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Assumptions underlying median-to-maximum horizontal intensity conversions in building code design spectra

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ABSTRACT

Current earthquake-resistant design codes in the US define their response spectra using maximum pseudo-spectral accelerations across all horizontal orientations, usually referred to as RotD100. However, the ground motion models (GMMs) used within the probabilistic seismic hazard analyses (PSHA) that define the response spectra usually use the median pseudo-spectral accelerations across all horizontal orientations (i.e., RotD50). Thus, to transform a RotD50 intensity into a RotD100 intensity, the output response spectra of the PSHA are multiplied by a factor that depends only on period. We show that there are two implicit assumptions within this simple multiplication procedure. The first assumption is that the average factor remains constant for all earthquakes considered in the PSHA. Using a ground motion database from shallow crustal earthquakes, we show that strike-slip earthquakes tend to produce ~2-4% larger average factors than other styles of faulting at long periods, which would not satisfy the assumption. Previous studies have also shown minor dependencies of this factor to magnitude and source-to-site distances. The second assumption is that the logarithmic standard deviation of GMMs developed for RotD100 would be the same as that of GMMs developed for RotD50, which could be tested by future studies.

Introduction

Horizontal earthquake ground motion intensity, such as pseudo-spectral accelerations, can vary significantly depending on horizontal orientation [1,2], a phenomenon known as ground motion directionality. Earthquake-resistant design codes in the US define their response spectra using the maximum intensity across all horizontal orientations [3], usually referred to as RotD100 [4]. However, the ground motion models (GMMs) used to compute seismic hazard are generally developed for an average component (e.g., [5]), most often the median across all horizontal orientations (typically referred to as RotD50, [4]). The design spectra are therefore constructed by directly multiplying RotD50 seismic hazard intensities by a period-dependent factor [6].

In this study, we show that this multiplication procedure has some implicit assumptions. One assumption is that the geometric mean of the multiplication factor is constant for all earthquake scenarios included in the probabilistic seismic hazard analysis. Prior studies have shown minor dependencies of the factor on earthquake magnitude and source-to-site distance [6,7]. We show that, at long periods, the factor also depends on the style of faulting, with ground motions from strike-slip earthquakes having larger average factors.

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Ground Motion Directionality

To illustrate the variation of ground motion intensity with horizontal orientation and the computation of RotD50 and RotD100, we use a record from the 2024 M_w 7.0 Cape Mendocino earthquake (Fig. 1). At each period, the RotD50 (median) and RotD100 (maximum) pseudo-spectral accelerations (PSAs) are computed from non-redundant orientations, spaced by one degree within 180 degrees, as shown in Figs. 1a and 1b. The ratio between RotD100 and RotD50 always falls between 1 and $\sqrt{2}$, which correspond respectively to limiting cases where the intensity is the same across all orientations and where the motion is completely polarized in one orientation. Thus, this ratio is sometimes used as a ground motion directionality metric, with larger values representing more polarized intensity measures. Repeating the calculation for all periods shows that, for this example record, PSAs tend to become more polarized at longer periods (Fig. 1c).

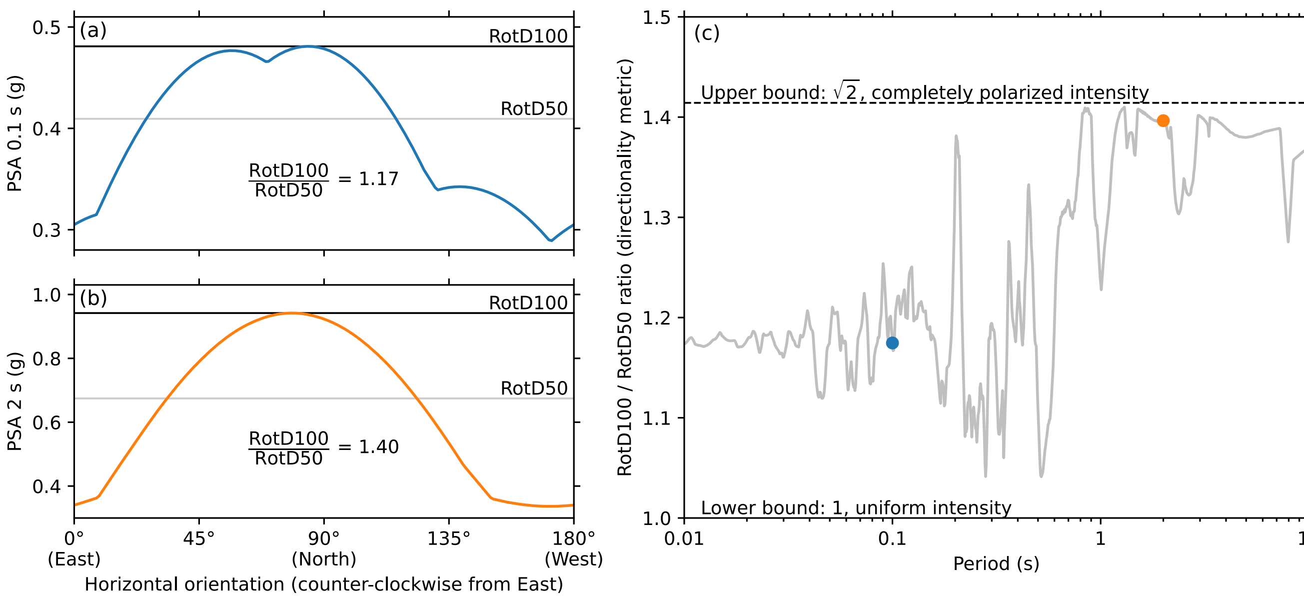

Figure 1. Variation with horizontal orientation of the pseudo-spectral acceleration (PSA) at (a) 0.1 s and (b) 2 s for a record from the 2024 M_w 7.0 Cape Mendocino earthquake at the Cooskie Peak station. (c) Ratio between the maximum (RotD100) and the median (RotD50) PSA across all horizontal orientations as a function of period.

The RotD100/RotD50 ratios of many ground motions recorded from multiple earthquakes can be used to convert GMMs from RotD50 to RotD100. Specifically, the geometric mean of these ratios, $\nu = \exp\left(\mu_{\ln(\mathrm{RotD100/RotD50})}\right)$, can be used as an additive factor to convert the mean of the logarithms of a RotD50 intensity ($\mu_{\ln \mathrm{RotD50}}$), which is provided by most GMMs, to an equivalent mean for RotD100 ($\mu_{\ln \mathrm{RotD100}}$):

$$
\begin{aligned}
\mu_{\ln \mathrm{RotD100}} &= \mu_{\ln(\mathrm{RotD100/RotD50})} + \mu_{\ln \mathrm{RotD50}} \\
&= \ln \nu + \mu_{\ln \mathrm{RotD50}}
\end{aligned} \tag{1}
$$

where $\mu_{(\cdot)}$ represents the mean or expected value. Fig. 2a shows ν ratios computed by prior studies using subsets of the NGA-West2 ground motion database [2,6]. Although some variation exists between these studies, they generally report an increase in ν as the period becomes longer, from approximately 1.2 at short periods to 1.29 at a period of 10 s. Based on the work of [6], the ASCE 7 building code [3] uses a simplified piecewise linear function shown in Fig. 2a (note that it seems nonlinear in the figure because of the logarithmic horizontal scale). The RotD100/RotD50 ratios, however, have significant variability, as shown in Figs. 2b and 2c. A model that explains part of this variability could improve conversions such as the one shown in Eq. (1).

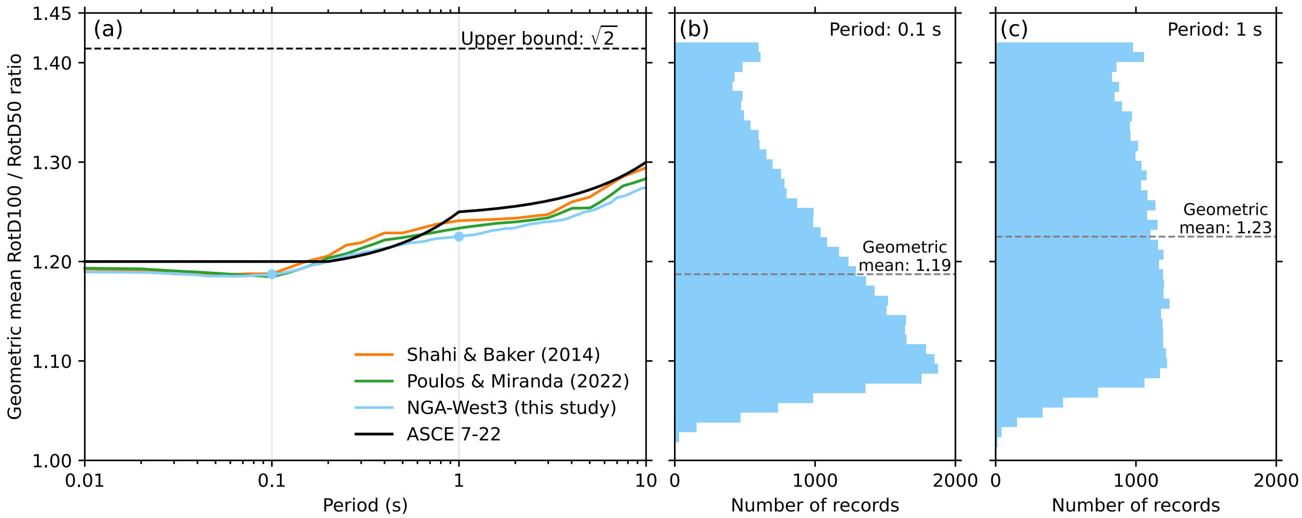

Figure 2. Distribution of the RotD100/RotD50 ratio: (a) geometric mean as a function of period; distribution for pseudo-spectral accelerations at (b) 0.1 s and (c) 1 s.

Probabilistic Seismic Hazard Analysis Using Maximum Horizontal Intensity

The seismic hazard for RotD100 can be derived from the seismic hazard of RotD50 under some assumptions. PSHA computes the mean annual rate of exceedance of a ground motion intensity measure, typically referred to as the seismic hazard curve, using a finite set of earthquake rupture scenarios $\mathcal{R}$. This is usually computed as a weighted sum of the probability of exceedance for each rupture:

$$\lambda_{\mathrm{RotD50}}(x) = \sum_{r\in\mathcal{R}} \lambda_r P(\mathrm{RotD50}_r > x) = \sum_{r\in\mathcal{R}} \lambda_r \left[1 - \Phi\left(\frac{\ln(x) - \mu_{\ln \mathrm{RotD50}_r}}{\sigma_{\ln \mathrm{RotD50}_r}}\right)\right] \tag{2}$$

where λ_r is the mean annual rate of rupture r; $P(\mathrm{RotD50}_r > x)$ is the probability that the RotD50 intensity exceeds a certain value x for rupture r, which is computed assuming that RotD50 follows a lognormal probability distribution; $\Phi(\cdot)$ is the cumulative distribution function of a standard normal distribution; and μ_{RotD50_r} and $\sigma_{\mathrm{RotD50}_r}$ are the parameters of the lognormal distribution given by a GMM for rupture r. The same procedure can be used for the RotD100 hazard curve, now using Eq. (1) to replace μ_{RotD100_r}:

$$\lambda_{\mathrm{RotD100}}(x) = \sum_{r\in\mathcal{R}} \lambda_r \left[1 - \Phi\left(\frac{\ln(x) - [\ln(\nu_r) + \mu_{\ln \mathrm{RotD50}_r}]}{\sigma_{\ln \mathrm{RotD100}_r}}\right)\right] \tag{3}$$

If we assume that: (1) the ν_r ratio is constant for all ruptures and equal to ν, and (2) the logarithmic standard deviation of RotD100 is the same as that of RotD50, then the hazard curves are related by a simple expression:

$$\lambda_{\mathrm{RotD100}}(x) = \sum_{r\in\mathcal{R}} \lambda_r \left[1 - \Phi\left(\frac{\ln\left(\frac{x}{\nu}\right) - \mu_{\ln \mathrm{RotD50}_r}}{\sigma_{\ln \mathrm{RotD50}_r}}\right)\right] = \lambda_{\mathrm{RotD50}}(x/\nu) \tag{4}$$

The RotD100 intensity at a specific return period, such as the 2,475 years used in design (2% in 50 years), can then be computed by simple multiplication, that is, $\lambda^{-1}_{\mathrm{RotD100}}(1/2475) = \nu \cdot \lambda^{-1}_{\mathrm{RotD50}}(1/2475)$.

Variability of the Geometric Mean RotD100 to RotD50 Ratio

One of the discussed assumptions is that the geometric mean RotD100/RotD50 ratio (ν) is independent of rupture scenario. Prior studies found minor dependence on source-to-site distance [6,7] and magnitude [7]. Here, we examine dependence on style of faulting, motivated by evidence that it influences RotD100 orientations [8,9]. We selected ~40,000 records from the recently developed NGA-West3 database [10]. The selection criteria included using free-field sites, earthquake magnitudes greater than 5.0, and excluding records with missing data or with multiple wavetrains from synchronous earthquakes. We find that strike-slip earthquakes have larger ν than earthquakes with reverse and normal faulting for periods > 1 s (Figure 3a). For example, at 10 s, ν is approximately 1.29 for strike-slip earthquakes versus 1.26 for normal and reverse earthquakes, implying ~12% higher amplification when converting the RotD50 hazard to RotD100.

The higher polarization for strike-slip earthquakes likely results from the radiation pattern of shear waves, which dominate ground motion intensities at distances of engineering significance. Vertical strike-slip faults tend to radiate stronger transverse SH waves than radial SV waves, producing more polarized ground motions. In contrast, reverse and normal faults tend to have more comparable SH and SV amplitudes that vary significantly with source-to-site distance and azimuth. These effects tend to disappear at short periods, likely due to wave scattering. Within strike-slip earthquakes, we also observe lower ν values for stations where SH and SV amplitudes are more comparable. The SH wave radiation pattern peaks along the nodal planes (the fault and a line perpendicular to the fault) and decreases away from them. Grouping by the minimum angular distance to a nodal plane (β), we find that ν tends to decrease with increasing β (Figure 3b). These trends are consistent with [11], who found a comparable radiation-pattern dependence for a similar ratio between RotD100 and GMRotI50 [12].

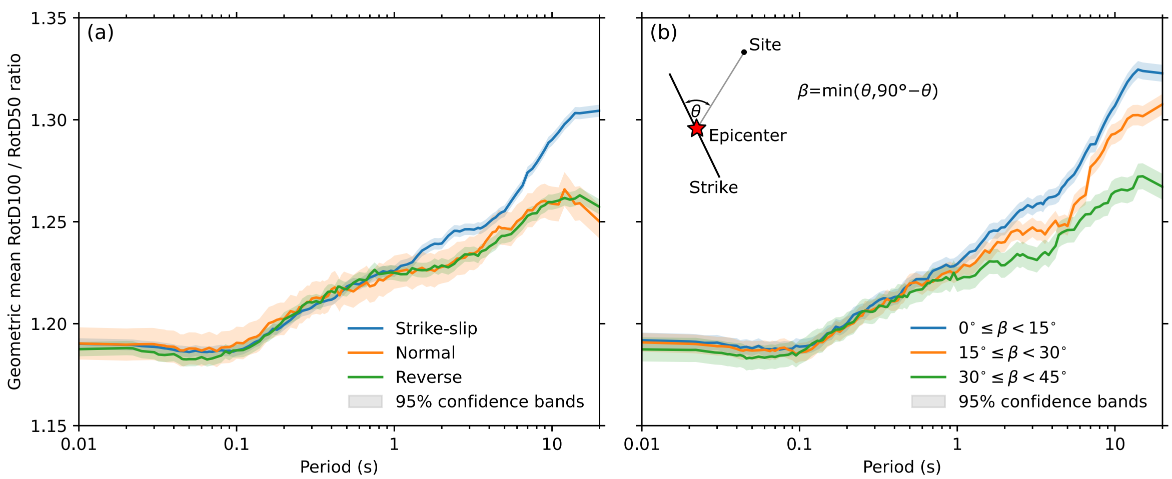

Figure 3. Geometric mean RotD100/RotD50 ratios for (a) different styles of faulting and (b) strike-slip earthquakes with varying β angles. The top-left inset in panel (b) illustrates how β is computed from the strike and the station location relative to the epicenter. Shaded areas indicate pointwise 95% confidence bands of the geometric mean ratios.

Conclusions

Design spectra in the US, which are based on the maximum ground motion intensity across all horizontal orientations (RotD100), are constructed by multiplying the median horizontal (RotD50) hazard by a period-dependent factor. We show that this procedure assumes that: (1) the geometric mean factor is constant for all earthquake scenarios, and (2) the standard deviation of a RotD100 ground motion model is the same as that of a RotD50 model. We find that the first assumption does not hold under certain circumstances. Specifically, ground motions from strike-slip earthquakes have statistically significantly higher factors at long periods than those of reverse or normal earthquakes, which can be attributed to shear-wave radiation pattern effects. Future work could test the second assumption by developing a ground motion model for RotD100.

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