaged over a bandwidth centered on the fundamental frequency of the structure. This target variability could be achieved by performing spectral matching with a relatively high tolerance for the degree of matching.

Although only tested for a single structure subjected to a single component of horizontal motion, Buratti et al. [50] have proposed a potentially very promising approach for estimating the distribution of inter-story or roof drift, making use of the 3-point approximation to a continuous distribution and the strong correlation between the spectral acceleration at the initial fundamental frequency of the structure and the drift response. A seed record is chosen that has a shape very close to that of the target spectrum and this record is then scaled to these ordinates plus two other targets created by multiplying and dividing the original target by factors determined as the roots of a third-order Hermite polynomial distribution. The median response and the logarithmic standard deviation of the associated distribution (as estimated from nonlinear structural analyses using 1,666 unscaled records, following Hancock et al. [38]) can be found from analyses with just these three records [50]. Using a second triplet of scaled records improves the estimates, but only slightly. Whether the procedure can be adapted to other measures of structural response remains to be investigated.

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