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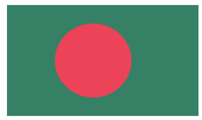
Earthquake Vulnerability and Systemic Risk Assessment in Bangladesh



Interim Substantive Report as at 31 December 2023

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. The work undertaken on various aspects of this project between 15th September 2023 (end of the last reporting period) and 31st December 2023 is summarised briefly in the sections below.

Historic and hypothetical earthquake scenario development

We completed the work of identifying major historical events and potential hypothetical future events for the purposes of scenario development. We have constructed the rupture geometries for these events and also identified a set of ground motion models that can be used for each event. The full scenario set consists of six historical events from 1664-1918, chosen out of many in this time, supplemented by five hypothetical events.

All historical ruptures have been placed on known faults, rather than hypocenters from inversions of historical intensity data. The set of historical ruptures is shown below in Figure 1. In addition, we have also selected five potential hypothetical ruptures, mostly in the east, placed on well-known, fast-slipping faults. These are shown below in Figure 2. Some of these represent worst case earthquakes for Bangladesh, and while their likelihoods of occurrence remain small, they are nevertheless, deemed plausible events. In the final phase of the project, we will be concluding the scenario assessment by estimating the ground shaking, damage, economic losses, and potential fatalities that could be caused by each of these 11 scenario events.

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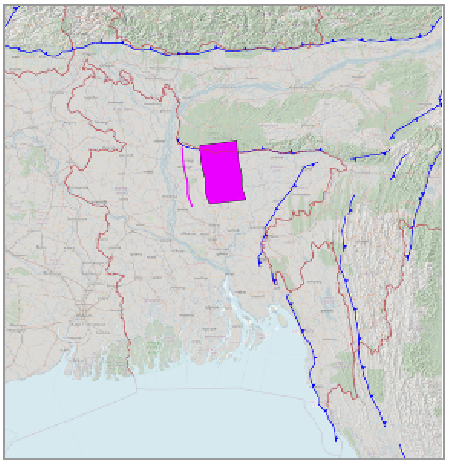
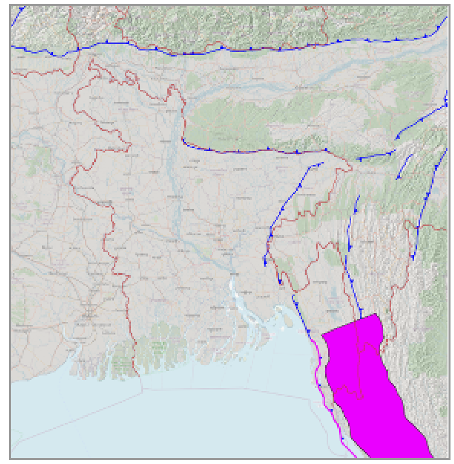
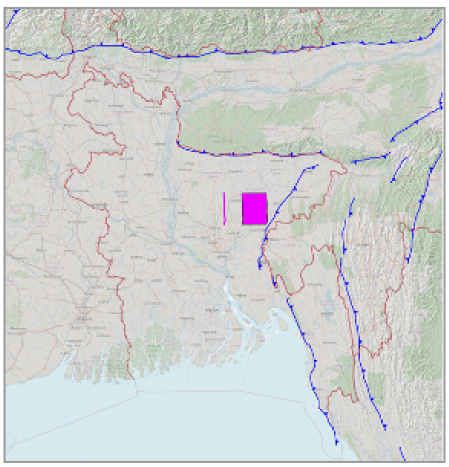


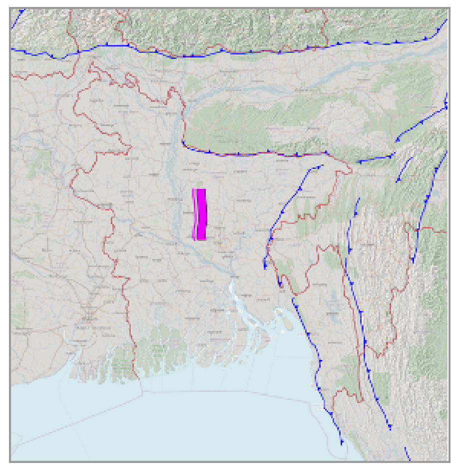
1664 M7.7 North Bangladesh earthquake



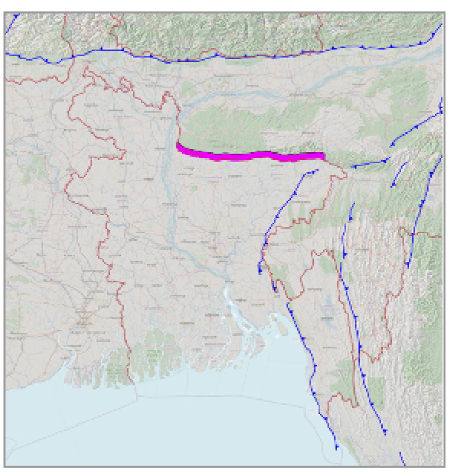
1762 M8.5 Arakan earthquake



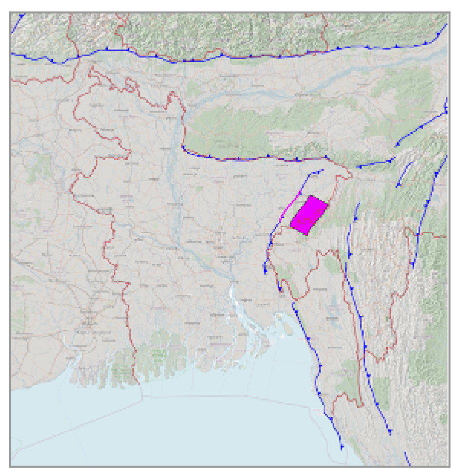
1822 M7.1 Kishoreganj earthquake



1885 M7.2 Manikganj earthquake

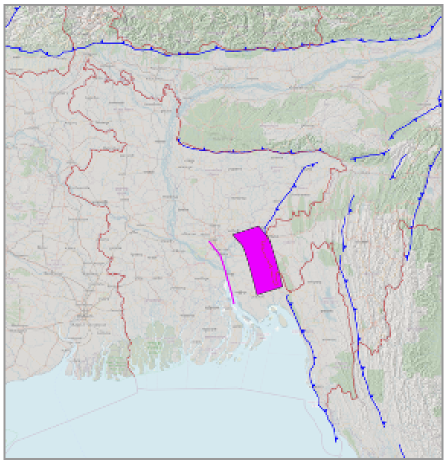


1897 M8.7 Shillong earthquake

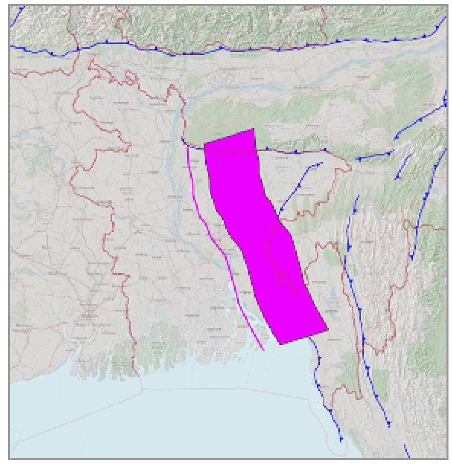


1918 M7.4 Srimangal earthquake

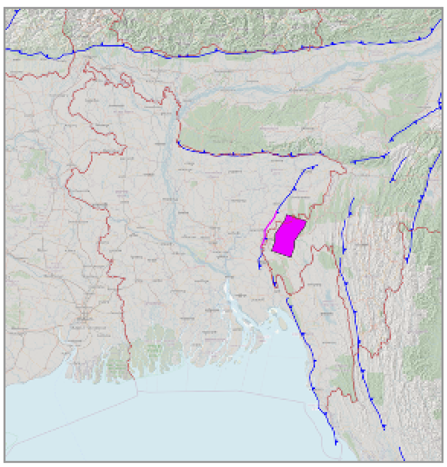
Figure 1. Set of historical earthquake scenarios



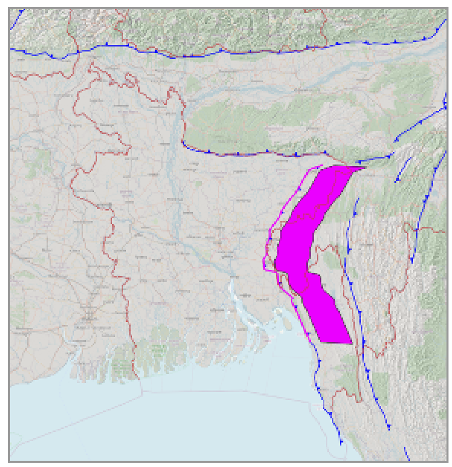
M7.7 Western deformation front – partial rupture



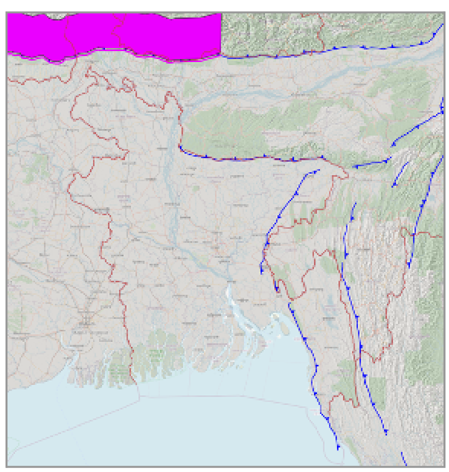
M8.5 Western deformation front – full rupture



M7.25 Chittagong thrust – moderate rupture



M8.2 Chittagong/Sylhet-Assam – full rupture



M8.5 Sikkim Main Himalayan Thrust

Figure 2. Set of hypothetical earthquake scenarios

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Liquefaction susceptibility and hazard assessment

A common practice in seismic risk assessment is to estimate the annual rate of exceeding a decision variable of interest to stakeholders (e.g., fatalities, economic loss) due to *ground shaking*. Assessing the hazard and risk due to *ground failure*, however, is still uncommon, despite the severe consequences of ground failures (e.g., soil liquefaction). The reasons are numerous, some of them being relatively lower losses compared to those caused by ground shaking and an insufficient amount of observations that would assist in developing robust large-scale assessment procedures (e.g., urban, national, and regional). Losses due to liquefaction contributed to 2.2% of direct economic losses in earthquake events worldwide, a statistic compiled from over 7,000 global earthquakes between 1900 and 2012 (Daniell et al., 2012[1]). Considering indirect losses as well, the contribution increases to 3.6% (Paolella et al., 2021[2]). However, in the case of Bangladesh, we have reason to expect damage and losses from earthquake-induced liquefaction to be much higher than the global average, considering that the major part of the country is situated in a river delta with deep deposits of saturated soft soils combined with high average annual precipitation which can significantly increase the susceptibility of liquefaction.

Soil liquefaction is a spatially localised phenomenon in a saturated, cohesionless medium when the shear strength and stiffness decrease due to increased pore water pressure. Liquefaction hazard assessment requires answering several questions, starting with whether the soil deposit is susceptible to liquefaction occurrence or not. If yes, what is the level of shaking (e.g., amplitude, duration) that will lead to liquefaction occurrence (scenario-based analysis)? One can also conduct an event-based analysis to include all the events contributing to the total liquefaction hazard (annual rate of occurrence) with non-negligible probabilities. Lastly, one should answer how severe the consequences (e.g., ground settlement, lateral spreading) triggered by liquefaction occurrence are. Soil liquefaction is a localised phenomenon that does not happen everywhere but is rather limited to specific geological settings, where the sedimentation process, age of deposition, water depth, grain-size distribution, and geologic history characterise the ground failure susceptibility. Younger deposits (Holocene age) are more susceptible than older deposits (Pleistocene age). Areas settled in coastal regions to accommodate the growing population needs are typically filled in with hydraulic fill, artificial landfills, or young mud deposits, which are characterised by higher susceptibility. Given the topography, once the liquefaction is initiated, various ground failure types may occur, such as a crack opening in flat terrain, landslide-type failure on steep terrain, and lateral spreading on gentle slopes. These induced effects could lead to significant damage beyond economic repair.

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[1] Daniell, J. E., Khazai, B., Wenzel, F., & Vervaeck, A. (2012). The Worldwide Economic Impact of Historic Earthquakes. *15th World Conference on Earthquake Engineering*, Paper No. 2038.

[2] Paolella, L., Spacagna, R. L., Chiaro, G., & Modoni, G. (2021). A simplified vulnerability model for the extensive liquefaction risk assessment of buildings. *Bulletin of Earthquake Engineering*, *19*(10), 3933–3961. https://doi.org/10.1007/s10518-020-00911-2

Despite having seen no significant earthquakes in the last century, Bangladesh is an earthquake-prone country, ranging from the highly active Himalayan belt in the north to the peninsula in the south which has witnessed less frequent yet destructive events such as the 1762 Mw 8.5 Arakan earthquake. The earthquake sources near high population density centres such as Dhaka (e.g., Madhupur fault) show potential for generating shallow crustal events. Furthermore, the country is underlain by deposits with a high potential for amplifying ground motions and liquefaction.

To address the assessment of liquefaction hazard, we conducted both scenario-based analyses (liquefaction potential due to specific earthquake ruptures) and event-based analysis in which we assessed the contribution of various earthquake sources to the total liquefaction hazard (Figure 4). To perform the analysis on a national scale, we used geospatial models that rely on globally available proxies used to explain the mechanics behind liquefaction occurrence – such as average shear wave velocity in the top 30 metres of soil, average annual precipitation, distance to the nearest river or coast, and peak ground velocity and acceleration due to earthquake ground shaking. Geospatial models are more broadly applicable for regional analysis (though perhaps with reduced prediction accuracy) in comparison to locally applicable "site-specific" methods, which rely extensively on the use of field surveys to measure soil parameters that correlate with soil liquefaction occurrence. The liquefaction analyses were conducted using OpenQuake engine (Pagani et al., 2014[3]).

We compared two models: a parametric model described by Allstadt et al. (2022)[4], which is the model used within the USGS Ground Failure Product, and a non-parametric model proposed by Todorovic and Silva (2022)[5]. The results of the scenario-based analysis are displayed qualitatively (with classifications ranging from "exceptionally unlikely" to "virtually certain"), i.e., describing the likelihood of soil liquefaction using the IPCC (2010)[6] likelihood scale for describing the quantified uncertainty. We considered each of the 11 scenarios described in the previous section; however, we only show

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[3] Pagani, M. M., Monelli, D., Weatherill, G. A., Danciu, L., Crowley, H. M., Silva, V., Henshaw, P., Butler, L., Nastasi, M., Panzeri, L., Simionato, M., & Viganò, D. (2014). OpenQuake Engine: An Open Hazard (and Risk) Software for the Global Earthquake Model. *Seismological Research Letters*, *85*(3), 692–702. https://doi.org/10.1785/0220130087

[4] Allstadt, K. E., Thompson, E. M., Jibson, R. W., Wald, D. J., Hearne, M. G., 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. https://doi.org/10.1177/87552930211032685

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

[6] Mastrandrea, M. D., Field, C. B., Stocker, T. F., Edenhofer, O., Ebi, K. L., Frame, D. J., Held, H., Kriegler, E., Mach, K. J., Matschoss, P. R., Plattner, G. K., Yohe, G. W., & Zwiers, F. W. (2010). Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties IPCC Cross-Working Group Meeting on Consistent Treatment of Uncertainties. *Intergovernmental Panel on Climate Change (IPCC)*, http://www.ipcc-wg2.gov/meetings/CGCs/index.html#U.

here the results from the historical 1885 Mw7.25 "Manikganj" earthquake (Figure 3) that ruptured the Madhupur fault and caused destruction in Dhaka.

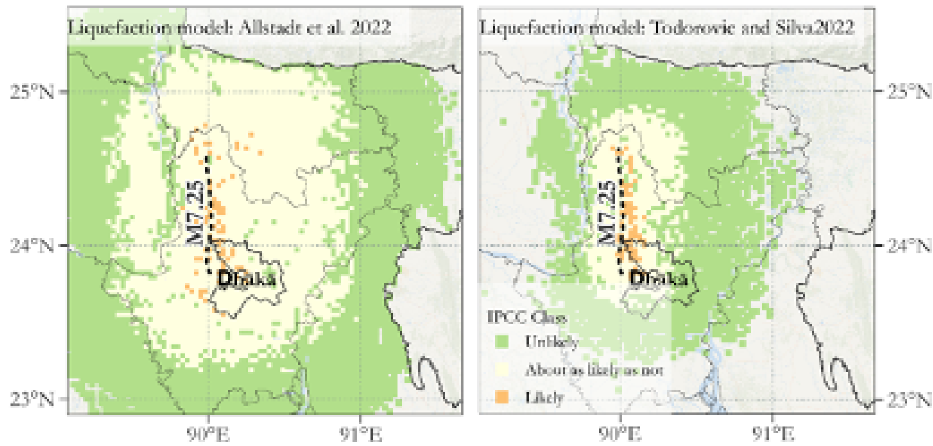


Figure 3. Scenario-based liquefaction assessment considering the 1885 M7.25 Manikganj earthquake; (left) using the parametric model described in Allstadt et al. (2022); (right) using the non-parametric model proposed by Todorovic and Silva (2022).

In addition to scenario-based liquefaction assessment, we also undertook stochastic event-based liquefaction assessment, where we now consider the contribution of all possible earthquake sources to the total liquefaction hazard. The primary outcome of this analysis is the annual occurrence frequency of liquefaction (Figure 4), an outcome that is typically convolved with the exposure and vulnerability models to conduct probabilistic seismic risk assessment.

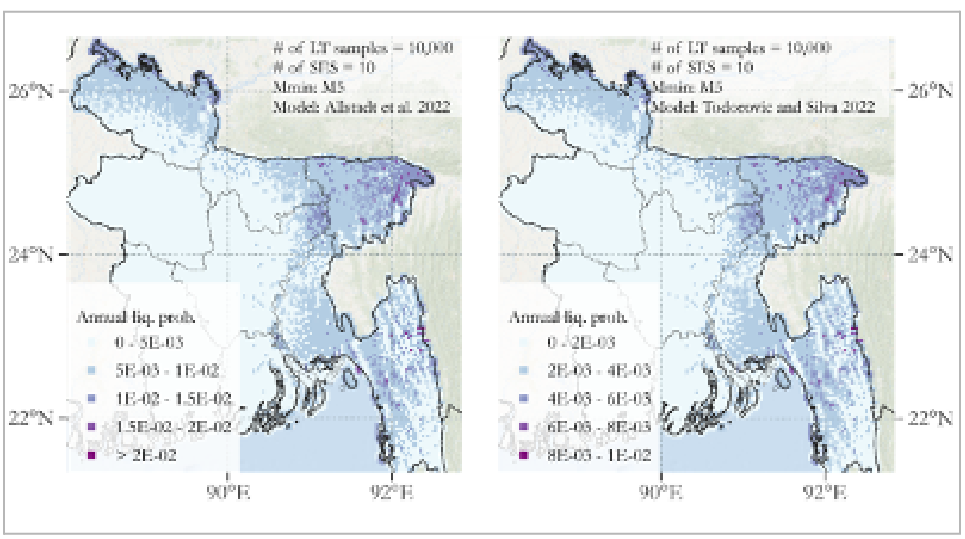


Figure 4. Annual occurrence frequency of liquefaction considering the contribution of all possible sources that can generate M5+ earthquakes; (left) using the parametric model described in Allstadt et al. (2022); (right) using the non-parametric model proposed by Todorovic and Silva (2022).

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.

GEM's exposure model for Bangladesh has been deeply informed by the zila-level information regarding wall materials used for construction of houses that is available through the 2011 Population and Housing census (see Figure 5 below).

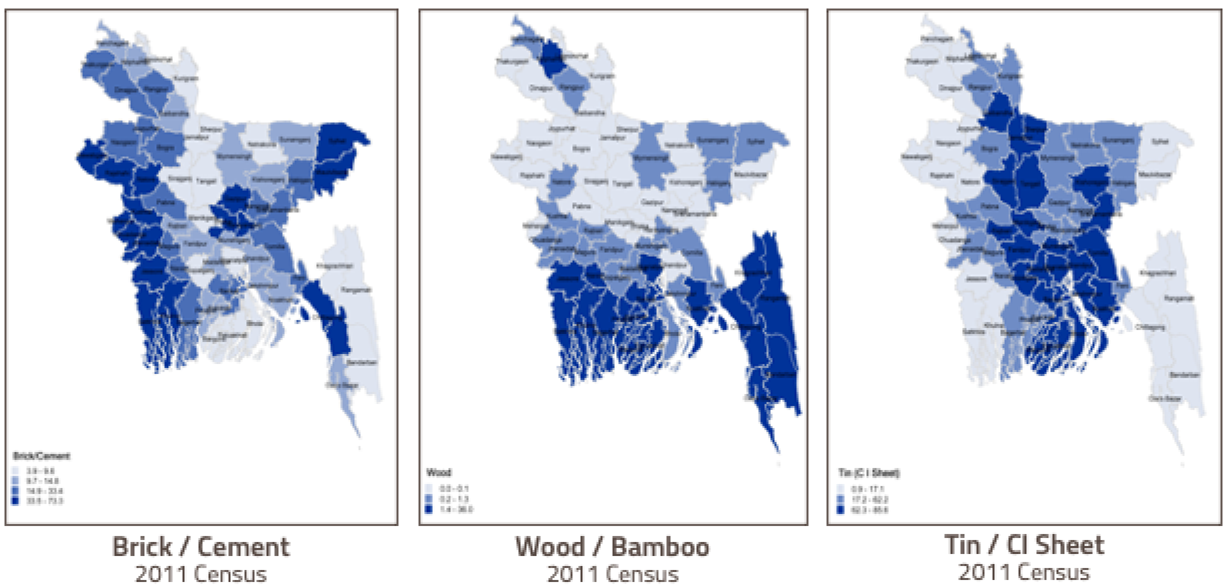


Figure 5. Geographical variation in predominant wall material of residential buildings. Source: 2011 Population and Housing Census, BBS.

As part of this project, we are undertaking an update of the residential exposure model to reflect the findings of the latest census. With support from the UN RC office in Dhaka, we sent in an official request for upazila-level information about wall, floor, and roof materials used for housing construction collected during the 2022 Population and Housing Census of Bangladesh. This request was granted and the said information has been recently made available to us for use in this project. Mr. Md. Dilder Hossain, project manager for the 2022 Population and Housing Census of Bangladesh kindly presented the key findings of the latest census to the project technical panel, including changes observed in the construction materials used across the country (see Figure 6 below).

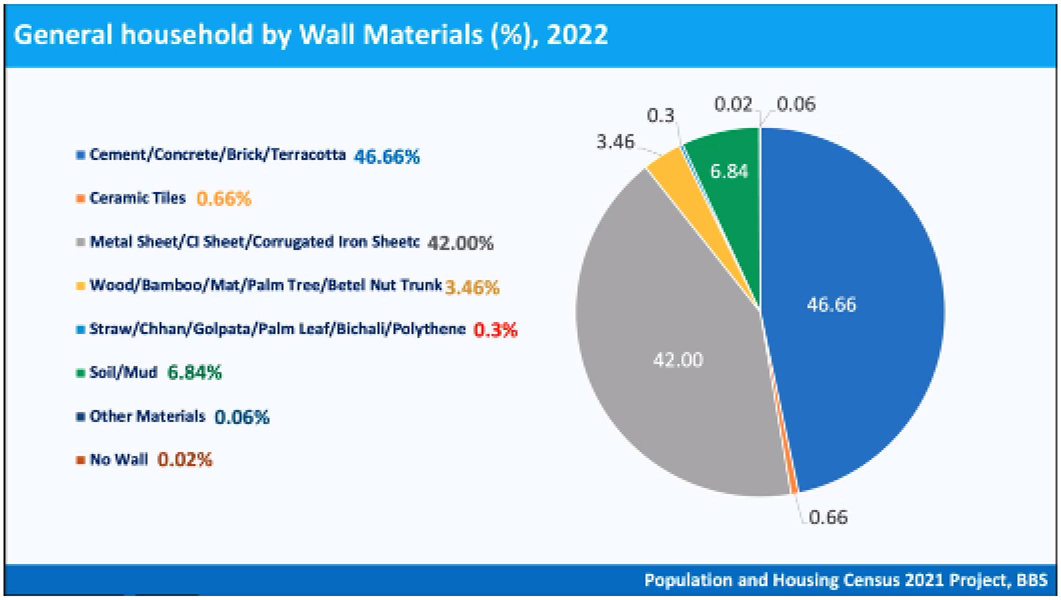


Figure 6. Distribution of households by wall material.

Source: Population and Housing Census 2022, BBS. Courtesy: Md. Dilder Hossain

We are also making an attempt to model the informal constructions in urban areas by using information from the 2014 Census of Slum Areas and Floating Population (Table 1). In this case, the specific material of construction is not known, however, the type of dwelling unit – *jhupri*, *katcha*, *semi-pucca*, *pucca* – allows us to infer the vulnerability class of these structures.

Table 1. Distribution of slum dwellings by type of dwelling.

Source: Census of Slum Areas and Floating Population 2014, BBS.

Type of dwelling unit	Slum Census 2014		Slum Census 1997	
	Household	Percentage	Household	Percentage
Jhupri	36875	6.20	142476	42.61
Katcha/Tin	371485	62.45	178586	53.40
Semi-pucca	157243	26.43	10319	3.08
Pucca	24169	4.06	3050	0.91
Others	5089	0.86	NA	NA
National	**594861**	**100.00**	**334431**	**100.00**

NB: Tong, Chhai etc. included in katcha structure.

Finally, in addition to residential, industrial and commercial structures that were previously covered by GEM's exposure models at zila level (which have been updated to upazila level during the course of this project), we have also developed exposure models for the healthcare and educational facilities in the country, including all hospitals and clinics, and all schools, colleges, and universities (see Figure 7).

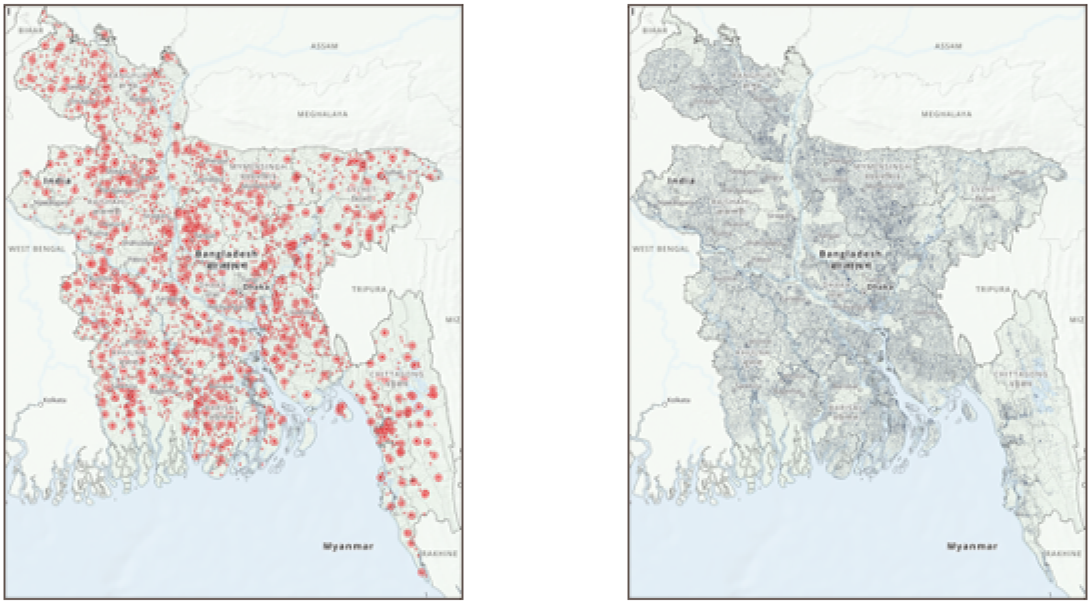


Figure 7. Distribution of hospitals and clinics (left) and schools and colleges (right).
Source: Hospitals & Clinics Management Section, Directorate General of Health Services (DGHS), Bangladesh Bureau of Educational Information and Statistics (BANBEIS), Ministry of Education, and Bangladesh Primary Education Statistics & Annual Primary School Census 2021, Ministry of Primary and Mass Education

Social vulnerability modelling

In this quarter, we also began work on developing a socio-economic vulnerability model for Bangladesh. We are adopting the approach of Cutter et al. (2003)[7], as exemplified by Roncancio et al. (2020)[8] for Colombia and de Loyola Hummell (2016)[9] for Brazil. The initial part of this work involves collecting at the subnational level, several variables that have been demonstrated to have a correlation with social vulnerability, including poverty level, education level, fraction of the population that is urban or rural, female participation in the workforce, median age of the population, access to clean water and sanitation, etc (see Table 2 below for the full list of variables and Figures 8 and 9 for examples and sources of individual variables collected).

These variables are then normalised to percentages or density functions. A test of multicollinearity is used to eliminate redundant variables and reduce the set of variables, and a factor analysis using principal component analysis (PCA) is conducted. In the final phase of the project, the social

[7] Cutter, S. L., Boruff, B. J., & Shirley, W. L. (2003). Social vulnerability to environmental hazards. *Social Science Quarterly*, *84*(2), 242–261. https://doi.org/10.1111/1540-6237.8402002

[8] Roncancio, D. J., Cutter, S. L., & Nardocci, A. C. (2020). Social vulnerability in Colombia. *International Journal of Disaster Risk Reduction*, *50*(September), 101872. https://doi.org/10.1016/j.ijdrr.2020.101872

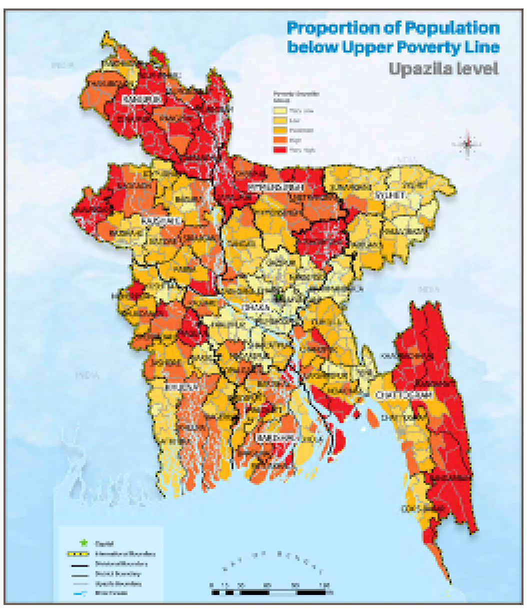
[9] de Loyola Hummell, B. M., Cutter, S. L., & Emrich, C. T. (2016). Social Vulnerability to Natural Hazards in Brazil. *International Journal of Disaster Risk Science*, *7*(2), 111–122. https://doi.org/10.1007/s13753-016-0090-9

vulnerability index will be computed for each upazila. This social vulnerability index will be added to the INFORM sub-national risk index for Bangladesh (Figure 10), which was developed in 2022 by the UN Resident Coordinator's Office (UNRCO), in collaboration with the Ministry of Disaster Management and Relief (MoDMR).

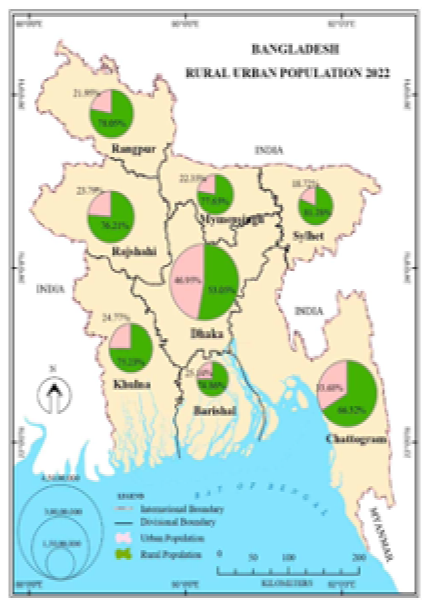
Table 2. Variables collected for the socio-economic vulnerability assessment

Concept	SoVI® variables
Socioeconomic status	Extreme poverty
	Overcrowded households
	No phone
Gender	% of females
	Females in work force
	Ratio F/M income
Religion and ethnicity	% by ethnicity
Age	Median age
Employment lost	Single sector reliance
Urban/Rural	% urban population
	Population density
Renters	% of renters
Occupation	Legally registered
	Not legal register
	Subsistence workers

Concept	SoVI® variables
Family structure	% Female headed households
	People per household
Education	% illiterates over 15
	Population incompleted highschool
	Complete college degree
Population change	Population change within the decade
Medical services & access	Labor force working in health
	Health coverage
Social dependency	# of Benefits granted
Special needs population	% population with disability
	% population high deficiency
Quality of the built environment	Households no water
	Households no sewer
	Households no garbage
	Households no electricity



2016 Poverty Maps of Bangladesh



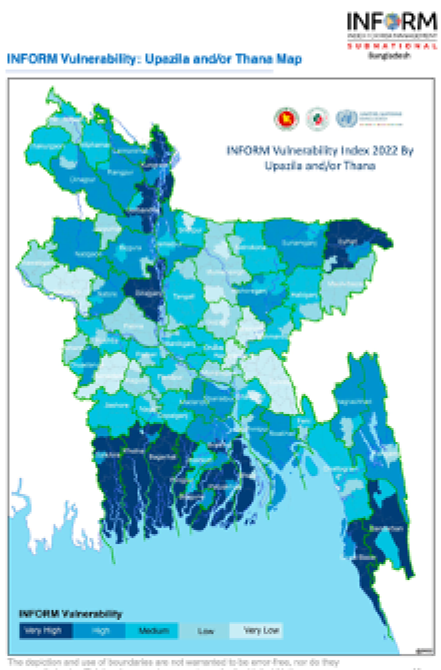
2022 Population & Housing Census

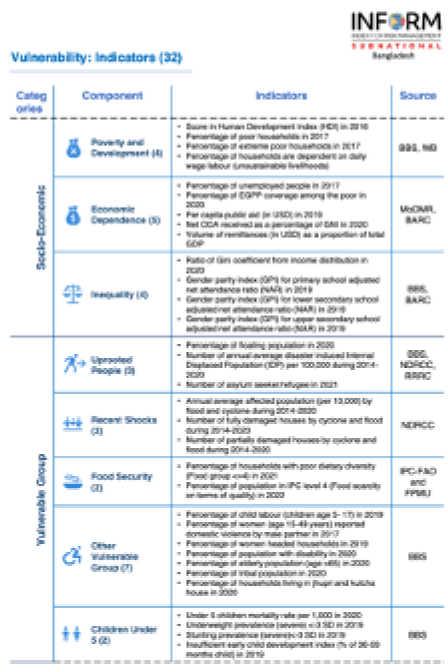
Figure 8. Proportion of population below the poverty line (left) and urban-rural population split by region (right). Source: 2016 Poverty Maps of Bangladesh, and 2022 Population and Housing Census, BBS

2021 Bangladesh Sample Vital Statistics

2021 Bangladesh Sample Vital Statistics

Figure 9. Adult literacy rate (left) and disability (right).
Source: 2021 Bangladesh Sample Vital Statistics, BBS





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Vulnerability: Indicators (32)

Categories	Component	Indicators	Source
Socio-Economic	Poverty and Development (4)	• Score in Human Development Index (HDI) in 2019 • Percentage of poor households in 2017 • Percentage of extreme poor households in 2017 • Percentage of households are dependent on daily wage labour (unsustainable livelihoods)	BBS, WB
	Economic Dependence (5)	• Percentage of unemployed people in 2017 • Percentage of EGPP coverage among the poor in 2020 • Per capita public aid (in USD) in 2019 • Net ODA received as a percentage of GNI in 2020 • Volume of remittances (in USD) as a proportion of total GDP	MoDMR, BARC
	Inequality (4)	• Ratio of Gini coefficient from income distribution in 2020 • Gender parity index (GPI) for primary school adjusted net attendance ratio (NAR) in 2019 • Gender parity index (GPI) for lower secondary school adjusted net attendance ratio (NAR) in 2019 • Gender parity index (GPI) for upper secondary school adjusted net attendance ratio (NAR) in 2019	BBS, BARC
Vulnerable Group	Uprooted People (3)	• Percentage of floating population in 2020 • Number of annual average disaster induced Internal Displaced Population (IDP) per 100,000 during 2014-2020 • Number of asylum seeker/refugee in 2021	BBS, NDRCC, RRRC
	Recent Shocks (3)	• Annual average affected population (per 10,000) by flood and cyclone during 2014-2020 • Number of fully damaged houses by cyclone and flood during 2014-2020 • Number of partially damaged houses by cyclone and flood during 2014-2020	NDRCC
	Food Security (2)	• Percentage of households with poor dietary diversity (Food group <=4) in 2021 • Percentage of population in IPC level 4 (Food scarcity on terms of quality) in 2020	IPC-FAO and FPMU
	Other Vulnerable Group (7)	• Percentage of child labour (children age 5-17) in 2019 • Percentage of women (age 15-49 years) reported domestic violence by male partner in 2017 • Percentage of women headed households in 2019 • Percentage of population with disability in 2020 • Percentage of elderly population (age >65) in 2020 • Percentage of tribal population in 2020 • Percentage of households living in jhupri and kutcha house in 2020	BBS
	Children Under 5 (4)	• Under 5 children mortality rate per 1,000 in 2020 • Underweight prevalence (severe) <-3 SD in 2019 • Stunting prevalence (severe)<-3 SD in 2019 • Insufficient early child development index (% of 36-59 months child) in 2019	BBS

Figure 10. INFORM Vulnerability Index (left) and INFORM Vulnerability Indicators

Technical panel engagement

The technical advisory panel, comprising key technical experts and stakeholders, met three times in the last quarter. The panel is 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 3 provides the updated and complete list of members of the technical advisory panel.

Engagement with the panel began with an introductory meeting on October 9th, where UNDRR and GEM introduced the goals and objectives of the project, and the panel members introduced themselves and described their focus areas in the government, academia, or otherwise.

Figure 10. Technical panel members (partial)

In depth technical discussions began with the second meeting, which was held on October 31st. The topics of discussion for the second session included the development of the probabilistic seismic hazard model for Bangladesh, and the development of the historical and hypothetical earthquake scenario set for Bangladesh presented by GEM. We also had two presentations from members of the technical panel in this session, including one on probabilistic seismic hazard assessment for

Bangladesh by Prof. Dewan Mohammad Enamul Haque of Dhaka University, and the second by Mr. Sabbir Siddique and Ms. Faria Sharmin, also on the same subject.

The third session with the technical panel was conducted on November 30th, focusing on the development of the exposure and physical vulnerability models, and on socio-economic vulnerability modelling for Bangladesh. In this session, Mr. Dilder Hossain, project manager of the 2022 Population and Housing Census of Bangladesh, presented some of the key findings of the latest census that are relevant for the purposes of disaster risk assessment and mitigation efforts. We also invited Prof. Mahbuba Nasreen of Dhaka University to present some of her pioneering work on gender and social vulnerability in the context of disasters in Bangladesh.

A final online session with the technical panel is planned for the third week of January, where we will present some of the preliminary results of the probabilistic seismic risk assessment at upazila level, damage and fatality estimates for the scenario set, and earthquake induced liquefaction hazard. Feedback and suggestions from the panel are being 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 3. Technical panel members (complete list)

Name	Designation	Organisation	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
Md. Asif Ahasan	Officer	Ministry of Housing & Public Works	a.ahasan75@gmail.com
Dr. Syed Humayun Akhter	Professor	Department of Geology, University of Dhaka	geology@du.ac.bd
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

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