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Virtual Fault Ruptures in Area Source Zones for PSHA: Are They Always Needed?

Julian J Bommer & Valentina Montaldo Falero

Julian J Bommer (corresponding author)
Civil & Environmental Engineering
Skempton Building
Imperial College London
South Kensington campus
London SW7 2AZ
U.K.
Email: j.bommer@imperial.ac.uk

Valentina Motaldo-Falero
Wood plc
180 Grand Avenue
Oakland
CA 94612
U.S.A.
Email: valentina.montaldo@woodplc.com

Abstract
Seismic source models for probabilistic seismic hazard analysis (PSHA), except when using zoneless approaches based directly on the earthquake catalog, invariably include area source zones, even if active fault sources are modeled explicitly. Since most modern ground-motion prediction equations (GMPEs) employ source-to-site distance metrics defined relative to extended fault ruptures rather than to the epicenter or hypocenter, it becomes necessary to generate virtual fault ruptures within the area source zones to enable calculation of the correct distance of each earthquake scenario from the site of interest. For a site-specific PSHA, the work of defining the virtual rupture characteristics such as strike, dip and style-of-faulting, for more distant source zones, and the computational effort of simulating these ruptures for each earthquake scenario in the hazard calculations, may be unnecessary. Beyond a certain distance from the site, it can be demonstrated that the loss of accuracy introduced by modeling the individual earthquake scenarios as point sources rather than as extended ruptures is usually sufficiently small to allow the distance metric in the GMPEs to be treated as epicentral or hypocentral distance. Such simplifications can significantly increase the efficiency of the hazard calculations, and also relieve the seismic source modelers of considerable effort to characterize virtual ruptures far beyond the host zone of the site. Treating earthquake scenarios in the more remote source zones as points also brings the additional benefit of avoiding problems that can arise with the largest magnitude scenarios leading to ruptures that approach the site in cases where the ruptures are not constrained to remain within the source boundaries.

INTRODUCTION

In essence, probabilistic seismic hazard analysis (PSHA) involves the integration over (at least) three random variables: earthquake magnitude, m, source-to-site distance, r, and number of standard deviations above the median estimates from the ground-motion prediction equation (GMPE), ε (*e.g.*, Bommer and Crowley, 2017). The distribution of distances is determined by the geometry of the seismic source model, which defines the locations of potential future earthquake scenarios. Ideally, all seismic sources, at least for shallow crustal earthquakes, would be defined on the basis of mapped geological faults, but it is generally impossible to associate unambiguously all observed seismicity with known faults due to hypocentral location uncertainties and the fact that many faults are not mapped. Consequently, seismic source models for PSHA, even when these include explicit fault sources, invariably include area source zones, within which earthquake scenarios are considered at every location. An exception, of course, is when zoneless approaches (*e.g.*, Frankel, 1995; Woo, 1996) are invoked, but otherwise PSHA calculations will always include integration over the contributions from area sources, generally including a source zone within which the site of interest is situated, referred to as the host zone.

The simplest approach to integration over an area source zone is to discretize the source into small elements and represent the earthquake scenarios within each element as a point, *i.e.*, an epicenter or hypocenter. This approach would work perfectly well if the distance metric used in the GMPE were defined relative to a point representation of the earthquake

source, namely epicentral or hypocentral distance. However, most modern GMPEs use measures of source-to-site distance defined relative to the extended fault rupture. Consequently, in PSHA calculations it becomes necessary to either generate virtual fault ruptures associated with each hypothetical earthquake scenario considered in the calculations or else to apply a conversion between rupture-based and point-source distance metrics; see Figs. 1 and 2 in Monelli et al. (2014) for an illustration of the concept of virtual ruptures. Both approaches have been used in practice although the generation of virtual ruptures is the more common approach and could now be considered standard practice. As a result, seismic source modelers invest effort in defining the characteristics of these virtual ruptures in all source zones and hazard calculations must step through the generation of these virtual ruptures for every scenario earthquake considered in the calculations. While this is a positive state-of-affairs in terms of insuring correct hazard calculations, it is also likely that a great deal of effort is being spent unnecessarily when it comes to integrating hazard contributions from source zones. The purpose of this paper is to explain why this is the case and to provide guidance on deciding when virtual ruptures are necessary and when the work involved in their generation can be legitimately avoided.

To set the scene, we begin with a brief discussion of how distance metrics in GMPEs evolved over time and how PSHA practice then developed to ensure consistency between representation of individual earthquakes in seismic source zones and the distance metrics used in GMPEs. The main body of the paper then explores the sensitivity of ground-motion estimates and hazard calculations to the correct modeling of finite ruptures at locations away from the site of interest. On the basis of these analyses, guidelines are offered for when it may be unnecessary to generate virtual fault ruptures. The paper concludes with some discussion of benefits that may be obtained by avoiding the need for virtual ruptures in remote source zones and some implications for GMPE development.

THE EVOLUTION OF DISTANCE METRICS IN GROUND-MOTION PREDICTION EQUATIONS

The two indispensable elements in all GMPEs are a measure of the strength of the radiation of seismic energy from the earthquake source—invariably represented by the magnitude and in modern equations this is almost always moment magnitude—and a measure of the propagation path from the source to the site over which the energy is reduced due to geometric spreading and anelastic attenuation. Joyner and Boore (1981) proposed that the ideal measure of this distance would be defined relative to the location on the source from which the wave dominating the ground-motion parameter to be predicted was radiated. As Douglas (2003) points out, this is difficult to determine for past earthquakes and practically impossible to predict for future events. Douglas (2003) describes 10 different definitions of source-to-site distance that have been proposed for use in ground-motion prediction. The earliest GMPEs all used epicentral distance or hypocentral distance, definitions that treat the earthquake source as a point, which is analogous to how earthquakes are modeled in seismology for location and magnitude calculation. While this approximation is perfectly reasonable for the analysis of recordings obtained at teleseismic distances, it can be very

unrealistic in terms of measuring the distance travelled by the seismic waves for sites close enough to the source to experience strong ground shaking. A good example of when a point-source distance metric is not appropriate is the Tabas station recording of the **M** 7.3 Tabas, Iran, earthquake of 16 September 1978, which had a horizontal PGA (peak ground acceleration) in excess of 1*g*. The recording station was at the opposite end of the fault rupture from the epicenter, with the result that the epicentral distance, R_{epi}, was 57 km, whereas the station was only 11 km from the closest point on the fault rupture (Akkar et al., 2014a).

With the exception of Donovan and Berstein (1978), who used several distance metrics including those measured relative to the fault rupture and also relative to the poorly-defined center of energy release, most GMPEs used epicentral or hypocentral distance, R_{hyp}, until the early 1980s. Campbell (1981) presented a GMPE based on the rupture distance, R_{rup}, and Joyner and Boore (1981) introduced the distance to the closest point on the surface project of the fault rupture. This latter distance, which subsequently became known at the Joyner-Boore distance, R_{jb}, is easier to estimate than R_{rup} since it can be inferred from the distribution of short-term aftershock epicenters without knowledge of the fault plane depth and geometry. Nonetheless, the publication of GMPEs based on R_{epi} or R_{hyp} was common right up to the end of last century, even when applicable to larger magnitudes (Douglas, 2003). However, GMPEs for crustal earthquakes have increasingly moved towards the use of rupture-based distance metrics (*e.g.*, Abrahamson and Shedlock, 1997), the most commonly used nowadays being R_{rup} and R_{jb}. Indeed, it would be hard to justify using R_{epi} or R_{hyp} for a GMPE intended for application to shallow crustal earthquakes of engineering interest, with the possible exception of models for smaller-magnitude induced seismicity.

A few GMPEs have been presented with alternative versions using different distance metrics such as Akkar et al. (2014b), who presented equations in terms of R_{epi}, R_{hyp} and R_{jb}, and Bindi et al.(2014) who derived equations in terms of R_{hyp} and R_{jb}. Figure 1 illustrates the very different results that are obtained using point-source based distance metrics and using distances measured relative to the extended rupture, plotting each GMPE against its own distance metric and treating the two distances as equivalent.

The first and most striking observation is that at short distances, the R_{epi}-based GMPE predicts significantly higher levels of acceleration than the R_{jb}-based model, the difference between the two increasing with the earthquake magnitude. These differences could be viewed as an inconsistency since adjacent to the source the same levels of ground shaking might be expected regardless of how the distance is measured. However, to correctly interpret the observed patterns it is necessary to consider the ground-motion fields being predicted rather than the estimates at a single location. The R_{epi}-based model predicts higher PGA values distributed over circular areas defined by radii around the epicenter, whereas the R_{jb}-based model predicted lower accelerations over larger areas having the form a racetrack defined by semi-circular areas either end of a rectangular area with dimensions equal to the source-to-site distance measure and to the length of the fault rupture (Figure 2). In other words, the second model predicts uniform median motions over a boundary that is longer by 2L, where L is the rupture length, which grows exponentially

with the magnitude (see overview by Stirling et al., 2013). Therefore, in terms of the total energy in the predicted ground-motion field, the two models are consistent; the R_{jb}-based model, however, predicts a more realistic ground-motion field than the R_{epi}-based model.

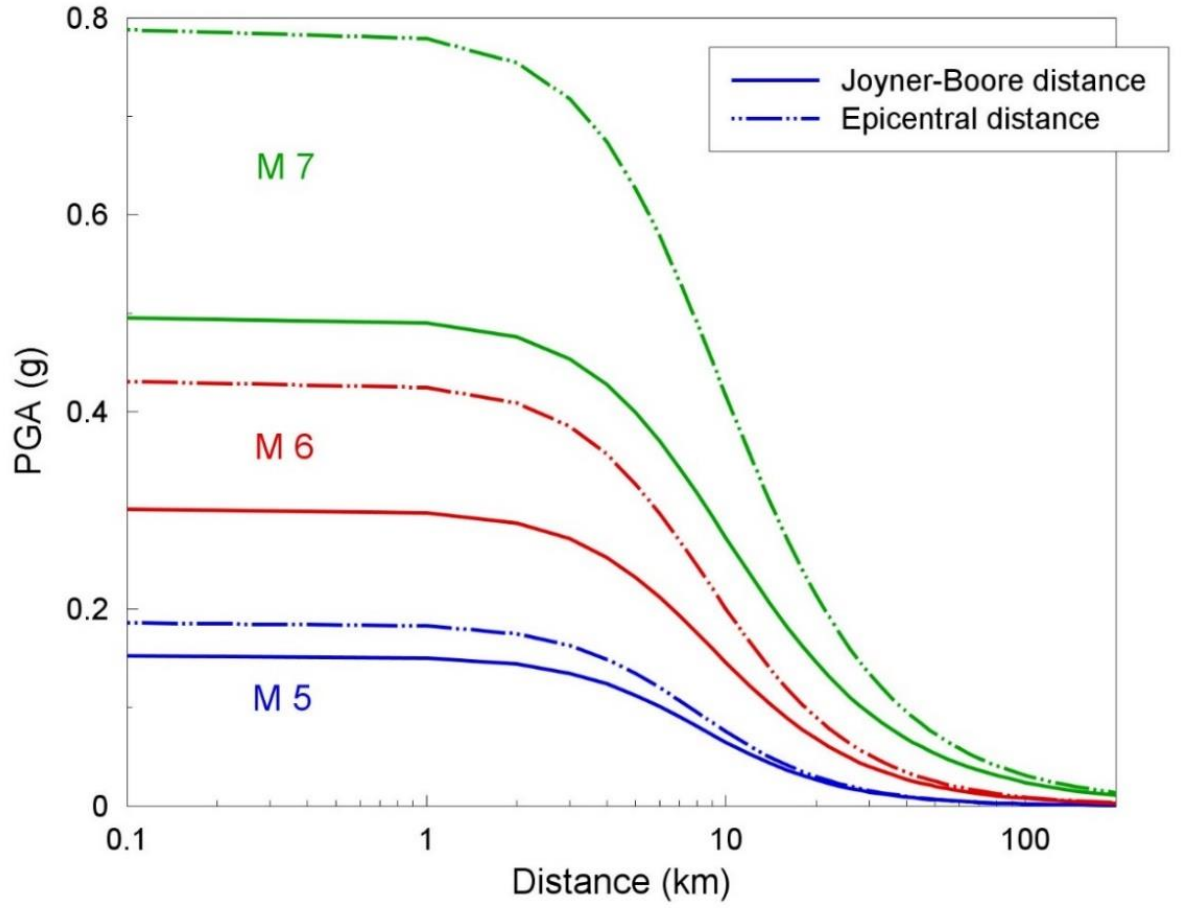

Figure 1. Predicted horizontal PGA on soft rock (V_{S30} 760 m/s) from the GMPEs of Akkar et al. (2014b) based on epicentral and Joyner-Boore distance for three different magnitudes. The x-axis is drawn assuming the two distance metrics to be equivalent

The second important observation to be made from Figure 1 is that the differences between the predictions using different distance metrics decays with distance with the ratios of predicted PGAs tending towards unity at greater distances, which logically increase with the earthquake magnitude. Although the two models may only predict the same value at considerable distances for large magnitudes, from a hazard perspective it is important to note that the differences must be viewed in terms of the relative incremental contributions to the site hazard. This is important because while the ratios of the two predicted PGA values may not reach unity until distances beyond 100 km for larger earthquakes, the incremental contributions to the hazard from such remote scenarios may already be very small and differences of even 20% or so in the predicted median amplitudes may represent an extremely small difference to the calculated hazard.

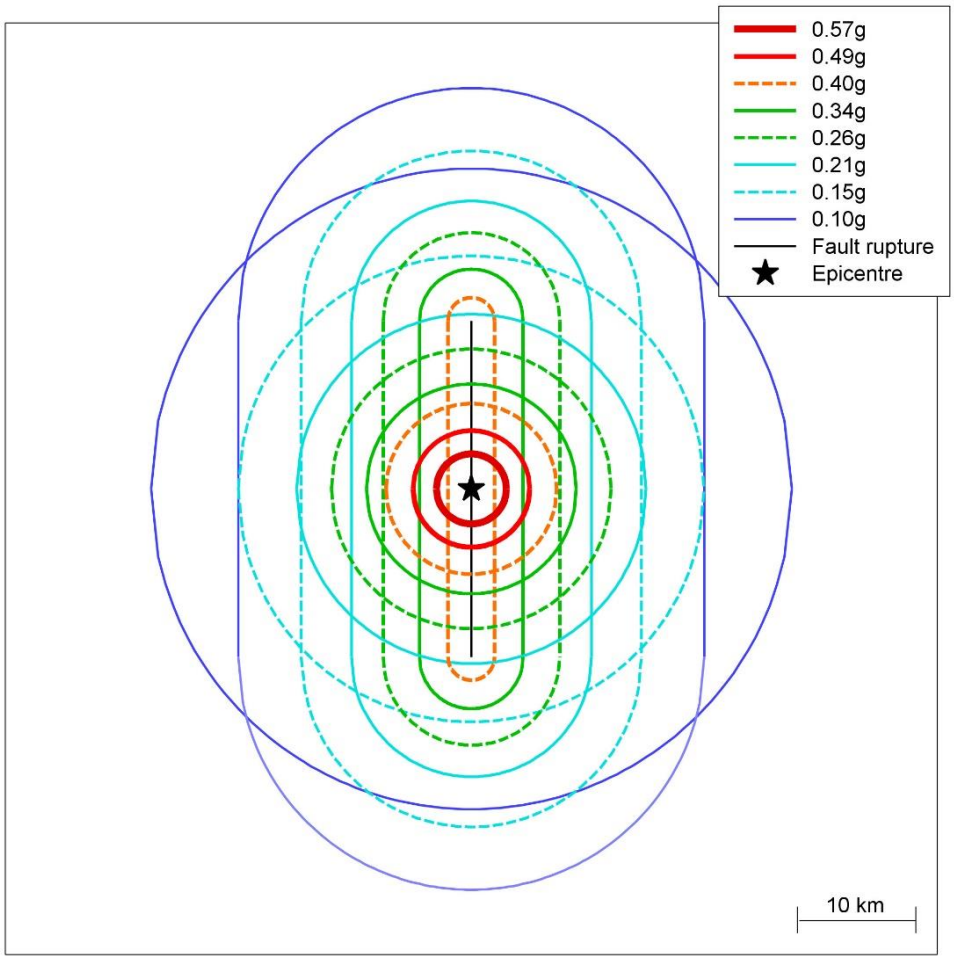

Figure 2. Contours of median PGA for soft rock sites calculated with the Akkar et al. (2014b) GMPEs using R_{epi} and R_{jb} relative to the epicenter (star) and fault rupture (black line) of an earthquake of **M** 6.5 on a vertical strike-slip fault.

The discussion so far has focused only the median predictions, whereas the results of PSHA are equally dependent on the value of the standard deviation of the logarithmic residuals, commonly referred to as sigma (*e.g.,* Strasser et al., 2009). The use of point-source distance metrics will lead to greater variability in the predictions if the data include recordings of larger magnitude earthquakes, as demonstrated by the standard deviations of ln(PGA) in the Akkar et al. (2014b) equations, which are 0.71 when using R_{jb} and 0.73 when using R_{epi}. The difference in such cases may be underestimated if the number of recordings at short distances is a small proportion of the dataset and in practice the additional variability that results from using point-source metrics should vary with both magnitude and distance. Using dense ground-motion field sampled from an R_{jb}-based GMPE and then re-sampled using epicentral distances, Bommer et al. (2016) derived a model for the additional component of within-event variability ($\delta\phi$) as a function of magnitude and distance, as shown in Figure 3. Similar functions were also presented in EPRI (2004) and EPRI (2013) and by Thompson and Worden (2018). Figure 3 shows that the additional variability is strongly dependent on both magnitude and distance, assuming small values at very short distances and then increasing with distance until diminishing beyond a certain distance that increases with earthquake magnitude.

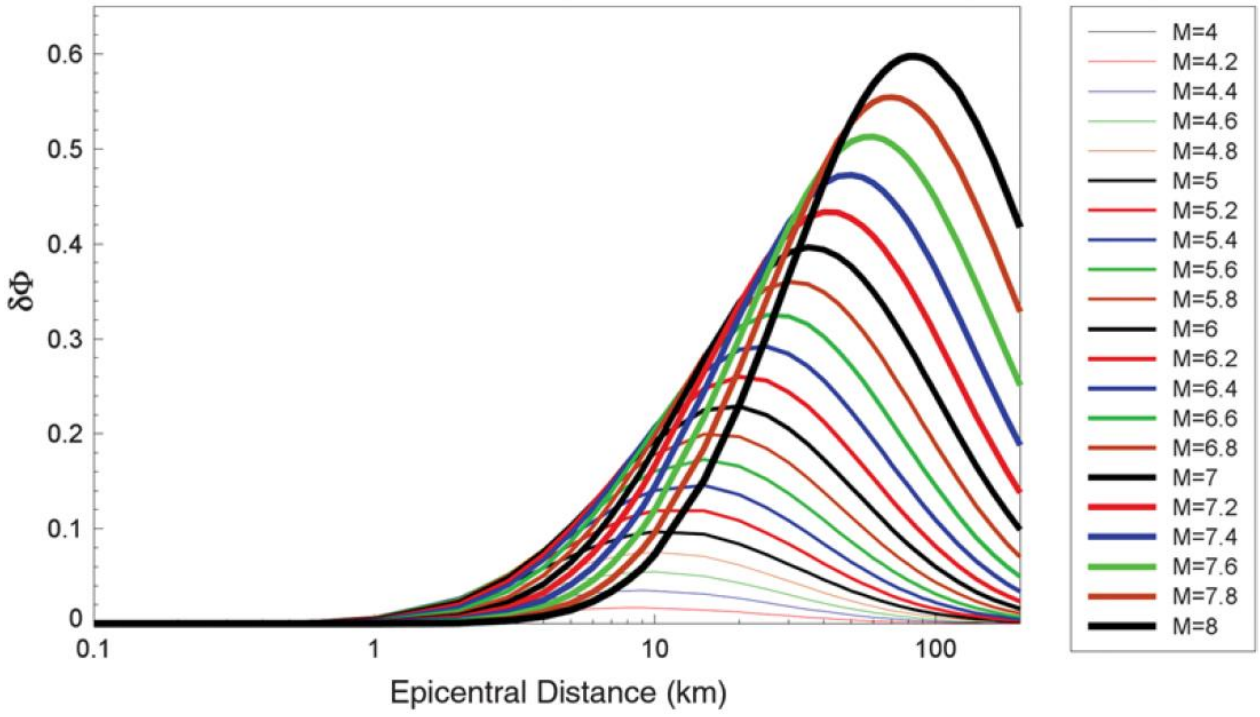

Figure 3. Additional within-event variability ($\delta\phi$) of ground-motion predictions arising from using R_{epi} rather than R_{jb}, as a function of moment magnitude and distance (Bommer et al., 2016).

CONSISTENT DISTANCE DEFINITIONS IN HAZARD CALCULATIONS

As noted above, the simplest approach to integrating the hazard contributions from area source zones is to model small elements of the zone and to treat these as point sources for the earthquakes occurring at that location. Such an approach was used in some of the earlier PSHA codes that were freely distributed and widely used in practice. If such an approach is combined with a GMPE that deploys a distance metric defined relative to extended fault ruptures, the result will be a systematic underestimation of the hazard. This was shown by Bommer and Akkar (2012) and confirmed by Monelli et al. (2014) who demonstrated how the hazard is increased by the explicit modeling of the finite rupture dimensions rather than using point-source representations (Figure 4).

There are several ways to address the need for consistency in PSHA calculations with regards to the modeling of earthquake sources within area source zones and in the derivation of GMPEs. The simplest approach is to always use point-source representations in both: for example, Bindi et al. (2017) adopt R_{hyp} for their GMPE "*since the hazard assessment is based on source area models*." While an expedient solution, it could be argued that it is a poor representation of the physics for earthquakes occurring close to the site and therefore it might be viewed as a sub-optimal choice.

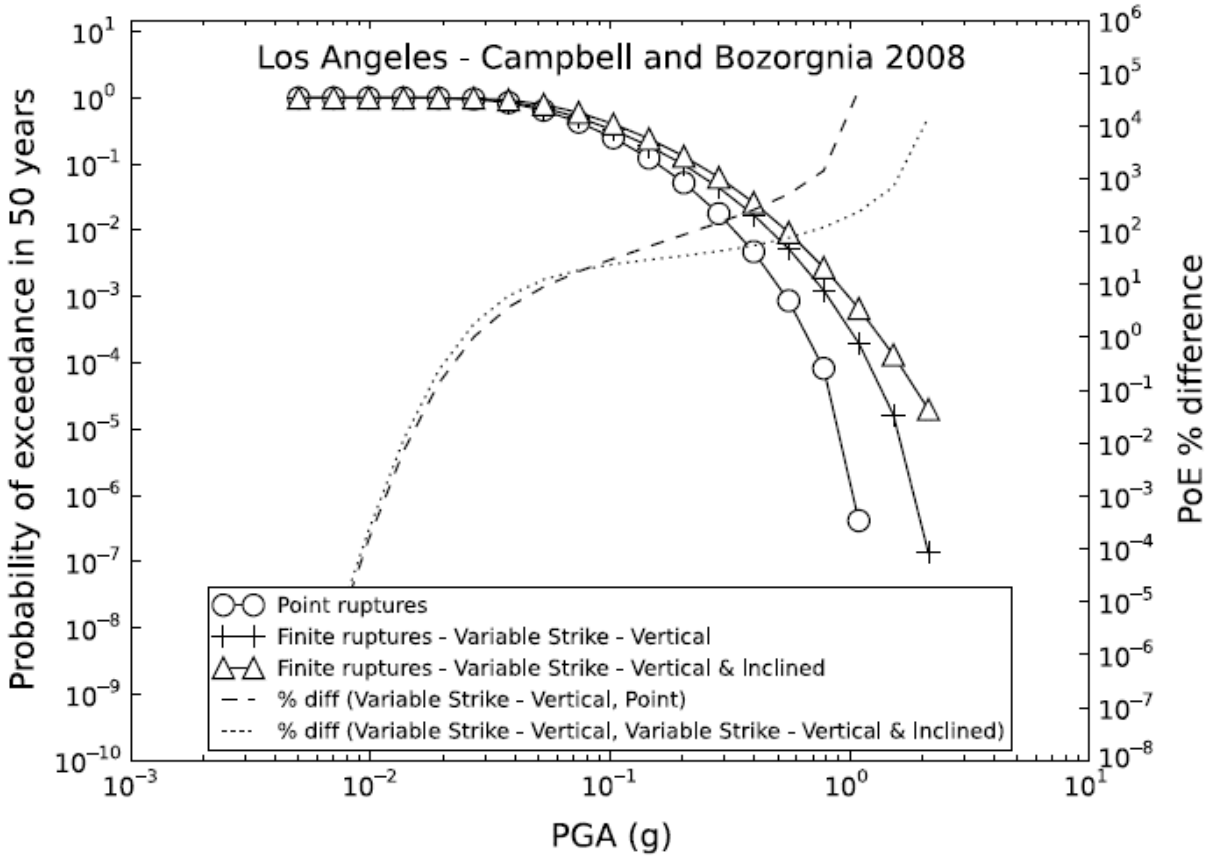

Figure 4. Comparison of PGA hazard curves for a site in Los Angeles obtained using the GMPE of Campbell and Bozorgnia (2008) when using point-source representations within source zones and when using the generation of vertical and dipping (50°) virtual ruptures (Monelli et al., 2014). The right-hand axis refers to the percentage difference in the calculated hazard, as shown by the thin dashed and dotted lines.

To employ GMPEs using R_{jb} or R_{rup} and avoid inconsistent treatment of the distances, it is necessary to calculate the Joyner-Boore or rupture distance to the site of interest for each earthquake scenario considered in the PSHA calculations. This can be done in one or two ways, the first being to apply a conversion to the epicentral or hypocentral distances to transform these to Joyner-Boore or rupture distances. Such conversions have been derived by Scherbaum et al. (2004), EPRI (2004) and EPRI (2013) using simulations of ground-motion fields around extended ruptures. A common feature of the studies is the conclusion that the variability associated with these conversions can be considerable and this additional variability should be propagated into the sigma of the ground-motion model. As indicated in Figure 2, this additional variability is strongly dependent on magnitude and distance, leading to dependence of the final GMPE sigma on these two parameters, which then presents an additional challenge for implementation in PSHA. To develop such conversions that account for all possible configurations in terms of hypocentral location on the fault rupture and to correctly carry through the additional variability into the hazard calculations mean that this approach is not necessarily very straightforward to apply and it might be considered a poor approximation to reality for earthquakes in the host source zone (the one within which the site of interest is located). In this regard, however, the work of Thompson and Worden (2018)

advances the approach by numerically integrating the conversion factors from point-source to rupture-based distance metrics rather than randomizing rupture and site parameters. Moreover, they extended the integration to include variability in dip, style-of-faulting, rupture area, depth to the top of rupture, and the position of the hypocenter within the rupture plane. In this way, Thompson and Worden (2018) produced a suite of generic distance conversions and associated uncertainty factors for application to existing GMPEs, especially in the generation of Shake Maps and in PSHA using gridded seismicity where fault orientations are unknown.

The second approach is to simulate fault ruptures within the area source zones, which may be considered a more rigorous solution. For each earthquake scenario considered in the hazard integrations, a fault rupture is generated with dimensions determined from the earthquake magnitude, requiring the specification of an appropriate scaling relationship. A rigorous approach will include specification of the thickness of the seismogenic crust and account for saturation of this width above a certain magnitude (see Stafford, 2014). The source modelers also need to specify the strike and dip of the fault ruptures, which might be expressed as distributions, and also the depth distribution, which could be focal depth distributions combined with specifications of the proportion of the rupture width above the hypocenter or else a distribution of depths to the top of ruptures. Assumptions regarding the location of epicenter along the length of the fault rupture must also be specified. Differences in how the virtual ruptures are generated from one hazard code to another can lead to differences in the computed hazard (*e.g.*, Bommer et al., 2013). The divergence between the two hazard curves in Figure 3 obtained using virtual ruptures—with fixed and variable fault strike—illustrates how the modeling choices can influence the computed hazard. In this regard, however, it is worth noting that the generation of conversion relationships between distance metrics, as discussed above, requires most of the same modeling choices to be made.

WHEN ARE VIRTUAL RUPTURES NEEDED?

The recognition of the need to avoid internal inconsistencies in PSHA calculations is a positive development, and it is now generally considered unacceptable to perform hazard calculations by simulating earthquake scenarios as points and combining these with GMPEs using distance metrics defined relative to extended ruptures. However, in view of the work that is needed to generate virtual fault ruptures within area source zones to avoid such inconsistency, it is worthwhile asking whether such effort is always required.

For seismic hazard mapping, which is generally undertaken for return periods of 2,500 years or shorter, it is unlikely that large magnitude earthquakes close to the site make dominant contributions to the hazard estimates. If this is the case, then the approach proposed by Bindi et al. (2017) to use R_{hyp}-based GMPEs and simply integrate over the source zones using an appropriate spatial discretization may be a perfectly acceptable way to proceed. If such practices are to be adopted, then it would be beneficial for GMPE developers to generate models in terms of both point-source based and extended-rupture based measures of source-to-site distance, as proposed by Bommer and Akkar (2012). Alternatively, the

calculations could be performed with R_{jb}- or R_{rup}-based GMPEs by applying the adjustment factors of Thompson and Worden (2018).

For site-specific PSHA studies, however, it would be difficult to justify the point-source approximation. While it is an expedient approach, it disregards some fundamental physics of ground-motion generation and consequently finite rupture-related effects cannot be modeled. For example, in a region of dip-slip faulting, hanging wall effects (Donahue and Abrahamson, 2014) could not be accounted for in the hazard calculations unless fault ruptures are explicitly modeled. In theory, the approach of Thomspon and Worden (2018) could be extended to include hanging wall effects, but this has not been done to date. The question that then arises is whether virtual ruptures need to also be generated in source zones whose closest boundary is remote from the site and beyond the range of influence of such finite rupture effects.

Insight to distances beyond which the effect of the dimensions of virtual ruptures becomes unimportant could be obtained using the distance adjustment factors of Thompson and Worden (2018). In the following we illustrate how this question can be addressed for a site-specific PSHA, we perform a simple experiment involving two adjacent seismic source zones with uniformly distributed seismicity (Figure 5). The sources are both 200 km x 200 km squares and the hazard is calculated for sites located within the host zone at distances from the boundary between the two sources that vary from 10 to 180 km. The hazard is calculated using the GMPE of Chiou and Youngs (2014) and assuming a site with V_{S30} = 760 m/s. The *b*-value of the Gutenberg-Richter recurrence relationship is set to 1 in both sources, and the same distribution of maximum magnitudes, M_{max}, is applied in both sources with the following values and associated weights: 7.0 (0.2), 7.2 (0.6) and 7.4 (0.2). We emphasize from the outset that this is an illustration of a general approach rather than any attempt to derive generalized rules for the conditions under which it is an acceptable approximation to model earthquakes as point sources rather than generating virtual ruptures. We also acknowledge that these options are end members, with approaches such as that proposed by Thompson and Worden (2018) being an intermediate option.

The only difference considered in the recurrence models for the two sources is the activity rate, which is kept constant for the host source zone and varied in the neighboring zone such that the ratio of host-to-neighbor activity rates vary from 0.1 to 10. Virtual strike-slip ruptures are generated with areas determined from the magnitude of the earthquake using the empirical relationship of Hanks and Bakun (2008). The ruptures are generated with north-south strike (*i.e*., parallel to the boundary between the source zones) and vertical dip. For each ratio of the activity rates, the hazard is calculated at each of the 18 points (Fig. 5). The calculations are then repeated with virtual ruptures in the host zone but using only dimensionless point sources (hypocenters) in the neighboring zone and treating the hypocentral distances as rupture distances in the GMPE. The acceleration levels are then determined for fixed return periods for the two cases and in Figures 6 and 7 we plot the ratios of the spectral accelerations, SA (for oscillator periods of 0.1 and 1.0 s) obtained with the point-source approximation to those obtained using virtual ruptures as a function of distance from the boundary between the sources and the ratio of activity rates.

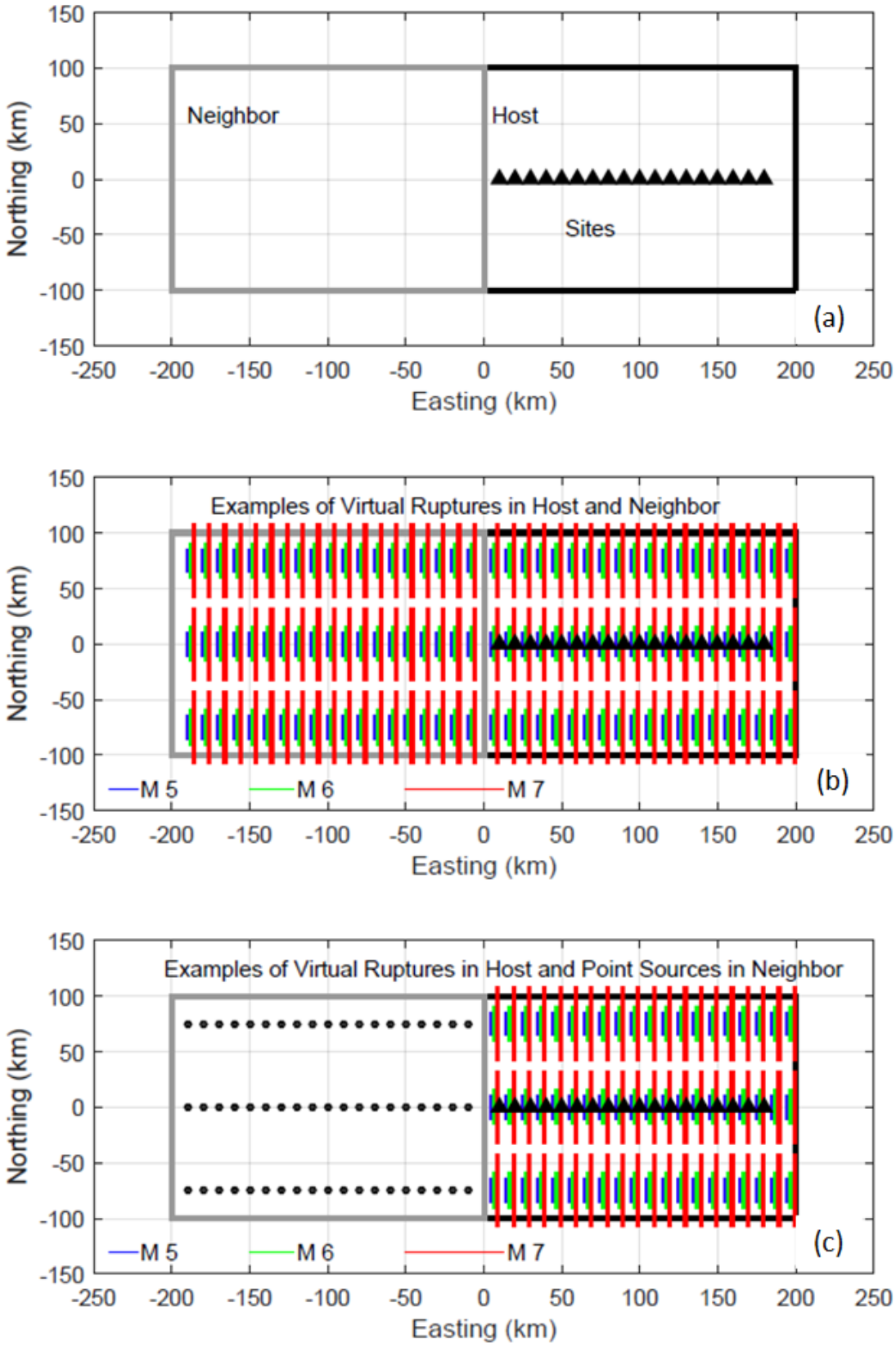

Figure 5. (a) Seismic source zones and location of sites for PSHA calculations; (b) examples of virtual ruptures generated in both the host and neighbor source zones for scenarios of different magnitudes; (c) as (b) but with point sources in the neighbor source zone.

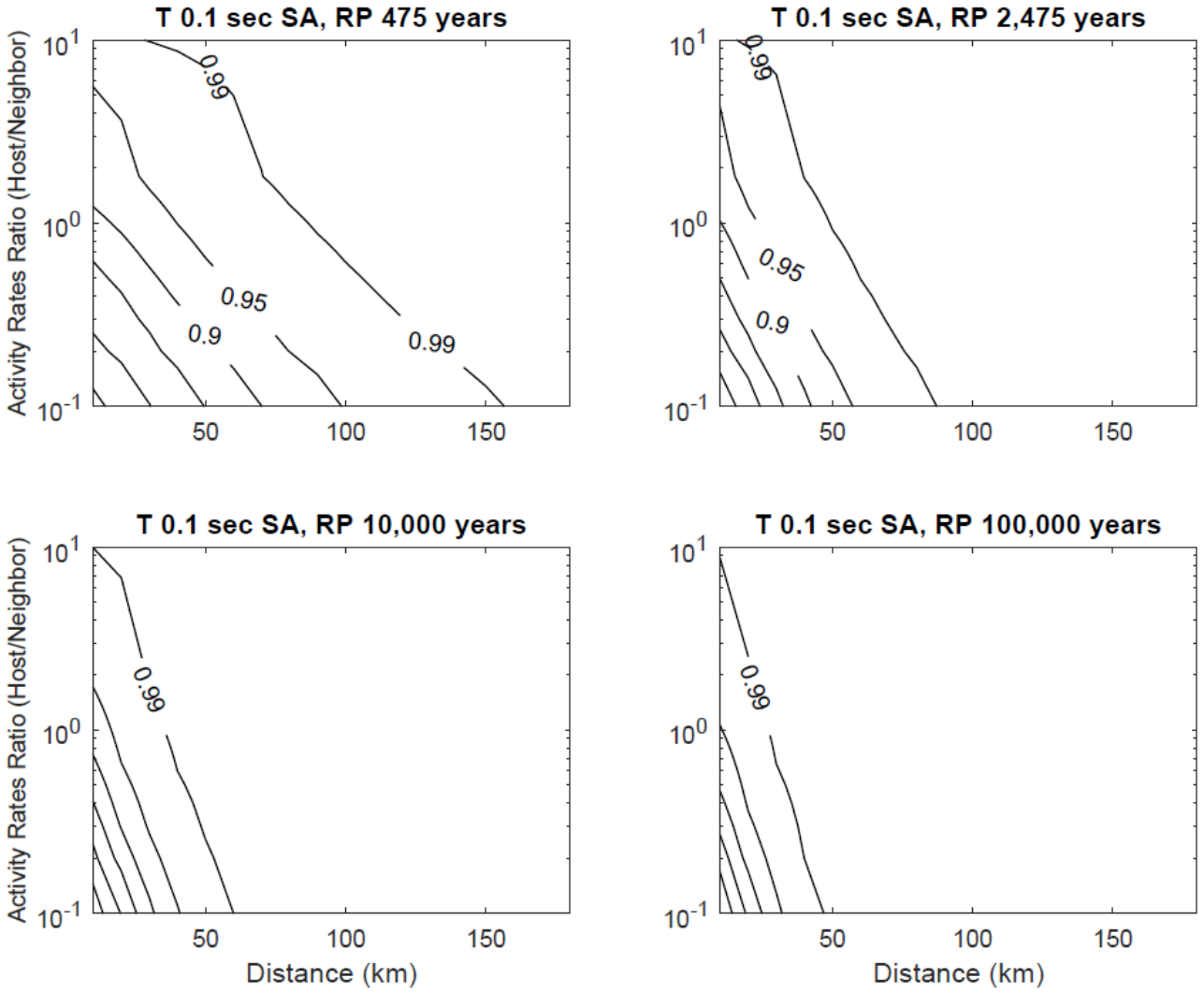

Figure 6. Ratios of SA(0.1s) at four return periods from hazard calculations for the source-site configurations illustrated in Fig. 3 obtained using point sources in the neighboring source to those obtained using virtual ruptures in both zones, plotted as a function of the distance of the site from the boundary between the sources and the ratio of activity rates in the host and neighboring zones. The contours below 0.99 are for 0.95 and subsequent values decreasing in 0.05 increments. RP is return period.

For the interpretation of these plots it can be stated that all for distance and activity rate combinations that lie to the right of the 0.99 contour, the hazard results can be considered insensitive to the use of point source approximations rather than virtual ruptures for earthquake scenarios occurring outside the host source zone. As one moves to the left of the 0.99 contour, the error—which is always underestimation—resulting from the simplified modeling of the ruptures as dimensionless hypocenters grows and for some combinations reaches as much as 25-30%. The gradient of the contours reflects the ratio of earthquake activity rates in the two source zones. Therefore, it becomes immediately clear that whether or not the generation of virtual ruptures can be obviated in any non-host source will depend on the distance separating the site of interest from the closest boundary of that source as well as on whether or not earthquake activity in that source is higher or lower than in the host source zone. These observations clearly also depend on the distance attenuation rates

implicit in the GMPE deployed in the hazard calculations: in the examples presented here the GMPE is for an active crustal region and the contours would be expected to shift to the right when using a GMPE representative of the slower attenuation rates in stable continental regions.

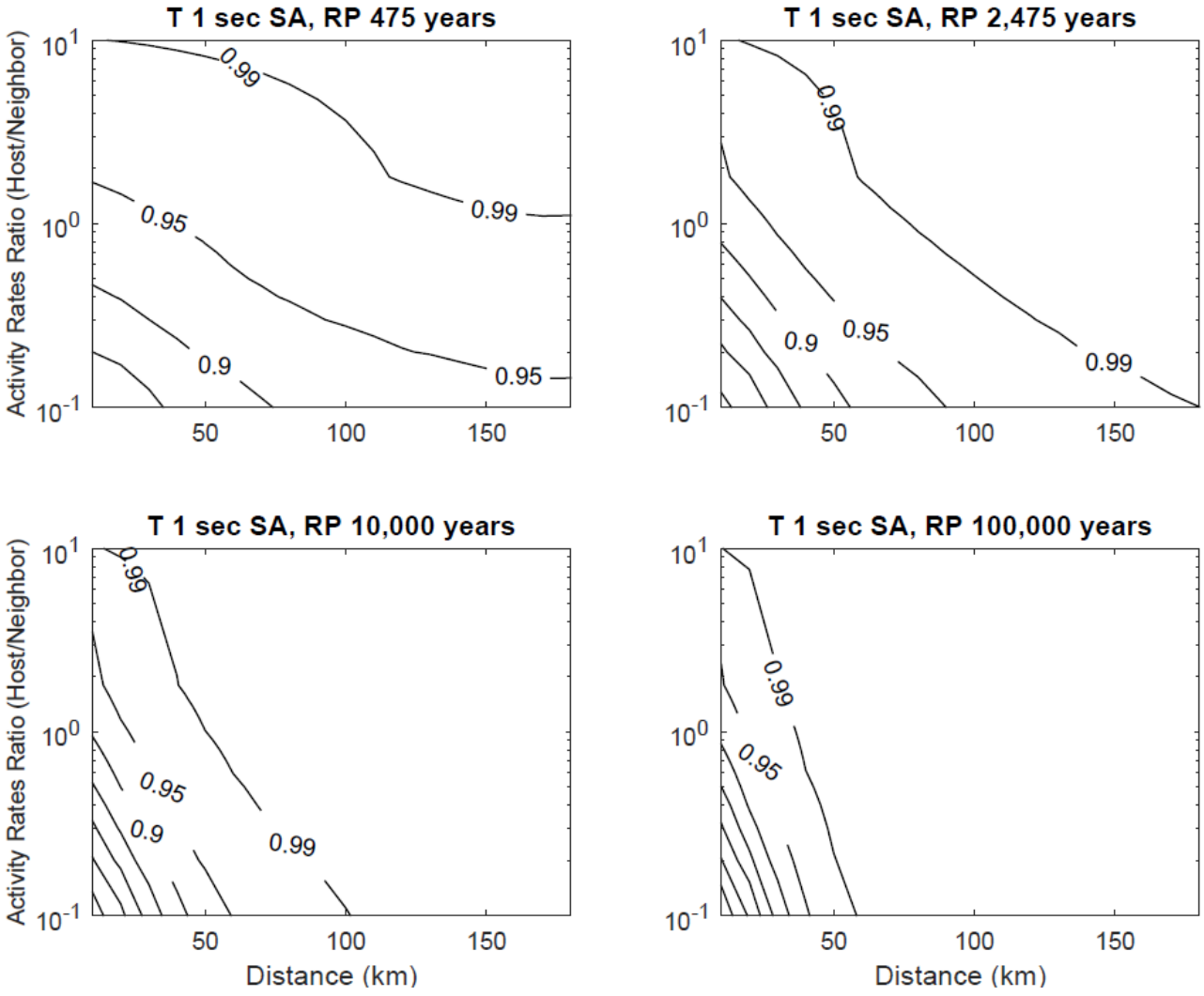

Figure 7. As Fig. 6, but for SA(1.0s).

Another important observation from Figures 6 and 7 is that the differences obtained in hazard results when using hypocenters as opposed to virtual ruptures are greater for the 1-second response spectral ordinates than for SA(0.1s). This is not a surprising result given that longer period response ordinates scale more strongly with increasing magnitude and hence are more sensitive to increase in rupture dimensions for larger earthquakes. This suggests than if tests are to be designed for a site-specific PSHA to determine for which source zones the generation of virtual ruptures could be neglected, it is advisable to perform the sensitivity calculations for intermediate-to-long response periods rather than short-period ordinates. The results will obviously also depend on the values of M_{max} in the host and neighboring sources, with greater sensitivity to the point-source approximation if larger M_{max} values are assigned to seismic sources beyond the host zone.

A noteworthy feature of the results displayed in Figures 5 and 6 is the fact that the distance ranges over which the hazard estimates are biased by the point-source approximations reduce appreciably as the return period increases. This is a consequence of the fact that at longer return periods, the hazard in increasingly dominated by earthquake scenarios close to the site. This is a significant observation because site-specific PSHA studies will generally be required for projects of sufficient importance that their design is likely to be based on longer return periods, such as those in the 10,000 to 100,000 year range typical for nuclear facilities. The seismic source zones defined for such studies will often extend to distances of several hundred kilometers from the site, partly as a consequence of regulatory guidance that indicates that the geological and seismological investigations to underpin the seismic source model should cover an area defined by a radius of at least 300 km from site (IAEA, 2010; USNRC, 2007). Consequently, with source zones that may extend to 400-500 km from the site and results in Figure 6 that suggest that even with much higher activity rates within distance sources, the use of hypocenters rather than virtual ruptures may be acceptable beyond 100 km, it will nearly always be the case that the generation of virtual ruptures can be avoided in several of the more remote sources.

There is a temptation to generate results similar to those in Figs. 6 and 7 covering a wider range of possibilities, including alternative GMPEs and site conditions as well as varying M_{max} and *b*-values in the source zones, with the intention of developing look-up tables that could be used to determine the distances beyond which virtual ruptures are not required. While this would be attractive and convenient, it could potentially be misleading since the conclusions of any such sensitivity analyses will depend on several other factors, including the scaling relationships and rules (aspect ratios, depth-to-top-of-rupture, thickness of seismogenic crust, location of hypocenter within the rupture plane, *etc*.) used to generate the virtual ruptures, as well as their geometry in terms of strike and dip. The purpose of the examples presented here is therefore only illustrative and our recommendation is for simple sensitivity analyses to be performed to determine where the hazard calculations can dispense with virtual ruptures.

DISCUSSION AND CONCLUSIONS

The practice of generating virtual fault ruptures within seismic source zones to ensure consistency with GMPEs that use distance metrics defined relative to extended fault ruptures represents a clear case of good practice in PSHA and avoids the unintended underestimation of hazard that results from combining such GMPEs with point-source representations of the earthquakes within a source zone. However, we have demonstrated that the effort involved in defining the characteristics of these fault ruptures and in simulating the ruptures within the hazard calculations may be unnecessary in some circumstances.

For most, if not all, site-specific PSHAs, there will be some seismic source zones outside the host zone (where the site is located) for which the generation of virtual faults can be by-passed without introducing any appreciable inaccuracy to the hazard calculations. In those

source zones, each earthquake scenario can then be represented simply by a hypocenter without dimensions. The calculations can then be performed substituting hypocentral distance for rupture distance or epicentral distance for Joyner-Boore distance in the GMPE. For such situations, however, it may be advantageous for GMPEs to be derived using both rupture-based and point-based distance metrics. However, in such cases, unless the standard deviation is modeled with distance dependence, it may be preferable to use the sigma values obtained with the rupture-based metric in order to avoid inflation of the variability at greater distances.

The most obvious benefits of not generating virtual ruptures, at least in more distant source zones in site-specific PSHA studies, is that it obviates the need to model the characteristics of those ruptures while also rendering the PSHA calculations considerably faster. However, there is another potential benefit in that it helps to avoid an issue that may affect many PSHA studies although it may often pass without notice.

Consider the case of a remote source zone, within which the seismogenic crust is defined as having a given thickness and ruptures are generated according to a selected scaling relationship that ensures that the rupture area scales with magnitude. For the upper end of the maximum magnitude distribution, ruptures can be generated that require exceptional lengths given that their widths will be constrained by the seismogenic thickness and the fault dip. Depending on the range of strikes permitted for the ruptures, it is perfectly feasible—unless expressly inhibited in the model implementation—for these exceptionally long ruptures to propagate out of the source zone in which they originate and towards the site in question. Such scenarios could lead to inflation of the hazard estimates for the site and apparent contributions to the hazard from the host zone that are actually related to earthquake activity in another zone that is farther away. This problem can be avoided by defining non-leaky boundaries for the source zones (*i.e.*, fault ruptures are prevented from crossing some or all of the source boundaries) or else be ensuring that the rupture orientations do not favor propagation towards the site. Avoiding the need to generate virtual ruptures in distant sources, however, removes the possibility of this problem arising.

Eliminating the need to characterize virtual fault ruptures in distant source zones allows greater attention to be given to those elements of the seismic source model that exert greatest influence on the hazard estimates. Obviating the need to generate these virtual ruptures as part of the hazard calculations accelerates the PSHA computations and thus facilitates the execution of sensitivity analyses that can provide so much useful feedback to the hazard modelers.

Data and Resources

Results presented in this paper are either from previous publication, for which full citation details are provided, or from calculations based on hypothetical scenarios described in the text.

Acknowledgments

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