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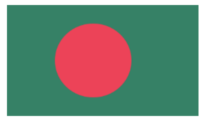
Earthquake Vulnerability and Systemic Risk Assessment in Bangladesh



Needs and Gaps Assessment and Interim Substantive Report as at 15 September 2023

Context analysis

Bangladesh is one of the world's most densely populated countries. Large parts of the landmass of Bangladesh and its surroundings are susceptible to earthquakes, ranging from the highly active Himalayan belt to the north of the country to the peninsula in the south which also suffers less frequent but nevertheless destructive earthquakes. Figure 1 shows the subduction plate boundaries around Bangladesh, with known earthquakes mapped on the southern end, and sections (shown in black) in the northern end that have not ruptured in the historic past but could potentially rupture.

Although much progress has been made in the last few decades in the field of earthquake engineering and on the development of seismic provisions for building codes in Bangladesh, a distressing proportion of the predominant building typologies, including much of the recent construction, is highly vulnerable to earthquakes. The rise of increasingly dense urban agglomerations in regions with moderate-to-high seismic hazard, the presence of easily liquefiable soils in the river deltas, the overwhelming prevalence of non-engineered structures, the lack of enforcement for code-compliance and absence of ductile detailing practices for buildings, and little-to-no maintenance of the ageing building stock makes for high seismic risk in many parts of Bangladesh.

Apart from direct human and economic losses, earthquakes can also lead to large-scale social disruptions and business interruptions, and recovering from these effects can often take several years. At present, evaluating the patterns of seismic risk across the country is of utmost importance to develop risk-informed building design guidelines, for more careful land-use planning, to optimise earthquake insurance pricing, and to enhance general earthquake risk awareness and preparedness. Decisions on the relative prioritisation of various earthquake risk mitigation policies can also be supported by the availability of an earthquake risk model for the country.

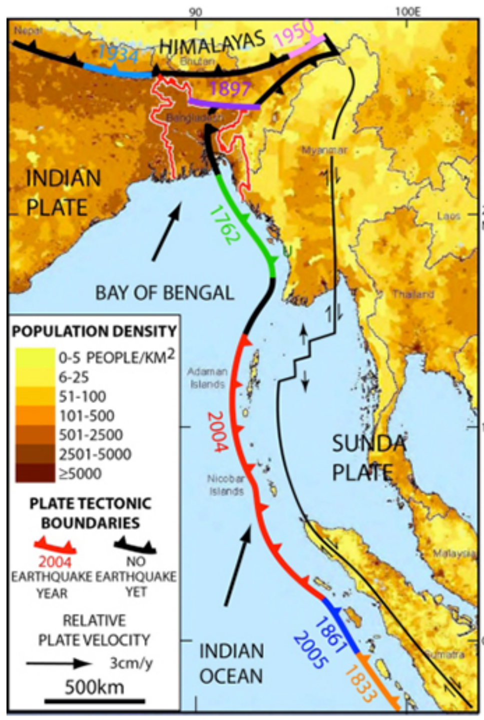


Figure 1. Subduction plate boundaries around Bangladesh.
Source: Michael Steckler / Lamont-Doherty Earth Observatory

In order to fully characterise the seismic risk across the country, each of the three major components that contribute to the risk needs to be studied and modelled in detail: (1) the seismic hazard component, which involves estimating the levels of shaking intensity that can be expected to occur in different regions of the country and their frequencies of occurrence; (2) the exposure component, which describes the geographical distribution and physical characteristics of buildings, infrastructure, and population; and (3) the seismic vulnerability component, which involves studying the behaviour of structures under earthquake loading to quantify the susceptibility of different types of buildings to the impacts of earthquakes. Whereas scenario-based or ''deterministic'' seismic risk analyses typically focus on highlighting the potential earthquake-induced damage and losses likely to occur for the scenario under consideration, a fully probabilistic seismic risk model takes into account any inherent variabilities and uncertainties that have been identified at every step, in an attempt to provide a more holistic representation of the earthquake risk in the region of interest.

There is clearly a gap signalled by the absence of an open seismic risk model for Bangladesh that may undermine the efficacy of earthquake risk management policies, programs, and investments. Within the scope of this project, we aim to bridge this gap to develop an open-source probabilistic seismic risk model for Bangladesh, and transfer key insights from the risk assessment to decision makers in the government and other key stakeholders in the disaster risk mitigation community in the country.

Needs and gaps assessment

Since its creation in 1972, the Ministry of Disaster Management and Relief (MoDMR) of Bangladesh has undertaken various disaster risk assessment and mitigation projects in collaboration with national and international organisations. The Comprehensive Disaster Management Plan (CDMP) was developed in 2004 as a collaboration between the MoDMR and United Nations Development Programme (UNDP). In recent years, several studies have been completed under the aegis of the CDMP, including studies on Engineering Geological Mapping, Quaternary Geological Mapping, Time-Predictable Fault Modeling, Seismic Hazard Assessment, and Seismic Vulnerability Assessment for the city corporations of Dhaka, Chittagong, and Sylhet. The CDMP project also involved the development of a building inventory through three levels of surveys of increasing detail in six cities in Bangladesh.

With the support of the Global Facility for Disaster Reduction and Recovery (GFDRR), the World Bank has also been working with the Government of Bangladesh (GoB) and the Earthquakes and Megacities Initiative (EMI) since 2012, through the Bangladesh Urban Earthquake Resilience Project (BUERP) to understand the structural vulnerability of urban buildings and infrastructure and address the seismic risk. The first phase of this project culminated in 2014 with the publication of the Dhaka Profile and Risk Atlas and the companion Dhaka Hazards, Vulnerability and Risk Assessment (HVRA) Guidebook. The vulnerability and risk analyses undertaken within BUERP relied significantly on the previous studies such as the CDMP.

More recently, a localised, sub-national Index for Risk Management (INFORM) was developed by the United Nations Resident Coordinator's Office (UNRCO) with funding from UNDRR and in collaboration with MoDMR with support from the Network for Information, Response and Preparedness Activities on Disaster (NIRAPAD) and the Bangladesh Bureau of Statistics (BBS). In addition to the INFORM, CDMP, and BUERP studies, there are also a significant number of informative publications in academic journals related to the earthquake hazard and risk in Bangladesh, eg. Morino et al. (2014)[1] who studied the Dauki fault, Alam and Dominey-Howes (2016)[2] who have compiled an earthquake

[1] Morino, M., Kamal, A. S. M. M., Akhter, S. H., Rahman, M. Z., Ali, R. M. E., Talukder, A., Khan, M. M. H., Matsuo, J., & Kaneko, F. (2014). A paleo-seismological study of the Dauki fault at Jaflong, Sylhet, Bangladesh: Historical seismic events and an attempted rupture segmentation model. *Journal of Asian Earth Sciences*, *91*, 218–226. doi:10.1016/j.jseaes.2014.06.002

[2] Alam, E., & Dominey-Howes, D. (2016). A catalogue of earthquakes between 810BC and 2012 for the Bay of Bengal. *Natural Hazards*, *81*(3), 2031–2102. https://doi.org/10.1007/s11069-016-2174-7

catalogue for the Bay of Bengal and Bangladesh, Rahman et al. (2020)[3] and Haque et al. (2020)[4] on probabilistic seismic hazard analysis. Rahman et al. (2015)[5] have also undertaken a liquefaction hazard mapping for Dhaka.

In consultation with key stakeholders within the disaster risk management domain in the country, including the National Disaster Management Organization (NDMO) and other national and local government authorities, these previous studies and others are being reviewed to develop a shared understanding of what already exists in the country in terms of datasets and knowledge, and to identify gaps and the needs and priorities of the potential end-users of the risk model and information.

Technical approach and methodology

The main objective of this project is to develop a detailed, open, sub-national earthquake risk model and evaluate seismic risk for Bangladesh at the zila and upazila level. The complete risk model itself comprises a probabilistic seismic hazard model, a building exposure model, and a seismic fragility and vulnerability model for the building stock of Bangladesh. Additionally, it also includes critical modelled scenarios for key cities, identified based on the results of the probabilistic risk assessment and in consultation with local stakeholders and experts.

For the earthquake hazard and risk assessment for Bangladesh we are starting from the Seismic Hazard and Risk Model for Bangladesh developed by the GEM Foundation. The updates and improvements on GEM's existing models undertaken during the course of this project, are described in the sections below.

Seismic hazard modelling and mapping

For the seismic hazard calculations, we started with the probabilistic seismic hazard model for the Indian subcontinent developed by Nath and Thingbaijam (2012)[6]. This seismic hazard model covers India, Bangladesh, Bhutan, and Nepal. An update and implementation of this model for the

[3] Rahman, M. Z., Siddiqua, S., & Kamal, A. S. M. M. (2020). Seismic source modelling and probabilistic seismic hazard analysis for Bangladesh. *Natural Hazards*, *103*(2), 2489–2532. doi:10.1007/s11069-020-04094-6

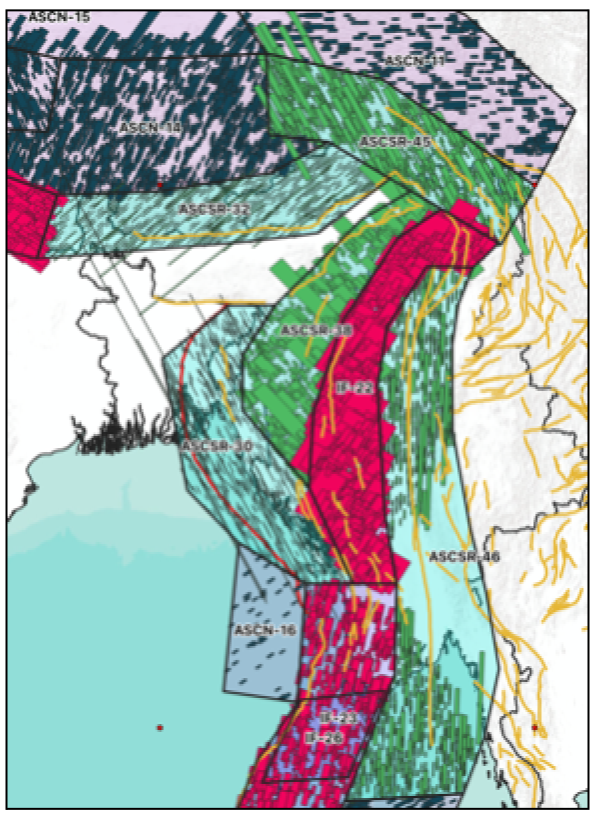
[4] Haque, D. M. E., Khan, N. W., Selim, M., Kamal, A. S. M. M., & Chowdhury, S. H. (2020). Towards Improved Probabilistic Seismic Hazard Assessment for Bangladesh. *Pure and Applied Geophysics*, *177*(7), 3089–3118. doi:10.1007/s00024-019-02393-z

[5] Rahman, M. Z., Siddiqua, S., & Maksud Kamal, A. S. M. (2015). Liquefaction hazard mapping by liquefaction potential index for Dhaka City, Bangladesh. *Engineering Geology*, *188*, 137–147. doi:10.1016/j.enggeo.2015.01.012

[6] *Nath, S. K., & Thingbaijam, K. K. S. (2012). Probabilistic Seismic Hazard Assessment of India. Seismological Research Letters, 83(1), 135–149. doi:10.1785/gssrl.83.1.135*

OpenQuake engine has been undertaken by Ackerley (2016)[7]. This model contains three seismogenic source models to account for epistemic uncertainties in the definition of earthquake occurrence: a single set of areal seismogenic source zones, and two smoothed-gridded point source models. A wide range of tectonic regions are considered, and epistemic uncertainties affecting the modelling of ground-shaking are accounted for by using multiple ground motion models (GMMs) per tectonic region. This model was also used to evaluate the seismic hazard in the Indian subcontinent for GEM's Global Seismic Hazard Map (version 2019.1).

We reviewed the seismic source model for northeast India to try to improve the earthquake source characterization in areas where the ruptures generated by the Nath and Thingbaijam (2012) model have unrealistic dimensions or orientations that would badly impact ground motion fields. We focused on two aspects: (1) ruptures of magnitude larger than M9 generated by source zone ASCSR-30 (see Figure 2 below), which includes the on-shore extent of the Arakan trench source and allows for events up to M9.55 which leads to some super large ruptures with unreasonable geometries (i.e. ones that completely cross Bangladesh with a very thin surface projection), and (2) sources with counter intuitive rupture orientations, including the two layers of intraslab ruptures in this area.



[7] *Ackerley, N. (2016). An Open Model for Probabilistic Seismic Hazard Assessment on the Indian Subcontinent. Istituto Universitario di Studi Superiori (IUSS), Pavia, Italy.*

Figure 2. Active shallow crust source regions

The Nath and Thingbaijam (2012) model uses area sources for the Main Himalayan Thrust (MHT). This creates really long, narrow ruptures that are considered unreasonable – for instance, the ruptures in pink in Bangladesh depicted below in Figure 3. We have replaced a few of the area sources in Nath and Thingbaijam (2012) with a simple fault source used to model the Main Himalayan Thrust in GEM's China seismic hazard model. This has the advantage that it now improves the geometry of the ruptures, although a potential disadvantage could be that it reduces along-strike variability in earthquake rates.

Figure 3. Main Himalayan Thrust

For the ground motion characterisation, we completed a thorough review of the existing logic tree, including both the assignment of sources to tectonic regions types (TRTs), and the ground motion models (GMMs) assigned to each TRT, ultimately reducing the number of TRTs (i.e. using a single one for the active shallow crust (ASC), independent of focal mechanism), using ASC GMMs for the Himalayan Thrust, and removing GMMs that have unrealistic trends, or those constrained or selected using limited data.

In addition to the probabilistic seismic hazard modelling, we also made an attempt to identify key historical earthquakes and potential hypothetical future earthquakes, and began the work of modelling the rupture geometries for these events, which would be useful for scenario-type hazard and risk analyses.

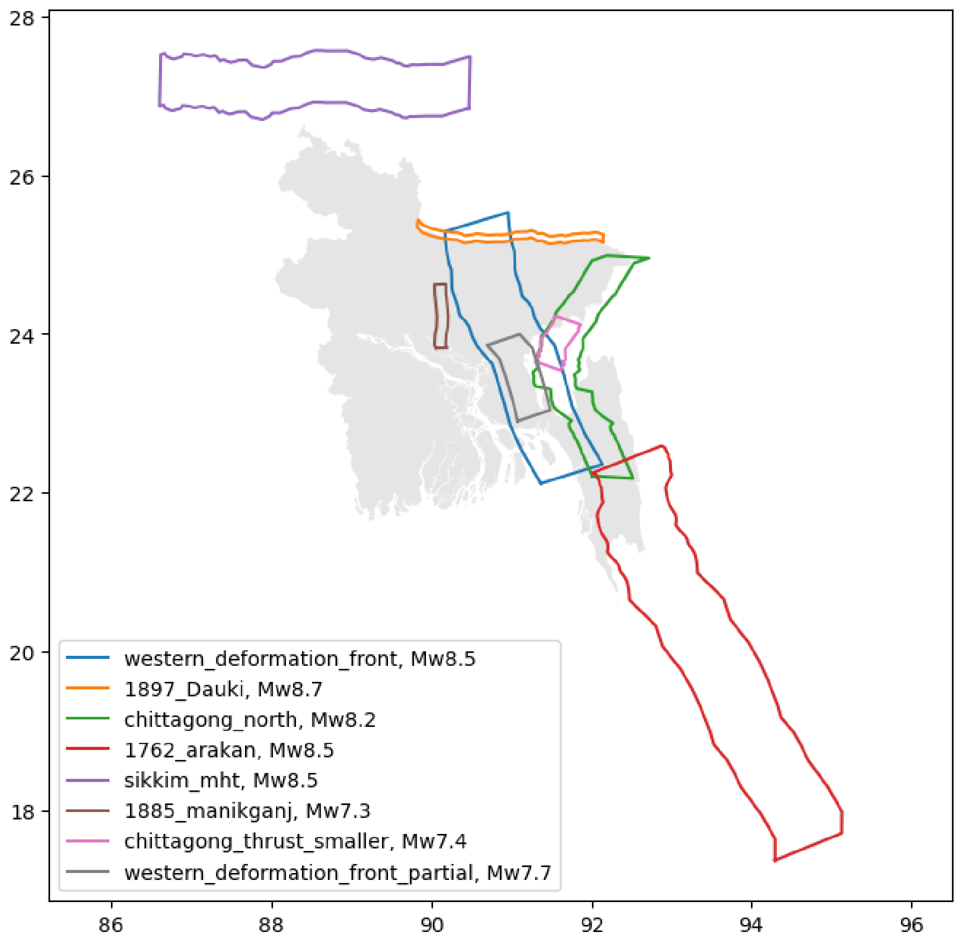


Figure 3. Preliminary scenario set, including both historical and hypothetical earthquakes

Liquefaction susceptibility and hazard assessment

We added several recently published regional liquefaction occurrence models to the OpenQuake engine, including the models described in Allstadt et al. (2022)[8] which are currently used within the US Geological Survey's (USGS) ground failure (GF) product, and the machine learning based nonparametric model of Todorovic and Silva (2022)[9]. These regional models attempt to predict ground failure using existing mapped information and above-ground inferences of below-ground conditions, generally at coarse spatial resolutions, and are more suitable for the national scale liquefaction

[8] Allstadt, K. E., Thompson, E. M., Jibson, R. W., Wald, D. J., Hearne, M., Hunter, E. J., Fee, J., Schovanec, H., Slosky, D., & Haynie, K. L. (2022). The US Geological Survey ground failure product: Near-real-time estimates of earthquake-triggered landslides and liquefaction. *Earthquake Spectra*, *38*(1), 5–36. doi:10.1177/87552930211032685

[9] Todorovic, L., & Silva, V. (2022). A liquefaction occurrence model for regional analysis. *Soil Dynamics and Earthquake Engineering*, *161*(February), 107430. doi:10.1016/j.soildyn.2022.107430

hazard assessment that we plan to do in the second phase of this project, in comparison to some other semi-empirical "stress-based" or "energy-based" models which use in situ geotechnical data and mechanistic principles to predict liquefaction response for individual sites or for areas where detailed soil profiles and geotechnical data are available.

Exposure modelling

Exposure models for seismic risk assessment need to contain information regarding the number of buildings, geographical location, replacement costs (including the structural and nonstructural components, and the building contents), number of occupants, and vulnerability classes of the building stock characterised using the well-known and widely used GEM Building Taxonomy. Overall, GEM's current exposure data for Bangladesh covers the residential, commercial, and industrial built assets in the country. GEM's exposure dataset contains aggregated information about the building stock at the district (zila) and sub-district (upazila) level. GEM's residential exposure model for Bangladesh is based on the 2011 Population and Housing Census, and the commercial and industrial exposure model is based on the 2013 Economic Census.

We have updated the administrative division hierarchy used in the exposure model to reflect the current structure as of December 2022. Although the detailed housing tables from the 2022 Population and Housing census at the upazila and further levels (i.e., union/ward, mauzas/mahallas, and village level) are not yet available, the preliminary population and household counts at the zila level have been released recently and have been used to update the respective counts in the residential exposure model. Figure 4 below shows the population counts at the upazila level, from the preliminary results of the 2022 Population and Housing census.

Similarly, the commercial and industrial building exposure models have been updated based on the results of the 2022 Bangladesh Economic Review. Any additional information obtained from the Ministry of Housing, MoDMR, Bangladesh Bureau of Statistics, or other ministries will also be taken into consideration during the exposure model update phase, for example social service infrastructure such as schools, clinics, hospitals, water utilities, etc. Figure 5 shows the proportion of the exposed value according to primary construction class at the national and division level. While these summaries are shown at the division level, similar insights are currently being generated at the zila and upazila levels.

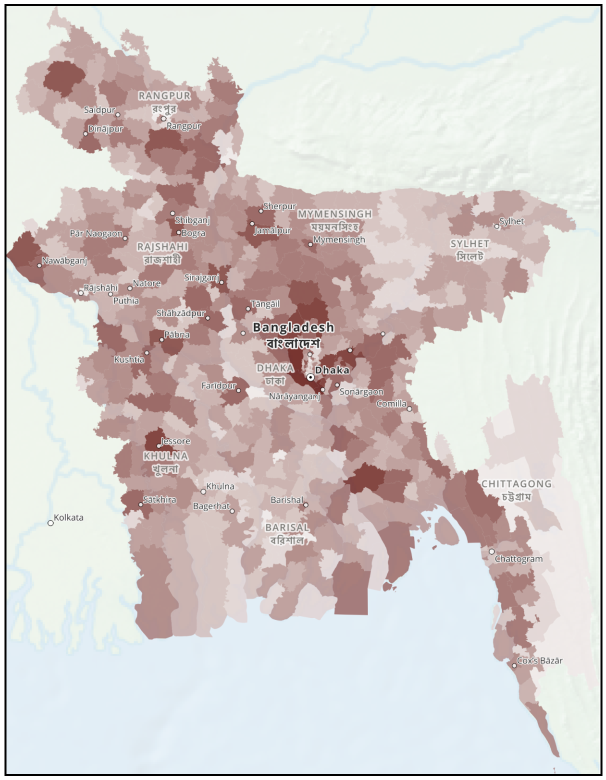


Figure 4. Population at the upazila level, from the preliminary results of the 2022 Population and Housing census

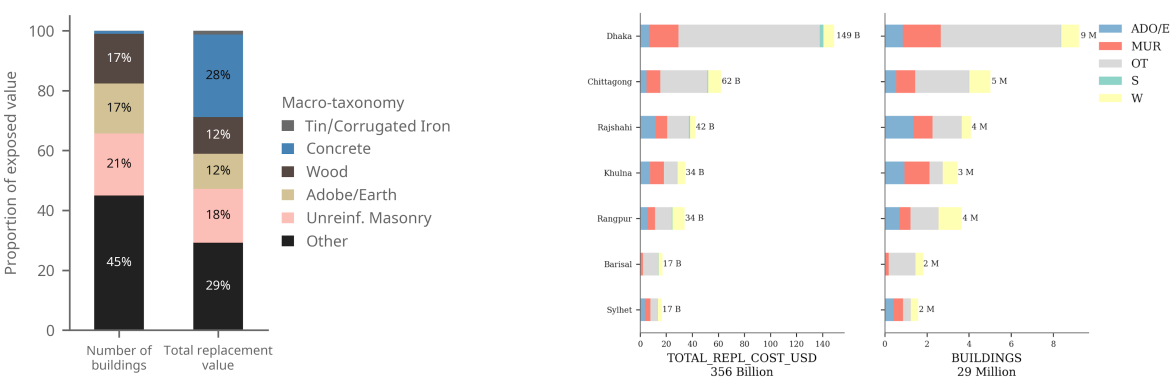


Figure 5. Proportion of exposure according to primary construction class at national and division level

Seismic fragility and vulnerability model

Earthquake fragility and vulnerability models are a critical component for seismic risk assessment. These models describe the potential for damage and expected loss in buildings, other infrastructure elements, and for human occupants, conditional on the intensity of ground shaking due to an earthquake experienced at the location of the assets. In principle, such models can be developed by empirical methods using large datasets of damage and economic losses considering the impact of past destructive events. However, the lack of damage data from previous earthquakes in Bangladesh, or insufficient detail in the available information from neighbouring countries prevents the direct use of empirical models in earthquake loss estimation.

Thus, for the earthquake risk model for Bangladesh, we are planning to employ a set of analytically derived fragility and vulnerability functions for the assessment of the economic losses. While the initial set of vulnerability functions used in this loss model have been selected from GEM's global earthquake vulnerability database[10], the specific characteristics of the building stock of Bangladesh are being accounted for through adjustments that reflect the structural particularities described in the exposure component. Adjustments to existing vulnerability functions, and the derivation of new functions was particularly necessary for the informal construction, including kutcha houses made of corrugated iron or tin sheets that are common in rural areas, and for houses made from thatch, polythene sheets or scrap material which are observed in the informal settlement areas in cities. In addition to assessing the vulnerability of the building stock, we have also leveraged existing datasets, including the highly detailed demographic data from the 2011 national census, to map the socio-economic vulnerability of the population. Updated information regarding the wall type, roof type, and floor type of houses across the country has been collected as part of the 2022 Household Income and Expenditure Survey (HIES) conducted by the Bangladesh Bureau of Statistics (BBS), and this information can be incorporated into the exposure model conditioned on the availability of the microdata from the survey.

Seismic risk assessment

The estimation of the seismic risk metrics is being performed using the stochastic event-based risk assessment calculator of the OpenQuake-engine. In this calculator, the previously described probabilistic seismic hazard analysis model is used to create an earthquake rupture forecast (i.e., a list of all of the possible ruptures that can occur in the region of interest with the associated probability of occurrence in a given time span), which is then employed to generate a stochastic event set (SES) spanning a long (say 100,000 year) period. Economic and human losses are calculated for every event in the SES, generating event loss tables (ELT) and year loss tables (YLT). These loss tables are then used for the calculation of various risk metrics, including exceedance probability curves and average annualised losses. Fatality and injury estimates are based on human vulnerability models that are conditioned on structural collapse, and informed by human casualties reported in past earthquakes globally, but with particular weight given to developing countries in South Asia and Southeast Asia that have building stocks similar in structural characteristics to Bangladesh. All of the aforementioned risk metrics are being computed and tabulated at the national, divisional, district (zila), and subdistrict (upazila) levels. Figure 5 shows the maps for exposure, seismic hazard, and average annual losses at

[10] Martins, L., & Silva, V. (2020). Development of a fragility and vulnerability model for global seismic risk analyses. *Bulletin of Earthquake Engineering*. https://doi.org/10.1007/s10518-020-00885-1

the divisional level, computed using GEM's current hazard and risk models for Bangladesh. Similar maps will also be generated at the zila and upazila levels.

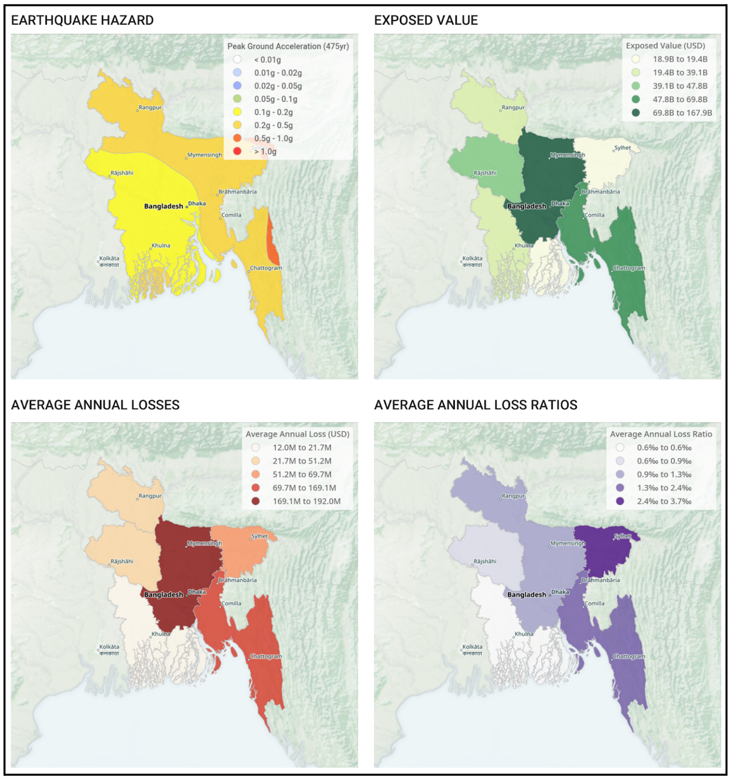


Figure 5. Clockwise from top-left: (i) Seismic hazard map for Peak Ground Acceleration (PGA) at the 10% in 50-year hazard level, (ii) Exposed value at the division level, (iii) Average Annual Loss Ratios (AALR) at the division level, and (iv) Average Annual Loss

In addition to the building stock, we are also assessing the exposure of healthcare facilities (including hospitals), educational facilities, and the national road network to seismic hazards. If information about other critical lifelines such as the water supply network or the electricity network is made available through the Local Government Engineering Department (LGED) or other governmental bodies, we will also be able to assess the seismic risk for these systems. As mentioned in the seismic hazard section previously in this report, we have also begun identifying scenario earthquakes for key cities, including both events representing a combination of historical earthquakes that have affected Bangladesh, as well as potential hypothetical future events.

Technical panel formation and engagement

The UN Resident Coordinator's Office in Bangladesh has helped identify key technical experts and stakeholders, who will form the technical panel. The panel will be headed by the Additional Secretary of the Ministry of Disaster Management and Relief (MoDMR) of Bangladesh, and includes representatives from the Department Of Disaster Management (DDM), the Fire Service and Civil Defence of Bangladesh, the Ministry of Housing & Public Works (MoHPW), and the Statistics and Informatics Division (SID) of the Bangladesh Bureau of Statistics (BBS). The panel also includes national experts in seismic hazard and risk assessment from the University of Dhaka (DU), Bangladesh University of Engineering and Technology (BUET), and Jahangirnagar University (JU). The Geological Survey of Bangladesh, the Centre for Urban Studies (CUS), and United Nations Development Programme (UNDP), Bangladesh are also represented on the panel of experts. Table 1 below lists the members of the technical advisory panel. A series of four (online) meetings are being planned with the technical panel, starting with an introductory session on October 9th. This will be followed by focussed discussions on the seismic hazard component, exposure and vulnerability component, and social vulnerability and seismic risk. Feedback and suggestions from the panel will be incorporated into the modelling workflows and outcomes of the project. The panel members will also be invited to participate in the final in-person workshops near the end of the project.

Table 1. Technical Panel

Name	Designation	Organization	Contact
Md. Hasan Sarwar	Additional Secretary	Ministry of Disaster Management and Relief (MoDMR)	rchmodmr@gmail.com
Kazi Wasi Uddin	Secretary	Ministry of Housing & Public Works	secretary@mohpw.gov.bd
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Dr. Mehedi Ahmed Ansary	Professor	Department of Civil Engineering, Bangladesh University of Engineering and Technology	ansary@ce.buet.ac.bd
Dr. Raquib Ahsan	Professor	Department of Civil Engineering, Bangladesh University of Engineering and Technology	raquibahsan@ce.buet.ac.bd
Mohammad Elius Hossain	Director General (Additional Charge)	Geological Survey of Bangladesh	geologicalsurveybd@gmail.com

Brig. Gen. Nayeem Md. Shahidullah	Former Director General	Fire Service and Civil Defence	nayeem.shahidullah@gmail.com
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Dr. Khandakar Hasan Mahmud	Professor	Jahangirnagar University	khmmahmud@geography-juniv.edu.bd
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