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Modelling In-slab Subduction Earthquakes in PSHA: Current Practice and Challenges for the Future

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Abstract

The seismic threat that active subduction zones present to populations located within the fore- and back-arc regions is well recognised by scientists and policy makers. Recent megathrust earthquakes such as the 2004 Sumatra earthquake and the 2011 Tohoku event illustrated just how catastrophic the impacts of large subduction events, both local and global, can be. By virtue of their deeper sources and typically smaller magnitudes, however, intra-slab earthquakes are often seen as less consequential in probabilistic models of seismic hazard. Yet events such as the 2009 Padang, Indonesia earthquake (M 7.6) demonstrate that their potential impacts on cities is far from negligible.

A review of national and regional probabilistic seismic hazard models for subduction regions reveal an absence of consensus on the approaches taken to characterize earthquakes originating within the Benioff zone. Amongst the different approaches are smoothed seismicity, the adoption of uniform volumetric zones, or in some cases a series of characteristic faulting planes. Adding further complexity to the problem is the representation of subduction sources within current ground motion prediction equations created for application to subduction regions. As a result of these potential inconsistencies, some recently published seismic hazard models have retained point-source representations, whilst others based on finite-rupture provide little indication as to how to scale the rupture surface in a manner that is consistent with the physical characteristics of the ruptures within the subducted slab.

The current study outlines several requirements for seismogenic source characterisation for in-slab earthquakes in probabilistic seismic hazard analysis (PSHA). These include the constraints that the slab geometry place upon both the source location and the finite rupture extent of seismicity and flexibility to account for changes in rupture properties (such as orientation and style of faulting) within the Benioff zone. We present a new in-slab source modelling methodology using in the OpenQuake-engine software for PSHA, which aims to satisfy these requirements in a clear, flexible and efficient manner. The methodology is compared against existing techniques for characterising in-slab sources in PSHA using a branchmark test for in-slab seismicity proposed as part of the Pacific Earthquake Engineering Research Center (PEER) tests for PSHA software verification. This exploration may help to guide future revisions to national and regional hazard models and it may help identifying those elements of the subduction system upon which efforts to better constrain its physical properties should be placed in order to model more consistently, and perhaps reduce, the uncertainty in future seismic hazard studies.

Keywords: in-slab seismicity, subduction, probabilistic seismic hazard analysis, OpenQuake

1. Introduction

The threat that subduction earthquakes pose to life and property in coastal regions is well recognised by scientists and society alike. Recent large megathrust events such as the 2004 Sumatra, 2010 Chile and 2011 Tohoku earthquakes illustrate this clearly, and, due in no small part to the awesome scale of their destructiveness and their fundamental insights into the earthquake process, have captivated scientists and the public alike. Yet, whilst the impacts of the large interface events are both frequently observed and justly feared, subduction zones produce other types of events that can, in many circumstances pose a significant threat to life and property. This threat emerges from the within-slab events. Such events occur mostly on fractures found with the deforming oceanic slab as it subducts beneath the more buoyant continental crust. In-slab sources are generally considered incapable of generating very large magnitude events (i.e. $M_W \geq 8.5$), but the locations of these ruptures, though deep, are often situated further toward the continental side of the subduction zone. Earthquakes of this type are frequently widely felt, and the largest of these have resulted in extensive damage in some cases. The 2009

Padang, Sumatra, earthquake (M_W 7.6) is one such example of an in-slab event causing widespread damage and destruction to vulnerable cities. Other large damaging events have occurred at shallower depths within the slab (e.g. 1931 Hyuganda (Japan) earthquake, 1941 Olympia, Cascadia, 1931 Oaxaca (Mexico)), highlighting the potential threat that such earthquakes may still pose to the urban environment in coastal regions close to subduction zones. Furthermore, the relative contribution of subduction in-slab sources to the seismic hazard may be higher for urban environments located in the backarc of certain subduction regions. One such example is the city of Jakarta, Indonesia, located above a deeper slab portion of the Sumatra-Java subduction. Though several hundred kilometres away from the main subduction interface, the city has experienced widespread shaking from deep earthquakes in the past. As an area of rapid economic growth and urbanization, with newly constructed tall buildings and deep alluvial soils, the potential losses from a large in-slab earthquake may be high. Appropriate characterization of both the seismogenic source, as well as the ground motion model can have a significant influence on the likely estimates of earthquake loss for large earthquakes beneath the island of Java.

In this paper we use the Global Earthquake Model database of national and regional probabilistic seismic hazard models (http://hazardwiki.openquake.org), to briefly review the various, methodologies adopted for the characterization of in-slab sources in PSHA. In light of the varied approaches we find in practice, and their respective limitations, we propose a set of criteria that we believe to be desirable for a general methodology for subduction in-slab modeling. From these criteria we adapt elements of the OpenQuake-engine [1] to produce a novel technique that can be used to characterize in-slab seismogenesis in PSHA. We believe our approach to be flexible in allowing the modeller to easily adapt the configuration in accordance with the local tectonic environment, whilst ensuring consistency with the finite-rupture characterization required by existing and potentially forthcoming subduction ground motion prediction equations (GMPEs). This last point is particularly relevant as different in-slab GMPEs found in the literature may consider source to site distance metrics that are defined with respect to a point (i.e. hypocentral distance), with respect to a finite rupture, or with respect to a specific configuration of finite rupture and hypocentral location.

To demonstrate the potential impact of the choice of in-slab source characterisation methodology on PSHA, including the method proposed within this manuscript, we use the in-slab seismicity test case found within the most recent set of the hazard calculation benchmark tests proposed in a project coordinated by the Pacific Earthquake Engineering Research Center (PEER). As the PEER hazard software tests are intended for comparison of many different PSHA codes, several different in-slab source modeling options are permitted for consideration. OpenQuake-engine is one of only a small subset of the participating PSHA software that is able to implement all of the permitted methodologies, thus making it useful as a means of comparing the methods themselves and not simply the software. Whilst the results of the in-slab PEER test are insightful to understand the relative differences between methodologies, it will be seen that the PEER test itself has an idealized configuration to allow many modeling approaches to be compared. In reality, not all approaches considered can be adapted to more complex subduction zone geometries, and may limit the options available to the modeller. The method itself has already been applied successfully in a regional seismic hazard model for South America [2], and we believe the brief insights provided will serve to assist seismic hazard modellers should they wish to adopt this methodology in the future.

2. In-slab Seismicity: Seismic Hazard Modelling Approaches

Whilst the scientific understanding of the subduction process has increased significantly within recent decades, the different approaches by which in-slab earthquakes are modeled have largely converged around a few common methodologies. A key factor underpinning these modeling choices is the need for practicality of application. This may apply to the actual means of implementation within the PSHA calculation, but also within the means by which the seismogenic sources and corresponding activity rates are determined from the available earthquake data.

2.1 Smoothed Seismicity

The smoothed seismicity approach finds widespread application largely because it places a key emphasis on the observed earthquake catalogue, one of the elemental datasets in any earthquake hazard analysis. The ubiquity of the method in different regional scale hazard models originates from the methodology commonly adopted by the United States Geological Survey (USGS) in their national seismic hazard maps from 1996 to 2014 to model intermediate and deep seismicity in the Northwestern United States [3, 4, 5]. It has subsequently found application in other regions such as Southeast Asia [6], where the seismic hazard models are constructed using modeling approaches that mirror those typically adopted by the USGS for the conterminous United States [4, 5]. Independently from the USGS approach, however, the Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 Hanford Site PSHA [7] also adopts a smoothed seismicity model for in-slab seismicity within the Cascadia region.

Smoothed seismicity is a versatile approach for modeling seismic hazard in many regions. Requiring only an earthquake catalogue for a region, the approach determines the activity rates across a regular grid of points by applying a spatial kernel function to the location in order to re-distribute the contribution of each earthquake across the grid. In the USGS approach a fixed-width isotropic Gaussian kernel is used [3], albeit more recent studies have explored the use of adaptive kernels [e.g. 7, 8], i.e. kernels where the bandwidth for smoothing each event is determined by the density of nearby seismicity.

As earthquake catalogues are a necessary requirement of any seismic hazard analysis, adoption of a smoothed seismicity approach ensures that a seemingly stationary estimate of the activity rate can be obtained in any region. In practice, however, the smoothed seismicity approach has limitations that require careful consideration when applied in a subduction environment. The method of Frankel [3] – one of the most common methodologies used in PSHA analysis – operates within two-dimensions, i.e. considering only the epicentral distribution and a single layer grid. When the goal is to model the down-slab variation in seismic depth using this methodology, the hazard modeler is left with only a small number of options: the first is to divide the catalogue into different depth layers and apply the smoothing independently for each layer, an alternative is to apply the smoothing kernel in a single "deep" layer and subsequently adjust the model depths for grid cells along the zone to reflect the changes in depth within the Benioff zone. The first approach may lead to sharp offsets in activity rates across the layers as seismicity in each layer is treated independently, whilst the latter may require a degree of unspecified judgment in assigning appropriate depths.

The problem of smoothed seismicity is complicated further if one recalls that the majority of recent in-slab subduction GMPEs may require that in-slab earthquakes remain represented by finite rupture distance metrics. In the USGS approach the "average" closest-rupture distance is inferred from the point distance and magnitude scaling relation, following the method described in Appendix C of the documentation of the 2008 US National Seismic Hazard Map [4]. Whilst such an approach can provide an approximate correction on the distance measure, it implicitly assumes a vertically dipping fault and a uniform distribution of rupture orientation. Neither of these assumptions may be entirely appropriate for an in-slab subduction source, particularly for the larger magnitudes that would be the most likely to make any contribution to the seismic hazard for a site onshore.

2.2 Area Sources

Another approach for modeling in-slab seismicity sources commonly encountered in national and regional seismic hazard maps is based on the use of uniform area sources placed at different depths. Examples of this can be found in the 2014 National Seismic Hazard Map of Canada [9], the European Seismic Hazard Model (ESHM13) [10] and the RESIS II model for Central America [11]. As with smoothed seismicity, this approach can be adopted even in areas where only the observed earthquake catalogue can provide constraint on the in-slab source seismicity. However, this method offers an additional advantage since further information on the extent of the slab volume can also be incorporated to refine definition of the area sources. The combination of area sources, whose spatial extents and upper and lower depth limits are intended to capture the geometry of the Benioff zone, effectively form a "staircase". In doing so, changes in seismicity recurrence, focal mechanism type and depth distribution within the subducting slab can be captured in the model.

2.3 "Staggered" Fault Sources within the Slab

The third approach for in-slab seismogenic source modeling found in some national models is to define a series of fault sources that are staggered down the slab volume, a "fill-with-faults" methodology. In this case, all in-slab seismicity is rendered onto the set of fault surfaces, whose individual activity rates are determined by partitioning the magnitude frequency distribution for the whole slab among the different faults. Typically, individual ruptures can be moved, or "floated", across the fault surfaces in order to describe the probability distribution of source-to-site distances. Examples of seismic hazard models adopting this approach include the

2015 National Seismic Hazard Model of Taiwan [12], and the 2014 National Seismic Hazard Map of Japan [13] (albeit the latter also adopts a smoothed seismicity model in addition to the large finite ruptures). This method has some key benefits; principally among them is the means of generating in-slab seismicity in the form of finite-fault ruptures distributed across the faults surfaces, in the same manner as that often used to model the earthquake distribution on shallow faults. Some limitations emerge, however, as more complex elements of in-slab seismotectonic behavior are difficult to constrain. These can include changes in faulting mechanism along the subduction zone and/or down-slab.

3. A New Approach to In-slab Subduction Zone Modelling

Each of the methods described previously adapts otherwise common seismogenic source geometries for the purpose of defining the within slab seismicity. These facilitate their application in a variety of seismic hazard analysis software, yet each individual approach may not always be sufficiently flexible to model the diverse range of characteristics of the subduction zone geometry. Furthermore, some of the methods described offer limited flexibility for the characterisation of finite ruptures, and their respective boundaries and orientation with respect to the subducting slab itself. In view of the limitations highlighted for each of the aforementioned in-slab modeling methodologies, it is helpful to identify what might constitute the key requirements for an in-slab source characterisation method for use in probabilistic seismic hazard analysis. A few such requirements are outlined as follows:

1. The seismogenic source should, in a manner that is reasonable, conform to the geometry of the subducting slab. In the majority of cases the three-dimensional volume of the subducting slab may be characterized, at a minimum, by the three-dimensional surface of the interface and a single measure of the slab thickness.
2. The seismogenic source should be able to generate finite ruptures from which all of the distance metrics required by subduction GMPEs can be determined.
3. Finite ruptures generated within the subducting slab should respect the geometry of the slab, avoiding unphysical circumstances such as the propagation of ruptures through the mantle or to shallow depths in the continental or oceanic crust
4. The strike and dip of the finite ruptures can vary with depth or slab orientation, usually reflecting the changes in dip of the interface, but potentially due to other localisations of stress due to the flexure of the subducting crust
5. Earthquake recurrence within the subducting slab may be considered either constant or spatially variable. Where spatial variation occurs this may reflect along-slab segmentation of the subduction zone, or down-slab segmentation representing changes in the seismogenic processes inherent within the slab.
6. In the optimum case, the methodology should be sufficiently flexible to allow for application to many different subduction zone environments.

By its very nature, the subduction interface can be quite irregular from a geometric perspective, as the arcuate shape of many subducting slabs means that the fault surface changes strike along its length, and changes dip down its width. This is well illustrated in the Slab 1.0 representations of the subduction interface [14], which are constructed for each subduction zone by fitting series of spline functions to cross-sections of interface seismicity at regularly spaced intervals along trench.

3.1 A Flexible Inslab Source Model

In the methodology presented herein, the subducting slab is defined from two critical pieces of information: the three-dimensional surface of the subduction interface and the slab thickness. In the present examples the slab thickness is assumed to be constant, although this does not necessarily need to be the case since, in lieu of the thickness, it is possible for the modeler to define a three-dimensional surface describing the lower surface of the seismogenic portion of the slab. In the current methodology the subduction interface is input as an instance of OpenQuake-engine's "complex fault" source type [1]. This defines the interface from a series of edges representing the upper and lower limits, as well as any "hinge" points in the interface at which the dip might be expected to change. A mesh of points is rendered across the surface defined by the set of edges, the spacing of which is usually defined by the user. An example of the interface surface is shown in Figure 1a. From the interface the lower seismogenic surface is generated by projecting the interface mesh either vertically downward, or on a normal trajectory with respect to the interface (Figure 1b). One or more layers of points are generated within the slab volume. The location of the layer is determined by user-defined fractions of the slab thickness. A three-layer example (0.25, 0.5 and 0.75) is shown in Figure 1c.

The points rendered in the previous step form the nucleation centres of the in-slab rupture. However, in the PSHA calculations we wish to construct a virtual fault, i.e. a planar surface whose dimensions are consistent with the defined area magnitude scaling relation specified for the in-slab source. In Figure 1 we use the subduction in-slab magnitude-to-area scaling relationship of Strasser et al. [15]. The user must also specify the initial aspect ratio of ruptures, although as will be seen in due course, this will not necessarily correspond to the aspect ratio of the largest ruptures generated by the source as these may eventually be constrained by the slab volume.

In the fourth step of the modeling methodology the finite ruptures are generated with the centroids anchored to the nucleation points defined in the previous step. Within the subducting slab, however, finite ruptures require specific constraints on both their spatial extent and their orientation, in accordance with the local conditions of the slab. We give the modeler a degree of control over how to constrain the orientation of the rupture and its variability with depth. To do so, the modeler must specify, for a given range of hypocentral depths, a nodal plane distribution. This takes the form of a set of rupture orientations, as tuples of strike, dip and rake, each with its corresponding probability. The orientations of the strike and dip can be specified either as “absolute” strike and dip, i.e. the azimuth with respect to geographic north and the inclination with respect to the horizontal plane, or the “relative” strike and dip given in terms of the angle with respect to the local strike and local dip of each grid cell.

Figure 1d illustrates how the distribution of the rupture orientations within the slab can be controlled. In the example show, for the shallowest depths, less than 40 km, the strike of the ruptures is believed to be mostly parallel with respect to the local azimuth of the trench. Hence, they are assigned a relative strike of 0˚. Likewise, a relative dip of 20˚ with respect to the local inclination of the interface is assigned. The rake of the events can be set depending on whether these events may be largely compressional or extensional nature, the dominant mechanism being controlled by either the flexure of the slab or the slab pull. In this case we assume only a single focal mechanism in the layer, with probability of unity. Ambiguity in the compressional or extensional nature of the ruptures, or even simply uncertainty in the potential orientation of inslab events, can be accounted for by specifying multiple nodal plane distributions with corresponding weights.

The second depth layer spans 40 km to 80 km and retains some of the characteristic of the previous layer. The strike of the ruptures is parallel to the strike of the interface, but the angle of dip is increased to 30˚ with respect to the inclination of the local interface. This increase in dip with respect to the interface, in combination with the increased dip of the interface itself combines to produce much more steeply dipping ruptures (potentially, 60˚ to 70˚) in this portion of the slab. Focal mechanisms for events within this region are relatively evenly divided between normal faulting and reverse faulting [16], with normal faulting predominant in strongly coupled plate boundaries.

The third layer in the current example (events deeper than 80 km) contrasts greatly with the two previous layers, as here the orientation of the strike of the ruptures is changed such that they are nearly oblique to the local strike of the trench. In addition the relative dip is increased further to 50˚ with respect to the inclination of the interface. This, in effect, makes the ruptures vertical or sub-vertical, and in some cases will reverse the dip direction. Whilst not necessarily appropriate for the example of the Scotia trench, which Figure 1 is illustrating, this drastic change of mechanism can be seen in several places throughout the globe (e.g. the Hellenic arc), with several different causes. Examples might include a proposed tear in the slab at depth, or local contortions or hinges where the trench bends sharply, causing horizontal compression or extensional stress axes.

The example of the control on the rupture orientation shown in Figure 1 is important to ensure that the orientation of the rupture planes are consistent with the axes of stress within the slab. Ambiguities relating to the role of extension or compression may be important to resolve from the perspective of the tectonic modeling, yet at the time of writing no GMPE for in-slab subduction events has an explicit style-of-faulting dependence. So, for the short-term at least, we do not consider this issue to be critical for probabilistic seismic hazard analysis. Instead, the constraints imposed by the geometrical limits of the slab on the ruptures require careful attention. The finite faults are represented as planar surfaces, whose dimensions scale in proportion to the defined magnitude. It is easy to anticipate that in the case of large in-slab events the conditions imposed upon the rupture by the orientation and aspect, however reasonable, can lead to unphysical or, at least undesirable, behavior in the simulated ruptures. The most critical case is probably the one where the rupture plane propagates beyond the geometric limits of the slab into the upper mantle or even the continental crust. This would fail to fulfill criterion number 3. We therefore introduce configurable controls on the slab *permeability*.

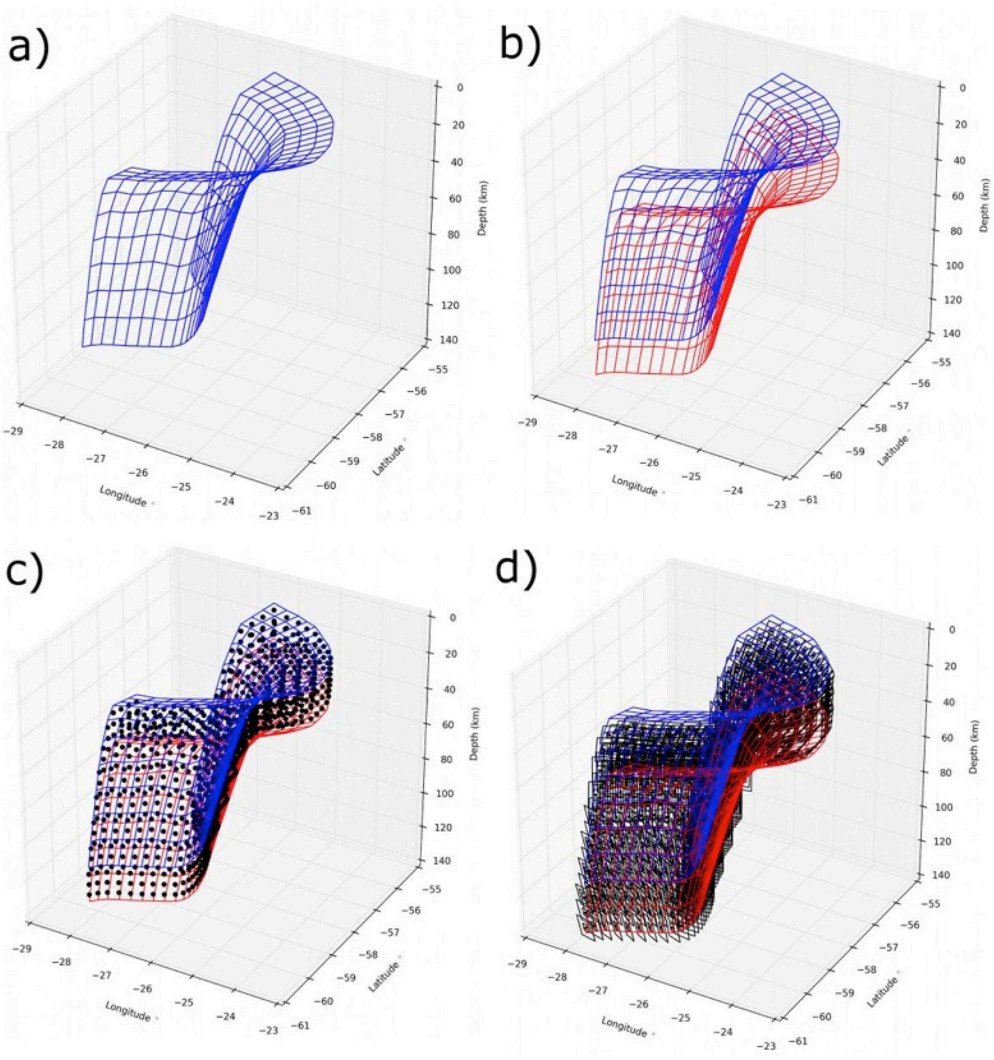

Fig. 1 – Components of the proposed in-slab modeling methodology: a) subduction interface as "complex" surface, b) lower surface defined by the interface and slab thickness, c) layers of nucleation points within the slab, d) generation of finite ruptures with the properties described in the text

The use of *permeability* requires some clarification regarding its specific definition. Impermeable slab boundaries in the current methodology place limits on the upper and lower depths of seismogenesis that are specific to each location within the slab volume and the corresponding rupture orientation. This ensures that ruptures cannot propagate to depths shallower than the interface or deeper than the lower boundary of the slab for the given location and orientation in question. Instead, should the rupture be sufficiently large that the area cannot be contained within the seismogenic depth limits, the aspect ratio will no longer be preserved and the rupture will be allowed to propagate laterally in order to achieve the area required by the magnitude scaling relation. It may be argued that the same logic of impermeability should apply also to lateral bounds as well as vertical bounds. We opt not to enforce this case. Aside from the incurred cost of solving the computational geometry to determine the points of intersection between two three dimensional surfaces of arbitrary complexity, impermeability in both the depth and lateral limits can enforce a location specific upper bound on the rupture size that may be significantly different from that inferred by the maximum magnitude determined by the hazard modeler for the source.

As with the case of the nodal plane distribution, to allow the hazard modeler maximum flexibility in the in-slab source modeling, the permeability is configurable and can be changed for different depth ranges. The modeler can therefore chose to make certain depth layers permeable, whilst retaining impermeability in other layers. This is in evidence in Figure 1d, where the boundaries can be seen to be impermeable in the 0.0 to 80 km, but then permeable for ruptures greater than 100 km. We allow this parameter to be configurable as there may be specific circumstances in which permeability is desirable, or impermeability simply too restrictive. In the example shown, permeability was allowed for the deeper ruptures whose strikes were oblique to the local strike of the interface. This can be useful if the three-dimensional surface of the slab is less certain at depth, therefore the boundary should not be considered strict, or if a potential slab tear or similar mechanism is hypothesized, in which case the true geometry is more complex than the standard slab model.

A corollary to the discussion of permeability with respect to the interface and lower surface limits of the slab, is that of the lateral permeability of the entire subduction region itself. How far beyond the geographical limits of the subduction zone should ruptures be allowed to extend, what are the physical barriers that act to contain in-slab ruptures within the slab volume itself and how are these defined? Such issues are not well resolved in current models, albeit in many cases the free edges of the slab may be considered impermeable for large ruptures. Concentrations of seismicity on the edges of subducting slabs, such as the Mendocino triple junction, infer a more complex pattern of local stresses that are more difficult to resolve.

3.2 Recurrence and Segmentation

With the characterization of the finite ruptures described, the final point to consider is the magnitude frequency distribution across the sources. For each given slab section an individual magnitude frequency distribution is defined, from which the activity rates are distributed equally amongst the points within the volume. A particular advantage of this methodology is the ability to partition the in-slab volume into different sub-regions, both along the trench and down the slab. Although the subduction interface itself represents a continuous surface, for the in-slab sources it serves only as a geometrical reference (both for the nucleation of the points and, later, the seismogenic depth constraints). In this methodology, by subdividing the interface into smaller sections the modeler has the capacity to partition the slab into subsections, adjusting the properties of seismogenesis for each subsection, be it the magnitude frequency distribution itself or any of the properties controlling the geometry of the finite ruptures (described in section 3.1). Accordingly, variations in activity rate or changes in rupture behavior along the subduction zone are readily supported.

4. Comparing Inslab Source Modelling Methodologies in PSHA

With the proposal of a new methodology for the creation of in-slab seismogenic source for PSHA modeling, it is of interest to compare them in application against existing in-slab source modeling methods described in section 2. Fortunately, a test that would allow such comparison in a hazard modeling context has been designed by the Pacific Earthquake Engineering Research Center (PEER) and forms part of the current suite of benchmark tests for existing PSHA software in the second generation PEER Tests project [17]. The in-slab seismicity test case of the PEER project permits the modeling of the seismogenic source in each of the different manners described previously. We use the OpenQuake-engine software to implement each one of the seismogenic source modeling methods, and calculate the hazard at several selected sites around the subduction zone. In the current paper, we emphasise that we are not comparing OpenQuake-engine with other software, but are instead using the flexibility of OpenQuake-engine as a means of comparing the different modeling methods, both against each other and against the new method proposed in this paper.

4.1 The PEER Inslab Benchmark Test

The PEER in-slab test case defines a slab volume extending 100 km in length (from south to north), dipping to the east, and has a defined thickness of 12.5 km. The slab is divided into two sections of equal down-dip width (65.0 km), the first section dips at 30˚, whilst the second section is more steeply dipping at 45˚. The very top of the upper section is located at a depth of 25 km. A single magnitude frequency distribution is assumed for the whole slab value, which corresponds to a truncated exponential recurrence model with maximum magnitude

$M_{MAX} = 7.0$, minimum magnitude $M_{MIN} = 5.0$, b-value equal to 0.8 and a rate of occurrence above the minimum magnitude ($N(M_{MIN}) \geq 5.0$) of 0.013 /yr. Ruptures inside the slab should be modeled as finite faults with orientations parallel to the trench (i.e. strike = 0.0˚) but dipping at an angle of 35˚ with respect to the angle of dip of the slab surface. An aspect ratio of 2.0 is assumed for all of the ruptures, for those tests in which it is required. The specifications of the PEER test require the use of the Zhao *et al.* [18] GMPE, rather than the more recent BC Hydro model [19]. This is because Zhao *et al.* requires the definition of the shortest distance to the rupture surface (r_{rup}) for in-slab sources, whilst BC Hydro relies solely on hypocentral distance (r_{hypo}). A rock class (class I in the definition of [18]) is used for the site conditions, which for the current purposes is assumed equal to a 30-m averaged shear-wave velocity (V_{S30}) of 760 m/s.

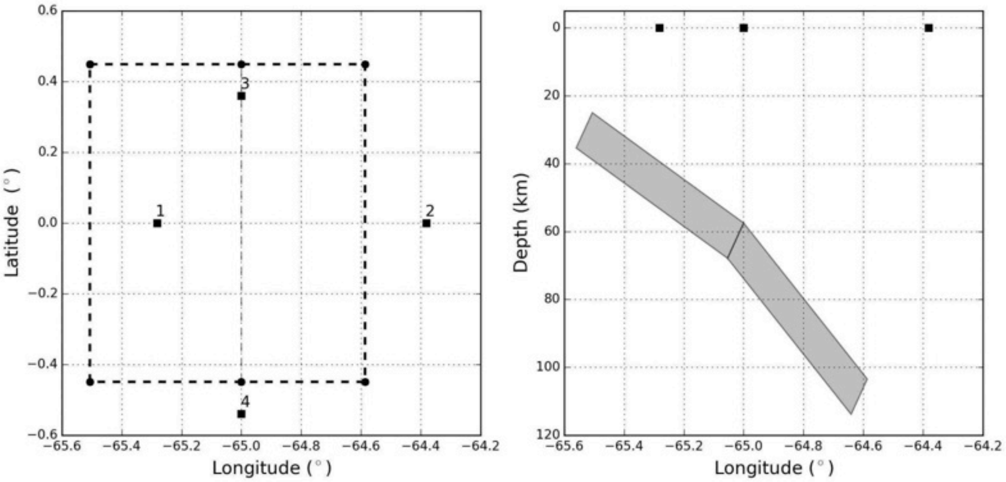

Fig. 2 – PEER In-slab test source and site configuration in plan view (left) and section view (right). The dashed line in the left panel shows the surface projection of the fault surface.

To model the in-slab sources, the PEER test permits the following methods: i. the use of a series of faults staggered down the slab volume (FLTS), ii. the use of a set of area sources staggered down the slab volume (AREA_PNTS, where point ruptures are assumed within the area source, AREA_VFLTS where virtual faults are assumed within the area source), iii. a fault surface on top of the slab volume (essentially equivalent to using the interface) (TOS) and iv. a fault surface of equal dimension to the top of the slab but placed in the middle of the slab volume (MOS). Also included in the PEER test is the new methodology presented within this paper. The slab interface and thickness are as described, only a single nodal plane distribution is required with a "relative" strike and dip corresponding to those given. Rake is assumed to be 90˚ (i.e. compressional) but this has no influence in this particular test. No variation in the nodal plane distribution with depth is required. The slab is assumed to be impermeable by depth; however, ruptures can extend beyond the lateral limits of the boundaries. From Figure 1 (and section 3) it is seen that the nucleation points can be set in multiple layers within the slab volume. To illustrate the sensitivity of the hazard calculation to the number of layers of nucleation points we define two different source models: the first assuming a single layer of nucleation points placed in the middle of the slab volume (GEM_1LYR), the second assuming two layers of points placed at one third and two thirds of the slab thickness (GEM_2LYR). The spacing between points within each of the layers is fixed at 2 km. The full geometrical configurations for the respective tests are shown in Figure 3.

In the original PEER configuration hazard curves are compared for only two sites, both placed at the midpoint of the length of the subduction zone. Site 1 is located above the shallower dipping section of the slab, whilst site 2 is located east of the down-dip limit of the whole slab. However, in order to explore some of the potential nuances of the different modeling approaches we extend the test further by considering additional sites placed near and off of the lateral limits of the slab (sites 3 and 4 respectively).

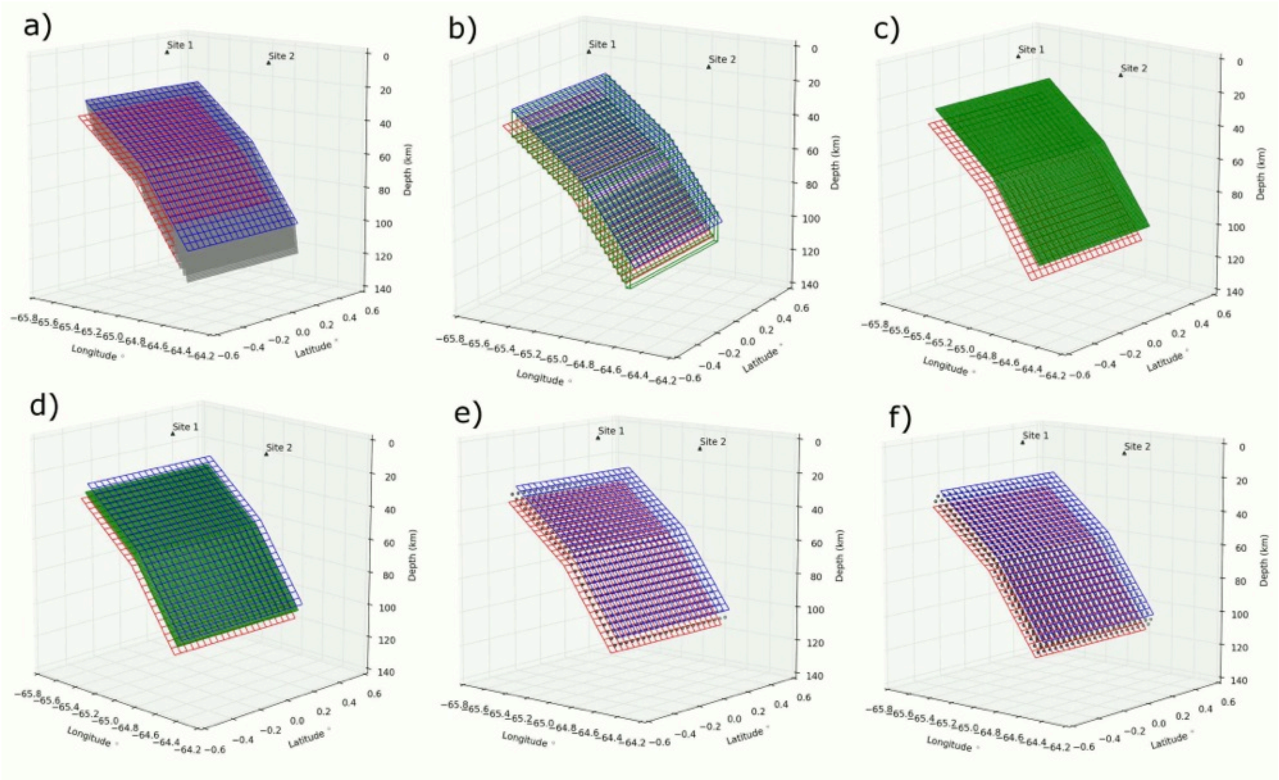

Fig. 3 – PEER test in-slab source configurations with interface marked in blue, lower surface marked in red and the source locations marked in green. a) Staggered faults FLTS, b) area sources down the slab volume (AREA_PNTS/AREA_VFLTS), c) top of slab (TOS), d) middle of slab (MOS), e) new approach with one layer of points (GEM_1LYR) and f) new approach with two layers of points (GEM_2LYR)

When finite ruptures are used (in the case of Zhao et al) we observe that for the site located above the slab (site 1) both the top-of-slab model (TOS) and the staggered faults (FLTS) produce the highest hazard across all ground motion levels, whilst the middle-of-slab (MOS) and area source with point ruptures (AREA_PNTS) produce the lowest. For this same site, both the area sources with virtual fault ruptures (AREA_VFLTS) and the GEM 1- and 2-layer approaches produce similar results. The most likely factor is the range of source-to-site distances, which will be shorter in the TOS and FLTS case, and longer in the AREA_PNTS and MOS cases. In this relatively simplified context the AREA_VFLTS and GEM approaches produces virtual ruptures that are similar in location and alignment. In both models the ruptures are allowed to extend beyond the lateral limits of the slab, whereas for the TOS and FLTS cases all of the ruptures (and consequently all of the moment release) takes place within the slab volume itself. Interestingly, where finite ruptures are required the GEM_1LAYER and GEM_2LAYER approaches produce extremely similar results. This is simply due to the fact within the constrained slab volume, the location of the anchoring points is of less importance once the ruptures reach a given size. The AREA_VFLTS produces a similar effect as the upper and lower seimogenic depth limits contain the rupture within the slab and only the hypocentral depth distribution (here distributed evenly across ten hypocentral depths in each source) will differ. As fewer layers in the GEM model, and similarly fewer hypocentral depths for the other source models, reduces the calculation effort this demonstrates that the results are largely insensitive to this variable and a lower effort approach could be favoured.

Comparison with the BC Hydro ground motion prediction reveals a similarly complex picture. Generally we observe greater convergence between the methodologies, with the spread typically on the order of 5 to 10 %. For sites located above the slab (i.e. 1 and 3) the GEM and area source methods are generally in close agreement, with the area sources slighly higher due to the denser distribution of hypocentres within the slab. The TOS and FLTS methods predict higher hazard. The former is simply due to the shorter source to site distance, which is why when the hypocentres are then located in the middle of the slab (MOS) the differences with the other methods are quite minimal.

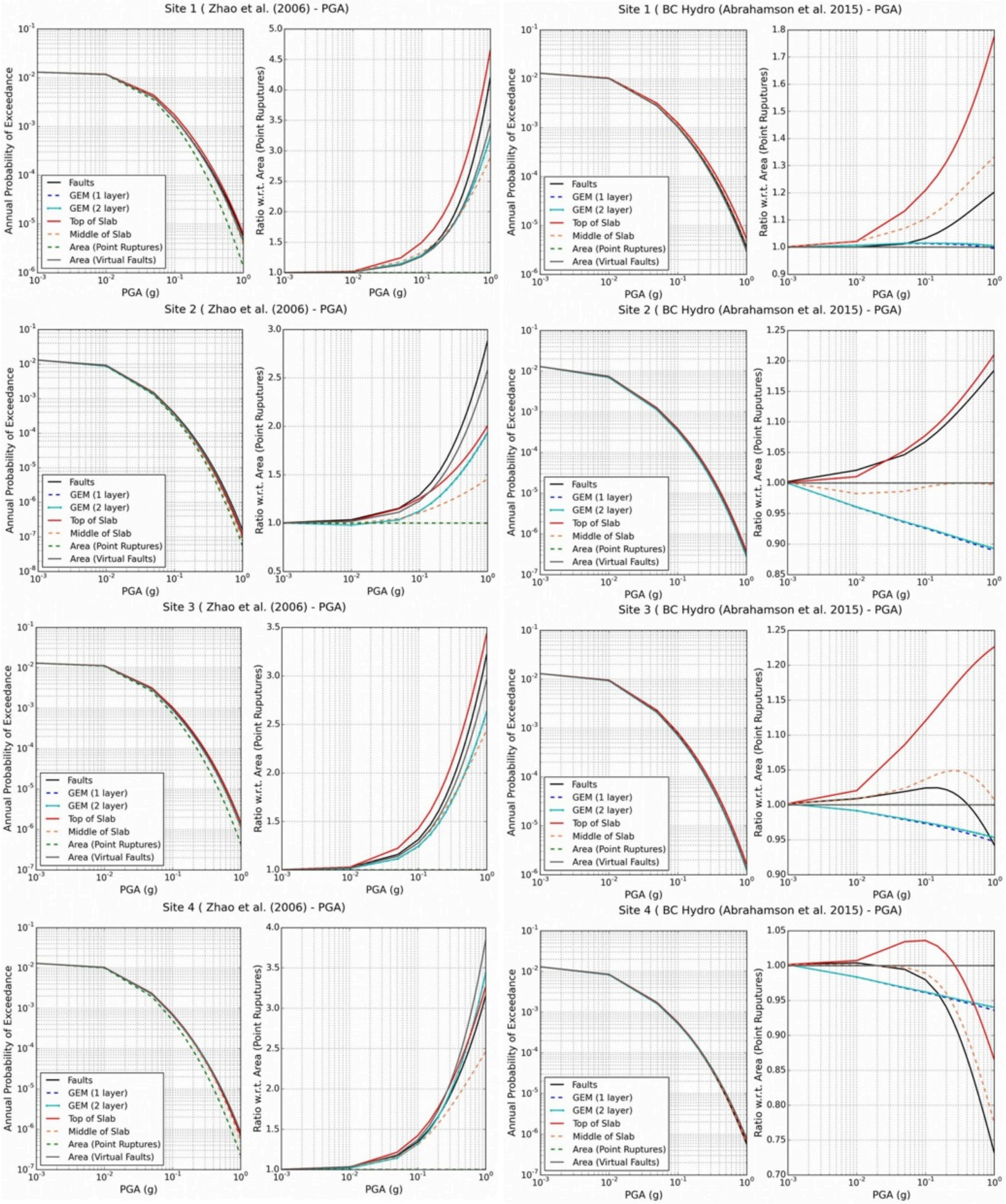

Fig 4. Peak Ground Acceleration (PGA) hazard curves (1st and 3rd columns) and corresponding ratios with respect to the AREA_PNTS case (2nd and 4th columns) for each of the four test sites. For the Zhao et al. GMPE [18] (1st and 2nd columns) and the BC Hydro GMPE [19] (3rd and 4th columns)

With the FLTS case it is the location of the hypocentre within the rupture plane that influences the resulting hazard. In this methodology the hypocentre is located at the centre of each rupture floated along the fault plane. For larger ruptures this actually places the hypocentre further away from the lateral limits of the subduction zone, so for sites located outside the vertical projection of the slab the hazard from the FLTS method actually drops below that of the other methods for higher accelerations. These results show that the interaction between the finite rupture characterisation and the representation of the hypocentre within the plane can have an impact on the hazard at a site. This highlights the need for care to be taken in interpeting the epistemic uncertainty range if combining in a logic tree framework in-slab GMPEs requiring explicit point-source representations with those that assume finite-ruptures.

5. Conclusions and Considerations for Application

The methodology for in-slab source characterisation proposed in this work is an attempt to ensure consistency between the definition of the seismic source and the corresponding requirements implicitly included in the various ground motion models, whilst also providing seismic hazard modellers with a means to incorporate more of the underlying seismotectonics of the subduction process into future PSHA models. Key benefits of the method are flexibility and relative ease of usage. The former is present by virtue of the ways in which the subducting slab can be readily subdivided into regions with different rupture properties, or distributions of rupture properties, as well as different magnitude frequency distributions. We anticipate, however, that there remain many cases where only minimal information regarding the in-slab process may be inferred from observed data. Not only can this information be inferred, with considerable uncertainty, from the distribution of seismicity, but seismic tomography may serve this purpose. Slab thickness could also be estimated by considering the distribution of rupture aspect ratio with magnitude, with the aspect ratios for larger magnitudes being used to infer the maximum down-dip rupture width within the slab volume. For the distribution of rupture orientations, we expect that focal mechanisms will likely play the key role in providing the majority of seismic hazard modellers the necessary insight to infer how rupture mechanism will vary within the slab.

The application of the PEER test for in-slab seismicity provides insight into the impact of the different modelling techniques on the resulting PSHA calculation. When it is necessary to take into account rupture finiteness the choice of modelling techniques has a greater impact than if considering the ruptures only as points. We can see that differences in hazard on the order of 20 to 30 % could be attributable to the modelling choice alone within this application, depending on the location of the site and the choice of ground motion model. Furthermore, whilst the PEER test serves an extremely useful purpose as a means of calibrating the modelling techniques, it is a considerably simplified application compared to the more complex geometries associated with real subduction zones. Not all methods permitted therein can be adapted readily to more realistic geometries, and many would be unable to provide sufficient flexibility to the modeller to localise the rupture characteristics in accordance with the physical properties of the subducting slab. The method proposed herein is designed to fulfil some of the key criteria that would ensure a physically appropriate model of seismogenisis within the slab, whilst also being highly efficient to construct and execute within the PSHA calculation. It has already proven successful when implemented in the South America region [2], and further testing is underway to apply it across many different subduction zones.

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