Description of metrics included in our GOF measure

Our GOF measure is a weighted average using up to 10 different metrics. Here, we provide a description of the metrics, and a justification of why the chosen metrics are important ingredients in a GOF estimate.

Cross-correlation

The GOF algorithm uses a cross-correlation metric (*Xcor*; eq. S1), specifically applicable to low-frequency synthetics (LFSs):

$$Xcor = 100 * \max\left(\left(\frac{\sum_{i=1}^{N}(x_i * y_i)}{\sqrt{\sum_{i=1}^{N} x_i^2} * \sqrt{\sum_{i=1}^{N} y_i^2}}\right), 0\right) \quad . \qquad \text{(S1)}$$

The low-frequency content of the BBSs is typically obtained using deterministic modeling. For simulation of historical earthquakes, for example using source models obtained from kinematic inversion, LFSs can be generated with very good waveform fits to data. *Xcor* measures the phase-sensitive, amplitude-independent correlation between two seismogram waveforms (*x* and *y*). If the correlation coefficient is negative then the *Xcor* is set to 0 to ensure that the GOF value is restricted between the values of 0 and 100. The cross-correlation is sensitive to delays or advances of the arrivals, for example due to errors in the velocity model used to generate the synthetic seismograms. It is possible to automatically obtain the maximum in the cross-correlation for a range of different time delays. However, this maximum may not align the traces appropriately, for example due to the presence of noise or mis-modeled phases. For this reason, we recommend to manually adjust the timing of the traces before the cross-correlation, and if that is not feasible, leave *Xcor* out of an average GOF estimate.

Cumulative Kinetic Energy and Duration

Energy release (EN) is an important metric when considering the fit between two ground motion time series. Cumulative kinetic energy density is calculated as $0.5\ \rho \int v^2\, dt$, where ρ is density and v is the particle velocity. To calculate the energy release, we compute and compare the final value of the cumulative energy vectors.

The duration (DUR) is calculated as the amount of time required for the normalized cumulative kinetic energy of the seismograms to progress from 5% to 75% (Jarpe and Kasameyer, 1996). This measure is important in geotechnical issues such as slope stability (Bray and Rathje, 1998) and for nonlinear ductile deformation calculations, particularly in large flexible buildings (Hall, 1995).

Time Domain Peak Ground Motions

We include peak ground accelerations (PGAs), peak ground velocities (PGVs), and peak ground displacements (PGDs) in our GOF algorithm. PGAs are used for a basic quantification of the ground motions and for generalized predictions of damage to smaller structures. They also provide a simple approximation of the peak spectral acceleration at very short periods. PGAs have been related to intensity measurements (Wu et al., 2003). Wald and others found that PGAs provide a good indication of intensities not exceeding

VII (Wald et. al., 1999), since lower intensities are attributed to felt reports and the human body responds to peak accelerations more readily than peak velocities when in moderation. PGVs are used for a basic quantification of the ground motions and for generalized predictions of damage to larger structures. PGVs have been related to intensity measurements in Japan (Wu et al., 2003), and Wald et al. (1999) found that PGVs provide a good indication of intensity when the intensity level exceeds VII. As with PGV's, PGDs are used for a basic quantification of the ground motions and for generalized predictions of damage to larger structures (e.g., Hall et. Al., 1995). Displacement time series are used extensively in many structural and geotechnical analyses (e.g., Bray and Travasarou, 2007; Bray and Rathje, 1998).

Spectral Acceleration

Spectral acceleration is the absolute peak acceleration (SA, see eq. S2) of a single degree of freedom oscillator (SDOF) that is subjected to a seismic load (a_i):

$$\ddot{x} + 2\beta\omega\dot{x} + \omega^2 x = -a(t) \text{ and}$$

$$SA = \max\left(\ddot{x} + a_i\right) = \max\left(2\beta\omega\dot{x}_i + \omega^2 x_i\right), \qquad \text{(S2)}$$

where β is the fraction of critical damping, traditionally chosen as 5%, ω is the natural frequency of vibration in the SDOF, and $\ddot{x}$, $\dot{x}$, and x are the acceleration, velocity and displacement time series for the SDOF oscillators motion, respectively. The elastic acceleration response spectrum is used as a basic measure for the estimation of potential intensity on frequency-dependent structures. This metric is also used to determine the effects of ground motion in geotechnical applications (Bray and Travasarou, 2007).

We compute our linear spectral accelerations based on an iterative method proposed by Nigam and Jennings (1968), from which we extract the absolute peak acceleration of the SDOF oscillator. The computations are done for 991 different periods (RS; 901 values at periods between 0.1 s and 1 s with 0.01 s spacing; 90 values at periods between 1.1 s and 10 s with 0.1 s spacing) and for 16 specific periods used by the NGA relations (SA16, Power et al., 2008; - 0.1 s, 0.15 s, 0.2 s, 0.25 s, 0.3 s, 0.4 s, 0.5 s, 0.75 s, 1 s, 1.5 s, 2 s, 3 s, 4 s, 5 s, 7.5 s, and 10 s). Generating a GOF value for the entire acceleration spectrum and at discrete periods is important due to the effects of ductile deformation. When a structure's deformation becomes ductile the fundamental period of the building is lengthened. This shift in the fundamental period of motion makes it important to consider a spectral band around the fundamental period (Hall et. al. 1995).

Nonlinear Response Spectral Ratios

Structures that are put under a strong seismic load are expected to respond in a non-linear manner. This nonlinearity is not captured in the linear elastic response calculated in the spectral acceleration metrics described above. A simple way of quantifying this nonlinearity is with a comparative ratio of the peak inelastic displacement of a bilinear oscillator versus the peak elastic displacement of a SDOF oscillator (IE ratios). The IE ratios can be plotted against the strength-reduction factor R (elastic displacement [T] / yield displacement) where T is the period used in the elastic and inelastic displacement calculations (Tothong and Cornell, 2006). Here, we follow BJ08 and calculate the IE ratio for 16 different periods. The ratio R records the discrepancy between IE ratios by varying the yield displacement. For example, with low values of R the yield displacement is high (relative to the elastic displacement) and therefore the IE ratio is ~1. As the value of R increases the yield displacement decreases and the IE ratio usually increases as the inelastic nonlinear response begins to dominate the structural response to the seismic loading.

Once the elastic response is calculated we can determine the values of the yield displacements required by the inelastic calculation (Nico Luco, Personal Communication, 2008; Chopra, 1995) based on specified R values (1-10). The criterion $\frac{dt}{T_{\min}} \leq 0.551$ must be met to ensure stability of the method used to calculate the inelastic response. In addition to the commonly used 5% damping ratio we use a strain hardening ratio of 2% as suggested by Luco and Bazzurro (2004); however, this ratio can easily be modified for specific engineering applications. Finally, we calculate the IE ratio curves at the 16 periods used by the NGA relations. The GOF values for the IE metric are calculated on the maximum difference in the IE curves for each period. This calculation is made on each individual component and for an average of the horizontal:

$$IEGOFx(R,T) = 100 * erfc\left[\frac{2*|IE1x(R,T) - IE2x(R,T)|}{\left(IE1x(R,T) + IE2x(R,T)\right)}\right]$$

$$IEGOFy(R,T) = 100 * erfc\left[\frac{2*|IE1y(R,T) - IE2y(R,T)|}{\left(IE1y(R,T) + IE2y(R,T)\right)}\right]$$

$$IEGOFh(R,T) = \frac{IEGOFx(R,T) + IEGOFy(R,T)}{2},\qquad \text{(S3)}$$

where IE1 and IE2 are the calculated IE ratios FOR each value of R and for each period considered, and IEGOFx and IEGOFy are the GOF values for the x and y components, respectively. The overall values are then calculated as the minimum GOF across each value of R, averaged across the desired set of period

$$IEGOFhT(T_j) = \min\left(mean_j\left(IEGOFh(R,T_j)\right)\right),\qquad \text{(S4)}$$

where T_j represents the selected period range and IEGOFhT is the overall GOF value of the horizontal components for the selected bandwidth. The mean is calculated across the selected bandwidth, for each value of R. The minimum is then calculated from the 19 mean values corresponding to each value of R.

An example of site-specific calculation of the IE ratios is shown in Figure S1, at station SMS for the Chino Hills event, analyzed in this study. At 0.3 s, the IE GOF value, the minimum horizontal average (30.2) is given by the value at R=10, here dominated by a poor fit for the EW component. At periods of 1 s and 4 s, the IE GOF values (43.2 and 56.0, respectively), are obtained for R of 8 and 10, respectively. This example shows that the IE GOF values can vary significantly between components of the ground motion.

Fourier Spectra

Intensity measures for strong ground motions have been found to be directly correlated to narrow bands within the Fourier amplitude spectrum. For example, Sokolov and

Chernov (1998) noted that small intensities have been linked to frequencies between 7 and 8 Hz, and large intensities to frequencies between 0.7 and 1 Hz. We calculate the Fourier amplitude spectra of the input time series (eqs. S5-S6) and generate a GOF measure (FS) using a smoothed (eq. S6) Fourier spectrum to reduce its generally large variance (Bendat and Piersol, 1967):

$$FAS(i) = \sqrt{\left(FASre(i)\right)^2 + \left(\frac{FASim(i)}{\sqrt{-1}}\right)^2} \quad , \qquad \text{(S5)}$$

$$FSs(i) = \left[mean\left(\left(FAS(i - fqi)\right) : \left(FAS(i + fqi)\right)\right]\right. \quad , \qquad \text{(S6)}$$

$$NRfs_i = \frac{2 * |FSsx_i - FSsy_i|}{FSsx_i + FSsy_i}, \text{ and}$$

$$FS = \frac{100}{N} * \sum_i erfc\left[NRfs_i\right], \qquad \text{(S7)}$$

where i is the vector index, FAS(i) is the Fourier amplitude spectrum, *re* and *im* denote the real and imaginary parts, FSs(i) is the smoothed Fourier amplitude spectrum, *fqi* is the number of frequency steps, and N is the number of values in the Fourier spectrum vector. The smoothing is done by taking the average of the FAS (eq. S5) across a 0.2 Hz-wide bandwidth. The smoothing in eq (S6) ensures that FS in eq. (S7) relates to the general shape and amplitude of the Fourier spectrum, and makes the FS measure less sensitive to large variations within the smoothing window.

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