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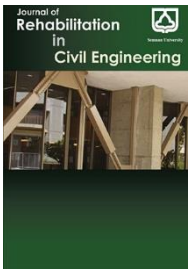

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Earthquake Induced Deterministic Damage and Economic Loss Estimation for Kolkata, India

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ABSTRACT

The city of Kolkata, the State Capital of West Bengal is jolted by earthquakes time and again from the tectonic regimes of the Central Himalaya, highly seismogenic Northeast India and the active tectonics of Bengal Basin which is a pericratonic tertiary basin on which the City is located. Earthquake disaster mitigation and management necessitates seismic hazard assessment for the generation of design response spectra at a site of interest with a zone factor for the computation of seismic coefficient to be adapted in building codes. The surface consistent probabilistic seismic hazard model of Kolkata for 475 years of return period have been used for the modeling of damage potential of buildings, human casualty and economic loss employing the widely used SEismic Loss EstimatioN applying a logic tree Approach (SELENA) in a relational analysis protocol considering eleven model building types. The demand spectrum curve of a spectral acceleration through a judicious interaction with the building capacity curve and fragility curve yields the damage state probability of the same in terms of slight, moderate, extensive and complete. Human casualty levels are also computed applying SELENA for three different times of the day *viz*. Night, Day and Commuting time. The economic loss to the tune of ~231 billion of Indian Rupees due to building damage only have been estimated within 300 socioeconomic clusters in the City. It is expected that this model will go a long way in safe urbanization process with well-defined disaster mitigation and management guidelines for the city of Kolkata.

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1. Introduction

Earthquake is the worst natural disaster that causes widespread damage and destruction to society. India is considered an earthquake-prone country as it has experienced a large number of major to great earthquakes in the past causing lakhs of fatalities and destroying properties worth billions of rupees, thus necessitating sound disaster mitigation and management plans through a judicious interplay of seismic hazard, vulnerability, risk, damage, casualty, and economic loss. Kolkata, the State Capital of West Bengal faces the seismic threat from any of the three seismogenic provinces namely, the Central Himalaya, Northeast India and the Bengal Basin itself, even though there is sparse seismicity in the region as such.

The city of Kolkata, one of the most urbanized and densely populated regions in the world, has developed primarily along the eastern bank of the River Hooghly about 150 km north of the Bay of Bengal. The major tectonic framework of Eocene Hinge Zone, Main Boundary Thrust (MBT), Main Central Thrust (MCT), Main Frontal Thrust (MFT), Dhubri Fault, Dauki Fault, Oldham Fault, Garhmoyna–Khandaghosh Fault, Jangipur-Gaibandha Fault, Pingla Fault, Debagram-Bogra Fault, Rajmahal Fault, Malda-Kishanganj Fault, Sainthia-Bahmani Fault, Purulia Shear Zone, Tista Lineament, and Purulia Lineament in an around Bengal Basin pose seismic threat to Kolkata and its adjoining region. The significant near field earthquakes which have shaken the region include the 1906 Kolkata earthquake with MM Intensity V–VI [1], the 1935 Pabna earthquake of M_w 6.2 with MM Intensity V [2] and the 1964 Sagar Island earthquake of M_w 5.4 with damage Intensity of MM VI–VII in the area surrounding the city of Kolkata [3,4]. However, the occurrence of the destructive far-field earthquakes *viz*. the great 1897 Shillong earthquake of M_w 8.1, the 1950 Assam earthquake of M_w 8.7, the 1934 Bihar–Nepal earthquake of M_w 8.1, the 2011 Sikkim earthquake of M_w 6.9 and the recent 2015 Nepal earthquake of M_w 7.8 accentuated the seismic hazard of the province. The Seismotectonic provinces of the Bengal Basin and its adjoining region with seismicity distribution is presented in Fig. 1.

The surface consistent Probabilistic Seismic Hazard of the City on integration with other hazard contributing attributes *viz*. Geomorphology, Site class, Sediment Class, PGA with 10% probability of exceedance in 50 years at surface level, Geology, Groundwater table, and Liquefaction Potential Index (LPI) applying Analytical Hierarchy Process (AHP) by [5]on GIS platform divides the City into four hazard zones *viz*. ‘Severe’ in the techno commercial hub of Saltlake and the new industrial hub in New Town areas, ‘High’ mostly in Barabazar, Anandapur, Belgachhiya, Bagdoba areas of the expanding City, ‘Moderate’ in most parts of South and West Kolkata and ‘Low’ zones in the rest of the City as presented in Fig. 2 [6]. Evidently, the City which was earlier placed at the border of Bureau of Indian Standard [7] Seismic Zones III and IV is no more associated with it rather drifted to much higher Peak Ground Acceleration (PGA) values with higher zone factors [6].

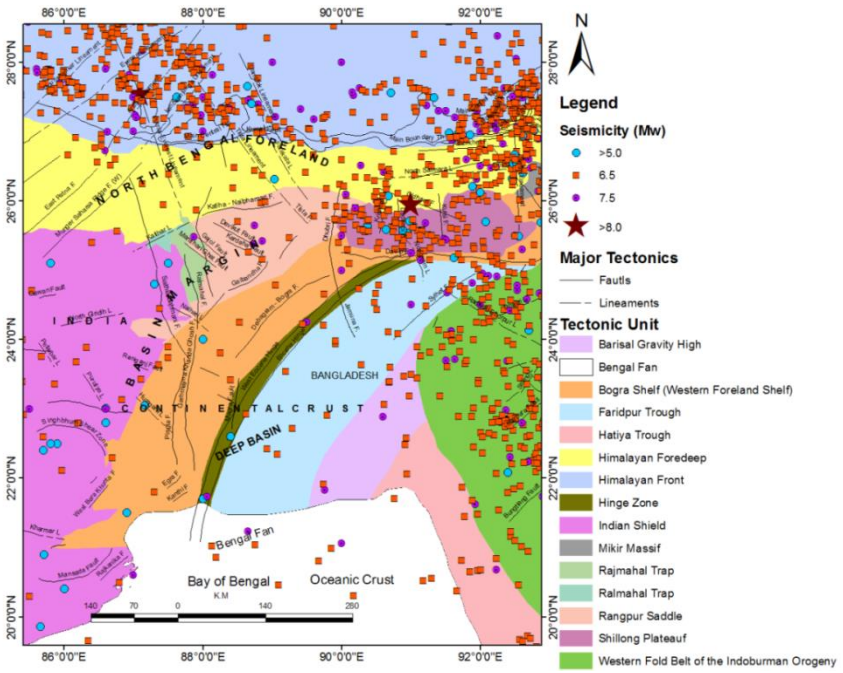


Fig. 1. Seismotectonic provinces of the Bengal Basin and its adjoining region [8,4].

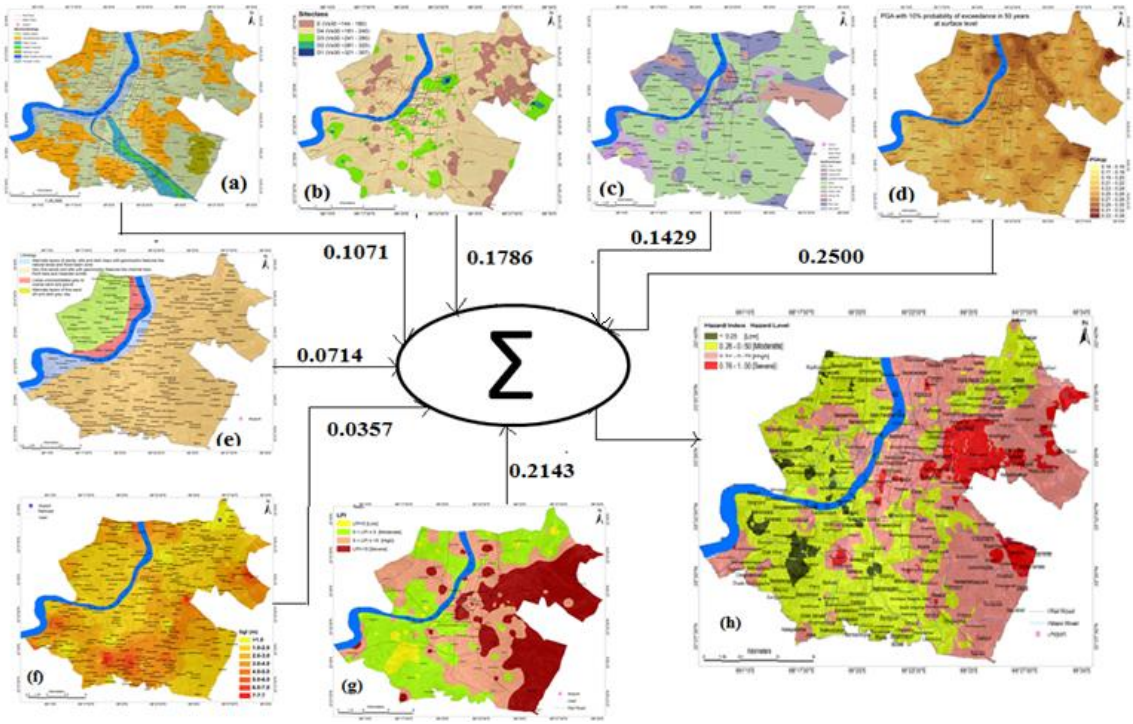


Fig. 2. Seismic Hazard Microzonation protocol for Kolkata showing the weights assigned to each theme labeled according to hazard contribution, (a) Geomorphology (b) NEHRP site class (c) Sediment Class, (d) Spatial distribution of PGA in Kolkata with 10% probability of exceedance in 50 years at surface level, (e) Geology, (f) Groundwater table, (g) Liquefaction Potential Index (LPI) distribution, and (h) Seismic Hazard Microzonation Map of Kolkata [6].

Unplanned urbanization, seismic deficient building codes are continuously increasing the earthquake vulnerability of Kolkata which as mentioned above is already in a

high earthquake alert zone with four probabilistic microzones with PGA values touching as high a value as 0.34g drifting away from BIS Seismic Zone IV thus implicating logical assessment of seismic damage by recognizing contributing factors of seismic risk in terms of structural aspects. The structural risk (SR) elements *viz*. Building Typology, Building Height and Building Age have been integrated with seismic hazard to identify the Structural Risk Index (SRI) defined as $0.75<SRI\leq1.0$ indicating severe risk, $0.50<SRI\leq0.75$ indicating high risk, $0.25<SRI\leq0.50$ moderate risk, while $SRI<0.25$ presents a completely risk free regime [9,10]. At the onslaught of a destructive earthquake in a region, the pre-disaster preparedness and post-disaster relief, rescue and rehabilitation are worked out using any of the tools such as, HAZUS (Hazard-US), RADIUS (Risk Assessment Tools for Diagnosis of Urban areas against Seismic Disasters), ELER (Earthquake Loss Estimation Routine), EPEDAT (The Early Post-Earthquake Damage Assessment Tool), SELENA (SEismic Loss EstimatioN using a logic tree Approach) either individually or in unison. In order to understand the implications of the new seismic hazard microzones, an attempt has been made here to model the building damage scenario, casualty and the economic loss thereof considering 300 socioeconomic clusters in Kolkata. We used SELENA [11,12] as the computational platform in the present analysis. In order to have a conservative deterministic prediction, surface consistent probabilistic seismic hazard in terms of PGA, PSA at 0.3 and 1.0 sec with 10% probability of exceedance in 50 years with a return period of 475 years have been used for the estimation of structural damage, earthquake casualty and probable economic loss for the city of Kolkata.

SELENA is an open-source MATLAB based seismic risk estimation tool developed by NORSAR (Norwegian Seismic Array /International Center for Geohazards, Norway) and the University of Alicante (Spain) for systematic seismic risk assessment using the capacity spectrum method [11,12]. Yang et al. (2011)[13] used this technique to estimate seismic damage and human loss correlated to primary schools during the Mw 7.9 Wenchuan earthquake that occurred on 12 May 2008 at Sichuan Province, China. Lang et al. [14] carried out an analytical based damage and loss estimation for Dehradun city in Northern India, applying the SELENA based approach. The risk-estimates are satisfactorily compared with an earlier empirical intensity-based study. To determine the probability of damage and loss, a detailed information regarding the number of buildings, building area, building footprint, the earthquake sources, empirical ground-motion prediction relationships, soil map, capacity and fragility functions and cost schedules of different model building types are essential. Based on typology and height and applying the stipulated building nomenclature given in HAZUS (1999)[15], WHE-PAGER (2008)[16] and FEMA (2000)[17], eleven model building types have been identified in the city of Kolkata *viz*., A1, RS2, URML, URMM, C1L, C1M, C1H, C3L,C3M, C3H and HER with the respective capacity curves obtained from NIBS (2002)[18]. The dense urbanization of the City with a pictorial representation of different Model Building types is presented in Fig. 3.

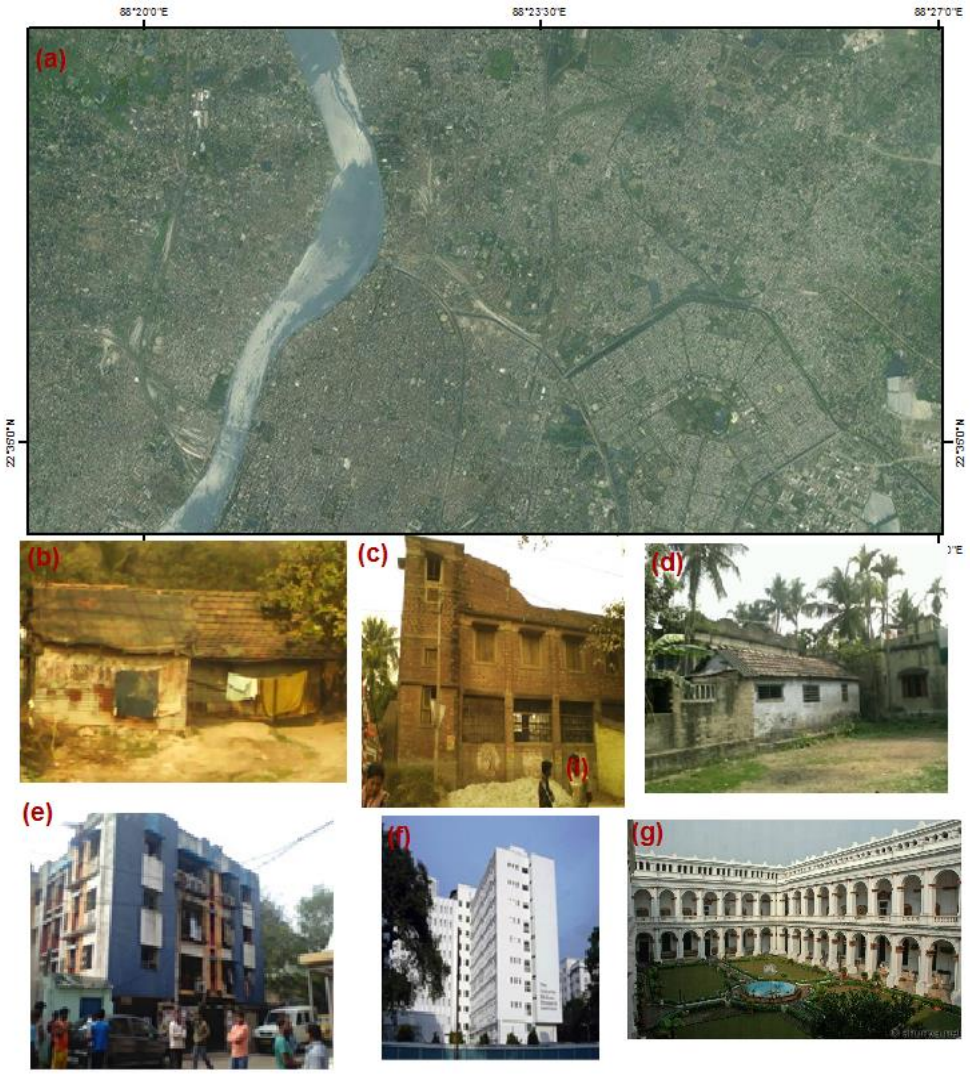


Fig. 3. The city of Kolkata accomplished with (a) Dense Built environment extracted from Google Earth and different building types *viz*., (b) A1, (c) RS2 (d) URM (e) C1 (f) C3, & (g) HER (Indian Museum located at Chowringhee: Lat : 22° 33′ 29″ N, Long : 88° 21′ 3″ E).

2. SELENA Protocol for Damage, Casualty and Economic Loss Prediction for Kolkata

The basic principle underlying SELENA is the capacity spectrum method where the input ground motion in terms of response spectra are combined with the building-specific capacity curve [2]. Capacity curve changes with model building types implicating local building regulations and construction practices, thus influencing the methodology and the results thereof. Based on building typology, building age, and height, eleven model building types have been identified in Kolkata with the respective capacity curves obtained from NIBS (2002)[18]. The building stock used in this study consists of 554,907 buildings with various occupancy classes such as residential, commercial, residential-commercial, and religious, governmental, and educational. It considers assessment at the level of a geographical unit termed 'geounit' which is a tiny area. Damage

probability of different model building types has been determined in five different damage states *viz*. 'none', 'slight', 'moderate', 'extensive' and 'complete' in terms of the total damaged area or the number of damaged buildings. The probable economic loss has been calculated from the convolution of building damage state and building construction cost. Human causality in terms of total injury at three different times of the day (e.g., 10:00 am, 5:00 pm and 2:00 am) has been estimated considering the demographic distribution of the City as obtained from Census, 2011 for 300 socioeconomic clusters of the City. The computational protocol of SELENA has been illustrated in Fig. 4.

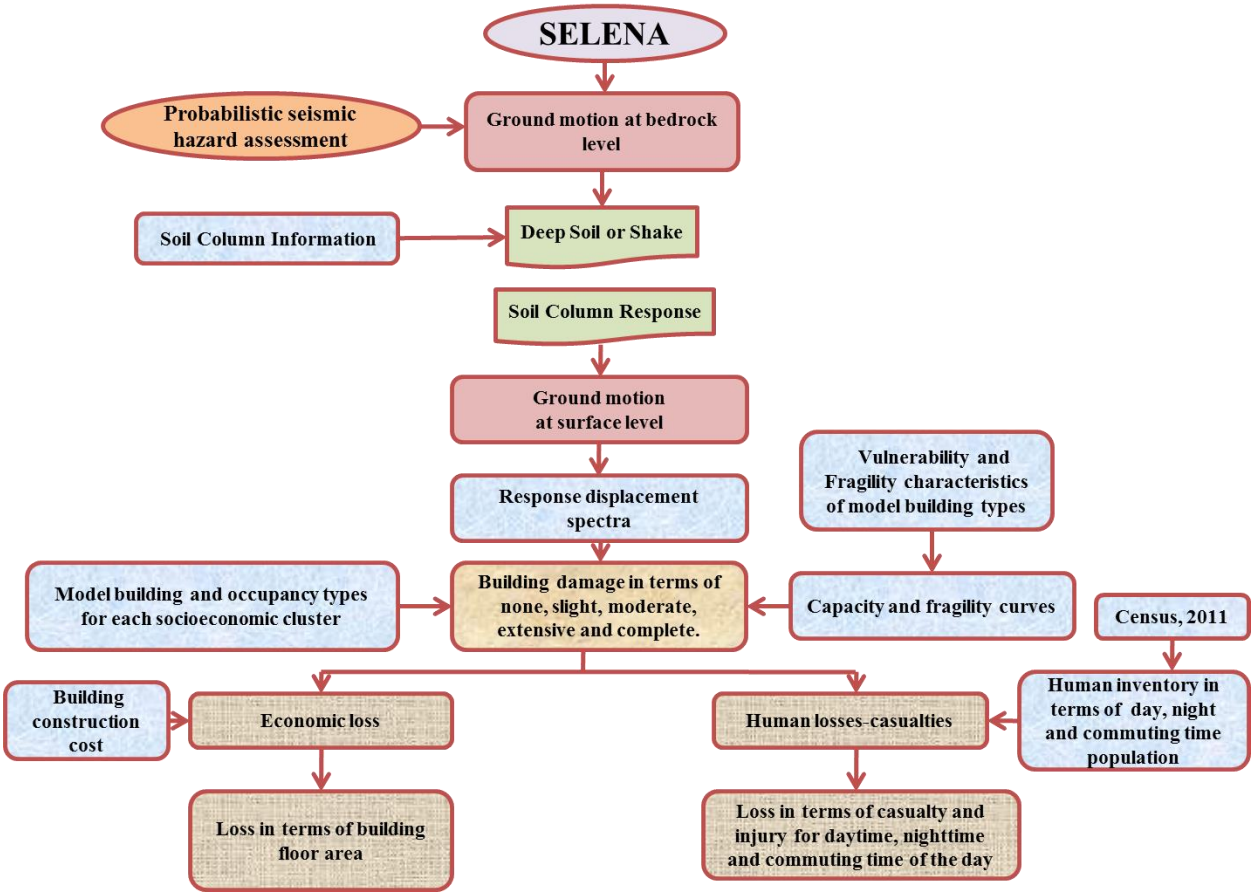


Fig 4. Computational protocol of SELENA.

3. Deterministic Structural Damage Scenario for the City of Kolkata

3.1. Building Inventory

In this article, building inventories are classified according to different Model Building types as defined by HAZUS (1999)[15], WHE-PAGER (2008)[16] and FEMA (2000)[17], etc. A total of 300 socioeconomic clusters consisting of 554,907 buildings obtained from Rapid Visual Screening (RVS) and Google Earth 3D data are rearranged in eleven Model Building Types *viz*. A1, RS2, URML, URMM, C1L, C1M, C1H, C3L, C3M, C3H, and HER as presented in Table 1. The percentage of building floor area for different Model Building Types is shown in Fig. 5.

Table 1. Different model building types used in the present [17,16]

Model Building Type	Description	Height	Stories
HER	Heritage building		
C1L	Ductile reinforced concrete frame with or without infill	Low-Rise	1 – 3
C1M		Mid-Rise	4 - 6
C1H		High-Rise	7+
C3L	Non-ductile reinforced concrete frame with masonry infill walls	Low-Rise	1 - 3
C3M		Mid-Rise	4 - 6
C3H		High-Rise	7+
A1	Adobe Block, Mud Mortar, Wood Roof and Floors	Low-Rise	1-2
RS2	Rubble stone masonry walls with timber frame and roof	Low-Rise	1-2
URML	Unreinforced masonry bearing wall	Low-Rise	2-3
URMM		Mid-Rise	3-4

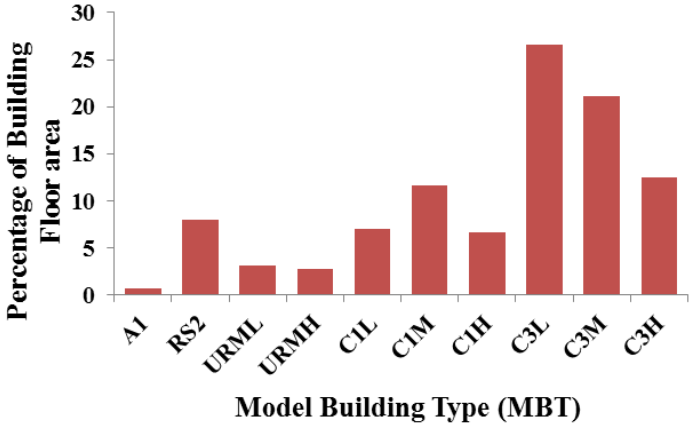


Fig. 5. Percentage of Building Floor area for eleven Model Building types in Kolkata.

3.2. Seismic Demand Input

A probabilistic seismic hazard model of Kolkata have been developed considering 33 polygonal seismogenic sources at two hypocentral depth ranges *viz*. 0-25 km and 25-70 km based on seismicity patterns, fault networks, and similar focal mechanisms [6]. Surface consistent seismic hazard in terms of PGA and PSA at 0.3 sec and 1.0 sec have been determined for 10% probability of exceedance in 50 years by propagating those at engineering bedrock [6] through 1-D soil column at each grind point of the City having shear wave velocity information wherein site amplification got convolved with the bedrock ground motion to assess surface consistent seismic hazard of Kolkata [6]. The response spectra determined based on PGA variation between 0.14g and 0.34g and PSA at 0.3 sec and 1.0 sec from 0.22g to 0.95g and 0.061g to 0.242g respectively at surface level are used to generate seismic damage and loss assessment protocol as shown in Fig. 6. Thereafter, the spectral displacement has been calculated from the response spectra for the assessment of the ultimate capacity of the building by applying the following equation,

$$S_D = 9.8 \times S_A \times T^2 / 4\pi^2 \quad (1)$$

Where, S_D is the spectral displacement, S_A is the spectral acceleration in g and T is the spectral period.

3.3 Computation, Results and Discussion

The probability of damage in each geounit is calculated in a relationship with the provided ground motion [19-21]. It consists of steps like Generation of the capacity spectrum, Computation of demand spectrum, and Determination of performance point. Structural capacity is represented by a force-displacement curve. Pushover analysis is performed for a structure with boosting lateral forces, representing the inertial forces of the structure under seismic demand. The process is continued until the structure becomes unstable. The seismic demand curve is represented by the response spectrum curve in the spectral displacement – spectral acceleration space. The performance point is the intersection between the seismic demand curve and the building capacity curve. In this study, the Capacity and Fragility curve for each Model Building Type has been taken from [18]. Representative Capacity and Fragility function for C1 Model Building Types is illustrated in Fig. 7.

The Performance point (d_p) is identified from the intersection between the seismic demand and building capacity curve, as illustrated in Fig. 8(a). For the computation of damage probabilities, vulnerability curves, or fragility curves for four damage states are essential, which are developed as the lognormal probability distribution of damage from the capacity curve, as shown in Fig. 8(b). The cumulative damage probabilities have been calculated as (NIBS, 2002)[18],

$$p\left[ds / S_d\right] = \phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{S_{d,ds}}\right)\right] \tag{2}$$

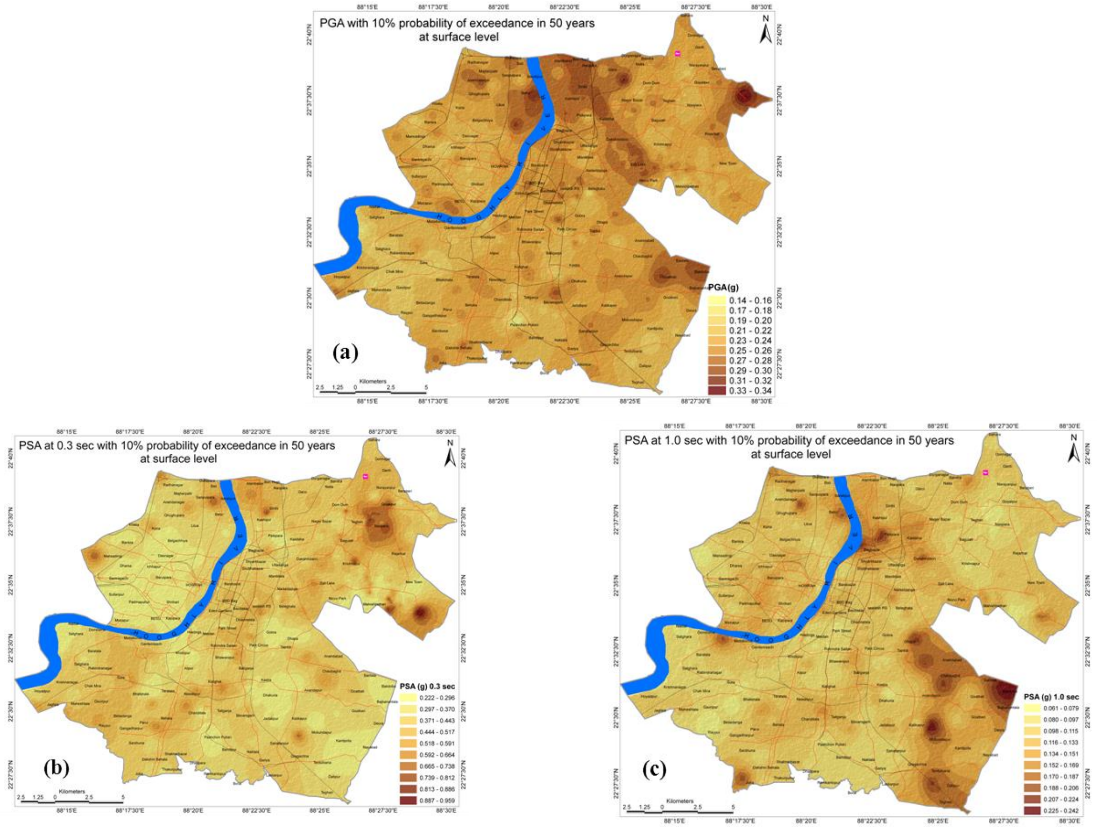


Fig. 6. Surface consistent Probabilistic PGA distribution in terms of (a) PGA, (b) PSA at 0.3 sec, and (c) 1.0 sec for 10% probability of exceedance in 50 years [6].

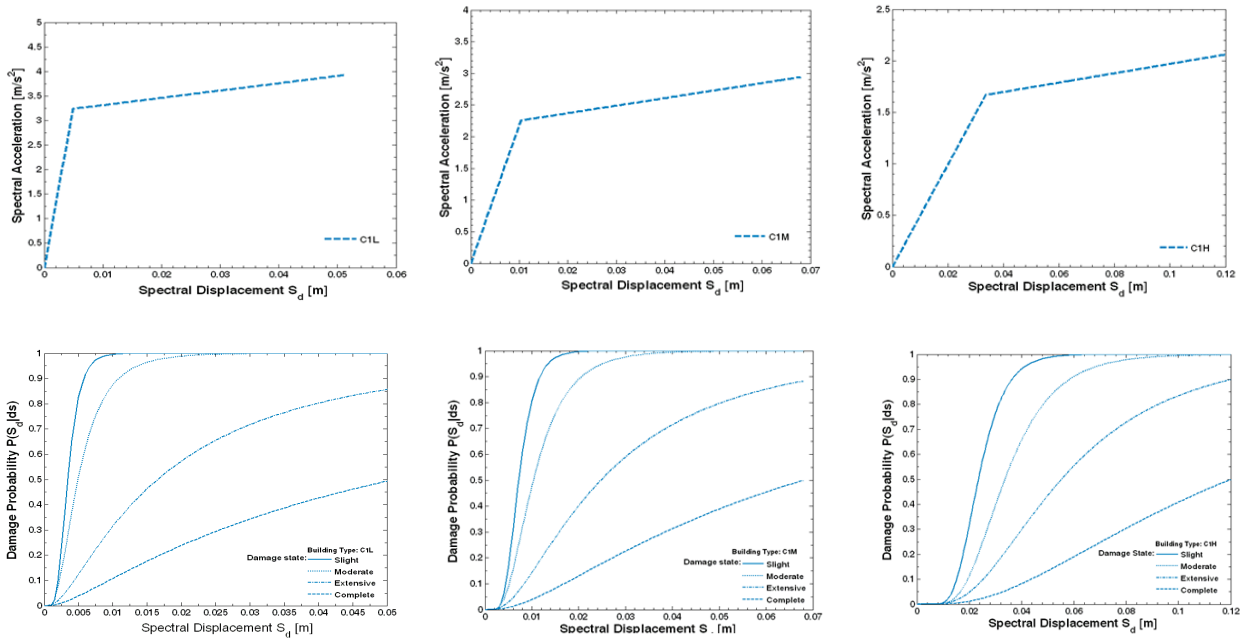
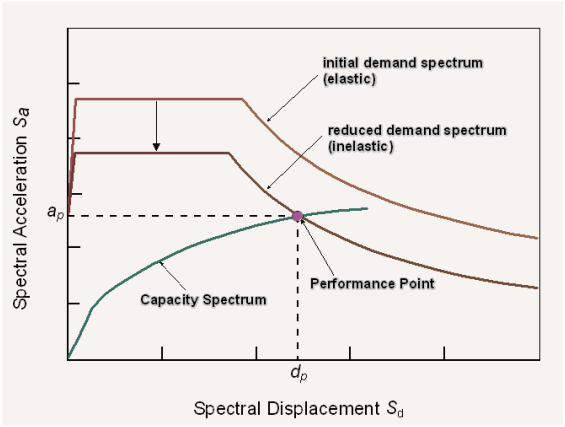
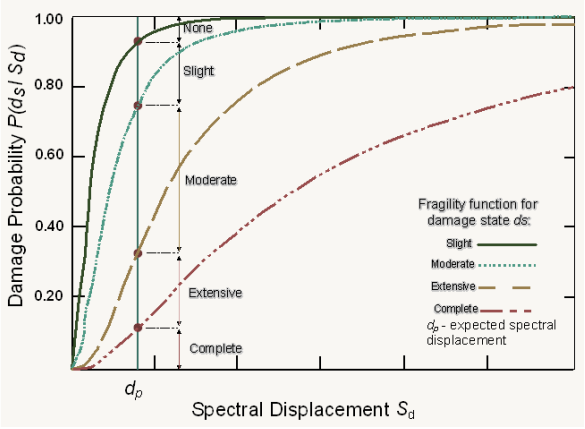


Fig. 7. Capacity and Fragility curve for C1 Model Building Types [18,10].

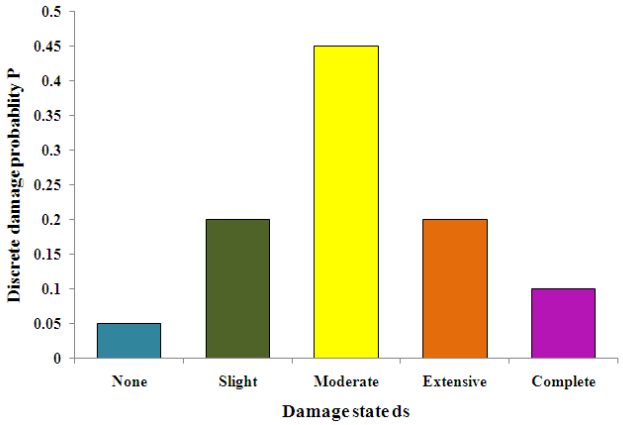
Where, $p\left[ds / S_d\right]$ is the Probability of being in or exceeding a damage state, ds ; S_d is the given spectral displacement in inches; $\overline{S}_{ds}$ is the Median value of S_d at which the building reaches the threshold of the damage state ds; β_{ds} is the Lognormal standard deviation of spectral displacement of damage state, ds ; and ϕ is the standard normal cumulative distribution function. Both Sd,ds, and βds depend on a building type and its seismic design level (FEMA, 2000) [17]. The damage state (ds) of a structure is classified into four states: 'slight', 'moderate', 'extensive', and 'complete' as depicted in Fig. 8(b). For an expected displacement, cumulative probabilities are defined to obtain discrete probabilities of being in each of the five different damage states as portrayed in Fig. 8 (c).



(a)



(b)



(c)

Fig. 8. (a) Building specific capacity spectrum intersected by the demand spectrum representing the performance point, (b) Fragility curves showing the extent of different damage states (*ds*), and (c) The discrete probabilities of different damage states, *ds*.

It has been estimated from the protocol that out of 554,907 buildings in Kolkata approximately 34% are expected to suffer from 'moderate' damage followed by ~26% 'complete', ~18% 'extensive', and ~15% 'slight' damage. Approximately 7% of buildings are seismic resistant in the City as collectively illustrated in Fig. 9. Unreinforced masonry buildings are the most seismically vulnerable (Spence, 2007) ones and, therefore, face the chance of 'complete' damage.

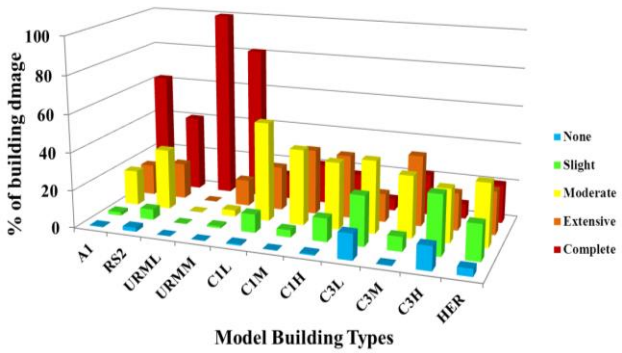


Fig. 9. Predicted damage probability in terms of 'None', 'Slight', 'Moderate', 'Extensive', and 'Complete' for the identified model building types in the City.

3.3.1. Damage Estimation for 'A1' Model Building Types

'A1' building type is non-engineered and mainly made up of adobe block, mud mortar, wood roof, and floors. This building type is vulnerable to earthquakes and, therefore, 62% of this type of buildings will be completely damaged as presented in Fig. 10.

3.3.2. Damage Estimation for 'RS2' Model Building Types

'RS2' Model building type is also vulnerable to earthquakes and will face 'moderate' to 'complete' damage if the City surge by any moderate to large earthquakes in the future. The different damage states for this model building type, as shown in Fig. 11 depicts that most of the buildings of various parts of the City will be destroyed completely. It is evident that 40% of the total 'RS2' model buildings of Kolkata is expected to damage completely, followed by 20% 'extensive', 32% 'moderate' and 6% 'slight' damage.

3.3.3. Damage Estimation for 'URM' Model Building Types

Unreinforced masonry buildings are the most seismically vulnerable [22] and, consequently, the chance of 'complete' damage state of this type of buildings are very high. About 90% of both the low-rise (URML) and mid-rise (URMM) buildings of this type will face 'complete' damage in Kolkata as presented in Fig. 12 (a) and (b) respectively.

3.3.4. Damage Estimation for 'C1' Model Building Types

'C1' building type is mostly ductile reinforced concrete frame with or without infill. The damage distributions of 'C1' type of buildings (Low-rise, Mid-rise, and High rise) are presented in Fig. 13(a), (b) and (c) respectively. Mid-rise and High rise buildings of this type of building will face 'moderate' to 'extensive' damage, while Low rise will face 'slight' to 'moderate' damage.

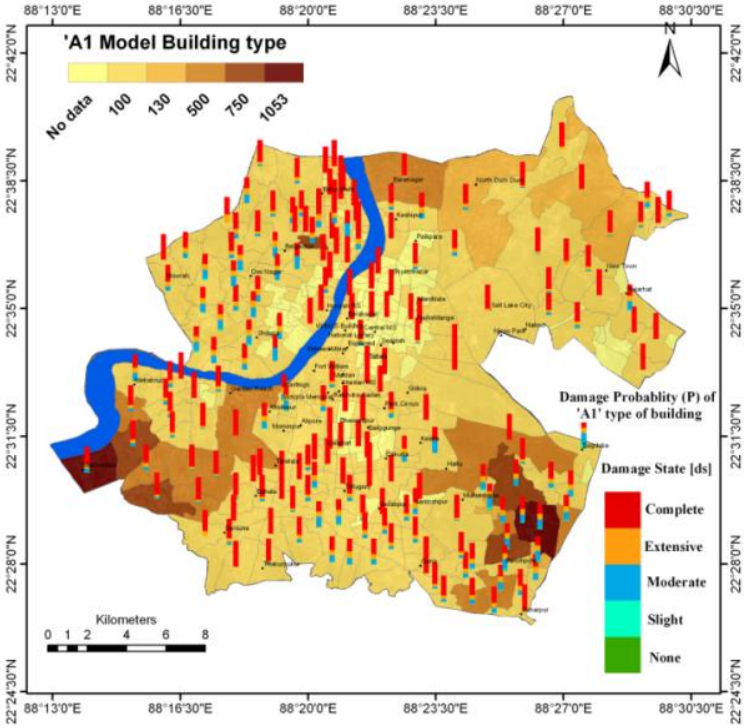


Fig. 10. Damage distribution for 'A1' type buildings in Kolkata.

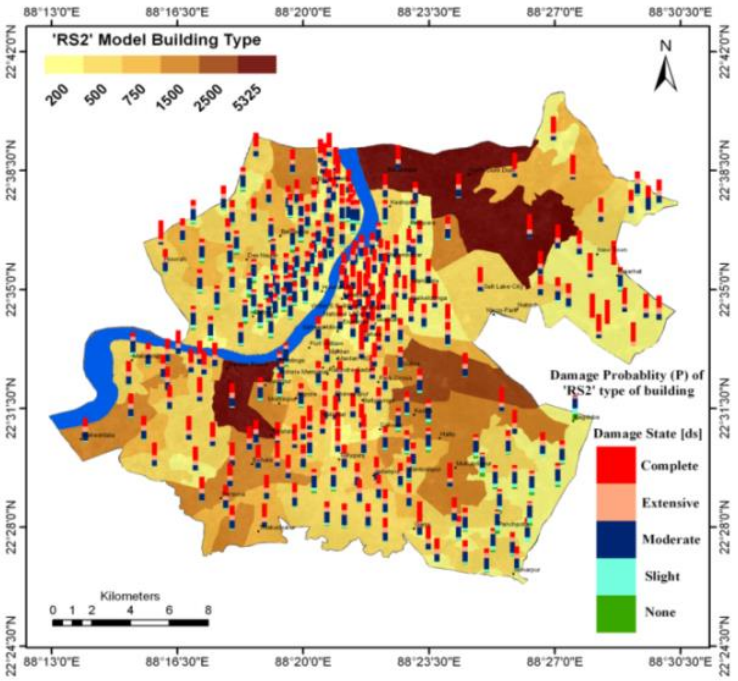


Fig. 11. Damage distribution for RS2 type buildings in Kolkata.

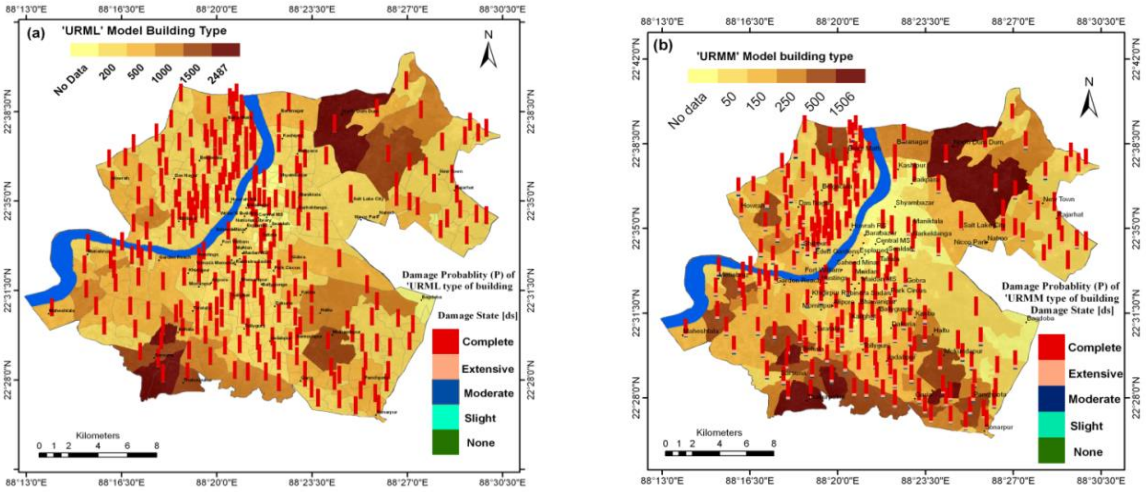


Fig. 12. Damage distribution for (a) 'URML' and (b) 'URMM' type buildings in Kolkata.

3.3.5 Damage Estimation for 'C3' Model Building Types

'C3' building type is mainly ductile reinforced concrete frame with infill, and they are mostly seismic resistant. The damage distribution of 'C3' model building type represents that most of the concrete building of low and high rise will suffer 'slight' to 'moderate' damage as illustrated in Fig. 14(a) and 14(c), while mid-rise buildings (C3M) will face 'moderate' to 'extensive' damage as depicted in Fig. 14(b) which is attributed to high hazard conditions at these building localities and also the proportionate increase in the construction of these type of mid-rise buildings as compared to the low-rise and high-rise ones.

3.3.6 Damage Estimation for 'HER' Model Building Types

The damage distribution pattern for heritage type buildings has been depicted in Fig. 15. It is evident that most of the Heritage buildings of Kolkata are mainly present in Central Kolkata and will face 'slight' to 'moderate' damage. Less than 15% of these buildings are expected to face 'complete' damage as per the conservative estimate through SELENA.

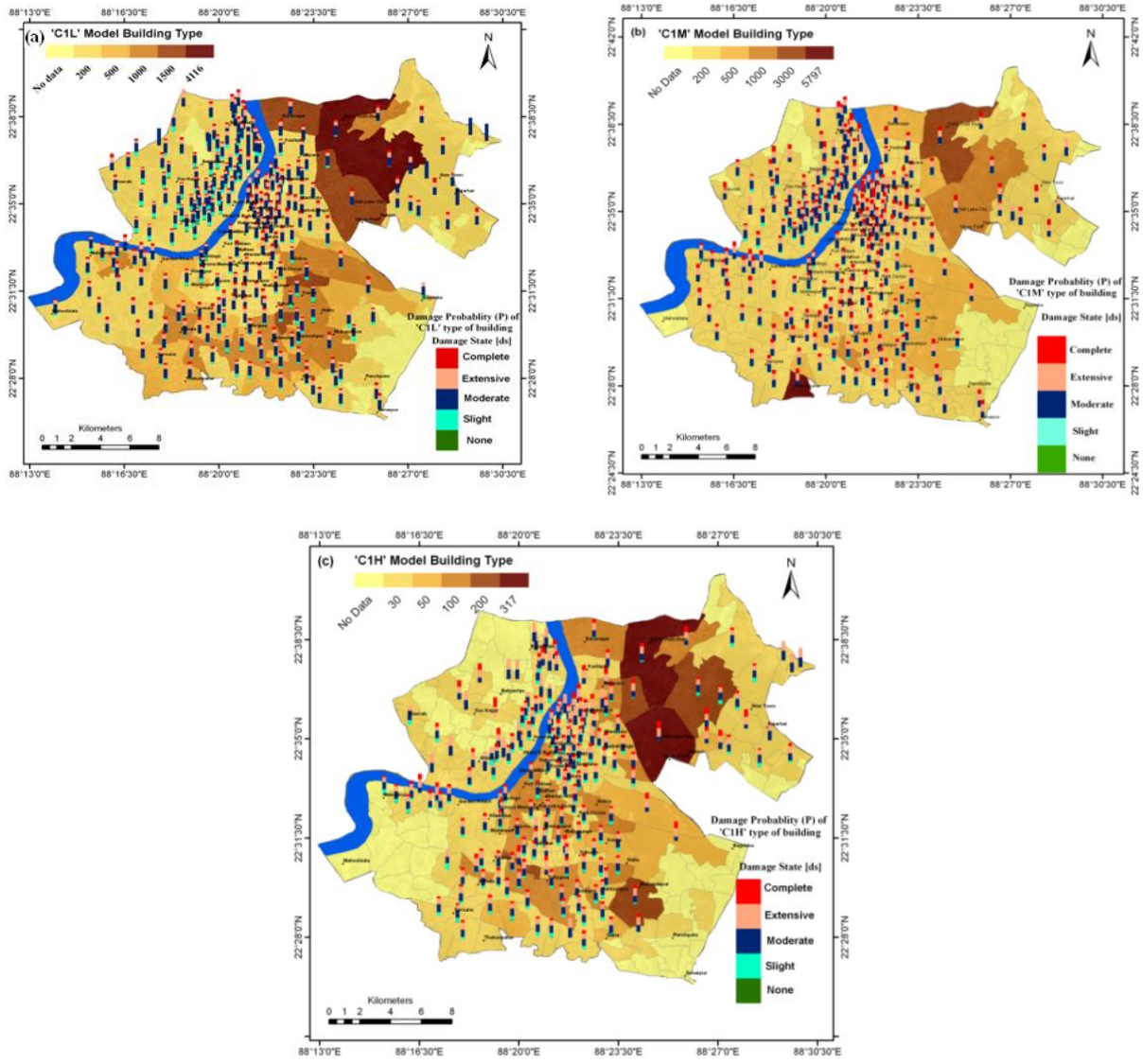


Fig. 13. Damage distribution for (a) 'C1L', (b) 'C1M', and (c) 'C1H' type buildings in Kolkata.

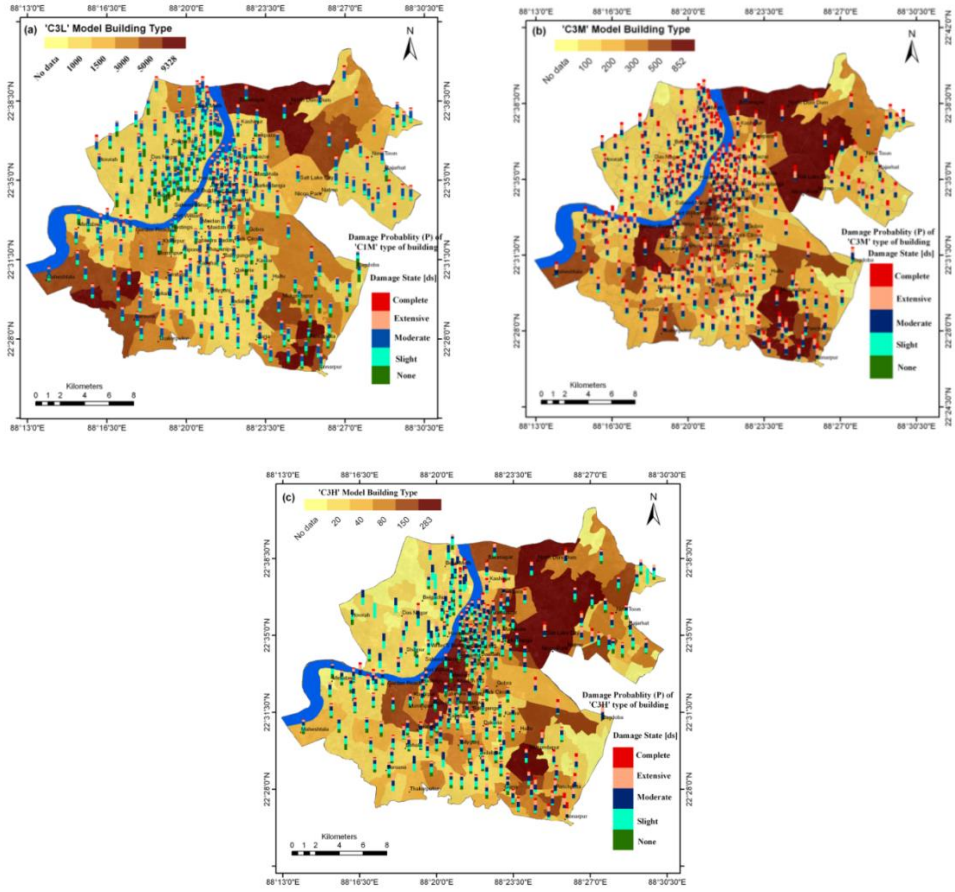


Fig. 14. Damage distribution for (a) 'C3L', (b) 'C3M', and (c) 'C3H' type buildings in Kolkata.

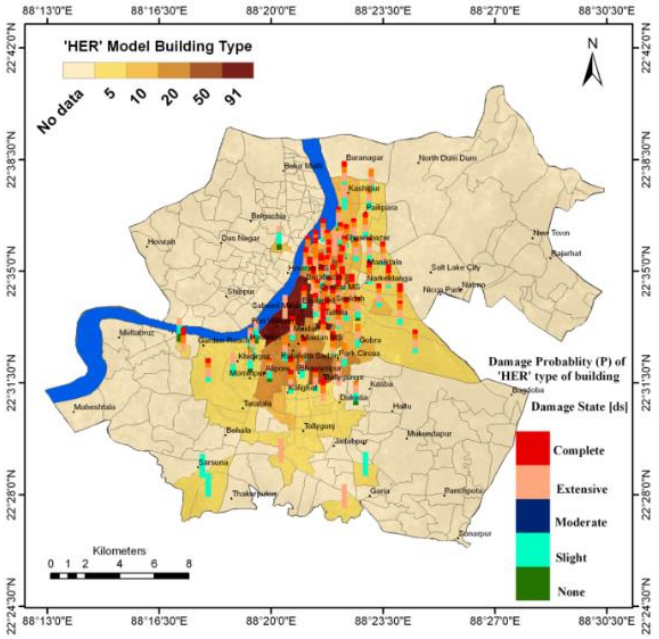


Fig. 15. Damage distribution for 'HER' buildings in Kolkata.

4. Prediction of Deterministic Economic Loss for a Probabilistic Hazard Scenario with a Return Period of 475 Years for the City of Kolkata

The total economic loss caused due to the damage to all model building types in each geounit has been primarily estimated by considering the loss due to direct physical damage to the structural components. To compute the total economic loss caused by the damage to a certain model building type, specific construction values are essential. The prevailing construction schedules per square meter for different model building types in Kolkata are given in Table 2.

Table 2. Prevailing Construction cost per square meter for different model building types in Kolkata (After Kolkata Municipal Development Authority (KMDA))

Building Types/Stories	Stories 1	Stories 2	Stories 3	Stories 4	Stories 5	Stories 6	Stories 7	Stories 8+
C1L	15441	9157	9695	-	-	-	-	-
C1M	-	-	-	10104	10138	10332	10462	-
C1H	-	-	-	-	-	-	-	41175
C3L	14928	11261	10039	-	-	-	-	-
C3M	-	-	-	9768	9325	9035	8986	-
C3H	-	-	-	-	-	-	-	10350
A1	8608	-	-	-	-	-	-	-
RS2	-	8925	8630	-	-	-	-	-
URML	12500	12360	-	-	-	-	-	-
URMM	-	-	14200	13525	-	-	-	-

The total economic loss caused due to damage to all model building types in each geounit has been primarily estimated by considering the loss due to direct physical damage to the structural components. The economic loss for the building structural damage is calculated applying the formulation of [12] as given by,

$$L_{eco} = C_r \sum_{i=1}^{N_{OT}} \sum_{j=1}^{N_{BT}} \sum_{k=1}^{N_{DS}} A_{i,j} P_{j,k,} C_{i,j,k} \qquad (3)$$

Where, N_{OT}= Number of occupancy type, N_{BT}=Number of building typology, N_{DS}=Number of damage state ds, C_r = Regional cost multiplier, $A_{i,j}$= Built area of the model building type j in the occupancy type i, $P_{j,k}$= damage probability of structural damage k for the model building type j, $C_{i,j,k}$= Cost (by m^2) in the input currency of damage state k for occupancy i and model building type j.

The main purpose of earthquake loss assessment studies is to generate reliable estimates of expected structural damages and the associated economic and social losses incurred thereof. Here the estimated building damage is converted into economic loss by using the available inventory database, including the floor area, construction cost estimates, *viz*. the amount of money in Indian Rupees per square meter as provided by the local authorities. The economic loss of a building is primarily dependent on the building type, occupancy class, and the structural damage state. The estimated probable loss that may be aroused in the event of the occurrence of a seismic hazard condition with 10% probability of

exceedance in 50 years is ~ 231 billion rupees for the city of Kolkata from building damage point of view only. The economic loss distribution in the GIS platform, as shown in Fig. 16 exhibits that Saltlake, Baranagar, North Dumdum, Garden Reach and part of Central Kolkata are expected to incur the highest economic loss.

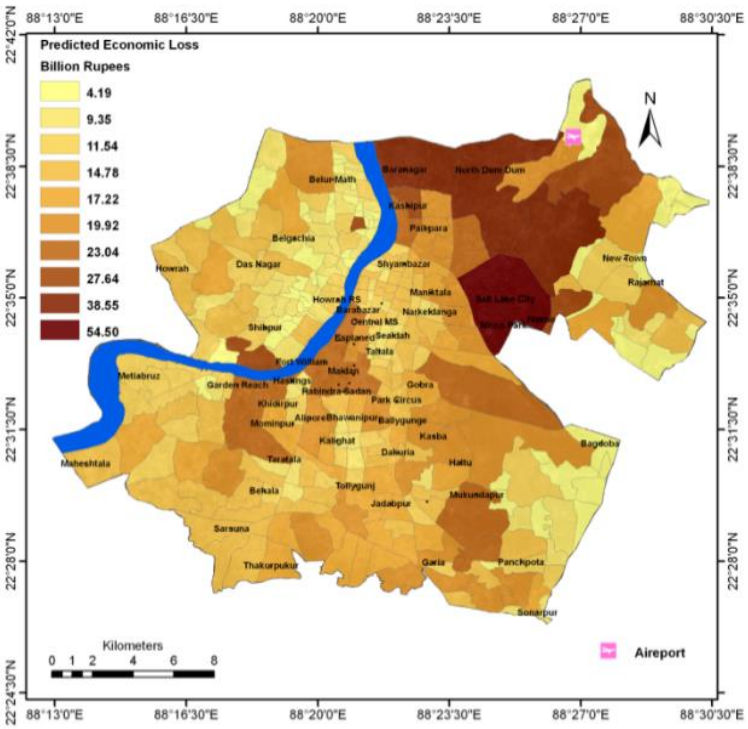


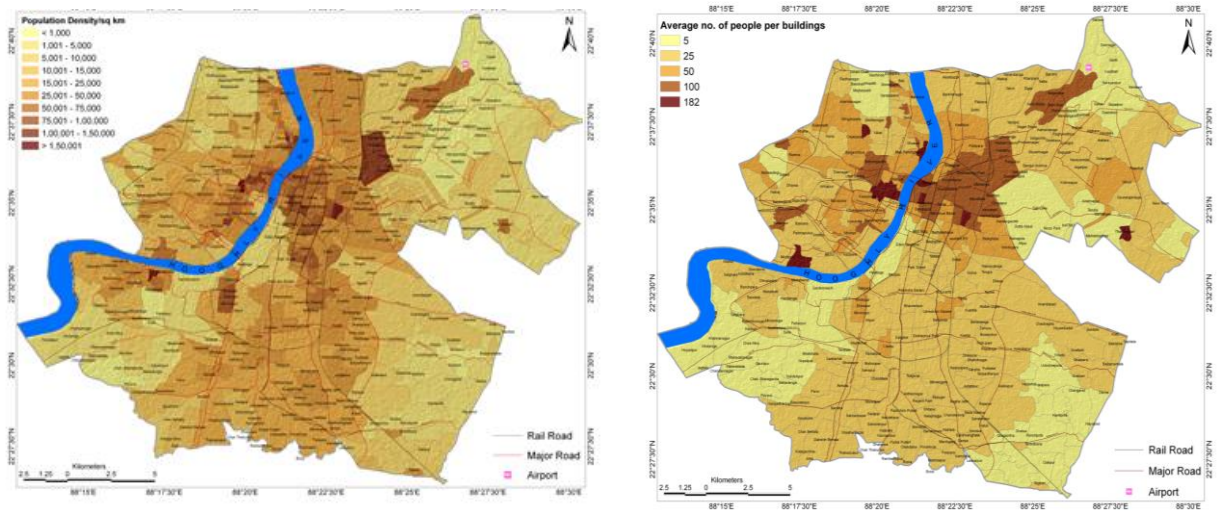
Fig. 16. Economic loss estimation for the probable hazard in Kolkata.

5. Deterministic Casualty Scenario of Kolkata for a Seismic Hazard Scenario with a Return Period of 475 Years

A well-organized demographic data is required for casualty estimation, calculated at the census tract level. In the city of Kolkata, population density, gender-based population ratio, age-wise population on below seven and above sixty-five, day time and night time population are estimated from census data, 2011 as input for loss estimation. It will normally give the average number of persons per geounit area and also a relation to building types. Fig. 17(a) exhibits that population density is very high in Taratala, Khidirpur, Barabazar, Shyambazar, and Metiabruze area [9]. The average number of people residing in each building has also been extracted from the Census, 2011, and its spatial distribution is illustrated in Fig. 17(b).

Human casualty/injury levels are determined to apply SELENA considering the probabilistic seismic hazard condition for a 10% probability of exceedance in 50 years at a surface level. In order to consider cases of occupancy which are dependent on the time of the day, the number of casualties have been determined for three different times of the day *viz*. the night time scenario (at 02:00

am), the day time scenario (at 10:00 am), and the commuting time scenario (at 05:00 pm). The methodology provides estimations regarding the number of human casualties (indoor and outdoor both) caused by building collapse only. The percentage indoor and outdoor population of a particular time is adopted from [12] and is illustrated in Table 3.



(a) (b)

Fig. 17. (a) Demographic distribution of the city of Kolkata [9] and (b) the Average number of people residing in each building in the City.

Table 3. Percentage of the indoor and outdoor population dependent on the time of the day [12]

Occupancy Class	Night (at 2:00 am)	Day (at 10:00 am)	Commuting (at 5:00 pm)
Indoor	98 %	90%	36%
Outdoor	2%	10%	64%
Sum Σ	100 %	100 %	100 %

Casualty is the indirect effect of earthquake impact, while the building damage is the direct one. The number of casualty has initially been calculated applying HAZUS, later modified using the formulation of Coburn and Spence (2002)[23] as,

$$K=K^S+K'+K_2 \quad (4)$$

Where,

K^S = number of casualties due to structural damage,

K' = number of non-structural damage,

K_2 = number of casualties due to following on hazards, such as landslide, fires, etc.

By considering the severity of the injury the equation is further modified by Coburn and Spence (2002)[23] as:

$$K_i=K_i^S+K_i'+K_{2i} \quad (5)$$

Where i is the representative level of injury ranging from low injury (i=1), moderate injury (i=2), heavy injury (i=3) to death (i=4).

SELENA determines the injury level by applying two types of methodologies: Basic methodology and HAZUS methodology. In the present study, casualties have been estimated using the formulation of Molina et al. (2010)[2]:

$$K_s^i = \{Injuries(Severitiy)\} = \sum_{J=1}^{N_{BT}} \sum_{K=1}^{N_{DS}} c_{i,j}^{CSR} P_{i,j} N_j^{POP} \quad (6)$$

In which, $c_{i,j}^{CSR}$ = Casualty rate of severity i for damage state j, $P_{i,j}$ = structural damage probability for the damage state k for the model building type j, N_j^{POP} = Number of people in the model building type j. As the number of casualties is strongly depended on time of the day at which the estimation is performed, injury level is, consequently, calculated at three times of the day *viz*. day time (at 10:00 am), night time (at 02:00 am) and commuting time (at 05:00 pm).

Nighttime Scenario (at 02:00 am)

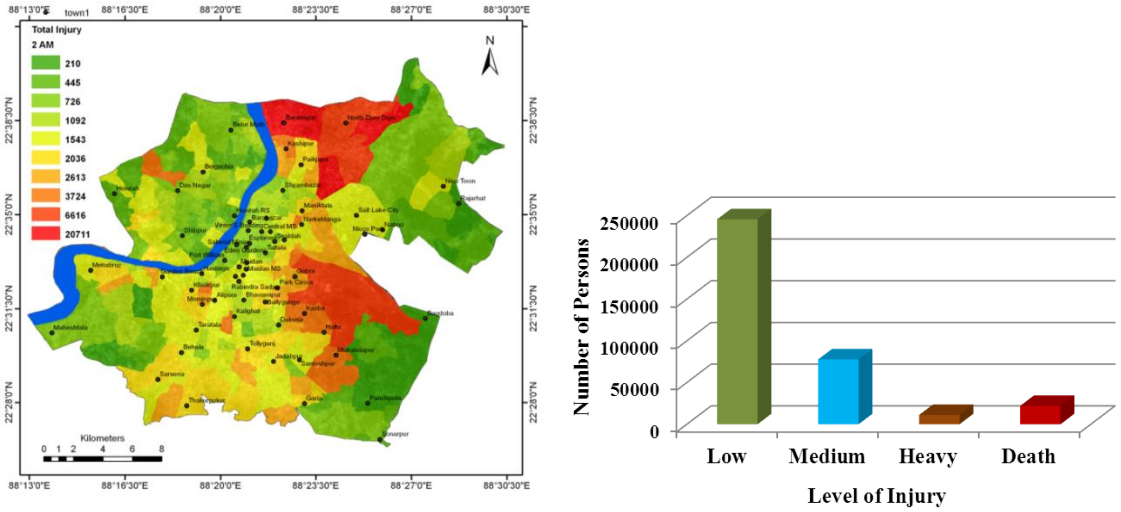
This scenario is expected to generate the larger casualty for the population at home in the night time. The methodology assumes that at night, 98% population resides indoors. Distribution of casualty/injury at different places is illustrated in Fig. 18(a), where it is evident that Saltlake, Behala, New Town and part of Howrah region may suffer moderate to high casualty in terms of different levels of injury from low to heavy and even death. According to this scenario, more than 245,616 people of the study region may suffer from a minor injury, and approximately 21,962 people may even lose their lives, as depicted in Fig. 18(b).

Day Time Scenario (at 10:00 am)

Day time scenario (at 10:00 am) has also been generated when most of the people are at their work or educational institutions. Here it is assumed that 90% population was residing indoors and 10% was outdoors. Fig. 19(a) depicts that the population of Saltlake, Behala, New Town, Park Circus and parts of Howrah will suffer moderate to high causality, while those in Dumdum will be the extensive sufferers. Therefore, the estimated casualty for day time scenario reveals that more than 198,450 persons may suffer from a minor injury, followed by ~20,000 persons suffering from a medium injury while ~62,761 persons may be critically injured as depicted in Fig. 19(b). Approximately 17,746 persons from different localities may even die under the futuristic hazard condition for the City.

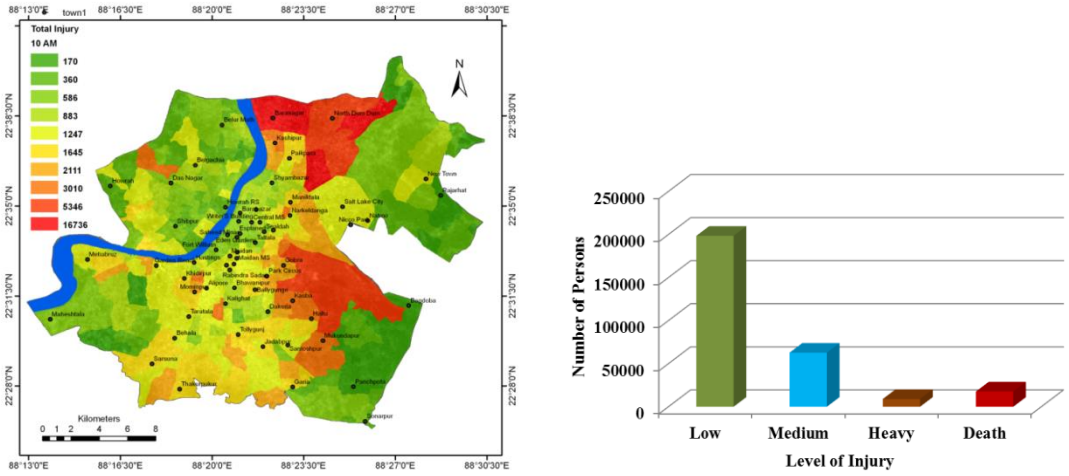
Commuting Time Scenario (at 05:00 pm)

The scenario has been generated for the commuting time, i.e. the rush hour by assuming that the maximum number of people was outdoors (64%). It reduces the chances of a casualty by only building damage and generates the minimum casualty scenario for the hazard in question. Fig. 20(a) illustrates that the population at Saltlake, Behala, Thakurpukur, New Town, Tollygunge and part of Howrah will suffer moderate to high casualty, while those in Dumdum would suffer the most. The population distribution for five types of severity level is depicted in Fig. 20(b) from which it is evident that ~37,215, ~11,767 and ~1,685 people may have an injury in terms of minor, medium and critical respectively, while ~3,326 people may lose their life.



(a) (b)

Fig. 18. (a) Distribution of injured persons at night time (at 2:00 am), and (b) predicted night time scenario in terms of different severity levels.



(a) (b)

Fig. 19. (a) Distribution of injured persons at day time (at 10:00 am), and (b) predicted day time scenario in terms of different severity levels.

6. Conclusion

The structural damage and its associated economic loss and casualty have been estimated for the probable earthquake scenario of the city of Kolkata for a return period of 475 years with a view to possible disaster mitigation and management. The damage and economic loss scenario of Kolkata can be applied for the land use and urban city planning and up-gradation of seismic building code provisions. The emergency response capabilities can be significantly improved to reduce casualties by rapid, selective, and effective use of provided services. The architects and civil engineers may also apply this information to assess the failure risk of the existing structures and thus design future earthquake resistant structures in Kolkata.

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