Research Paper

Proposal of orientation-independent measure of intensity for earthquake-resistant design

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Alan Poulos,[1] M.EERI, and Eduardo Miranda,[1] M.EERI

Abstract

A new measure of ground motion intensity in the horizontal direction is proposed. Similarly to other recently proposed measures of intensity, the proposed intensity measure is also independent of the as-installed orientation of horizontal sensors at recording stations. This new measure of horizontal intensity, referred to as MaxRotD50, is defined using the maximum 5%-damped response spectral ordinate of two orthogonal horizontal directions and then computing the 50th percentile for all non-redundant rotation angles, that is, the median of the set of spectral ordinates in a range of 90^{o}. This proposed measure of intensity is always between the median and maximum spectral ordinate for all non-redundant orientations, commonly referred to as RotD50 and RotD100, respectively. A set of 5065 ground motion records is used to show that MaxRotD50 is, on average, approximately 13-16% higher than Rot50 and 6% lower than RotD100. The new measure of intensity is particularly well suited for earthquake-resistant design where a major concern for structural engineers is the probability that the design ground motion intensity is exceeded in at least one of the two principal horizontal components of the structure, which for most structures are orthogonal to each other. Currently, design codes in the United States are based on RotD100, and hence using MaxRotD50 for structures with two orthogonal principal horizontal components would result in a reduction of the ground motion intensities used for design purposes.

Keywords

Ground motion intensity, earthquake-resistant design, horizontal ground motion, directionality, seismic hazard analysis

[1]Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, USA

Corresponding author:

Alan Poulos, Department of Civil and Environmental Engineering, 473 Via Ortega, Stanford University, Stanford, CA 94305, USA.

Email: apoulos@stanford.edu

Introduction

The intensity of horizontal earthquake ground motions varies significantly with changes in orientation. To estimate the probability of exceedance of a given intensity at a site in future earthquakes or in general for earthquake-resistant design, this orientation dependence is usually simplified by characterizing horizontal ground motion intensity by a single measure of intensity (i.e., a scalar). Several ways of combining the intensity of recorded motions in two orthogonal horizontal directions have been proposed and used over the years to provide a scalar measure of intensity for use in ground motion prediction models (GMPMs) and as a basis for establishing design spectra for earthquake-resistant design. Two options, that were used for many years, are the use of the intensity in an arbitrary (also referred to as random) component and the geometric mean of the two as-recorded directions of the pseudo-acceleration spectral ordinates of 5%-damped linear elastic oscillators. When computed from many records, the median of these two measures of horizontal earthquake ground motion intensity is essentially the same, but the variability of the former is larger, and therefore, if one uses the geometric mean of the intensities in the two as-recorded horizontal directions as a measure of intensity in a GMPM but wishes to use the arbitrary component as basis for conducting probabilistic seismic hazard analysis or for design purposes, then the variability must be increased (e.g., Boore et al. 1993, 1997; Watson-Lamprey and Boore 2007).

Boore et al. (2006) noted that the geometric mean of response spectra for two orthogonal horizontal components of motion, which was commonly used for many years as a measure of horizontal intensity in GMPMs, depends on the orientation of the sensors as installed in the field. In particular, they noted that in the case of a linearly polarized ground motion in which one of the recording sensors is aligned with the direction of polarization, the spectral ordinate in the orthogonal direction would be zero leading to a geometric mean that it is also zero regardless of the spectral amplitude in the polarized direction. Hence, they proposed new measures of ground motion intensity in the horizontal direction by computing the geometric mean of response spectral ordinates for all non-redundant rotations of the two ground motions recorded in orthogonal horizontal directions and then finding a certain percentile of the resulting set of geometric means. There is a periodicity of 90^{o} in the geometric means as a function of rotation angles. Therefore, the non-redundant set of rotation angles spans a range from 0^{o} to 90^{o}. They proposed an orientation-independent geometric mean measure of intensity using period-dependent rotation angles, referred to as GMRotDpp where "pp" indicates the percentile value used for the intensity measure. They noted that one disadvantage of GMRotDpp is that the period-dependent rotations might seem to obscure the physical interpretation of the intensity measure, so they also proposed another orientation-independent geometric mean measure of intensity using period-independent rotation angles, referred to as GMRotIpp where again "pp" indicates the percentile value used for the intensity measure. They proposed a method to use a single period-independent rotation of the motions computed by selecting an angle of rotation that minimizes a penalty function that depends on the angle of rotation and that seeks to avoid extreme variations away from the desired percentile value over all periods and avoids having very small geometric means in the case of strongly correlated motions. GMRotI50 was selected as the measure of horizontal ground motion intensity in the Next Generation Attenuation (NGA) project (Power et al. 2008).

A disadvantage of GMRotIpp is that it requires selecting a period range for its computation and care must be taken to make sure that the upper end of the period range is large enough to capture the peaks in the displacement response spectra (Boore et al. 2006). Furthermore, while GMRotI50 may still be an adequate measure of the median motion, the conceptual simplicity of the relation between the different fractal levels is lost for the period-independent-rotation-angle measures (Boore 2010). Due to these limitations, Boore (2010) introduced an alternative measure of horizontal-component seismic intensity that represents any percentile consistently without computing geometric means that are also independent of the orientation of the recording sensors. In this alternative measure of intensity referred to as RotDpp, 5% spectral ordinates are computed for each period of vibration in a range of rotation angles of 180º, which are then sorted to compute the pp-th percentile. RotD50, which provides a measure of median horizontal intensity, was selected as the measure of horizontal-component seismic intensity in the NGA-West2 project (Bozorgnia et al. 2014). The latest generation of seismic maps in the United States are based on probabilistic seismic hazard analyses using this parameter (Petersen et al. 2020).

Huang et al. (2008) noted that spectral ordinates corresponding to the maximum component (i.e., RotD100) substantially exceed GMRotI50 demands in the near-fault region, which has significant implications for seismic design and seismic performance assessment. As a result of that study and work of the so-called Project 07 of the Building Seismic Safety Council, the values of the seismic design parameters reported in the 2010 and 2016 versions of Minimum Design Loads for Buildings and Other Structures, ASCE 7 (American Society of Civil Engineers (ASCE) 2010, 2016); in the 2009 (FEMA P-750), 2015 (FEMA P-1050), and 2020 (FEMA P-2082) versions of NEHRP Recommended Seismic Provisions for New Buildings and Other Structures (Building Seismic Safety Council (BSSC) 2009, 2015, 2020); and in the 2012, 2015 and 2018 versions of the International Building Code (International Code Council (ICC) 2011, 2014, 2017) are all defined in terms of maximum spectral demand rather than geometric-mean spectral acceleration demand in the horizontal plane. The maximum direction was adopted for use in seismic design in lieu of explicit consideration of directional effects (ASCE, 2010). Since GMPMs are currently not available for RotD100, ASCE 7-10 makes use of approximate period-dependent amplification factors of 1.1 for short periods and 1.3 for the 1.0 s spectral ordinates which are used to construct design spectra in these design documents. According to the commentary of ASCE 7-10, these approximate amplification factors are based on studies by Huang et al. (2008) to account for ratios of the maximum direction spectral demand (RotD100) to geometric mean spectral response acceleration maps developed by the United States Geological Survey (USGS). Based on the result of Shahi and Baker (2014), these factors were recently modified in FEMA P-2082 to 1.2 for short periods and 1.25 for the 1.0 s spectral ordinates (BSSC, 2020). Huang et al. (2011) indicated that the use of maximum spectral demand for force-based design is not overly conservative since there is typically an axis where the spectral demands are close or equal to the maximum demands.

Hong and Goda (2007) conducted an assessment of the probability that a spectral ordinate along a random orientation exceeds the geometric mean of the two recorded horizontal components of strong ground motions by using two sets of ground motions, one with 108 records of a set that was originally compiled by Boore et al. (1997) and another set of 592 records from the NGA ground motion database. They concluded that on average the exceedance probability of a spectral ordinate along a random orientation exceeding the geometric mean of recorded intensities is slightly higher than 50%. Additionally, they developed an orientation-dependent ground motion measure based on the ratio of the spectral acceleration for a pair of ground motions at a given orientation and period to the maximum spectral demand at the period. Based on this work, Nievas and Sullivan (2017) proposed a method to compute probabilities of exceedance of elastic spectral ordinates that accounts for the orientation dependence of horizontal ground motion intensity and structural typology.

In an opinion article, Stewart et al. (2011) described the adoption of the maximum direction as a basis for design as controversial. They argued that the use of the maximum direction for design introduces an overly conservative bias to design ground motions because it effectively assumes that the azimuth of maximum ground motion coincides with the directions of principal structural response, which is unlikely. They asserted that the 10 to 30% increase in ground motion intensity from the use of RotD100 instead of GMRotI50 affects the costs of new construction and retrofits. They estimated these increments would then lead to additional construction costs on the order of magnitude of 1% that would correspond to an added premium of $500 million US dollars per year in California alone. They argued that the use of the existing USGS probabilistic ground motion maps combined with NEHRP site and risk factors represents the most reasonable (probabilistically most consistent) basis currently available for evaluating design ground motions along the principal axes of structures.

There is no doubt that for axisymmetric structures, that is, structures having a vertical cylindrical symmetry in which the structure has the same properties (i.e., mass, lateral stiffness, and lateral strength) when rotating about a vertical axis, design ground motions should be based on the maximum direction intensity. Some examples of these types of structures include cylindrical liquid storage tanks (e.g., water tanks, oil tanks, liquid natural gas tanks, wine tanks, etc.), spherical storage tanks, vertical pressure vessels, isolated cylindrical storage silos, dome structures, cylindrical or truncated conical chimneys and stacks, hyperbolic cooling towers in power plants, water reservoir cylindrical intake towers, cylindrical containment structures in nuclear power plants, and isolated cylindrical structures in oil refineries (e.g., distillation columns, fluid catalytic cracking units, hydrocracker units, coker units, etc.). However, these types of structures represent only a small percentage of structures in seismic regions, therefore the use of the maximum direction intensity for the design of all structures is overly conservative. Moreover, it should be noted that many apparently axisymmetric structures lose this characteristic by the presence of external columns and bracing or because of being supported by four legs. The former is very frequent in many vertical cylindrical structures in oil refineries in seismic regions, and examples of the latter are vertical pressure vessels or stainless-steel wine tanks supported by four legs.

Because of the geometry of the structure and/or the arrangement of their laterally resisting elements, most structures have two principal axes that are orthogonal with respect to each other (e.g., transverse and longitudinal). At present time, most structures are designed using equivalent force or response spectrum analysis where the loading is applied to these principal axes. Since seismic responses are typically dominated by only a few modes and in particular lateral deformation demands are often strongly dominated by the fundamental mode, it is then reasonable to assume that a limit state used for designing a structure (e.g., a displacement serviceability limit such as the peak interstory drift) will be exceeded if the limit is exceeded in at least one of these principal axes. Thus, of particular interest to structural engineers is to assess the probability that the design ground motion intensity will be exceeded in at least one of these two principal axes. In general, the direction of the maximum ground motion intensity relative to these principal axes is unknown, but it will be at most 45^{o} from one of the two principal directions of the structure, therefore it is very likely that one of the two principal axes will experience an intensity larger than the median intensity of all non-redundant angles of rotation. Therefore, the probability of exceeding the ground motion intensity in one of the principal axes of the structure is higher than the probability of exceeding the RotD50 intensity currently used in the USGS seismic maps.

Maximum ground motion intensities of two orthogonal horizontal directions have been used in some GMPMs (e.g., Sabetta and Pugliese 1987; Boore et al. 1993; Munson and Thurber 1997) and by the

ShakeMap software (Worden et al. 2020) considering the two as-recorded directions. However, these as-recorded directions do not necessarily coincide with the principal axes of the structure. Moreover, in recent years, orientation-independent measures of ground motion intensity have been preferred because they remove the effect of sensor orientation (e.g., Boore et al. 2006; Boore 2010).

This work starts by studying the likelihood that the commonly used RotD50 measure is exceeded in at least one of the orthogonal principal directions of a structure. It then proposes a new orientation-independent measure of ground motion intensity, MaxRotDpp, which is the pp-th percentile of the maximum spectral acceleration from two horizontal orthogonal at all non-redundant orientations. The new measure is compared to the commonly used median and maximum single orientations components (i.e., RotD50 and RotD100, respectively). Finally, the implications of its use in probabilistic seismic hazard analysis (PSHA) and structural design are highlighted using a simple example.

Orientation dependence of ground motion intensity

The intensity of horizontal earthquake ground motion varies with orientation (i.e., with changes in azimuth). Horizontal ground motions are almost always recorded in two orthogonal directions, represented by the x and y axes in Figure 1. A linear elastic single-degree-of-freedom (SDOF) system with a given damping ratio (assumed to be 5% in this work) and a given period of vibration T_n, will respond to the ground motion with displacements relative to the ground of $u_x(t)$ and $u_y(t)$ in the x and y direction, respectively. The response of the SDOF system in any direction defined by an arbitrary rotation angle θ is a linear combination of the responses in the two as-recorded directions:

$$u(t,\theta) = u_x(t)\cos(\theta) + u_y(t)\sin(\theta) \tag{1}$$

The most commonly used measure of ground motion intensity is the peak response of a linear elastic oscillator. In particular, most GMPMs and earthquake-resistant design codes use pseudo-spectral acceleration (Sa) as a measure of ground motion intensity, which can be computed for each θ by taking the maximum absolute amplitude of the response:

$$Sa(\theta) = \omega_n^2 \max_t u(t,\theta) \tag{2}$$

where ω_n is the natural angular frequency of the SDOF system.

Figure 1b presents the responses of an SDOF system with a period of vibration of 1.0 s for a ground motion recorded during the 1989 MW 6.9 Loma Prieta earthquake in the Corralitos station (NGA-West2 record sequence number 753). The peak relative displacement, Sd, for the example ground motion is shown by a circle in Figure 1b for the two recorded components and the longitudinal and transverse directions of a building with θ = 50^{o}, and the numerical values of Sa are shown next to each response. The orientation that maximizes Sa is presented by a red line in Figure 1a and will be at most at 45^{o} from either the longitudinal or the transverse direction of the building.

The two-dimensional relative displacement trace of the SDOF system, when subjected to the example ground motion, is shown in Figure 2a and is multiplied by ω_n^2 to obtain traces of pseudo-acceleration. Figure 2b shows the variation of ground motion intensity Sa as a function of the rotation angle, θ, which is also shown in a polar representation in Figure 2a. The figures also show the median Sa value of all non-redundant orientations (i.e., RotD50) and the intensity in the orientation where the intensity is maximum

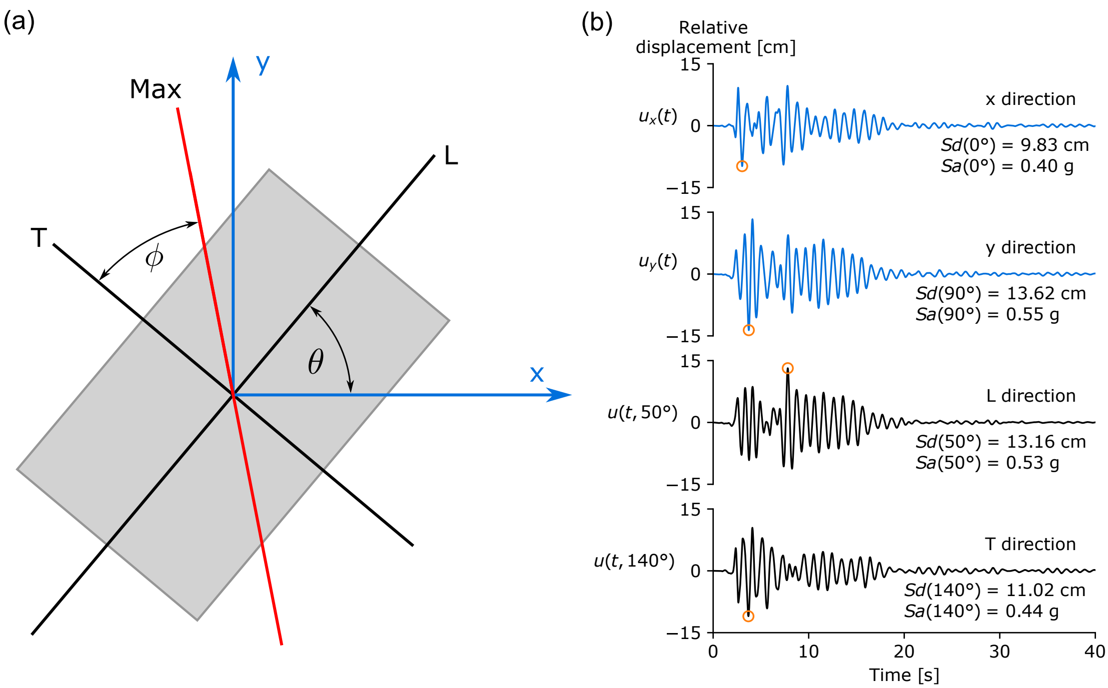

Figure 1. (a) Orientation of a typical building with two orthogonal horizontal principal directions with respect to the two as-recorded directions of ground motion, x and y. (b) Response in terms of relative displacement of an SDOF system with a period of vibration of 1.0 s oriented in four different directions.

(i.e., RotD100). On purpose we have not chosen a highly polarized record as an example, yet, the peak intensity varies from 0.36 g occurring at an angle of rotation of about θ = 155° to a maximum intensity of 0.56 g occurring at an angle of rotation of about θ = 101°, which for this record and period is about 56% higher than the minimum intensity. Since Sa is computed using an absolute value, the peak can be reached for a positive or a negative displacement, which correspond to rotation angles θ and θ+180° (i.e., the opposite direction), respectively. Hence, Sa repeats every 180°. To differentiate between these two cases, Figure 2a presents Sa with a solid line when the maximum occurs in the same direction and with a dashed line when the maximum was reached in the opposite direction.

The times when the maximum displacements are achieved are shown in Figure 2c as a function of the rotation angle and are marked with circles in the displacement trace of Figure 2a. Different colors are used throughout Figure 2 to signal when the maximum displacement occurs at different orbits. It can be seen that the variation of the intensity with changes in the rotation angle is characterized by lobes whose widths coincide with times in which the peak responses occur. In particular, the V-shaped "valleys" coincide with changes in the time in which peak response occurs. Also shown in Figures 2a and 2b are the intensities of the fully polarized case, which leads to a null intensity in a direction orthogonal to the one that produces the maximum intensity.

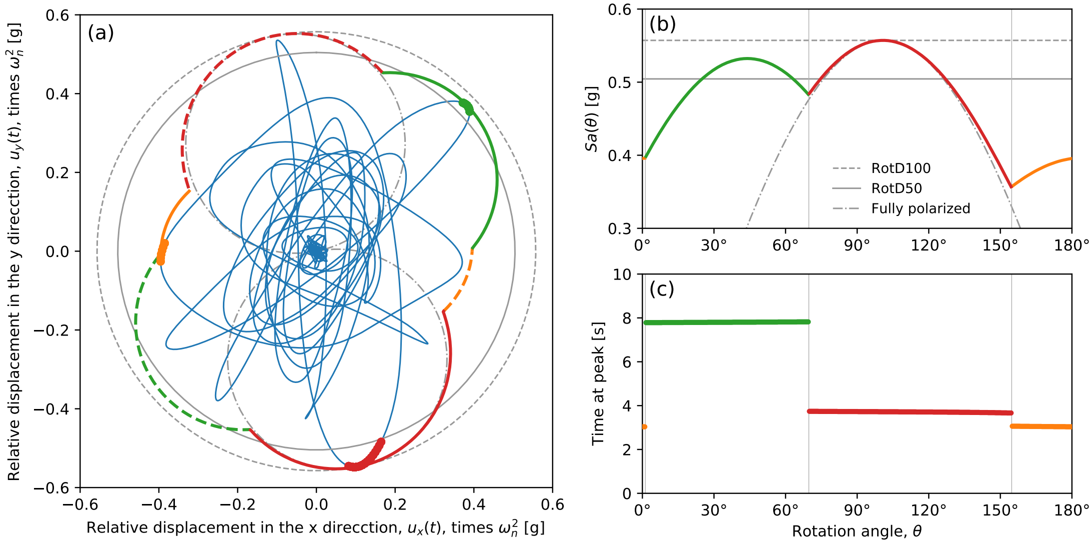

Figure 2. Response of an SDOF system with a period of vibration of 1.0 s to an example ground motion: (a) relative displacement trace; (b) Sa as a function of the rotation angle; and (c) time when the absolute relative displacement is maximum as a function of the rotation angle.

Most buildings have two orthogonal horizontal principal directions, which are denoted as longitudinal (L) and transverse (T) in Figure 1. The Sa that occurs in each of these directions is presented in Figure 3 as a function of rotation angle θ, which represents the orientation of the principal directions of the building with respect to the horizontal components of the ground motion record. Shaded areas correspond to the range of rotation angles where RotD50 is exceeded, which, by definition, corresponds to half of the rotation angles. In other words, if all rotation angles are equally likely, the probability that RotD50 will be exceeded in the longitudinal direction is 50% and the probability that the RotD50 intensity will be exceeded in the transverse direction (or any other specific direction) is also 50%. However, of particular interest to structural engineers is not the probability of exceedance in the longitudinal or transverse direction, but the probability that it will be exceeded either in the longitudinal direction *OR* in the transverse direction. To analyze this more important case in earthquake-resistant design, the figure also presents the maximum Sa from two orthogonal directions at each rotation angle, which is the peak intensity that would control the response of the building in the principal directions and is computed as:

$$Sa_{\max}(\theta) = \max\{Sa(\theta), Sa(\theta + 90^\circ)\} \tag{3}$$

The shaded areas now indicate rotation angles that lead to the RotD50 intensity being exceeded either in the longitudinal or transverse direction. The percentage of angles where $Sa_{\max}$ exceeds RotD50 is now 87% for the example ground motion, which is significantly higher than the single direction case. In other words, for this record and period of vibration, the probability that the RotD50 intensity will be exceeded in either the longitudinal or transverse direction is 87%, much higher than the probability of exceeding it

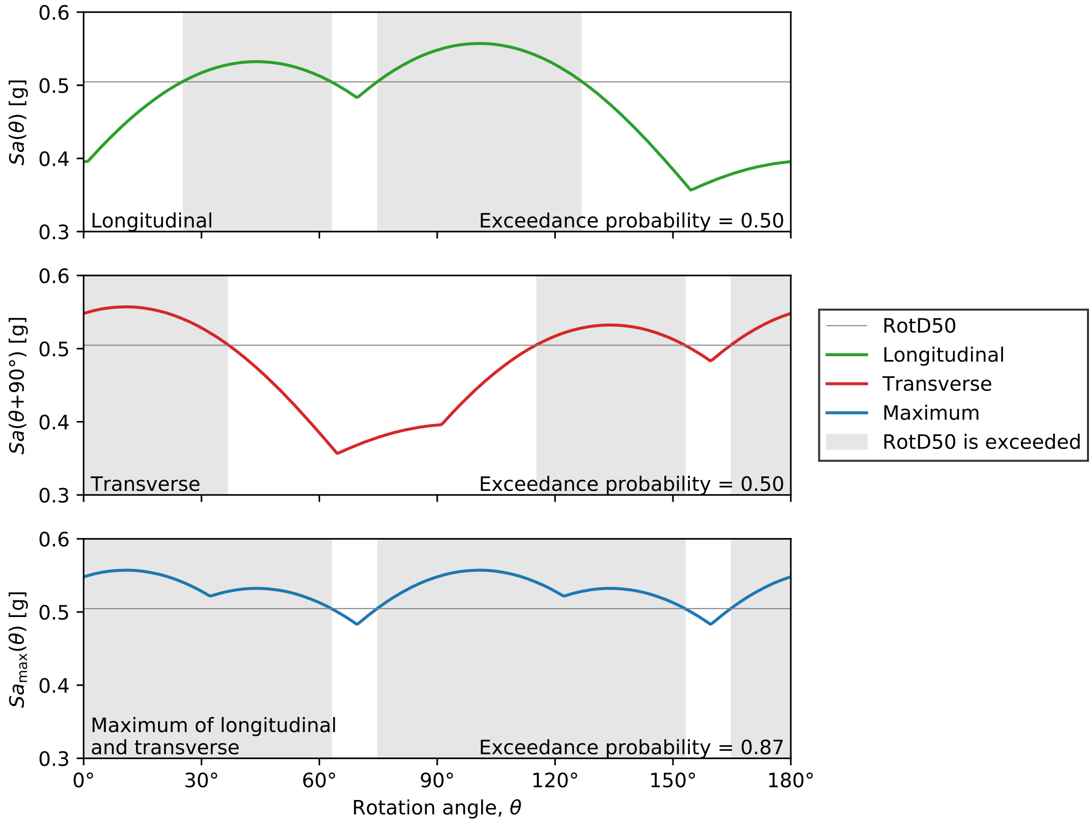

Figure 3. Sa at a structural period of 1.0 s for two orthogonal horizontal directions, longitudinal and transverse, as a function of the rotation angle, and maximum Sa of both directions. Shaded areas represent rotation angles where RotD50 is exceeded.

in the longitudinal or of exceeding it in the transverse direction. It is easy to see that this percentage must always be higher than 50%.

Since Sa repeats every 180º of the rotation angle, and both principal directions of the building (L and T) are separated by 90º (because they are orthogonal), the maximum Sa between the intensity occurring in the longitudinal direction and the intensity occurring in the transverse direction repeats every 90º, which is clearly seen in Figure 3. Thus, computing the maximum for rotation angles in a range of 90º is enough to account for all non-redundant directions. Figure 4 presents the same computations for four additional example ground motions obtained from the NGA-West2 database (Ancheta et al. 2014): (a) the 1999 MW 7.7 Chi-Chi earthquake recorded by the CHY002 station, (b) the 1989 MW 6.9 Loma Prieta earthquake recorded by the Salinas station, (c) the 1994 MW 6.7 Northridge earthquake recorded by the Canoga Park station, and (d) the 1979 MW 6.5 Imperial Valley earthquake recorder by the El Centro

Array #13 station. The record sequence numbers of these ground motions in the NGA-West2 database are 1180, 800, 959, and 176, respectively. The percentage of rotation angles where RotD50 is exceeded is again significantly higher than 50% for all four ground motions. For the more polarized 1994 Northridge and 1979 Imperial Valley example ground motions, the probability of exceeding the RotD50 intensity in the longitudinal or in the transverse direction of a building is 100%, that is, the RotD50 intensity would be exceeded regardless of the orientation of the building. Another way to see it is that for these two ground motions the probability of exceeding the RotD50 intensity in either the L or T directions is twice as large as the probability of exceeding it in the L direction or the probability of exceeding it in the T direction. For the other two example records, despite not being particularly polarized, the probability of exceeding the RotD50 intensity in either the L or T direction is 86% and 95%, which is respectively 72% and 90% higher than the probability of exceeding it in the L direction or the probability of exceeding it in the T direction.

In order to obtain results that are more statistically significant, the computations were repeated for a set of 5065 pairs of horizontal ground motions from the NGA-West2 database (Ancheta et al. 2014) that reasonably reflect free-field conditions following the procedure used by Boore et al. (2014), have moment magnitudes greater than 5, and where recorded in stations with NEHRP site class B, C, or D. The histograms of the percentage of rotation angles where the RotD50 intensity is exceeded are presented in Figure 5 for structural periods of 0.2 and 1.0 s, which at present time are used in the United States to define design spectra (ASCE, 2016). For most ground motions, RotD50 is exceeded for all rotation angles. For the 0.2 s oscillators, in 55% of the records, the RotD50 intensity is exceeded in either the L or T directions for any angle of rotation. That is, for these records there is certainty that the RotD50 level of intensity will be exceeded regardless of the orientation of the structure with respect to the ground motion. For the oscillators with a period of vibration of 1.0 s, the percentage of records for which this occurs is even higher at 68%. Moreover, for this set of records, the mean percentage of rotation angles where RotD50 is exceeded in either the L or T direction of the structure is 92.9% and 94.9% for periods of 0.2 s and 1.0 s, respectively, which is significantly higher than the percentage of angles where RotD50 is exceeded in the L direction or the percentage in the T direction (i.e., 50%). If the orientation of the structure is assumed to be uniformly distributed between $\theta = 0^{\mathrm{o}}$ and 360^{o}, the percentage of rotation angles can be interpreted as the probability that the RotD50 intensity will be exceeded in either the L or T direction (Hong and Goda 2007).

The same distribution of Figure 5 was also computed for the 21 positive periods of the multi-period design response spectrum from the latest NEHRP Recommended Seismic Provisions for New Buildings and Other Structures (BSSC, 2020). Figure 6 presents some properties of these distributions as a function of period, which again shows that the percentage of rotation angles where RotD50 is exceeded in either the L or T direction is significantly higher than 50%. Indeed, the mean percentage of these rotation angles ranges from approximately 91% for short periods to 98% for 10 s. Moreover, Figure 6b shows that a significant percentage of the records exceed RotD50 in either the L or T direction regardless of the orientation of the structure with respect to the ground motion, with this percentage raging from approximately 45% for short periods to 85% for 10 s. Furthermore, as shown in Figure 6a, in approximately 99% of the records the percentage of rotation angles where RotD50 is exceeded is more than 60%.

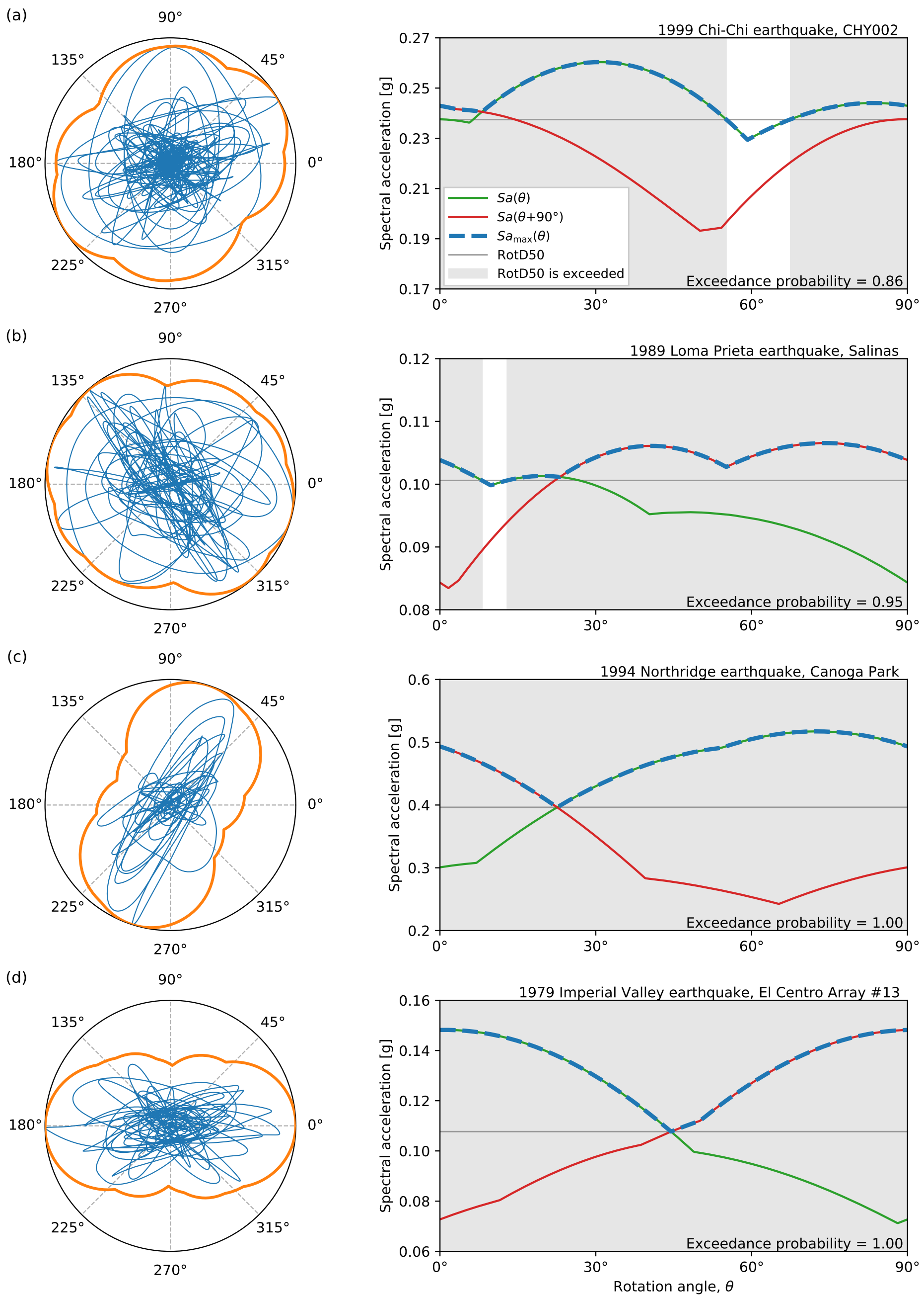

Figure 4. Sa at period 1.0 s as a function of the rotation angle of four example ground motions. The left panels present the relative displacement trace of the oscillator and the right panels present the maximum Sa of two orthogonal orientations as a function of the rotation angle.

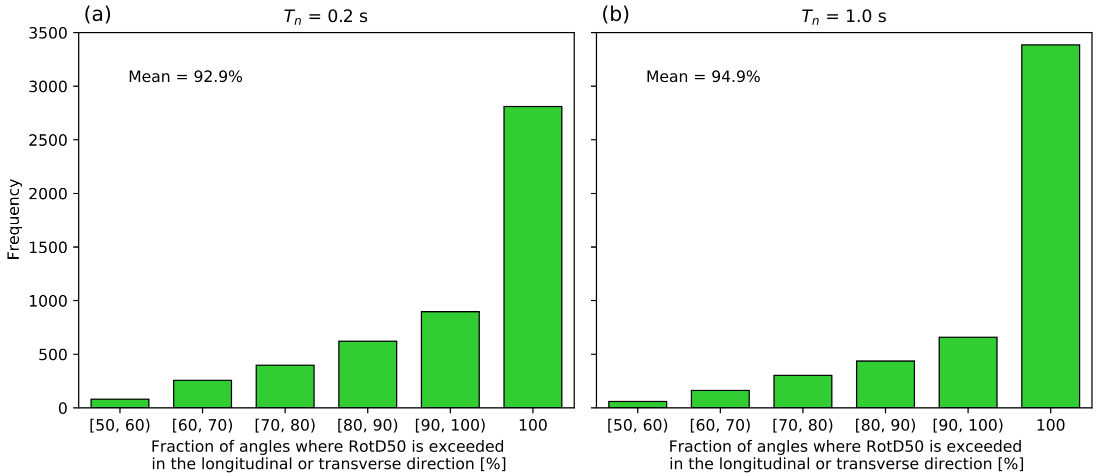

Figure 5. Distribution of the fraction of rotation angles where RotD50 is exceeded in the longitudinal or transverse directions for all ground motion pairs and structural periods of (a) 0.2 s and (b) 1.0 s.

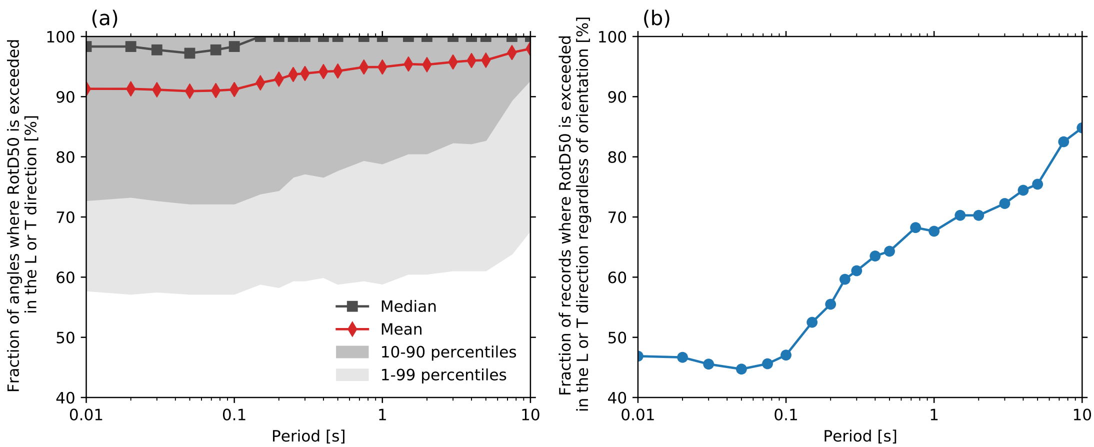

Figure 6. Fraction of rotation angles where RotD50 is exceeded in the longitudinal or transverse direction as a function of structural period: (a) median, mean, 1st percentile, and 10th percentile; and (b) percentage of records where RotD50 is exceeded in the longitudinal or transverse direction for all possible rotation angles.

Maximum of two horizontal components

The authors coincide with Stewart et al. (2011) that it is too conservative to design all buildings using the maximum intensity RotD100, especially given that only a small fraction of structures (probably less than 5%) are axisymmetric and that it would make more sense to apply a multiplier larger than

1 when designing that small fraction of structures. On the other hand, we believe that using RotD50 is not adequate either because, as shown here, the probability that the RotD50 intensity is exceeded in one of the two principal directions of the building is very high (91-98%).

We propose a new measure of seismic intensity that is based on the maximum of two orthogonal horizontal directions of ground motion. The proposed measure of horizontal earthquake ground motion intensity is similar to the one used by Boore et al. (1993) or the one used by Munson and Thurber (1997), who developed GMPMs for the larger intensity of the two as-recorded components. However, they have the inconvenience of being affected by the orientation of the recording instruments. Therefore, we propose a new orientation-independent measure of horizontal ground motion intensity. Following the same naming convention proposed by Boore et al. (2006), the new intensity measure is referred to as MaxRotDpp, where the Max indicates the maximum of the two horizontal components and pp is used to indicate that the intensity is the pp-th percentile for all non-redundant rotation angles and is computed independently for each structural period (i.e., similarly to RotD50, the rotation angle of the pp-th percentile in MaxRotD50 is also period dependent). MaxRotDpp can be computed using the same algorithm proposed by Boore et al. (2006) but changing the geometric mean of two orthogonal components by the maximum. The following steps are a summarized version of the algorithm:

1. Select a structural period and damping ratio. Compute the relative displacement of an SDOF system in two orthogonal horizontal directions (e.g., the as-recorded directions).
2. Compute Sa for all non-redundant rotation angles, i.e. $\theta \in [0^\circ, 180^\circ)$, using Equations (1) and (2). Increments of 1 degree are enough to obtain stable results.
3. Calculate the maximum Sa between two orthogonal directions in a range of 90° using Equation (3).
4. Finally, compute MaxRotDpp as the pp-th percentile of the computed $Sa_{\max}$ values. For example, the median value (i.e., 50th percentile) is denoted by MaxRotD50.

Following the rationale used in the GMPMs developed by the NGA-West2 project (e.g., Boore et al. 2014), which used the median intensity from all non-redundant rotation angles (i.e., RotD50), we propose MaxRotD50 as the basis for earthquake-resistant design for structures with two orthogonal horizontal principal axes, as it represents an intensity having a 50% probability of being exceeded in at least one of the two orthogonal axes for a ground motion experiencing this level of intensity. Under these loading conditions, a first mode dominated structure designed with equivalent force or response spectrum analysis where MaxRotD50 is applied to the principal axes would have a probability of exceeding the design limit state of the building that is close to 50%. Similarly, we propose that the design of axisymmetric structures (e.g., circular chimneys and stacks, isolated circular silos, and hyperboloid cooling towers) be designed for MaxRotD100, which, by definition, is the same as RotD100, whose use in earthquake-resistant design was proposed by Huang et al. (2008) and that since 2010 was adopted in the United States for the design of new buildings (ASCE, 2010). The main difference with the approach of ASCE 7-10 is that RotD100 is proposed to be used for axisymmetric structures and MaxRotD50 for structures with two orthogonal horizontal principal axes, which is the large majority of structures.

The proposed orientation-independent measure of horizontal earthquake ground motion intensity is now compared to intensities commonly used in recent studies (RotD50 and RotD100). The same ground motion set from the previous section was used to compute MaxRotD50, RotD50, and RotD100 at structural periods of 0.2 and 1.0 s, which are used as the basis for constructing design spectra in the

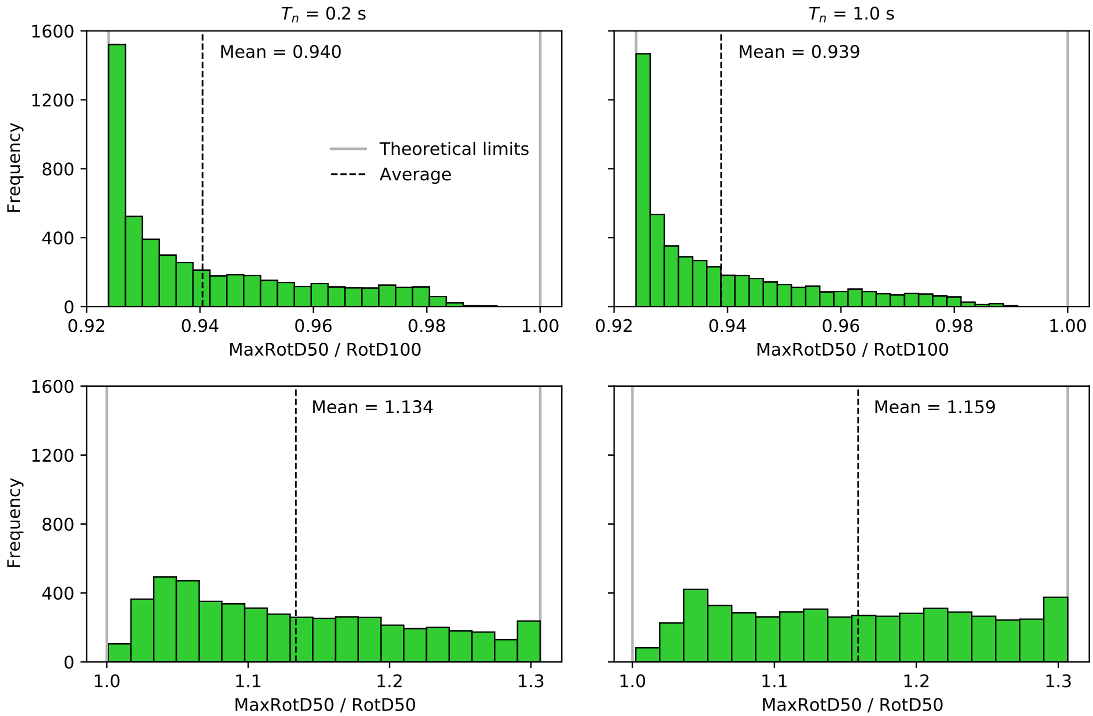

Figure 7. Distribution of MaxRotD50/RotD100 and MaxRotD50/RotD50 ratios from the set of 5065 ground motions for structural periods of 0.2 and 1.0 s.

ASCE 7-16 Standard (ASCE, 2016). Figure 7 presents histograms with the distribution of the ratios between MaxRotD50 and RotD50, and the ratios between MaxRotD50 and RotD100. On average, the new intensity measure is closer to RotD100 than to RotD50, with mean ratios of approximately 0.94 and 1.13-1.16, respectively. In other words, for these structural periods, the proposed orientation-independent measure of intensity is on average 13-16% higher than RotD50 but on average 6% lower than RotD100. Moreover, MaxRotD50 is always smaller than RotD100 and always greater than RotD50, which can easily be deduced from their definitions. Furthermore, the ratios are also bounded by the case of a fully polarized ground motion, which limits MaxRotD50/RotD100 to be always greater than $\cos(22.5°) \approx 0.924$ and MaxRotD50/RotD50 to be always smaller than $\cos(22.5°)/\cos(45°) \approx 1.307$. The influence of earthquake magnitude, source-to-site distance, site class of the recording station, and structural period on the ratios shown in Figure 7 is presented elsewhere (Poulos and Miranda 2021).

Effects on PSHA

This section illustrates the effects and some of the implications of selecting MaxRotD50 instead of RotD50 or RotD100 when performing PSHA using a simple example. All results presented herein use

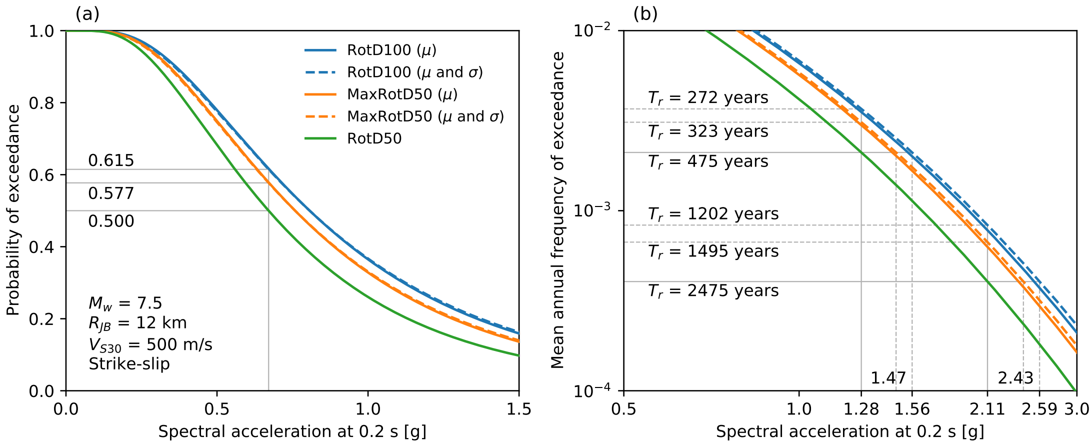

Figure 8. Effects of the choice of intensity measure on: (a) the probability of exceedance for a given earthquake scenario, and (b) the hazard curve of the example site. Solid lines correspond to results where only the logarithmic mean was changed (μ) and dashed lines consider changes in the logarithmic mean and standard deviation (μ and σ).

the GMPM proposed by Boore et al. (2014), which was developed for RotD50, for a site with an average shear wave velocity in the top 30 m of soil (Vs30) of 500 m/s. The logarithmic mean and standard deviation of the GMPM were converted from RotD50 to MaxRotD50 and RotD100 with Equations (1) and (2) of Watson-Lamprey and Boore (2007) using the statistics of the ratio required for the conversion obtained from the same database used in the previous section (Figure 7).

Figure 8a shows the probability distribution of Sa at a structural period of 0.2 s for a strike-slip earthquake scenario with MW 7.5 at a Joyner-Boore distance of 12 km. The probability distributions are presented considering only changes in the logarithmic mean and changes in both the logarithmic mean and standard deviation. As shown in the figure, changing the logarithmic mean impacts the resulting distribution significantly, whereas the impact of updating the logarithmic standard deviation is negligible. According to the GMPM, the median RotD50 for this scenario is 0.67 g, which by definition has a probability of exceedance of 0.5 in any direction. The probability of exceedance for the same acceleration value is 0.577 for MaxRotD50 and 0.615 for RotD100, which correspond to increases of approximately 15% and 23%, respectively.

The effect of using MaxRotD50 was also measured in terms of its impact on seismic hazard curves computed using PSHA. A very simple case consisting of a single linear segment strike-slip fault of length 50 km was considered. The site was assumed to be located at the midlength of the line segment at a distance of 5 km from the fault. The fault generates earthquakes of magnitudes ranging from 4.0 to 7.0 and has a Gutenberg-Richter magnitude frequency distribution with parameters a = 4 and b = 1. Rupture planes were assumed to be vertical and their lengths were computed using the relation developed empirically by Wells and Coppersmith (1994), which depends on earthquake magnitude. The resulting hazard curves for Sa for a period of vibration of 0.2 s are shown in Figure 8b. Similarly to the results of the probability of exceedance curves shown in Figure 8a, the changes in logarithmic mean are much more important than the changes produced by changes in the logarithmic standard deviation. However, the changes in the hazard curves when considering the logarithmic standard deviation are not negligible. A possible explanation for this increased importance is that high return periods require computing probabilities of exceedance for extreme values of Sa, where, as seen in Figure 8a, the distributions with and without the changes in logarithmic standard deviation start to differ.

Figure 8b also highlights the Sa values corresponding to return periods of 475 and 2475 years (i.e., 10% and 2% probability of exceedance in 50 years), which are commonly used for structural design, and correspond to RotD50 values of 1.28 and 2.11 g, respectively. If these same intensity values are interpreted as MaxRotD50, their associated return periods are 323 and 1495 years, which correspond to reductions of approximately 32% and 40%, respectively. This means that, for this example, an intensity with a 2% probability of exceedance in 50 years in the longitudinal direction of a building corresponds to a probability of 3.3% in 50 years in either the longitudinal or transverse direction, a 65% increase in probability. Moreover, the Sa values with a return period of 475 years increase to 1.47 and 1.56 g for MaxRotD50 and RotD100, respectively, values that are 14.8% and 21.9% higher than those of RotD50. If the return period is fixed at 2475 years (i.e., 2% probability of exceedance in 50 years), as used to define the probabilistic maximum considered earthquake (MCE) in previous versions of U.S. codes, these same values are now 2.43 and 2.59 g, respectively. Thus, for this example, MaxRotD50 is 6.2% lower than RotD100 for the MCE intensity. The procedure developed by Luco et al. (2007) was then used to compute the risk-targeted maximum considered earthquake (MCE_R) that is used in ASCE 7-16, resulting in a very similar reduction of 5.7% from 2.79 g for RotD100 to 2.63 g for MaxRotD50. Both reductions are very similar to the mean MaxRotD50/RotD100 ratio of the recorded ground motions shown in Figure 7.

Direct implications for current practice

Currently, design ground motion intensities in the United States are based on RotD100 (ASCE, 2016). Changing to MaxRotD50 would lead to ground motion intensities that are, on average, approximately 6% lower than those corresponding to RotD100, as shown by the distributions of the MaxRotD50/RotD100 ratio in Figure 7. MaxRotD50 design maps could then be constructed by amplifying the USGS seismic hazard maps for RotD50 by the mean MaxRotD50/RotD50 ratios presented in Table 1 (also shown in Figure 7). Table 1 also presents the maximum-response scale factors of ASCE 7-16 to adjust from average horizontal response to RotD100, which are 1.1 for 0.2 s and 1.3 for 1.0 s. This implies that, for a period of 0.2 s, the resulting MaxRotD50 intensity would be approximately 3.1% higher than the current RotD100 value, which, by definition, is impossible. This inconsistency occurs because the adjustment factor that was adopted in ASCE 7-16 for short periods is significantly lower than the average factors from recorded ground motions, as shown, for example, by Shahi and Baker (2014). Based on this same study, FEMA P-2082 modified/improved the maximum-response scale factors to adjust to RotD100, which are now 1.2 for 0.2 s and 1.25 for 1.0 s (BSSC, 2020). These new adjustment factors imply that MaxRotD50 would be approximately 5.5% and 7.3% lower than RotD100 for periods of 0.2 s and 1.0 s, respectively, which are close to the 6% reductions estimated directly using the set of ground motion of this study.

Table 1. Maximum-response scale factor used for design maps.

Period [s]	MaxRotD50	RotD100	
	This study	ASCE 7-16	FEMA P-2082
0.2	1.134	1.100	1.200
1.0	1.159	1.300	1.250

Summary and conclusions

At present time, design ground motions in the United States are based on the maximum horizontal component. Although this is arguably the best choice for designing the small percentage of structures that are axisymmetric, it is overly conservative for the vast majority of the structures because it is unlikely that the maximum direction will occur in one of the principal axes of a structure. A better choice would be to design using another less conservative measure of horizontal ground motion intensity and applying an amplification factor for the small percentage of structures that are axisymmetric. Some seismologists, geotechnical engineers, and structural engineers have argued that a better choice is to use design ground motions based on median measures of horizontal ground motion intensity such as GMRotI50 or RotD50, which have been used in recent versions of seismic hazard maps in the United States (e.g., Petersen et al. 2020). However, structures will not be subjected to a median intensity across a range of 180^{o}.

A particular concern to structural engineers is the horizontal ground motion intensity acting on the principal axes of the structure, which are usually orthogonal with respect to each other. Even though it is indeed unlikely that the direction of maximum intensity will be aligned with one of the principal axes of the structure, the orientation of the maximum direction will be at most at 45^{o} from one of the principal axes of the structure and, therefore, the ground motion intensity in one of the two principal axes of the structure will not be much lower than the maximum intensity. Hence, the intensity of the ground motion in one of the two principal axes of the structure is very likely to be significantly larger than the RotD50, suggesting that this latter measure of ground motion intensity in the horizontal direction is not adequate either.

Using a database of 5065 horizontal ground motion pairs, this study shows that the probability that the RotD50 intensity measure will be exceeded in either the longitudinal or transverse direction of a structure, given that the site is subjected to a median intensity equal to the RotD50 intensity, ranged from approximately 91% for short periods to 98% for 10 s. Furthermore, in a high percentage of ground motions (e.g., 55% for 0.2 s and 68% for 1.0 s), the intensity in one of the two orthogonal axes exceeds the RotD50 intensity regardless of orientation of the structure with respect to the ground motion.

A new measure of horizontal ground motion intensity is hence proposed that is more directly relevant to earthquake-resistant design, where a primary concern is the probability that the design intensity will be exceeded in at least one of the two principal axes of the structures. Similar to other recently proposed measures of horizontal intensity, the proposed measure of horizontal ground motion intensity is also independent of the orientation of the sensors in the recording station. The new measure of horizontal intensity, referred to as MaxRotDpp, is defined as the pp-th percentile of the maximum spectral ordinate of two orthogonal directions computed for all possible non-redundant orientations. The median value of the proposed measure, MaxRotD50, is always between the median and the maximum spectral acceleration ordinates obtained from all rotation angles, i.e. RotD50 and RotD100, respectively.

However, MaxRotD50 is usually closer to the maximum than to the median intensity, being on average approximately 13% and 16% higher than RotD50 for structural periods of 0.2 s and 1.0 s, respectively. On the other hand, MaxRotD50 is on average 6% lower than RotD100 for periods of vibration of 0.2 and 1.0 s. Given that design intensities in the United States are currently based on RotD100 (ASCE, 2016), using MaxRotD50 would therefore cause reductions in the cost of new construction and retrofits of existing structures.

The implications of using MaxRotD50 in probabilistic seismic hazard analysis instead of the commonly used RotD50 intensity are presented using a simple example. The results show that the intensities associated with commonly used return periods of 475 and 2475 years (i.e., 10% and 2% probability of exceedance in 50 years) have significantly lower return periods when considering MaxRotD50, with 323 and 1495 years, respectively. In other words, for this example, the probability of exceeding RotD50 ground motions intensities in at least one of the principal axes of the structure are 14.4% in 50 years (44% higher than the 10% in 50 years implicit in a seismic hazard map based on RotD50) and 3.3% in 50 years (65% higher than the 2% in 50 years implicit in a seismic hazard map based on RotD50), respectively. Using seismic hazard maps based on MaxRotD50 instead of based on RotD50 would lead to probabilities of exceeding the design intensity that are consistent with the probability of exceeding them in at least one of the two principal directions of structures, therefore, providing levels of intensity that are consistent with one of the primary concerns of structural engineers.

Although the results presented here are for 5%-damped pseudo-spectral acceleration ordinates, the proposed orientation-independent measure can also be applied to other ground motion intensity measures, such as peak ground acceleration, peak ground velocity, significant duration, or recently proposed intensity measures such as Sa_{avg} (Eads et al. 2015) or $FIV3$ (Dávalos and Miranda 2019).

Future work could develop GMPMs for MaxRotD50, which would be required to carry out seismic hazard analyses. Alternatively, computing the ratios between the proposed measure and other commonly used intensity measures for a larger number of ground motion records and structural periods would enable the use of previously developed GMPMs with minor adjustments, as done for the example PSHA presented in this study.

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References

American Society of Civil Engineers (ASCE) (2010) *Minimum design loads for buildings and other structures*. ASCE 7-10. Reston, VA: American Society of Civil Engineers.

American Society of Civil Engineers (ASCE) (2016) *Minimum design loads and associated criteria for buildings and other structures*. ASCE 7-16. Reston, VA: American Society of Civil Engineers.

Ancheta TD, Darragh RB, Stewart JP, Seyhan E, Silva WJ, Chiou BSJ, Wooddell KE, Graves RW, Kottke AR, Boore DM, Kishida T and Donahue JL (2014) NGA-West2 database. *Earthquake Spectra* 30(3): 989–1005.

Boore DM (2010) Orientation-independent, nongeometric-mean measures of seismic intensity from two horizontal components of motion. *Bulletin of the Seismological Society of America* 100(4): 1830–1835.

Boore DM, Joyner WB and Fumal TE (1993) *Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report*. Open-File Report 93-509. Menlo Park, CA: United States Geological Survey.

Boore DM, Joyner WB and Fumal TE (1997) Equations for estimating horizontal response spectra and peak acceleration from western north american earthquakes: A summary of recent work. *Seismological Research Letters* 68(1): 128–153.

Boore DM, Stewart JP, Seyhan E and Atkinson GM (2014) NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes. *Earthquake Spectra* 30(3): 1057–1085.

Boore DM, Watson-Lamprey J and Abrahamson NA (2006) Orientation-independent measures of ground motion. *Bulletin of the Seismological Society of America* 96(4A): 1502–1511.

Bozorgnia Y, Abrahamson NA, Atik LA, Ancheta TD, Atkinson GM, Baker JW, Baltay A, Boore DM, Campbell KW, Chiou BSJ et al. (2014) NGA-West2 research project. *Earthquake Spectra* 30(3): 973–987.

Building Seismic Safety Council (BSSC) (2009) *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*. FEMA P-750. Washington, D.C.: Federal Emergency Management Agency.

Building Seismic Safety Council (BSSC) (2015) *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, Volume I: Part 1 Provisions, Part 2 Commentary*. FEMA P-1050-1. Washington, D.C.: Federal Emergency Management Agency.

Building Seismic Safety Council (BSSC) (2020) *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures, Volume I: Part 1 Provisions, Part 2 Commentary*. FEMA P-2082-1. Washington, D.C.: Federal Emergency Management Agency.

Dávalos H and Miranda E (2019) Filtered incremental velocity: A novel approach in intensity measures for seismic collapse estimation. *Earthquake Engineering & Structural Dynamics* 48(12): 1384–1405.

Eads L, Miranda E and Lignos DG (2015) Average spectral acceleration as an intensity measure for collapse risk assessment. *Earthquake Engineering & Structural Dynamics* 44(12): 2057–2073.

Hong HP and Goda K (2007) Orientation-dependent ground-motion measure for seismic-hazard assessment. *Bulletin of the seismological Society of America* 97(5): 1525–1538.

Huang YN, Whittaker AS and Luco N (2008) Maximum spectral demands in the near-fault region. *Earthquake Spectra* 24(1): 319–341.

Huang YN, Whittaker AS and Luco N (2011) *Establishing maximum spectral demand for performance-based earthquake engineering: collaborative research with the University at Buffalo and the USGS*. Technical Report: USGS Award Number 08HQGR0017. Reston, VA.

International Code Council (ICC) (2011) *2012 International Building Code*. Country Club Hills, IL: International Code Council.

International Code Council (ICC) (2014) *2015 International Building Code*. Country Club Hills, IL: International Code Council.

International Code Council (ICC) (2017) *2018 International Building Code*. Country Club Hills, IL: International Code Council.

Luco N, Ellingwood BR, Hamburger RO, Hooper JD, Kimball JK and Kircher CA (2007) Risk-targeted versus current seismic design maps for the conterminous United States. In: *SEAOC 2007 convention proceedings*. Squaw Creek, CA.

Munson CG and Thurber CH (1997) Analysis of the attenuation of strong ground motion on the island of Hawaii. *Bulletin of the Seismological Society of America* 87(4): 945–960.

Nievas CI and Sullivan TJ (2017) Accounting for directionality as a function of structural typology in performance-based earthquake engineering design. *Earthquake Engineering & Structural Dynamics* 46(5): 791–809.

Petersen MD, Shumway AM, Powers PM, Mueller CS, Moschetti MP, Frankel AD, Rezaeian S, McNamara DE, Luco N, Boyd OS et al. (2020) The 2018 update of the US national seismic hazard model: Overview of model and implications. *Earthquake Spectra* 36(1): 5–41.

Poulos A and Miranda E (2021) Relations between MaxRotD50 and some horizontal components of ground-motion intensity used in practice. *Bulletin of the Seismological Society of America* 111(4): 2167–2176.

Power M, Chiou B, Abrahamson N, Bozorgnia Y, Shantz T and Roblee C (2008) An overview of the NGA project. *Earthquake spectra* 24(1): 3–21.

Sabetta F and Pugliese A (1987) Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records. *Bulletin of the Seismological Society of America* 77(5): 1491–1513.

Shahi SK and Baker JW (2014) NGA-West2 models for ground motion directionality. *Earthquake Spectra* 30(3): 1285–1300.

Stewart JP, Abrahamson NA, Atkinson GM, Baker JW, Boore DM, Bozorgnia Y, Campbell KW, Comartin CD, Idriss I, Lew M et al. (2011) Representation of bidirectional ground motions for design spectra in building codes. *Earthquake Spectra* 27(3): 927–937.

Watson-Lamprey JA and Boore DM (2007) Beyond Sa_{GMRotI}: Conversion to Sa_{Arb}, Sa_{SN}, and Sa_{MaxRot}. *Bulletin of the seismological Society of America* 97(5): 1511–1524.

Wells DL and Coppersmith KJ (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the seismological Society of America* 84(4): 974–1002.

Worden CB, Thompson EM, Hearne MG and J WD (2020) Shakemap manual online: Technical manual, user's guide, and software guide. Available at: https://usgs.github.io/shakemap.