



PSHA input model documentation for Turkiye (TUR)

GEM Hazard Team

Version history

Table 1 summarises version history for the TUR input model, named according to the versioning system described [here](#), and indicating which version was used in each of the global maps produced since 2018. Refer to the [GEM Products Page](#) for information on which model versions are available for various use cases. The changelog describes the changes between consecutive versions and are additive for all versions with the same model year.

Table 1 – Version history for the TUR input model.

Version	2018.1	2019.1	2022.1	2023.1	2026.1	Changelog
v2026.0.0					X	A new model developed by the GEM Secretariat for Turkey only.

The following text describes v2026.0.0.

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1 Summary

The model for Türkiye was developed alongside the larger model for the Middle East (MIE) during the EMME24 project. This model contains only the GEM sources covering Türkiye, as the EMME2024 model does not officially cover Türkiye.

The model was originally developed for the [OpenQuake \(OQ\) engine](#).

2 Tectonic overview

Türkiye sits at the junction of a number of major tectonic plates. The Eurasian plate lies in the north, and the Arabian plate moves obliquely against it in the southeast, with the relative plate motion accommodated by a distributed transpressional fault system extending northeast into the Caucasus region and to the southeast into the Alborz and Zagros thrust belts of Iran. Central and Southwestern Türkiye are on the Anatolian plate, which rotates counterclockwise relative to Eurasia, causing strike-slip faulting of 2 cm/yr on the North Anatolian fault in northern Türkiye (the source of many M 7 earthquakes in the 20th century), as well as distributed transtension into the Aegean Sea. The Anatolian plate moves to the southwest relative to the Arabian plate, with the East Anatolian fault as the primary plate-boundary fault, which hosted the 2023 M 7.8 Kahramanmaraş earthquake. The African plate subducts under the Anatolian plate in the Hellenic subduction zone in the Mediterranean sea south and southwest of the country.

3 Basic Datasets

The seismic source zones for region are constructed using the GEM global homogenised catalogue (Appendix A.1). Fault sources are developed from block modelling and inversion of faults as a system into single- and multi-fault ruptures with given probabilities. This is done using GEM's tools Oiler and Fermi, see B.

The ground motion logic tree was developed as part of the MIE model, using strong-motion data by B. Güryuva, O. Kale, and A.Sandikkaya.

4 Hazard Model

4.1 Seismic Source Characterisation

The seismic source model consists of a combination of distributed seismicity for 'off-fault' seismicity and multi-fault ruptures generated with Fermi.

The distributed component consists of 9 distributed seismicity sources, which were defined in the context of the Middle East model (MIE) and extend significantly beyond country boundaries. The catalogue is split into on and off-fault seismicity with the ‘off-fault’ events defined as > 30km from fault locations for $M > 6$ and all seismicity for $M < 6$. Each branch employs a different approach to declustering (Gardner and Knopoff, Gruenthal, and Uhrhammer, see Appendix A.5), and uses a fixed-kernel smoothing approach (similar to *Frankel (1995)*) to distribute rates spatially.

The ‘on-fault’ seismicity is instead used to calibrate an inversion for multi-fault ruptures with Fermi.

The final model is then a combination of distributed and fault components, with different branches for declustering weighted at 0.3, 0.3 and 0.4 respectively.

4.2 Ground Motion Characterisation

The ground motion models used in the TUR model are the same as those developed during the EMME24 project for the greater region. The ground motion logic tree for MIE 2026 considers a smaller number of core backbone ground motion models (GMM) to which a set of adjustments are applied. The epistemic uncertainties in ground motion are considered within these adjustments. For brevity, the weights of the modifications are not shown here, in reality the ground motion model is much more complicated than it appears.

Epistemic Uncertainties For every tectonic region, epistemic uncertainty is considered by using multiple GMPEs, each with an associated logic tree weight.

Active Shallow Crust	Weight
EMME24BB_GMM1SGM1 backbone	1.00
Subduction Interface	Weight
BCHydroESHM20SInter backbone	1.0
Subduction Inslab	Weight
BCHydroESHM20SSlab backbone	1.0
Deep Seismicity	Weight
BCHydroESHM20SSlab backbone	1.0

Table 2 – GMM weights by tectonic region

5 Results

Hazard curves were computed with the [OQ engine](#) for the following:

- Intensity measure types (IMTs): peak ground acceleration (PGA) and spectral acceleration (SA) at 0.1s, 0.2s, 0.3s, 0.6s, 1.0s, and 2s

- reference site conditions with shear wave velocity in the upper 30 meters (V_{s30}) of 760-800 m/s, as well as for V_{s30} derived from a topography proxy (Allen and Wald, 2009)

Hazard maps were generated for each reference site condition-IMT pair for 10% and 2% probabilities of exceedance (POEs) in 50 yrs. Additionally, disaggregation by magnitude, distance, and epsilon was computed for the following cities: Mbabane, Maseru and Pretoria. The results were produced as csv files and bar plots for each of the following combinations:

- hazard levels for 10% and 2% POE in 50 yrs
- PGA and SA at 0.1s, 0.2s, 0.3s, 0.6s, 1.0s and 2.0s
- $V_{s30}=800$ m/s

All calculations used a ground motion sigma truncation of 5. Onshore results were computed for sites with 6 km spacing.

Visit the [GEM Interactive Viewer](#) to explore the Global Seismic Hazard Map values (PGA for $V_{s30}=800$ m/s, 10% poe in 50 years). For a comprehensive set of hazard and risk results, see the [GEM Products Page](#).

6 References

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A Catalogues

Much of PSHA depends on the assumption that future seismicity will occur near observed past seismicity, and at rates that can be approximated by empirical or physical models. Thus, the early steps in PSHA include compiling and processing an earthquake catalogue. Beyond collecting instrumental and historic earthquake records, catalogues must be homogenized (expressed in uniform units), declustered (devoid of aftershocks and foreshocks), and filtered for completeness. The assumptions and uncertainties in the catalogue should be well understood by the modeler.

Most source types used in hazard models built by the GEM Secretariat use magnitude-frequency distributions (MFDs, Section ??) based on seismicity. Together with ground motion prediction equations (GMPEs), MFDs govern the computed hazard levels for time frames of interest, and so their robust calculation - and thus careful preparation of the input catalogue - is critical.

Here, we describe the GEM global catalogue which contributes the majority of earthquakes used in hazard models built internally by GEM; the workflow for combining other earthquake records with the global catalogue; and the remaining steps to prepare the catalogue for rate and spatial analysis. We emphasize that while most of these steps are routinely applied outside of GEM models, the following explanations only account for our own best practices.

A.1 The GEM global catalogue

The GEM global catalogue is a homogenised catalogue combining three global catalogues: the [ISCGEM](#) catalogue (*International Seismological Centre, 2025; Storchak et al., 2013, 2015; Di Giacomo et al., 2018*), the [Global CMT catalogue](#) (*Dziwonski et al., 1981; Ekström et al., 2012*) and the [comcat/ANSS](#) (*USGS, 2017*) catalogue and includes events from 1900, homogenised to M_W . This catalogue is periodically updated with new releases of the ISCGEM catalogue and to include more recent events from GCMT and comcat.

Recent regional models developed by the GEM Secretariat use the GEM extended catalogue, augmented by data from local agencies when possible.

A.2 Processing of seismicity catalogues

A.3 Catalogue homogenization

In order to use the bulletins from multiple agencies together in statistical analyses, records must be homogenized to meet the same criteria, e.g., to use the same measure of magnitude. Usually, moment magnitude (M_W) is selected, since it does not saturate at high magnitudes. Thus, magnitudes reported in other scales must be converted. When possible, this is done using empirical relations developed for independent local datasets, but relies on global relations when too few calibration events are available.

The homogenization methodology used to build the catalogues is described in detail in *Weatherill et al. (2016)*.

A.4 Completeness analysis

Catalogue completeness analysis accounts for the variability in instrumentation coverage throughout the catalogue duration, admitting that any catalogue is missing earthquakes beneath a magnitude threshold. This type of filtering prevents rate analysis of an incomplete catalogue - a modeling mistake that will propagate into hazard estimates. Importantly, completeness analysis must be applied to a declustered catalogue as to not confuse dependent earthquakes (such as aftershocks) with magnitude completeness.

The completeness algorithms that are applicable to *any* instrumental catalogue must depend on properties of the earthquakes, and not the stations, thus focusing on the statistics of the catalogue sample rather than the probability that a station at a known position would record an earthquake. The most common algorithmic method is by Stepp (1971), which compares the observed rate of seismicity to a predicted Poissonian rate for each magnitude, and returns a spatially constant table of time-variable magnitude thresholds. Importantly, the validity of this methodology is subject to the judgement of the user.

The Stepp (1971) is implemented in the OpenQuake Engine, and used in some steps of the modeling procedure for hazard models built by the GEM Secretariat. In other cases, we determine the completeness manually from 3D histograms that count earthquakes for magnitude-time bins, visually identifying the timings at which the occurrences rates stabilize. In recent models, we use a newly-developed approach that jointly estimates the completeness and recurrence parameters, implemented in the OQ Model Builder's toolkit (MBTK, Pagani et. al, 2026). This approach reflects the inter-dependence of these parameters.

A.5 Declustering

Catalogue declustering is applied in order to isolate mainshock earthquakes - that is, earthquakes that occur independently of each other - from a complete catalogue. The resulting declustered catalogue should therefore reflect the Poissonian rate at which earthquakes occur within a greater tectonic region. PSHA aims to model the hazard from seismicity occurring at this background Poissonian rate.

Declustering algorithms identify mainshocks by comparing individual earthquakes to the "cluster" of earthquakes that occurred within a given proximity and time to that earthquake, choosing the largest for a given set of magnitude-dependent "triggering windows". The theory of declustering algorithms is described in detail in *Stiphout et. al., 2012*. The [OpenQuake Hazard Modeler's Toolkit](#) provides three different windowing options: the original implementation of Gardner and Knopoff (1974), and additionally the configurations of Uhrhammer (1986) and Gruenthal (see Stiphout et al., 2012).

In subduction zones or other complex environments, we first classify the seismicity by tectonic domain (described below), and then decluster groups of domains within which we expect seismicity to interact (i.e., interface mainshocks can trigger crustal aftershocks), and then separate the deemed mainshocks into subcatalogues based on their tectonic classification. We typically use two groups: crustal, interface, and shallow slab seismicity (that beneath the interface but with intraslab mechanisms); and deep intraslab seismicity. The declustering algorithm comparing epicentral (*not* hypocentral) proximities, and thus, declustering by groups is crucial for seismicity within slab-type volumes.

A.6 Classification of seismicity

The workflow used by GEM to construct seismic source models in complex tectonic regions is dependent on the use of classified seismicity, that is, the assignment of each earthquake to a tectonic domain. Separating earthquakes in this manner allows us to compute MFDs from only the seismicity occurring within a delineated domain, thus more accurately characterizing individual seismic sources or source zones. For example, in subduction zones, we separate earthquakes occurring on the interface itself from those within the downgoing slab or the overriding plate. This allows us to model the hazard from these source types using the appropriate GMPEs.

At GEM, we classify seismicity using an procedure with similar theory to *Zhao et al., (2015)* and *Garcia et al., (2012)*, which assigns earthquakes to tectonic domains defined by the modeler. In subduction zones, earthquakes are usually categorized as crustal, interface, or intraslab based on hypocentral proximity to the Moho, and the interface and slab-top complex surfaces defined by the ([Subduction Toolkit](#)). Where subduction zones are modeled as segmented interfaces or slabs, the domains are divided accordingly. Each tectonic domain is defined by a surface and a buffer region based on general characteristics of the corresponding cross sections. The modeler provides a tectonic hierarchy that chooses among multiple assignments for earthquakes occurring within overlapping buffers of two or more domains. Usually, we specify interface superseding intraslab, and intraslab superseding crustal. Earthquakes that do not correspond to any of the defined domains are deemed “unclassified”.

The classification routine includes workarounds to correct some common misclassifications, such as to seclude dominant groups of earthquakes beneath a polygon (e.g., volcanic events); to classify large magnitude earthquakes from historic catalogues only by epicenter; and the ability to manually classify earthquakes by their event IDs.

A.7 References

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B Fault source characterisation

The most recent PSHA input models developed by GEM use two internally developed tools – Oiler and Fermi – to characterise active faults using block modeling and then construct seismic source models accordingly. The two tools and workflows are described here.

B.0.1 Geodetic-Geologic Block Model

GEM's state of practice has moved toward using geodetic-geologic block modeling to develop fault databases that can be used seamlessly as inputs to our fault source modelling tools. Fault slip rates are determined from an elastic block model which inverts geologic and geodetic data to estimate the motions of crustal blocks in the region, and the slip rates of intervening faults. The block modeling is performed using Oiler, GEM's program created for the purpose, and written in the Julia scientific computing language.

Block modeling is a well-established geoscience technique, building off of the fundamental mathematics of plate tectonics. Essentially, blocks are coherent bodies of the Earth's crust that are bound by faults or non-fault deforming zones (generally not seismically expressive). The instantaneous motion of any block can be described as a rotation around an 'Euler pole' or pole of rotation located at some position on the Earth. As no natural reference frame for global block motion exists, all rotations are relative to some arbitrary or convenient reference frame. The slip rate of a fault is the relative motion between adjacent blocks at the fault location.

For models built by the GEM Secretariat, blocks are mapped in QGIS at the same time as fault mapping. This allows for maximum compatibility between the faults and blocks and optimizes the geometry of each. The blocks are drawn so that they encompass the maximum amount of similar geodetic data available while still honoring the geometries of the faults and accounting for natural changes in rate along strike of a fault or due to branching or other complexities. Generally, blocks within a deforming zone have a handful of geodetic data in each, while the large tectonic plates surrounding the region (e.g., the Indian or Arabian plates) have hundreds or thousands.

Oiler assembles a system of equations for the motion of each block relative to the reference frame for each geodetic vector or geologic slip rate. The equations account for the effects of fault locking on the geodetic deformation field, but this does not affect the geologic slip rates. The system of equations is augmented by plate circuit constraints that ensure that the relative motion between any three plates is consistent regardless of the reference frame or basis of comparison, and then given additional regularization in the form of damping of velocities that prevent spurious solutions in underconstrained regions. The global system of equations is sparse, and solved through a weighted linear least squares solution using *LU* factorization using the SuiteSparse solvers. Once the system of equations is factorized, the global optimal solution is found. Then, uncertainties in the results are found through a Monte Carlo approach: the data vector is perturbed hundreds or thousands of times by sampling each data point from its uncertainty distribution, and then the factorized system

is iteratively solved. This produces a robust propagation of data uncertainties into the solution, which is then propagated into the uncertainties for the fault slip rates.

B.0.2 Fault Source Construction

Fault sources are created from fault information (e.g. geometries and kinematics) using GEM's tool Fermi for fault network rupture modeling, which yields faults that are capable of subfault ruptures (which involve a section of the fault surface) to multifault ruptures (in which single-fault ruptures on multiple faults rupture jointly). The fault surfaces are the same as those in the mapping and block model, i.e. there is no additional simplification of the fault geometries. The fault surfaces are first broken up into subfaults of equal dimensions, typically targeting 10 x 10 km. These subfaults are the smallest independent sources of fault ruptures on the fault system, producing ruptures about M_w 6.0. Then, larger ruptures are formed on each fault by assembling all contiguous, rectangular sets of subfaults that either a) have realistic aspect ratios (i.e., with a minimum along-strike width to down-dip length ratio of just under one and a maximum of 3), or b) fully saturate the down-dip extent of the fault, in which case there is no maximum aspect ratio. The minimum magnitude of rupture for a given fault is the smallest subfault, and the maximum magnitude is the largest multifault rupture that a fault participates in. Therefore, these parameters are determined through the fault network configuration and geometry, rather than imposed directly.

Once all of the single-fault ruptures have been created, multifault ruptures are found. First, all of the pairs faults that are within a specified maximum separation or 'jump distance' of 10 km are identified. From these pairs, an adjacency graph is created. Then, all possible multifault ruptures are enumerated through a depth-first search on the adjacency graph, with a maximum number of single-fault ruptures in an individual multifault rupture. For a regional model (such as many of the GEM Cones), only full-fault ruptures are allowed to participate in multifault ruptures, otherwise, billions of ruptures would be created, which is overly computationally demanding without adding much realism. After the ruptures are created, a score for the geometric and kinematic plausibility of each is calculated, and the rupture set is stochastically filtered proportionally to the plausibility.

Once the rupture set has been selected, the annual occurrence rates for each rupture are determined through an inversion of geological and seismological constraints. Inversion seeks to match the slip rates for each subfault (Figure 1), as well as matching a b -value on each subfault that is calibrated to match the regional seismicity rates and magnitude-frequency distribution a model-wide magnitude-frequency distribution may also be imposed. This calibration indicates a seismic slip rate fraction (the component of fault slip that is released in earthquakes modeled on the faults) that can be used to adjust the rupture rates to better reflect observations.

The rupture rate inversion creates a system of linear equations that is solved in a weighted, non-negative least squares sense using a simulated annealing solver. Figure 1 shows an example for the Central Asia (CEA) model, for which the both the slip rates and regional

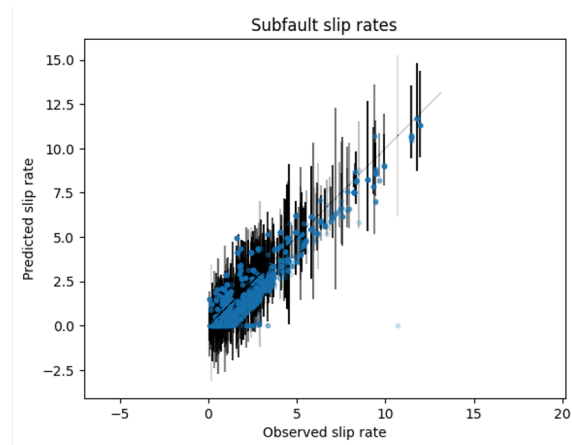


Figure 1 – Comparison between observed and modeled slip rates on the various faults within the investigated area. Observed slip rates are in black, with error bars shown on the y axis. The modeled slip rates are shown in blue. The diagonal black line indicates a 1:1 relationship (i.e., a perfect fit).

sesimicity constraints fit well.

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