Report on the Research Visit to ETH Zürich

During the research visit to ETH Zürich, carried out within the framework of the Geo-INQUIRE Transnational Access program, several activities related to the development of the seismogenic source model (SSM) and probabilistic seismic hazard assessment (PSHA) for North Macedonia were conducted.

The primary objective of the visit was to refine the input datasets and modelling strategy for the updated national seismic hazard model of North Macedonia, with particular focus on the earthquake catalogue curation and the development of the seismic source logic tree. These components represent fundamental inputs for probabilistic seismic hazard analysis, as the reliability of the hazard estimates strongly depends on the quality of the earthquake catalogue and the proper representation of seismic sources.

Earthquake Catalogue Curation

A significant portion of the visit was dedicated to the review and curation of the earthquake catalogue that will serve as the primary dataset for seismicity analysis. Earthquake catalogues are among the most important seismological products, since seismic hazard assessments rely heavily on the statistical analysis of past earthquake occurrence (e.g., frequency–magnitude distribution and spatial patterns of seismicity)

During the visit, the compiled catalogue for North Macedonia and the surrounding region was reviewed and finalized. The catalogue integrates multiple sources of information, including the national earthquake catalogue provided by the Seismological Observatory, as well as regional and international datasets. Historical earthquakes were compiled from sources such as the BSHAP catalogue and EPICA, while instrumental data were complemented with information from the ISC bulletin and other international databases. The catalogue was homogenized in terms of moment magnitude (Mw), ensuring compatibility with modern probabilistic seismic hazard analysis methodologies.

Particular attention was given to magnitude harmonization and consistency checks between different catalogues. Where necessary, magnitude conversions were applied to express all events in moment magnitude Mw, which is the preferred magnitude scale for PSHA studies. The final curated catalogue therefore represents a homogeneous dataset covering both historical and instrumental periods and provides the basis for further statistical analyses of seismicity.

Development of the Seismic Source Logic Tree

Another key objective of the visit was the development of the seismic source logic tree that will be implemented in the national hazard model. The logic tree approach allows the representation of epistemic uncertainties associated with different modelling assumptions and datasets. During the discussions at ETH Zürich, several alternative source models were defined to capture the range of possible representations of seismicity in the region.

- The first branch of the logic tree consists of area source models. Two alternative area source zonations were considered. The first zonation is based on the regional models used in the European Seismic Hazard Model 2020 (ESHM20) and the Balkan Seismic Hazard Assessment

Project (BSHAP). The second zonation follows the previous national seismogenic zonation that was used in the currently implemented seismic hazard model for North Macedonia. By including both alternatives in the logic tree, the modelling framework captures the epistemic uncertainty related to the spatial delineation of seismic sources.

For the earthquake catalogue processing, a declustering procedure was evaluated through sensitivity analyses. Based on the obtained results, it was decided to adopt the Gardner and Knopoff declustering algorithm as the preferred method for removing dependent events such as aftershocks and foreshocks. This choice ensures consistency of the earthquake rate estimation across the defined source zones.

In some of the defined area sources the number of earthquakes was insufficient to reliably estimate seismicity parameters. In such cases, a recalculation of the seismicity rates was performed by redistributing the number of events proportionally among neighbouring zones to obtain statistically meaningful estimates of the Gutenberg–Richter parameters.

To represent epistemic uncertainty in the seismicity parameters, three branches were defined for the a-value and b-value of the Gutenberg–Richter relation. These branches include the central estimated value and two additional values obtained by applying increments equal to the average standard deviation of the parameters

Similarly, three branches were adopted for the maximum magnitude (Mmax). The smallest value corresponds to the maximum observed magnitude within each source zone, while the other two branches were defined by adding increments of +0.3 and +0.5 magnitude units, respectively. This approach allows the hazard model to capture the uncertainty associated with the largest possible earthquakes that may occur within each zone.

In addition to the area source models, two further alternative approaches for representing seismicity were included in the logic tree.

- The second branch consists of a fault-based source model combined with background seismicity, which will be adopted directly from the ESHM20 model. This decision was taken due to the current lack of sufficiently detailed national datasets for the parametrization of active faults in North Macedonia. Therefore, the fault geometries and associated parameters from the European Fault-Source Model will be used as a regional reference.
- The third branch corresponds to smoothed seismicity models for the entire study region. Two alternatives will be considered: one using a fixed smoothing kernel and the other using an adaptive kernel approach. Smoothed seismicity models represent earthquake occurrence directly from the spatial distribution of past seismicity and provide an additional independent representation of seismic sources.

By incorporating area sources, fault-based sources, and smoothed seismicity models within the logic tree, the modelling framework captures the main alternative conceptualizations of seismic sources and therefore ensures a comprehensive treatment of epistemic uncertainty.

Training on OpenQuake and PSHA Concepts

In addition to the research activities described above, the visit also included a one-day intensive training session on the OpenQuake Engine, the open-source platform developed by the Global Earthquake Model (GEM) Foundation for probabilistic seismic hazard and risk calculations.

During this session, the fundamental concepts of probabilistic seismic hazard assessment were reviewed, including the role of seismic source models, ground-motion models, and logic tree structures in hazard calculations. The architecture and capabilities of the OpenQuake Engine were also presented, together with practical examples of hazard model implementation.

This training provided valuable insights into the workflow of PSHA calculations and the integration of input datasets into the OpenQuake framework.

Concluding Remarks

The research visit to ETH Zürich provided an excellent opportunity to advance the development of the seismogenic source model for North Macedonia. The activities carried out during the visit resulted in a curated and harmonized earthquake catalogue and a clearly defined seismic source logic tree that incorporates multiple alternative source representations.

The collaboration with experts at ETH Zürich also facilitated knowledge transfer related to modern PSHA methodologies and the practical use of the OpenQuake Engine. These outcomes represent an important step toward the development of the next generation seismic hazard model for North Macedonia.

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