11

Surface Consistent Probabilistic Seismic Hazard Microzonation of Kolkata

11.1 Introduction

Natural disasters inflicted by earthquakes cannot be prevented, nor is there any possibility in the near future for accurate and socially useful short-term prediction for an impending earthquake. The damage pattern due to an earthquake depends largely on the local site condition and the social infrastructure of the region with the most important condition being the intensity of ground shaking at the time of an earthquake. Contrasting seismic response is observed even within a short distance over small changes in geology of the site. Therefore, the role of geological, geophysical and geotechnical information is becoming very crucial in seismic hazard microzonation particular to new urbanization, which can recognize, control and prevent geological hazards (Rau, 1994; Dai *et al*., 1994; 2001; Van Rooy and Stiff, 2001; Nath and Thingbaijam, 2011b).

Seismic Microzonation is a process of estimating site-specific effect due to an earthquake on urban centers for its disaster mitigation and management. Therefore, Seismic Hazard Microzonation, which is defined as the subdivision of a zone into subzones having relatively similar exposure to seismic shaking and accompanying environmental effects, such as surface faulting, liquefaction and landslides on the basis of different soil response with respect to ground motion characteristics taking into account source, path and site conditions (Nath, 2011), has been recognized as the most accepted tool in earthquake hazard and risk evaluation. The first attempt in seismic microzonation of urban areas was made in the city of Yokohama, Japan in 1954 considering various seismic sources, site conditions and seismic design coefficients for different types of structures. Subsequently, the hazard microzonation studies were conducted in various earthquake prone urban areas *viz.* Bursa (Topal *et al.*, 2003), Bucharest (Moldoveanu *et al.*, 2004), Algiers (Harbi *et al.*, 2004), Alexandria (El–Sayed *et al*., 2004), Beijing (Ding *et al*., 2004), Napoli (Nunziata, 2004), Santiago de Cuba (Alvarez *et al*., 2004), Sofia (Slavov *et al*., 2004), Zagreb (Herak *et al*., 2004) *etc.*

As per the existing seismic zoning map of India (BIS, 2002), the country has been divided into four seismic zones. However, the zone factor and seismic coefficient worked out as per the recommendation of BIS 1893-2002 may be different from the actual values for different sites within a same zone. This is due to the variability in locations of earthquakes, their epicentral distances from the sites and other site-specific details. Therefore, existing seismic zonation map is not sufficient in the assessment of site-specific seismic risk, thus, necessitating locale-specific seismic zoning for successful earthquake disaster mitigation and management. Accordingly, seismic microzonation studies introduced in India and the first level multi-criteria assessment of hazard leading to seismic microzonation has already been completed in several cities *viz.* Guwahati, the Sikkim Himalaya, NCR Delhi, Bangalore, Jabalpur, Dehradun and Chennai to name a few.

The challenge in urban hazard mapping is to predict the ground motion effects related to various source, path and site characteristics with an acceptable level of reliability. Seismic microzonation is the first and foremost step in minimizing earthquake inflicted damage to life and property. A Seismic Microzonation framework is shown in Figure 11.1 illustrating the causative seismological and geological attributes. The scheme outlines compilation of information related to seismicity, identification of potential seismic source zones, development of seismicity models, maximum earthquake prognosis based on homogeneous earthquake catalogues and other relevant database such as tectonic and ground-rupture data bases. The local level assessments involve mapping of surficial geological & geomorphological features, development of geotechnical database, and evaluation of different surficial soil attributes *viz*. density, rigidity, compressibility, damping, water content *etc.* Therefore, the Seismic Hazard Microzonation framework encompasses the seismicity, seismic sources and earthquake potential of a region based on available historical & instrumental data covering hundreds of years, micro- and macro-seismicity, regional tectonics & neo-tectonics (faults/lineaments), geology, geo-hydrology, crustal structure, subsurface lithostratigraphy, ground rupture hazard and soil liquefaction. A general methodology for performing seismic microzonation of a region can broadly be divided into the followings:

i) Establish the geological and geomorphological units of the region and its surrounding areas, including the subsurface lithostratigraphy.

ii) Identify and characterize major/minor faults, lineaments and seismotectonic units that are seismically active.

iii) Estimate ground motion parameters using the historical seismicity and recorded earthquake ground motion that include the location of potential sources, magnitude, faulting mechanism, epicentral distance *etc.*

iv) Perform site characterization using geological, geomorphological, geophysical and geotechnical data.

v) Assess local site effects that include NEHRP site classes, site amplification, predominant frequency and liquefaction susceptibility mapping.

vi) Assess site-specific probabilistic seismic hazard.

In order to understand the combined effect of geological and seismological hazard themes, maps of various hazard attributes are integrated on GIS platform using suitable weightage and rank through a pair-wise comparison matrix.

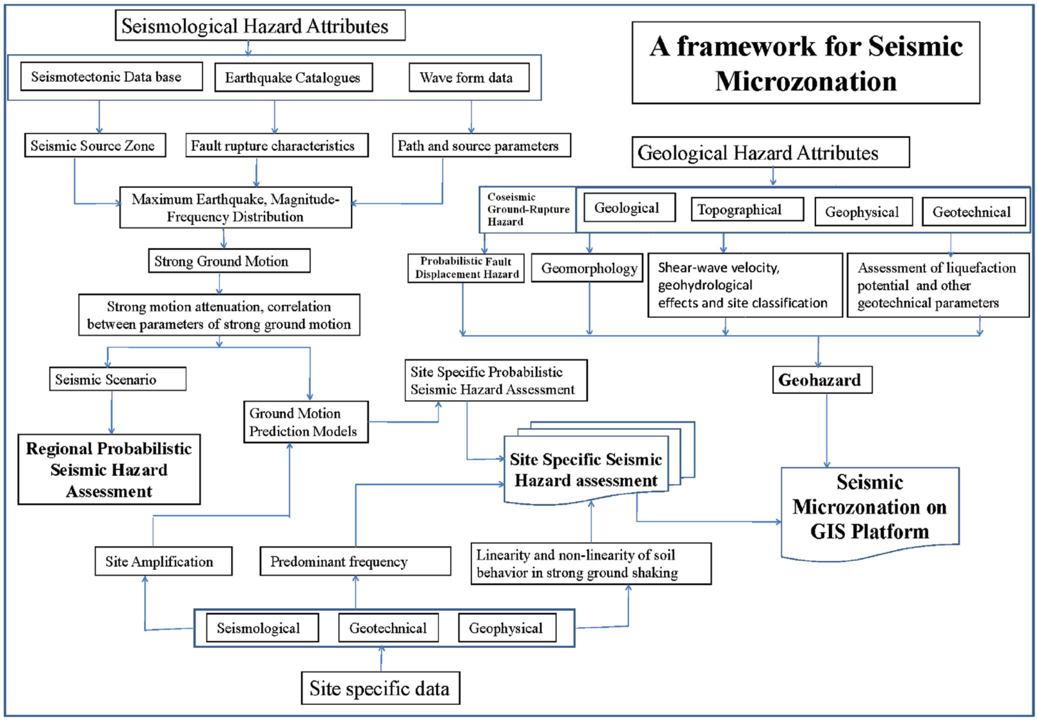


Figure 11.1 **A site-specific Seismic Hazard Microzonation Framework for the city of Kolkata.**

11.2 GIS-aided Seismic Microzonation Study

The development in Geographic Information System (GIS) and its versatility exhibits GIS playing an important role in the natural disaster programs. The amount, quality and cost of information required for mapping generally increases with greater levels of certainty. Collected data can then be processed into a series of GIS layers followed by quantitative evaluation of hazard potential. Therefore, GIS platform has been adopted as a primary working tool in preparing seismic hazard microzonation attributes for the city of Kolkata. Multitasking functionality of GIS makes it ideally suited for seismic microzonation as it enables automation of data manipulation and information of thematic layers. The complex spatial analyses associated with seismic microzonation necessitate GIS technology for data dissemination and its management. The ability of GIS to handle large volume of data, its flexibility, accuracy and its capability to upgrade the database and to integrate the same in a short time has proved to be indispensable in the field of seismic microzonation. A

GIS approach comprises of three distinct phases (Sander, 1998): (1) data acquisition, (2) data processing, and (3) data analysis. A GIS based schematic process is shown in Figure 11.2. The most important features of GIS is the manipulation and analysis of both the spatial (graphic) and non-spatial (non-graphic) data. The GIS can be used for hazard management at various levels of development planning. At the national level, it can provide a general familiarity with the study area giving planners a reference to an overall hazard condition. At the regional level, it can be used in the hazard assessment for resource analysis and project identification, while, at the local level, it can be used to formulate investment projects and specific mitigation strategies. Therefore, it is hard to conceive a micro-seismic programme without its very intimate coupling with GIS.

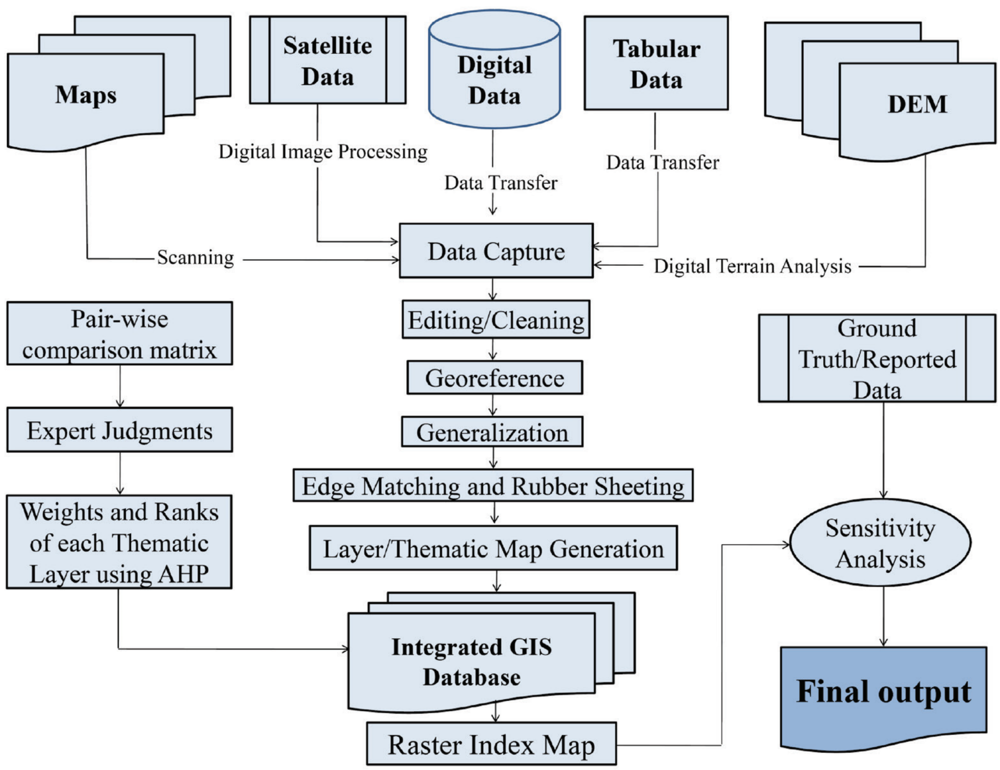


Figure 11.2 **A schematic process flow in GIS based Thematic Mapping and Spatial analysis.**

A seismic microzonation process is initiated with rudimentary assessments based on the existing regional/local level hazard estimation, seismotectonic and macro-seismic studies. Several site specific hazard attributes are, thereafter, evaluated through geological, geophysical, geotechnical and seismological investigations and mapped on the GIS platform with a uniform and consistent georeferencing scheme. The representation and interpretation of uncertainty related to the classification of individual locations is provided by fuzzy logic based on location attributes. The main idea of fuzzy logic which implements classes or grouping of data with boundaries is aided by the Analytic Hierarchy Process (AHP). From the structural viewpoint, GIS is very similar to the conventional Data Base Management System (DBMS), except for the fact that the database in GIS is more sophisticated and has the capability of associating and manipulating enormous volume of spatially referenced interrelated data (Star *et al.,* 1997; Foresman, 1997; Longley and Batty, 1997; Hanna and Culpepper, 1998). Therefore, in the present study, a GIS based holistic seismic hazard microzonation protocol is considered to deliver a decision support tool for landuse planning and in the developmental projects.

11.3 Site-specific Geological and Seismological Hazard Parameters

Site-specific Hazard attribution necessitates (i) precise geomorphologic definition of the terrain including the lithological characterization and sediment classification, (ii) In-depth surface geophysical and downhole/SPT geotechnical investigations for shallow shear wave velocity estimation and site classification following the National Earthquake Hazard Reduction Program (NEHRP), USGS and FEMA nomenclature, (iii) Site Response analysis and Probabilistic Seismic Hazard Assessment at surface consistent level propagating the bedrock ground motion with 10% probability of exceedance in 50 years through 1-D sediment column performing equivalent linear analysis of an otherwise non-linear system through DEEPSOIL (Hashash, 2009), and (iv) Assessment of Liquefaction Potential Index from insitu borehole geotechnical data and N-value/ shear wave velocity profiles. Therefore, in the present study, a holistic seismic hazard microzonation mapping achieved through multi-criteria based decision support system formulated as Analytical Hierarchal Process (AHP) incorporates all the hazard themes *viz.* (i) Geomorphology, (ii) Geology, (iii) Sediment Class, (iv) NEHRP Site Class, (v) Peak Ground Acceleration with 10% probability of exceedance in 50 years at surface, (vi) Ground Water Table, and (vii) Liquefaction Potential Index materialized on the GIS platform.

11.3.1 Geomorphology of Kolkata

Kolkata overlies the Bengal Basin, which is formed by the Ganga-Brahmaputra river system and is also one of the largest deltas in the world. The basin consists of fluvio-marine sediment of a pericratonic Tertiary basin. The surficial geology in and around Kolkata is rather uniform, characterized by the presence of 10–15 m of silty clay, below which relatively coarser sediments occur that consist of either silt/clay with kankar or sand (Vaccari *et al*., 2011). Geomorphologically, it is a typical deltaic flat land with surface elevation ranging between 6.4 to 9.5 m above msl sloping mostly towards south. Deltaic plain, interdistributary marsh, palaeo channels, younger levees adjacent to the river Hoogly and older levees on both the sides of the old Adi Ganga are the important geomorphological units (Roy *et al.*, 2012; Nath *et al*., 2014) as depicted in Figure 11.3. The detailed geomorphological attributes of Kolkata have already been discussed in Chapter 2 in Section 2.9.1. Youd and Perkins (1978) classified the geomorphological units into high, moderate and low susceptible to liquefaction with the maximum likelihood in deltas, river channels and uncompact artificial fills whereas, Ganapathy and Rajawat (2012) asserted abandoned river channel to be ‘likely’ liquefiable. Thus, in Kolkata all geomorphological units have potential to liquefaction susceptibility during strong seismic shaking.

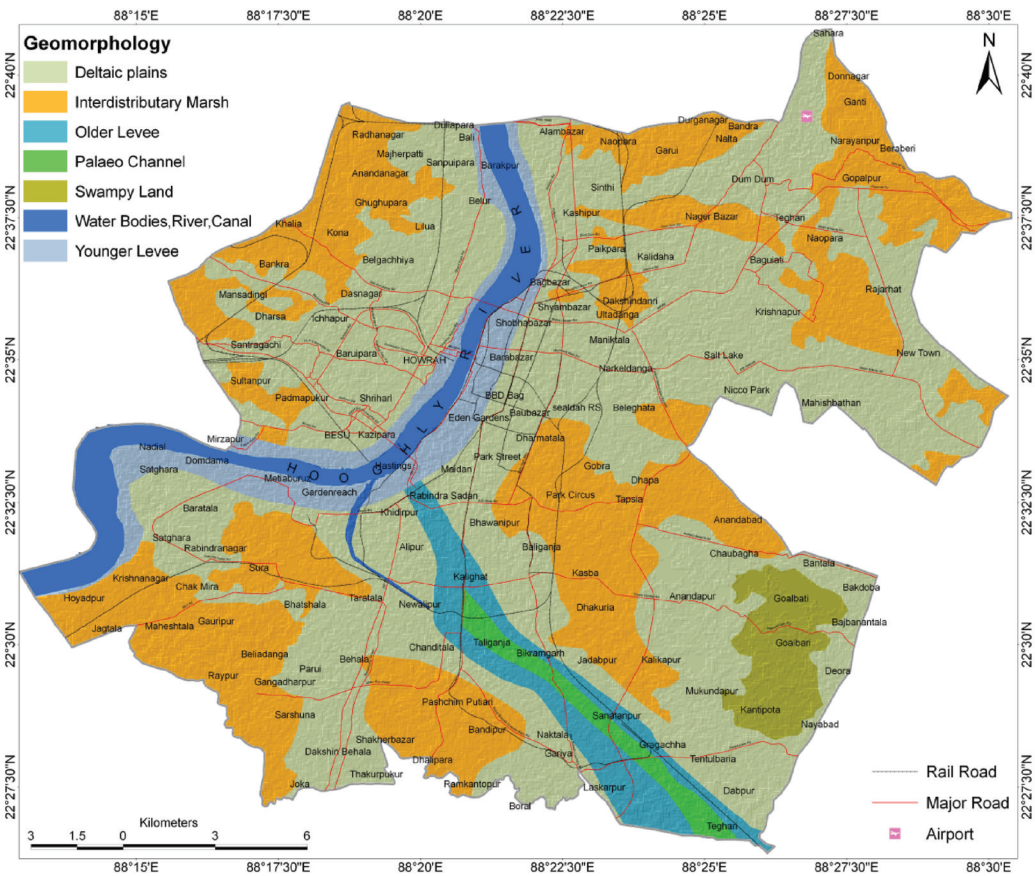


Figure 11.3 Geomorphology map of Kolkata on GIS.

11.3.2 Geology of Kolkata

The Kolkata city is covered by thick alluvium of about 450 m Quaternary sediments. The geology in and around Kolkata is rather uniform, characterized by the presence of 30-60 m thick grey sticky clay followed by relatively coarser sediments consisting of either silt/fine to medium sand or coarse sand with or without pebbles/cobbles (Chatterjee *et al.*, 1964). Local variations in the characteristics of the alluvial deposits played an integral role in the occurrence of ground failure (Boulanger and Idriss, 2006). The recent geological formations, poorly consolidated/unconsolidated water charged sediments and man-made landfills posed favorable conditions for liquefaction in the City. The detailed geological attributes of Kolkata have been discussed in Chapter 2 in Section 2.9.2.

More than half of the study area, *i.e.* nearly 330 km^2, extending from northeast to southeast of the region is covered with very fine sand and silt in channel bars, point bars as well as meander scrolls. The northwest region of the study area is nearly 57 km^2 characterized by unconsolidated sediments, alternate layers of fine sand, silt and dark clay, which belongs to the Panskura formation or equivalent to the Chinskura formation as shown in Figure 11.4. Alternate bands of sands, silts and dark clays from the Panskura/Chinskura formation equivalent to the Arambag formation are exhibited to the eastern part of the River Hooghly on natural levees and flood zone. Loose unconsolidated grey to coarse sand and gravel from Hooghly formation of the Late Holocene age covered the minimum areal extent in the west of the Hooghly River.

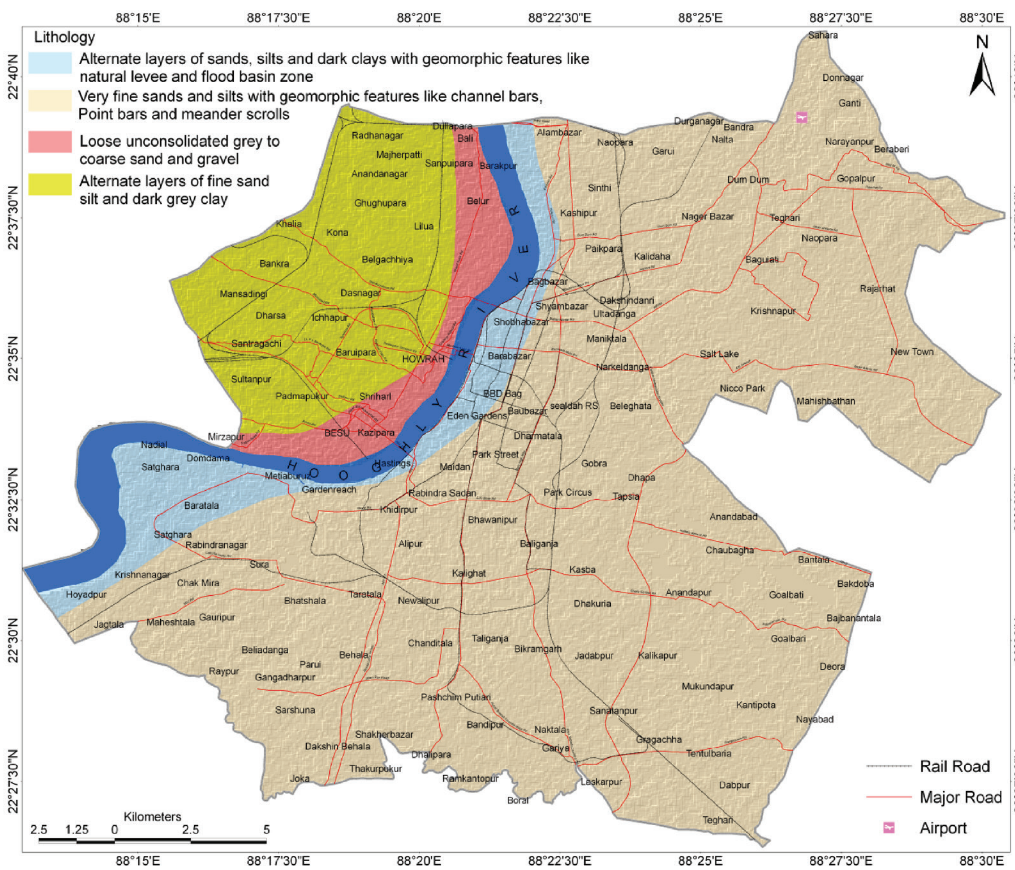


Figure 11.4 **Geology map of Kolkata on GIS.**

11.3.3 Sediment Classification Map of Kolkata

Based on the proportions of sand, silt and clay-sized particles obtained from 654 boreholes in Kolkata, the bottom sediments have been classified according to Shepard's diagram (O'Malley, 2007) which is an example of a ternary diagram - a device for graphing a three-component system summing to 100% (Shepard, 1954). In this case, the components are the percentages of sand, silt, and clay comprising a sediment sample. Each sediment sample plots as a point within or along the sides of the diagram, depending on its specific grain size composition. The detailed subsurface sediment classification of Kolkata has already been discussed in Chapter 6 in Section 6.4. Using the borehole lithologs and the Shepard Classification System, the shallow sediment classification of Kolkata is performed that exhibit highly liquefiable sediments *viz.* sand, sand-silt clay, sandy clay, silty sand and silty clay (Updike *et al*., 1988; Yamamuro and Hade, 1999) upto about ~5 m as shown in Figure 11.5.

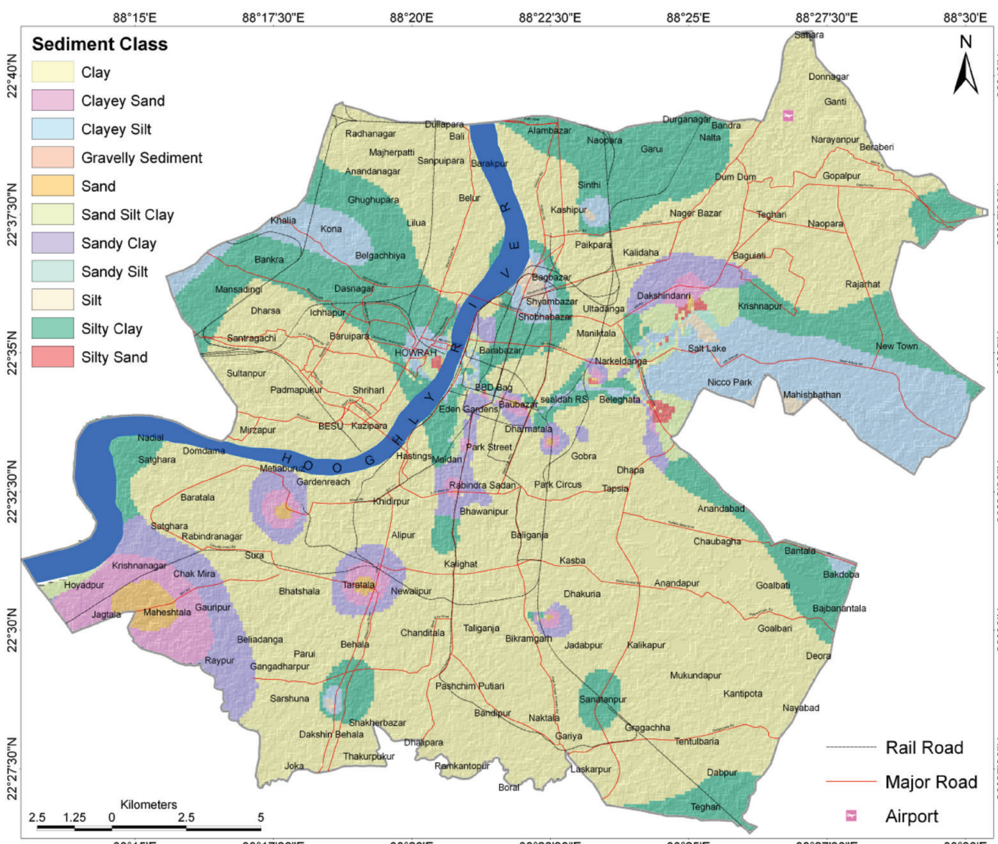


Figure 11.5 **Top ~5m Sediment Classification map on GIS as derived from geotechnical parameters obtained from 654 boreholes in Kolkata.**

11.3.4 Site Classification Map of Kolkata

Effective shear wave velocity (V_s^{30}) for 30 m soil column is one of the most important parameters used in the understanding of geotechnical earthquake engineering problems. Site classification is achieved through the estimation of V_s^{30} by both the insitu measurements and the surface geophysical investigations correlating each other through linear/nonlinear regression analysis. Therefore, effective shear wave velocity is estimated from 1-D V_s profiles at 1957 locations obtained from 654 geotechnical borehole sites, 85 MASW sites, 1200 Microtremor survey locations and 18 insitu downhole seismic survey sites (discussed in greater details in Chapters 5 and 6). The estimated effective shear wave velocity varies from 144 m/s to 357 m/s in the City with the dominance in the velocity range of 174-210 m/s, thus suggesting the soft soil conditions in the terrain.

Site Classification map of Kolkata performed based on NEHRP, USGS, FEMA and Sun (2004) regulations places the entire City in D1 (V_s^{30}: 320-360 ms^{-1}), D2 (V_s^{30}: 320-280 ms^{-1}), D3 (V_s^{30}: 280-240 ms^{-1}), D4 (V_s^{30}: 240-180 ms^{-1}) and E (V_s^{30}: <180 ms^{-1}) classes as depicted in Figure 11.6. From the diagram it is evident that the dominance of Site Classes corresponding to low shear wave velocity *viz.* D4 is followed by Site Class D3 and Site Class E in the region which may be attributed to the presence of a low velocity layer of high plastic silty clay associated with decomposed wood/ peat. Site Class E marks its presence in parts of the City at Howrah, Shibpur, Saltlake, Nicco Park, Dhapa, Jadabpur *etc.* Site Class D4 is covering mostly the southeastern region of the City and also partly in Mukundapur, Saltlake, Narkeldanga, Sealdah, Alipur, Metiabruz, Howrah *etc.* These areas are predominantly underlain by silty clay/clayey silt and silty sandy clay. The areas classified as Site Class D3 found in Rabindra Sadan, Maidan, Garia, Maniktala, Shobhabazar are composed of stiff soil with varying sediment deposits of clay associated mostly with silt followed by sand. In contrast, Site Class D2 and D1 have been identified in small patches in Ultadanga,

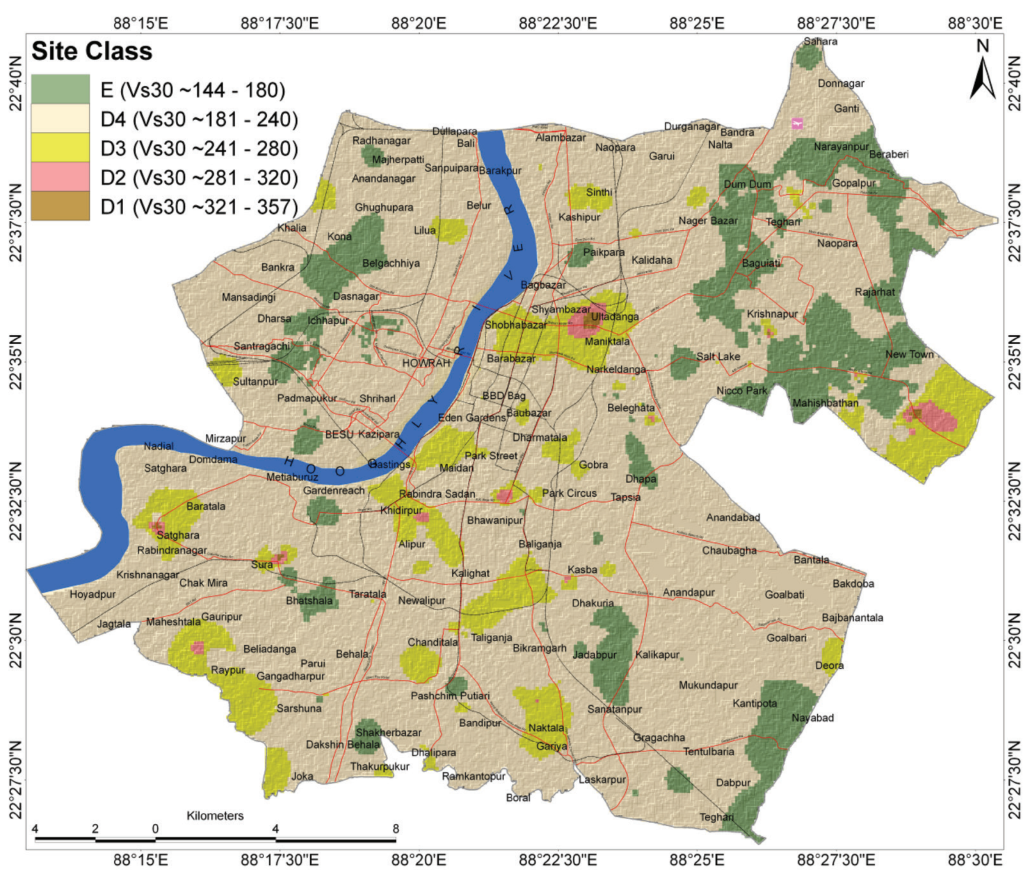


Figure 11.6 Site Classification map of Kolkata adhering to NEHRP, USGS, FEMA, Sun (2004), Sun and Shin (2009) & Sun *et al.* (2009) and displaying the presence of Site Classes E, D4, D3, D2 & D1 in the terrain with the dominance of Site Class D4 followed by Site Class D3 and Site Class E in the region.

Khidirpur and outskirts of Rajarhat which comprise of very stiff to very dense soil and soft rock, such as boulders, cobbles or near-surface fractured rocks. The detailed seismic site classification of Kolkata has already been discussed in Chapter 6 in Section 6.9.

11.3.5 Surface Consistent Probabilistic PGA distribution

The amplification of ground motion over soft sediments occurs fundamentally due to the impedance contrast between sediments and the underlying bedrock resulting in the trapping of seismic waves. The geotechnical parameters like soil type, thickness of the layer, unit weight, atterberg limits and shear wave velocity of the material have been used for the estimation of site effects by propagating the bedrock ground motion to the surface through 1-D soil column using equivalent linear analysis of a nonlinear system. A 5% damping is used for all soil types while synthesizing the subsoil response for earthquake engineering purposes. The input time series obtained by Inverse Fourier Transform of Pseudo Spectral Acceleration computed for 10% probability of exceedance in 50 years at engineering bedrock is used to model the nonlinear behavior of 30 m soil column at 1957 locations having precise 1-D V_s profiles to generate site amplification and hence to compute surface consistent PGA at each location. The detailed description of surface consistent probabilistic seismic hazard assessment has been given in Chapter 8 in Section 8.3. The PGA for 10% probability of exceedance in 50 years at the surface is presented in Figure 11.7 that exhibits a variation from

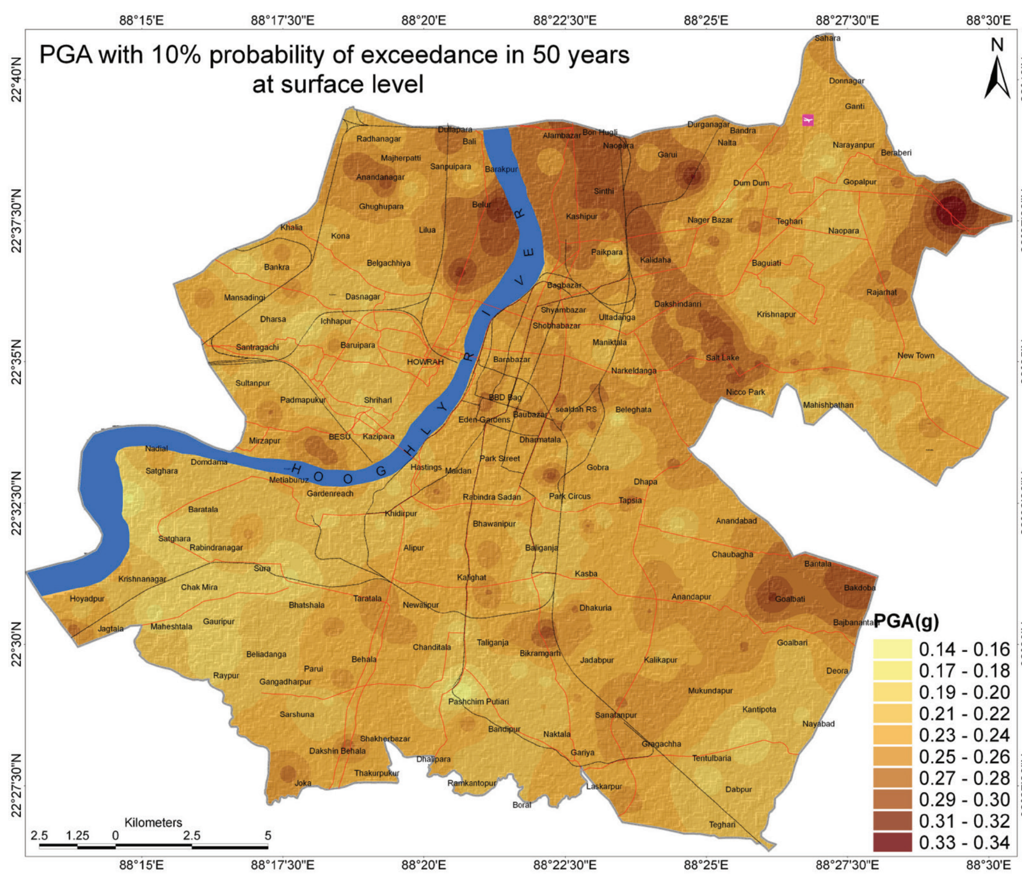


Figure 11.7 **Spatial distribution of PGA in Kolkata with 10% probability of exceedance in 50 years at surface level.**

0.14 to 0.34g. The urban centers like Saltlake, Rajarhat, Bagdoba, Belur and Sinthi exhibit higher hazard to the tune of 0.25g to 0.3g while relatively lower hazard has been observed in the southern and southwestern parts of the City encompassing Kasba, Garia, Sonarpur, Maheshtala *etc.*

11.3.6 Ground Water Table variation in Kolkata

Ground water table depth is among the major contributors affecting the stability of soil. The shallow ground water may contribute favorably to conditions for the occurrence of swelling of clays (Yilmaz, 2008). On the other hand, liquefaction potential of the soil is also controlled by the ground water level at a particular site. The shallow ground water levels create favorable conditions for triggering liquefaction under seismic excitation (Yilmaz and Bagci, 2006; Nath *et al.*, 2014). The main water bearing formation of the region is Quaternary alluvium consisting of sands of various grades interbedded with silt and clay. In the present study, water table depths obtained from 654 boreholes calibrated with a post monsoon Piezometer/Dug Well survey are used to generate a water table depth variation map of the City as shown in Figure 11.8 depicting water table level ranging between 0.5 - 7.7 m. The detailed description of ground water table fluctuations in Kolkata has been discussed in Chapter 7. The majority of the region is in the shallow ground water table zone within a range of 0.5 -5 m.

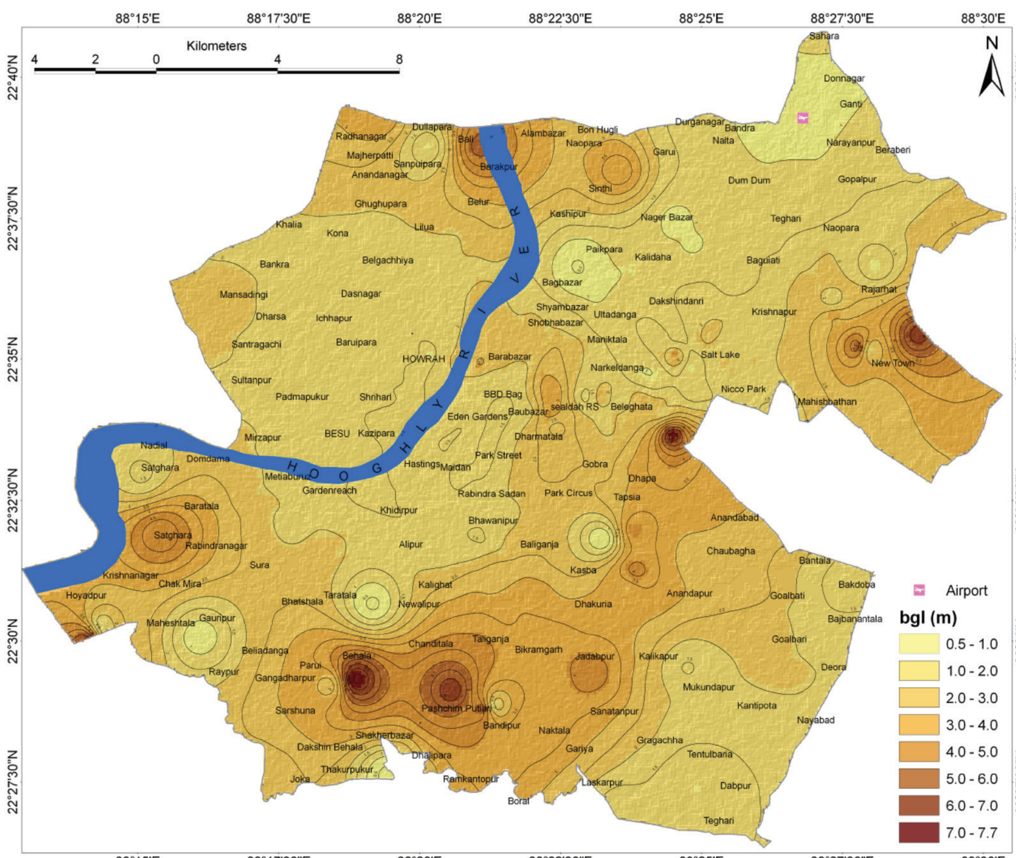


Figure 11.8 **Ground Water Table variation in Kolkata derived from Geotechnical Borehole data, Piezometric survey, and Dug Well information.**

11.3.7 Soil Liquefaction Assessment in Kolkata

Soil liquefaction is a secondary phenomenon associated with an earthquake which plays a major role in increasing the seismic risk of a province. It is generally observed in cohesionless saturated soil, when, because of dynamic loading and increase in pore water pressure, the shear strength of the soil decreases to zero. The liquefaction potential is conventionally expressed as the Factor of Safety (FOS) which indicates the site ability to resist liquefaction and assumes a value greater or smaller than 1, according to whether the site is considered to be safe or not. FOS does not give any information about the severity of liquefaction, which can be quantified by the Probability of Liquefaction (P_L). Also to consider the hazard of liquefaction for the entire soil column Liquefaction Potential Index (LPI) for a depth upto 20 meter is calculated. A holistic framework for soil liquefaction assessment based on Seed and Idriss (1971), Youd *et al*. (2001), Idriss and Boulanger (2006) and Iwasaki *et al*. (1982) formulations is used to generate a deterministic liquefaction scenario (Juang and Li, 2007) in the City corresponding to the surface PGA distribution with 10% probability of exceedance in 50 years. To generate the Liquefaction Susceptibility Map of the city of Kolkata an LPI distribution map is prepared in a GIS platform as shown in Figure 11.9. The LPI values

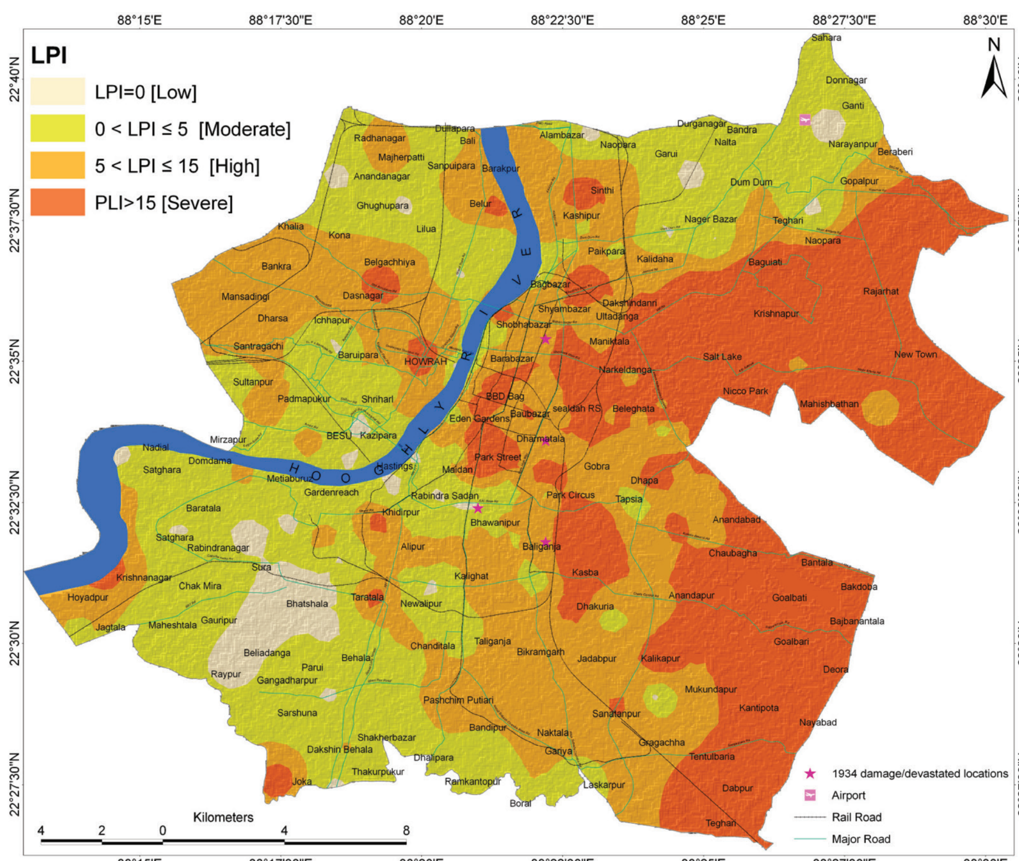


Figure 11.9 Liquefaction Potential Index Distribution in Kolkata. An LPI> 15 indicates a severe liquefaction hazard condition, an LPI between 5 and 15 showing highly liquefy, an LPI between 0.1 and 5 exhibits tendency to liquefy while LPI around 0 depicts a non-liquefiable condition.

have been categorized according to Iwasaki *et al*. (1982) as: Low (LPI = 0), Moderate (0< LPI≤ 5), High (5< LPI≤ 15) and Severe (LPI > 15). A large patch of severe liquefaction potential zone has been identified in the eastern region of the City encompassing Saltlake, Rajarhat, New Town and Nicco Park. The detailed description of liquefaction susceptibility mapping in Kolkata has been discussed in Chapter 9 in section 9.6.

11.4 Multi-criteria Seismic Hazard Microzonation of Kolkata

Multi-criteria seismic hazard microzonation has been carried out previously in other Indian regions–Guwahati City (Nath *et al*., 2007), Sikkim Himalaya (Nath, 2004; Pal *et al*., 2008), Delhi (Mohanty *et al*., 2007), Bangalore (Anbazhagan *et al.,* 2010) and Chennai (Ganapathy, 2011). The hazard mapping is achieved through multi-criteria based decision support tool formulated by Saaty (1980) referred to as Analytical Hierarchal Process (AHP). AHP uses hierarchical structures to quantify relative priorities for a given set of elements on a ratio scale, which is based on the discernment of the user. From the judgments between two particular elements, a pair-wise comparison matrix is constructed on a scale of integer factors 1–7, indicating an increasing importance of the elements. The ratio between such factors defines the relative importance of one element to another (Anbazhagan *et al*., 2010). The pair-wise comparison matrix prepared is used to derive the individual normalized weights of each element. The weights of each criterion are calculated by summing up all the ratios in the relative matrix column and then divide each element in the matrix by its column total to generate a normalized pair-wise matrix; finally the weighted matrix is generated by dividing the sum of the normalized row to the number of criteria used. The Consistency Index (CI) is an important feature of the AHP that enables in determining the rating inconsistencies (Saaty, 2000). The Consistency Ratio (CR), which is a comparison between the Consistency Index (CI) and the Random Index (RI) obtained using the AHP method is <0.1. Saaty (1980) developed an average Random Index (RI) for different matrix orders. The weights are normalized to 1 and can be used in deriving the weighted sums of rating for each region of polygons of the mapped layers. Within each theme, the values vary significantly and are hence reclassified into various ranges or types collectively referred to as feature of a thematic layer. The associated feature attributes are scored within the theme. The initial integral scoring, X_{j}, is normalized to ensure that no layer exerts an influence beyond its determined weight using the following relation (Nath, 2004)

$$X_j = \frac{R_j - R_{\min}}{R_{\max} - R_{\min}} \tag{11.1}$$

where, R_j is the row score, $R_{\max}$ and $R_{\min}$ are the maximum and minimum scores of a particular layer.

The hazard themes, pertaining to the study region materialized as thematic layers on the GIS platform are (i) Peak Ground Acceleration (PGA) at the surface, (ii) Liquefaction Potential Index

(LPI), (iii) NEHRP Site Class (SC), (iv) Sediment Class (SEC), (v) Geomorphology (GM), (vi) Geology (GE) and (vii) Ground Water Table (GWT). Each thematic layer has been georectified on Universal Transverse Mercator projection system. The corresponding weights, the ranks to each thematic layer and the theme attribute score thereof are assigned values according to the apparent contribution of the layers to the overall seismic hazard. For example, in the geomorphology theme we have assigned ranking as ‘high’ for swampy land, water bodies and river channel in comparison to ‘low’ assigned to palaeo channel with regards to severity to liquefaction (Youd and Perkins, 1978; Ganapathy and Rajawat, 2012). In the Sediment Class higher rank is assigned to sand, clayey sand, silty sand whereas lowest rank is assigned to clay, considering the effect on the Factor of Safety (Youd and Perkins, 1978; Yamamuro and Hade, 1999). Table 11.1 presents the pair-wise comparison matrix for the respective themes and their normalized weights. The normalized ranks assigned to the features of each theme are listed in Table 11.2.

Table 11.1 **Pair-wise comparison matrix of themes used for seismic hazard microzonation and their normalized weights**

Themes	PGA	LPI	SC	SEC	GM	GE	GWT	Weightage
Peak Ground Acceleration (PGA)	1	7/6	7/5	7/4	7/3	7/2	7/1	0.2500
Liquefaction Potential Index (LPI)	6/7	1	6/5	6/4	6/3	6/2	6/1	0.2143
Site Class (SC)	5/7	5/6	1	5/4	5/3	5/2	5/1	0.1786
Sediment Class (SEC)	4/7	4/6	4/5	1	4/3	4/2	4/1	0.1429
Geomorphology (GM)	3/7	3/6	3/5	3/4	1	3/2	3/1	0.1071
Geology (GE)	2/7	2/6	2/5	2/4	2/3	1	2/1	0.0714
Ground Water Table (GWT)	1/7	1/6	1/5	1/4	1/3	1/2	1	0.0357

Table 11.2 **Normalized weights and ranks assigned to respective themes and the features thereof for thematic integration**

Theme	Weight	Attributes	Rating	Normalized Rating
Peak Ground Acceleration (PGA)	0.2500	0.14 – 0.16g	1	0.00
		0.17 – 0.18g	2	0.11
		0.19 – 0.20g	3	0.22
		0.21 – 0.22g	4	0.33
		0.23 – 0.24g	5	0.44
		0.25 – 0.26g	6	0.56
		0.27 – 0.28g	7	0.67
		0.29 – 0.30g	8	0.78
		0.31 – 0.32g	9	0.89
		0.33 – 0.34g	10	1.00

Theme	Weight	Attributes	Rating	Normalized Rating
Liquefaction Potential Index (LPI)	0.2143	0 (Low)	1	0.00
		0.1-5.0 (Moderate)	2	0.33
		5.1-15.0 (High)	3	0.66
		> 15.0 (Severe)	4	1.00
Site Class (SC)	0.1786	D1 (V_s^{30}:321 – 357 ms^{-1})	1	0.00
		D2 (V_s^{30}:281 – 320 ms^{-1})	2	0.25
		D3 (V_s^{30}:241 – 280 ms^{-1})	3	0.50
		D4 (V_s^{30}:181 – 240 ms^{-1})	4	0.75
		E (V_s^{30}:144 – 180 ms^{-1})	5	1.00
Sediment Class (SEC)	0.1429	Clay	1	0.00
		Gravelly sediment	2	0.25
		Silty Clay, Silt, Clayey Silt	3	0.50
		Sandy Clay, Sand Silt Clay, Sandy Silt	4	0.75
		Sand, Clayey Sand, Silty Sand	5	1.00
Geomorphology (GM)	01071	Palaeo Channel	1	0.00
		Older Levee	2	0.25
		Interdistributary Marsh	3	0.50
		Deltaic Plains, Younger Levee	4	0.75
		Water Bodies, Canal, River, Swampy Land	5	1.00
Geology (GE)	0.0714	Alternate layers of fine sand silt and dark grey clay	1	0.00
		Loose unconsolidated grey to coarse sand and gravel	2	0.33
		Alternate layers of sands, silts and dark clays with geomorphic features like natural levee and flood basin zone	3	0.66
		Very fine sands and silts with geomorphic features like channel bars, Point bars and meander scrolls	4	1.00

Theme	Weight	Attributes	Rating	Normalized Rating
Ground Water Table (GWT)	0.0357	0.5 – 1.0 m	8	1.00
		1.0 – 2.0 m	7	0.86
		2.1 – 3.0 m	6	0.71
		3.1 – 4.0 m	5	0.52
		4.1 – 5.0 m	4	0.42
		5.1 – 6.0 m	3	0.29
		6.1 – 7.0 m	2	0.14
		7.1 – 7.7 m	1	0.00

All the geo-referenced thematic layers are integrated step-by-step using the aggregation method in GIS to generate Seismic Hazard Microzonation Map (SHM) as

$$SHM = \left[PGA_w PGA_r + LPI_w LPI_r + SC_w SC_r + SEC_w SEC_r + GM_w GM_r + GE_w GE_r + GWT_w GWT_r\right] / \sum w \qquad (11.2)$$

where, '*w*' represents the normalized weight of a theme and '*r*' is the normalized rank of a feature in the theme. Thereafter, a 3×3 'majority filter' has been applied to the SHM as a post-classification filter to reduce the high frequency variation. SHM is a dimensionless quantity that helps in indexing the seismic hazard and hence the microzonation of a region on a qualitative scheme such as 'Low', 'Moderate', 'High' and 'Severe'. The GIS integration scheme is shown in Figure 11.10.

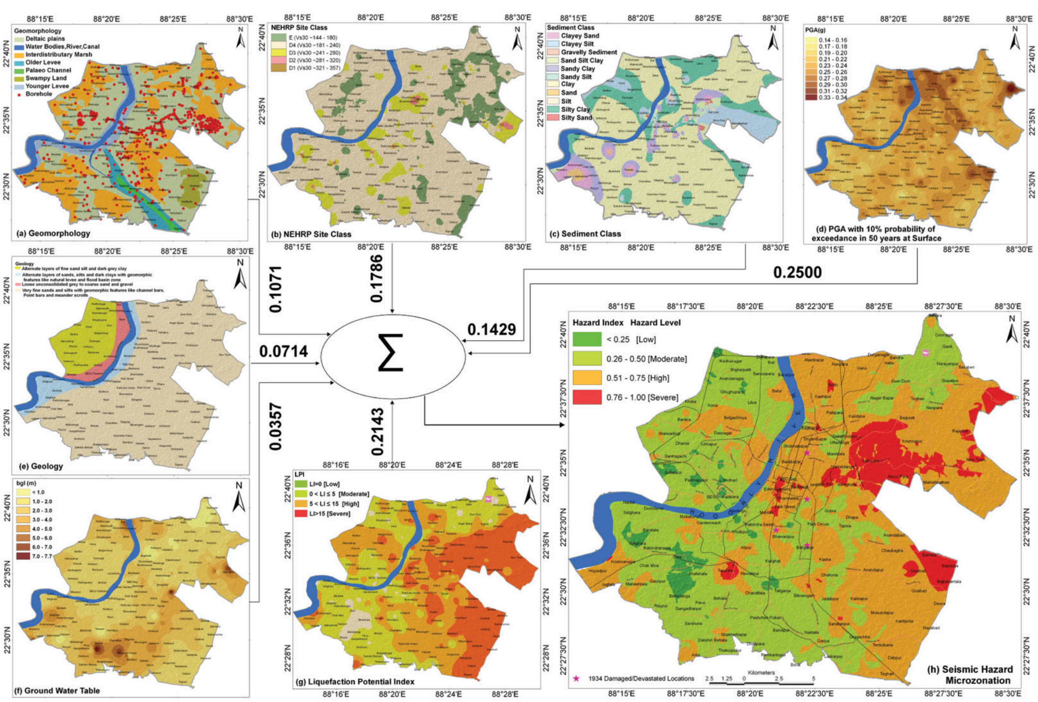


Figure 11.10 **Seismic Hazard Microzonation protocol for Kolkata showing the weights assigned to each theme labeled according to hazard contribution, (a) Geomorphology (b) NEHRP site class (c) Sediment Class, (d) Spatial distribution of PGA in Kolkata with 10% probability of exceedance in 50 years at surface level (e) Geology, (f) Ground water table, (g) Liquefaction Potential Index (LPI) distribution, and (h) Seismic Hazard Microzonation Map of Kolkata.**

The Probabilistic Seismic Hazard Microzonation map of Kolkata shown in Figure 11.11 depicts four broad divisions with hazard index (HI) defined for 0.75<HI≤1.00 as 'Severe' hazard condition in Saltlake, New Town areas, 0.50<HI≤0.75 as 'High' hazard condition mostly in Barabazar, Anandapur, Belgachiya, Bagdoba areas of the expanding City, 0.25<HI≤0.50 as 'moderate' hazard condition in most parts of South and West Kolkata. The damage distributions due to the 1934 Bihar-Nepal earthquake are mostly identified in the high to severe hazard zone (marked by a '★'). The detailed Seismological and Geohazard attributions for each division are presented in Table 11.3. The proposed Zone Factor (Z_F) with equivalent design response spectra and liquefaction susceptibility for different hazard subzones in Kolkata has been depicted in Table 11.4.

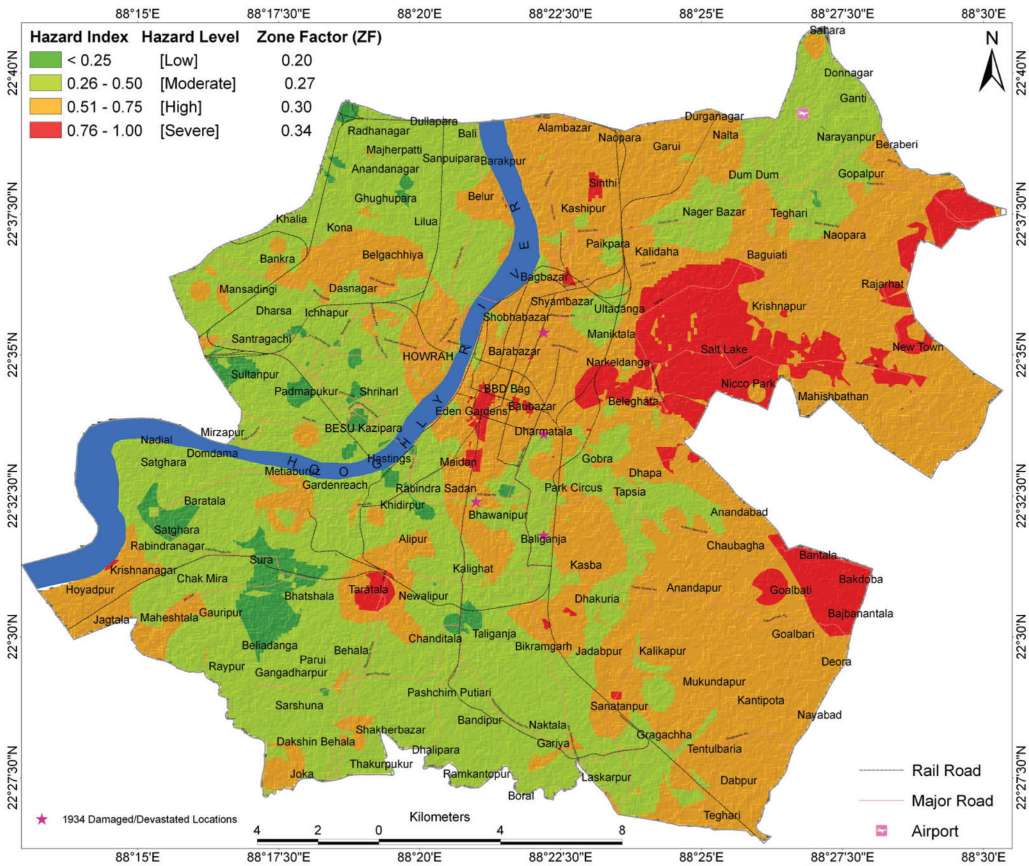


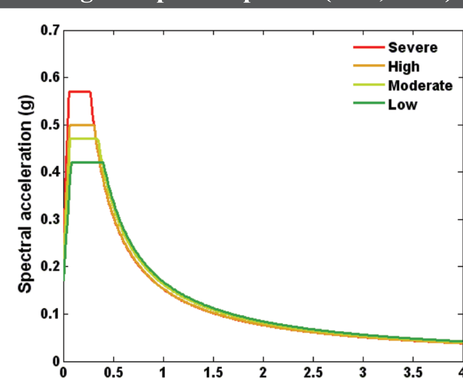
Figure 11.11 **Probabilistic Seismic Hazard Microzonation map of Kolkata. Four broad divisions have been identified with hazard index (HI) defined as 0.75<HI≤1.00 indicating severe hazard condition in Saltlake, New Town areas, 0.50<HI≤0.75 indicating High hazard condition mostly in Barabazar, Anandapur, Belgachiya, Bagdoba areas of the expanding City, 0.25< HI≤0.50 indicating moderate hazard condition in the most part of South and West Kolkata, while HI<0.25 presents a completely hazard free regime. The damage distribution due to the 1934 Bihar-Nepal earthquake of M_w 8.1 is mostly identified in the High to Severe Hazard zones (marked by a '★').**

Table 11.3 **Microzonation Hazard level with corresponding geophysical and geotechnical attributes at selected locations in Kolkata**

Location	Hazard Level	PGA (g)	P_F	LPI	$SC\backslash V_s^{30}$	I_{MM}	S_A
Behala	Moderate	0.234	1.27	3.3 (Moderate)	D4\205.8	VII	3.87
Rajdanga	Moderate	0.239	1.52	12.0 (High)	D4\209.5	VII	4.02
Shyambazar	High	0.250	1.27	13.5 (High)	D3\241.6	VII	3.52
Dum Dum	Moderate	0.245	1.27	5.7 (High)	E\168.7	VII	3.78
Barahanagar	High	0.260	1.27	11.4 (High)	D4\232.3	VII	4.63
Bali	Moderate	0.261	1.08	7.8 (High)	D4\204.8	VII	4.47
Kona	Moderate	0.218	1.27	9.3 (High)	D4\203.3	VII	4.81
Maheshtala	Moderate	0.200	1.27	6.6 (High)	D4\199.3	VII	4.44
Alipur	High	0.196	1.08	10.1 (High)	D4\237.6	VII	4.10
Metiaburuz	Moderate	0.219	1.08	6.6 (High)	D4\193.9	VII	4.40
Dabpur	High	0.205	1.27	15.5 (Severe)	D4\198.6	VII	4.67
Jadabpur	Moderate	0.225	1.27	13.5 (High)	D4\188.9	VII	4.08
Kalighat	Moderate	0.232	1.08	6.1 (High)	D4\226.9	VII	4.08
Thakurpukur	Moderate	0.237	1.27	4.3 (Moderate)	D4\231.9	VII	4.17
Satghara	Moderate	0.220	1.27	14.0 (High)	D4\202.4	VII	4.63
Belur	High	0.274	1.08	11.7 (High)	D4\231.6	VII	4.25
Bagdoba	Severe	0.284	1.52	18.6 (Severe)	D4\183.1	VII	4.08
Paikpara	High	0.263	1.08	12.0 (High)	D4\171.2	VII	4.63
Park Street	High	0.236	1.52	15.3 (Severe)	D4\213.9	VII	4.20
Saltlake	Severe	0.288	1.52	28.0 (Severe)	E\162.3	VII	4.97
New Town	Severe	0.224	1.27	26.5 (Severe)	E\175.1	VII	3.92
Rajarhat	Severe	0.265	0.88	34.2 (Severe)	E\174.8	VII	4.63

P_F: Predominant Frequency (Hz); LPI: Liquefaction Potential Index; $SC\backslash V_s^{30}$: NEHRP site class\Average shear wave velocity (m/s) of ~30 m soil column; I_{MM}: Predicted MM Intensity; S_A: Site Amplification.

Table 11.4 **The proposed Zone Factors (Z_F) for Seismic Hazard subzones in Kolkata with corresponding Design Response Spectra and Liquefaction Susceptibility (L_S)**

Hazard Level	Z_F (g)	L_S	Design Response Spectra (IBC, 2009)
Low	0.20	LPI=0	
Moderate	0.27	0< LPI≤7	
High	0.30	4< LPI≤16	
Severe	0.34	LPI> 15	

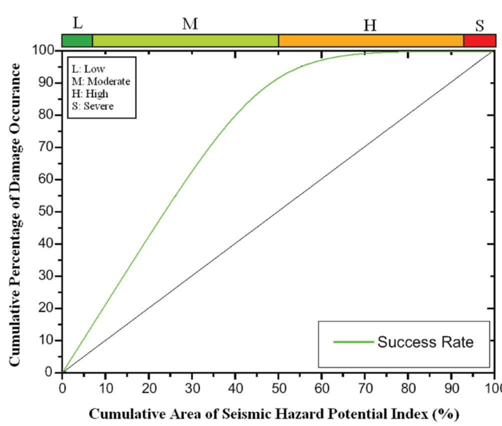
The predictive power of the resulting final integrated weight map has been tested by analyzing the success rate curve and *R*-Index. The success rate is calculated by ordering the pixels of SHM in a number of classes, from high to low values, based on the frequency information from the histogram. After that an overlay is made with the available reported damaged sites and the joint frequency is calculated. The success rate indicates how much percentage of all reported damaged sites occurs in the pixels with the highest values in the different combination maps. For example, 50 percent of all reported damaged sites are predicted by 10 percent of the pixels with the highest value in the SHM. The success rate curve for seismic microzonation map is depicted in Figure 11.12(a).

Seismic Hazard Microzonation Map has also been validated by means of earthquake damage structures/sites corresponding to the hazard levels. SHM generated in this study exploit the R-index method to assess the relationship between the hazard index and the reported damage sites. The damage structures/sites have been collected by an extensive literature review process (GSI, 1939; Dasgupta *et al.*, 2000; https://sites.google.com/site/indiaquake/earthquake-damage-in-calcutta-kolkata/; Chakrabarti, 2013). Validation of seismic hazard microzonation map is performed with the formulation defined by Baeza and Corominas (2001) as follows

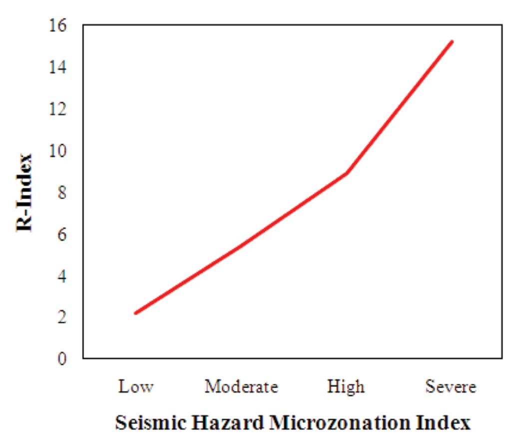
$$R = \left(\left(\frac{n_i}{N_i}\right) / \sum\left(\frac{n_i}{N_i}\right)\right) \times 100 \qquad (11.3)$$

where, n_i is the number of damaged states reported in the sensitivity class *i* and N_i is the number of pixels in the same sensitivity class *i*.

Figure 11.12(b) shows the *R*-index for each microzonation level. It is seen that *R*-index increases with the level of hazard index. Thus it can be concluded that the earthquake affected sites observed in these levels indicate consistency in hazard levels.



(a)



(b)

Figure 11.12 **(a) Validation of Seismic Hazard Microzonation map through success rate curve, and (b) Validation of Seismic Hazard Microzonation map using R-index.**

11.5 Concluding Remarks

The Seismic Microzonation has emerged as an important issue in high risk urban centers across the globe and is considered an integral part of earthquake induced disaster mitigation practices. A new perspective of multi-criteria holistic Seismic Hazard Microzonation aspect has been presented here for Kolkata, one of the most densely populated cities in the world being placed in a high seismic zone in the Bengal Basin in the tectonic setup of North Bengal Foreland, Basin Margin Fault Zone, Stable Shelf, Hinge Zone and the Deep Basin with a sedimentary thickness of the order of 7.5 km above the crystalline basement. The adopted microzonation framework is based on enriched homogeneous earthquake catalogue, upgraded tectonic database, Seismotectonic implications, Geological, Geotechnical and Geophysical database, judiciously integrated in a logic tree protocol using sophisticated analytical/numerical technologies coupled with Geographical Information System. SHM has provided an enhanced Seismic Scenario in micro scale (1:25,000) with NEHRP Site Characterization, Liquefaction Scenario and surface consistent PGA distribution depicting different hazard index values for an appropriate modification in the building code. Thus, if the principles of microzonation adopted in the present analysis are correctly and judiciously implemented, it could be useful in establishing criteria for landuse planning and a strategy for the formulation of systematic and informed decision making process for the development of new communities in the region.