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# NEW ORIENTATION-INDEPENDENT MEASURE OF HORIZONTAL GROUND MOTION INTENSITY THAT ACCOUNTS FOR DIRECTIONALITY IN EARTHQUAKE-RESISTANT DESIGN

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## ABSTRACT

Currently, design spectra in the U.S. are based on the spectral intensity occurring in the direction of maximum intensity at a site, usually referred to as RotD100. Using this definition for design is conservative because it implies that the orientation of maximum response coincides with one of the principal axes of the building. Other alternatives include the use of a measure of central tendency of the intensity at a site, such as the median spectral ordinate from those at all possible orientations, usually referred to as RotD50. However, most buildings have two horizontal principal axes that are orthogonal with respect to each other, and the design will be controlled by the maximum intensity in these orientations. Thus, this work proposes using the maximum between two orthogonal horizontal components at all non-redundant orientations and then taking the median value, referred to as MaxRotD50. Using a ground motion database of 5065 records, response spectra computed with MaxRotD50 are shown to be, on average, 16% higher than those computed with RotD50 and 6% lower than those computed with RotD100. Thus, the adoption of MaxRotD50 would result in a reduction of the ground motion intensities used for design.

## Introduction

Although response spectral ordinates of horizontal ground motions vary significantly with changes in orientation, this directionality has traditionally been neglected when estimating the ground motion intensity. For example, ground motion models usually use a measure of central tendency of the intensity occurring in various orientations at a site, such as the geometric mean of the pseudo-acceleration response spectral ordinates of the two horizontal components of the ground motion recorded at a site or more recently the median value between all possible orientations, known as RotD50 [1]. Meanwhile, in the last ten years, design spectra of U.S. building codes [2] use the maximum spectral ordinate between those occurring at all possible orientations, known as RotD100 [1].

Many seismologists, geotechnical engineers, and structural engineers consider the use of RotD100 overly conservative for earthquake-resistant design because it assumes that the orientation of maximum ground motion intensity coincides with the principal axes of the building which is very unlikely except for a very small number of structures which are axisymmetric [3].

Most structures have two principal axes of structural response that are orthogonal with respect to each

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other due to their geometry and/or the arrangement of their lateral resisting elements. Structures are usually designed by equivalent force or response spectrum analysis where the design spectrum is applied to the two horizontal principal axes of the structure. Given that seismic responses, in particular lateral deformation demands, are often strongly dominated by the fundamental mode, it is reasonable to assume that structural design will be controlled by the maximum ground motion intensity that occurs at these two principal axes. If all orientations of the ground motion with respect to the structure are assumed to be equally likely, the probability that the ground motion intensity in at least one of the two principal axes of a structure exceeds the RotD50 intensity is much higher than 50%, ranging from an average of 91% for short periods to 98% for a period of 10 s [4]. Thus, using RotD50 for design would lead to response spectra that have higher probabilities of exceedance in at least one of the principal axes of the building than that implied by the return period of the RotD50 seismic hazard curve at the site. This means that the return periods associated with the probability of exceeding the displacement in one of the two principal axes of a structure are much lower than commonly used referenced return periods in design documents (e.g., 475 years).

This paper presents a recently proposed definition of the horizontal component to construct design spectra, referred to as MaxRotD50 [4]. This definition has the advantage that, if all orientations of the ground motion with respect to the structure are assumed to be equally likely, the probability of it being exceeded in at least one of the two principal axes of a building is 50%. This work presents a procedure to compute MaxRotD50 and compares it to RotD50 and RotD100 using a ground motion database consisting of 5,065 ground motions recorded in shallow crustal earthquakes in active tectonic regimes.

## Horizontal ground motion intensity

Response spectral ordinates of horizontal ground motions vary significantly with changes in orientation. For example, Fig. 1 shows the relative displacement trace of two 5%-damped linear elastic oscillators with periods of 0.2 s and 1.0 s when subjected to the two horizontal components recorded in the Anaheim station during the 1994 $M_W$ 6.7 Northridge earthquake (record sequence number 944 in the NGA-West2 database). The pseudo-acceleration spectral ordinates at all orientations are represented in Fig. 1 by red curves, which are computed at any given orientation $\theta$ by taking the maximum absolute response (i.e., peak response) in that orientation which is computed by projecting the displacement response history at the recorded components by using the following equation:

$$Sa(\theta) = \omega_n^2 \max_t \left| u_x(t)\cos(\theta) + u_y(t)\sin(\theta) \right| \tag{1}$$

where $\omega_n$ is the natural angular frequency of the oscillator, $u_x(t)$ and $u_y(t)$ are the relative displacements response histories of the oscillator in two orthogonal orientations (usually selected as the as-recorded orientations), and $\theta$ is the angular difference between the orientation of interest and the $x$-direction.

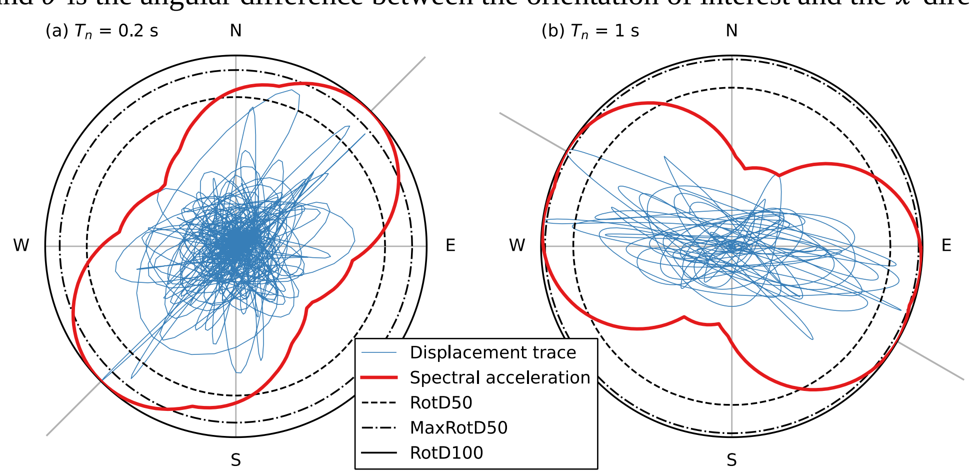


Figure 1. Relative displacement traces of oscillator of (a) 0.2 s and (b) 1 s, when subjected to the two horizontal ground motion components of the example record.

As shown in Fig. 1, for both periods, $Sa$ varies significantly with changes in orientation. For example, for a period of 0.2 s, the maximum $Sa$ among all orientations is 2.03 times higher than the minimum $Sa$. For the 1.0 s oscillator, this ratio is even higher and equal to 2.43. Neglecting directionality would only be appropriate if the variability were to be small with changes in orientation, but this is not the case and therefore directionality must be explicitly taken into account in earthquake-resistant design. Using a measure of central tendency such as RotD50 as the basis for design is inadequate while using the maximum of the peak intensity of all orientations (RotD100) is overly conservative. Thus, there is a need for an intermediate, more rational measure of intensity to be used in earthquake-resistant design.

## Proposed intensity

Using RotD100 for earthquake-resistant design, as currently done by the US building codes [2], implies that the orientation where the maximum $Sa$ occurs coincides with one of the principal directions of the building. Apart from this being unlikely for a given period, it will not occur for all periods because the orientation of maximum $Sa$ is period-dependent, as evidenced by Fig. 1. On the other hand, using RotD50 would result in a response spectrum that has a 50% probability of being exceeded in a random horizontal orientation but since buildings usually have two horizontal principal axes that are orthogonal to each other the probabilities of exceeding RotD50 in one of the two principal directions is between 91% and 98% depending on the period of the structure. Thus, Poulos and Miranda [4] proposed an alternative definition of the horizontal component to be used for earthquake-resistant design referred to as MaxRotD50, which is based on the maximum $Sa$ of two orthogonal directions. For a given ground motion record and structural period, MaxRotD50 can be computed with the following steps:

1. Compute the relative displacement of a linear elastic oscillator in two orthogonal horizontal orientations, $u_x(t)$ and $u_y(t)$.
2. Calculate $Sa$ at all non-redundant orientations (i.e., $\theta \in [0°, 180°)$) using Eq. (1).
3. Compute the maximum $Sa$ between two orthogonal orientations: $Sa_{\max}(\theta) = \max\{Sa(\theta), Sa(\theta + 90°)\}$, at all non-redundant orientations, i.e., $\theta \in [0°, 90°)$.
4. MaxRotD50 is finally computed as the median of the $Sa_{\max}(\theta)$ values.

Fig. 2 illustrates the computation of MaxRotD50 for periods of 0.2 s and 1 s using the same ground motion record of Fig. 1. Note that, for the example record, $Sa_{\max}(\theta)$ exceeds RotD50 for any rotation angle. Poulos and Miranda [4] found that the percentage of angles where this occurs is, on average, between 91% for short periods to 98% for 10 s. Moreover, it is easy to see from the definition of MaxRotD50 that it will always be greater than RotD50 and smaller than RotD100.

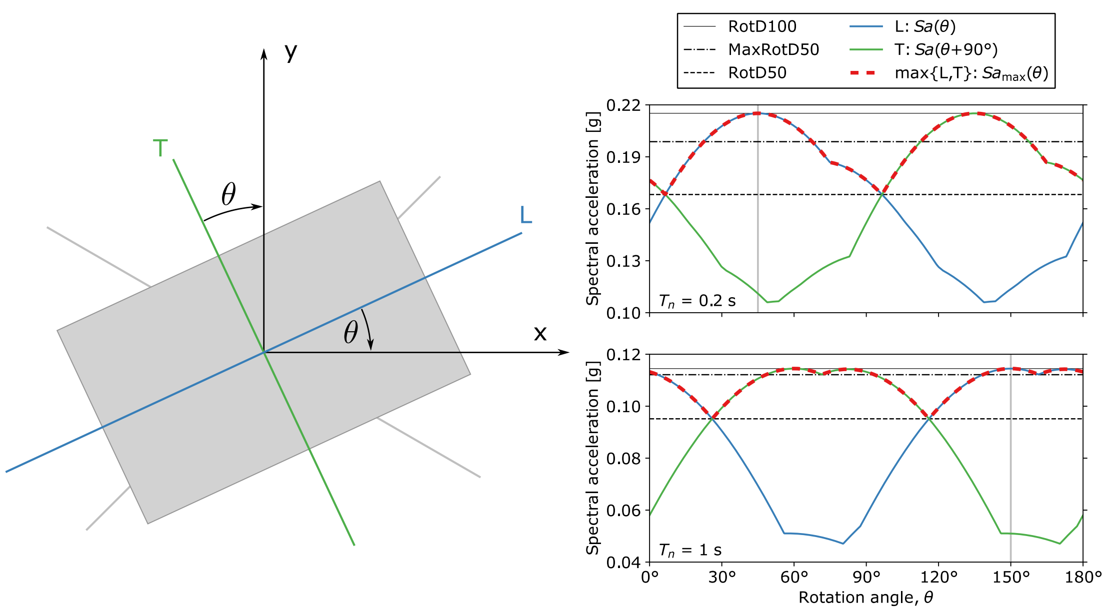


Figure 2. Computation of MaxRotD50.

## Ratios between MaxRotD50 and previous definitions

The proposed measure of intensity MaxRotD50 presented in the previous section was computed for 5,065 ground motion records at 40 logarithmically-space periods between 0.01 s and 10 s. The records were obtained from the NGA-West2 database [5] and were recorded during earthquakes of magnitudes greater than or equal to 5.0 at stations that reasonably reflect free-field condition (according to [6]) with NEHRP site classes B, C, or D. The records were also used to compute RotD50 and RotD100, and the ratios between these definitions and MaxRotD50 are presented in Fig. 3 as a function of period. As seen in the figure, the ratios vary from record to record. The average ratio between RotD100 and MaxRotD50 remains relatively stable throughout the period range at approximately 1.06. In other words, MaxRotD50 has an intensity approximately 6% lower than RotD100, which is currently used in the U.S. design of buildings. The average ratio between RotD50 and MaxRotD50 is period-dependent, ranging from approximately 0.89 at short periods to 0.84 at a period of 10 s. That is, the proposed MaxRotD50 is 12% to 19% higher than RotD50 used in recent GMMs. A more detailed description of these ratios, together with ratios to five other definitions of the horizontal component used in practice, is presented in [7] and can be used to transform logarithmic means and standard deviations given by a ground motion model that uses any of these seven definitions into MaxRotD50.

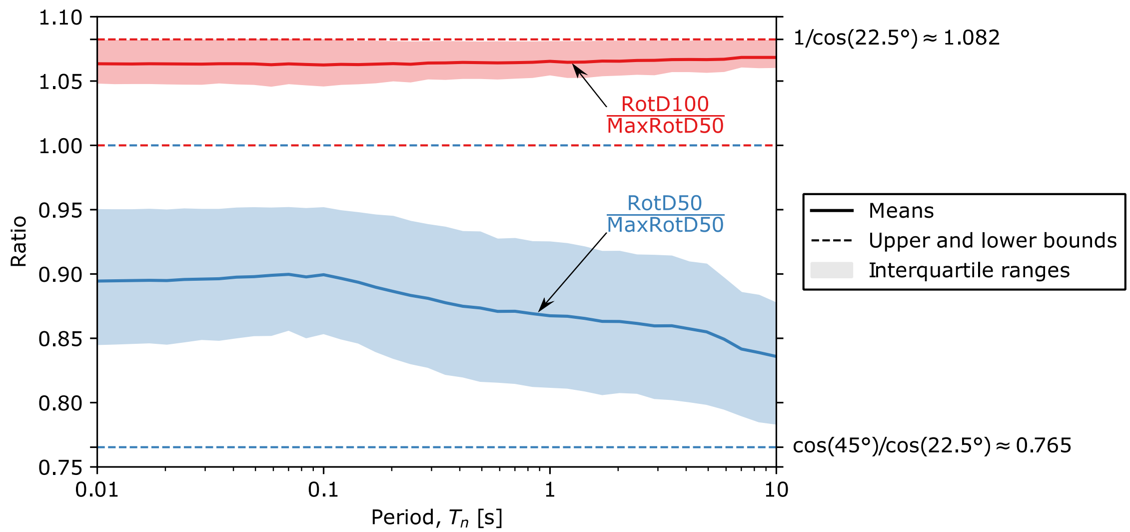


Figure 3. RotD100/MaxRotD50 and RotD50/MaxRotD50 ratios obtained from the records of the ground motion database.

## Conclusions

This work presents a new orientation-independent measure of ground motion intensity that is proposed for earthquake-resistant design of structures with two horizontal principal axes that are orthogonal with respect to each other. It has the advantage of eliminating the overly conservative assumption that the direction of maximum spectral intensity will coincide with one of the principal axes of the structure, which is implied when using RotD100, as currently done by U.S. building codes. Similarly, instead of using RotD50, which has a probability of being exceeded between 91% and 98% depending on the period of the structure, the new measure, named MaxRotD50, explicitly takes into account ground motion directionality and is computed using the maximum spectral ordinate between two orthogonal horizontal directions and then taking the median for all non-redundant orientations, and hence has a 50% probability of being exceeded in at least one of the principal axes of the structure. Using a ground motion database of 5065 records, MaxRotD50 is shown to be, on average, between 12% and 19% higher than RotD50 (depending on period) and approximately 6% lower than RotD100 for all periods. Thus, using MaxRotD50 would result in a reduction of design spectra.

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