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Conditional Spectra

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Synonyms

Conditional mean spectrum; Hazard-consistent ground motion selection; Response spectrum; Scenario spectrum; Spectral shape

Introduction

The conditional spectrum (CS) is a response spectrum that specifies the probability distribution of spectral accelerations, *Sa*, over a range of periods of vibration, T_i, conditioned on spectral acceleration at a conditioning period, T^*, of interest. The conditional spectrum utilizes the correlations between spectral accelerations at different periods (e.g., Baker and Jayaram 2008) to compute the expected (logarithmic mean) response spectrum (Baker and Cornell 2006; Baker 2011) and additionally account for the variability (variance) of the response spectra (Jayaram et al. 2011; Lin et al. 2013a). Assuming the distribution of logarithmic spectral accelerations is multivariate normal (Jayaram and Baker 2008), then the first two moments (i.e., the means, standard deviations, and correlations) fully describe the conditional spectrum. The CS provides the link between seismic hazard and structural response, the first two elements of performance-based earthquake engineering (PBEE). To maintain consistency with probabilistic seismic hazard analysis (PSHA), the computation of the CS is refined by incorporating multiple causal earthquakes and ground motion prediction models (GMPMs, also known as ground motion prediction equations, attention relationships) (Lin et al. 2013a). The CS can be used as a target response spectrum for site- and structure-specific ground motion selection (e.g., Lin et al. 2013b, c).

Baker and Cornell (2006) and Baker (2011) described the "conditional spectrum" as the "conditional mean spectrum" (CMS) with an emphasis on the mean spectrum and its associated ground motion selection where the best ground motion candidates have response spectra as close to the CMS as possible. Bradley (2010) extended the concept of the CMS to ground motion parameters other than response spectra and referred the resulting distribution as a "generalized conditional intensity measure" (GCIM). Bradley (2012) also developed an algorithm to select ground motions based on the GCIM. Abrahamson and Al Atik (2010) coined the term "conditional spectrum", but represented the CS distribution directly by realizations of the CS rather than an analytical distribution. Wang (2011) developed a ground motion selection algorithm that captures response spectrum characteristics and variability of scenario earthquakes. Gulerce and Abrahamson (2011) extended the CS concept to vertical ground motions. Jayaram et al. (2011) developed a computationally efficient algorithm to select ground motions that match the conditional mean and variance of the response spectrum.

Lin et al. (2013a) for the first time used the term "conditional spectrum" which was used to represent an analytical distribution of response spectra in the manner described here. The CS builds upon the CMS (which focuses on the mean) and includes a measure of the variance in addition to the mean. Figure 1a depicts the analytical distribution of the conditional spectrum with conditional mean spectrum as the thick

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solid line as well as conditional mean +/− conditional standard deviation as the thick dashed lines. Lin et al. (2013b, c) utilized the conditional spectrum to select ground motions for nonlinear dynamic analysis (also known as response history analysis) in risk-based and intensity-based assessments respectively. Intensity-based assessment estimates structural response given ground motions with a specified intensity level. Risk-based assessment (also known as PEER integral, drift hazard, time-based assessment, and probabilistic seismic demand analysis) estimates the mean annual rate of exceeding a specified structural response amplitude and can be obtained by integrating intensity-based assessment results at various intensity levels with the associated seismic hazard curve. As illustrated in Fig. 1a, the thin lines represent response spectra from individual ground motion records selected to match the mean and variance of the CS (thick solid and dashed lines) for a specified intensity level, i.e., spectral acceleration at the period of 2.6 s ("pinched" conditioning period) associated with 2 % in 50 years probability of exceedance in Palo Alto, California, USA.

The consideration of the variability in the CS is important to capture the full distribution of the target *Sa* and its subsequent structural response analysis based on a target response spectrum. Lin et al. (2013c) compared the conditional spectrum (Fig. 1a) to such alternative response spectra as the conditional mean spectrum (Fig. 1b) and the uniform hazard spectrum (UHS) (Fig. 1c); the issue of the choice of the conditioning period was also discussed. The CMS (thick solid line) and UHS (thick dash-dot line) are superimposed on the CS as reference spectra in Fig. 1a. Figure 1b depicts the CMS as the target response spectrum, whereas the thin lines represent individual record response spectra selected to match the mean. Figure 1c illustrates the UHS as the target response spectrum and individual record spectra selected to

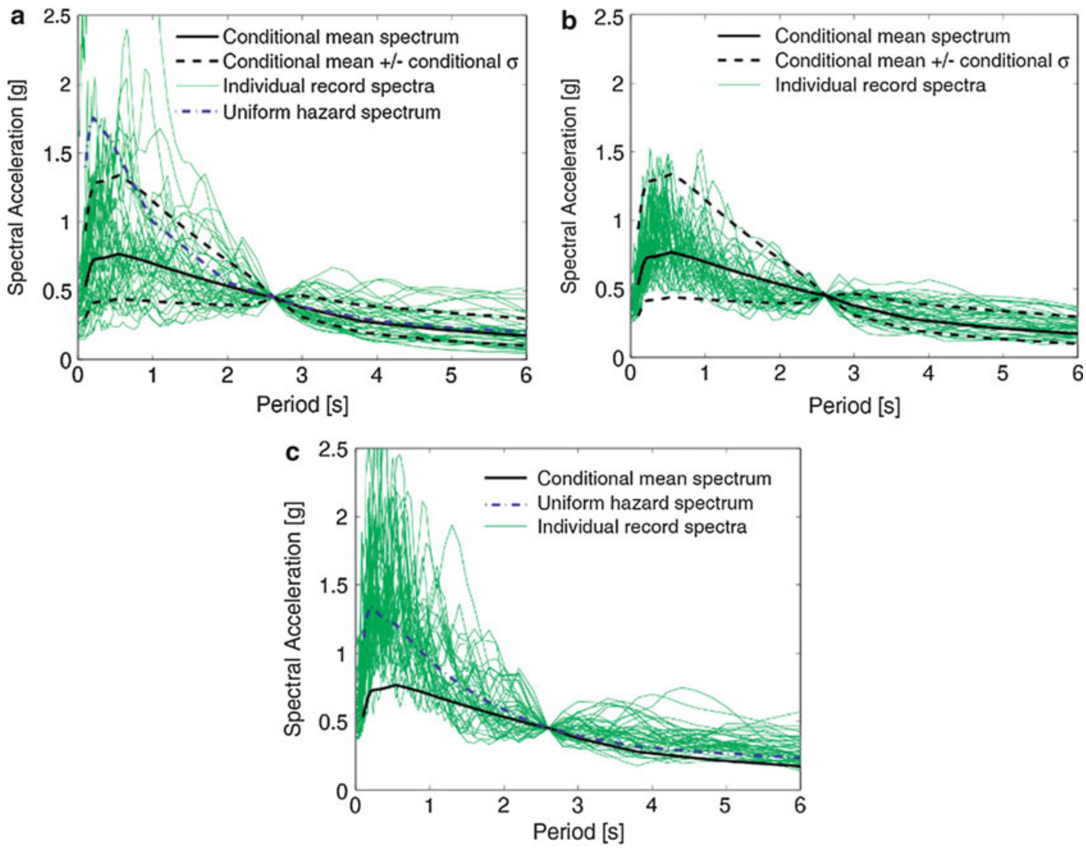

Fig. 1 Response spectra of ground motions selected and scaled with (**a**) conditional spectrum, (**b**) conditional mean spectrum, and (**c**) uniform hazard spectrum as target spectra for *Sa*(2.6 s) associated with 2 % in 50 years probability of exceedance for an illustrative structure in Palo Alto, California, USA

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match the UHS. Unlike the UHS (Fig. 1c), the CS (Fig. 1a) has a lower mean at periods away from the conditioning period. Unlike the CMS (Fig. 1b), the CS additionally considers the spectral uncertainty about the mean.

Background

Performance-based earthquake engineering quantifies the seismic hazard, predicts the structural response, estimates the damage to building elements (structural, non-structural, and content), in order to assess resulting losses in terms of dollars, downtime, and deaths (e.g., Cornell and Krawinkler 2000). One key input to seismic design and analysis of structures is earthquake ground motion. Ground motion selection determines ground motion input for a structure at a specific site for nonlinear dynamic analysis. Ground motion selection provides a significant basis for conclusions regarding structural safety, since ground motion uncertainty contributes considerably to uncertainty in structural analysis output.

The source of ground motion inputs can come from (1) simulations, either physics-based (physics-based ground motion simulation), stochastic (stochastic ground motion simulation), or hybrid; (2) spectral matching; (3) selection and scaling of recorded ground motions from ground motion databases (selection of ground motions for response history analysis). Physics-based simulations attempt to depict the physical phenomenon of earthquake fault rupture and wave propagation using analytical models while stochastic simulations rely heavily on empirical calibration with an attempt to generate ground motions using fewer random variables. Hybrid simulations, on the other hand, combine the two by utilizing physics-based simulations for low-frequency components and stochastic simulations for high-frequency components. A semi-artificial ground motion modification technique is spectral matching that changes the frequency content of the response spectra to be compatible with the target. Another modification technique is selection and scaling of ground motions (e.g., Katsanos et al. 2010) that involves selecting recorded ground motions from ground motion databases and applying amplitude scaling to match the target.

To ensure the proper quantification of ground motion uncertainty, it is important to link ground motion selection to probabilistic seismic hazard analysis (e.g., Cornell 1968). PSHA (probabilistic seismic hazard models) is commonly used in structural dynamic analysis and geotechnical earthquake engineering to identify the ground motion hazard for which structural and geotechnical systems are analyzed and designed. PSHA accounts for the aleatory uncertainties (which are inherently random) of causal earthquakes with different magnitudes and distances with predictions of resulting ground motion intensity in order to compute seismic hazard at a site. PSHA also incorporates epistemic uncertainties (which are due to limited knowledge) in ground motion predictions, by considering multiple ground motion prediction models using a logic tree that also includes seismic source models.

Ground motion selection is often associated with a target response spectrum. For instance, the target response spectrum in current building codes (e.g., ASCE 2010) is based on the uniform hazard spectrum, which assumes equal probabilities of exceedance of spectral accelerations at all periods. However, no single ground motion is likely to produce a response spectrum as high as that of the UHS over a wide range of periods (e.g., Naeim and Lew 1995). The conditional mean spectrum utilizes the correlations of *Sa* across periods to more realistically compute the expected *Sa* values at all periods given a target *Sa* value at a period of interest (e.g., Baker and Cornell 2006). The conditional spectrum quantifies the conditional distribution (mean and variance) of *Sa* at all periods given *Sa* at a period of interest (e.g., Lin et al. 2013a). The spectral shapes of conditional mean spectra (mean of conditional spectra) change with amplitudes (Fig. 2a). Uniform hazard spectrum is the envelope of conditional mean spectra at various periods (Fig. 2b).

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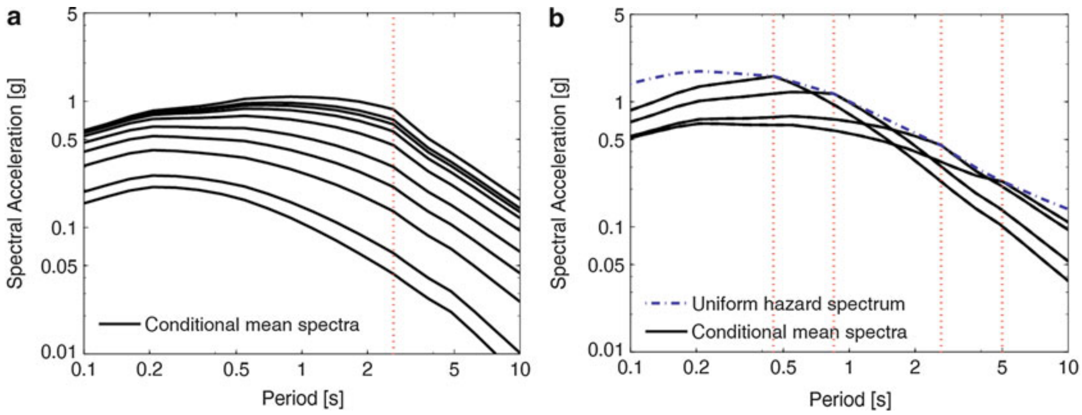

Fig. 2 (**a**) Conditional mean spectra at $T^* = 2.6$ s at various intensity levels (from 50 % in 30 years to 1 % in 200 years) and (**b**) conditional mean spectra at various conditioning periods (compared to uniform hazard spectrum) at the 2 % in 50-year intensity level

The target response spectrum used when selecting ground motions has an impact on the distribution of structural responses from resulting nonlinear dynamic analysis (e.g., Jayaram et al. 2011; Lin et al. 2013c). Matching target response variance (in the CS compared to the CMS) increases the dispersion of structural responses, thereby affecting the distribution of structural responses and consequently the damage state and loss estimation computations in performance-based earthquake engineering. The increase in the dispersion leads to higher and lower extremes of structural responses and the associated damage states and losses. The increased dispersion can also lead to a larger probability of structural collapse. Incorporating the variability in the CS has significant implications for applications where the dispersion of the responses is an important consideration.

Basic Computation

The basic computation of the conditional spectrum requires (1) input earthquake parameters such as magnitude and distance (similar to those required by a GMPM), (2) specification of a conditioning period, (3) a ground motion prediction model to estimate mean and standard deviation of logarithmic spectral acceleration, and (4) a correlation model of spectral accelerations across periods. The computation procedure is outlined as follows:

(a) Obtain input earthquake parameters: Obtain the target spectral acceleration at the conditioning period T^*, $Sa(T^*)$, from PSHA, and its associated mean causal earthquake magnitude (M), distance (R), and other parameters (if available) such as rupture mechanism and site condition (θ), from deaggregation (e.g., McGuire 1995).

(b) Compute mean and standard deviation of $lnSa(T_i)$: Use a GMPM (e.g., Abrahamson et al. 2008) to compute the logarithmic mean and standard deviation of Sa at all periods T_i, denoted as $\mu_{lnSa}(M, R, \theta, T_i)$ and $\sigma_{lnSa}(M, \theta, T_i)$.

(c) Compute epsilon, $\varepsilon(T_i)$: For any $Sa(T_i)$, compute $\varepsilon(T_i)$, the number of standard deviations by which $lnSa(T_i)$ differs from the mean spectral ordinate predicted by a given GMPM, $\mu_{lnSa}(M, R, \theta, T_i)$, at T_i

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$$\epsilon(T_i) = \frac{lnSa(T_i) - \mu_{lnSa}(M, R, \theta, T_i)}{\sigma_{lnSa}(M, \theta, T_i)} \tag{1}$$

The target $\varepsilon(T^*)$ can also be computed using this equation. Spectral shape is characterized by ε.

(d) Compute conditional mean $\mu_{lnSa(Ti)|lnSa(T^*)}$: Using a correlation model (e.g., Baker and Jayaram 2008) that specifies the correlation coefficient between pairs of epsilon values at two periods, $\rho(\epsilon T_i), \epsilon(T^*))$ (hereinafter referred to as $\rho(T_i, T^*)$), the conditional mean logarithmic spectral acceleration at other periods T_i, $\mu_{lnSa(Ti)|lnSa(T^*)}$ is computed

$$\mu_{lnSa(T_i)|lnSa(T^*)} = \mu_{lnSa}(M, R, \theta, T_i) + \rho(T_i, T^*)\sigma_{lnSa}(M, \theta, T_i) \tag{2}$$

The spectrum defined by $\mu_{lnSa(Ti)|lnSa(T^*)}$ is termed the "conditional mean spectrum", as it specifies the mean values of $lnSa(T_i)$ conditional on the value of $lnSa(T^*)$. Assuming Sa is lognormally distributed, the exponentials of μ_{lnSa} are equivalent to the median values of Sa.

(e) Compute conditional standard deviation $\sigma_{lnSa(Ti)|lnSa(T^*)}$: The standard deviation of logarithmic spectral acceleration at period T_i conditioned on the value of $lnSa(T^*)$ is

$$\sigma_{lnSa(T_i)|lnSa(T^*)} = \sigma_{lnSa}(M, \theta, T_i)\sqrt{1 - \rho^2(T_i, T^*)} \tag{3}$$

The conditional standard deviation $\sigma_{lnSa(Ti)|lnSa(T^*)}$, when combined with the conditional mean value $\mu_{lnSa(Ti)|lnSa(T^*)}$, specifies a complete distribution of logarithmic spectral acceleration values at all periods (where the distribution at a given period is Gaussian, as justified by Jayaram and Baker 2008). The resulting spectrum distribution is termed the "conditional spectrum", to be distinguished from the CMS that does not consider the variability.

Deaggregation of Ground Motion Prediction Models

Probabilistic seismic hazard deaggregation of GMPMs links the computation of a target spectrum (for ground motion selection) to the total hazard prediction (from PSHA). Computation of a target spectrum requires deaggregation (via Bayes' rule) to identify the causal ground motion parameters, along with the predictions from multiple GMPMs. Hazard-consistent ground motion selection incorporates the aleatory uncertainties from earthquake scenarios and the epistemic uncertainties from multiple GMPMs, through deaggregation of GMPMs (Lin and Baker 2011).

This GMPM deaggregation is consistent with the probabilistic treatment of the magnitude and distance random variables in traditional PSHA. The deaggregation of GMPMs provides additional insights into which GMPM contributes most to prediction of Sa values of interest. To match the contribution of each GMPM to its associated ground motion parameters, separate deaggregation of earthquake parameters for each GMPM is also performed. First, seismic hazard is estimated using PSHA that incorporates multiple GMPMs. Next, the relative contributions of events and GMPMs to the hazard prediction are identified using the refined deaggregation procedures.

The deaggregation of GMPMs is performed as an intermediate step to develop a refined mean and, more importantly, a refined standard deviation of the CS. This can also be used to develop, in general, any new target response spectrum that is consistent with PSHA. The side product of this computation is the deaggregation (posterior) weights of GMPMs, instead of the logic-tree (prior) weights. This methodology

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for deaggregation of prediction models can also be immediately applicable to other procedures which require multiple prediction models in an earlier stage of total prediction and a later stage of new target computation.

Refined Computational Methods

Approximate and exact implementations of CS computations are outlined and used for example calculations at Stanford, Bissell, and Seattle (Lin et al. 2013a). Figure 3 illustrates CS mean and standard deviation computational methods using multiple GMPMs at Bissell. Exact CS mean and standard deviation calculations (Method 4) can incorporate multiple GMPMs and causal earthquake *M*/*R* combinations. Varying levels of approximations are also considered, that replace multiple *M*/*R* combinations with the mean *M*/*R* from deaggregation (Methods 1–3), and either consider only a single GMPM (Method 1) or perform an approximate weighting of several GMPMs (Methods 2–3). Methods 1–2 utilize the overall mean *M/R*, whereas Method 2 considers multiple GMPMs with logic-tree weights. The deaggregation of GMPMs provides GMPM-specific mean *M/R* and GMPM deaggregation weights, both of which are incorporated in Method 3. The most accurate computation, Method 4, accounts for the contribution that each GMPM and each earthquake *M/R* makes to the seismic hazard (Fig. 3). Subscript k denotes that the calculations are based on a specific GMPM indexed by k, whereas subscript j denotes that the parameters such as *M*/*R* are associated with a specific earthquake indexed by j. For each GMPM k and causal earthquake combination M_j/R_j, mean and standard deviation of the CS can be obtained (using Eqs. 12 and 13, respectively) that are then combined with corresponding deaggregation weights, $p_{j,k}{}^{d}$ (Eqs. 14 and 15). The weight for model k is denoted as $p_k{}^{l}$ where the superscript l refers to logic-tree; similarly, the superscript d in $p_k{}^{d}$ and $p_{j,k}{}^{d}$ refers to deaggregation.

Method 1: Approximate CS using mean *M*/*R* and a single GMPM (basic computation)

$$\mu_{lnSa,\,k(T_i)|lnSa(T^*)} \approx \mu_{lnSa,\,k}\left(\overline{M},\overline{R},\overline{\theta},T_i\right) + \rho(T_i,T^*)\sigma_{lnSa,\,k}\left(\overline{M},\overline{\theta},T_i\right)\overline{\epsilon}(T^*) \quad (4)$$

$$\sigma_{lnSa,\,k(T_i)|lnSa(T^*)} \approx \sigma_{lnSa,\,k}\left(\overline{M},\overline{\theta},T_i\right)\sqrt{1-\rho^2(T_i,T^*)} \quad (5)$$

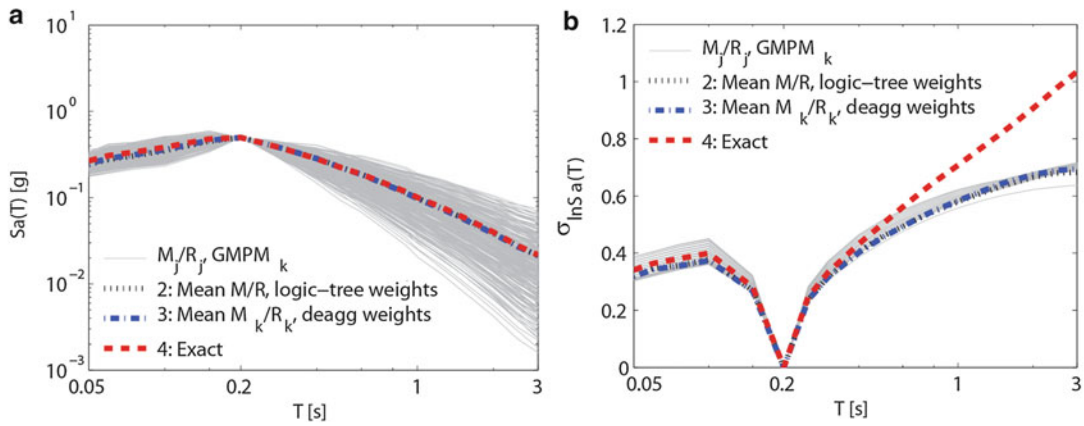

Fig. 3 (**a**) Conditional means and (**b**) conditional standard deviations of the CS computed using Methods 2–4 for *Sa*(0.2 s) with 10 % probability of exceedance in 50 years at Bissell

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Method 2: Approximate CS using mean *M*/*R* and GMPMs with logic-tree weights

$$\mu_{lnSa(T_i)|lnSa(T^*)} \approx \sum_k p_k^l \mu_{lnSa,\,k(T_i)|lnSa(T^*)} \tag{6}$$

$$\sigma_{lnSa(T_i)|lnSa(T^*)} \approx \sqrt{\sum_k p_k^l \left(\sigma^2_{lnSa,\,k(T_i)|lnSa(T^*)} + \left(\mu_{lnSa,\,k(T_i)|lnSa(T^*)} - \mu_{lnSa(T_i)|lnSa(T^*)}\right)^2\right)} \tag{7}$$

Method 3: Approximate CS using GMPM-specific mean *M*/*R* and GMPMs with deaggregation weights

$$\mu_{lnSa,\,k(T_i)|lnSa(T^*)} \approx \mu_{lnSa,\,k}\left(\overline{M}_k, \overline{R}_k, \overline{\theta}_k, T_i\right) + \rho(T_i, T^*)\sigma_{lnSa,\,k}\left(\overline{M}_k, \overline{\theta}_k, T_i\right)\overline{\epsilon}_k(T^*) \tag{8}$$

$$\sigma_{lnSa,\,k(T_i)|lnSa(T^*)} \approx \sigma_{lnSa,\,k}\left(\overline{M}_k, \overline{\theta}_k, T_i\right)\sqrt{1-\rho^2(T_i, T^*)} \tag{9}$$

$$\mu_{lnSa(T_i)|lnSa(T^*)} \approx \sum_k p_k^d \mu_{lnSa,\,k(T_i)|lnSa(T^*)} \tag{10}$$

$$\sigma_{lnSa(T_i)|lnSa(T^*)} \approx \sqrt{\sum_k p_k^d \left(\sigma^2_{lnSa,\,k(T_i)|lnSa(T^*)} + \left(\mu_{lnSa,\,k(T_i)|lnSa(T^*)} - \mu_{lnSa,\,k(T_i)|lnSa(T^*)}\right)^2\right)} \tag{11}$$

Method 4: "Exact" CS using multiple causal earthquake *M*/*R* and GMPMs with deaggregation weights

$$\mu_{lnSa,j,\,k(T_i)|lnSa(T^*)} = \mu_{lnSa,\,k}\left(M_j, R_j, \theta_j, T_i\right) + \rho(T^*, T_i)\epsilon_j(T^*)\sigma_{lnSa,\,k}\left(M_j, \theta_j, T_i\right) \tag{12}$$

$$\sigma_{lnSa,j,\,k(T_i)|lnSa(T^*)} = \sigma_{lnSa,\,k}\left(M_j, \theta_j, T_i\right)\sqrt{1-\rho^2(T_i, T^*)} \tag{13}$$

$$\mu_{lnSa(T_i)|lnSa(T^*)} = \sum_k \sum_j p_{j,\,k}^d \mu_{lnSa,j,\,k(T_i)|lnSa(T^*)} \tag{14}$$

$$\sigma_{lnSa(T_i)|lnSa(T^*)} = \sqrt{\sum_k \sum_j p_{j,\,k}^d \left(\sigma^2_{lnSa,j,\,k(T_i)|lnSa(T^*)} + \left(\mu_{lnSa,j,\,k(T_i)|lnSa(T^*)} - \mu_{lnSa(T_i)|lnSa(T^*)}\right)^2\right)} \tag{15}$$

Implementations

The refined CS computational methods increase with accuracy and complexity. Several factors contribute to the accuracy of approximations. First, the importance of considering multiple causal earthquakes depends upon how many differing causal earthquake *M*/*R* values contribute significantly to the hazard. In addition, variation in other parameters besides *M* and *R*, such as depth to the top of rupture for different source types, can affect the accuracy of the approximation since they contribute to the *Sa* prediction. Second, the similarity of the GMPMs affects approximations in their treatment. For cases where the ground motion predictions for a given *M*/*R* vary significantly between models, approximate treatment of GMPMs is less effective. Third, as the GMPM deaggregation weights differ more from the GMPM

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logic-tree weights, approximate treatment of those weights works less effectively. The exact conditional standard deviation is always higher than approximate results (Fig. 3b) because of the additional contribution from the variance in mean logarithmic spectral accelerations (Fig. 3a) due to variation in causal earthquakes and GMPMs. The impact of CS approximations on engineering decisions depends upon the difference between approximate and exact spectra: as the difference increases, more refined target spectra will have increasing benefits for ground motion selection and structural response assessment (Lin et al. 2013a).

The deaggregation of ground motion prediction models and the exact conditional mean spectrum (incorporating multiple causal earthquakes and multiple GMPMs) have been implemented in the United States Geological Survey hazard mapping tools (http://geohazards.usgs.gov/deaggint/2008/). Carlton and Abrahamson (2014) proposed an alternative Method 2.5 for a simplified implementation of the CS, which gives similar results to Method 3 in Lin et al. (2013a). Deaggregation weights, instead of logic-tree weights, of GMPMs were recommended when multiple GMPMs were used to compute the CS (e.g., Lin et al. 2013a; Carlton and Abrahamson 2014). Gulerce and Abrahamson (2011) extended the CS concept to vertical ground motions. Bradley (2010) developed a generalized conditional intensity measure approach to include intensity measures other than *Sa*.

Ground Motion Selection Algorithms

The conditional spectrum can be used as the target spectrum to select "representative" ground motions from a ground motion database for performance-based earthquake engineering. A computationally efficient algorithm (Jayaram et al. 2011) suitable for such CS-based ground motion selection (http://www.stanford.edu/~bakerjw/gm_selection.html) computes a target spectrum, and then selects and scales ground motions from the PEER NGA database to match the target spectrum mean and variance. This selection algorithm (1) probabilistically generates multiple response spectra from a target distribution, and then (2) selects recorded ground motions whose response spectra individually match the simulated response spectra. (3) A greedy optimization technique further improves the match between the target and the sample means and variances. This algorithm has been adopted by the global earthquake model (http://www.globalquakemodel.org/) for ground motion selection. Alternative algorithms that can be used for CS-based ground motion selection include those by, e.g., Wang (2011) and Bradley (2012).

If the uniform hazard spectrum or the conditional mean spectrum, instead of the conditional spectrum, is used as the target spectrum to select (and optionally scale) ground motions, the PEER ground motion database (http://peer.berkeley.edu/products/strong_ground_motion_db.html) is an online tool appropriate for such applications. In addition to CS-based ground motion selection (as shown in Fig. 1a), Jayaram et al. (2011) algorithm can also be modified to accommodate CMS- and UHS-based ground motion selection, as illustrated in Fig. 1b, c respectively.

Hazard Consistency in Risk-Based Assessments

Risk-based assessment estimates the mean annual rate of exceeding a specified structural response amplitude. The conditional spectrum computation requires specification of a conditioning period. The sensitivity of risk-based assessment results to the choice of conditioning period using CS-based ground motion selection is investigated in Lin et al. (2013b). This study focuses on risk-based assessments, with a specific emphasis on the rates of exceeding various levels of peak story drift ratio (i.e., drift hazard calculations) in the structure. Some additional engineering demand parameters (EDPs) are also

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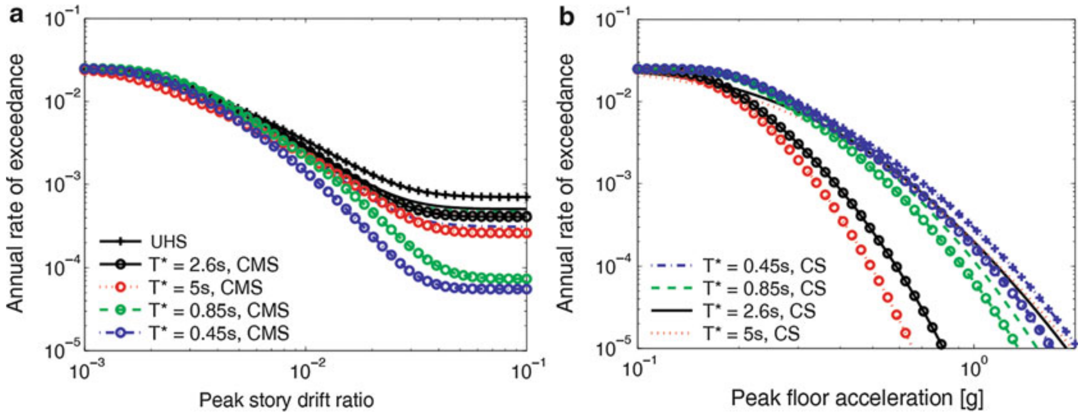

Fig. 4 Risk-based assessments of (**a**) peak story drift ratio and (**b**) peak floor acceleration of a 20-story reinforced concrete frame structure obtained from ground motions selected to match the CS, the CMS, and the UHS

considered, such as the peak floor acceleration over the full building heights, a single-story story drift ratio, and a single-story floor acceleration. The primary structure considered is a 20-story reinforced concrete frame structure assumed to be located in Palo Alto, California, using a structural model (Haselton and Deierlein 2007) with strength and stiffness deterioration that is believed to reasonably capture the responses up to the point of collapse due to dynamic instability.

The risk-based assessments are performed several times, using ground motions selected and scaled to match conditional spectra, where the conditioning period used for these calculations is varied from 0.45 to 5.0 s (i.e., the building's third-mode structural period up to approximately twice the first-mode period). For each case, the risk-based assessment results are found to be similar (Fig. 4). The similarity of the results stems from the fact that the careful record selection ensures that the distributions of response spectra at all periods are nominally comparable, so the distribution of resulting structural responses should also be comparable (to the extent that response spectra describe the relationship between the ground motions and structural responses).

From these results, it is observed that if the analysis goal is to perform a risk-based assessment obtaining the mean annual frequency of exceeding an EDP, then one should be able to obtain an accurate result using any conditioning period, provided that the ground motions are selected carefully to ensure proper representation of spectral values and other ground motion parameters of interest. Here "proper representation" refers to consistency with the site ground motion hazard curves at all relevant periods, and this is achieved by using the CS approach to determine target response spectra for the selected ground motions. The reproducibility of the risk-based assessment results, for varying conditioning periods, then results from the fact that the ground motion intensity measure used to link the ground motion hazard and the structural response is not an inherent physical part of the seismic reliability problem considered; it is only a useful link to decouple the hazard and structural analysis. If this link is maintained carefully then one should obtain a consistent prediction of the risk-based assessment in every case.

Intensity-Based Assessments and Evaluation of Alternative Target Spectra

Intensity-based assessment estimates structural response given ground motions with a specified intensity level. A study on the sensitivity of intensity-based assessment results to the choice of conditioning period when the CS is used as a target for ground motion selection and scaling is conducted by Lin et al. (2013c). This study also investigates the sensitivity of both risk-based and intensity-based assessments to the

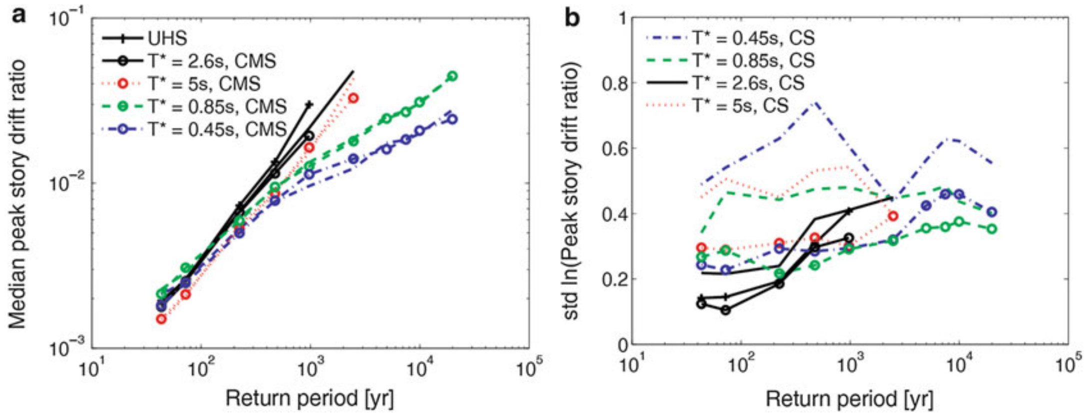

Fig. 5 Intensity-based assessments of peak story drift ratio (median and logarithmic standard deviation in (**a**) and (**b**) respectively) of a 20-story reinforced concrete frame structure obtained from ground motions selected to match the CS, the CMS, and the UHS

choice of target spectrum, including evaluation of the uniform hazard spectrum and the conditional mean spectrum.

The study shows the different effects of conditioning periods on intensity-based and risk-based assessments. In contrast to risk-based assessments, which are relatively insensitive to the choice of conditioning period in the CS, the choice of conditioning period for the CS can substantially impact structural response estimates for an intensity-based assessment (NIST 2011). It is therefore critical to specify the structural analysis objective clearly.

The study also demonstrates the importance of target spectrum. For intensity-based assessments, use of the CMS, instead of the CS, does not significantly affect the median response estimates (Fig. 5a) but does decrease both the dispersion of the response (Fig. 5b) and the probability of collapse, while use of the UHS typically results in higher median response (Fig. 5a). For risk-based assessments, use of the CMS, instead of the CS, results in underestimation of structural response hazard due to the omission of spectral variability (Fig. 4), while use of the UHS results in overestimation in the structural response hazard (Fig. 4).

An important issue regarding conditioning period arises when an intensity-based assessment is being used and the purpose is to compute the mean or median response associated with an $Sa(T^*)$ having a specified probability of exceedance (e.g., for a building-code-type check). In this extremely common case, the response prediction will always change depending upon the choice of conditioning period. This comes from the fact that the choice of conditioning period is an inherent part of the problem statement, and so in this case changing the conditioning period changes the question that is being asked. For example, computing the median drift response for a building subjected to a 2 % in 50 year exceedance *Sa*(1 s) is not the same as computing the median drift response for a building subjected to a 2 % in to 50 year exceedance *Sa*(2 s); these are two different questions. Resolution of this issue likely lies in identifying a conditioning period and performance check that, when passed, confirms satisfactory reliability of the structural system.

Summary

The conditional spectrum (CS) is a target response spectrum (with mean and variance) for ground motion selection to perform nonlinear dynamic analysis. The computation of the CS requires (1) input earthquake parameters of magnitude, distance, relevant seismological and site characteristics (e.g., fault type and soil

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type); (2) specification of a conditioning period; (3) ground motion prediction model(s) (GMPMs) to estimate mean and standard deviation of logarithmic spectral accelerations; and (4) correlation model (s) to relate spectral accelerations between different periods of vibration. Refined computation of the CS incorporates multiple causal earthquakes and multiple ground motion prediction models. The level of complexity in computation increases from Methods 1 (single earthquake and single ground motion prediction model) to 4 (multiple earthquakes and multiple ground motion prediction models with corresponding deaggregation weights). Factors that affect the accuracy of the approximations include (1) the input causal earthquake parameters, (2) the GMPMs used, and (3) the GMPM deaggregation weights. Hence, exact calculation methods may be needed for locations with hazard contributions from multiple earthquake sources especially with multiple source types, and/or for sites with larger variation in predictions from various GMPMs (Lin et al. 2013a). An intermediate method, Method 2.5, was proposed by Carlton and Abrahamson (2014) as a simpler practical alternative to Method 3 in Lin et al. (2013a). Probabilistic seismic hazard deaggregation of GMPMs (Lin and Baker 2011), which computes the relative contribution of GMPMs to a given intensity level, facilitates the refined CS computation. Deaggregation weights, instead of logic-tree weights, of GMPMs were recommended when multiple GMPMs were used to compute the CS (e.g., Lin et al. 2013a; Carlton and Abrahamson 2014). Notable extensions of the CS concept include the CS for vertical motions (Gulerce and Abrahamson 2011) and the generalized conditional intensity measure (Bradley 2010).

The computation and use of the CS advances hazard-consistent ground motion selection for performance-based earthquake engineering. The automation via USGS hazard mapping interface and ground motion selection web-based algorithms enhances practical applications of the CS. Challenges in the CS remain in (1) the choice of the conditioning period, (2) the appropriate question to ask in design-orientated intensity-based assessment, (3) a larger number of distinct ground motions that are used at various intensity levels, and (4) issues related to scaling ground motions. Progress has been made towards the effect of conditioning period in intensity- and risk-based assessments (Lin et al. 2013b, c; Carlton and Abrahamson 2014), the performance goal and design check via design spectrum calibration (Loth and Baker 2013), and a new method termed "adaptive incremental dynamic analysis" (AIDA) (Lin and Baker 2013) that allows overlap of ground motions across intensity levels. Research is ongoing to provide insights on the current engineering practice of ground motion scaling and the seismological counterpart in direct ground motion simulation.

Cross-References

- ► Physics-Based Ground Motion Simulation
- ► Probabilistic Seismic Hazard Models
- ► Selection of Ground Motions for Response History Analysis
- ► Stochastic Ground Motion Simulation

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