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EARTHQUAKE DAMAGE AND LOSS MODEL FOR THE CITY OF GUWAHATI, ASSAM, INDIA

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Abstract:*The main scope of this article is to describe the different technical aspects that were implemented for the development of an earthquake damage and loss model for the City of Guwahati, capital of the state of Assam in Northeast India. Guwahati is considered as one of the most rapidly growing cities in India. In 1971, the city's population was just 200,000 while the 2011 census revealed a population of more than 960,000, and a population density of more than 2010 persons/sq.km. According to the seismic zoning map of India's current seismic building code IS 1893-Part 1: 2016, Guwahati falls into the country's highest seismic zone. In addition to the region's seismic hazard and risk situation, unplanned land use patterns of surrounding hills as well as hillocks that are located within the city contribute to an additional landslide risk. The development of the herein presented earthquake damage and loss model has involved both extensive fieldwork and computational efforts including ground shaking modelling considering soil amplification effects, defining ground shaking scenarios for earthquakes on local active faults and for significant historical earthquakes, demarcation of the Guwahati city area and its subdivision into geographical units, definition of building typology classes and generating their vulnerability functions, collection of building inventory data and socioeconomic information throughout the city, and finally the computation of damage and loss scenarios. The developed damage and loss model for Guwahati city can be used as guidance to local authorities on future city planning and earthquake mitigation actions.*

Introduction

The city of Guwahati (state of Assam) is one of the most rapidly growing cities in India, at the same time being the most important hub of Northeast (NE) India (Figure 1a). In 1971, the city's population was just 200,000 while the 2011 census revealed a population of more than 960,000 and population density of more than 2010 persons/sq.km.

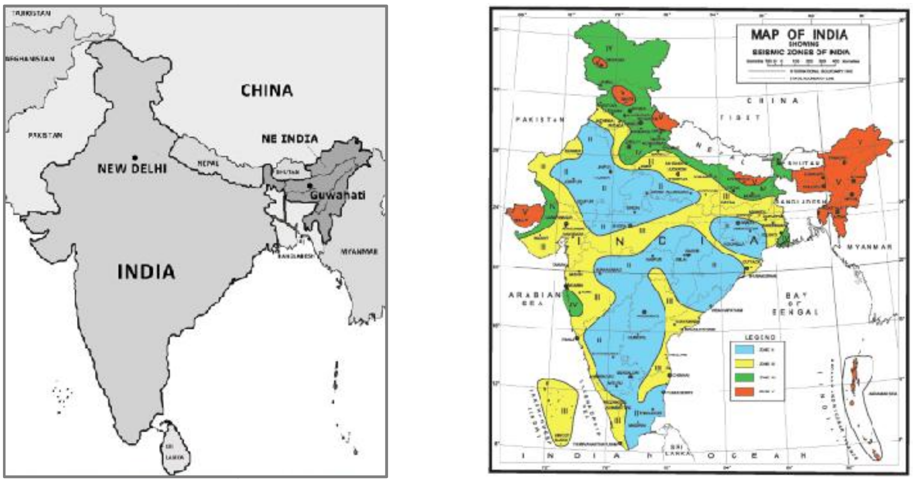

Figure 1. (a) Location of Guwahati in Northeast India. (b) Seismic zonation map subdividing India into four hazard zones (IS 1893-Part 1: 2016).

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According to the reported seismic activity in India, the entire North-eastern region, where Guwahati city falls into, is among the most seismically active parts of the Indian subcontinent and even of entire South Asia. The seismicity of NE India has been proven by a large number of damaging earthquakes in the past and is also reflected by the seismic zoning map of India's current seismic building code IS 1893-Part 1 (2016) which classifies the entire region into Zone V, i.e., the country's highest seismic zone (Figure 1b). Due to the state of Assam's elongated slender shape, and also since it covers almost 30% of NE India, the state of Assam has been affected by most larger earthquakes that have occurred in both NE India and neighbouring regions, often severely. Two of India's five largest historical earthquakes caused huge losses in the state of Assam, i.e., the 1897 Shillong earthquake (Hough et al 2002) and the 1950 Assam earthquake (Tandon 1954). A compendium of historical earthquakes in NE India and the state of Assam is given elsewhere, e.g. Department of Science & Technology, Govt. of India (2007).

Seismic hazard situation of Guwahati

Historically, the city of Guwahati has been affected by a large number of earthquakes that had been generated by various faults either directly surrounding the city or from larger distances. Being located in a highly seismic active zone flanked by the Shillong Plateau to the south and the Mikir Plateau to the east, the city has been affected by both crustal and interpolate earthquakes during the last several hundred years. The region is associated with complex geological and tectonic features (Figure 2). The area of Guwahati city, located on the banks of river Bramaputra in the Assam valley, falls in a wedged tectonic block between the Himalayan collision zone to the north (bounded by the Main Boundary Thrust MBT and the Main Central Thrust MCT) and the Indo-Myanmar subduction zone to the southeast. The Shillong plateau to the south of Assam valley represents a "pop-up" tectonic block (Bilham and England 2002) between two E–W trending boundary faults, i.e., the Dauki Fault to the south and the Oldham (and/or the Brahmaputra Fault) to the north (Erteleva 2014).

Figure 2. Major tectonic features of the region around the city of Guwahati. Locations of the fault lines taken from Baruah and Hazarika (Baruah and Hazarika 2008).

With respect to the more ancient earthquakes, large uncertainties exist with respect to locations and magnitudes. An overview of the larger historical earthquakes that had been felt in Guwahati city and that even produced damage to its building stock is provided in Erteleva et al. (2014).However, with the tremendous growth in population density and built area over the past 50 years, the historical damage reports only provide vague ideas on how todays Guwahati may suffer under a future large earthquake.

Earthquake loss estimates: methodology and tool

The earthquake risk study of Guwahati city was carried out using SELENA, an open-source tool developed jointly by NORSAR (Norway) and the University of Alicante (Spain). The software can provide local, state and regional institutions with a state-of-the-art decision-support tool for estimating possible losses from future earthquakes (Molina et al 2015). The methodology for the present study is based on "scenario earthquakes" and a suite of empirical ground-motion prediction models (GMPE) to evaluate the seismic ground-motion distribution and corresponding losses for the city. The user needs to provide earthquake sources, GMPEs, soil in-formation along with soil amplification factors, built-up areas or number of buildings distributed over the various building typologies, corresponding capacity curves and fragility curves, and finally cost estimates (i.e., building repair and replacement values). Using this information, SELENA computes the probabilities for each of the four levels of damage (i.e., slight, moderate, extensive and complete), and provides the mean damage ratio for each geounit and building typology. Economic losses and casualty numbers are also estimated.

Hazard, exposure and vulnerability models for Guwahati

Scale and resolution of risk modelling

The scale of an earthquake loss estimation may range from an entire country to cities or even a city district. The decision on the size of each Geounit and how to demarcate it has to be made considering different variables such as geological conditions, constant surface topography or level of infrastructure quality within the demarcated area (socio-economic aspects). The larger the study area, the more likely it is that ground shaking-induced damage to buildings will dominate the overall losses, and that any secondary hazards affecting a particular zone, such as earthquake-induced liquefaction or landslides, will be of less significance. The smaller the size of the Geounits, the higher will be both the level of detail and the reliability of results for an individual infrastructure. However, this could also result in an increased number of Geounits, which will increase the efforts required to set up the inventory data model and perform an assessment of a given region. For the present study, the derived demarcation of the Guwahati city into Geounits (a total number of the 258 geographical units is done considering various aspects:

- In order to provide Geounits of homogenous spatial size, wards of larger dimension were subdivided into sub-units.
- Since the study area is surrounded by hilly terrain (with rock soil conditions) and furthercharacterized by a number of steep rocky hillocks that are protruding from the sedimentary plains (with very soft soil conditions), wards were subdivided taking into account these topographic-geological differences.
- Those (outer) parts of the study area that are not covered by the original ward map are subdivided into geounits with equal topographical-geological conditions as well as numbers of buildings. The geounit limits are assigned following major streets or natural borders (i.e., rivers, streams, topography contours) as well as equal building inventory patterns.

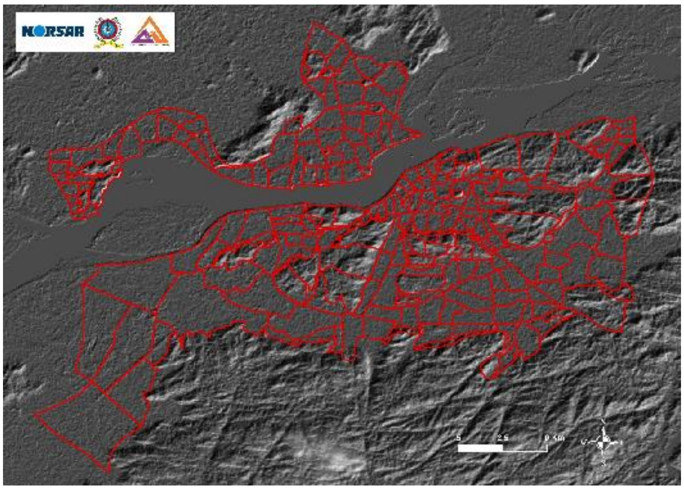

Figure 3. Demarcation of the 2025 Guwahati Master Plan area into 258 geographical units, illustrated with respect to the varying topographical-geological conditions.

Scenario earthquakes

Table 1 lists historical earthquakes and hypothetical scenario earthquakes that have been chosen to serve as the basis for scenario events for the present study. Judging from their location and hence distance to the city as well as magnitude, the selected earthquake events have been evaluated to be able to cause damage to the building stock of Guwahati. The table also provides information on these events which was collected from various sources.

Scenario event	**Lat [N]**	**Lon [E]**	**Focal depth**	**Mw**	**Strike**	**Dip**	**Rake**	**Mechanism**
1897 Chedrang	26.00°	92.67°	10 km	8.7	155°	45°	reverse	1897 Chedrang
1897 Oldham	26.80°	91.44°	10 km	8.7	110°	45°	reverse	1897 Oldham
Kopili	27.34°	91.41°	30 km	7.7	148°	90°	strike-slip	Kopili
USLRP - MFT	26.80°	91.44°	10 km	7.7	265°	45°	reverse	USLRP - MFT
Kulsi	25.87°	91.47°	10 km	6.0	90°	60°	reverse	Kulsi

Table 1. Overview of scenario earthquakes with decided focal parameters.

Ground motion attenuation

For the current study in Northeast India it is necessary to select ground motion prediction equations (GMPEs) that represent both the present seismotectonic situation (seismogenic faults and zones) and the seismic hazard level (distance to active faults, magnitude and depths range of expected earthquakes). So far, customized GMPEs have not yet been developed for Northeast India. It is therefore essential to choose alternative GMPEs that are considered representative for the considered seismotectonics conditions and scenario earthquakes. For the present study, it has been decided to select the GMPE model by Ambraseys et al. (2005), which has been developed using data from Europe and Middle East with magnitude range Mw 5.0 – 7.6 (lack of data for Mw > 6.5), and distance range rjB< 100 km. In total, five earthquake scenarios are defined for Guwahati city and for which damage and economic losses have been estimated. The corresponding site-specific design response spectra that are considered local subsoil amplification are computed following provisions of the current Indian seismic building code IS 1893-Part 1 (2016).

Soil model

Guwahati city falls into the Lower Assam valley which is located between the Eastern Himalayas to the north and the Shillong Plateau to the south. The Lower Assam valley mainly consists of crystalline rocks covered by gently dipping Tertiary and younger sediments (DST 2007). Thick-nesses of overlying sediments vary from ten to few hundred meters. The study area is located in the valley of Brahmaputra river with large areas characterized by very soft water-saturated sediments. In contrast to the low altitude sedimentary valleys, many relatively steep-sided granite hillocks are distributed over the city. In the course of Guwahati's Microzonation project conducted in 2007 (DST 2007), large efforts were made in order to identify the near-surface geology of the area and to identify the main geotechnical parameters of the various soil types. Figure 4 shows the soil characteristics profile and associated average shear-wave velocities ($V_{S,30}$) values that have been developed and used as soil model input data for the present study.

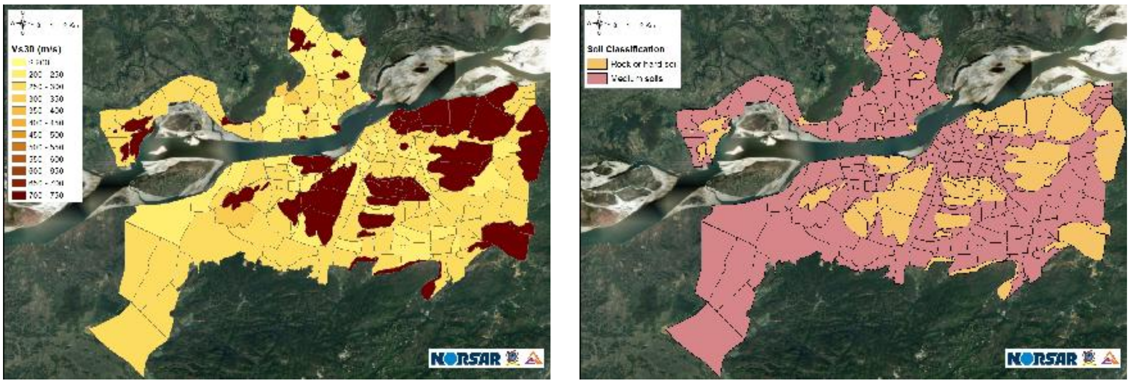

Figure 4. Soil characteristics (represented by average shear-wave velocities) and soil classes assigned to Guwahati's Geounits: (a) average shear-wave velocities ($V_{S,30}$) profile; (b) Soil classification

Building inventory model

<u>*Visual walk-down surveys*</u>: A building stock inventory of 4,003 individual buildings was initially compiled by Assam Engineering College (Pathak 2008) and which was considered to be satisfactory as it guaranteed a certain level of reliability. However, the collected samples did not cover the entire study area, rather they covered only certain pockets of certain wards. Since the distribution of the building stock can vary greatly not only between urban, rural and sub-urban areas but also between different neighboring wards, it was decided to generate a larger inventory database through the con-duct of additional walk-down surveys. During a one-month field trip in September-October 2013, additional walk-down surveys were conducted in each Geounit of the study area. During this time, data of additional 11,531 individual buildings was collected.

The results of the walk-down surveys, i.e., the Geounit-wise building stock distributions, are utilized to set up the Geounit-based inventory model for the entire study area. In doing so, two steps were accomplished: *Step-1*: identification of the building typology distributions in each of the 258 Geounits that were investigated during the field; *Step-2*: identification of the total amount of individual buildings in each of the 258 Geounits using available satellite imagery (e.g. Google Earth images). In doing so, the database used in this study consists of 117,484 individual building. Linear interpolation has been implemented to estimate the distribution of the buildings according to their typologies and occupancy types. Based on these typology distributions as well as the estimated number of buildings in each Geounits, the building-wise inventory for the entire study area was generated.

Figure 5. Example of existing and predominant building typology classes in Guwahati city: (a) Traditional Assam-type (Ikra) house; (b) Confined masonry building; (c) Older (non-ductile) RC frame building; (d) Ductile RC frame building under construction

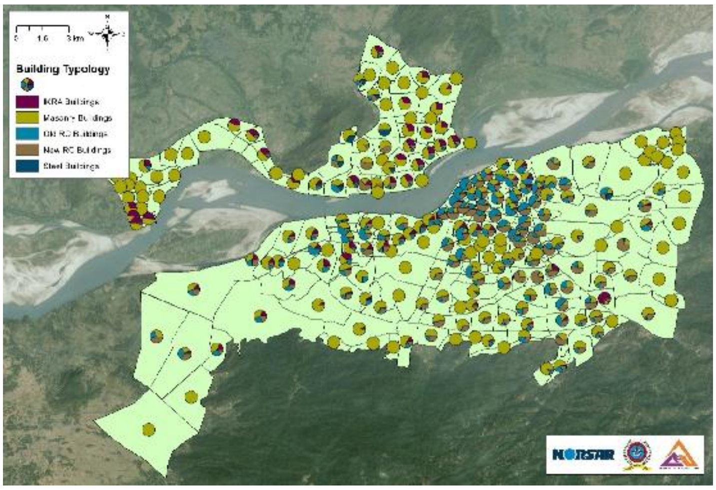

Figure 6. Building typology class distributions in each geographical unit (Geounit)

<u>*Building classification scheme*</u>: The building classification scheme that is described herein resulted from various inventory surveys in Guwahati conducted by Assam Engineering College (AEC) in recent years as well as more recent investigations on the current building stock. It reflects the building typologies and materials identified in the Guwahati urban area as well as in several revenue villages around Guwahati city. The building classification may thus be only representative to the municipal and suburban area around the city of Guwahati and may require adjustment or amendment if applied to surrounding regions or other Indian cities. However, the identified typologies can be considered as representative for the entire building stock in the

urban and rural areas of Assam. Accordingly, the building stock in Guwahati city is considered to be dominated by three groups of building typologies (see Figures5 and 6): traditional Assam-type houses (generally denoted as "Ikra houses"), confined clay brick masonry houses, as well as ductile and non-ductile RC frame structures. The description of available building typologies in Guwahati is summarized in Table 2.

Classification		Lateral Load-Resisting System		Roof	Floor	**Story range**
		System Type	Material	System/Material	System/Material	
Wood	Load-Bearing Timber Frame	Ikra (Assam-type, wattle and daub)	Large timber frames with wattle-and-daub infills, cement plaster	Timber or steel truss, CI sheet	Timber or steel truss, CI sheet	1 (2)
Masonry	Unreinforced Masonry	Load-Bearing Wall	masonry wall made of rectangular fired clay bricks, with cement mortar	Timber or steel truss, CI sheet	Timber or steel truss, CI sheet	1
	Confined Masonry	Load-Bearing Wall	Masonry wall made of rectangular fired clay bricks, in cement mortar with reinforced concrete confinements	Timber or steel truss, CI sheet,	Timber or steel truss, CI sheet,	1-2 (3)
Reinforced Concrete	Frame System (Beams and Columns)	Nonductile moment resisting frame	RC moment frame with unreinforced masonry infills made of rectangular fired bricks	RC slabs, (for low-rise: timber/steel trusses, CI sheets)	RC slabs, (for low-rise: timber/steel trusses, CI sheets)	1—3
						4—6
		Nonductile moment resisting frame with Open ground floor	RC moment frame with unreinforced masonry infills made of rectangular fired bricks	RC slabs, (for low-rise: timber/steel trusses, CI sheets)	RC slabs, (for low-rise: timber/steel trusses, CI sheets)	1–3
						4–6
		Ductile moment resisting frame	RC frames, with unreinforced masonry infills made of rectangular fired bricks	RC slabs, (for low-rise: timber/steel trusses, CI sheets)	RC slabs, (for low-rise: timber/steel trusses, CI sheets)	1–3
						4–6
						7+
Steel	Light Metal Frame	Steel metal frames	Steel light frames	Steel trusses with CI sheets	Steel trusses with CI sheets	1 (2)
	Moment Resisting Frame	Moment Resisting Frame	Steel frame with unreinforced masonry infills made of rectangular fired bricks	Steel trusses with CI sheets	Steel trusses with CI sheets	1 (2)

Table 2. Building typology classes observed in Guwahati city.

Structural vulnerability model

Vulnerability functions, which are one of the major components of earthquake loss estimation studies, represent the structural capacity and behaviour of a given building typology and define the probability of suffering a certain level of damage along a given ground motion intensity parameter. In this respect, a thorough vulnerability model (i.e., capacity curves and fragility functions) for the building stock in Guwahati was developed considering the building classification scheme presented earlier. The vulnerability functions were generated based on the use of nonlinear static-based approaches, taking into account the dispersion due to the uncertainty in structural characteristics-related parameters, building-to-building variability, as well as the record-to-record dispersion in ground motion. For instance, the structural characteristics-related parameters that have been considered in creating the numerical models for the analysis of RC buildings are those associated to mechanical properties and structural details; i.e., compressive strength of concrete, yield strength of reinforcing steel bars, and transverse reinforcement spacing. In terms of dispersion, the choice of expected mean and standard deviation for each of these parameters is based on the results of structural characteristics assessment as well as the requirements from different versions of earlier seismic codes in India (Table 3).

Fragility curves are defined as the conditional probability of being in or exceeding a particular damage state ds_i given the spectral displacement S_d:

$$P\left[ds \geq ds_i \mid S_d\right] = \Phi\left[\frac{1}{{}_{ds_i}} ln\left(\frac{S_d}{\overline{S_{d,ds_i}}}\right)\right] \tag{1}$$

where, $\overline{S_{d,ds_i}}$ is the median value of spectral displacement at which the building reaches the threshold of damage state ds_i ;$\beta_{ds_i}$is the standard deviation of the natural logarithm of spectral displacement for damage state ds_i ; Φ is the standard normal cumulative distribution function. (ds_1: represents the attainment of Slight Damage level - SD; ds_2 : represents the attainment of Moderate Damage level - MD; ds_3: represents the attainment of Extensive Damage level - ED; ds_4 : represents the attainment of Complete Damage level - CD).

The different values of median capacity, $\overline{S_{d,ds_i}}$, corresponding to different damage states, are obtained as the 50% of all the spectral displacements from the capacity curves recorded at each damage state threshold.

The total dispersion parameter,β_{ds_i} , includes: the dispersion in structural capacity (which represents the variability at the level of single building and variability at the level of building-to-building (β_{C,ds_i}), uncertainties in capturing the real behaviour of the modelled buildings (β_{DM}) in the overall estimation of the total dispersion (Liel et al 2009), test data variability (β_{BTD}) representing available test data (knowledge) related to material properties (FEMA P695), and the record-to-record variability characterizing the randomness in the demand imposed on the structure by the earthquake ground motion. The following Equation could be used for the calculation of total dispersion:

$$\beta_{ds_i} = \sqrt{\beta_{C,ds_i}^2 + \beta_M^2 + \beta_{BTD}^2 + \beta_D^2} \tag{2}$$

β_{C,ds_i}^2 is the dispersion in structural capacity and which is estimated directly as the lognormal standard deviation for the selected capacity curves. The following formula is used to calculate the dispersion in structural capacity associated to each damage threshold (Wen et al. 2004):

$$\beta_{C,ds_i} = \sqrt{ln(1 + CoV^2)} \quad where \quad CoV = \frac{STDEV}{Mean} \tag{3}$$

The derivation of a capacity curve by use of pushover analysis, does not directly account for the specific seismic motion, as the dynamic characteristics of demand and response system are not taken into account in the analysis. Hence, dispersion for record-to-record variability β_D is assumed through default values suggested by ATC-58 (FEMA P-58, 2012). Given the fundamental period of the structure and a strength ratio, the values of β_D can be chosen in a range between 0.05 and 0.45. If data on the above two parameters is lacking or uncertain, a maximum default value of 0.45 can be used.

In addition, it has been estimated that a value of 0.65 can be used for a combined record and modelling uncertainties (Deierlein et al. 2007). And also, a value of 0.20 that can be added for Test data variability (β_{BTD}) representing available test data (knowledge) related to material properties (FEMA P695). Hence, from Equation 2 we obtain the following:

$$\beta_{ds_i} = \sqrt{\beta_{C,ds_i}^2 + 0{,}65^2 \; + \; 0{,}20^2} \tag{4}$$

System	Parameter	Quality / Expected mean and range of value		
		Lower Bound Quality	Central Quality	Upper Bound Quality
Ductile RC Buildings	Compressive strength of concrete [MPa]	18	20	24
	Tensile strength of steel bars [MPa]	415	415	500
	Transverse reinforcement spacing [mm]	150	125	100
Nonductile RC Buildings	Compressive strength of concrete [MPa]	10	15	18
	Tensile strength of steel bars [MPa]	250	250	415
	Transverse reinforcement spacing [mm]	250	200	200

Table 3. Range of values of the structural characteristics-related parameters for the existing RC buildings in Guwahati.

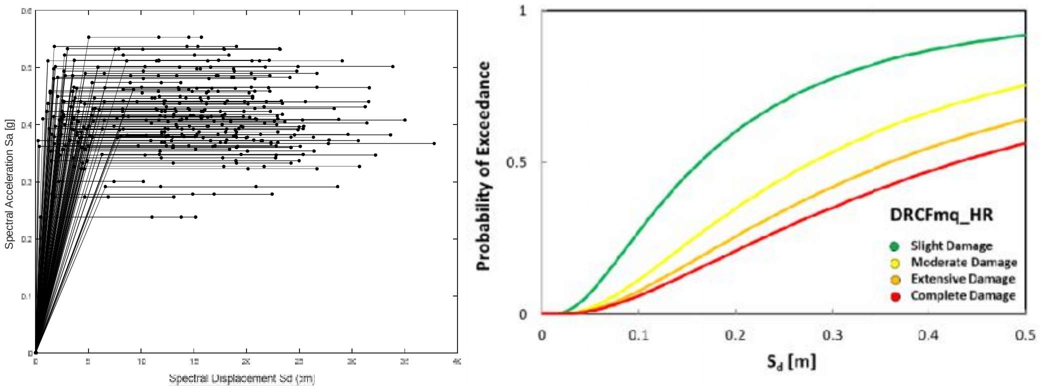

Figure 7. Pushover analysis and example plot of structural capacity and fragility curves for RC building

Economic values of building inventory

In order to compute direct economic loss estimates related to the direct structural damage of the building stock, repair and replacement values are to be provided for the various building typologies. As a building's function or utilization (occupancy class) strongly affects its eco-nomic value (mainly caused by the non-structural components and contents, e.g. in the case of hospitals), repair and replacement values may differ for the same building typology but different occupancy. In general, repair values for the lower damage states (slight, moderate, in some cases extensive) are a fraction of the replacement value (i.e., complete damage state). The repair and replacement values may be provided in a user-defined currency (e.g. Euro, US Dollars, or in the present case preferably Indian Rupee) representing the costs required to repair or replace one square meter (1 m^2) of the respective building typology. The value may incorporate the values of non-structural components and contents as well as the costs required to, e.g., demolish a severely damaged building, and/or to remove the debris. It should also be considered that the relative replacement (construction) costs (i.e., costs per square meter) may differ with height (Lang et al 2012). The economic model for the building stock of Guwahati is based on actual construction cost estimates provided by the Schedule of Rates for P.W.D. Buildings (Civil Works) 2013–2014 (Public Works Department, Assam 2014) for different categories of buildings (separated for engineered and non-engineered typologies).

Damage and loss computation: results and discussion

In the following the results of the scenario-based earthquake risk assessment are illustrated in terms of earthquake ground motion distribution, damage distribution,and economic loss distribution. The computations are implemented for each selected historical earthquake generated by the various faults as per results of hazard assessment presented in the previous section. Figure 8 exemplarily illustrates results for a scenario representing the 8.7 magnitude Shillong earthquake of 1897, generated by the Oldham fault approximately at 80 km distance to Guwahati's city center.

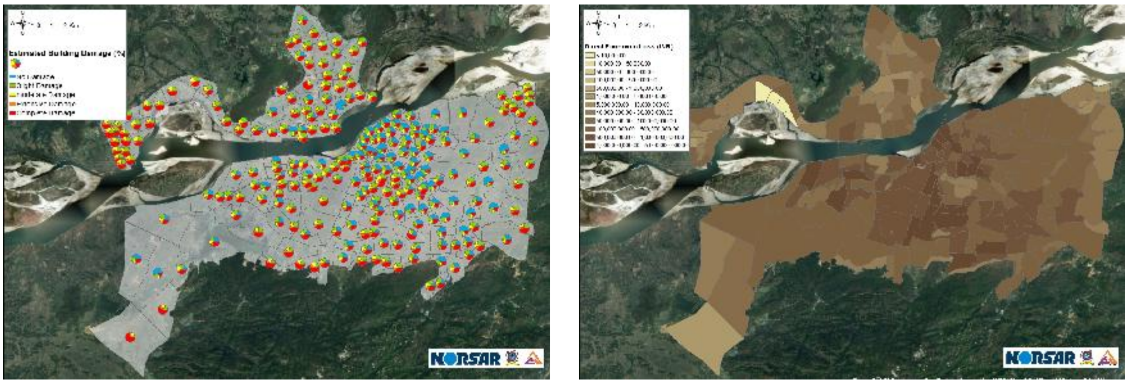

Figure 8. Predicted earthquake damage and loss estimates for a repeat of the 1897 Shillong earthquake (Magnitude 8.7, located at 80 km distance to the city center): (a) Damage probabilities; (b) Economic losses

Figures 9 to 10 graphically summarize results for the different earthquake damage and loss assessment scenarios. The earthquake scenario with a maximum magnitude 8.7 and 80 km distance to the city centre (almost similar to the historical 1897 Shillong earthquake) and which can possibly be generated by the Oldham fault, will be the most devastating event compared to the other considered scenarios. This scenario is estimated as being capable to cause severe damage to many building typologies (extensive and complete damage states of up to 36% of the total building stock) which will be connected to significant economic losses and casualties in almost all districts of Guwahati. Similarly, a repeat of the 1897 earthquake, but assuming to be generated by the Chedrang fault at 112 km distance to the city centre with a magnitude of 8.7, will also cause severe damage to many building typologies (extensive and complete damage states of up to 13% of the total building stock). On the other hand, moderate to low damage and losses have been evaluated for the scenario of the MFT fault (M 7.7 in 73 km distance), as well as for the Kopili fault earthquake scenario (M 7.7 in 89 km distance), where no significant damages and losses are expected to the majority of the building stock, and only some of the most vulnerable building typologies will suffer heavy damage. For the selected hypothetical scenario earthquake, to be generated by the Kulsi fault (M 6.0 in 58 km distance), no damages and losses are expected to the building stock, maybe only slight to very slight damage can be observed in some of the most vulnerable building typologies.

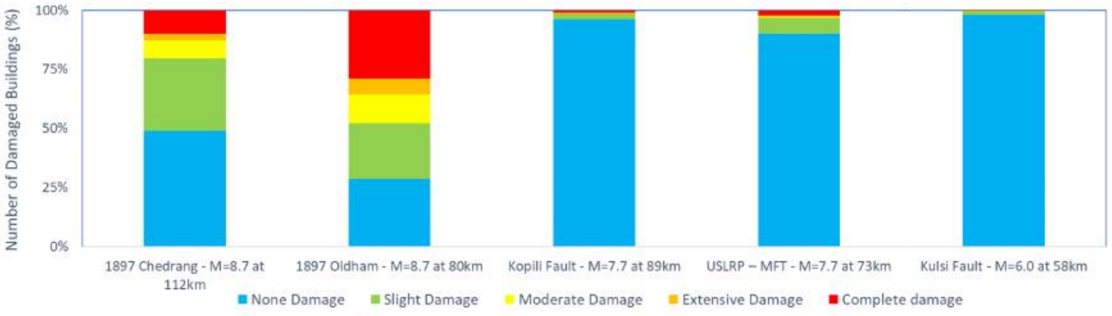

Figure 9. Comparison of the estimated building damage for the different earthquake scenarios.

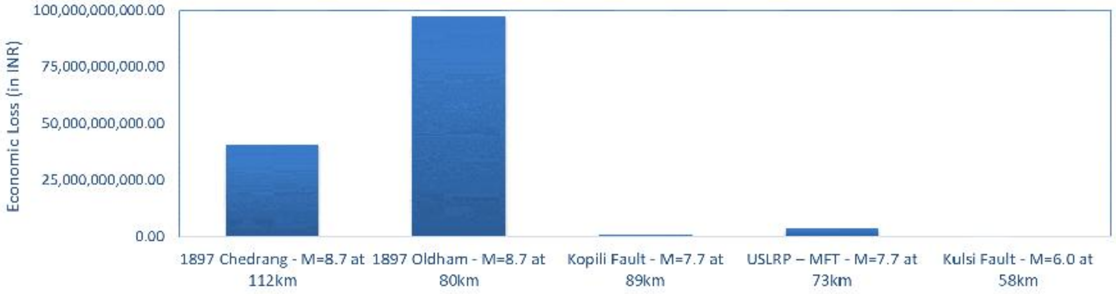

Figure 10. Comparison of the estimated economic losses for the different earthquake scenarios.

The effect of magnitude as well as distance can be clearly seen from the figures. If we consider, for instance, the 1897 Chedrang earthquake and the 1897 Oldham earthquake, it can be clearly seen that the effect of magnitude as a factor could be quite significant. The resulted damage ratio and losses considering the two events are associated with a relative difference of more than 40%. On the other hand, the effect of distance can, for instance, be seen when comparing the Kopili fault earthquake (M 7.7 located at 89 km) with the USLRP-MFT earthquake (M 7.7 at 73 km). The resulted damage ratio and losses considering the two events are associated with a relative difference of up to 25%.

Conclusion

The aim of this project was to provide local authorities with an earthquake risk model that can be used as guidance for future city planning and earthquake mitigation actions. In total, five deterministic earthquake scenarios were considered. The outcomes of the risk assessment show that large portions of building typology classes which are considered to be seismically deficient and highly vulnerable would suffer severe damage. However, it is important to note that all damage and loss results presented in this study are associated with a number of epistemic uncertainties that need to be taken into account at the mitigation-planning phase.

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