

A risk-targeted Regional Earthquake Model for South-East Asia

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ABSTRACT: The last decade has shown the social and economic vulnerability of countries in South-East Asia to earthquake hazard and risk. While many disaster mitigation programs to improve societal earthquake resilience are under way focusing on saving lives and livelihoods, the risk management sector is challenged to model economic consequences. We present the hazard component suitable for a South-East Asia earthquake risk model covering Indonesia, Malaysia, the Philippines and Indochine countries. The consistent regional model builds upon refined modelling approaches for 1) background seismicity, i.e. earthquakes not occurring on mapped fault structures, 2) seismic activity from geologic and geodetic data on crustal faults and 3) along the interface of subduction zones. We elaborate on building a self-consistent rate model for crustal fault systems (e.g. Sumatra fault zone, Philippine fault zone) as well as the subduction zone, showcase its characteristics and combine this with an up-to-date ground motion model. We aim to present insights on the impact of the different hazard components on the final risk model.

1 INTRODUCTION

Over the past decades, the societies of many countries in Southeast Asia including mainland and maritime countries have suffered several severe earthquake catastrophes in terms of human casualties, loss of livelihoods and economic losses. The 2004 M9.0 Andaman-Sumatra Earthquake and the associated tsunami caused more than 225,000 fatalities, generating significant attention internationally due to the scale of its impact across the Indian Ocean. Overall economic losses from the disaster were approximately US\$10 billion, with the majority of loss attributed to tsunami damage in Indonesia, Thailand, Sri Lanka, and India.

The history of deadly earthquakes rupturing both, subduction zones and crustal faults, is well documented historically and are often accompanied by cascading effects such as tsunamis, landslides, and liquefaction. Examples of recent major destructive events on crustal faults along the Indonesian Islands include the December 1992 M7.8 Flores Earthquake with more than 2,500 fatalities, the May 2006 M7.7 Java-Yogyakarta Earthquake with more than 5,500 fatalities, and the September 2009 M7.9 Sumatra Earthquake with more than 1,000 fatalities. Similarly, the Philippines have experienced recent destructive earthquakes such as the August 1976 M8.0 Moro Gulf Earthquake on the trench southeast of Mindanao with more than 5,000 fatalities, and the July 1990 M7.8 Luzon Earthquake on the Philippines Fault with more than 1,600 fatalities.

The seismic risk has increased due to the rapidly growing populations and economies. As an example, the wider urban area of Jakarta (Indonesia) today has a high exposure density, is the most populous city in Southeast Asia and the fastest growing among the world's emerging economies. Metropolitan Manila, another area of high exposure density, has the second largest economy in Southeast Asia and accounts for 33% of the Philippines' GDP – while it is build largely on soft lake sediments and across the Marikina Valley Fault system that is capable of hosting M7+ events (see Valley fault atlas of the Philippine Institute for Volcanology and Seismology, PhiVolcs). Due to the combination of inevitable natural hazards and the rapid growth of exposure throughout the region, it is imperative to assess the societal and economic impacts for the entire Southeast Asia region.

We approach this challenge with a modeling philosophy that values the nature of the four basic modules for risk assessment (Fig. 1) and here primarily focus on the preparation of a comprehensive earthquake source model at the base of the stochastic event set and of the ground motion model. Rather than characterizing earthquake sources for single countries, we assess the national hazard across the national boundaries and assess the earthquake rates disregarding human-imposed boundaries, thus build a comprehensive earthquake source model for the existing large tectonic system (Fig. 2 left). While this is beneficial for the describing earthquake activity and ground motion modeling, it is important to include country-specific construction practices and cultural attitudes when assessing possible damage and quantifying risk metrics, both for mitigating risk for human lives or financial loss. This combined approach makes the model a unique source for its application in the region.

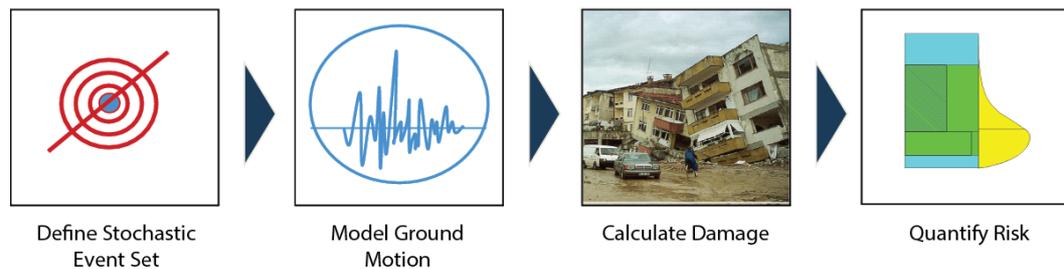


Figure 1: The four modules of seismic risk assessment (from left to right): The Stochastic Event Set module derived from the earthquake source model that characterizes long-term earthquake probabilities (rates); the Ground Motion Model with which the ground shaking spectral parameters are calculated for each event in the SES; the damage calculation module to assess average damage and uncertainties; the Risk of Financial Model to quantify the financial impact for all perspectives.

1.1 Tectonic Setting

Southeast Asia spans a tectonically complex area, characterized by high seismic and volcanic activity. The region is exposed to seismic hazard and its triggered effects such as tsunamis and/or landslides, originating from the forces causing the convergence of the tectonic plates. The Sunda block is centered in the heart of Southeast Asia and defines a stable region covering large areas of Indonesia, Malaysia, Thailand, and the Indochina countries up to southern China. The Sunda block is surrounded by active subduction zones and interfaces with the Eurasian/ Indian plate to the west, the Australian plate to the South, the Philippine plate to the east, and the stable southern China block to the north (Simons et al, 2007; Bird, 2003).

The Indian-Australian / Australian plate subducts at varying rates and angles between 45-55mm/year beneath the Sunda block, with an oblique direction along the Andaman-Sumatra trench section to a perpendicular direction at the Sunda and Java trench. The change in relative motion links directly to the transform faulting on the island of Sumatra prone to generate large crustal earthquakes. Complexity increases to the southeast of Indonesia, where multiple smaller plates exist due to the collision with the Australian and the Philippine plates, creating multiple smaller plates (Bird, 2003). The subduction zone system on the eastern side remains one of the least understood tectonic systems while converging with slip rates between 30-100mm/y and uncertain plate coupling ratios. The geometry of the bending subduction zone interface around the Banda sea, the double subduction zone of the Sangihe and Halmahera and their interplay are yet to be resolved. The Philippine Islands are squeezed in between the Philippine subduction zone in the east and the more irregular structures to the west, from Cotabato to the Manila subduction interfaces.

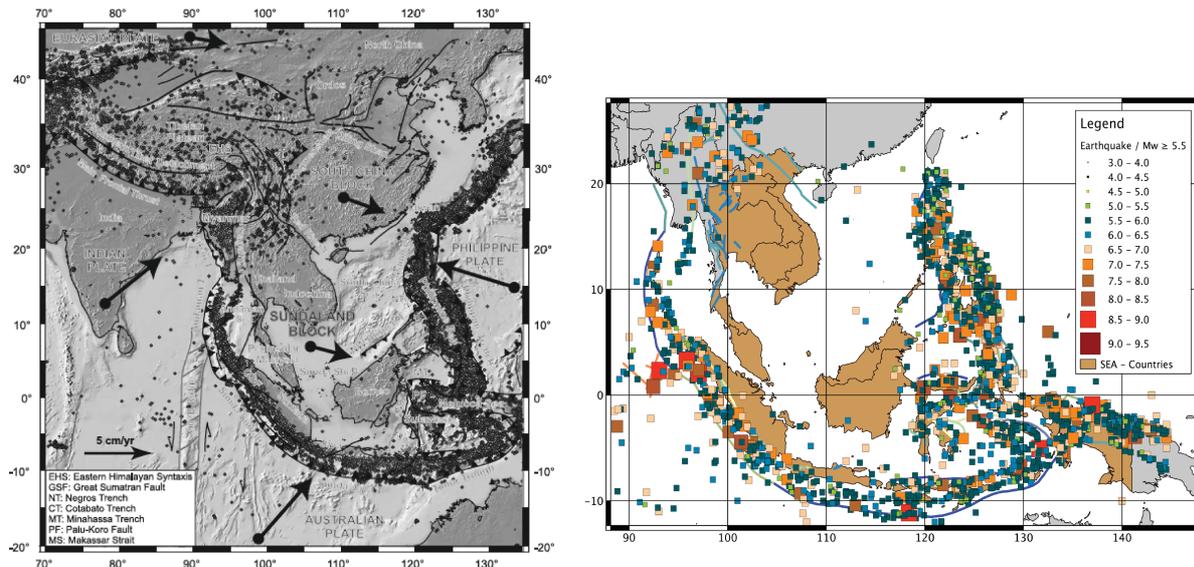


Figure 2: (Left) Tectonic overview for SE-Asia as depicted by Simons et al. (2007). (Right) Map of crustal earthquakes with depth $d \leq 50$ km and $M_w \geq 5.5$ since 1900.

Major intracontinental crustal strike-slip fault systems such as the Sumatra fault zone (Sieh and Natawidjaja 2000), the Philippine fault zone (e.g. Galgana, 2007) or the less broadly known Sulu-Sorong and the Palu-Koro fault systems (e.g. Molnar & Dayem, 2010; Simons et al., 2007; Socquet et al., 2006) act and form the regional tectonics and complicate the partitioning of the ongoing deformation.

Seismicity occurs throughout the known seismically active depth range and concentrates along the subduction zones and the tectonically related crustal faults: from events rupturing along crustal strike-slip faults (~ 0 -40 km depth) along the Sumatran fault, to the mega-thrust earthquakes on the subduction interface (~ 20 -60 km depth), and to deep focus inslab earthquakes (up to 700 km depth) below the Molucca and Banda Sea. These very deep events are not found historically in either the Sunda-Java section or the Andaman-Sumatra section that have recently shown the highest activity and the largest events in the region, such as the December 26, 2004, M_w 9.0 event. Last but not least, the region features some of the most unexpected events. Two examples are the 2012 Wharton basin $M8+$ event off-Sumatra, the largest strike-slip earthquake ever measured (Wei et al. 2013), and the 1977 Sumba $M8+$ normal faulting event in the outer rise of the Java subduction zone segment, that caused severe damage on the Indonesian islands.

2. DATA COMPILATION AND SOURCE MODELLING APPROACH

2.1 Earthquake catalog

We compiled an earthquake catalog from local and global sources following simple and reproducible rules. The catalog includes earthquakes listed in the IASPEI Centennial Earthquake Catalog (1900 - 2002) (Engdahl and Villaseñor 2002), USGS/NEIC PDE catalog (1973 - 2014.5) at (<http://neic.usgs.gov>), the ISC catalog (1901 - 2012) (<http://www.isc.ac.uk>), 4) and the GCMT (1976 - 2011) (Ekström et al. 2012) (Figure 2, right panel).

All catalogs provide in general differing hypocentral locations and various magnitudes types. Magnitudes of the same type are often not determined with the same algorithms and/or the same base parameters, thus all of them represent also a model of the “observed” seismicity. In a first step we derive a moment magnitude for each event using global scaling relations such as (Sipkin 2003; Lolli et

al. 2014) and if possible propagate the uncertainties in magnitude and location. We then compile a catalog using simple and hierarchical rules in line with the suggestions by the ISC (Di Giacomo et al., 2015, IUGG 1112). We define a preference scheme based on the choice of the catalog, the magnitude within the catalog, and the occurrence time of the event based on which duplicate selection is performed. The catalog is then declustered using windowing approaches to understand sensitivities and clustering foreshock and aftershocks (Woessner et al. 2015). As an example, less than 40,000 events remain when using the original Gardner and Knopoff (1974) windows (Figure 3).

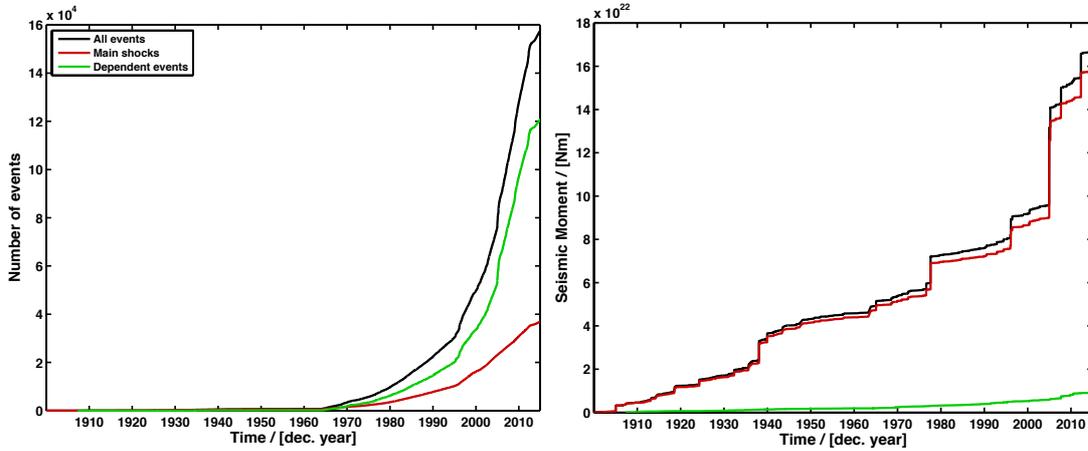


Figure 3: Number of events (left) and seismic moment release (right) for the entire compiled catalog as well as main shocks and dependent events. Dependent events include foreshocks and aftershocks.

2.2 Crustal Fault Model (CFM)

Earthquakes occur on faults and the majority of damaging events occur on major fault systems that are known to a certain limit. Several major intra-continental strike-slip fault systems are mapped or are currently being mapped by geological, seismic, or geodetic techniques such as the Sagaing fault in Myanmar (e.g. Wang et al. 2014), the Sumatra fault zone in Indonesia (e.g. Sieh and Natawidjaja 2000) or the Philippine fault zone mapped by scientists of PHIVOLCS and others. However, many more fault systems exist across the area that are less well known yet also capable of causing disastrous events.

We compile a crustal fault model that includes geometric and kinematic parameters to estimate earthquake activity rates based on multiple approaches. The model includes more than 22000km of surface traces and more than 100 fault sections (Figure 4). Similar to the earthquake catalog, the CFM is a compilation of data from multiple published resources. Faults are included whenever multiple independent sources reported slip rates.

The parameterization allows to generate several different activity rate models: characteristic-type models, moment constrained Gutenberg-Richter type models, and also seismicity based models with earthquakes associated with the fault systems. For each fault zone, a combination will be defined via a logic-tree.

2.3 Subduction Interface Model (SM)

Knowledge on the tectonics and therefore quality of the subduction zone geometry across the region varies considerably. Wherever possible, we use the Slab1.0 model available at the USGS websites, otherwise we delineate the interface geometry with simpler modeling approaches using the trench onsets (Bird, 2013) and a predefined constant dip such as in Heuret et al. (2011). We evaluate the interface geometry with comparisons to seismicity in cross-sections and results of tomography studies.

Subduction zone interfaces are characterized in the same way as crustal faults, thus we build a combination of the similar model types. We additionally use information on plate coupling when inferring possible recurrence times if available from published research. In-slab seismicity is treated within the background seismicity model at different depth levels in 50km volumes.

The subduction zone interface is modeled within large segments applying a doubly-truncated Gutenberg-Richter model and a characteristic rate for events above $M=8$. Segmentation is currently based on convergence rate variability, changes in convergence geometry, age of sea-floor and seismic productivity.

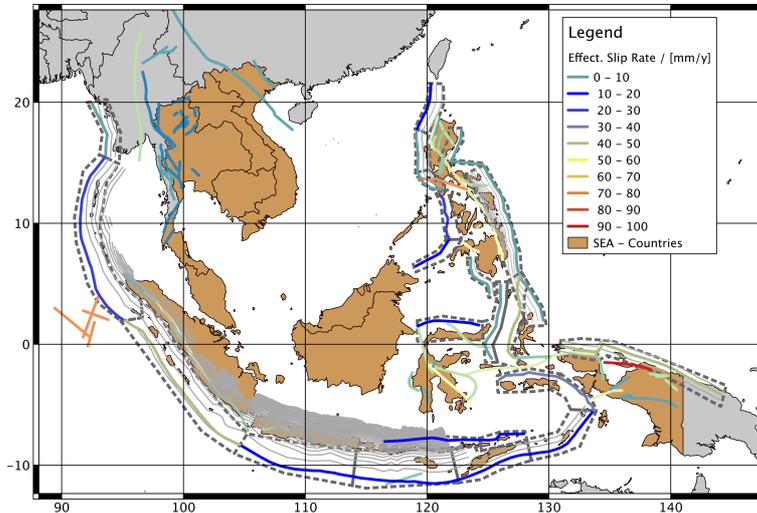


Figure 4: Preliminary subduction zones with their segmentation (dashed grey), and crustal faults differentiated by their effective slip rate.

2.4. Source Modelling Philosophy

We build a logic-tree based hazard model that combines the three the description of earthquakes on unmapped faults, or the background model (BGM), activity rates from the crustal fault model (CFM) and the subduction zone model (SM). We focus with more detail on the seismicity within the first 50km and model all seismicity that occurs below within the background model, as we focus to generate a risk-targeted event set.

The background seismicity is modeled with smoothed seismicity approach using an adaptive kernel approach as in (Hiemer et al. 2013; Woessner et al. 2015) applying an optimized kernel width. We use only events that are not associated to any fault or subduction zone to estimate kernel widths. We assume events up to magnitudes of $M8.8$ to occur in the background of the Indian / Australian plate based on the 2012 Wharton Basin (Wei et al. 2013) and assume values up to $M7.5$ in the Sunda-block region.

Crustal fault seismicity and subduction interface seismicity are both modelled with doubly-truncated Gutenberg Richter and characteristic type models as evidence for both behaviours exist (e.g. Bilek et al. 2007; Tormann et al. 2015; Meltzner et al. 2015) along subduction zones as well as along strike-slip systems. We also consider in particular for the CF model a moment balanced approach to estimate activity rates following Anderson and Luco (1983). The contributions of the models to the final logic-tree vary per region due to our perspective on the quality of the data and appropriateness of the approach.

3. GROUND MOTION MODEL

One of the important components for seismic hazard assesment is a well-selected suite of ground motion prediction equations (GMPEs) that are appropriate for the region of interest. This is required to 1) accurately capture the median ground motion and its uncertainty and 2) implement source parameters (e.g. earthquake magnitude) and path parameters such as site-to-source distance to define the seismic hazard at a site – that can be represented by peak ground acceleration (PGA) and pseudo-spectral acceleration (PSA) and 3) predict probability of exceedance of strong ground motion

parameters.

Southeast Asia has variable seismic hazard ranging from high seismic hazard associated with subduction zones beneath the Indonesian and Philippine archipelagos to moderately low seismic hazard across large stable region containing the Malaysian peninsula. There is a mix of reverse, thrust, strike-slip and normal-faulting within the region (Fig. 2 right). Therefore, we divided Southeast Asia into three different tectonic settings. Accordingly, we preliminary selected a set of GMPEs that are applicable to each region that covers countries of Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. We normalized all GMPEs to reference rock conditions (NEHRP B/C) with time averaged shear-wave velocity within top 30m of soil (V_{s30}) of 760m/s that is compatible with Southeast Asia seismic hazard maps (Building Seismic Safety Council, 2003).

3.2. Selection of GMPEs

The scarcity of strong ground motion data in Southeast Asia affects the reliability of GMPEs derived for this region, especially at near-field. This requires a careful selection of local and global GMPEs with comparable regions. We implement GMPEs to three tectonic regimes within Southeast Asia that are crustal interplate earthquakes from stable continental regions, crustal interplate earthquakes near plate boundaries, and interface earthquakes for subduction zones including intermediate and deep earthquakes within the slab. We define the selected GMPEs for each region in the following subsections.

3.2.1. Crustal interplate GMPEs

The GMPEs in this category apply to crustal faults in Thailand and Indonesia. We use NGA-W2 (Next Generation Attenuation) GMPEs that are applicable to active crustal regions worldwide that include Abrahamson et al. (2014), Boore et al. (2014), Campbell and Bozorgnia (2014) and Chiou and Youngs (2014). We assign equal weights to each GMPE.

3.2.2. Crustal intraplate GMPEs

GMPEs in this category apply to stable Sunda plate. We selected following GMPEs that are appropriate for stable continental regions: Toro and others (1997), Frankel and others (1997), Atkinson and Boore (2006'), Somerville and others (2001), Campbell (2003), Tavakoli and Pezeshk (2005), Silva and others (2005), and Pezeshk and others (2011). Weights for each GMPE are taken from USGS Seismic Hazard Map document for stable continental regions. We converted GMPEs that are developed for hard-rock conditions to NEHRP B/C by applying frequency-dependent factors derived from Frankel et al. (1997) and Atkinson and Boore (2011).

3.2.3. Subduction Zone GMPEs

Among the available GMPEs for subduction seismic sources, we decided to use globally developed subduction zone GMPEs that contain Zhao and others (2006), Atkinson and Boore (2003), and Abrahamson et al. (2015). We also investigated usage of Adnan and others (2014) that is specific for Peninsular Malaysia.

4. IMPACT ON RISK ASSESSMENT

The impact of the model choices on the hazard and risk metrics are at date of the revision preliminary and subject to change. Results will be presented during the conference.

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