2.6 Paleoenvironment of Bengal Basin

The paleoenvironment of an area captured in the rock formation at the time of deposition is reflected in the lithological characteristics of the rock. From the previous observations and records, it is perceived that the Bay of Bengal has not been static in terms of climatic conditions (Rashid *et al.*, 2013). During the last Glacial period in 18000 yr BP, the Bengal lowland experienced dry climatic conditions and sea level was 100 m or more lower than the present sea level (Umitsu, 1987). By 12000 yr BP, the south-west monsoon became prominent and caused heavy rainfall and sea level started rising very rapidly (Monsur, 1995). During the early to middle Holocene period, Indian Summer Monsoon (ISM) was stronger than today, with intensity peaks identified in 8500, 6400 and 2700 yr BP as detected in numerous ISM records (USGS-BGAT, 2001). During the Mid Holocene period, the sea level of the Bay of Bengal was slightly higher with warmer climatic condition increasing the rivers' discharge in the basin upto two and half times more than the present times (Umitsu, 1993; Kudrass *et al*., 1999; Goodbred and Kuehl, 2000a). It is estimated that around 6000 yr BP, eustatic sea level was higher than the present sea level (Rasid, 2011). In Holocene period, the carbon isotopic composition of the organic matter showed episodic negative excursion representing the arrival of humid condition and a decline in the monsoon rainfall in the Ganga-Brahmaputra catchment evidenced by marine sediments (Chakraborty *et al*., 2011).

2.7 Geological settings of Bengal Basin and its adjoining region

The Bengal Basin is bounded by the tertiary rocks of the Himalaya and Amphibolite-Granulite facies basement of the Shillong plateau in the North (Nandy, 2001). The Lateritic uplands and the Rajmahal volcanic in the west of the basin and folded/faulted belt of Indo-Burmese in the east marks the basin boundary (Morgan and McIntire, 1959). The oldest rock formation of the western margin of the basin belongs to the Precambrian rocks of the Indian shield (Alam *et al*., 2003) which are equivalent to the rocks found in Shillong Plateau and commonly consists of gneisses, schist, diorite, granodiorite, and granite (Zaher and Rahman, 1980). Several studies revealed that these rocks are predominantly composed of tonalite, diorite and granodiorite with subordinate granite, gneiss and schist (Khan *et al*., 1997; Ameen *et al*., 1998, 2001; Alam *et al*., 2003). Figure 2.23 depicts the major geological units of the Bengal Basin and its adjoining region (Dasgupta *et al.,* 2000).

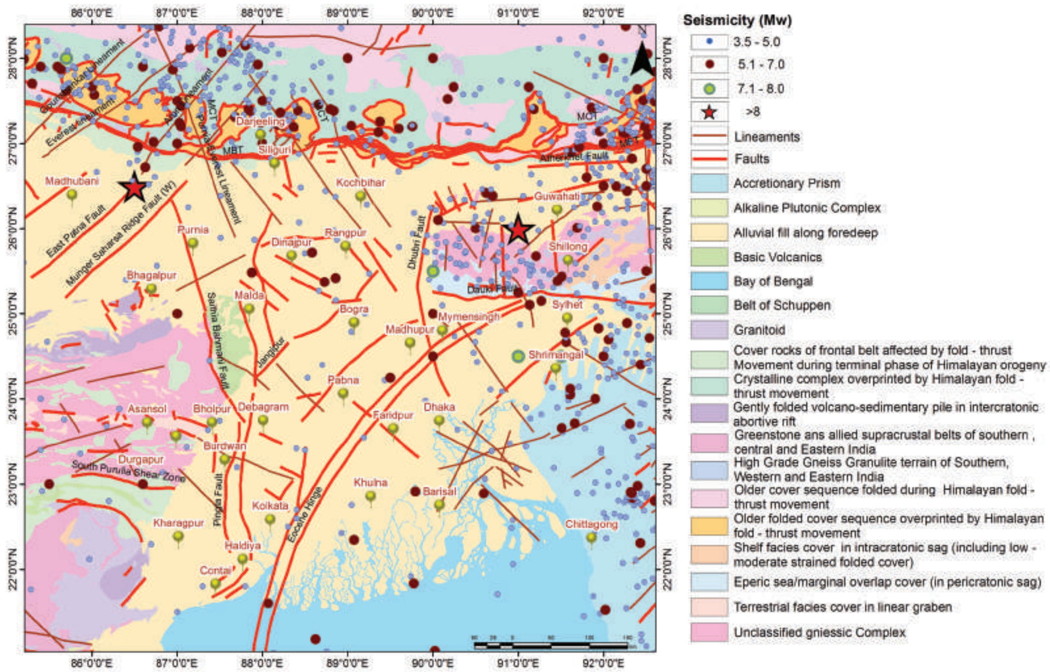

Figure 2.23 **Major Geological units of the Bengal Basin and its adjoining region (modified after Dasgupta *et al.*, 2000; www.usgs.com).**

The western limit of the Bengal Basin ends up at the Indian peninsular region in the Chhottanagpur Plateau. The Gondwana sediments have deposited over the Gneissic complexes in the intracratonic basin (Khan and Chouhan, 1996). The upliftment of the Himalayan region in the Eocene period had changed the altitude of the region that made the area as a depocenter of sediments supplied by the Ganga, the Brahmaputra and its tributaries. For this reason, approximately 75 percent of the region is covered by alluvium and deltaic deposits. Geologically the West Bengal represents the three major units:

1. The Extra-Peninsular region covering the northern part *i.e.* the terrain of the Darjeeling Himalayas,
2. The Peninsular mass in the south west covers Bankura, Purulia, Medinipur, Bhirbhum and Bardhaman districts, and
3. The eastern and southern regions of alluvium and deltaic plain covering Kolkata, Howrah districts.

2.7.1 Geology of Extra Peninsula region

The major lithological units of the extra peninsular region belong to the central Crystalline Gneissic Complex and comprise of the Daling Group, the Gondwana Supergroup, the Siwalik Group and the Quaternary formation. The formation of the northern part occurs partially by the Himalayan foothills and partly by the Precambrian rocks of the elevated Shillong Plateau and the Precambrian Indian shield (Ganguly, 1997). Detailed geological study of this region has been done by Dasgupta *et al*. (2000), Ganguly (1997), Roy Barman (1983; 1992), Woodside (1983) and Mukherjee and Neogi (1993). The North Bengal Foreland is formed by the tertiary outcrops and the Siwalik sequence, which directly overlie the Gondwana formation (Ganguly and Rao, 1970). The Basin Margin Fault zone is oriented slightly in the NE-SW direction and is bounded by the complex crystalline basement as shown in Figure 2.23. The hard rock terrain broadly observed in two distinct regions covering the extra peninsular mountain ranges of the Darjeeling Himalayas in the north and the peninsular tract comprising of a rolling topography in the southwestern region. Most of the northern part of the extra peninsular region comprises of older sequences subjected to folded and thrusted sediments. The other unit of the northern extra peninsular region is a crystalline complex overprinted by Himalayan fold-thrust movements, this region covers nearly about 58822 km^2 area. The Darjeeling and the Jalpaiguri districts are represented by the Darjeeling Gneiss, the Lingtse Gneiss and the Daling group of rocks of the Precambrian formation (Acharyya, 2007; Gupta *et al*., 2010). The Darjeeling gneiss consists of migmatitic-banded gneiss containing enclaves of high grade schist. The Lingtse Gneiss occurs as linear, medium to coarse grained, foliated biotite gneiss occupying mostly the mountain peaks of the Singalila range. The Gondwana group of rocks occurring in the Darjeeling and the Jalpaiguri districts consists of pebble/boulder, quartzite, sandstone, slates, carbonaceous slates and coal seams. In the northern part of the Jalpaiguri, the Cooch Behar and the Darjeeling districts, the alluvial belt of tertiary age is underlain by soft Quaternary formation comprising sand, silt and clay with fine texture sediments as depicted in Figure 2.23. The detailed description of the extra Peninsular India and the corresponding litho-units of the area are given in Table 2.6.

Table 2.6 **Generalized stratigraphic succession of the rock units of the Extra Peninsular region**

Geological Time	Formation	Lithology
Quaternary	Present day flood plain deposits Baikunthapur/Shaugaon Formation	Sand, Silt and Clay
	Duars formation Chalsa member, Matiali member, Thaljhora member, Samsing member	Boulders, Gravels, Pebbles, Sand and Silts
	Unconformity	

Geological Time	Formation	Lithology
Tertiary	Siwalik group	Siltstone, Coarse - grained Sandstone and Conglomerate intercalated with shale and impure calcareous horizons at the basal part
	Main Boundary Thrust	
Upper Carboniferous to Permian	Damuda Group Gondwana Supergroup	Feldspathic and Micaceous quartzite, Sandstone, Carbonaceous slates with thin seams of crushed coal.
	Talchir Group	Basal pebbles and Boulder bed
Proterozoic	Daling Group Buxa Formation	Predominantly Dolostone, Chert and variegated states.
	Reyang Formation	Ortho and Proto-quartzite, variegated slates & phyllites
	Gorubathan Formation	Green Slate, Phyllite, Phyllonite, Cherty Chlorite Quartzite, Green tuffaceous wacke with basic metavolcanics
	Kanchenjunga Augen Gneiss/Darjeeling Gneiss	Calc- Gneiss, Calc granulite, Augen Gneiss, marble, sillimanite Gneiss, Graphite Schist *etc*.
Proterozoic (Undifferentiated)	Chungthang Formation	Banded gneiss, Augen Gneiss, streaky Gneiss, migmatites *etc*. with profuse intrusion of Granite, Aplite and Pegmatite

2.7.2 Geology of Peninsular region of West Bengal

The western margin of the Bengal Basin comprises of the oldest rock complex. The peninsular region comprises of Chhotanagpur Gneissic complex, Singhbhum Group, Gondwana Supergroup and unclassified metamorphics, subjected to intrusion by many dyke swarms as evidenced by volcanic activities in the past geological epochs. The unclassified metamorphics from Chhotanagpur Gneissic Complex (CGC) represents oldest litho-unit of Archean Era occupied by the southern part of Purulia district and the western part of the Bankura, Bardhman, Birbhum and Midnapore districts. The Gondwana sequences occur between Damodar, Ajay and Trans-Damodar areas of Birbhum coalfield. Rajmahal hills in the central part of the State have dark to very dark hard Amygdular and fine grained Basalt containing Olivine in large amount. The detailed stratigraphic successions are given in Table 2.7.

Table 2.7 **Generalized stratigraphic succession of the rock unit of the Peninsular region**

Era	Period	Formation	Lithology
Cenozoic	**Quaternary**	Arambagh Formation/ Ganga-Kosi Formation, Katwa Formation	Recent to Subrecent Soil/alluvium/ sandy clay/loose sand/ lateritic sediment with Calcretes.
		Pansukura Formation/ Chinsura Formation/ Malda Formation/ Jalpaiguri Formation/ Bethuadahari Formation	Ferrous shale, mudstone/Calc mud/ impure limestone, fine to coarse Sandstone with floral remains
		Sijua Formation	Ferruginous Sandstone clay/thin pebbles bed/impure limestone/ green clay/Carbo. Lay with rich floral assemblage and plant roots.
		Barind Formation/ Baikunthapur Formation/ Lalgarh Formation	Alternating clay and sand beds
	Tertiary	Siwalik Group	Ferruginous sandstone, pebbly grit, red Shale, clay, Gravel and fossil wood.
Mesozoic	Gondwana supergroup	Durgapur Formation	Compact, thinly laminated quartzite, Carbo. Shale, with fossils of algae and Foraminifera.
		Unconformity	
		Rajmahal Formation/ Dubrapur Formation/ Supra-Panchet Formation	Traps with intertrappeans, ferruginous sandstone, red shale/ clay stone
		Unconformity (local)	
Paleozoic		Raniganj Formation	Sandstone and Shale with thick Coal seams
		Barren Measure Formation	Grey shale nodule of Iron ores
		Barkar Formation	Sandstone with coal seams
		Talchir Formation	Conglomerate, Siltstone, Shale and Sandstone

Era	Period	Formation	Lithology
Proterozoic	Lower to Middle Proterozoic	Manbhum Granite/ Kuilpal Granite	Granite containing phenocrysts of feldspar
		Dalma Volcanics	Ultramafics, mica schist, phyllites, Quartzites, tuffs, cherts and calc silicates
	Archean		Slicified metamorphic, Anopthosites, Bankura, Purulia district) Schist, marble/ Calc. Granulites/Quartzites, Amphibolites/Granulite/ Hornblende schist/composite Gneiss, Biotite Gneiss
	Proterozoic	Chhotanagpur Gneissic Complex	-

2.7.3 Geology of Basinal Region

The Bengal Basin made up of smaller units is known for its thick alluvium deposits over the Precambrian basement (Ghosh, 2002). Gondwana supergroup rocks are the oldest rocks in the eastern part of the Basin. The detailed stratigraphy of the Basinal region was described by Zaher and Rahaman (1980) and Alam *et al*., (2003). The details of the stratigraphic units in the Basinal region are given in Table 2.8.

Table 2.8 **Major stratigraphic units of the Cenozoic and Quaternary sediments within the Bengal Basin (After Alam *et al.*, 1990)**

Stage	Group	Formation	Lithology
Holocene	Madhupur	Alluvium	Silt, sand, gravel and clay
Pleistocene/ Pliocene (up to 6375 m)		Dihing Formation/	Yellow to yellowish grey, massive, fine to medium sandstone and
		Madhupur Clay	claystone/sticky clay
		Dupi Tila Formation	Yellow to ochre, pink, light brown, light grey to greyish-white sandstone, siltstone and conglomerate. Several oxidized, iron-rich, clayey palaeosols. Petrified wood
Pleistocene/ Neogene	Tipam Group (U. Jamalganj in NW)	Girujan Clay	Grey to greenish grey, red mottled, silty shale, shale and claystone

Stage	Group	Formation	Lithology
Neogene	Surma Group (L. Jamalganj in NW)	Tipam Sandstone	Light yellow to yellowish grey, grey, brownish grey and orange fine to medium grained pebbly sandstone, siltstone and shale
		BokaBil Formation	Greenish to bluish grey and yellowish grey marine pyritic shale, siltstone and very fine to medium grained sandstone, marine fossils
Miocene (3100 m)	Jaintia Group	Bhuban Formation	Grey to bluish grey fine to medium sandstone, siltstone, claystone
Oligocene (800–1000 m)		Barail Formation	Brown, yellow-brown, pink and grey sandstone, siltstone and carbonaceous Shale
		Bogra Formation in the NW	
Late Eocene (Eocene 600–800 m) Middle–Early Eocene		Kopili Formation	Grey, greenish grey to black silty claystone, fossiliferous shale, thin beds of glauconitic sandstone and limestone
Eocene and Palaeocene		Sylhet Limestone	Grey to greyish brown massive nummulitic limestone
		Tura Formation	Grey, brown, pink and greyish-white ferruginous sandstone, coal and shale
Late-Middle Cretaceous	Upper Gondwana	Sibganj Trapwash	Coarse yellow brown sandstone; white clay; volcanic ash
Early Cretaceous–Jurassic		Rajmahal Traps	Amygdaloidal basalt, serpentinised and esite, shale, agglomerate
Late Permian	Lower Gondwana	Paharpur Formation	Sandstone, feldspathic greywacke, coal, shale, coarse sandstone
Early Permian	Lower Gondwana	Kuchma Formation	Coarse grained sandstone, shale, thick coal seams
Precambrian		Basement Complex	Gneiss and schist

Quaternary geology of the Bengal Basin is driven by many factors such as Global climatic changes, uplift of the Himalayas and subsidence in the Bengal Basin (Umitsu, 1993; Ravenscroft, 2003). The Holocene-Pleistocene period is defined by the rise of sea level or just by the end of the Glacial period known as the Last Glacial Maximum (BGS, 2001). The period 10000 yr BP is marked as an important change in the sedimentation pattern of the Ganges-Brahmaputra-Meghna (GBM) delta with a rapid rise in sea level that initiated the extensive accumulation of deltaic sediments in the Bengal Basin (Goodbred and Kuhel, 2000a). The Quaternary period comprises of four stages that are the Holocene (0-10 ka BP), the Upper Pleistocene (128-10 ka BP) with

Glacial maximum at 21 ka BP, the Middle Pleistocene (750-128 ka BP) and the Lower Pleistocene (1800-750 ka BP) (BGS, 2001). Quaternary deposition in the order of superposition as given by BGS, 2001 are (i) Recent Tidal flats and beach ridge complex, (ii) Younger Fluvio-deltaic plain, (iii) Paleo/sub deltaic plain, and (iv) Lateritic upland. Major stratigraphic units within the Bengal Basin as enlisted in Table 2.9.

Table 2.9 **Quaternary stratigraphy of Bengal Basin in the western part (modified from Roy and Chattopadhyay, 1997; Monsuret *et al.*, 2001; Ahmed *et al.*, 2004; Ravenscroft *et al.*, 2005)**

Epoch	Age	Quaternary in West Bengal	Lithology
Holocene	Upper	Alluvium Diara Formation	Clay, silt, and fine sand with occasional peat and sometimes gravels
		Panskura Formation	Floodplain and Deltaic deposits, mostly fine sand
	Lower - Middle	Bethuadahari Formation	Gray colored, fine to medium sands, with occasional coarse sands, and organic mud and peat
		Sijua formation	Gray colored, fine to medium sand, with clay and peat. Floodplain deposits and alluvium
Pleistocene	Upper	Upper Lalgarh Formation	Pale yellowish-brown spotted sandy clay with iron concretions, detrital nodular laterites
	Lower-Middle	Lower Lalgarh Formation	Red - brown to gray mottled clay and silt residual deposits, Kaolinite and iron oxides. Lalgarh contains pebble conglomerate, Laterites with detrital silicified woods, highly oxidized gravels
Pliocene	Upper	Siwalik sediments	Yellowish-brown to grey, medium and coarse sand with clay, low in organic matters Siwalik sediment consists of sand, conglomerate, clay deposited in fluvial environments

2.8 Geological Factors relating to Liquefaction Susceptibility

Liquefaction is a phenomenon where saturated sand and silt take on the characteristics of a liquid during the intense ground shaking during an earthquake. Youd and Perkins (1978) studied the effects of lithological characteristics *viz*. (i) Depositional environment, (ii) Age of deposits, and (iii) Water table depth on liquefaction susceptibility.

(i) Depositional Environment

The degree of sorting, packing and grain size class of the sediments acted as the major factors of liquefaction susceptibility. As much as the sediments are well sorted and loosely packed may suffer higher liquefaction susceptibility. The Fluvial and Deltaic deposits are well sorted, usually having high porosity and hence, most commonly disturbed by liquefaction. Though deltaic deposits are not so widespread, but have similar feature as fluvial deposits indicating high liquefaction susceptibility (Youd and Hoose, 1977). The liquefaction sites reported from various earthquakes occurred in flood plain deposits of Bengal Basin as depicted in Figure 2.19. On the other hand the Glacial till and the laterite deposits are poorly sorted and have been found to be immune to liquefaction. Clay rich sediments having less or no porosity have shown maximum immunity to liquefaction susceptibility (Youd and Hoose, 1977).

(ii) Age of Deposits

The age of the deposits plays an important role in liquefaction susceptibility. As time passes, the buried sediments get harder and compact due to pressure of overlying sediments and digenesis processes. Thus Holocene deposits have been much more commonly disturbed by liquefaction in comparison to Pleistocene deposits. The Pre-Pleistocene deposits have been rarely affected by liquefaction (Youd and Perkins, 1978). Some other factors like topography, nature and depth of burial of sediments occasionally increases liquefaction susceptibility with age.

(iii) Groundwater Table

The reported liquefaction sites from different earthquakes have shown that most episodes apparently developed near the river courses (Youd and Perkins, 1978) as the water table is generally shallow near the river which makes the sites prone to liquefaction. Vulnerability to liquefaction shows direct relation to water table depth, *i.e.* liquefaction susceptibility is increased with shallower water table and decreased with a deeper water table. Liquefaction phenomenon has been observed in Bengal Basin along the river channel due to the occurrence of past seismic events as shown in Figure 2.19.

In the present study, a correlation has been established between the occurred liquefaction sites and the corresponding geomorphological features to identify liquefaction susceptibility in each geomorphological unit. The liquefaction susceptibility in different geomorphological units has been depicted in Table 2.10.

Table 2.10 **Liquefaction susceptibility of different geomorphological units in concern with a geological period (modified after Youd and Perkins, 1978)**

Type of Deposits	General distribution of cohesion less sediments in deposits	Likelihood that cohesion less sediments, when saturated, would be susceptible to liquefaction (by age of deposits)			No. of observed Liquefaction sites in Bengal Basin
Continental zone		<500 yr	Holocene	Pleistocene	-
River channel	Locally variable	Very High	High	Low	25

Type of Deposits	General distribution of cohesion less sediments in deposits	Likelihood that cohesion less sediments, when saturated, would be susceptible to liquefaction (by age of deposits)			No. of observed Liquefaction sites in Bengal Basin
Flood plain	Locally variable	High	Moderate	Low	25
Alluvium fan and plain	Widespread	Moderate	Low	Low	17
Delta and Fan-delta	Widespread	High	Moderate	Low	3 (Active) 6 (Inactive)
Lacustrine and Playa	Variable	High	Moderate	Low	-
Tephra surface	Widespread	High	Moderate		-
Coastal zone					
Delta	Widespread	Very high	High	Low	-
Esturine	Locally variable	High	Moderate	Low	-
Beach: High wave energy	-	-	-	-	-

2.9 Physiography and Geomorphology of Kolkata

The Kolkata city falls under the vicinity of Eocene Hinge Zone. The sediments on both the sides of the Eocene Hinge Zone are very distinct in the characteristics. Subsurface mapping of the Kolkata city revealed that the base of the City is built up with marine as well as the river sediments and carbonaceous shale with organic matter as peat layer indicates the swampy and deltaic environment. Physiography and Geomorphology of a region define the lithological characteristics.

2.9.1 Geomorphology of Kolkata

Geomorphologically the city of Kolkata conforms to flat topographic features with an average elevation of 6.4 m above mean sea level sloping mostly southward. The major geomorphic units exposed in Kolkata are broadly classified into six units *viz*. deltaic plains, interdistributary marshes, paleochannels, younger levees adjacent to the River Hoogly and older levees on both sides of the old Adi Ganga as shown in Figure 2.24 (Nath *et al*., 2014; Roy *et al*., 2012). The major part of the City is covered by the Deltaic plains with 233 km^2. Youd and Perkins (1978) classified the geomorphological units with affinity to high, moderate and low susceptibility to liquefaction, with the maximum likelihood in deltas, river channels and uncompacted artificial fills, whereas Ganapathy and Rajawat (2012) asserted abandoned river channel to be “likely” liquefiable. Geomorphologically Kolkata lie under the river channel, flood plain, alluvium fan/plain and delta/fan-delta depositional environment which indicate moderate to very high susceptibility to liquefaction (Youd and Perkins, 1978). However, Ambraseys and Bilham (2003a) mapped nearly eighty six liquefaction sites triggered by the near-and-far field earthquakes on depositional environment in the Bengal Basin as shown in Figure 2.19. Thus, in Kolkata, all the geomorphological units have potential liquefaction susceptibility during strong seismic shaking.

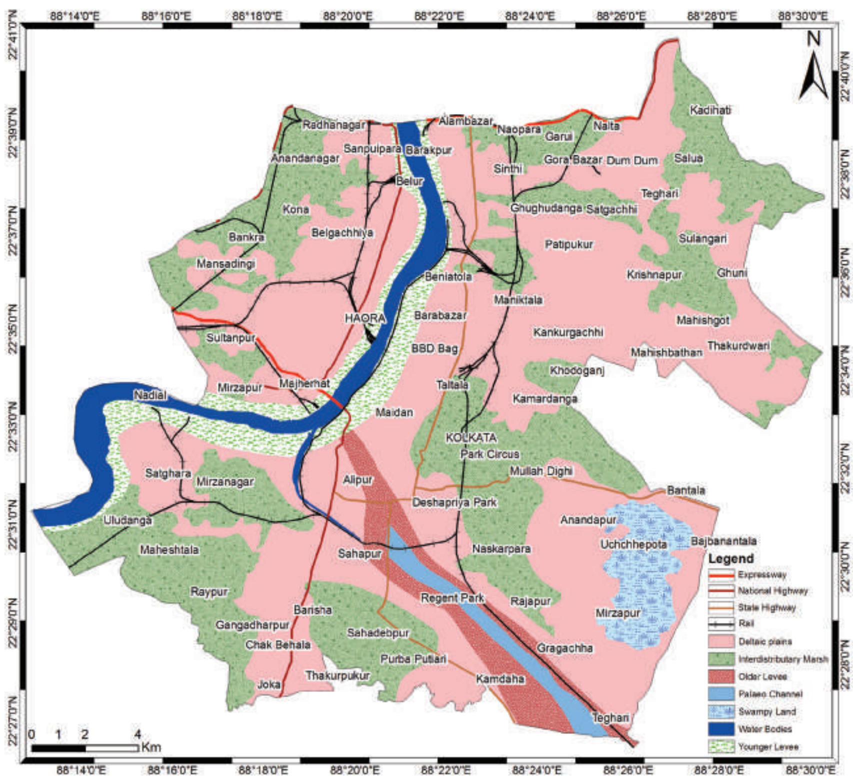

Figure 2.24 **Geomorphological units of Kolkata.**

2.9.2 Geology of Kolkata

Kolkata is located over a tiny part of the huge pericratonic Bengal Basin with an enormous thickness of fluvio-marine sediments. The sediment thickness and facies are significantly varied from the shelf area in the west and the deep basinal region in the east. The total sedimentary thickness below Kolkata is in the order of 7500 m above crystalline basement, out of which the top 350-450 m is Quaternary sediment followed by 4500-5500 m of Tertiary sediments, 500-700 m of Cretaceous Trap/Trap wash and 600-800 m of Permo-Carboniferous Gondwana rocks (Das and Chattopadhyay, 2009; Nandy, 2007).

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). The recent geological formations, poorly consolidated/unconsolidated water charged sediments and man-made landfills posed favorable conditions for liquefaction in the City. 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 2.25. 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. The spatial extent of these geological units is represented in Figure 2.25.

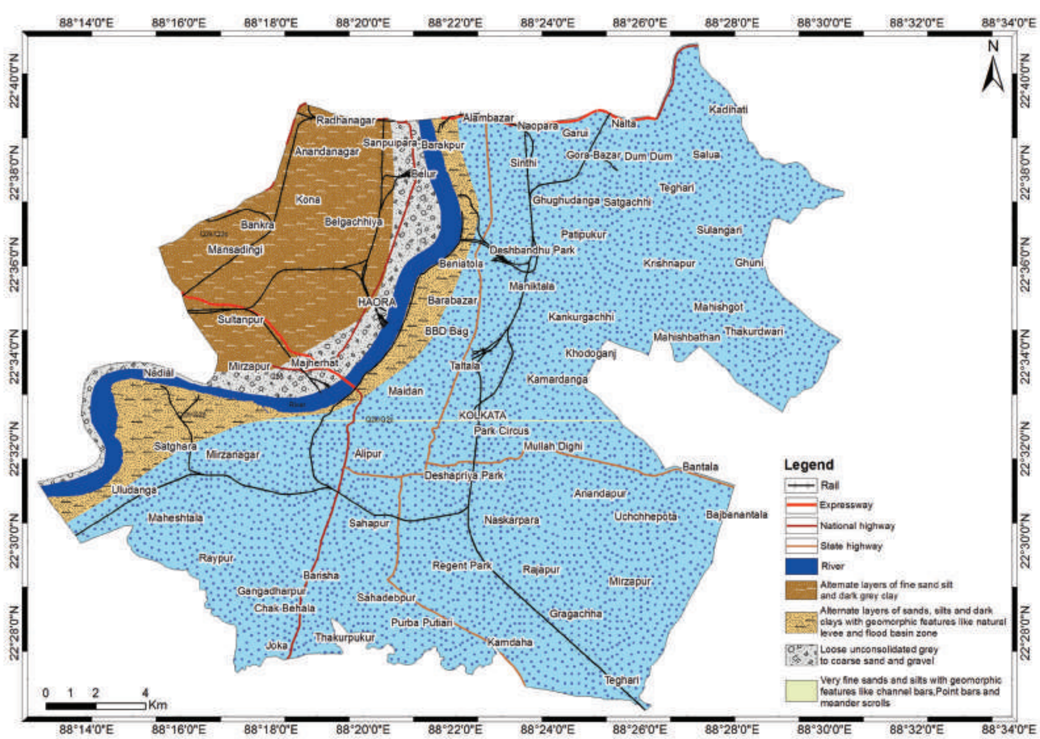

Figure 2.25 **Geology map of Kolkata constructed from borehole litholog data and district resource map published by GSI.**

2.9.3 Stratigraphy Model of Kolkata

The late Quaternary sediments in the Ganges Delta and its surrounding region consists mainly of sand, silt and distinctive beds of latest Pleistocene and Holocene sediments deposited after the lowest stands of sea-level during the last glacial maximum (Umitsu, 1993). A conceptual model of Holocene and Upper Pleistocene sediment distribution constructed from the borehole data is shown in Figure 2.26. The decomposed wood/peat has been observed in distinct layers at various depths. The decomposed wood intermixed with silty clay from 3 to 5 m and from 7 to 9 m has been observed, while as the depth increased coarse sediments took place of silty and clayey sediments with decomposed wood. Two distinct layers of peat/decomposed wood beneath Kolkata had been dated to 7300±200 calyr and 3600±150 calyr BP, which belongs to the Holocene period (Chakraborty *et al*., 2011). The Holocene and Pleistocene lithofacies have been distinguished in the exposed Quaternary sections of the Bengal Basin (Morgan and McIntire, 1959; Poddar *et al*., 1993; Roy and Chattopadhyay, 1997; Singh *et al*., 1998; Stanley and Hait, 2000). The major diagnostic features of late Pleistocene and Holocene sequences in Bengal Basin are given in Table 2.11 (Stanly and Hait, 2000).

Table 2.11 **Diagnostic features of Holocene and Pleistocene sediments of the southern Bengal Basin (After Stanley and Hait, 2000)**

Diagnostic features of the Late Pleistocene sequence	Diagnostic features of the Holocene sequence
Muds are significantly harder (termed stiff) than those of Holocene age, and record effects of Laterization with attributes that include highly weathered oxidized coloration (Yellow, Brown, Tan, mottled and rust).	Deposits do not display the typical signature of oxidation (yellow, orange, reddish, and brown colors), nor do they include hardened (stiff) muds with calcareous and/or iron concretions.
Some muds display rust stained (Iron oxide) spots, while other comprise calcareous and/or iron concretions, and are termed Kankar	In marked contrast to the Pleistocene, Holocene muds are very soft to moderately compact, grey to dark olive grey and black.
Sand is generally poorly sorted and somewhat coarser than those of Holocene age, in some cases granules and pebbles are present.	Muds have high organic matter content and locally may include abundant plant matter.
Sand and Silt facies are Tan and yellow, and in some cases with rust (Iron Oxide) stains.	Layers of peat, ranging in thickness from a few millimeters to 50 cm, are commonly interbedded in grey Holocene muds.
The late Pleistocene also can generally be distinguished by a lower amount of dispersed plant matter in both mud & sands and by the absence of interbedded peat layers.	Sands and silts tend to be finer grained than in Pleistocene sections, are usually grey and commonly include dispersed plant matter and shell fragments.

Diagnostic features of the Late Pleistocene sequence	Diagnostic features of the Holocene sequence
The sand-size fraction of most Pleistocene layers is also characterized by large proportions of fully iron-stained (approx. 19%) and partially iron-stained (approx. 27%). Compositional counts of the sand-size fraction record important proportions of aggregate grains and by low amounts of plant matter (approx. 1%)	Proportions of clear unstained quartz (average to -88% of all quartz grains), plant debris (to 1.6%), and well-to-moderately preserved foraminiferal tests (to 0.6%) in the sand-size fraction are generally higher than in Pleistocene sands, while aggregate grains (<3%) are present in lower proportions.

In the western part of the Basin, the Holocene sediment cover is relatively thin of about 15 m and thickens rapidly in the east of the basement hinged zone to 42-90 m (Banerjee and Sen, 1987; Hait *et al*., 1996; Stanley and Hait, 2000; Goodbred and Kuehl, 2000a). The depth of the Holocene sediment in the Saltlake region was estimated >11.3 m (Stanley and Hait, 2000).During the Kolkata metro rail project, the black peat layer was reported in distinct 3 beds up to 13 m. The age of the peat layer in Kolkata at the depth of 12.5 m as calculated by radiocarbon dating was 7030±150 yr BP and at 6 m depth the age calculated was 2640±150 yr BP (Barui and Chanda, 1992). Details of the radiocarbon dated at different places in and around Kolkata city have been illustrated in Table 2.12. The upper most Holocene Stratigraphic unit consists of sandy clay, silt and clay with occasional peat layer (Shamsudduha and Uddin, 2007). The Holocene sediment thickness effectively increasing towards S-E direction as shown in Figure 2.26.

Table 2.12 **Radiocarbon dating detail at two locations of Kolkata (After Umitsu, 1993; Stanley and Hait, 2000)**

Site	Age	Material	Depth	Reference
Sankrail, Howrah, Calcutta	2,615±100	Peat	1.37	Stanley and Hait, (2000); Umitsu, (1993)
	4,925±100	Wood	1.52	
	4,075±100	Peat	1.82	
	4,720±135	Peat	3.04	
	5,440±115	Wood	4.87	
	5,810±120	Peat	6.25	
Saltlake	3,990±70	Peat	4.25	
	24,200±580	Organic rich mud	13.20	
	3,860±30	Wood fragments	15.85	

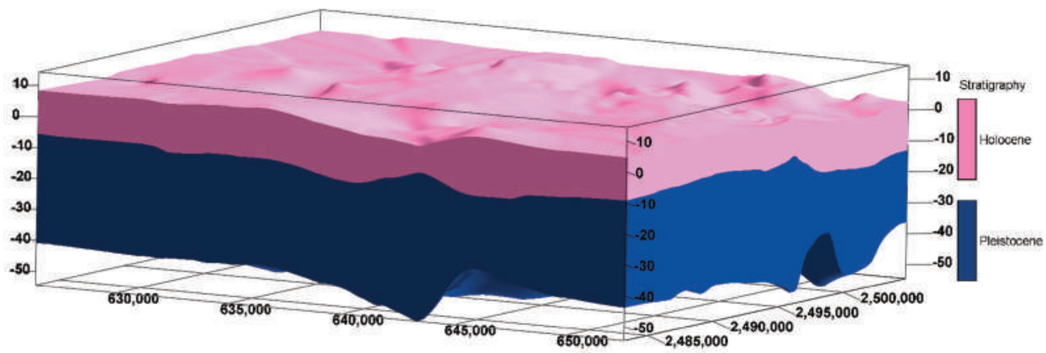

Figure 2.26 **Stratigraphy model of the study region considering 654 boreholes' information illustrating the Holocene and Pleistocene sediment layers in depth.**

2.9.4 Lithostratigraphy of Kolkata

The Kolkata city is covered with thick alluvium of about 450 m Quaternary sediments. Local variations in the characteristics of the alluvial sediments played an integral role in the occurrence of ground failure (Boulanger and Idriss, 2006). The first borehole drilled by British in the year 1840 near Fort William exhibited blue adhesive clay near the surface at 3.048 m which gradually became darker with the depth of burial as depicted in Figure 2.27 (Smith, 1841). The decayed wood/peat layer reported at 9 m to 15 m depth range is an admixture with clay. Historically in around 1717, the entire City was covered by dense forest and even Fort William and Esplanade were covered by dense jungle with scattered extensive salt lakes and marshes. As the town of Calcutta extended, the jungle was gradually cleared away, and the stagnant lakes filled in or drained. Therefore, the decayed wood/peat layers were the debris of this forest vegetation which was consolidated by an intermixture of mud and silt (Smith, 1841). Nearly 3 m thick calcareous stratum was found intermixed with concretionary limestone in the vicinity of Kolkata. Kankar stratum was found in nodular form in the bed of salt lake and in some jheels or shallow salt marshes. A 3 m stratum of calcareous clay was found followed by a thin bed of green siliceous clay extending from 18 m to 19 m in depth. At the depth of 22 m a bed of variegated sandy or arenaceous clay was observed and it continued to a depth of 36 m. Beneath this, a stratum of argillaceous marl of 1.5 m thickness was found followed by a thin bed of 1 m loose friable sandstone with the particles of sand being held loosely together by a clayey cement. At a depth of 53.34 m a coarse friable quartzose conglomerate was found. Ferruginous sand with thin beds of calcareous and arenaceous clay prevails in the depth range of 63 m to 115 m. The Fort fossils were found in two distinct deposits separated from each other by the interposition of a bed of shelly calcareous clay. The lithological characters of the superior and inferior fossiliferous deposits differ considerably from each other, the former being a fine and slightly indurated sandstone, the latter a coarse conglomerate formed of the debris of primary rocks, imbedded in an arenaceous matrix. Therefore, a series of lithological cross-section have been constructed using 654 borehole lithostratigraphy. The aim is to assess the lithological characteristics beneath Kolkata upto 50 m.

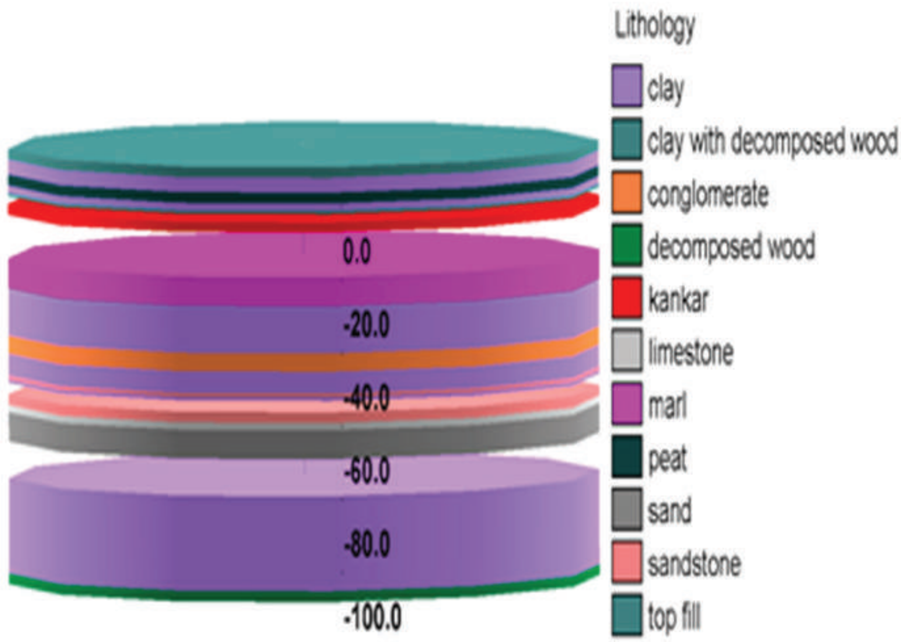

Figure 2.27 **Oldest Borehole in Kolkata drilled by British in 1840 (Smith, 1841).**

2.9.4.1 Lithostratigraphic cross-section of Kolkata

2.9.4.1.1 Cross-section AA´

The cross section *AA´* running from Liluah to Narayanpur revealed the subsurface lithology of Kolkata city as depicted in Figure 2.28. Loose soil has been observed near Naihat, followed by yellowish grey and bluish grey clayey silt with decomposed wood at 15 m depth. The trend of lithology continues to be the same as in the borehole at Johnnagar road. Along the section AA′, at Cossipore the top soil attains a thickness of 0.5 m to 2.2 m and is followed by bluish grey clayey silt. The stiffness of sediments in this borehole is comparatively high and is characterized by stiff bluish grey silty clay with traces of mica. Decomposed wood/peat layer found associated with stiff silty clay is followed by the calcareous nodules (Kankar) near Cossipore. The borehole near Dum Dum consists of fine sand followed by the silty clay with decomposed wood at a shallow depth of 5.1 m.

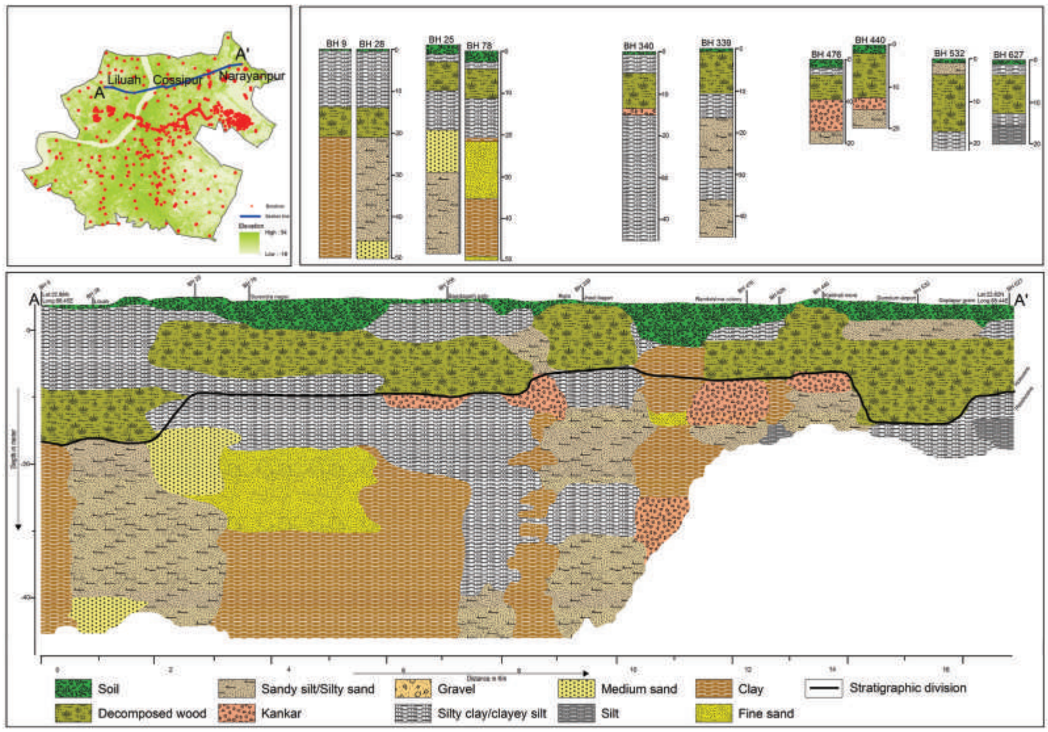

Figure 2.28 **Subsurface lithostratigraphy along the cross-section AA′, from Liluah to Narayanpur.**

2.9.4.1.2 Cross-section BB′

The cross-section *BB′* runs from Sitalatola (Howrah) to New Town as depicted in Figure 2.29. Grayish clayey silt/silty clay with decomposed wood observed at a depth range of 0 to 10 m along the cross-section exhibits favorable conditions for liquefaction. The decomposed wood and top soil is dominant in Saltlake, New Town at the eastern part of the cross-section. The kankar layer is found in the depth range of 10 to 30 m followed by silty clay/clayey silt. The Last Glacial Maximum boundary (Holocene sediments) varied from 8 m to 14 m in depth along the profile. It is also revealed that the silty clay/clayey silt material dominated up to a depth of 36 m and is followed by fine sand.

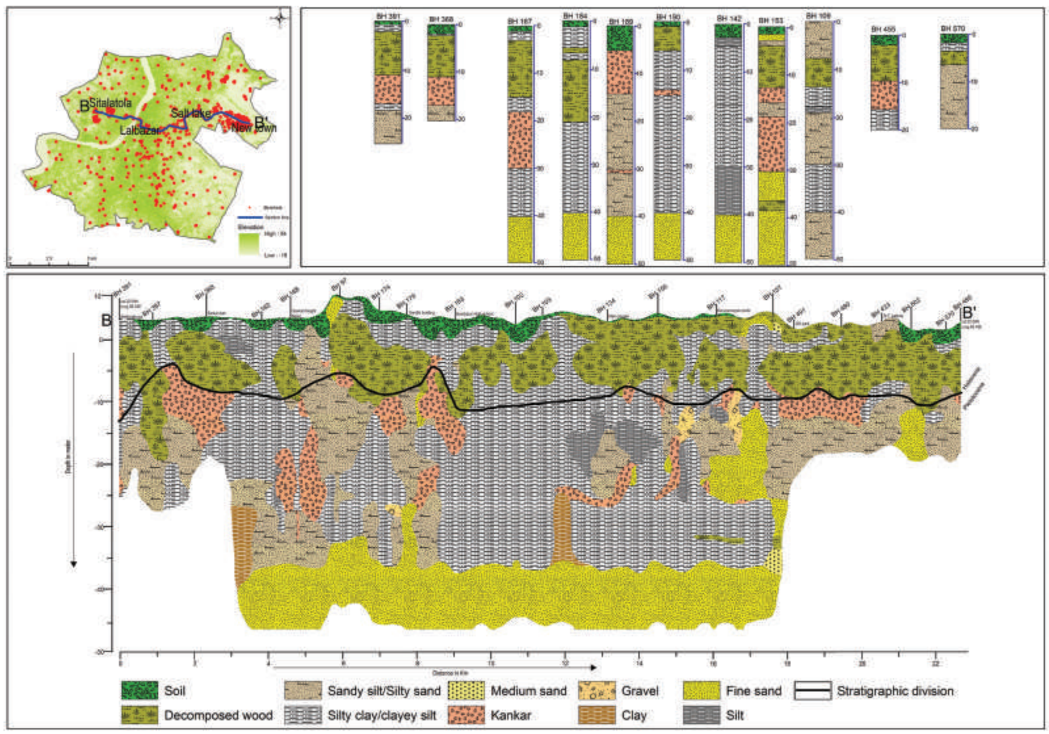

Figure 2.29 **Subsurface lithostratigraphy along the cross-section BB′, from Silatara to New Town.**

2.9.4.1.3 Cross-section CC´

The cross-section marked as CC´ runs from Kantipota to Baruipara as depicted in Figure 2.30. Near Ichapur Howrah, a peat layer is found at 6 m depth and stiff greenish silty clay mixed with kankar has been observed at a depth of 12.6 m. At Race Course decomposed wood layer has been observed at 15 m below the subsurface. The peat layer observed in two distinct depth zones near Bantola at a shallow depth of 4.95 m and at 45.45 m mixed with silty clay. The southeastern part of the cross-section is dominated by decomposed wood and top soil which is expected to amplify seismic ground motion induced by an earthquake.

2.9.4.1.4 Cross-section DD´

The cross-section *DD´* runs from Ayub Nagarbasti to Teghari as shown in Figure 2.31. The black clay has been observed at Badartala near Ayub Nagarbasti at a depth of 15.24 m followed by yellowish fine sand. The stiff silty clay with mica has been observed at a depth of 3 m followed by the soft silty clay with varying percentage of decomposed wood near Rabindra Nagar. The entire cross-section is filled up to 5 m depth by a thin top soil layer.

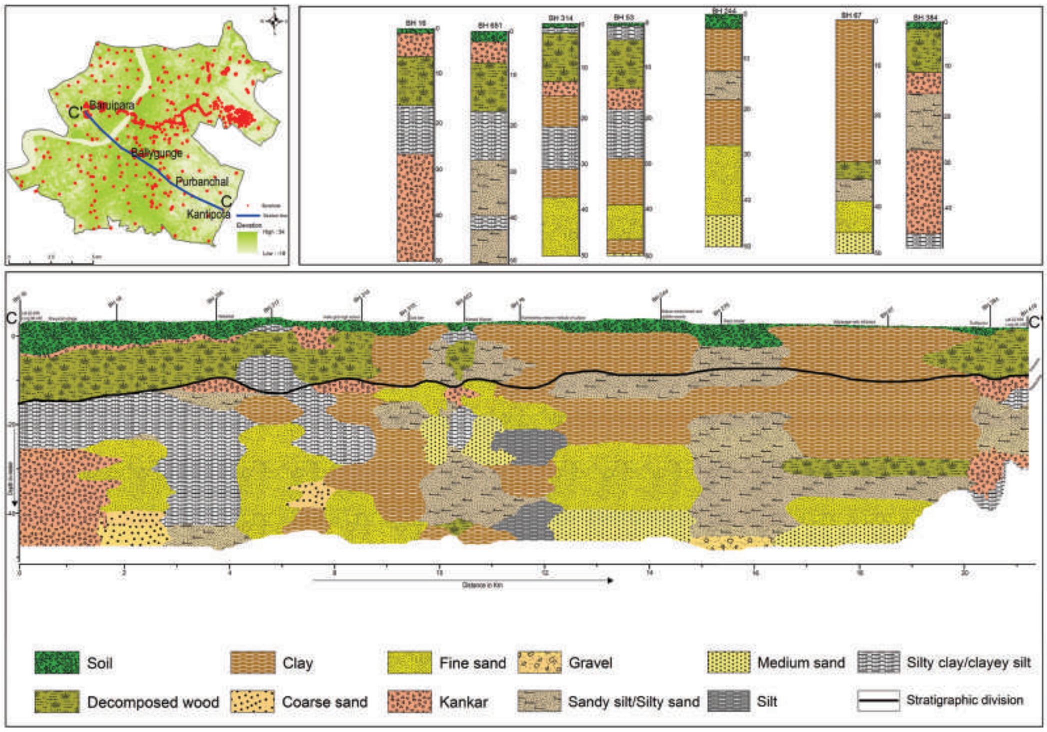

Figure 2.30 **Subsurface lithostratigraphy along the cross-section CC', from Kantipota to Baruipara.**

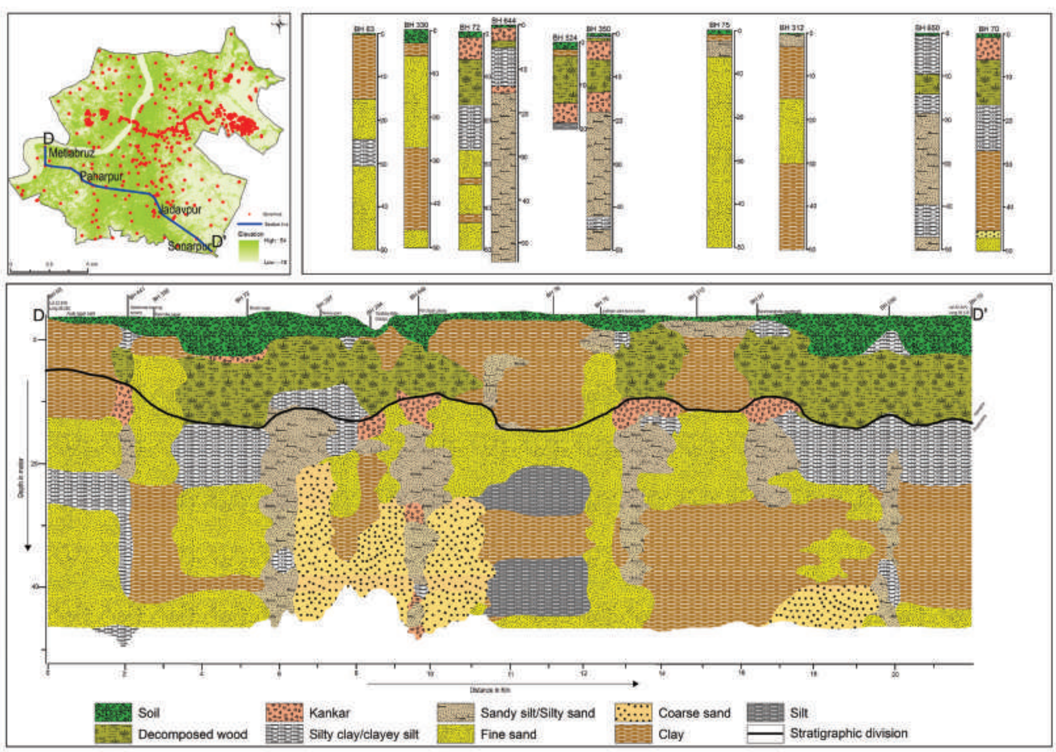

Figure 2.31 **Subsurface lithostratigraphy along the cross-section DD', from Ayub Nagarbasti to Teghari.**

2.9.4.1.5 Cross-section EE´

The cross-section EE´ runs from Dum Dum airport to Bijoygarh as depicted in Figure 2.32. The decomposed wood layer dominates the depth range of 5 m to 11 m along the profile section. The dark clay has been observed near Kasba pumping station at a depth of 20 m. It is observed that the fine sand upto 25 m is followed by a 3 m thick coarse sand layer and clayey silty sediments located at the lower depth ranges. Decomposed wood layer is observed in two distinct layers at 6 m depth and 14.2 m depth near Subhas Sarovar. The Holocene sediment increases in thickness near Kasba pumping station.

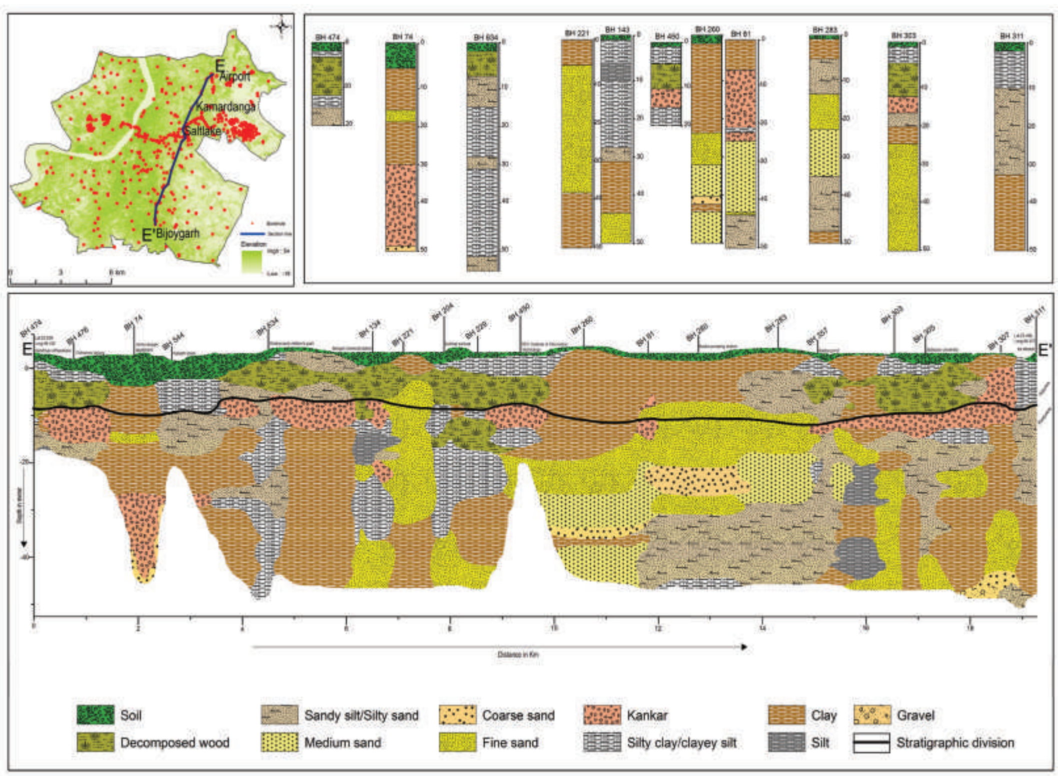

Figure 2.32 **Subsurface lithostratigraphy along the cross-section EE′, from Dum Dum airport to Bijoygarh.**

2.9.4.1.6 Cross-section FF´

The cross-section FF´ runs from Kona to Thakurpukur as depicted in Figure 2.33. Nearly 10 m thick decomposed wood/peat layer with silty clay underlain by soft bluish silty clay has been observed near Majerhat. The grayish silty clay with some percentage of decomposed wood/ peat has been observed at Ichhapur. The yellowish silty clay and decomposed wood are further observed to be followed by the stiff greenish silty clay, yellowish grey clayey silt at a depth of 17.1 m along the profile. This is the typical characteristics of Pleistocene sediments. Traces of mica followed by stiff silty clay with kankar layer has been observed in the southern part of the cross-section.

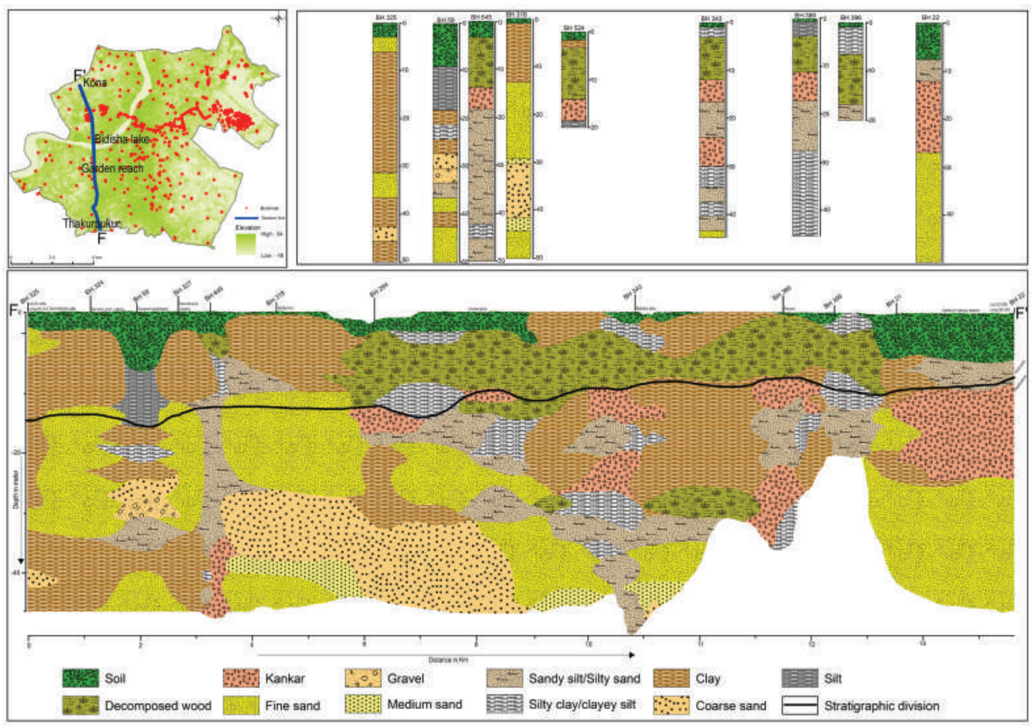

Figure 2.33 **Subsurface lithostratigraphy along the cross-section FF′, from Kona to Thakurpukur.**

2.9.4.2 Lithostratigraphic Fence Model of Kolkata

The lithostratigraphy model of Kolkata has been constructed from 654 borehole data upto 50 m depth using RockWork16 software. Lithologies are classified into ten major classes *viz*. clay, coarse sand, medium sand, fine sand, sandy silt/silty sand, gravel, kankar, silty clay/clayey silt and decomposed wood/peat. The lithostratigraphic model revealed that a layer of decomposed wood/peat covered the entire region with varying thickness. The decomposed wood/peat layer is deposited in three distinct layers at various places. The first layer is observed at a depth of 3 m to 11 m nearly in all the boreholes while the second and the third layers are found at depths of 14 m and 28 m to 30 m respectively especially in the eastern pert of the study region as depicted in Figure 2.34.

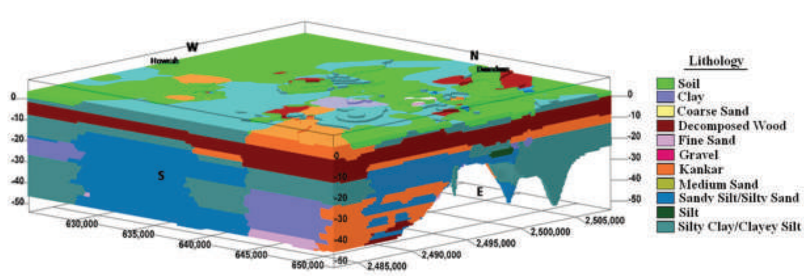

Figure 2.34 **Lithostratigraphic model of Kolkata constructed from 654 boreholes showing the lithologic variation beneath Kolkata.**

A fence diagram has also been drawn by correlating the lithologs of 654 boreholes for a better insight of the subsurface stratification of sediments underlying the region as depicted in Figure 2.35.

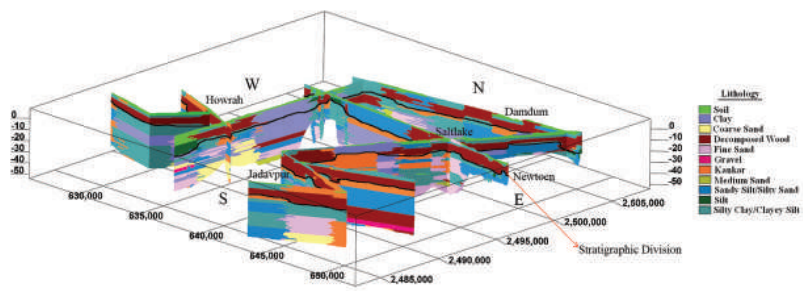

Figure 2.35 **Fence diagram depicting the subsurface stratification of Kolkata city.**

2.10 Concluding Remarks

The Bengal Basin sitting on a 7.5 km thick alluvium above the crystalline basement is highly vulnerable to earthquake disaster. The entire basin was affected by near-and-far seismogenic sources like Bihar-Nepal seismic zone in the Central Seismic Gap, Assam Seismic Gap, Shillong Plateau, Andaman-Nicobar seismic province, Bengal Basin itself and the N-E Himalayan extent. The maximum intensity reported in Kolkata is of the order of MM VII, generated from both the near-source earthquake of 1964 and the distant earthquake of 1934, making the province seismically vulnerable. Geomorphologically the Bengal Basin lies under the river channel, flood plain, alluvium fan/plain and delta/fan-delta depositional environment which indicate the moderate to very high susceptibility to liquefaction. However, Youd and Perkins (1978) classified the geomorphological units with affinity to high, moderate and low susceptibility to liquefaction, with the maximum likelihood in deltas, river channels and uncompacted artificial fills, whereas Ganapathy and Rajawat (2012) asserted abandoned river channel to be "likely" liquefiable. Thus, in Kolkata, all the geomorphological units have potential for liquefaction during a strong seismic shaking. On the other hand, the irregular character of shallow subsurface lithology below Kolkata indicates several significant variations in site condition thus affecting the site response due to strong ground motion. The filled-up areas in the eastern Kolkata *i.e.* Saltlake, Rajarhat, New Town, southeastern region of the City is underlain by abandoned river channels and natural levee of both side of Hoogly River which are likely to suffer from enhanced seismic shaking as well as susceptibility to liquefaction during an eventual moderate to strong earthquakes. Therefore, considering the level of seismicity, sub-surface lithostratrigraphy, size of the City, the dense demography and rampant urbanization on artificial non-engineered fill necessitate in-depth estimation of seismic hazard, vulnerability and risk of the city of Kolkata.