SEISMIC MICROZONATION OF COX'S BAZAR MUNICIPAL AREA

by

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A thesis submitted to the Department of Civil Engineering,
Bangladesh University of Engineering and Technology, Dhaka-1000
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING
(GEOTECHNICAL)

August 2009

The thesis titled Seismic Microzonation of Cox's Bazar Municipal Area, submitted by A. B. Afifa Imtiaz, Studentl No. 100704213F, Session October 2007, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering on 18th August 2009.

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ACKNOWLEDGEMENTS

All praises to the Almighty, the benevolent and the kind.

The author is greatly indebted to her supervisor, Dr. Mehedi Ahmed Ansary, Professor, Department of Civil Engineering, BUET, for his invaluable support, encouragement, supervision and useful suggestions throughout this thesis. His support and continuous guidance with his originality enabled successful completion of the research work.

The author conveys profound gratitude to Dr. Md. Zoynul Abedin, Professor and Head, Department of Civil Engineering, BUET, for his co-operation and kind guidance.

Sincerest gratitude is due to Prof. Jamilur Reza Choudhury, Vice-Chancellor, BRAC University for his valuable recommendations.

The author gratefully acknowledges to Dr. T. M. Al-Hussaini, Professor, Department of Civil Engineering, BUET, for his kind valuable suggestions and kind co-operation.

Many thanks to Dr. Ashutosh Sutra Dhar, Associate Professor, Department of Civil Engineering, BUET, for sharing soil exploration data of Cox's Bazar Municipal.

Many thanks to Md. Rais uddin Russel, an undergraduate student of the Department of Civil Engineering, BUET, for his cooperation in laboratory tests of soil samples and sharing the test results.

Finally, the author would like to pay tribute and appreciation to all those who extended their kind assistance and cooperation during the course of the study, in particular, officials of Cox's Bazar Municipality, Comprehensive Disaster Management Programme (CDMP), Geological Survey of Bangladesh (GSB), Department of Civil Engineering (BUET), Dhaka Soil and all other agencies and organisations.

ABSTRACT

The purpose of this study is to develop geotechnical microzonation maps using Geographical Information Systems (GIS). As study area, Cox's Bazar Municipal Area, located in the Southeastern region of Bangladesh, beside the Bay of Bengal, has been chosen. The model inputs include site amplification, liquefaction potential study and slope stability analyses. It is now well known, and widely accepted amongst the earthquake engineering community, that the effects of surface geology on seismic motion exist and can be large. Nearly all recent destructive earthquakes have brought additional evidence of the dramatic importance of site effects. Accounting for such "site effects" in seismic regulations, land use planning or design of critical facilities thus has become one goal of earthquake hazard reduction programs.

Cox's Bazar area, having been a great tourist resort, has experienced a rapid urbanization in the last few decades including various establishments, construction of significant number of buildings and other structures in an unregulated manner and without seismic design considerations. Landslide and related casualties have also become very common in the hilly areas of the locality. In order to assess seismic vulnerability based on ground susceptibility and adopt mitigation strategies for urban areas, seismic microzonation is considered to be the first step. This study deals with the microzonation of the Cox's Bazar Municipal Area using geographic information system (GIS) where reflection of ground shaking and the site attributes of soil amplification, liquefaction and landslide are the salient features. The probable earthquake hazard and expected ground motion for this area were assessed using probabilistic approach. The liquefaction potential was estimated from Standard Penetration Test (SPT) following the methods suggested by Seed and Idriss combined with Japanese Code of Bridge Design. SHAKE analysis was performed for estimation of 1D site amplification. Slope stability analyses were performed for samples from the hilly regions of the area using the program XSTABL. The results obtained for site amplification, liquefaction and landslide potential were exported in GIS environment and presented as microzonation maps.

The findings of the study show that the rock level Peak Ground Acceleration (PGA) of the area is 0.18g for a 7.5 magnitude earthquake having a return period of 200 years. The surface PGA could be as high as 0.41g for an average 2.3 times amplification factor if extreme or most severe condition is considered. For this, ground shaking amplified by 2, 2.5 and 3 times can affect 47%, 42% and 11% of the municipal area respectively. 87% of the study area is highly susceptible to liquefaction and approximately 8% of the municipality consists of hilly region whose 97% is very unsafe regarding natural slope stability. On the other hand, surface PGA will be 0.31g for an average amplification factor of 1.7 if a refined hazard condition is assumed based on average horizontal spectral acceleration technique. 89% area will be affected by 1.7 times amplification of ground shaking and 58% area will be prone to high liquefaction potential. 96% of the hilly region will become vulnerable if high landslide associates with only 1.7 times amplification of ground shaking.

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CHAPTER 1
INTRODUCTION

1.1 Background

Bangladesh runs a high risk of experiencing earthquakes due to her geological and tectonic structures. The northern region of Bangladesh lies above the seam of the Indian and Eurasian tectonic plates and the eastern part is above the joint of the Burmese and Indian plates. The Indian plate is edging north-east while the Burmese plate is moving north-west. The country's position adjacent to the very active Himalayan front and ongoing deformation in nearby parts of south-east Asia expose it to strong shaking. In the recent past, a good number of tremors of moderate to severe intensity had already taken place in and around Bangladesh. Cox's Bazar, located in the southeastern part of Bangladesh, is a strategically and economically important area of the country. The district is exposed to the most devastating natural disasters of the country. In the seismic zoning map of Bangladesh, provided in BNBC (Bangladesh National Building Code 1993), Cox's Bazar has been shown under Zone II with design Peak Ground Acceleration (PGA) value of 0.15g (Z=0.15). This level of acceleration may be considered as more or less equivalent to a seismic intensity between VII and VIII. Historical information reveals that earthquakes of magnitude between 6 and 7 have occurred around the area in the past. Thus Cox's Bazar and the nearby area are considered to fall in the High Risk Zone for earthquakes. The frequent earthquakes in and around the country, particularly Chittagong and Cox's Bazar regions, also point toward the potential of such intensity earthquakes, even much higher than that projected. Therefore, it is essential to assess the earthquake hazard and related secondary effects for the region in order to aid the earthquake risk mitigation efforts.

Cox's Bazar, having been a great tourist resort, a rapid urbanization has occurred in the last few decades including various establishments, construction of significant number of buildings and other structures in an unregulated manner and without seismic design considerations. The consequences of moderate to strong earthquake event can be catastrophic if such a densely populated urban area is affected and may have very severe long-term consequences for the entire country.

One of the major concerns during an earthquake is the presence of vulnerable soil near the ground surface. In order to assess seismic vulnerability based on ground susceptibility, seismic microzonation is considered to be the first step towards a seismic risk analysis and mitigation strategy for urban areas. Therefore this study deals with the microzonation of the Cox's Bazar Municipal Area based on liquefaction potential, site amplification and land slide potential. Figure 1.1 shows the location map of Cox's Bazar Municipal area.

Liquefaction phenomena can affect buildings, bridges, buried pipelines, lifelines and other constructed facilities in many different ways. Cox's Bazar is mostly a hilly region consisting of alluvial flood plain and sandy sea shore area. The area bottom of the hill can liquefy if the intensity of shaking is high, which may cause land slide in the hilly region. On the other hand floodplains and sea shore areas consisting of fine sand and silt deposit with shallow water table in most of the places may liquefy during a strong earthquake.

Site Amplification is an important basis of microzonation. The basic intention of amplification assessment is to estimate the effect of local site conditions through the site response analysis. This factor is highly dependent on the local soil conditions and on the expected earthquakes. Local soil effects can amplify the ground motion and thus lead to intensity greater than the projected ones in certain areas causing more damage. In the urbanization process it has become a common practice to fill up many low lying lands or shallow water bodies in the town area for construction. The filled soils in many cases are not properly compacted or consolidated. Furthermore, the low lying lands may also possess soft soils. These soft soil sites may cause amplification and modification of ground motion, producing larger seismic forces in buildings. Cox's Bazar area is also characterized by a significant amount of sediment and landfill, which may greatly amplify seismic waves and is another issue of concern for studying the site effects.

Landslide has become very common in the hilly areas of southeastern Bangladesh, especially in Bandarban, Rangamati, Khagrachhari and Cox's Bazar. Illegal hill-cutting due to rampant building has left some 70,000 (IRIN, 2008) people at risk of landslides in 18 sub-districts of the hill districts, as well as the city of Chittagong, warned specialists. Every year especially in the rainy season landslides take place in both natural and man-induced slopes. Considerable number of buildings, roads and other infrastructures are damaged and valuable lives are lost in these incidents. The loss of lives and properties due to landslide events in Cox's Bazar is also very significant. Now time has come to find out the cause of such events in the area and to take necessary preventions to avoid repeated casualties. Therefore assessment of landslide potential of Cox's Bazar has become very essential. Indiscriminate Hill cutting is one of the major causes of landslide. Landslide may be caused by earthquake in steep hill and loose land of steep periphery. Gentle angle or slope is mostly absent in the hills of Cox's Bazar due to human activities. Rock strata in this area are mostly found as soft or brittle sedimentary rocks which may easily be broken or slide. Since Cox's Bazar is on the threat of probable earthquake events, the hill-tops loosened by any means can cause massive destruction if a moderate to major tremor takes place.

Seismic hazard due to local site effects such as soil amplification, liquefaction, and landslide can be estimated by combining the available soil parameter data with the current hazard status of the region. Moreover, for accomplishing comprehensive regional hazard assessment, geographic information system (GIS) provides a perfect environment. Therefore this study deals with the microzonation of the Cox's Bazar Municipal Area using geographic information system where reflection of ground shaking and the site attributes of soil amplification, liquefaction and landslide are the salient features. Microzonation maps can be used for planning locations and construction of future facilities. The GIS-based analysis is useful to engineers, planners, emergency personnel, government officials, and anyone else who may be concerned with the potential consequences of seismic activity in a given region. Microzonation maps presented on a GIS platform provides the results of a regional seismic hazard and risk analysis that serve as an effective means of transferring information from the scientific community to the professional community of decision makers involved in hazard and risk mitigation. Hence these zonation maps will add value in planning of the coastal town Cox's Bazar by helping in finalizing design of many important structures and saving construction time and cost.

1.2 Objectives of the Study

The goal of the proposed research is to develop maps showing local site effects such as the liquefaction potential, site amplification and landslide potential for Cox's Bazar Municipal area in Bangladesh. The following are the specific objectives of the research:

1. To compile a subsoil investigation database for different locations of Cox's Bazar Municipal area
2. To determine the Site Amplification of the Area based on 1D-SHAKE analysis
3. To determine the Liquefaction Potential of the Area based on Geology, standard penetration test (SPT) and laboratory test results.
4. To demarcate the regions susceptible to Landslides due to natural slope instability
5. To determine the combined effects of the aforementioned hazards to ground shaking.
6. To present the results of the study in GIS based Maps.

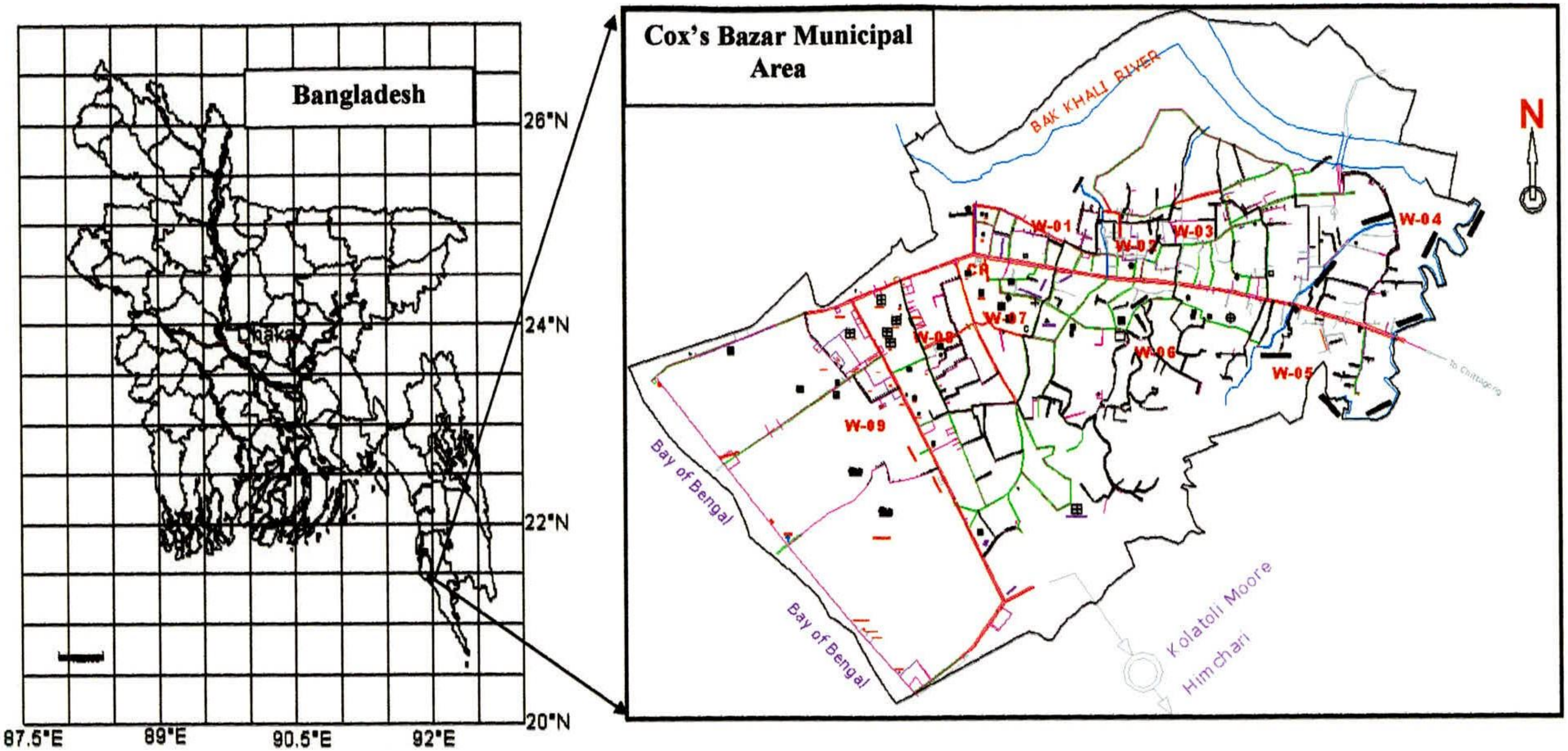


Figure 1.1: Location map of study area

1.3 Methodology of the Study

Bore-hole soil data, geophysical measurements, historical data, reports and published papers have been used to identify the vulnerable locations and estimate necessary soil parameters. Standard analytical methods have been used to develop site amplification scenarios, liquefaction potential and landslide potential of Cox's Bazar district.

SHAKE (Schanabel et. al., 1972) program which considers the responses in a system of homogeneous, visco-elastic layers of infinite horizontal extent subjected to vertically traveling shear waves has been used in this research for Site Amplification analyses. There are several empirical relations correlating (Tamura and Yamazaki, 2002) the SPT N-value and shear wave velocity. These relations have been used to convert SPT N-value into shear wave velocity, which is needed as one of the parameters for the program SHAKE.

Several laboratory tests are in practice to estimate the liquefaction potential of soils such as dynamic triaxial test, cyclic simple shear test and shaking table test. However, in this study liquefaction potential of Cox's Bazar area has been determined from Standard Penetration Test (SPT) and laboratory test results based on Seed and Idriss (1971) and Japanese Code of Bridge Design (Tatsuoka, et. al., 1980).

Landslide assessment for the purpose of estimating the probability of occurrence and likely severity of landslides can be carried out by various methods. Slope stability assessment program XSTABL has been used in this study in assessing the instability of slope or the probability of occurrence and the likely severity of landslides. The methodology adopted for this study can be described according to the following phases:

1. Digitizing the updated administrative boundary of the study area.
2. Conduction of field survey across the municipal area under Cox's Bazar and identifying locations to be investigated.
3. Collection of sub-soil data. Twelve subsoil investigations to be specifically carried out for this research. Soil parameters such as grain size (soil type and d_{50}) and SPT data for several sites to be compiled in database.

4. Surveying the hilly regions of the area and collection of samples for laboratory investigations including specific gravity test, grain size analysis, Atterberg limits, relative density, compaction test and direct shear test. Collection of location, height, slope and other relevant data of hills
5. Selection of earthquake source and estimation of the attenuation of earthquake ground motions in the bedrock level between the source and the region.
6. Estimation of Shear Wave Velocities by using SPT data and different co-relations (Tamura and Yamazaki 2002). Estimation of 1D site amplification by SHAKE.
7. Estimation of surface level ground hazard in terms of surface level Peak Ground Acceleration (PGA) from bedrock PGA and site amplification.
8. Estimation of liquefaction potential based on the methods Seed and Idriss (1971), and Japanese Code of Bridge Design using the sub-soil data.
9. Estimation of Landslide Potential by using computer program XSTABL.
10. Development of microzonation maps based on site amplification, liquefaction potential and landslide potential in GIS.
11. Development of microzonation maps by integrating the different intensities of the hazards.

1.4 The Study Area

The study area of the research, Cox's Bazar Municipal, lies in the Southeastern part of Bangladesh, beside the Bay of Bengal under the district Cox's Bazar. The area is famous her outstanding natural beauty. The district consists of 8 administrative units (Uddin et. al. 2005). The district has an area of 2491.86 sq km with a population of 17, 73, 709 (BBS, 2001). Cox's Bazar is one of the three municipalities under the district. Cox's Bazar municipality covers an area of 6.85 sq km with 27 mahallas and 9 wards; with a population density of 7,579.27/km² (BBS, 2007).

1.5 Organization of the Study

The remaining part of the study consists of four chapters.

Chapter 2 reviews background information (literature review) of the seismic environment, prevailing in Bangladesh as a part of the evaluation of seismic risk. Important tectonic features and seismic zoning maps of Bangladesh are discussed. Earthquake hazards, site amplification, soil liquefaction, landslides potential are described. The chapter also gives a description of a geographic information system (GIS). Spatial data structures, the functional elements of an integrated GIS and use of GIS for seismic microzonation study are also discussed.

Chapter 3 deals with the collection of basic data and their collection methodology. The data includes collection of borehole data from different sources, grain size distributions and laboratory investigations of hill samples.

Chapter 4 addresses earthquake analysis, assessments of the seismic hazards due to local site effects such as soil amplification, liquefaction and landslide potential. GIS-based methodologies for combining site attributes through a weighted average approach are presented.

Chapter 5 consists of the summary of the whole study and conclusions, recommendations and scope for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Cox's Bazar district is exposed to the most devastating natural disasters of the country where earthquake can be considered as an additional threat. There has been also a rapid urbanization of the town in the last few decades including construction of significant number of hotel buildings and other which can act as guideline for adopting earthquake mitigation approaches for the region. In order to achieve this goal, earthquake vulnerability of Cox's Bazar Town has been assessed on the basis of Potential of Earthquake Occurrences and Ground Susceptibility to Earthquake. This chapter presents a review of literature for developing methodology to conduct regional seismic hazard assessment including consideration of ground shaking and the secondary site effects of soil amplification, liquefaction, landslide etc.

2.2 Overview of the Study Area

Cox's Bazar is a town; a fishing port and a district headquarter in Bangladesh. It is known for its wide sandy beach which is claimed to be the longest natural sandy sea beach in the world. It is located along the Bay of Bengal in Southeastern Bangladesh and 150 km south of Chittagong. Cox's Bazar derives its name from Captain Cox, an officer serving in British India. Cox's Bazar thana was first established in 1854 and the municipality was constituted in 1869 (Banglapedia, 2004). In 1959 the municipality was turned into a town committee. The town committee was replaced by municipality in 1972 and it was elevated to B grade in 1989.

Cox's Bazar municipality covers an area of 6.85 sq km with 27 mahallas and 9 wards, is located at 21.58333°N 92.01667°E and bounded by Bakkhali River on the North and East, Bay of Bengal in the West, and Jhilwanja Union in the South. Population of the area is 51918 (BBS, 2001). As one of the most beautiful and famous tourist spots of Bangladesh, the major source of economy of Cox's Bazar is tourism. Millions of foreigners and Bangladeshi natives visit this coastal town every year. Therefore, a number of hotels, guest houses, and motels have been built in the town and coastal region.

2.2.1 Geomorphology of Cox's Bazar District

The district of Cox's Bazar is bounded on the west and south by the Bay of Bengal, on the east by the hill ranges of elevation around 100-200 m. Basin of Matamuhuri River and Bakkhali river form the morphological pattern on the North of the district. The landmass of the district of Cox's Bazar includes two distinct geological settings namely Tertiary folded belt and coastal deposits. The tertiary folded belt extends north-south as part of the Indo-Burmese mobile belt, which is characterized by long narrow folds (Alam et al., 1990). Flood plain and coastal deposit of Holocene age overlies late Tertiary formations at places presenting the surface form. The present day morphology of the area are believed to be influenced by the Holocene sea level rise, tidal and fluvial discharges and very special type of physical set up of the plain around Tertiary Hills (Huq and Ahmed, 1997).

Alam et al. (1999) present the morphology of Cox's Bazar coastal plain as shown in Figure 2.2. The schematic cross-section shows that the plain is elevated landward and gradually slope toward the sea. The elevation of the marginal part of the plain is of the order of 2 to 3 m above mean sea level. The characteristics of different landforms are shown in Table 2.1. Table shows that sediment of the plain varies from very fine silt to medium sand with finer particles at the flood plain and largest grain size for tidal creeks.

Table 2.1: Landform Characteristics of the Cox's Bazar Coastal Plain

(after Alam et al., 1999)

Feature	Height	Slope	Processes	Width	Mean Grain Size
Flood Plain	5	<1°	Mainly fluvial origin, flash flood and occasional marine wash over, minor rills are common	<5->3 km	Very fine sand to silt
Dunes	3-4	>10°	Undulating, develops parallel to the flood plain	highly variable	Fine Sand
Beach	2-3	4°-6°	Wave and wind actions are predominant with occasional storm surge induced flooding	<200m to >500m	Medium to Fine sand
Mudflat	≤1	<1°	Subject to erosion and accretion through regular tidal action and periodically submerged	50-200m	Clay to silty clay with very fine sand intercalations
Spit	1-2	Most cases steep, varies from 2°->4°	Exposed to wave and wind action and submerged to high spring tide	<50m from the ridge	Fine sand to silty clay
Tidal creek	0.5-1.5	Slopes gently down sea-ward	Limited wave action and exposed to regular tidal exchange	<10 m to 150m	Medium sand with occasional clay intercalation

2.2.2 Geology of Cox's Bazar Municipal Area

Cox's Bazar town is located at the Middle-West part of the district bounded by the Bakkhali River on the North and North-East. The area lies within the Eastern flank of Inani Anticline, trending towards NNW-SSW, whose Western Flank is eroded. The existing Eastern Flank of the anticline is also in the process of continuous erosion. Figure 2.3 shows the Surface Geology of Cox's Bazar Municipal area according to the Geological Map of Bangladesh (after Alam et al., 1990). The Western Figure reveals that the area around the city of Cox's Bazar predominantly composed of Valley Alluvium and Colluvium and Dihing Formation of Pliocene-Pleistocene age. Rocks of the Pliestocene, Pliocene and Neogene ages are also exposed in the area. The exposed rock units are mostly composed of sandstone and claystone. Six Lithostratigraphic units have been observed from the Geological Map of Bangladesh.

To the West of the Municipal Boundary, the strand of Coastal Deposit, **Beach and Dune Sand**, lies extending towards south. This is a narrow zone of Coastal Deposit along the western edge of the tectonically active Fold Belt. Beach and Dune Sand are characterized as light to whitish grey sand being medium to fine, well sorted, subrounded; containing concretion, shell fragments, heavy minerals, and rare clasts. It also includes small mud-flat deposits. This formation uncomfortably overlies Late Tertiary formations.

To the East of Beach and Sandstone, there lies another narrow zone of **Boka Bil Formation** of Neogene age. It is greenish to bluish-grey and yellowish grey shale, siltstone and sandstone. Sandstone is very fine to medium grained; flaser bedding and starved ripple marks are found to be very common. In the upper and lower parts of the formation, shale commonly dominates and is interbedded with siltstone and sandstone; middle part is dominated by massive, hard, locally calcerous, conglomeratic sandstone. Middle and lower parts contain calcareous lenses and concretions. It locally contains some fossiliferous beds as well.

A slight narrow zone **Tipam Sandstone** of Neogene age forms the Eastern side of Boka Bil zone. The layer is light yellow to yellowish grey, grey, brownish-grey, and orange, fine to medium-grained pebby sandstone, sub angular to sub rounded; siltstone, and shale; massive to thin-bedded, containing intraformational clasts and ferruginous concretions; soft and friable. It locally contains silicified wood and lignite. Upper and lower parts of the formation are predominantly sandstone; middle part is predominantly shale, silty shale and siltstone. The Neogene rock units represent sediments derived from the Himalayan and Shilong Plateau of India and derived from the Arakan-Yoma Mountains of Myanmar. These formations are probably time transgressive to the south and to the west; their lithology varies vertically and horizontally with distance from the source.

Along the East of Tipam Sandstone zone, another formation of Bedrock from Tipam Group that is **Girujan Clay** of Pleistocene and Neogene age lies. This zone is composed of Grey to greenish grey, red mottled, silty shale, shale and claystone and interbedded with subordinate thin-bedded siltstone and crossbedded sandstone. This formation contains calcareous claystone nodules, ferruginous sandy concretions, clay galls, quartzite pebbles, thin lignite beds, silicified wood and leaf impressions.

The North Eastern boundary of the town consists of Alluvial Deposits of **Valley Alluvium and Colluvium.** This formation consists of medium to dark-grey or light-brown silt, clayey silt, and fine to medium sand; locally contains coarse debris derived from local bedrock and organic matter. Colluvium is flushed into narrow valleys and reworked by alluvial processes. This unit is susceptoble to mass-movement processes such as landslides, earth slump and mud flows.

The south eastern part of the town has basically **Dihing Formation** Bedrock which is characterized by yellow to yellowish-grey, massive, fine to medium grained poorly consolidated sandstone and clayey sandstone. Mottled clay and pebble beds occur locally. In Fold Belt, pebbles are quartzite. It is highly weathered and contains silicified wood; ferruginous crust is present locally. Dupi Tila Formation of Pleistocene and Pilocene age lies to the south of Dihing Formation which might have a slight influence in the surface geology of the city. **Dupi Tila** is characterized as yellow to ochre, pink, light-brown, light-grey to grayish-white or bluish grey sandstone, siltstone and conglomerate. It is massive to thin bedded, containing quartz and shale pebbles, clay galls and pellets, silicified wood and lignite fragments. Upper part of the formation is dominated by fine to medium grained sandstone, subordinate thin beds of siltstone and claystone, intraformational siltstone breccias at top. Lower part is dominated by sandstone and the zone is locally crossbeded.

2.3 Regional Tectonics

Plate tectonics provide a physically simple mechanism for large-scale horizontal motions of separate portions of the earth's crust. One of the central concepts of plate tectonics is that a small number of large plates of high strength lithosphere, move rigidly with respect to one another at rates of 1 to 20 cm/year over the low-strength asthenosphere.

According to Molnar and Tapponnier (1975), for the past 40 million years the Indian subcontinent has been pushing the Eurasian plate northward at a rate of 5 cm/year, giving rise to the severest earthquakes and most diverse land forms known. Figure 2.4 shows continued drift of the Indian Plate towards Eurasian Plate.

Recently, Bilham et al. (2001) has pointed out that there is high possibility that a large earthquake will occur around the Himalayan region based on the difference between energy accumulations in this region. There is a seismic gap that is accumulating stress, and that a large earthquake may occur someday when the stress is relieved. Figure 2.5 shows the estimated slip potential along the Himalaya (after Bilham et al., 2001).

2.4 Seismo-tectonic Setup

The generalized tectonic map of Bangladesh and adjoining areas is given in Figure 2.6. The junction between the platform and the fore deep running Southwest from Mymensingh to Calcutta (the Hinge line) is considered to be a zone of weakness. However, no association of the hinge with earthquakes has so far been established. The Fore deep is terminated in the Northeast by a major fault, the Dauki fault at the Southern margin of the Shillong Plateau. Some major earthquakes can be related to this fault. There are numerous faults particularly in the eastern part of the folded flank of the fore deep. Here again there is no association with any major earthquake. Most recorded earthquakes had epicenter further East in Burma.

The Eastern margin of the Indian plate is supposed to run through Myanmar, not far from the Bangladesh border, and Northeast Assam (Arunachal Pradesh) is considered to be a corner of the Northern and Eastern margins of the plate. The Himalayan arc can be regarded as one of the most intensely active seismic regions of the world. In Northeast India, the Shillong plateau and adjacent syntaxis between the two actuate structures is one of the most unstable regions in the Alpine-Himalayan belt and faced three major earthquakes of magnitude greater than 8.0 within the last two hundred years.

The Bengal Basin gradually is being encroached on by the arcuate Indo-Burma ranges, almost 230 km wide active orogenic belt associated with eastward subduction of the Indian plate below Myanmar. Folds and thrust faults in the Indo-Burma ranges trend north south consistent with this eastward subduction. Earthquake data however, suggest that the basement of the Indian plate below the Indo-Burma ranges is moving north. Thus the shorting in the overlying rocks is partly decoupled from the basement. In the Indo-Burma ranges, on the northern part i.e. the Naga Hills region shows effects of Tertiary collisions between the Indian and Eurasian landmasses. At the northernmost extension, the Indo-Burma ranges merge with the west trending Himalayas in a complex structural zone, which is known as Assam Syntaxis.

The Main Boundary thrust Fault (MBT) initiated in late Miocene or Pliocene time is regarded as the present thrust front of the Himalayas and forms the northern margin of the Himalayan foredeep. The MBT is seismically very active. The Himalayan foredeep more frequently experiences moderate to high magnitude shocks. The MBT zone shows the presence of the entire disastrous Himalayan earthquake (M>8.0). In the eastern Himalayas the highest concentration of seismic activity is in the region of the Assam Syntaxial Bend.

Bengal Basin is bounded on the East by the western fold belt of the Indo-Burma ranges. The northern and the central portion of this fold belt are seismically active. The earthquakes in this fold belt seem to have a correlation with strike-slip transverse faults at shallow depth. A major event (M=7.5, 1762) southeast of Chittagong might have been associated with one of these faults.

Tripura fault zone is characterized by high concentration of earthquake events. A number of morphotectonic lineaments have been identified. Among these the Kopili lineament trending NW-SE is remarkable and is geologically recent in origin. Seismic section reveals that this lineament is the surface expression of deep seated subvertical fault and termed as the Kopili fault, which belongs to the category of high angle reverse fault. At the north of this zone Halflong-Dissang thrust is present. Morphotectonic lineaments around the Halflong-Dissang thrust zone trend NE-SW, E-W and NW-SE. Mikir hill is present to the northeast corner of the Halflong-Dissang thrust, which separates the Shillong plateau by Kopili fault.

2.5 Status of Earthquakes in Bangladesh

Bangladesh is a country located in south Asia. Figure 2.7 shows the seismicity of southern Asia according to British Geological Survey. It shows that Bangladesh is covered by many points indicating earthquake events. It is obvious that Bangladesh is surrounded by the regions of high seismicity, which include the Himalayan Arc and Shillong Platue in the north, the Burmese Arc, Arakan Yoma anticlinorium in the east and complex Naga-Disang-Jaflong thrust zones in the northeast (Rahman 2008, Sarker et al. 2004). It is also the site of the Dauki Fault system along with numerous subsurface active faults and a flexure zone called Hinge Zone. These weak regions are believed to provide the necessary zones for movements within the basin area.

Earthquake catalogue for Bangladesh and surrounding area (Sharfuddin, 2001) shows that 1200 earthquakes with magnitude 4.0 have occurred between 1865 to 1999. During the last 150 years, seven major earthquakes with magnitude 7.0 have affected Bangladesh. Two of them had their epicentres within Bangladesh and caused considerable damage locally. The 1897 Great Indian earthquake (M=8.7) in Shillong, considered to be one of the strongest earthquakes of the world, had its epicentre only 230 km away from Dhaka and caused extensive damage to brick masonry structures in Bangladesh including Dhaka. Figure 2.8 reveals earthquakes of different magnitudes in and around Bangladesh. It shows that the earthquakes of the greater magnitude occurred in the northern part of the country. From the figure it can be seen that Chittagong and Cox's Bazar area also fall under moderate earthquake zone having magnitude of 6 to 7 in Richter scale.

2.6 Historical Earthquakes in Bangladesh

Accurate historical information on earthquakes is very important in evaluating the seismicity of Bangladesh. Information on earthquakes in and around Bangladesh is available for the last 250 years. Appendix A provides a list of the historic earthquakes recorded in and around Bangladesh according to Scribd, 2008. The earthquake record suggests that since 1900 more than 100 moderate to large earthquakes occurred in Bangladesh, out of which more than 65 events occurred after 1960. This brings to light an increased frequency of earthquakes in the last 30 years. This increase in earthquake activity is an indication of fresh tectonic activity or propagation of fractures from the adjacent seismic zones. The Meteorological Department of Bangladesh established a seismic observatory at Chittagong in 1954 which is the only observatory in the country.

The major earthquakes that have affected Bangladesh since the middle of the last century are presented in Table 2.2.

Table 2.2: Great historical earthquakes in and around Bangladesh

Date	Name	Epicentre	Magnitude (M)
10-01-1869	Cachar Earthquake	Jantia Hill, Assam	7.5
14-07-1885	Bengal Earthquake	Sirajgonj, Bangladesh	7.0
12-06-1897	Great Indian Earthquake	Shillong Plateau	8.7*
18-07-1918	Srimangal Earthquake	Srimangal, Sylhet	7.6
02-07-1930	Dhubri Earthquake	Dhubri, Assam	7.1
15-01-1934	Bihar-Nepal Earthquake	Bihar, India	8.3

* Recently modified as 8.1(M) (Ambraseys, 2000)

2.7 Major Seismic Sources

The seismic hazard is typically determined using a combination of seismological, morphological, geological and geotechnical investigations, combined with the history of earthquake in the region. Figure 2.9 shows the distribution of faults and lineaments in Bangladesh.

Bolt (1987) analyzed different seismic sources in and around Bangladesh and arrived at conclusions related to maximum likely earthquake magnitude (Bolt, 1987). Bolt identified the following four major sources:

(i) Assam fault zone
(ii) Tripura fault zone
(iii) Sylhet fault zone
(iv) Bogra fault zone

Recently, Whitney (2004) has added two major possible source zones, namely Shahzibazar Fault and Tanor Fault. Figure 2.10 shows seismotectonic lineaments and faults capable of producing damaging earthquakes in Bangladesh. The magnitudes of earthquake suggested by Bolt is shown in Table 2.3 are the maximum magnitude generated in these blocks as recorded in the historical seismic catalogue. The historical seismic catalogue of the region covers approximately 250 years of (starting 1762) earthquake data. For example, the Assam and Tripura fault zones contain significant faults capable of producing magnitude 8.6 and 8.0 earthquakes respectively in future. Similarly maximum magnitude of 7.5 in Sub-Dauki fault zone and Bogra fault zones are not unlikely events.

Table 2.3: Significant seismic sources and maximum likely earthquake magnitude in Bangladesh (after Bolt, 1987)

Location	Maximum likely earthquake magnitude
Assam fault zone	8.0
Tripura fault zone	7.0
Sylhet fault zone	7.3
Bogra fault zone	7.0

After a thorough review of available data, Ali and Choudhury (1992) recommended magnitudes of Operational Basis Earthquakes and Maximum Credible Earthquakes as shown in Table 2.4.

Table 2.4: Operational basis earthquake, maximum credible Earthquake and depth of focus of earthquakes for different seismic sources (after Ali and Chowdhury, 1992)

Location	Operational basis earthquakes (Richter)	Maximum Credible earthquakes	Depth of focus (km)
Assam fault zone	8.0	8.7	0-70
Tripura fault zone	7.0	8.0	0-70
Sylhet fault zone	7.3	7.5	0-70
Bogra fault zone	7.0	7.5	0-70

A recent study taken through the Comprehensive Disaster Management Programme (CDMP) of Ministry of Food and Disaster Management (MoFDM), Government of Bangladesh, reveals the scenario model of five major faults in Bangladesh. Figure 2.11 shows the scenario fault model and Table 2.5 enlists different parameters of the faults.

Table 2.5: Different Fault Parameters in Bangladesh

Fault	**Mw**	**Depth to top of Fault (km)**	**Length (km)**	**Dip (degree)**	**Down-dip Rupture Width (km)**	**Fault Type**
Madhupur Fault (MF)	7.5	10	60	45	42	Reverse
Dauki Fault (DF)	8.0	3	233	60	43	Reverse
Plate Boundary Fault-1 (PBF-1)	8.5	3	795	20/30	337	Reverse
Plate Boundary Fault-2 (PBF-2)	8.0	3	270	20	137	Reverse
Plate Boundary Fault-3 (PBF-3)	8.3	3	504	20/30	337	Reverse

2.8 Historical Earthquakes in and around Cox's Bazar

In recent years, earthquakes have occurred quite frequently in Bangladesh and have caused alarm especially in Chittagong and Moheshkhali causing structural damage and casualties.

2.8.1 Chittagong Earthquake of 1762

Historical documents mention the occurrence of a large earthquake on April 2, 1762 (Rastogi et al., 2006) near Chittagong in the south-east which caused sea flooding, river waves inland, land mass changes etc. It is among the earliest known large earthquakes in South Asia. The earthquake, a major one (possibly M>7.0), was centred 40 km SE of Chittagong and 257 km SE of Dhaka, 61 km north of Cox's Bazar district. Chittagong suffered very severely; great explosion heard at first: earth opened in many places; quantities of water gushed out, great chasms remained unclosed and filled with water. Water spouted out like a fountain together with fine sand or mud, evidence of liquefaction. The great earthquake of April 2 raised the coast of some islands by several metres and also caused a permanent submergence of 155.40 sq km near Chittagong. At Dollazari houses fell. Near Luckipore, a circuit of land, about 15 miles in circumference, was swallowed up, and all the inhabitants and cattle perished. The earthquake also agitated the rivers and lakes of the country causing deaths inside the country.

2.8.2 Chittagong Earthquake of 1997

In November 21, 1997 another damaging earthquakes of body-wave magnitude 6.0 have occurred in Bangladesh (Sharfuddin, 2001). During this earthquake, 23 people were killed after collapse of an under-construction building in Chittagong. In Chittagong many low to middle rise buildings have suffered minor cracks although major damage has not been observed. The epicentral area (22.225N, 92.743E) is close to Ruma in Bandarban district of Chittagong Hill Tracts region. Many houses were damaged and old trees were uprooted in the epicentral region. Partial collapse of a long earthen dam (Prantik lake) has been observed.

2.8.3 Moheskhali Earthquake of 1999

On July 22, 1999, at 4:42 pm (local time), an intense earthquake shook the island of Moheskhali causing damage to several houses and some buildings, killing 6 people and injuring 200 people. The main damage has been reported to be in Shaplapur and Huanok Unions.

Dineshpur and Kaidabad under Shaplapur Union were reported to have heavy damages. Cracking and spalling in reinforced concrete columns at the beam-column joint occurred in a cyclone shelter at Dineshpur. Several rural houses with mud walls and thatched or tin roof construction were severely damaged. At Kaidabad EU cyclone shelter was also badly damaged. Severe cracking was formed in many mudwall houses at Bara Maheshkhali and Huanok Union. Some landslides were also observed which could have been triggered by the earthquake.

The hypocentre of the earthquake was initially estimated to be at 21.47°N, 91.90°E (focal depth = 10 km, origin time 16:42:12) (Sharfuddin, 2001). The focal depth of this earthquake was quite shallow. The location of the hypocenter was later corrected as at 21.54°N, 91.88°E. The magnitude of the main shock was 5.1 on bodywave magnitude scale. Three more aftershocks of smaller intensity occurred in the same island on the following night. Figure 2.12 shows the seismic intensity map based on the observed damage and questionnaire survey (Ansary et al., 2001).

2.8.4 Database of Earthquakes in and around Cox's Bazar

Historical data (1923-2008) for seismic activity affecting Cox's Bazar and surrounding area show that the area has undergone through frequent earthquakes of magnitude ranging from 5 to 6 in Richter scale. Epicenters of these earthquakes (Appendix B) with reference to the 250 km radius of the municipality reveal that the earthquake with the highest magnitude (6.5 in Richter scale) occurred in this region in 1955. Again, considering 450 km radius around the study area, it is observed that the highest magnitude earthquakes experienced occurred in 1664, 1858, 1912 with magnitudes 7.8, 7.66, 7.9 consecutively (Ansary, 2009). Figure 2.13 shows the plot of frequency of the earthquakes occurring from 1919 to 2008 over the decades. The figure depicts that earthquakes having magnitude higher than 5.0 are recurring in almost every decade in this region. Again the frequency of earthquakes with magnitude varied from 4.0 to 5.0 has increased markedly over the last four decades. These historical records and observations indicate the probable occurrence of moderate to high intensity earthquakes in the upcoming years in and around Cox's Bazar.

2.9 Seismic Zoning Maps

In the Bangladesh National Building Code (BNBC) published in 1993, a new seismic zoning map for Bangladesh has been presented. The pattern of ground surface acceleration contours having 200 year return period forms the basis of this seismic zoning map. The 1993 BNBC zoning map is shown in Figure 2.14. In this zoning map the country has been divided into three generalized seismic zones: zone-I, zone-II and zone-III.

Zone-I comprising the Northern and Eastern regions of Bangladesh with the presence of the Dauki Fault system of Eastern Sylhet and the deep seated Sylhet Fault, and proximity to the highly disturbed southeastern Assam region with the Jaflong thrust, Naga thrust and Disang thrust, is a zone of high seismic risk with a basic seismic zoning co-efficient of 0.25 (Rahman 2008, Sarker et al. 2004). Northern Bangladesh comprising greater Rangpur and Dinajpur districts is also a region of high seismicity because of the presence of the Jamuna Fault and the proximity to the active east-west running fault and the Main Boundary Fault to the north in India (Rahman 2008, Sarker et al. 2004). The Chittagong-Tripura Folded Belt experiences frequent earthquakes, as just to its east is the Burmese Arc where a large number of shallow depth earthquakes originate.

Zone-II comprising the central part of Bangladesh represents the regions of recent uplifted Pleistocene blocks of the Barind and Madhupur Tracts, and the western extension of the folded belt. The zone extends to the south covering Chittagong and Cox's Bazar. Seismic zoning coefficient for Zone II is 0.15.

The Zone-III comprising the southwestern part of Bangladesh is seismically quiet, with an estimated basic seismic zoning co-efficient of 0.075.

Bangladesh National Building Code (BNBC, 1993) placed Cox's Bazar in Seismic zone 2. The zoning map has recently been updated (Sharfuddin, 2001) and shown as Figure 2.18. The zoning in this updated map was based on consistent ground motion criterion such as equal peak ground acceleration levels. According to this map, Cox's Bazar falls in Zone 3. Based on the philosophy behind this seismic zoning and experience from recent earthquakes, it can reasonably be assumed that a major earthquake event in Cox's Bazar and surrounding region is liable to higher damage than that assumed in the existing zoning map (BNBC 1993).

2.10 Seismic Microzonation

Seismic microzonation can be defined as the subdivision of a region into zones that have relatively similar exposure to various earthquake related effects. It is the mapping of seismic hazard at local scales to incorporate the effects of local soil conditions. The earthquake damages are controlled basically by three interacting factor groups; earthquake source and path characteristics, local geological and geotechnical site conditions, structural design and construction features. Seismic microzonation can be considered as the assessment of the first two groups of factors. In general terms, it is the process for estimating the response of soil layers under earthquake excitations and thus the variation of earthquake characteristics on the ground surface. Seismic microzonation is the initial phase of earthquake risk mitigation and requires multidisciplinary approach with major contributions from geology, seismology, geotechnical and structural engineering. The final output contains recommendations suitable for application by local administrators, urban planners and engineers.

The national seismic zoning maps are generally prepared in small scales such as 1:1,000,000 or less neglecting numerous source and site factors that are important in assessing ground motion characteristics. Seismic microzonation maps are prepared based on larger scales for a particular region taking into consideration both earthquake source and regional geological and geotechnical site conditions in order to be used for urban and landuse planning. A Seismic microzonation study consists of four stages: (1) estimation of the regional seismic hazard that is asessment of the expected input motion, (2) determination of the local geological and geotechnical site conditions (3) assessment of the probable ground response and ground motion parameters on the ground surface (4) finally, preparation of microzonation maps.

2.11 Geographic Information System

The most universal definition in the literature for a GIS is given by the Federal Interagency Coordinating Committee (1988) as "A system of computer hardware, software, and procedures designed to support the capture, management, manipulation, analysis, modeling and display of spatially referenced data for solving complex planning and management problems." Figure 2.16, adapted from Frost, et al. (1992), shows how different information systems work together to function as a fully - interacted GIS. Modern geographic information system technology has evolved from thematic cartography combined with increased computational capabilities, refined analytical techniques, and a renewed interest in environmental/social responsibility. The primary goal is to take raw data and transform it, through overlays and other analytical operations, into new information that can support the decision making process (Parent and Church, 1987).

2.11.1 Function of GIS in Microzonation

The regional earthquake hazard analysis requires a map of the region that identifies the potential seismic sources. This procedure typically requires several geologic and geographic maps of the region. The bedrock motion in the region resulting from the seismic event must first be determined. This is often done by applying one of the attenuation functions within the GIS or by linking the function as an external executable program. The GIS-based procedure for estimating regional bedrock motion is straight-forward. Quantifying and integrating the seismic hazard due to local site effects (soil amplification, liquefaction, and landslide) is the main areas of development presented in this dissertation. The procedure involves developing models for each of the effects, assembling the necessary geologic and geographic maps and databases, applying the models either within the GIS or as linked external programs and then overlaying and combining the resulting hazard maps.

The results obtained from the analysis are microzonation maps for the study area. These maps typically require a detailed layout for the region, a quantification of the regional seismic hazard and accounts of susceptibility due to the expected hazards.

The spatial database structure of a GIS environment is ideal for this procedure. In this study "MapInfo Professional 7.0" software has been used for developing maps. The mapping process for microzonation through GIS is shown in Figure 2.17.

2.12 Seismic Hazard Assessment

The first step in microzonation is the estimation of seismic hazard. This involves the assessment of expected ground motion using the deterministic or probabilistic seismic hazard analysis. Numerous methods for earthquake hazard assessment in a given site are available today. Lomnitz and Epstein (1966) employed the Poisson process for the occurrence of large earthquakes which is still used. Cornell (1968) and Esteva (1968) derived the general basis for the most complete analysis of the whole seismic hazard problem with the inclusion of the propagation mechanism of the ground motion. Shah and Vagliente (1972) used the Markov model of earthquake prediction in seismic hazard analysis. A methodology for seismic hazard estimation based on historical earthquake occurrences is presented in detail in Tomatsu and Katayama (1988) and Molas and Yamazaki (1994). In Japan, the seismic risk method proposed by Kawasumi (1951) is still popular while in the United States, the basic method proposed by Cornell (1968) is often used

2.12.1 Deterministic Seismic Hazard Analysis

Krinitzsky (2005) highlights that a Deterministic Seismic Hazard Analysis (DSHA) uses geology and seismic history to identify earthquake sources and to interpret the strongest earthquake each source is capable of producing regardless of time. Those are the Maximum Credible Earthquakes (MCEs), the largest earthquake that appears possible along a recognized fault under the presently known or presumed tectonic activity which will cause the most severe consequences to the site.

The methodology followed for Deterministic Seismic Hazard Analysis is described as followed:

1. Source characterization, that includes identification and characterization of all earthquake sources which may cause significant ground motion in the study area. Here historic data of the earthquakes as well as the availability of the

source of earthquake such as faults are used to determine the potential of the earthquake occurrence.

2. Selection of the shortest distance between the source and site of interest.
3. Selection of controlling earthquake, that is, the earthquake that is expected to produce the strongest level of shaking. Controlling earthquake has been evaluated based on historic data and assumed subsurface fault rupture length.
4. Defining the hazard at the site formally in terms of the ground motion produced at the site by the controlling earthquakes.

2.12.2 Probabilistic Seismic Hazard Analysis

PSHA is the most commonly used approach to evaluate the seismic design load for the important engineering projects. PSHA method was initially developed by Cornell (1968) and its computer form was developed by McGuire (1978). Site ground motions are estimated for selected values of the probability of ground motion exceedance in a design period of the structures or for selected values of annual frequency or return period for ground motion exceedance. The probabilistic approach offers a rational framework for risk management by taking account of the frequency or probability of exceedance of the ground motion against which a structure or facility is designed. The occurrence of earthquakes in a seismic source is assumed as the Poisson distribution. The probability distribution is defined in terms of the annual rate of exceeding the ground motion level z at the site under consideration, due to all possible pairs (M, R) of the magnitude and epicentral distance of the earthquake event expected around the site, considering its random nature. This procedure can be described in the following four steps:

1. Identification of earthquake sources such as active faults, which may affect the study area. Characterize the probability distribution of potential rupture locations within the source.
2. Characterization of the seismicity of each source zone using a recurrence relationship, which specifies the average rate at which an earthquake of some size will be exceeded.

3. Estimation of the ground motion produced at the site by earthquakes of any possible size occurring at any possible point in each source zone using predictive relationships.
4. Obtaining the probability that the ground motion parameter will be exceeded during a particular time period.

2.12.3 Attenuation Law of Peak Ground Acceleration

The quantitative assessment of seismic hazard at any particular site within a region requires an attenuation law for the Peak Ground Acceleration (PGA). This describes the transfer of ground motions from the source to a particular site as a function of magnitude, distance and soil conditions. The maximum ground motion to be expected in the site constitutes a crucial problem in earthquake engineering. For Bangladesh, as in many other parts of the world, no PGA attenuation law has been developed, due mainly to the shortage of strong motion data. However, in order to assess the seismic hazard in this region, an attenuation law needs to be adopted from the literature. PGA attenuation relationships, predicting strong ground motions in terms of magnitudes, distance, site geology, and in some cases other factors, using various models and data sets are established for different parts of the world. Reviews of these laws are presented in Campbell (1997) and Joyner and Boore (1988). Some of the published attenuation functions are presented in Table 2.6. Attenuation relationships of ground motions are of the form:

$$log(y) = b_1 + b_2 (Ms) - b_3 \log (r) - b_4 (r)) + \sigma P \qquad (2.1)$$

where y is the ground motion parameter in consideration, M is earthquake magnitude, $b_{1,2,3,4}$ are constants determined for the ground motion parameter, σ is the standard deviation representing the scatter of data in the attenuation relationship and P is a parameter which takes the value of 0 (zero) when the predicted value represents the mean and P equals one when the predicted value represents the mean plus one standard deviation. 'r' is a distance parameter, usually of the form $r = \sqrt{(d^2 + h^2)}$.

Table 2.6: Published attenuation function (after Islam, 2005)

Author	Law
Duggal (1989)	$y=227x10^{0.308M}(d+30)^{-1.2}$
McGuire (1978)	$y=0.0306e^{0.89M}r^{-1.17}e^{-0.2S}$; Where S=0 for rock and S=1 for alluvium
Katayama (1974)	logy=2.308-1 637log(r+30)+0.411M
Sadigh, et al. (1986)	$\ln y = - 1.406 + 1.1\ M - 2.051\ (R + 1.353\ e^{0.406M})$; Where M > 6.5
Joyner and Boore (1988)	$\log y = 0.43 + 0.23\ (M - 6) - \log\ (r^2 + h^2)^{1/2} - 0.0027(r^2 + h^2)^{1/2}$; for rock
Ambraseys (1995)	log y=-1.43+0.245Ms-0.001r-0.786logr; here, $r=(d^2+2.7^2)^{1/2}$
Boore et al. (1997)	$\ln y = -0.2424 + 0.527(M-6) - 0.778\ \ln r - 0.371\ \ln V_s / 1.396$ where, $r = (r_b{}^2 + 5.57^2)^{1/2}$, r_b = epicentral distance in km, V_s = average shear wave velocity of surface 30 m
Joynner and Boore (1981)	$y = 0.0955\ e^{(.573M)}\ d^{(-1)}*\ e^{(-0.00587D)}$, $d= (r2+h^2)^{0.5}$, for rock

Where, y=PGA; M= surface magnitude; d=epicentral distance; r=hypocentral distance; h=focal depth

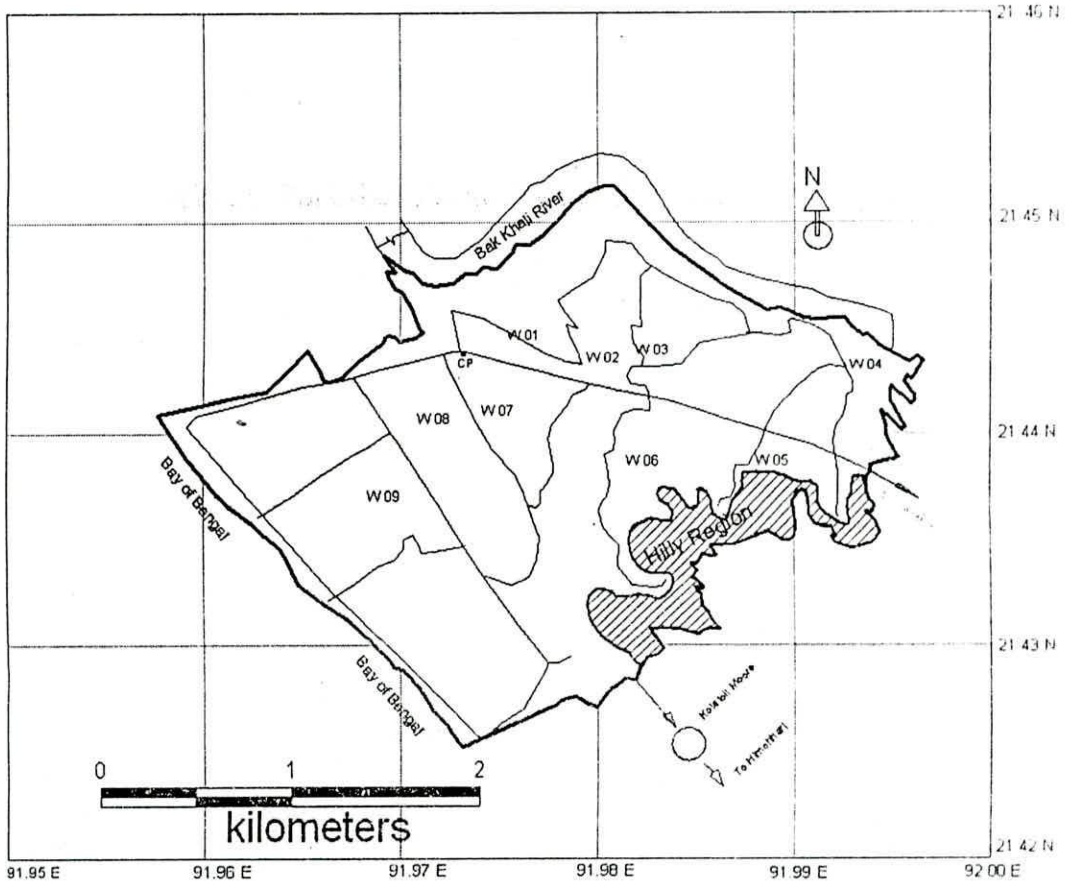


Figure 2.1: Map showing 9 wards in Cox's Bazar Municpal Area

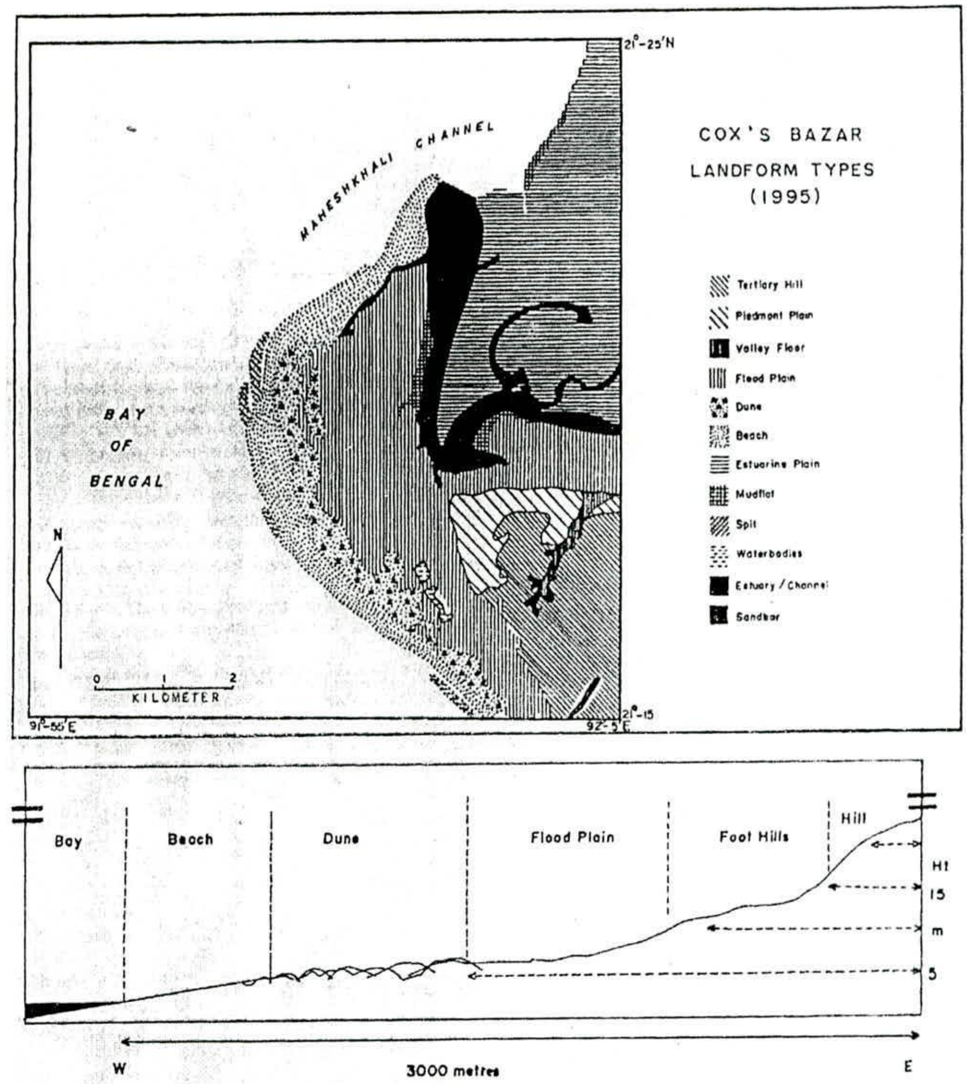
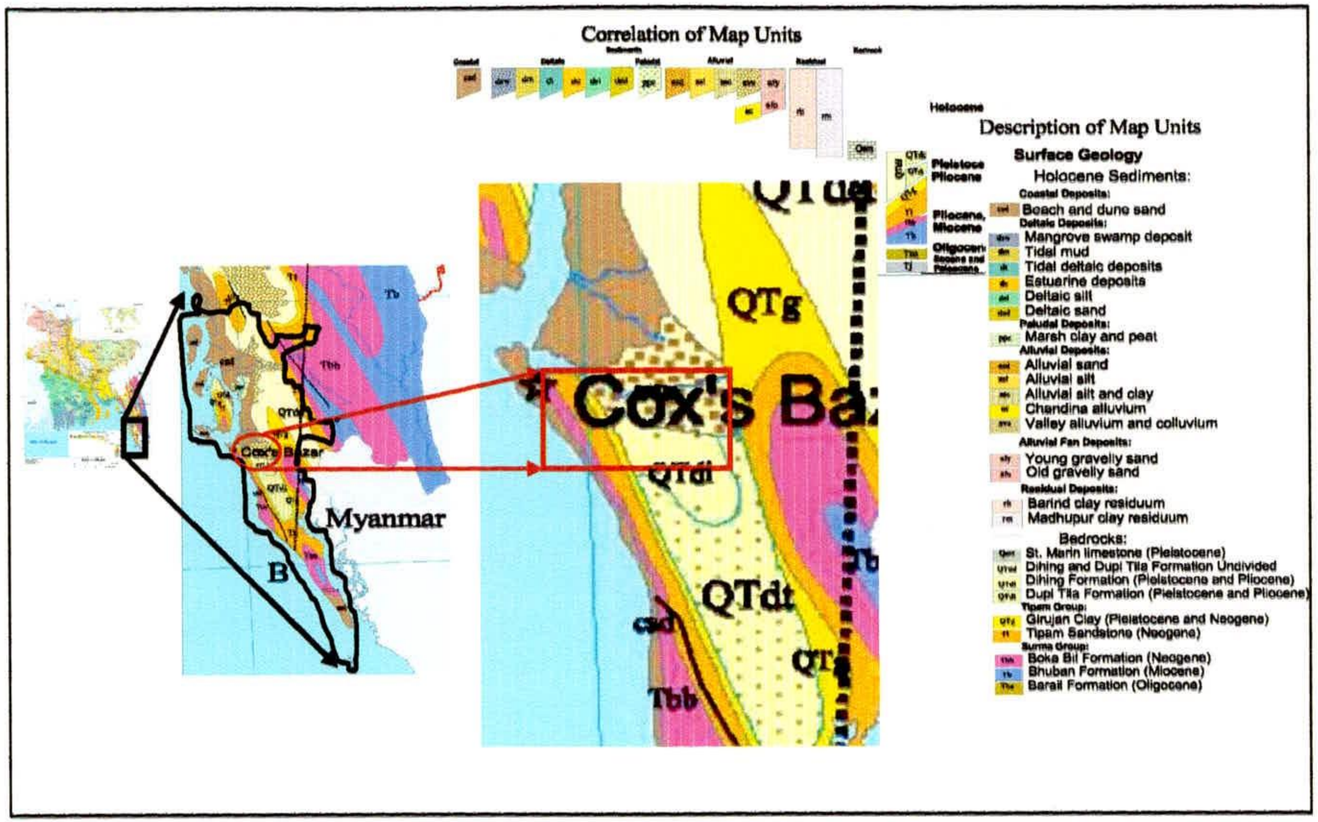


Figure 2.2: Morphology of Cox's Bazar Sadar (Alam et al., 1999)



Lithostratigraphic Units and Descriptions	
csd	Beach and Dune sand (Coastal deposit- Holocene Sediment)
QTdi	Dihing Formation (Pleistocene and Pilocene- Bedrock)
Tt	Tipam Sandstone (Neogene- Bedrock : Tipam Group)
ava	Valley alluvium and colluviums (Coastal deposit- Holocene Sediment)
QTg	Girujan Clay (Pleistocene & Neogene- Bedrock : Tipam Group)
Tbb	Boka Bil Formation (Neogene- Bedrock : Tipam Group)
QTdt	Dupitila Formation (Pleistocene and Pilocene- Bedrock)

Figure 2.3: Geology of Cox's Bazar Municipal (Alam et al, 1990)

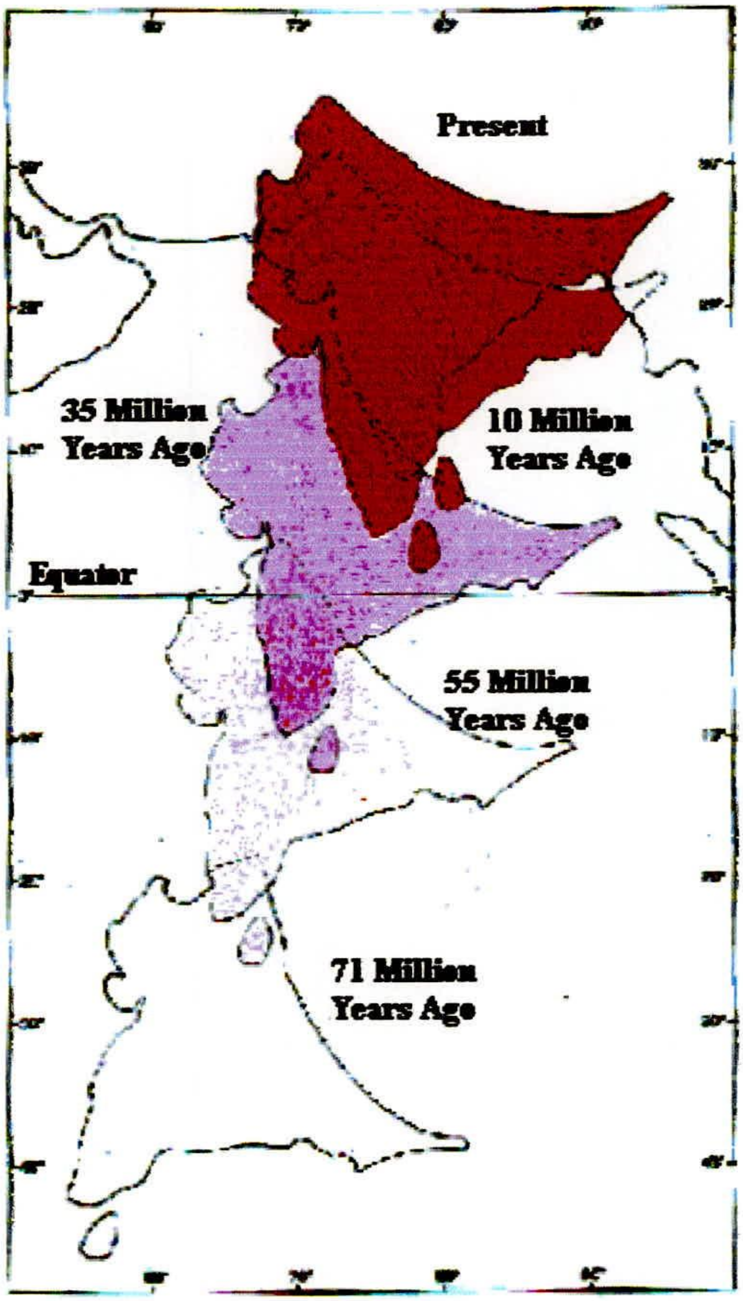


Figure 2.4: India's northward-drift by last 70 million years (Molnar and Tapponneir, 1975)

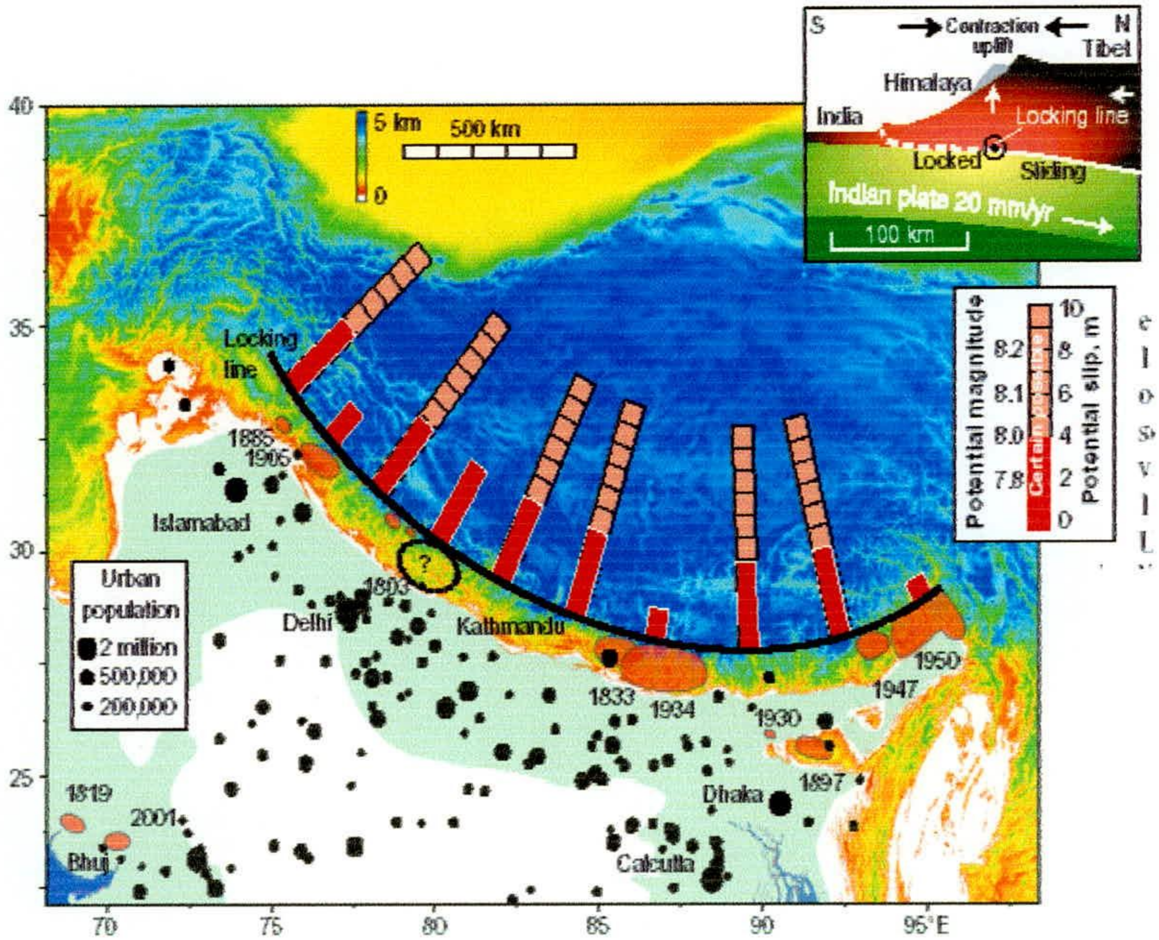


Figure 2.5: Estimated slip potential along the Himalaya
(Bilham et al., 2001)

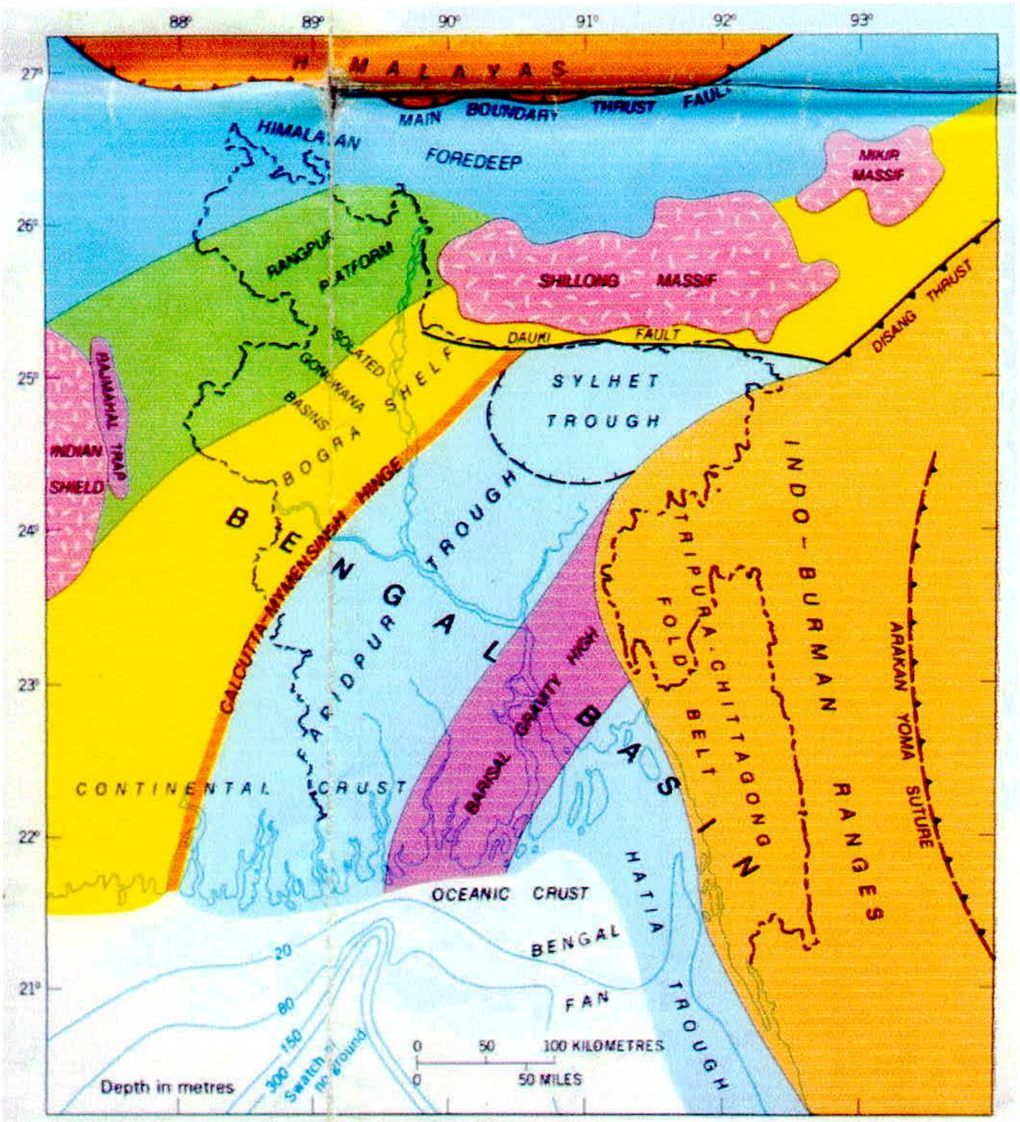


Figure 2.6: Generalized tectonic map of Bangladesh and adjoining areas (GSB, 1991)

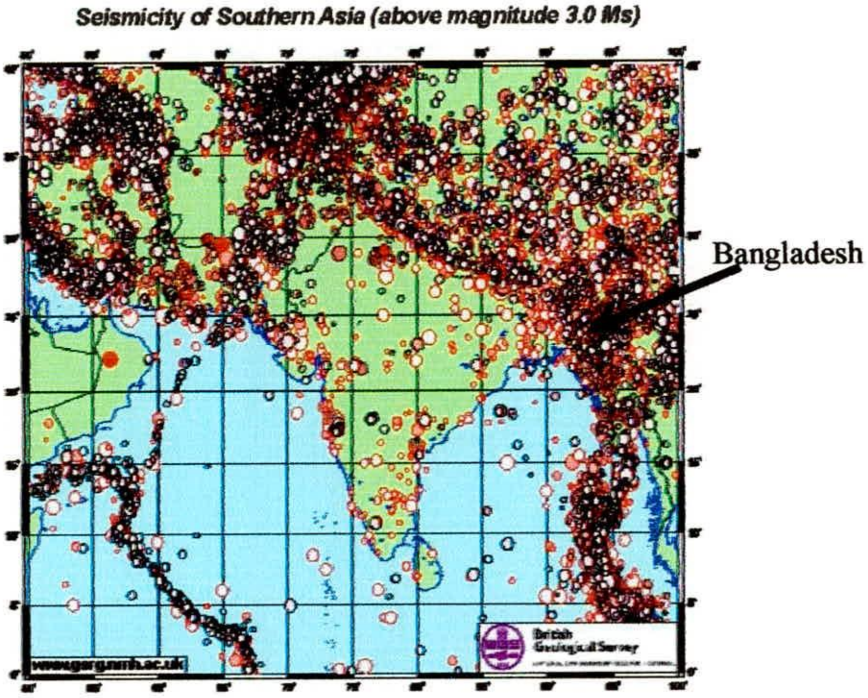


Figure 2.7: Seismicity of Southern Asia (The Tsunami Page, 2005)

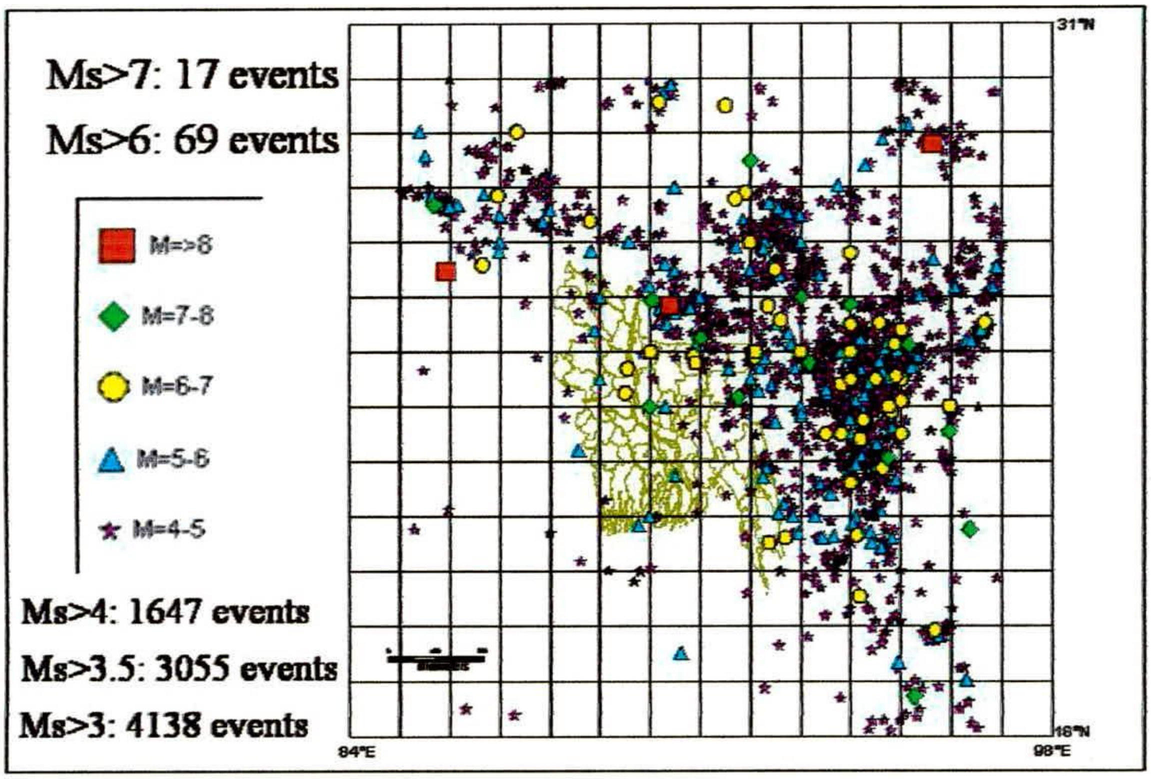


Figure 2.8: Earthquake in and around Bangladesh (1865-1995)

(after Ansary, 2009)

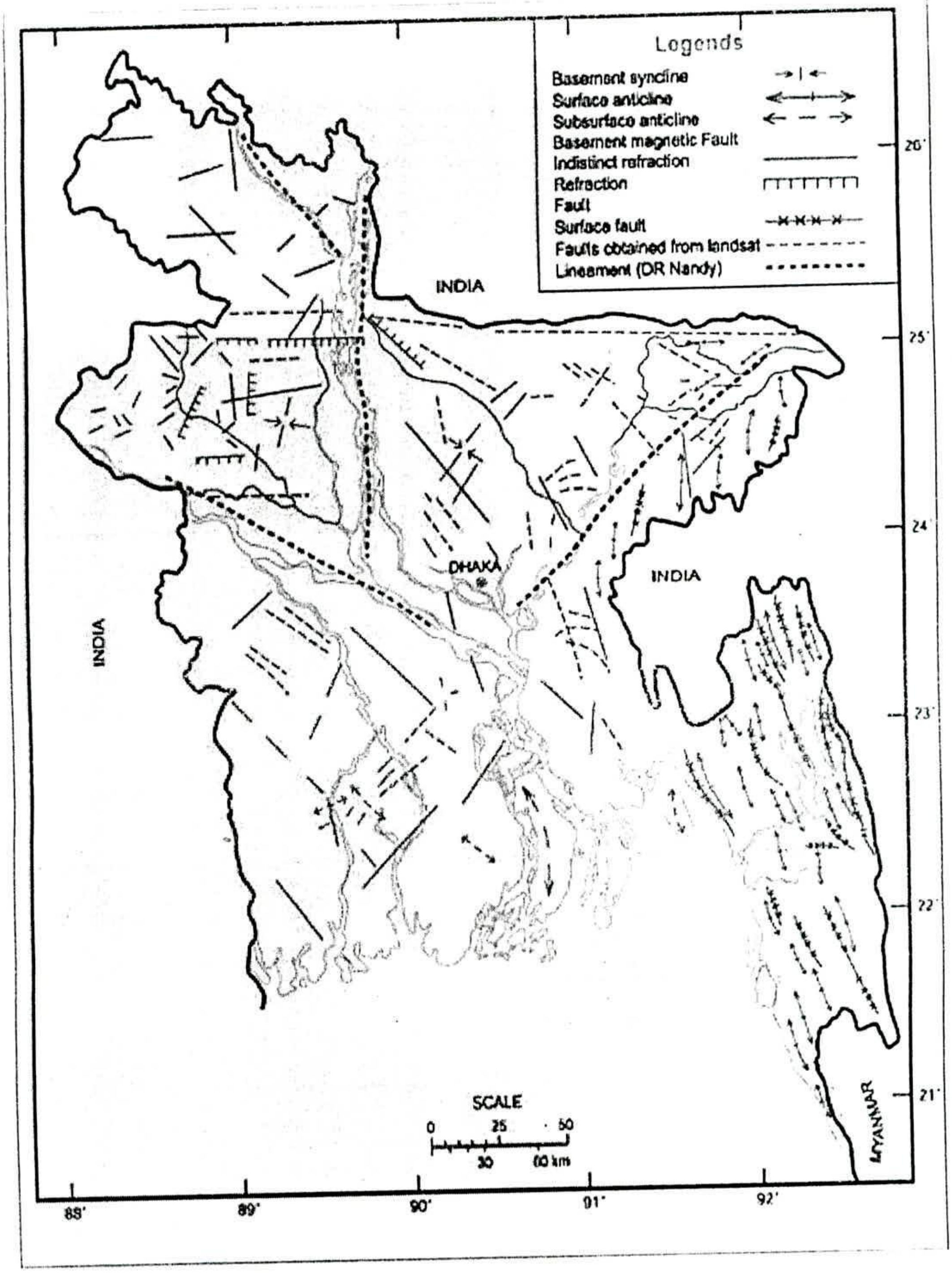


Figure 2.9: Distribution of faults and lineaments in Bangladesh (Banglapedia, 2004)

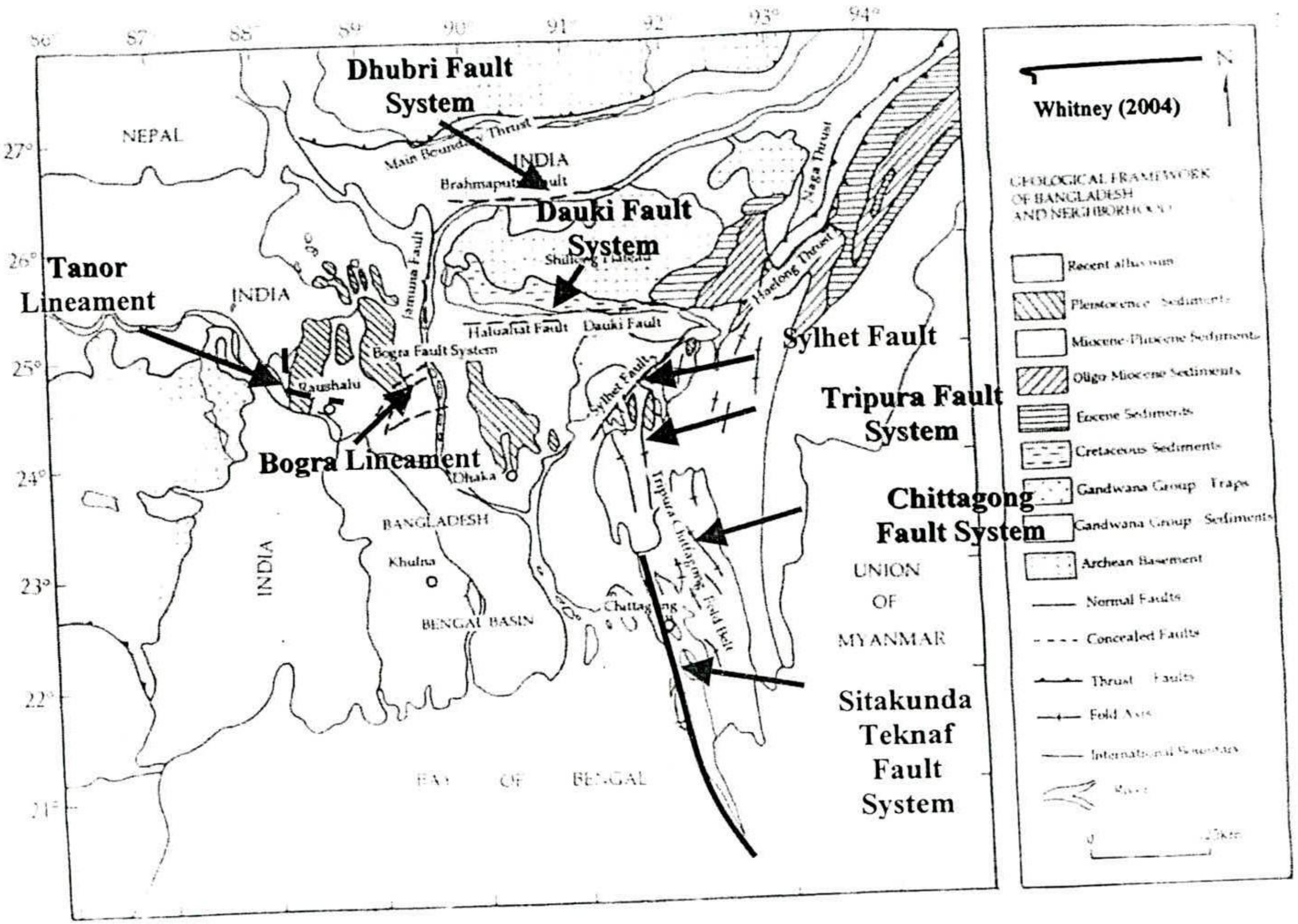


Figure 2.10: Seismo–tectonic lineaments and fault capable of producing damaging earthquakes (after Ali and Choudhury, 1992;Whitney. 2004, CDMP-UNDP, 2009)

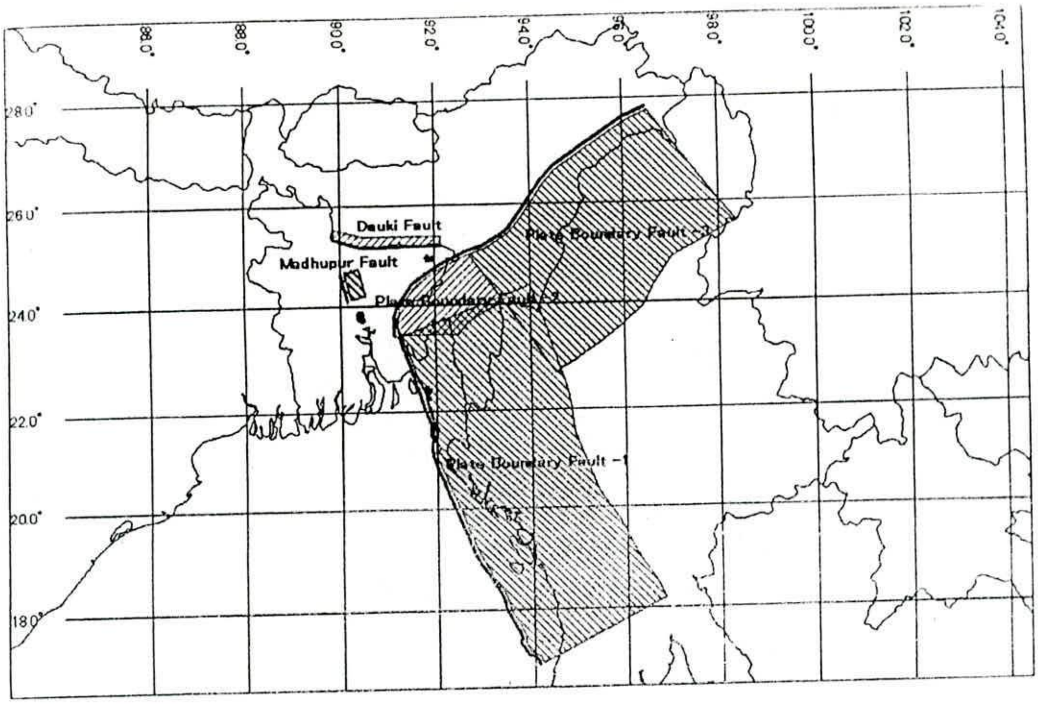


Figure 2.11: Scenario Earthquake Fault Model (CDMP-UNDP, 2009)

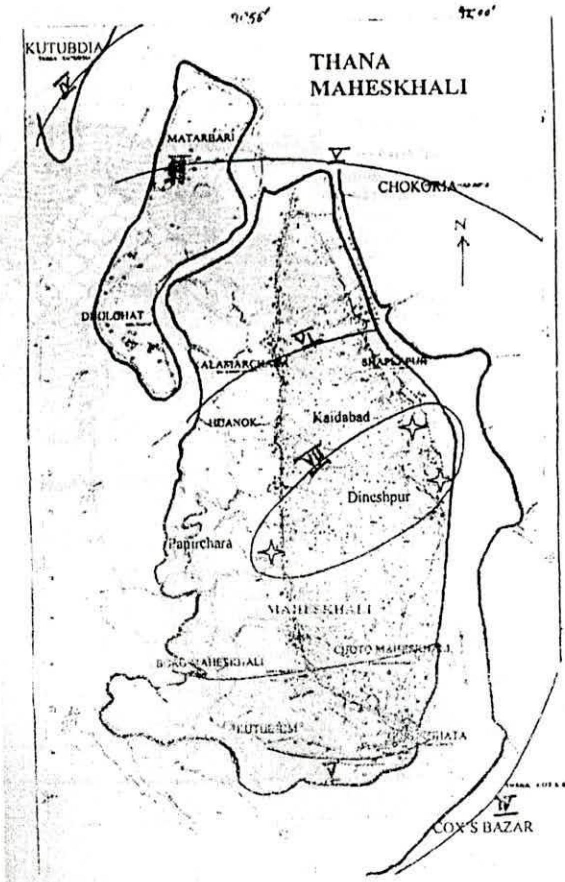


Figure 2.12: Isoseismal of Maheshkhali Earthquake of 1999 (Ansary et al., 1999)

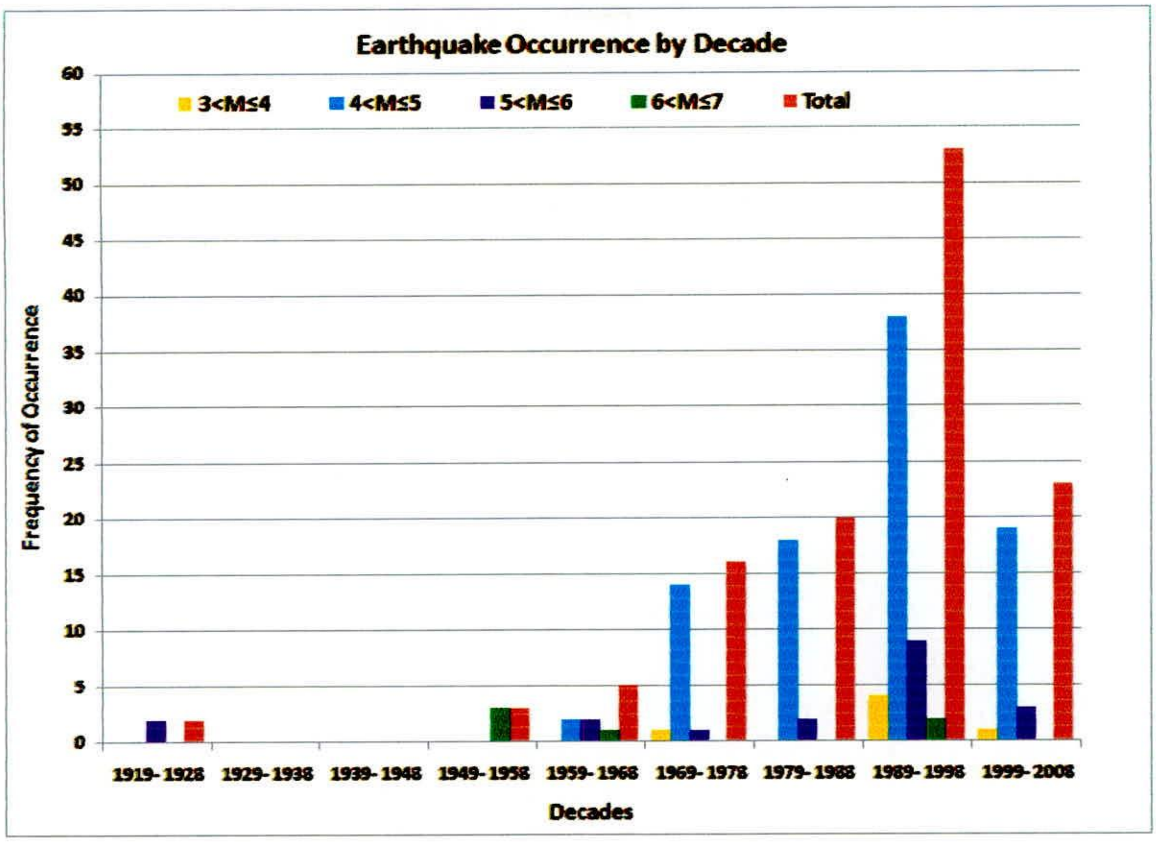


Figure 2.13: Earthquake Occurrences in and around Cox's Bazar municipal area (1919-2008) (after Ansary, 2009)

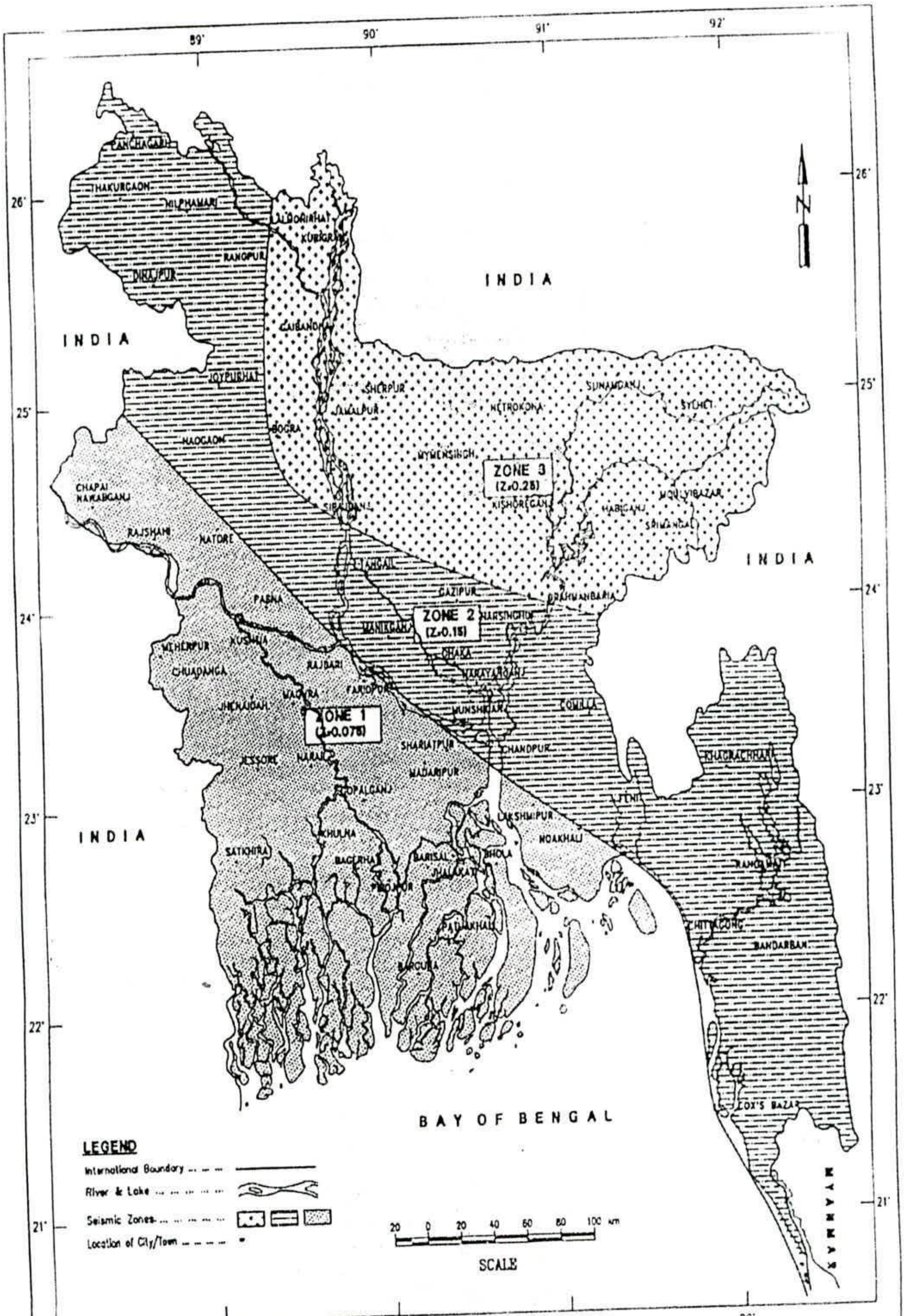


Figure 2.14: Seismic Zoning Map of Bangladesh
(BNBC, 1993)

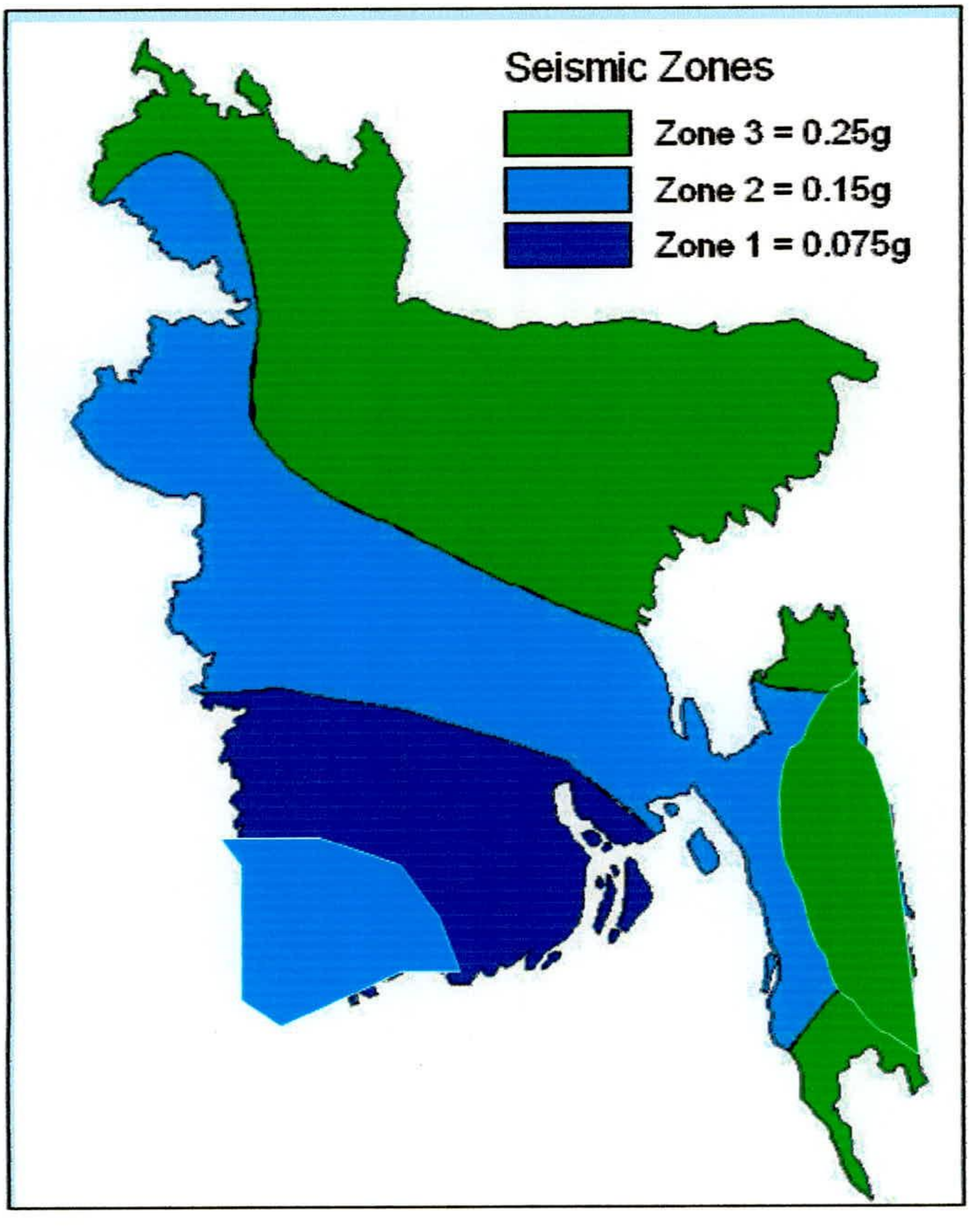


Figure 2.15: Updated Seismic Zoning Map of Bangladesh
(Ansary, 2009)

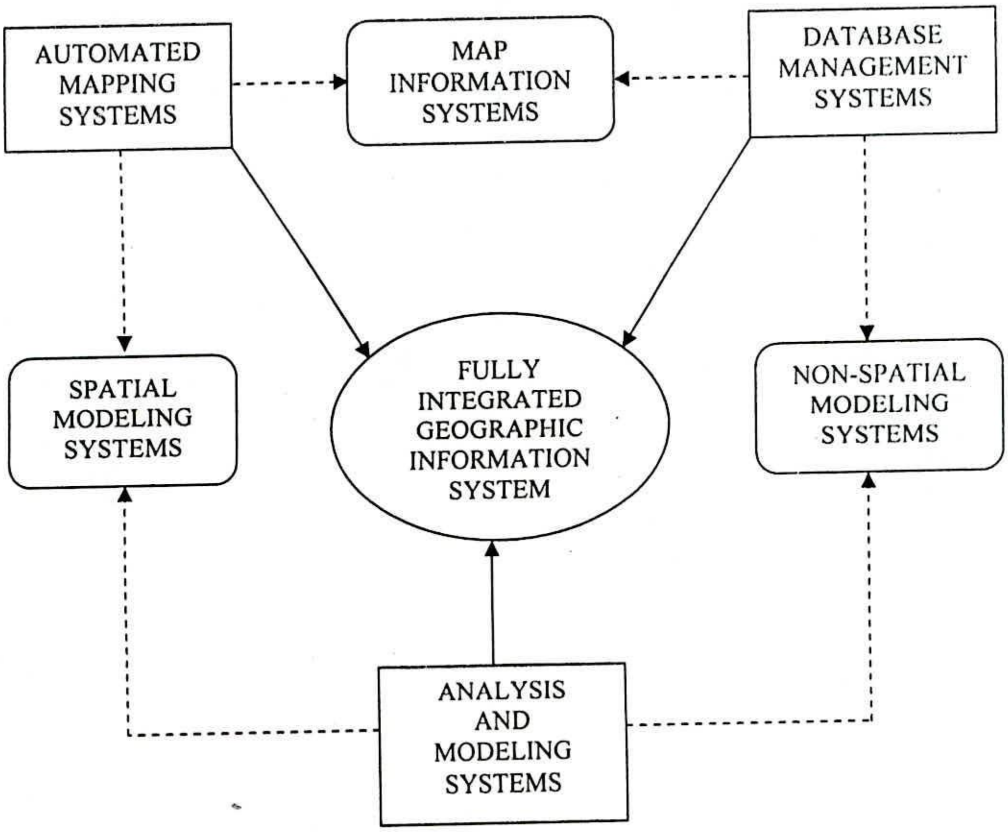


Figure 2.16: Components of a fully integrated geographic information system (Frost, et al., 1992)

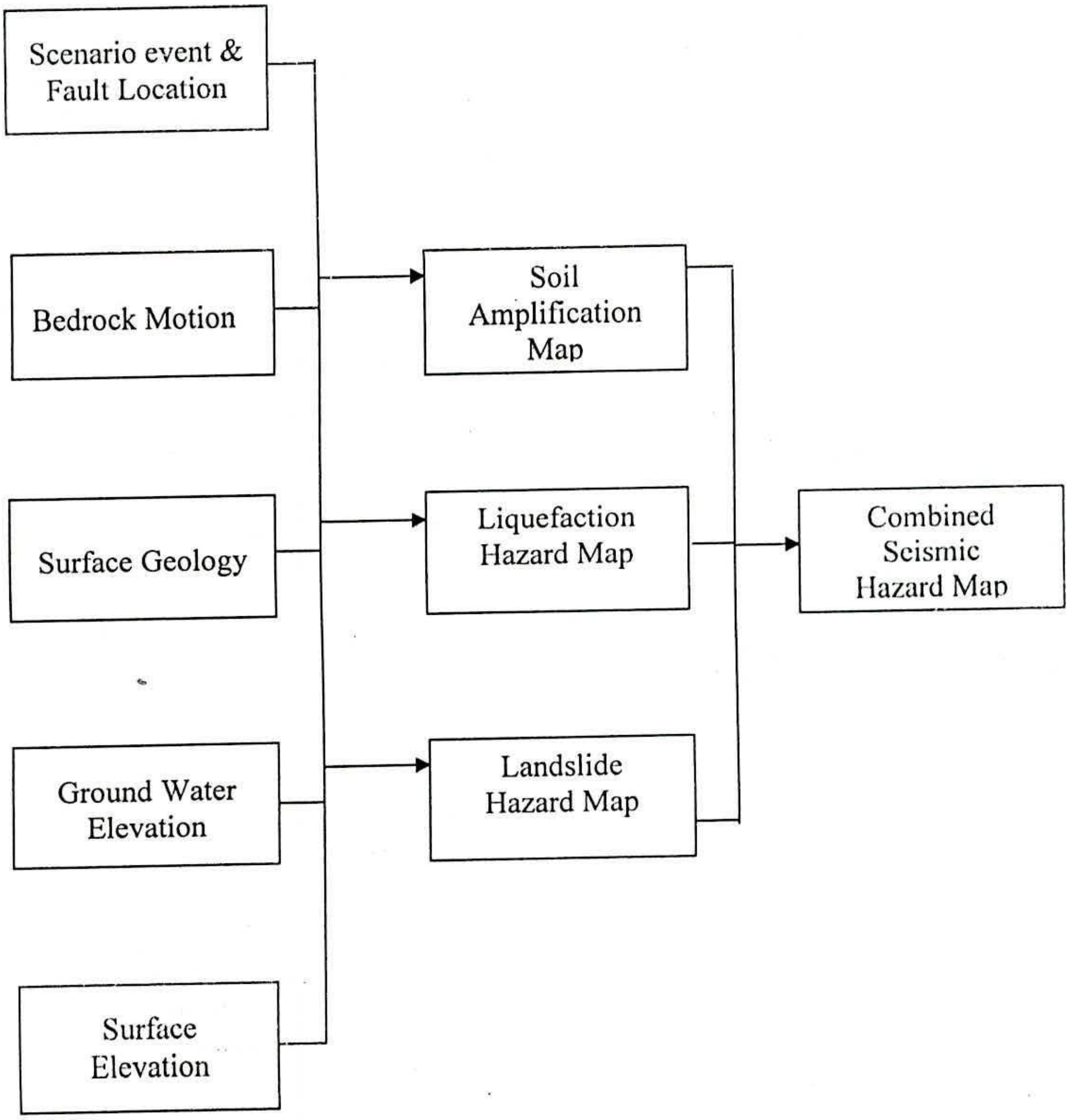


Figure 2.17: The mapping process for regional multi-hazard assessment through GIS (Map Info)

2.13 Local Site effects and Site Response Study

Site response analysis aims at determining the response of a soil deposit to the motion of the bedrock immediately beneath it. The overburden stress plays a very important role in determining the characteristics of the ground surface motion thus emphasizing the need for ground response analysis. A number of techniques have been developed for ground response analysis. These techniques can be grouped as one-, two-, and three-dimensional analyses according to the dimensionality of the problems they can address. A one-dimensional method can be used if the soil structure is essentially horizontal.

2.13.1 Assessment of Site Amplification

For Seismic Microzonation, obtaining a proper understanding of the local subsurface conditions and to evaluate ground shaking effects is essential. The effect of local soil conditions on the amplitude and frequency content of earthquake motions has been the subject of considerable interest and research in recent years. Physically the problem is to predict the characteristics of the seismic motions that can be expected at the free surface (or at any depth) of a soil stratum. Mathematically the problem is one of wave propagation in a continuous medium. If the medium is linearly elastic and the geometry is relatively simple, analytical solutions can be obtained for any kind of waves. In practice, since the wave content of a potential earthquake is hard to predict, solutions are often limited to the simple case of shear wave propagating vertically.

Many results for this case have been presented, and a discrete model with lumped masses and springs, based on a finite difference formulation, has enjoyed great popularity among practicing engineers. The continuous and the discrete formulations are equivalent. This part of the report describes the use of a one-dimensional wave propagation program to develop a microzonation map of Cox's Bazar District.

When P and S wave reach the ground surface, most of their energy is reflected back in to the crust, so that surface is affected simultaneously by upward and downward moving waves. For this reason considerable amplification of shaking typically occurs near the surface and enhances the shaking damages at the surface. Different types of ground affected by the same earthquake waves may vary in their severity of ground shaking and consequent destructiveness by one or more degrees of intensity.

Certain building types are more vulnerable to different frequencies of ground motion vibration than others. Seismic micro zoning can show the frequency content of vibration due to different local ground condition. It can be used to ensure that a match does not occur between buildings vulnerable to certain frequencies of vibration and ground conditions that are likely to vibrate in that frequency range and thus avoiding building being damaged by 'resonance effect' in zones where the ground is likely to vibrate in certain frequency ranges. Buildings should be designed either to have frequencies of natural vibration well outside the critical range or to be designed for the much higher seismic forces they are likely to experience. The frequency map could be used to impose restrictions on the types of building structures that may have similar frequency.

2.13.2 Methodology Review

Several methods for evaluating the effect of local soil conditions on ground response during earthquake are presently available. Most of these methods are based on the assumptions that the main response in a soil deposit are caused by the upward propagation of shear waves from the underlying rock formation. Analytical procedures based on this concept incorporating non-linear soil behavior, have been shown to give results in good agreement with field observations in a number of cases. Accordingly they are found in increasing use in earthquake engineering for predicting responses within soil deposits and the characteristics of ground surface motions.

The analytical procedure generally involves the following steps:

- **Determination of the characteristics of the motions likely to develop in the rock formation underlying the site, and selection of an accelerogram with these characteristics for use in the analysis:** The maximum acceleration, predominant period, and effective duration are the most important parameters of an earthquake motion. Empirical relationships between these parameters and the distance from the causative fault to the site have been established for different magnitude of earthquakes (Gutenberg and Richter, 1954, Seed et al., 1969, Schnable et al., 1972). A design motion with the desired characteristics can be selected from the strong motion accelerograms that have been recorded during previous earthquakes (Seed and Idriss, 1969) or from artificially generated accelerograms (Housner and Jennings, 1964).

- **Determination of the dynamic properties of the soil Deposit:** Average relationships between the dynamic shear moduli and damping ratios of soils, as functions of shear strain and static properties; have been established for various soil types (Hardin and Drnevich, 1970, Seed and Idriss, 1970). Thus a relatively simple testing program to obtain the static properties for use in these relationships will often serve to establish the dynamic properties with a sufficient degree of accuracy. However, more elaborate dynamic testing procedures are required for special problems and for cases involving soil types for which empirical relationships with static properties have not been established.

- **Computation of the response of the soil deposit to the base rock motion:** A one dimensional method of analysis can be used if the soil structure is essentially horizontal. Programs developed for performing this analysis are in general based on either the solution to the wave equation (Kanai, 1951) or on a lumped mass simulation (Idriss and Seed, 1968). More irregular soil deposits may require a finite element analysis.

2.13.3 Method for Amplification Anlysis

One dimensional method of ground response analysis is widely used in earthquake geotechnical engineering A number of different techniques are available for one-dimensional response analysis, which can be broadly categorized as linear analysis, equivalent linear analysis and nonlinear analysis. The most popular method used in professional practice is the "equivalent linear" approach which is incorporated in the computer program SHAKE. The program 'SHAKE' is capable of computing the responses for a known motion given anywhere in a system. It requires three input parameters such as bedrock motion, dynamic material properties and site specific soil properties The peak surface acceleration, ground response spectrum and period of soil column are obtained as output from this analysis. The accelerograms measured on a known soil deposit can be used to predict underlying rock motions using 'SHAKE', which, in turn, can be used to obtain the surface motion for other soil deposits as shown in Fig. 2.18 (after Schnable et al., 1971). The rock motion is assumed not to vary within a region. The program incorporates non-linear soil behavior, the effect of the elasticity of the base rock and systems with variable damping.

a. **Theory to the Program:** The theory (behind SHAKE) considers the responses associated with vertical propagation of shear waves through the linear visco-elastic system shown in Figure 2.28. The system consists of N horizontal layers which extend to infinity in the horizontal direction and has a half space as the bottom layer. Each layer is homogeneous and isotropic, and is characterized by the thickness, h, mass density, ρ, shear modulus, G, and damping factor, β.

2.13.4 Description of the Program SHAKE

Program SHAKE computes the responses in a system of homogeneous, visco-elastic layers of infinite horizontal extent subjected to vertically travelling shear waves. The system is shown in Figure 2.19. The program is based on the continuous solution to the wave- equation adapted for use with transient motions through the fast Fourier transform algorithm. The nonlinearity of the shear modulus and damping is accounted for by the use of equivalent linear soil properties using an iterative procedure to obtain values for modulus and damping compatible with the effective strains in each layer.

The following assumptions are implied in the analysis:

- The soil system extends infinitely in the horizontal direction. Each layer in the system is completely defined by its value of shear modulus, critical damping ratio, density, and thickness. These values are independent of frequency.
- The responses in the system are caused by the upward propagation of shear waves from the underlying rock formation.
- The shear waves are given as acceleration values of equally spaced time intervals. Cyclic repetition of the acceleration time history is implied in the solution.
- The strain dependence of modulus and damping is accounted for by an equivalent linear procedure based on an average effective strain level computed for each layer.

The program is able to handle systems with variation in both moduli and damping, and takes into account the effect of the elastic base. The motion used as a basis for the analysis, the object motion, can be given in any one layer in the system and new motions can be computed in any other layer.

The set of operations can be performed by the program:

- Read the input motion, find the maximum acceleration, scale the values up or down, and compute the predominant period.
- Read data for the soil deposit and compute the fundamental period of the deposit.
- Compute the maximum stresses and strains in the middle of each sub-layer and obtain new values for modulus and damping compatible with a specified percentage of the maximum strain.
- Compute new motions at the top of any sub-layer inside the system or outcropping from the system.

2.13.5 Use of SPT-value for Shear Wave Velocity

There are several empirical relations correlating the SPT-N value and Shear Wave Velocity (Vs) as Shown in Table 2.10. The Standard Penetration Test (SPT) has been widely used to investigate soil deposit for identifying subsurface soil profiles. The empirical relationships presented here can be used to convert SPT-N value into Shear Wave Velocity which is needed as one of the input parameters for the program SHAKE.

Table 2.7: Empirical Relations Correlating SPT-N value and Shear Wave Velocity (After TC4, 1993)

Researchers	**Equation**
Imai and Yoshimura (1970)	$Vs = 76\ N^{0.33}$
Ohba and Toriumi (1970)	$Vs = 84\ N^{0.31}$
Ohta and Goto (1978)	$Vs = 69\ N^{0.17}\ D^{0.2}\ F_1\ F_2$ Where $F_1 = 1.0$ (H); $F_2 = 1.00$ (clay) $= 1.3$ (P); $= 1.09$ (f. sand) $= 1.07$ (m. sand) $= 1.14$ (c. sand) $= 1.15$ (g. sand) $= 1.45$ (gravel)
Imai (1977)	$Vs = a\ N^b$ Where $a = 102$; $b = 0.29$ (H. clay) $= 81$; $= 0.33$ (H. sand) $= 114$ $= 0.29$ (P. clay) $= 97$ $= 0.32$ (P. sand)
Okamoto et al. (1989)	$Vs = 125\ N^{0.3}$ (P. clay)
Tamura and Yamazaki (2002)	$Vs = 105\ N^{0.187}\ D^{0.179}$

Here,

Vs = Shear Wave Velocity (m/s); N = Corrected SPT blow count

D = Depth (m); H = Holocene; P = Pleistocene

f = Fine; m = Medium; c = Coarse; g = Gravelly

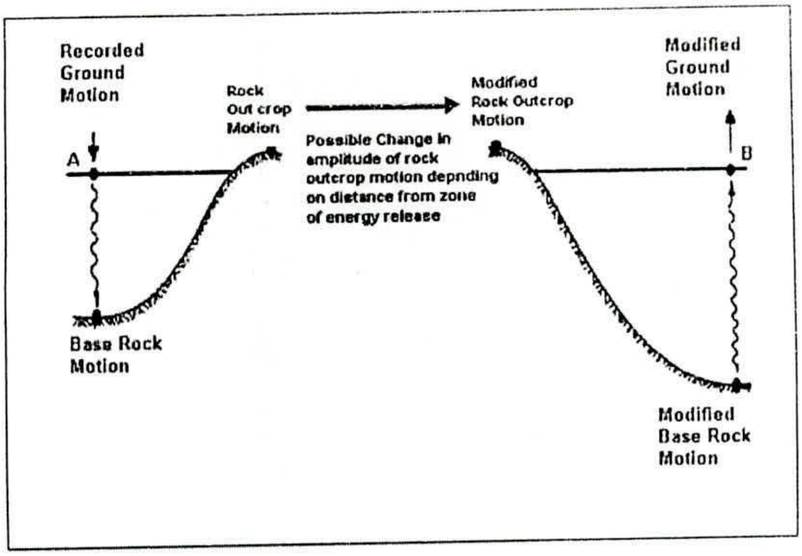


Figure 2.18: Schematic representation of procedure for computing effects of local soil conditions on ground motions (Schanbel et al., 1971)

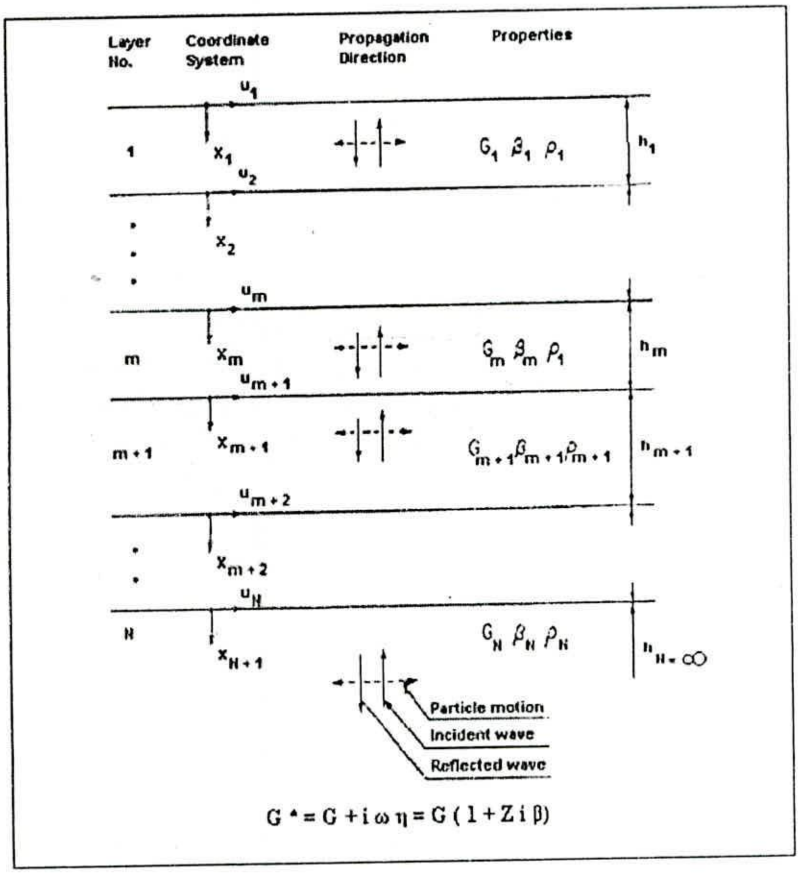


Figure 2.19: One dimensional wave propagation system (Schanbel et al., 1971)

2.14 Liquefaction Analysis

Soil liquefaction is a phenomenon in which a soil below the ground water table loses a substantial amount of strength due to pore pressure generation from strong earthquake ground shaking. Earthquake shaking induces shear stresses in the soil that cause the saturated cohesion less granular soil particles to rearrange and excess pore pressures to build up. Liquefaction can occur in moderate to major earthquakes resulting in severe damages to structures. It can have a significant and sometimes devastating effect on buildings supported on the upper soil layers constructed without consideration of its consequences of liquefaction. The damaging effects of soil liquefaction have been well recognized since the Niigata and Alaska earthquakes of the early 1960s. The types of failures associated with liquefaction include:

(i). Sinking or overturning of the structures,
(ii). Excessive differential settlement of the structures,
(iii). Sand boils; and
(iv). Surface lateral spreading.

2.14.1 Causes of Soil Liquefaction

The general trend on understanding about the basic causes of liquefaction of sands is a quite qualitative measure. If a loose saturated sand deposit is subjected to ground vibrations, it tends to compact and decrease in volume. The effective stress in the sand deposit is equal to the difference between the overburden pressure and the pore water pressure. If drainage is unable to occur, the tendency to decrease in volume results in an increase in pore water pressure. So, with increasing oscillation, the pore water pressure will be equal to the overburden pressure causing the effective stress to become zero. Since the shear strength of a cohesionless soil is directly proportional to the effective stress, the sand loses its strength completely and develops a liquefied state.

In more quantitative terms, it is now generally believed that the basic cause of liquefaction in saturated cohesionless soil during earthquake is the buildup of excess hydrostatic pressure due to the application of cyclic shear stress induced by the ground motions. These stresses are generally considered to be due primarily to upward propagation of shear waves in a soil deposit; although other forms of wave motions are also expected to occur. Thus, soil elements can be considered to undergo a series of cyclic stress conditions, the stress series being somewhat random in pattern but nevertheless cyclic in nature.

There are several factors that influence liquefaction such as the geologic history of the deposit, the depth of ground water table, the grain size distribution, the density of soil, duration of earthquake, amplitude and frequency of shaking, distance from epicenter, cohesion of the soil and permeability of the layer and ground slope. The liquefaction hazards are commonly associated with saturated sandy and silty soils having low plasticity and density.

2.14.2 Methodology for Liquefaction Analysis

Liquefaction susceptibility is a measure of a soil's inherent resistance to liquefaction, and can range from not susceptible, regardless of seismic loading, to highly susceptible, which means that very little seismic energy is required to induce liquefaction. There are a number of different methods by which the potential for liquefaction of a soil can be evaluated. The types of methods can be classified into four categories:

Category-1: Evaluation of liquefaction potential roughly based on topographical and geological information

Category-2: Evaluation of liquefaction potential from N-value and grain size distribution data, and estimates of peak surface acceleration.

Category-3: Evaluation of liquefaction potential from laboratory cyclic shear testing of undisturbed samples, in light of dynamic response analysis.

Category-4: Evaluation of liquefaction potential by conducting in-situ cyclic or blasting tests, or laboratory shaking table tests.

Because of their simplicity, methods that fall in the first and second category are generally useful for formulating microzonation maps of liquefaction potential for wide areas. Methods in the last two categories provide a more rigorous examination of liquefaction at a single site, but are too tedious and costly for survey-type applications. In this study, the second procedure was adopted to formulate microzonation map of liquefaction potential.

The second procedure involves a more direct use of geotechnical data, such as SPT-N value and means particle diameter, and estimates of peak surface acceleration (Seed and Idriss, 1971). A liquefaction resistance factor F_L, is calculated which is used to evaluate the liquefaction potential index, I_L. The method is briefly explained below.

2.14.3 Liquefaction Potential Based On SPT N-Values

The first step in calculation of liquefaction potential is to determine whether the soil has the potential to liquefy during the earthquake. This analysis is usually carried out by using simplified empirical procedure, originally developed by Seed and Idriss (1971). This method has been used here to evaluate the Liquefaction Resistance Factor, F_L which can also be termed as Factor of Safety. It is the most common and traditional method that uses correlations between the liquefaction characteristics of soils and the Standard penetration Tests or N-value along with other parameters such as grain size distribution curves of soils, overburden pressure, and estimated peak surface acceleration. The assessment of the liquefaction resistance factor at any depth involves comparison of the predicted cyclic stress ratio ($t/б'_0$) that would be induced by a given design earthquake (L) with the cyclic stress ratio required to induce liquefaction (R). For this method, F_L is calculated for a given depth of soil layer by the following formula.

$$F_L = \frac{R}{L} \tag{1}$$

Liquefaction is assumed to occur at that depth if F_L is less than 1.0. Here, R is the in-situ capacity of soil to resist liquefaction expressed by Cyclic Resistance Ratio (CRR) for earthquake of magnitude 7.5 and L is the earthquake load induced by a seismic motion expressed by Cyclic Stress Ratio (CSR). Cyclic Resistance Ratio for earthquake of magnitude 7.5 is determined based on corrected SPT and mean soil particle size (Seed et al. 1983).

Table 2.8: Magnitude Scaling Factor after Seed and Idriss (1983)

Earthquake Magnitude	**MSF**
6	1.32
6.75	1.13
7.5	1.00
8.5	0.89

Magnitude Scaling Factor (MSF), obtained from Table 2.9, is used to determine the Factor of Safety against Liquefaction for earthquakes other than that of magnitude 7.5 and calculated as

$$FS = F_L = \frac{CRR_{7.5}}{CSR} MSF \tag{2.2}$$

The shear stresses developed at any point in a soil deposit during an earthquake appear to be due primarily to the vertical propagation of shear waves in the deposit. If the soil column above a soil element at depth "h" behaved as a rigid body, the maximum stresses on the soil element would be

$$(\tau_{max})_r = \frac{\gamma h}{g} \alpha_{smax} = \frac{\sigma_0}{g} \alpha_{smax} \tag{2.3}$$

where

σ_o = total overburden pressure

α_{Smax} = estimated peak surface acceleration (in percentage of g)

γ = Unit weight of the soil

g = acceleration due to gravity;

Figure 2.20 illustrates the procedure for determining cyclic shear stress on a soil element during ground shaking and Figure 2.21 illustrates the procedure for determining maximum shear stress.

Because the soil column behaves as a deformable body, the actual shear stress at depth h, $(\tau_{max})_d$, as determined by the ground response analysis will be less than $(\tau_{max})_r$ and might be expressed by

$$(\tau_{max})_d = r_d \ (\tau_{max})_r \qquad (2.4)$$

Where

r_d = a stress reduction factor with a value less than 1 given by (1- 0.015z) in which

z = depth of ground surface in meters.

Computations of the value of r_d for a wide variety of earthquake motions and soil conditions having sand in the upper 50 ft. have shown that r_d generally falls within the range of values shown in Figure 2.22. It may be seen that in the upper 30 or 40 ft., the scatter of the results is not so great and, for any of the deposits, the error involved in using the average values shown by the dashed line would generally be less than about 5%. Thus to a depth of about 40 ft., a reasonably accurate assessment of the maximum shear stress developed during an earthquake can be made for the relationship given in equation (3.3) by using values of r_d to be taken from the dashed line in Figure 2.22.

The actual time history of shear stress at any depth in a soil deposit during an earthquake will have an irregular form such as that shown in Figure 2.23. From such relationships it is necessary to determine the equivalent uniform average shear stress. By appropriate weighting of the individual stress cycles, based on laboratory test data, this determination can readily be made. However, after making these determinations for a number of different cases it has been found that with a reasonable degree of accuracy, the average equivalent uniform shear stress, τ_{av}, is about 65% of the maximum shear stress, τ_{max}. Combining this result with the above expression for τ_{max}, the average cyclic stress ratio (τ_{av}/σ'_o) induced by an earthquake is given by the expression (Seed et al., 1983)

$$CSR = L = \frac{\tau_{av}}{\sigma'_0} = 0.65\left(\frac{\alpha_{s\max}}{g}\right)\left(\frac{\sigma_0}{\sigma'_0}\right)r_d \qquad (4)$$

Where,

$6'_0$ = effective overburden pressure

The cyclic stress ratio required to cause liquefaction has been evaluated using empirical relationship between cyclic stress ratio and N values. This curve is presented in Figure 2.24.

Since the standard penetration resistance, N, measured in the field actually reflects the influence of the soil properties and the effective confining pressure, it has been found desirable to eliminate the influence of confining pressure by using a normalized penetration resistance N_1, where N is the measured penetration resistance of the soil under an effective overburden pressure of 1 ton per sq. ft. Thus, before using the graph in Figure 2.25, normalized to the field SPT-N value is estimated as follows:

$$N_1 = C_N \, . \, N \qquad (2.5)$$

Where,

N_1 = modified N values

C_N = a correction factor

The correction factor, C_N was provided by Murthy (1991) and presented here as Figure 2.25.

The severity of foundation damage caused by soil liquefaction depends to a great extent on the severity of liquefaction, which cannot be evaluated solely by the F_L. Generally speaking, liquefaction under the following condition tends to be severe:

1. The liquefied layer is thick
2. The liquefied layer is shallow
3. The F_L of the liquefied layer is far less than 1.00

In order to account for these effects, the Japanese Bridge Code (Japanese Road Association, 1991) recommended a modification to the procedure suggested in Seed et al (1983). In this method the factor of safety values, F_L (Seed and Idriss, 1971) against resistance to liquefaction have been computed up to top 20 meters depth for all the bore holes and these values have been subsequently converted into liquefaction potential index (I_L) given by the following equation (Iwasaki et al., 1982):

$$I_L = \int_0^{20} F(z)w(z)dz \tag{2.6}$$

Where,

$F(z) = (1-F_L)$ for $F_L \leq 1.0$

$F(z) = 0$ for $F_L > 1.0$

$W(z) = (10 - 0.5Z)$ for $z \leq 20$ m

$W(z) = 0$ for $z > 20$ m

The value of liquefaction potential, I_L indicates that a soil mass is susceptible to liquefaction if $I_L > 0$. If the value of I_L is large, the soil is very susceptible for liquefaction.

Severity of liquefaction is then expressed as shown below:

$I_L = 0$, No Liquefaction

$= 0\text{-}5$, Low Liquefaction

$= 5\text{-}15$, Moderate Liquefaction

$= >15$, High Liquefaction

I_L has been used to express the measure of liquefaction potential for a particular location and for further zonation of the area based on a particular range of this index. Table 2.9 shows the interpretation of liquefaction potential in terms of intensity and ground susceptibility.

Table 2.9: Summary of the Liquefaction Potential Index (Iwasaki et al., 1986)

Liquefaction Potential	Criteria	Explanation
High	$15 < I_L$	Ground Improvement is indispensable
Moderate	$5 < I_L \leq 15$	Ground Improvement is required. `Investigation of important structures is indispensable
Low	$0 < I_L \leq 5$	Investigation of important structures is required
Very low	$I_L=0$	No measure is required

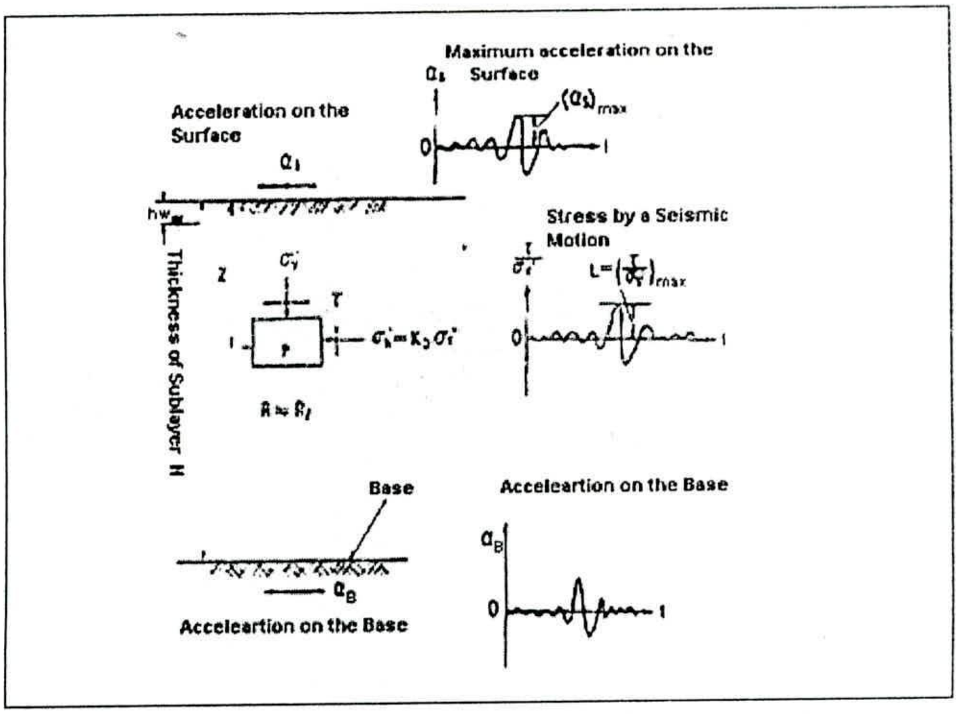


Figure 2.20: Cyclic shear stresses on a soil element during ground shaking (Iwasaki, 1982)

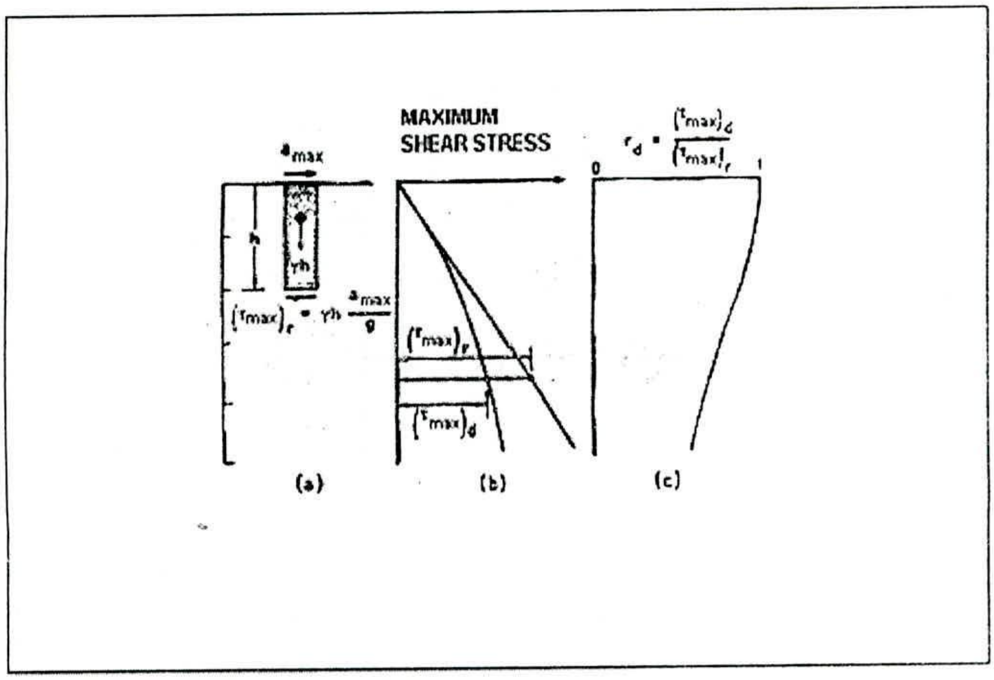


Figure 2.21: Procedure for determining maximum shear stress (Seed et al. 1983)

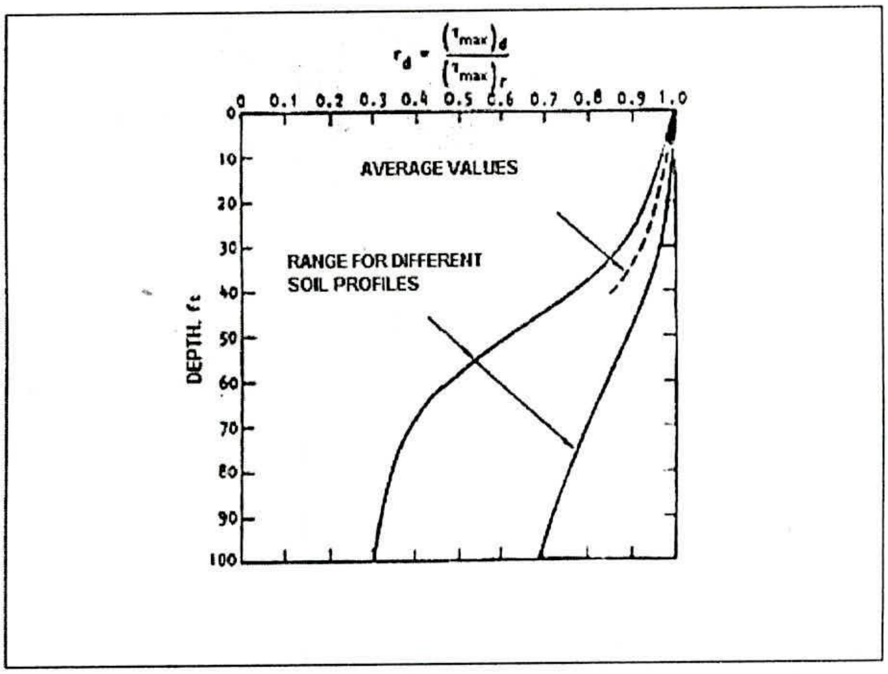


Figure 2.22: Range of Values of rd for different soil profiles (Seed et al., 1983)

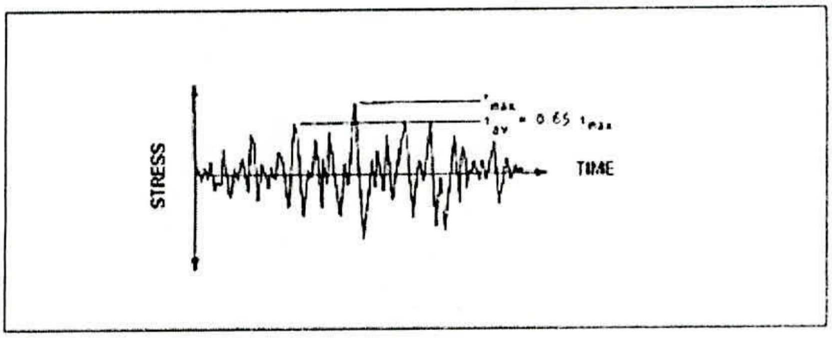


Figure 2.23: Time history of shear stresses during earthquake (Seed et al., 1983)

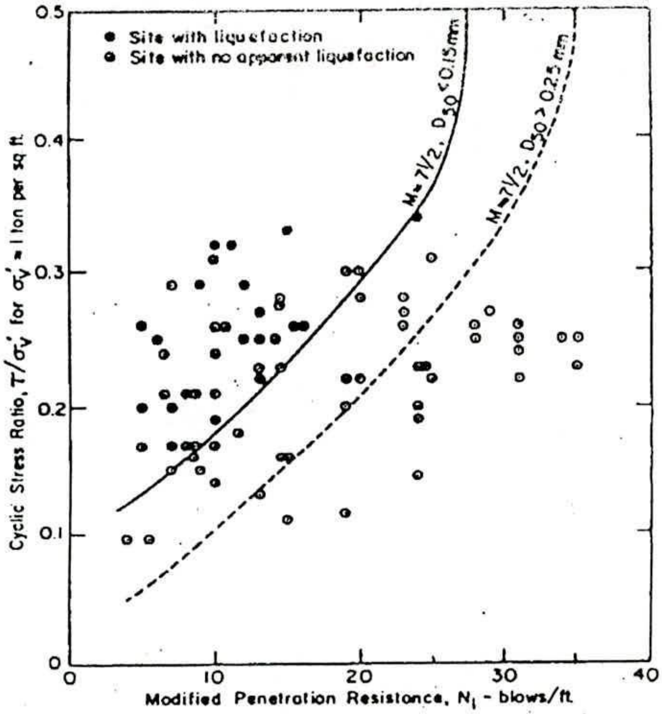


Figure 2.24: Correlation between field liquefaction behavior of Silty sands under level ground conditions and standard penetration resistance (after Seed et al., 1983)

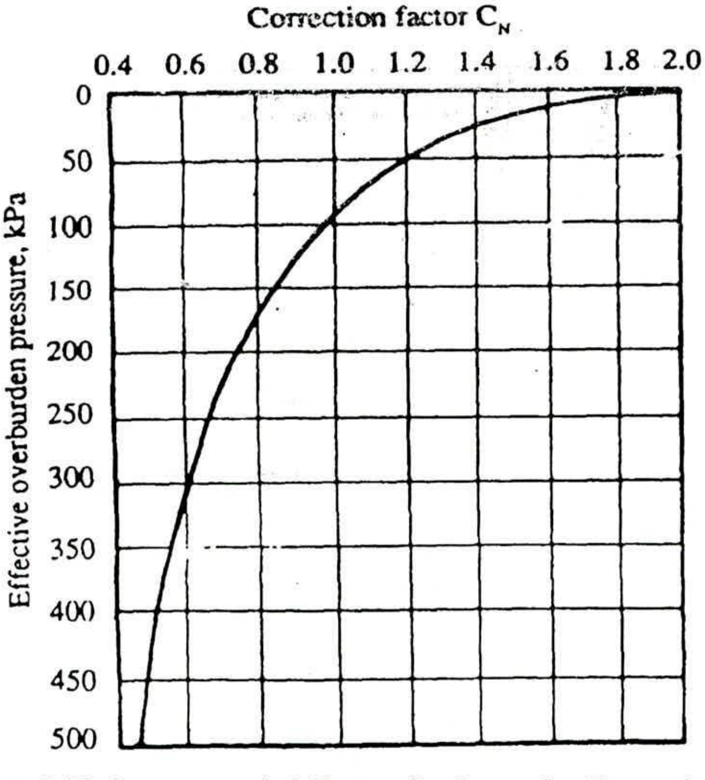


Figure 2.25: Recommended Curves for Correction Factor from Effective Overburden Pressure (after Murthy, 1991)

2.15 Landslide

A landslide is a geological phenomenon which includes a wide range of ground movement, such as rock falls, deep failure of slopes and shallow debris flows. Although the action of gravity on an over-steepened slope is the primary reason for a landslide, there are other contributing factors affecting the original slope stability. Typically, pre-conditional factors build up specific sub-surface conditions that make the area/slope prone to failure, whereas the actual landslide often requires a trigger before being released.

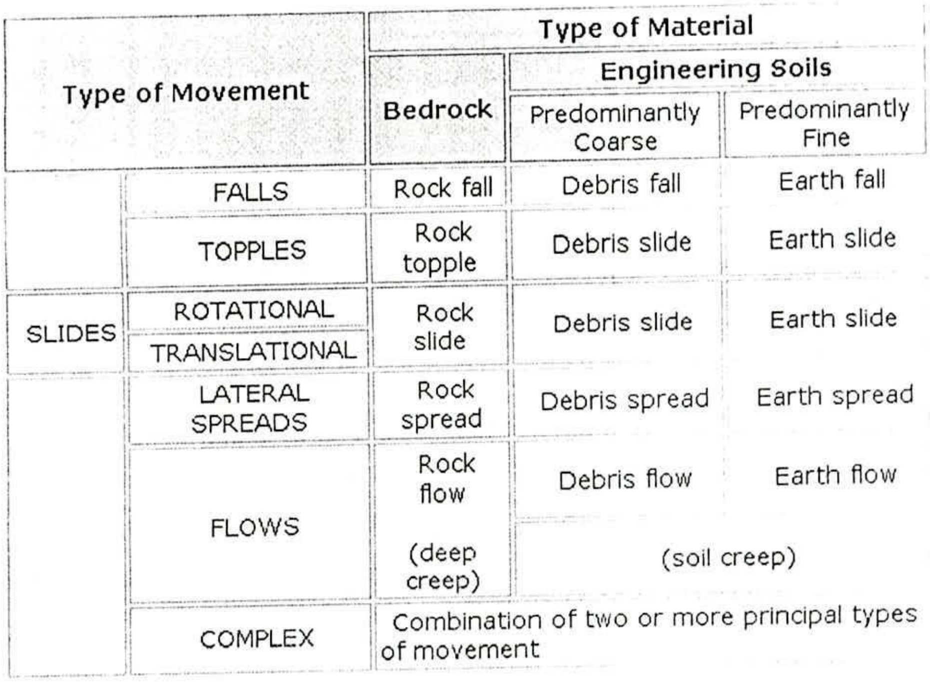
Landslides and other gravity-stimulated mass movements are a continual source of concern for geotechnical engineers and engineering geologists throughout the world, particularly in geologically active regions. They occur worldwide and are described as sudden, short-lived geomorphic events that involve the rapid to slow descent of soil or rock in sloping terrains. They can occur on any terrain give the right conditions of soil, moisture and the angle of slope. Risks of landslides are enhanced in the tropics, where thick, loose residual soil, the result of deep weathering, can be easily eroded.

2.15.1 Types of Landslides

The term "landslide" describes a wide variety of processes that result in the downward and outward movement of slope-forming materials including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing. Figure 2.26 shows a graphic illustration of a landslide, with the commonly accepted terminology describing its features.

The various types of landslides can be differentiated by the kinds of material involved and the mode of movement. A classification system based on these parameters is shown in Table 2.10.

Table 2.10: Types of landslides, Abbreviated version of Varnes', 1978 classification of slope movements (National Atlas, 2008)



Type of Movement		Type of Material		
		Bedrock	Engineering Soils	
			Predominantly Coarse	Predominantly Fine
	FALLS	Rock fall	Debris fall	Earth fall
	TOPPLES	Rock topple	Debris slide	Earth slide
SLIDES	ROTATIONAL TRANSLATIONAL	Rock slide	Debris slide	Earth slide
	LATERAL SPREADS	Rock spread	Debris spread	Earth spread
	FLOWS	Rock flow	Debris flow	Earth flow
		(deep creep)	(soil creep)	
	COMPLEX	Combination of two or more principal types of movement		

The most common types of landslides are described as follows and are illustrated in Figure 2.26 and Figure 2.27.

Slides: The term Slide refers to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides.

Rotational slide is a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (Figure 2.27A).

In Translational slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting (Figure 2.27B).

A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass (Figure 2.27C).

Falls: Falls are abrupt movements of masses of geologic materials, such as rocks and boulders, that become detached from steep slopes or cliffs (Figure 2.28 D).

Topples: Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks (Figure 2.28 E).

Flows: There are five basic categories of flows that differ from one another in fundamental ways.

a. Debris flow: A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope (Figure 2.28 F). Debris flows include <50% fines. Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material. Debris-flow source areas are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of debris fans at the mouths of gullies. Fires that denude slopes of vegetation intensify the susceptibility of slopes to debris flows.

b. Debris avalanche: This is a variety of very rapid to extremely rapid debris flow (Figure 2.28 G).

c. Earthflow: Earthflows have a characteristic "hourglass" shape (Figure 2.28 H). The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongate and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.

d. Mudflow: A mudflow is an earthflow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles. In some instances, for example in many newspaper reports, mudflows and debris flows are commonly referred to as "mudslides."

e. Creep: Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. There are generally three types of creep: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure as other types of mass movements. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges (Figure 2.28 I).

Lateral spreads: Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain (Figure 2.28 J). The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials movement occurs for no apparent reason. Combination of two or more of the above types is known as a complex landslide.

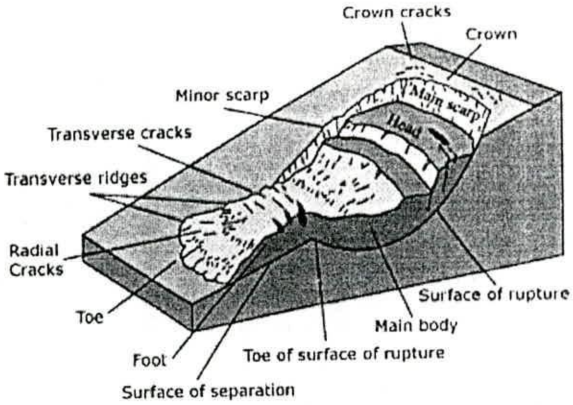
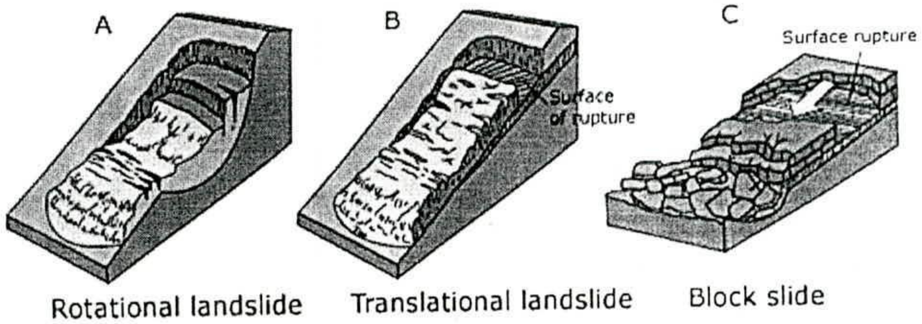


Figure 2.26: An idealized slump-earth flow showing commonly used nomenclature for labeling the parts of a landslide (National Atlas, 2008)



Rotational landslide Translational landslide Block slide

Figure 2.27: Schematics illustrating the types of slides (National Atlas, 2008)

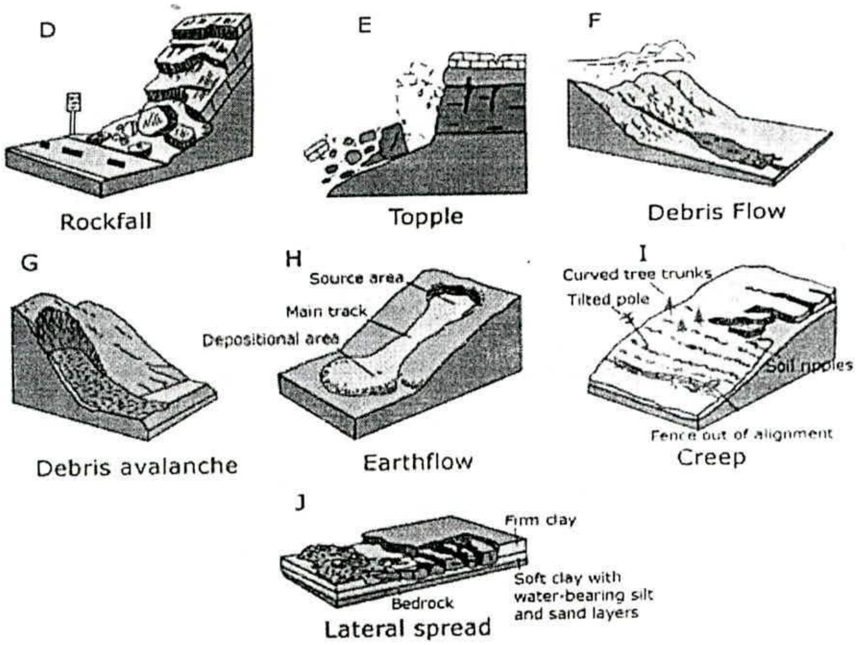


Figure 2.28: Schematics illustrating the major types of landslide movements (National Atlas, 2008)

2.15.2 Landslide in the South Eastern Bangladesh

Landslide is a regular geologic hazard in Bangladesh, especially in the South-Eastern part of the country. The steepness of a hill is the main factor for the movement of the materials that flow down towards the foot of the hill. Steep slope push down debris or mud converting gravitational energy into kinetic energy. A natural hill is a stable surface of the earth system having a balance of its components. Every natural hill is maintaining its stability by natural condition of the system that sometimes disturbed by improper interactions of human being. Landslide induced by human activities has become very common in the hilly areas of southeastern Bangladesh, especially in Bandarban, Rangamati, Khagrachhari and Cox's Bazar. Illegal hill-cutting due to rampant building has left some 70,000 (IRIN, 2008) people at risk of landslides in 18 sub-districts of the hill districts, as well as the city of Chittagong, warned specialists. Every year especially in the rainy season landslides take place in both natural and man-induced slopes. Considerable number of buildings, roads and other infrastructures are damaged and valuable lives are lost in these incidents. The loss of lives and properties due to Landslide events in Cox's Bazar is also very significant. In 15th June of 2003 (International Landslide Centre, 2006) total 6 casualties were reported at Cox's Bazar due to Landslides caused by heavy rain. The earthquake of July 30, 2003(Natural Hazards, 2007) with a magnitude of 5.9 hit the Chittagong area causing casualties of six persons in Cox's Bazar by landslide. In September 2006 landslide triggered by heavy rain killed two children and injured six people in the village Rajarkol. Nineteen people died in landslides in Cox's Bazar district in the first half of July 2008 (International Herald Tribune, 2006) alone. On 14 July two people died under a mudslide at Himchhari. On August 11, 2008 three members of a family were buried alive as their mud-hut collapsed in Cox's Bazar. Very recently, on July 31, 2009, ten people were killed in Bandarban due to landslide (South Asian Media Net, 2009).

Types, major nature and processes that cause landslides in Bangladesh are 1) removal of lateral support: a) erosion by rivers, b) previous slope movements such as slumps that create new slopes, c) human modifications of slopes such as cuts, pits, and canals; 2) addition of weight to the slope: a) accumulation of rain, b) increase in vegetation, c) construction of fill, d) weight of buildings and other structures, e) weight of water from leaking pipelines, sewers, canals, and reservoirs; 3) earthquakes; 4) regional tilting; 5) removal of underlying support: a) undercutting by rivers and waves; b) swelling of clays: 6) anthropogenic activities as jhum cultivation

Since Cox's Bazar, the study area for this dissertation, is one of the most landslide prone areas of the country, assessment of landslide potential of Cox's Bazar has become very essential. Indiscriminate Hill cutting is one of the major causes of landslide in this area. Land slide may also be caused by earthquake in steep hill and loose land of steep periphery. Gentle angle or slope is mostly absent in the hills of Cox's Bazar. Rock strata in this area are mostly found as soft or brittle sedimentary rocks which may easily be broken or slide. Since Cox's Bazar is on the threat of probable earthquake events, the hill-tops loosened by any means can cause massive destruction if a moderate to major tremor takes place.

The southern part of the municipal area is mostly hilly which consists of Dupi Tila Formation (Figure 2.3). Lower hill of the area are mainly underlain by little-consolidated sands and shales of the Dupi Tila formation, which may be from late-Miocence age (Brammer, 1996). These hills are mainly composed by unconsolidated or little-consolidated beds of sandstones, siltstones and shales, together with minor beds of limestone and conglomerates. Nature of parent materials strongly determines the texture of the soils. Shale results heavy silt loam or silty clay loam subsoil. Soils developed on sandstone have dominant textural class of sandy loams with occasional loamy sand or loam texture

There also exist hills of Tipam and Bokabil Formation, sparsely in the area. Previous studies on erosional hazards of Chittagong City (Banglapedia, 2006) disclose that the hills formed of Dupi Tila Formation is prone to three types of landslides and slope failures which are lateral spreading movement, rotational and translational movements. Planar or block movement have been observed to occur in Bokabil Formation and rotational, translational and planar or block failures occur in Tipam Formation.

The major landslide occurrences in and around Cox's Bazar municipal area have been listed in Appendix C (Banglapedia, 2006).

2.15.3 Landslide Hazard Analysis Method

The effects of earthquake-induced landslide have received much less research attention than the seismic effects of soil amplification and liquefaction. Landslide hazard is typically very difficult to quantify because landslide come in many forms and are caused by a variety of processes. The local site factors that affect landslides generally include slope stability, geology, slope angle, hydrological conditions, vegetation, land use, and severity of the earthquake. Most of these factors are necessary for the investigation of an individual slope, but for seismically induced landslide analysis on a broad regional basis, magnitude of the seismic event, and distance from the seismic source (Hansen and Franks, 1991).

As with liquefaction, regional landslide hazard has traditionally been analyzed in a qualitative manner utilizing expert opinion, although recently more quantitative geotechnical methods have been proposed. The qualitative methods typically produce microzone maps indicating the relative susceptibility of various regions to landslides with no investigation into the possible triggering mechanisms for the land movement. The maps often result from an expert analysis of regional factors such as previous landslide locations, geologic deposits, and topography.

The complicated nature of the landslide process has made regional estimates of this local site effect very difficult to define quantitatively. Most of the recent research in this field has focused on determining the critical level of a given ground motion parameter that will trigger landslide in various geologic deposits. Wieczorek, et al. (1985) models a landslide as a translational failure in an infinite slope with a depth of 3 meters. They define three classes of geological units, assign shear strength parameters for each class, and then perform stability analyses using dry and saturated conditions to obtain the static factor of safety (FS) for each class. Based on the static FS, the critical acceleration to begin the process of slope failure, a_c, is computed as

$$a_c = (FS-1)\ g \sin\theta \tag{2.7}$$

Where, θ = slope angle

FS = factor of safety determined from a static slope stability analysis

G = acceleration of gravity

These a_c values are compared to the regional estimates of surface peak ground acceleration to give a prediction for the occurrence of damaging earthquake-induced landslides in the area. There have been very few implementations of quantitative landslide hazard models in the GIS environment instead, a qualitative approach utilizing regional maps showing relative susceptibility of landslides in various geologic deposits will be used to describe earthquake-induced landslide hazard.

2.15.4 Slope Stability Analysis

The evolution of slope stability analyses in geotechnical engineering has followed closely the developments in soil and rock mechanics as a whole. Slopes either occur naturally or are engineered by humans. Slope stability problems have been faced throughout history when human or nature has disrupted the delicate balance of natural soil slopes. An understanding of geology, hydrology, and soil properties is central to applying slope stability principles properly. Analyses must be based upon a model that accurately represents site subsurface conditions, ground behavior, and applied loads. Judgments regarding acceptable risk or safety factors must be made to assess the results of analyses.

Civil engineers often are expected to make calculations to check the safety of natural slopes, slopes of excavations and compacted embankments. This check involves determining the shear stress developed along most likely rupture surface and comparing it with the shear strength of the soil. This process is called slope stability analysis. The most likely rupture surface is the critical surface that has the minimum factor of safety.

The stability analysis of a slope is difficult to perform. Evaluations of variables such as soil stratification and its in-place shear strength parameters may prove be a formidable task. Seepage through the slope and the choice of a potential slip surface add to the complexity of the problem. The forces of gravity tends to move soil from high levels to low levels and the forces that resists this action are on account of shear strength of soil. Presence of water increases weight reduces strength and decreases stability. The factor of safety is therefore chosen as a ratio of the available shear strength to that required to keep the slope stable.

2.15.5 Common Features of Slope Stability Analysis Methods

Sliding surfaces in landslides are commonly bowl- or dish-shaped in three dimensions. The widths of the slides are often the same order of magnitude as the down slope length, and stresses parallel to the strike of the ground surface are thought to influence the failure to only a limited extent. It is common to examine the stability of a series of two-dimensional sections in the dip direction and to calculate weights, forces and moments for unit width in the strike direction, Lodalen, Norway (Sevaldson, 1956). A section through the deepest part of the slide mass usually gives a conservative estimate of the stability. Averaging techniques (Lambe and Whitman, 1969) are available. Analysis of slides in jointed rock masses must often formally consider three-dimensional limiting equilibrium.

Various techniques of slope stability analysis include three broad categories Limit Equilibrium Methods, Limit Analysis Solutions and Probabilistic Methods. However, Limit Equilibrium Methods are more commonly used in practice. The basic assumptions of Limit Equilibrium Methods approach is that Coulomb's failure criterion is satisfied along an assumed failure surface, which can be a straight line, an arc of a circle, a logarithmic spiral or any other irregular surface.

Common Features of Slope Stability Analysis Methods include:

1. Safety Factor: $F = S/S_m$ where S = shear strength and S_m = mobilized shear resistance. $F = 1$: failure, $F > 1$: safety
2. Shape and location of failure is not known a priori but assumed (trial and error to find minimum F)
3. Static equilibrium (equilibrium of forces and moments on a sliding mass)
4. Two-dimensional analysis

Most Critical Failure Surface: In homogeneous soils relatively unaffected by faults or bedding, deep seated shear failure surfaces tend to form in a circular, rotational manner. The stability analysis aims to find the most dangerous, ie., the most critical surface, and using the assumption above, this surface can be found using "trial circles". This provides a basis for several methods used to assess the stability of slopes.

The method is as follows:-

1. A series of slip circles of different radii but the same centre of rotation is considered (Figure 2.29). The Factor of Safety (FoS) for each of these circles against radius is plotted (Figure 2.30), and the minimum FoS is found out.
2. This should be repeated for several circles, each investigated from an array of centres. The simplest way to do this is to form a rectangular grid from the centres (Figure 2.31).
3. Each centre will have a minimum FoS, and the overall lowest FoS from all the centres shows tha FoS for the whole slope. This assumes that enough circles, with a large spread of radii, and a large grid of centres have been investigated. Then an overall failure, surface, with smaller individual ones is also found out. (Figure 2.32).
4. Submerged Slopes: When an external water load is applied to a slope (Figure 2.33), the pressure it exerts tends to have a stabilising effect on the slope. The vertical and horizontal forces due to the water must be taken into account in our analysis of the slope.

Assumptions in Limit Equilibrium: Certain assumptions are needed to be made in analysing slopes using limit equilibrium:-

1. Assuming a Failure Mechanism: The shape and location of a failure surface rather are assumed then determining it by analysis.
2. Assuming Plane-Strain (2-D): 3-D effects (although of course in reality slopes are in three dimensions) are ignored. By neglecting these effects the analysis becomes conservative, ie. higher FoS is achieved by taking them into account.
3. Assuming Rigid Block Movement: The soil mass is assumed to be moved as a rigid block, with the movement only taking place on the failure surface itself.
4. Assuming Uniform Localisation of Shear Stresses: The shear stresses are not usually uniformly mobilised over the whole length of the failure surface but for the purpose of the analysis, it assumed that they are.

Factor of Safety: In slope design, and in fact generally in the area of geotechnical engineering, the factor which is very often in doubt is the shear strength of the soil. The loading is known more accurately because usually it merely consists of the self-weight of the slope. The FoS is therefore chosen as a ratio of the available shear strength to that required to keep the slope stable. A factor of safety is calculated by dividing the forces resisting movement by the forces driving movement. If the forces available to resist movement are greater than the forces driving movement, the slope is considered stable. When performing stability analyses usually more interest is put in the stability of the un-failed soil, and in determining a factor of safety, F, for the un-failed soil. To determine the factor of safety it is assumed that only some part of the frictional and cohesive forces have been mobilized, so that on the assumed failure plane the soil is not at a state of failure. Guidelines for limit equilibrium of a slope are given as table 2.11.

Table 2.11: Guidelines for limit equilibrium of a slope (Connolly, 1997)

Factor of Safety	**Details Of Slope**
<1.0	Unsafe
1.0-1.25	Questionable safety
1.25-1.4	Satisfactory for routine cuts and fills, Questionable for dams, or where failure would be catastrophic
>1.4	Satisfactory for dams

For highly unlikely loading conditions, factors of safety can be as low as 1.2-1.25, even for dams. e.g. situations based on seismic effects, or where there is rapid drawdown of the water level in a reservoir.

2.15.6 Methodology Review for Slope Stability Analysis

This section aims at presenting the methods of slope stability analysis, which are commonly available. The methods of analysis can be categorized as follows:

A. Granular Soils:

The C'=0 Method

B. Cohesive Soils:

Circular Failure Surface

- Method of Slices
- Fellenius' Method
- Bishop's Method

Non-Circular Failure Surface

- Janbu's Method
- Infinite Slope Method
- Stability Charts

Few of the methods are summarized in the following paragraphs.

Method of Slices: The method of slices is a method for analyzing the stability of a slope in two dimensions. The sliding mass above the failure surface is divided into a number of slices. The forces acting (Figure 2.34) on each slice are obtained by considering the mechanical equilibrium for the slices. It is assumed that the arc is circular, radius R, centre is O. The soil mass above a trial failure surface is divided into slices by vertical planes. Each slice is taken as having a straight line base. The Factor of Safety of each slice is assumed to be the same, implying mutual support between the slices, ie., there must be forces acting between the slices. To go about finding the FoS, the problem is now statically indeterminate and some assumptions are needed to be made about the interslice forces. This part is better performed by Fellenius Method.

Fellenius Method: This is a modified version of the Method of Slices.

Here it is assumed that E1 =E2 = X1 =X2 (Figure 2.35)

Then, $N = W \cos\alpha$ and $S = 1/F\,[c'l + (W\cos\alpha - ul)\tan\varphi]$

Using Moment Equilibrium,

$$\sum Wx = \sum SR$$

$$\sum WR \sin\alpha = \sum SR \text{ (Figure 2.39)}$$

$$\sum S = \sum W \sin\alpha = \sum 1/F\,[c'l + (W\cos\alpha - ul)\tan\varphi]$$

$$\text{So, } F = \frac{\sum 1/F\,[c'l + (W\cos\alpha - ul)\tan\varphi]}{\sum W \sin\alpha} \qquad (2.8)$$

Bishop's Method: The Modified (or Simplified) Bishop's Method is a method for calculating the stability of slopes. It is an extension of the Method of Slices. By making some simplifying assumptions, the problem becomes statically determinate and suitable for hand calculations. It is assumed that the forces on the sides of each slice are horizontal.

The method has been shown to produce factor of safety values within a few percent of the "correct" values.

$$F = \frac{\sum\left[\frac{c' + ((W/b) - u)\tan\phi'}{\psi}\right]}{\sum[(W/b)\sin\alpha]} \tag{2.9}$$

where

$$\psi = \cos\alpha + \frac{\sin\alpha\tan\phi}{F} \tag{2.10}$$

Here, c' is the effective cohesion

φ' is the effective internal angle of internal friction

b is the width of each slice, assuming that all slices have the same width

W is the weight of each slice

u is the water pressure at the base of each slice

As F is on both sides of the equation, it is solved iteratively. An initial value of F is obtained by carrying the “Fellenious Method” and multiplying the solution by 1.2. This value is inserted into the right hand side of the equation, and the left hand side value of F is calculated. This new value is then inserted into the Right hand side and the process is repeated until the Right hand side = Left hand side.

Janbu's Method: The difficulty in analysing a non-circular failure surface is that it is difficult to find a single point through which many of the force components act. So, the moment equilibrium method used for circular surfaces is no longer the most appropriate. Janbu chose instead to use the force equilibrium method in the analysis. The equation of Factor of Safety here is followed as Bishop’s Method. After discovering a certain amount of inaccuracy in this formula, Janbu decided on a correction factor f_0, which should be applied after iteration has taken place (in Bishop’s Method):

$F_{corrected} = f_0 * F_{iterative}$

The value of f_0 is found from the limiting graphs (Figure 2.36). For this method, it is necessary to use narrow slices.

Infinite Slope Analysis: The simplest form of sliding surface is a plane parallel to the ground surface (Figure 2.37). This may be observed in the field as large flake or planar slides in natural hillsides, which are often initiated by softening and weathering processes extending downwards from the ground surface; by high groundwater pressures; or by toe unloading (Skempton, 1964). The term infinite slope is used to designate a uniform slope of an extent large enough that a typical element can be considered representative of the slope as a whole and irregularities at the toe and the crest of the slide can be ignored. The soil properties and porewater pressure at any given distance below the ground surface are assumed constant. The analysis is simple and direct.

2.15.7 Computer Based Slope Stability Analysis

The calculations involved in slope stability analysis are repitetive and laborious. Thus the most problems in practice are now solved with the aid of computers. Details vary from program to program, but essentially the methods consist of reading the profile into the computer in the form of a series of straight lines and associated soil types, then superimposing on this profile a family of trial sliding surfaces which can be analysed to find the lowest safety factor for the slope. A good program eill permit specification of an irregular slope with variable soil properties expressed eithr in total or effective- stress terms. It will accommodate external water, line and earthquake loads, and can accept porewater pressures described by either a constant soil parameter $r_u = \mu/(\gamma H)$ or by a phreatic surface. It may also permit selection of the method of solution (for example, by Bishop's Method, Spencer's method etc.), and of the shape of the slide surface, whether cicular or non-circular (Fredlund, 1978).

The software XSTABL is such a program that provides an integrated environment for performing slope stability analyses running MS-DOS. There are many factors such as slope geometry and its surface conditions, roughness, weather and environmental conditions which influence stability of a slope. Considering the fact that it would be impossible to relate the stability to all these factors within the time and scope of this study, deep circle and shallow circle were considered for stability analyses using a computer code XSTABL.

XSTABL is a fully integrated slope stability analysis program. The Generalized Limit Equilibrium (GLE) method has been implemented in XSTABL. This method allows factors of safety to be calculated for force and moment equilibrium or for force equilibrium only, using different interslice force angle distributions. With this approach, the user can readily calculate the factor of safety according to Spencer's, Morgenstern-Price, or one of the methods proposed by the Corps of Engineers. If an analysis requires a search for the most critical failure surface, the simplified Bishop and Janbu methods of analysis are selected due to their relative ease of use. The program may be used to either search for the most critical circular, noncircular, or block-shaped surface, or alternatively, to analyze a single circular or non-circular surface. The critical surface is identified by automatically generating and analyzing failure surfaces between defined initiation/termination ranges or by connecting points randomly located within search boxes specified by the user. This aproach minimizes the required input parameters and can be effectively used to confine the surface generation within a narrow, well-defined zone. The soil strength along the failure surface may be described as either conventional (i.e., C, ø), undrained or non-linear Mohr Coulomb and can be either isotropic or anisotropic. The undrained strengths are assigned as a function of the vertical effective stress.

XSTABL is programmed to handle:

1. Heterogenous soil system
2. Anisotropic soil strength properties
3. Pore water pressure for effective stress analysis may be simulated by specifying
   a) A Peizometric surface
   b) Multiple Phreatic surfaces
   c) Pore pressure grid
   d) Pore pressure parameter, R_u
   e) Constant pore water pressure
4. Pseudo-static earthquake loading
5. Surcharge boundary loads.
6. Automatic generation and analysis of an unlimited number of circular, noncircular and block shaped failure surfaces.

Parameters Used in XSTABL

XSTABL uses a soil unit number to uniquely identify the different soils in the slope. The spatial distribution of the soils is then assigned by specifying the appropriate soil unit number corresponding to the soil beneath each boundary segment The parameters for each soil unit are assigned for isotropic and/or anisotropic soils using one of the options available under "SOIL" category.

A. Isotropic Soils

XSTABL can include soils that exhibit isotropic or anisotropic strength properties. For each soil unit, the following properties are required:

1. Moist Unit Weight: Used to calculate the weight of each portion of the discretized slice above the ground water level
2. Saturated Unit Weight: used to calculate the weight of each portion of the discretized slice below the ground water level
3. C- Value: Represents the intercept on the Mohr-Coulomb envelop for the strength parameters of the soil
4. Φ- Value: Represents the slope of the Mohr-Coulomb envelop for the strength parameters of the soil
5. R_u Factor: Used to model the pore water pressures as a fraction of Ru of the total vertical earth pressure within the slope.
6. Constant Pore Pressure: This option allows the users to specify a constant pore water pressure for all points within a soil layer.
7. Water Surface Index: Defines a phreatic or piezometric surface that influences the soil layer if a soil unit is not affected by a water surface, a water surface index of 0 (zero) should be specified in the soil property data table.

B. Anisotropic Soils

Soils anisotropic strength properties are described by assigning the Mohr-Coulomb strength parameters (i.e. c and Φ) to discrete angular ranges between -

90° to +90°, measured counterclockwise from the horizontal. Then, depending on the angle of the base of each discretized slice, the appropriate c and Φ values are selected from one of the specified ranges for the computing the factor of safety.

Assumptions Used in XSTABL

Water surfaces, associated with soil units, may be used to represent phreatic or piezometric surfaces for calculating pore water pressure at points within the soil mass if a water surface is not defined across the failure surface zone. In general the phreatic surface approach is more realistic and will calculate a higher effective strength. However, if piezometers have been installed, and pore water pressure data is available for a potential failure surface, the piezometric surface approach should be used for the analysis.

A. Phreatic Surface: These represent the free ground water level within the slope. In most slopes this groundwater level will be inclined, indicating ground water flow. Such conditions require that the pore water pressure calculations account for the seepage losses This requires the determination of the equipotential line passing through the center of the slice base. The equipotential line is assumed to be a vertical line. The inclination o the phreatic surface and the magnitude of the vertical distance between the phreatic surfaces is located above the ground surface, hydrostatic pressures are assumed to act upon the ground surface boundary.

B. Piezometric Surface: This presents the actual pressure head relative to a surface within the slopes. This relative surface, in two dimensions, will correspond to a line such as a potential failure surface. This option should only be used to examine the stability of single surfaces, or for a back analysis of an actual slope failure. Pore pressures are calculated according to the vertical distance between the base of the slice and piezometric surface corresponding to the appropriate soil unit.

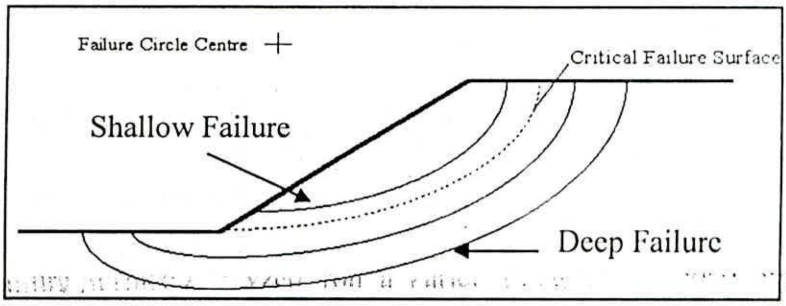


Figure 2.29: Variety of Slope Failure Circles Analysed at Varying Radii from a Single circle Center (Connolly, 1997)

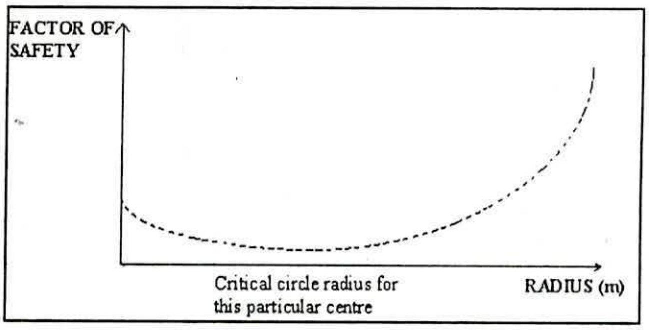


Figure 2.30: Graph Showing Factor of safety against Radius (Connolly, 1997)

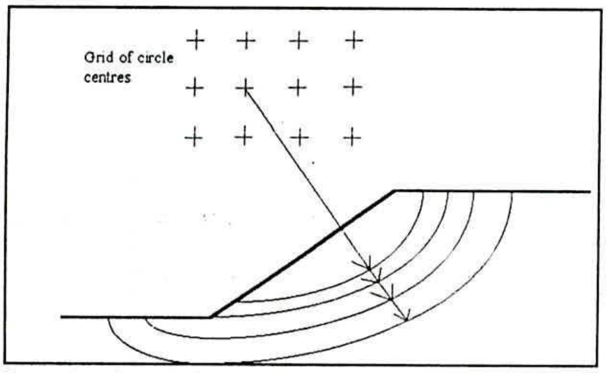
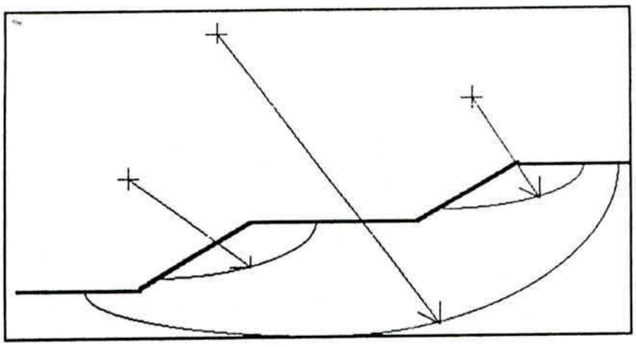


Figure 2.31: Failure Surface Analyzed from a Variety of circle Centers (Connolly, 1997)



2.32: Slope Showing Overall Failure Surface and Smaller Individual ones (Connolly, 1997)

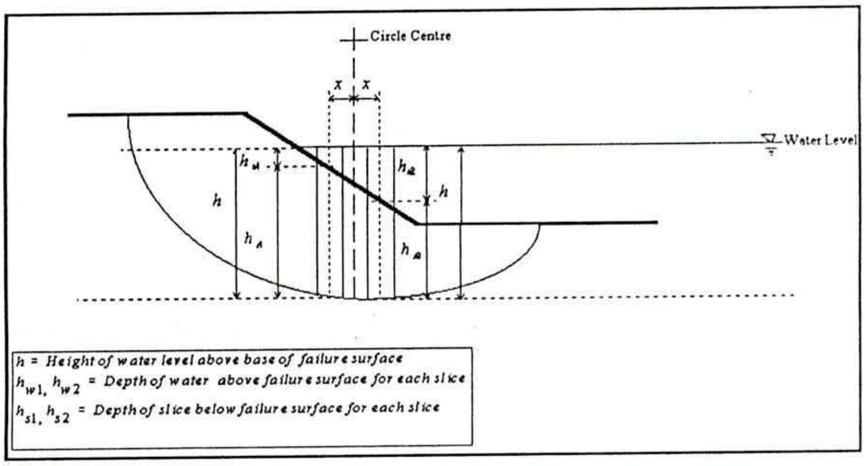


Figure 2.33: Analysing the Effect of External Water Load on a Slope (Connolly, 1997)

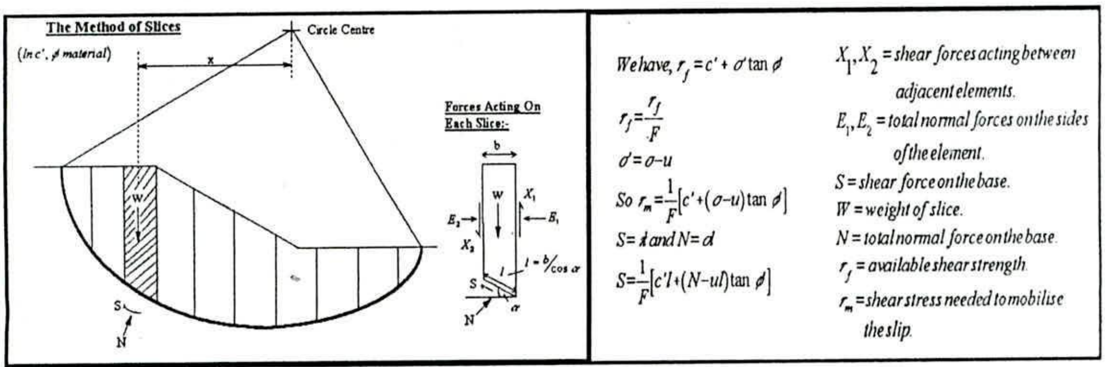


Figure 2.34: The Method of Slices (Connolly, 1997)

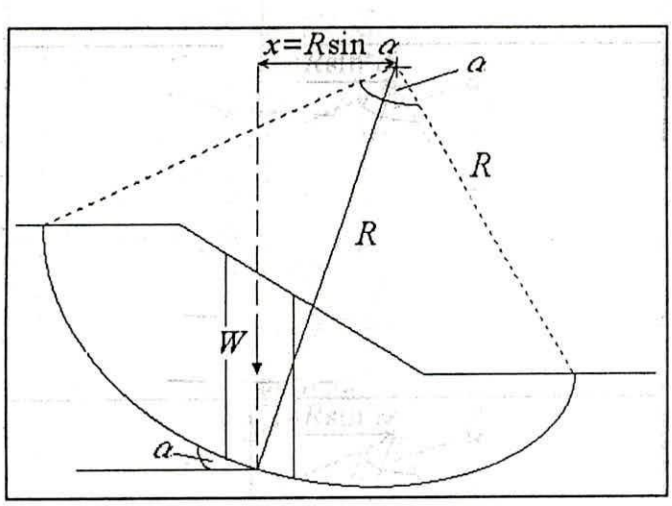


Figure 2.35: Fellenius Method (Connolly, 1997)

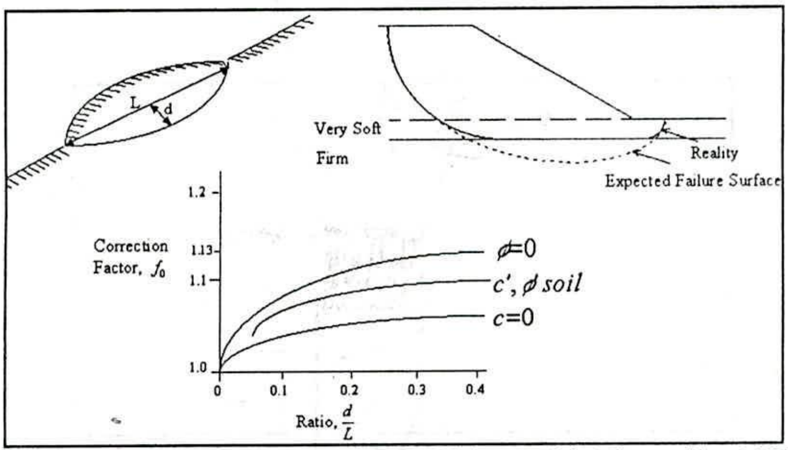


Figure 2.36: Limiting Graphs for Values of f_0 (Connolly, 1997)

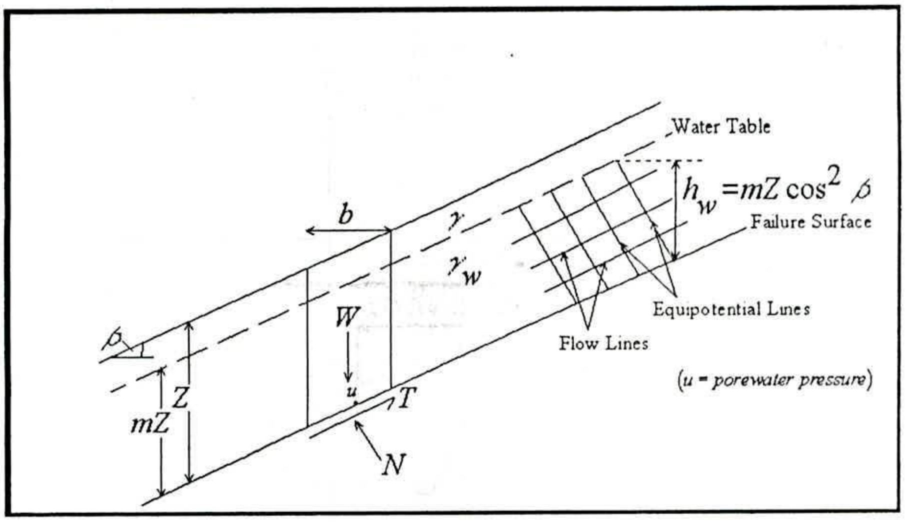


Figure 2.37: Infinite Slope Analysis (Connolly, 1997)

CHAPTER 3

BASIC DATA COLLECTION AND SOIL INVESTIGATIONS

3.1 General

The goal of this study is to produce microzonation maps in GIS environment by incorporating the hazard analyses results. GIS is considered to be the most valuable and powerful software for spatial data compilation, integration, analysis and graphical and non-graphical representation. Thus an updated administrative boundary map of the study area is essential to represent the outcomes of the research. For geotechnical data collection field and laboratory investigations were performed. The field investigation consisted of drilling boreholes, collecting samples and conduction of Standard Penetration Test. The laboratory tests included sieve analysis, index parameter tests, specific gravity test, standard compaction test and direct shear test.

3.2 Updated Administrative Boundary of Municipal Area

An important issue in developing a seismic microzonation map is the selection of an appropriate geographical reference, or geo-code, which will generally be driven by the availability of input data regarding soils conditions. Municipal areas are divided into wards and wards are divided into Mahallahs. For this study, Municipal administrative boundary incorporating locations of Wards was adopted as geographical reference (geo-code) for the microzonation. Recently Cox's Bazar municipality has been expanded and the administrative map has not been finalized yet. For this study the proposed map as of January 2009, was collected from Municipal Office where total area is divided in to 9 wards. The map is shown in Figure 3.1. GPS values of different core sites of the study area were collected. The existing municipal map was scanned and was converted into digital map. Thus GIS-based updated administrative boundary has been developed for the study area.

3.3 Geotechnical Data

Field survey was conducted at entire area under Cox's Bazar Municipality. In this survey, locations to be investigated for Standard Penetration Test and landslide potential were identified. Necessary data such as subsoil reports and geology, topography etc, was collected from different relevant sources. Twelve subsoil investigations were specifically carried out for this research. Also soil samples from eleven hills were collected and tested in laboratory. Fourteen other subsoil reports were collected from different sources. All the data were saved in MS Excel. For assessment of landslide potential Geological Map and Aerial Photograph are also essential, however; these were not available in the concerned authorities' office. Considering above limitations this study was carried out.

3.3.1 Standard Penetration Test

A total of 26 borehole SPT data were used to study site amplification as well as soil liquefaction potential characteristics of municipality area. Among them, twelve subsoil investigations have been carried out using CASR fund. The boreholes were drilled upto a depth of 15 metres. The borings were drilled vertically using the wash boring technique and equipment capable of pushing tube samplers by hydraulic pressure. SPT was carried out in each boring at nominal 1.5 m intervals and the N-values, i.e., number of blows count for each standard penetration was counted. The other fourteen boreholes' SPT data up to a depth of 30 metres were collected from a research project on Cox's Bazar District, carried out under the Department of Civil Engineering, BUET in 2007-2008 (Dhar et. Al., 2008). This ensures the authenticity of the collected data. Table 3.1 presents locations of borehole data from different areas of Cox's Bazar Municipal used for this study, where the first twelve locations are from primary source and the rest are from secondary source. Figure 3.1 shows borehole locations of primary (current study) and secondary (previous study) source points of borehole SPT data. All the bore log sheets are presented in Appendix D.

Table 3.1: Location of Borehole Data of Cox's Bazar Municipal Area

Sl No.	Location	Longitude	Latitude	Source
1	Cyclone Shelter near Diabetic Hospital	91.96212	21.44223	Current Study
2	Baharchhara High School	91.96673	21.43847	
3	Shaibal Hotel Water Tank	91.96683	21.43278	
4	Golf Field Laboni Moore	91.97415	21.43012	
5	Shamudra Bilash, Middle Saikat Para	91.98233	21.42287	
6	Baharchhara Gol Chattar Field	91.97402	21.43463	
7	Cox's Bazar Nursery	91.97487	21.43752	
8	Cox's Bazar KG & Model High School	91.97060	21.44402	
9	Fulbagh, Rice Market Road	91.98188	21.44445	
10	Tekpara, Near Pond	91.98612	21.44283	
11	Rumaliar Chhra, HSA Road	91.99183	21.44073	
12	Bibekanondo Bidya Niketon, Ghonarpara	91.97903	21.43757	
13	76/A, Kalatoli-3	91.97925	21.42755	Previous Study
14	Cox's Bazar Press Club	91.98680	21.47290	
15	Central Govt. PS cum CS	91.99040	21.45380	
16	Peskarpara Govt. PS cum CS	91.98630	21.45540	
17	Kosturaghat Govt. PS	91.98350	21.45320	
18	Kolatoli World Vision MCS	91.99240	21.41800	
19	Baitus Sharaf Jameya Mosque, South Baharchhara	91.98050	21.43550	
20	Bangladesh Red Crescent Society, Motel Road	91.97380	21.44230	
21	Bangladesh Water Development Board	91.97720	21.43980	
22	Tekpara Govt. PS	91.98730	21.44590	
23	Ghonarpara, Near Kaderia Non-Govt. PS	91.98360	21.43840	
24	Mosjid Compound, Ice Factory Road	91.99240	21.44630	
25	Ramkrisna Shebasram, Baiddorghona	91.98710	21.43980	
26	Primary Education Officers' Compund	91.99250	21.44010	

3.3.2 Grain Size Analysis from SPT Samples

To obtain soil parameters such as grain size (soil type and D_{50}) Grain Size Analyses of the SPT samples of different depth were performed in the laboratory. The grain size distribution curves are provided in Appendix E.

3.4 Landslide Estimation Data

Hill ranges and hillock mainly appear to the Northern part of the Cox's Bazar town. Baillarpara, Ghonarpara, Baiddorghona, Pahartali, Light House Para, Bus Terminal, Saikat Para, Kolatoli areas of the municipality are mainly consisted of these hillocks. These hills range from 15 meters to 40 meters in height. From the surface elevation map produced by the Geological Survey of Bangladesh (Alam et. al., 1990) it can be observed that the average height of this hilly range is 30 meters.

Hilly regions of this area have been surveyed and location, height, slope and other relevant data have been collected. The slopes of the hills range from 45 degree to almost 90 degrees. All most all the hill ranges contain some eroded slopes with almost vertical positioning. Photographs of some of the prominent hills have been presented in Appendix G. Dense population, houses and even multistoried buildings have been observed on these eroded slopes and at their vicinity.

Eleven disturbed samples from different locations (photographs are provided in Appendix H) of the municipal area were collected for laboratory investigations including specific gravity test, grain size analysis, Atterberg limits, standard compaction test and direct shear test. Summary of the tests are provided in Appendix I. Table 3.2 and Figure 3.2 show the locations of the samples.

Table 3.2: Sample locations for estimation of landslide potential

Sl No.	**Location**	**Longitude**	**Latitude**
1	Hill behind PTI School	91.98433	21.43933
2	Ghonarpara (Boiddorghona)	91.98280	21.43807
3	Light House Hill	91.97863	21.43055
4	Kolatoli Bipass	91.98728	21.41703
5	Boiddorghona (Behind Mediplus Pharmacy)	91.98290	21.43765
6	Kolatoli Sykat Para	91.98367	21.42183
7	Bus Terminal	91.99640	21.43642
8	Khaja Monjil, Pahartoli	91.98292	21.43498
9	Circuit House	91.97613	21.43650
10	Ghonerpara Road(M r. Subrata's House)	91.98102	21.43665
11	Boillarpara Temple Hill	91.98950	21.43533

3.5 Summary

This chapter discusses development of boundary map with ward locations of Cox's Bazar municipality, collection of soil samples and subsoil investigations which are basic data to carry out the study. The GPS locations of all the borehole investigation points and hill soil samples have been presented on the digitized municipality map. The summary of the bore logs and laboratory test results are provided in the Appendix.

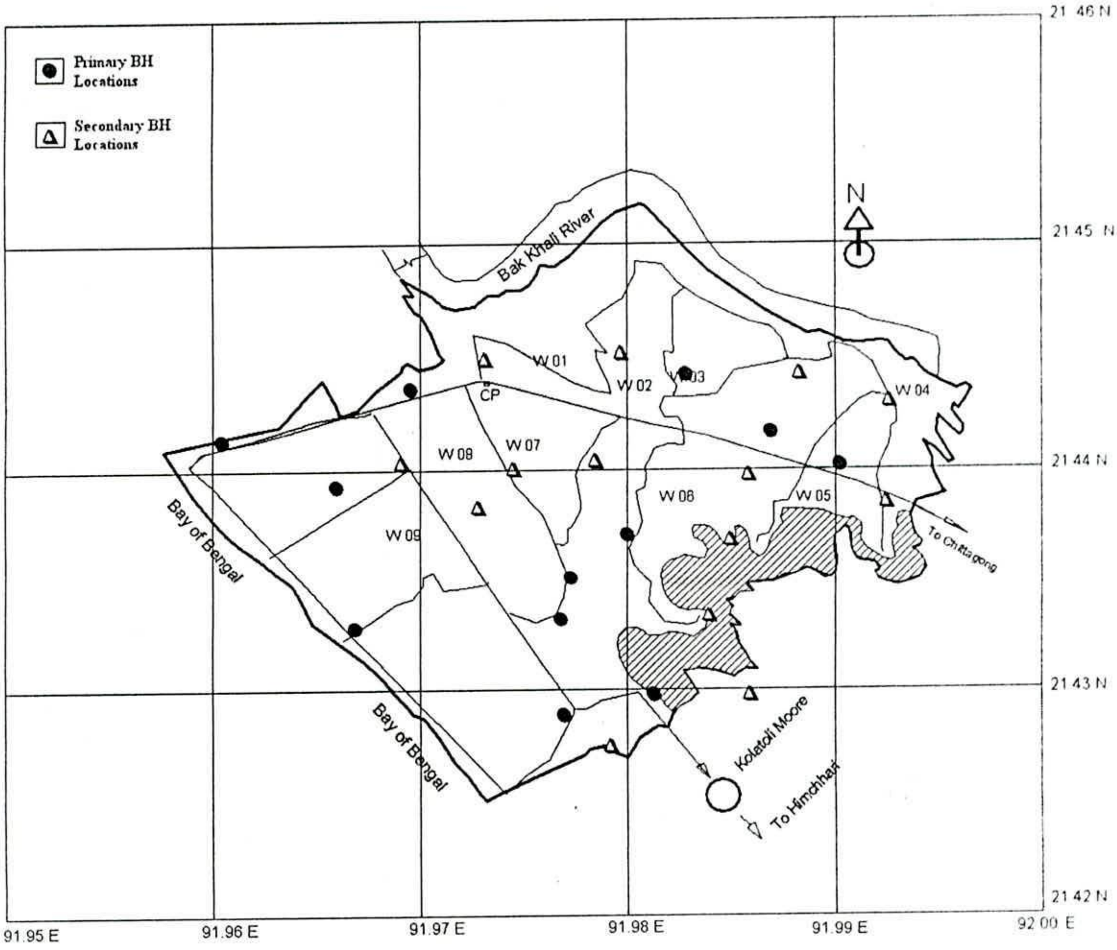


Figure 3.1: Cox's Bazar Municipal Area Map Showing Soil Borehole Locations

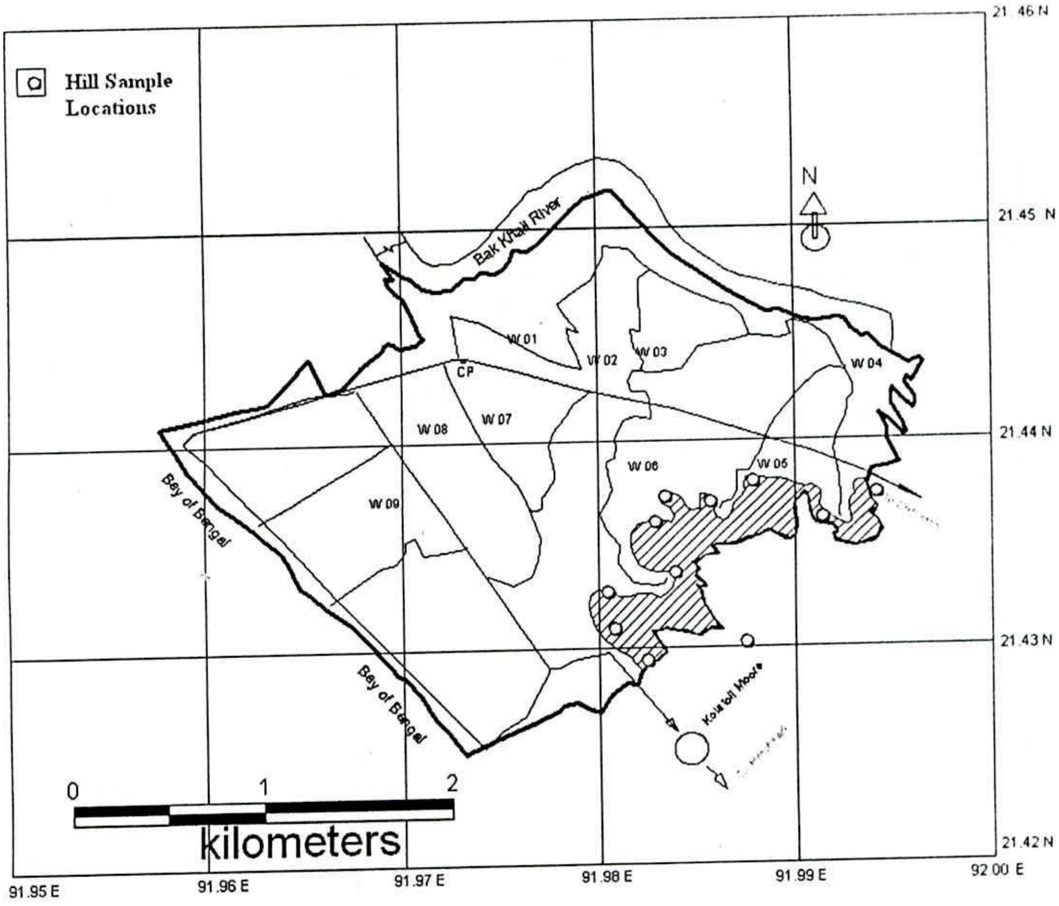


Figure 3.2: Soil sample locations for estimation of landslide potential

4.1 General

It is well understood that earthquake damage to life and property results primarily from strong-ground shaking and indirect shaking-induced hazards such as liquefaction, landslide etc. Severe earthquakes of the last decade in Armenia, China, India, Indonesia, Mexico, Taiwan, Tehran, Turkey and the United States have reemphasized the importance of local geologic site conditions in estimating the regional damage and consequent losses due to future major earthquakes. Again during land use management, city planning, engineering design and in similar applications, proper evaluation of earthquake hazard is needed. The first step in reducing the risk of the society from earthquake hazard is the assessment of the hazard itself. Seismic microzonation map for strong-ground shaking, liquefaction, and landslide can play a significant role in mitigating the effects of earthquake in urbanized regions.

Seismic hazard analysis involves the quantitative estimation of ground shaking hazards at a particular area. Seismic hazards can be analyzed deterministically as and when a particular earthquake scenario is assumed, or probabilistically, in which uncertainties in earthquake size, location, and time of occurrence are explicitly considered (Kramer, 1996). A critical part of seismic hazard analysis is the determination of Peak Ground Acceleration (PGA) for an area/site.

In this study, seismic hazard is defined as the probability that an event is exceeded for a given time interval and the frequency of occurrence of this event. Thus seismic risk analysis determines the probability of occurrence of a given event or conversely, the identification of the event for a given probability or risk for a given site or area. The event may be any parameter (e.g., PGA, PGV, PGD, Intensity) which is deemed to be representative of the effect which is to be studied. It is important to consider the parameters which will correlate well with the effect to be considered. For analyzing liquefaction potential, it is necessary to use PGA because it directly affects the lateral force imposed on soil. This expected lateral force is then considered in determining the safety factor for a particular soil location.

4.2 Methodology

Numerous methods for earthquake hazard assessment in a given site are available today. Lomnitz and Epstein (1966) employed the Poisson process for the occurrence of large earthquakes which is still used. Cornell (1968) and Esteva (1968) derived the general basis for the most complete analysis of the whole seismic hazard problem with the inclusion of the propagation mechanism of the ground motion. Shah and Vagliente (1972) used the Markov model of earthquake prediction in seismic hazard analysis. A methodology for seismic hazard estimation based on historical earthquake occurrences is presented in detail in Tomatsu and Katayama (1988) and Molas and Yamazaki (1994). In Japan, the seismic risk method proposed by Kawasumi (1951) is still popular while in the United States, the basic method proposed by Cornell (1968) is often used.

A methodology for seismic hazard estimation based on historical earthquake occurrences is presented in detail below. The seismic hazard evaluation at a specified site depends upon the definition of the following four models:

(a) *Earthquake source model:* It is based on geological evidence, Seismic sources are identified and modelled as a point, line, area or dipping plane. In this study, a point source model is used. Figure 4.1 shows different source models.

(b) *Seismicity model:* The seismicity of each of the modelled sources is first determined from past data available. The recurrence relationship relating the size of the past events in terms of Magnitude (M) and Peak Ground Acceleration (PGA) is derived, The seismicity model used in Molas and Yamazaki(1994) is usually taken as

$$\log(v) = a + b * M \tag{4.1}$$

$$\log(v) = a + b * \log(y) \tag{4.2}$$

where M is the earthquake magnitude and y is the peak ground acceleration, v is occurrence rate per year and a and b are regression constants. These relations can be written as

$$M = (-\log(T) - a)/b \tag{4.3}$$

$$\log(y) = (-\log(T) - a)/b \tag{4.4}$$

where T (=1/v) is the return period in years. Thus, the above equations represent magnitude and the peak ground acceleration for a return period of T years.

(c) Attenuation model of ground motion: This describes the transfer of ground motions from the source to a particular site as a function of magnitude, distance and soil conditions. Here, the peak ground acceleration is used to characterize the ground motion; the attenuation law is in the form

$$log(y) = b_1 + b_2 (Ms) - b_3 \, log (r) - b_4 (r) \qquad (4.5)$$

where $r^2 = d^2 + h^2$, r is the hypocentral distance (km), d is the epicentral distance (km), h is the focal depth and Ms is the surface-wave magnitude. The attenuation law is required to determine the peak ground acceleration at the site for different events and then to determine the regression constants a and b for Equation (4.4)

(d) Recurrence forecasting model- Various statistical models have been tested in numerous research papers; however, for practical purposes, earthquakes are considered to be random events, and the Poisson process is used, which implies assumptions of stability and independence over time. Since hazard analysis defines the occurrence of ground motions equal to or larger than a specified value, the probability of exceedance is used. For a Poisson process this may be expressed as

$$p = 1 - exp(- vt) \qquad (4.6)$$

where v is the mean annual occurrence rate of events of particular peak ground acceleration over a given time t. From equations the value of the peak ground acceleration for a given b and time period t can be calculated as:

$$log(y) = \log(-\ln(p/t)-a)/b \qquad (4.7)$$

From the assumption of the Poisson process, the relation between the probability of exceedance and the return period of peak ground acceleration, T, is given by

$$T = 1/v = -t/log(p) \qquad (4.8)$$

4.3 Earthquake Analysis

In the regional seismic loss estimation analysis it is needed to determine the bedrock motion in the region. The most common method involves the use of an empirical attenuation relationship. These relationships express a given ground motion parameter in a region as function of the size and location of an earthquake event. Applying statistical regression analyses to recorded data has developed numerous relationships in the past. Often these relationships are developed with different functional forms and with different definitions of ground motion, magnitude, distance, and site conditions. Figure 4.2 shows the flowchart for earthquake hazard analysis at bedrock level and Figure 4.3 shows flow chart for PGA estimation at ground surface.

4.3.1 Selection of Earthquakes around the Site

To estimate the seismic hazard in any particular site within a region requires a selection of earthquakes which affect significantly the value of the hazard output. However, there is no strict rule for selecting the maximum epicentral distance to the site. A small area around the site results in a smaller number of earthquakes to be considered and some events outside the zone considered may affect the hazard in the site. This, naturally, will decrease the data set for regression. On the other hand, a too large area may include earthquakes which do not affect the seismic hazard in the site and are thus useless. It has been observed (Sharfuddin, 2001) for an epicentral distance of 200 km and beyond, the b-coefficient of the Gutenberg-Richter formula is relatively stable. The evaluation of seismic hazard at a site is carried out only if the number of earthquakes in the area considered (200 km radius) is larger than 10 and the surface-wave magnitude is equal to or greater than 4.0.

In this study evaluation of seismic parameter has been carried out using the seismic data over an area having a 250 km radius around Cox's Bazar Municipal area (Appendix B, Figure 4.4).

4.3.2 Selection of Attenuation Law of Peak Ground Acceleration

In Bangladesh, no PGA based attenuation law exists. To get engineering bedrock level (depth of 30 m) PGA, equations presented in Table 2.6 (chapter 2) were used. The historical earthquakes around the study area and their magnitude, epicentral distance, focal depth and intensity were considered to estimate PGA (%g) value in this study.

To select the most suitable attenuation law for predicting rock motions, the methodology adopted in few previous studies were followed (Sabri 2001, Sharfuddin 2001). From these studies it is found that McGuire (1978) as well as Joyner and Boore (1981) equations follow the PGA trend of most large earthquakes in and around Bangladesh. Since, McGuire equation has already been used for Bangladesh for seismic hazard analysis (Sharfuddin, 2001) and due to its simple form it was selected for further use. Table 4.1 shows the PGA values at bedrock level from two attenuation laws for the most significant earthquakes around the study area. The attenuation laws for rock used in this study, McGuire (1978) and Joyner and Boore (1981) are presented as Equations 4.9 and 4.10 ewspectuvely.

$$PGA = 0.0306e^{0.89M}r^{-1.17} \quad (4.9)$$

$$PGA = 0.0955\ e^{(.573M)}\ d^{(-1)}*\ e^{(-0.00587d)},\ d= (r^2+h^2)^{0.5} \quad (4.10)$$

Where,

M = Earthquake Magnitude,

d = Epicentral Distance,

r = Hypocentral Distance and

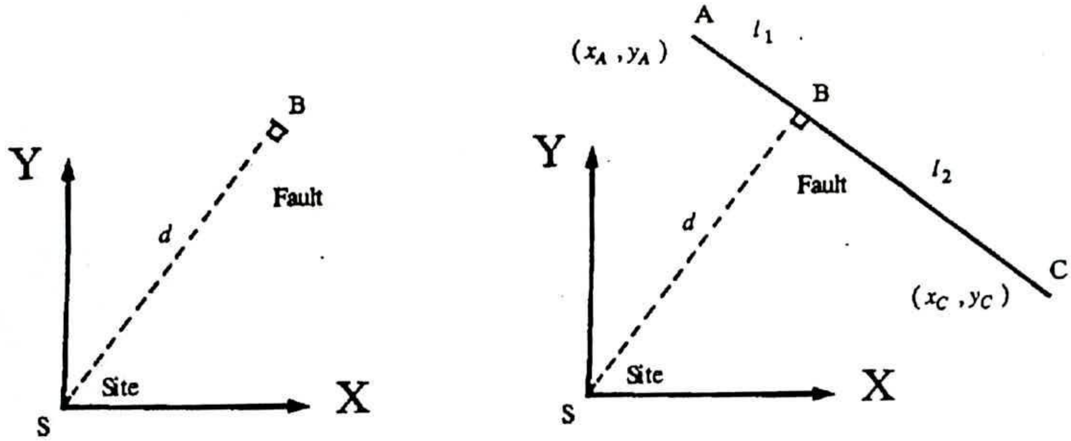
h = Depth

Table 4.1: PGA values (% of g) at bedrock level from different attenuation laws for different scenario events

Attenuation Law	M = 7.8 (1664)	M = 7.66 (1858)	M = 7.9 (1912)	M = 6.5 (1955)	M = 6.24 (1959)
McGuire (1978)	0.0330	0.0214	0.0266	0.0562	0.0780
Joyner and Boore (1981)	0.0029	0.0011	0.0013	0.0260	0.0401

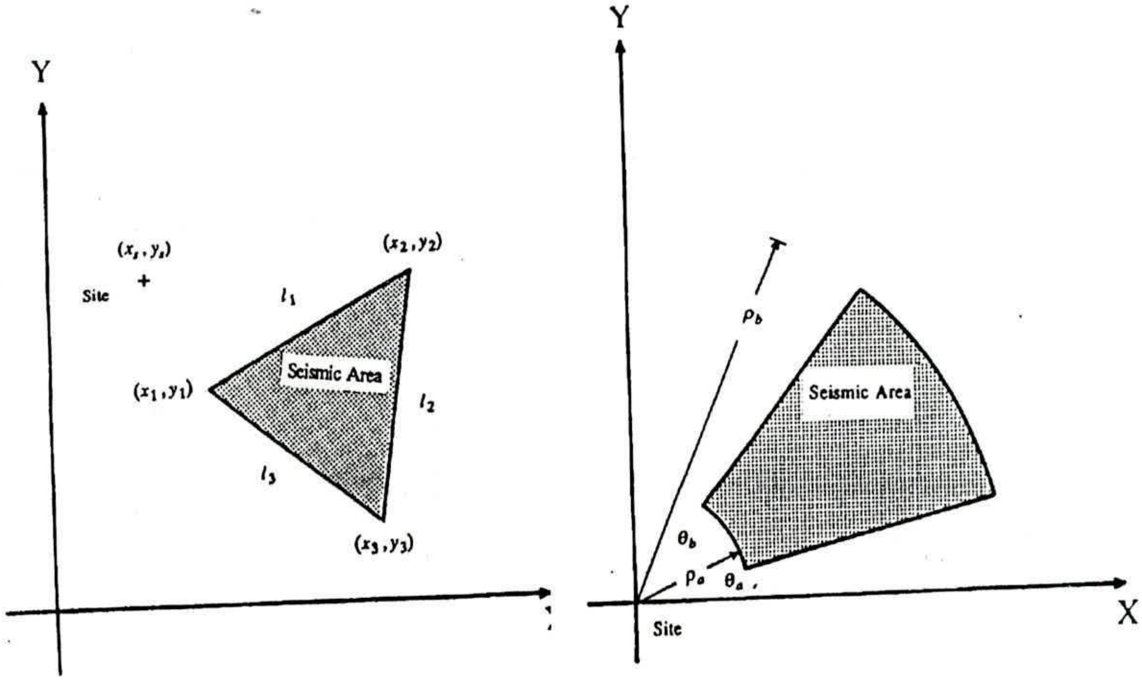
4.3.3 Regression Analysis

Seismic parameter b was evaluated from G-R relationship (Gutenberg and Richter, 1944), a method utilizing extreme, instrumented and complete catalogs. Linear regression was applied to each site which is taken as the centre of an area of 250 km radius where past earthquakes are likely to occur again. The hazard curves of Mean Annual Rate of Exceedance (v) versus Peak Ground Acceleration (PGA) and Mean Annual Rate of Exceedance (v) versus Earthquake Magnitude (M) were generated at the rock levels. Figure 4.5 and 4.6 show the regression curves fitting for Cox's Bazar Municipal area. The hazard in terms of the rock level PGA values and probable earthquake magnitude corresponding to return periods of 200 years were quantified from equation 4.3 and 4.4 as, 0.18g and 8.26 consecutively. Since the largest Magnitude earthquake around the 350-450 km radius of the study area is 7.9 and around 250 km radius is 6.5, a cut-off Magnitude of 7.5 earthquake was considered as the expected one in 200 years return period and thus used for further analyses.



(a) Point

(b) Line



(c) Different area sources

Figure 4.1: Different source models

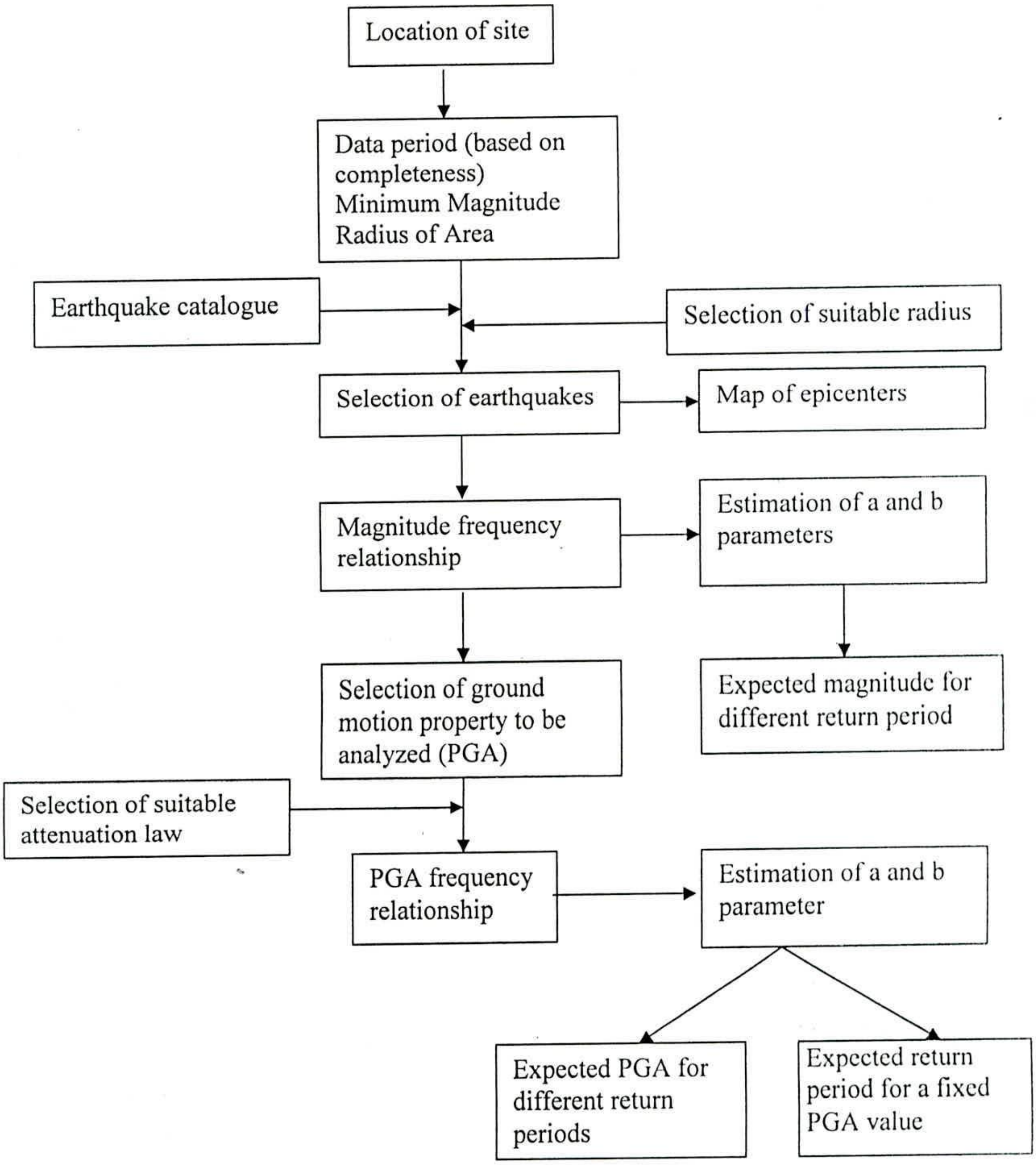


Figure 4.2: Schematic flow of PGA determination at bedrock

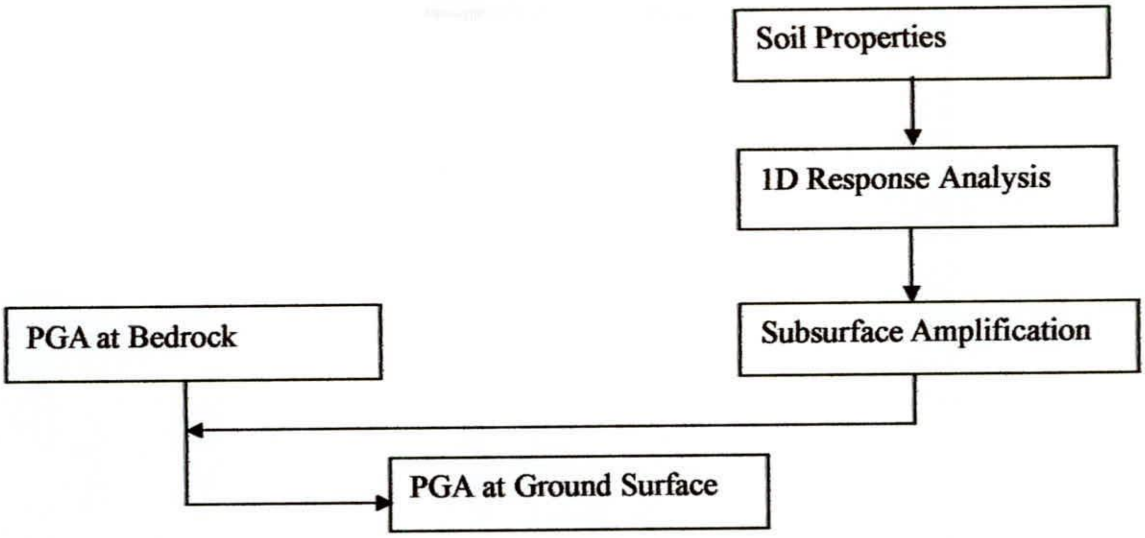


Figure 4.3: Flow chart for PGA determination at ground surface

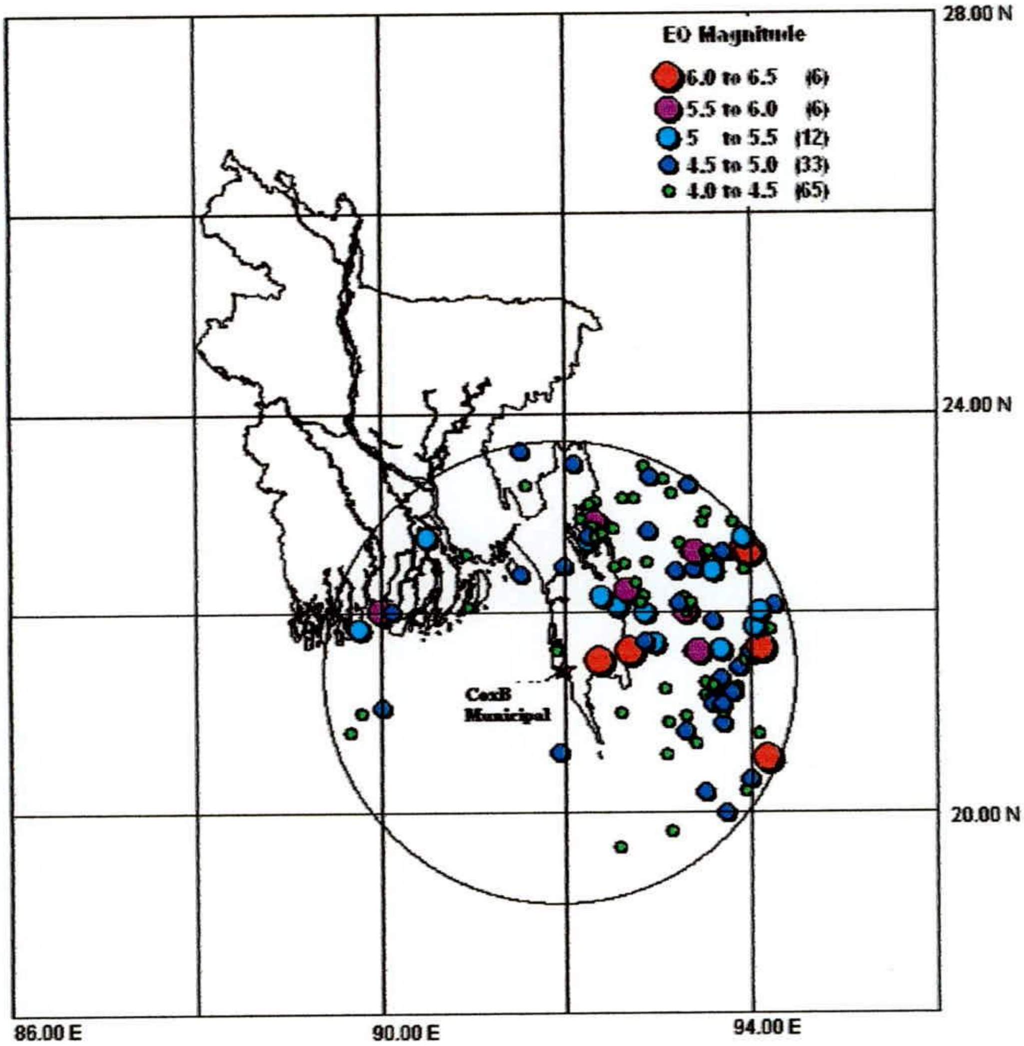


Figure 4.4: Historical Earthquakes around Cox's Bazar Municipal

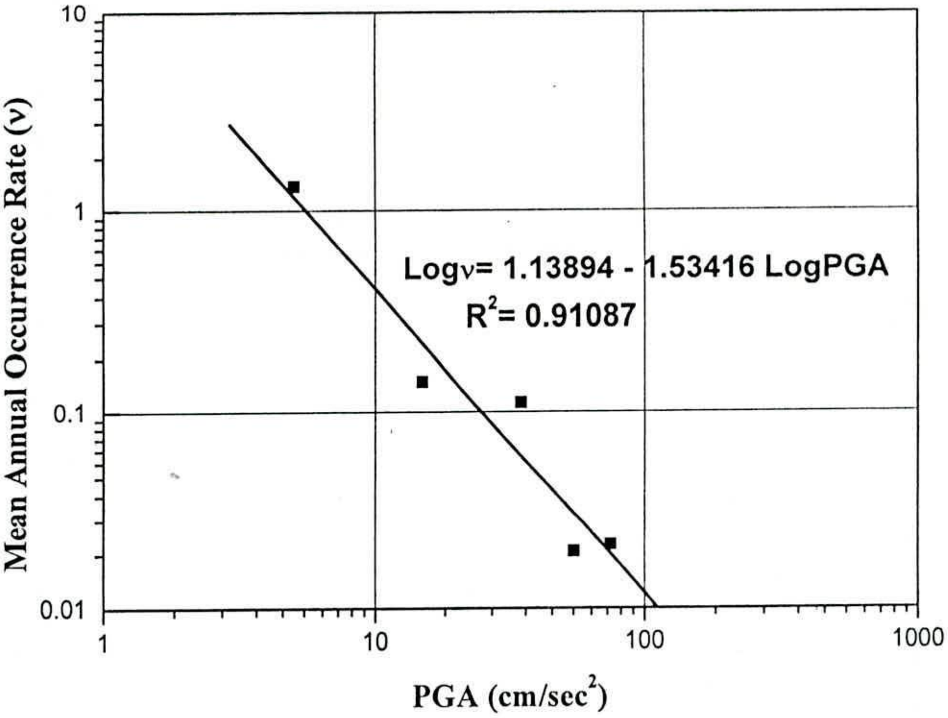


Figure 4.5: PGA versus mean occurrence rate for Cox's Bazar Municipal

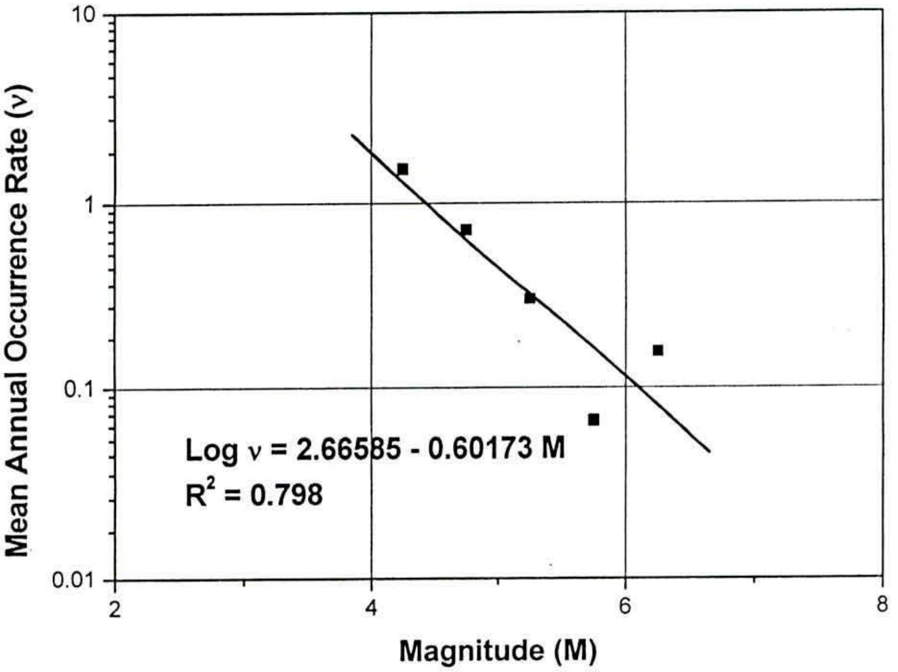


Figure 4.6: Magnitude versus mean occurrence rate for Cox's Bazar Municipal

4.4 Local Site Effects

Seismic zonation maps for strong-ground shaking, liquefaction and landslide can play a significant role in mitigating the effects of earthquakes. In Chapter 2 it is discussed how a geographic information system (GIS) provides an ideal environment for compiling and integrating regional databases of spatial geologic and geotechnical information for purposes of seismic zonation. The main aim of this research is the development of seismic hazard maps considering local site attributes for Cox's Bazar Municipality.

4.4.1 Site Amplification Analysis

For site amplification analysis, shear wave velocity for 26 borehole data up to a maximum depth of 30m were calculated by using equation of Tamura and Yamazaki (2002) presented in Table 2.7. This empirical relation combines both depth and SPT-N value with soil conditions. A soil database of 26 boreholes was developed in MS-EXCEL. In this study, the engineering bedrock was assumed to be the layer at which the shear wave velocity (V_s) exceeds 400 m/s, which exist almost 30 m deep from the surface of the study area. The calculations show that the shear wave velocities at bedrock level vary from 400 m/s to 500 m/s.

Vibration characteristics plotted as transfer functions at different points of the study area were estimated by employing one dimensional wave propagation program SHAKE. The computations were made in the frequency range 0 to 20 Hz at frequencies every 0.05 Hz interval. The loss of energy of seismic waves in the soil layers was also considered. An estimation of the fundamental frequency and the maximum value of the amplification were obtained for each site from the transfer functions. Typical graphical representation of frequency versus amplitude is shown in Figure 4.7. For estimating the site amplification and predominant frequency from the two approaches were taken into consideration. To evaluate the extreme and worst hazard condition first peak of the plot was considered assuming that the largest amplification of the soil will occur at the lowest natural frequency or its fundamental frequency. The other approach involved the estimation of average horizontal spectral amplification (AHSA). This was adopted to derive more precise quantitative relationship between surface geology and local amplification. In this case the average amplification value was estimated in the 0.1-10.0 Hz frequency range (Shima, 1978) and the frequency value corresponding to that average amplification factor were selected. Table 4.2 presents the site amplification factors and corresponding predominant frequencies estimated at different locations of Cox's Bazar Municipal area.

The computed results from the site amplification potential analysis were exported to a GIS environment for further processing and visualization. They were classified into different classes according to the extent of amplification factors and ranges of frequencies. The results were plotted on the Cox's Bazar municipal area map using spatial interpolation among the borehole locations and converting the vectorial point features into continuous raster map through grid generation. Thus microzonation maps (Figure 4.8 to Figure 4.11) based on site amplification (times) and fundamental frequencies (hz) were developed considering the two conditions.

In this study, the intensity attenuation law (Equation 4.11) for proposed by Sabri (2001) was also used to verify the surface PGA. These intensities were converted into PGAs by following Trifunac and Brady (1975) equation 4.12. The maximum PGA obtained from this relationship for alluvial soil was 0.25g for M = 6.24 earthquake of 1959. This PGA was further compared to the ground surface PGA obtained through imposing subsurface amplification to the bedrock PGA from McGuire (1978) equation.

$$I = 8.378+1.283*M-0.0007483*r-4.9*\log(r) \qquad (4.11)$$

$$\log PGA = 0.014+0.3 * I \qquad (4.12)$$

where, I = Intensity of Earthquake

M = Magnitude of Earthquake and

r = Hypocentral Distance

Table 4.2: Results of Amplification factor and corresponding predominant frequency at different locations of Cox's Bazar Municipal Area

Sl No.	**Location**	**Frequency (Hz)**		**Amplification**	
		1st Peak	**AHSA**	**1st Peak**	**AHSA**
1	Diabetic Hospital Cyclone Shelter	5.3	3.8	2.0	1.7
2	Baharchhara High School	5.2	3.6	2.3	1.7
3	Shaibal Hotel Water Tank	5.2	3.4	2.2	1.6
4	Golf Field Laboni Moore	5.0	3.3	2.0	1.6
5	Shamudra Bilash, Middle Saikat Para	5.3	3.6	2.0	1.6
6	Baharchhara Gol Chattar Field	5.9	4.1	2.1	1.7
7	Cox's Bazar Nursery	6.1	4.1	2.0	1.6
8	Cox's Bazar KG & Model High School	5.5	3.7	2.2	1.6
9	Fulbagh, Rice Market Road	4.2	3.6	2.2	1.6
10	Tekpara, Near Pond	4.6	3.2	3.6	2.0
11	Rumaliar Chhra, HSA Road	7.1	5.1	2.9	2.2
12	Bibekanondo Bidya Niketon, Ghonarpara	6.8	4.4	1.9	1.6
13	76/A, Kalatoli-3	5.9	4.2	2.2	1.7
14	Cox's bazar Press Club	5.6	4.0	2.6	1.9
15	Central Govt. PS cum CS	7.7	5.5	2.0	1.6
16	Peskarpara Govt. PS cum CS	8.0	5.2	2.8	2.1
17	Kosturaghat Govt. PS	7.7	5.2	2.2	1.7
18	Kolatoli World Vision MCS	8.1	5.4	2.2	1.7
19	Baitus Sharaf Jameya Mosque	7.9	4.7	1.9	1.5
20	Bangladesh Red Crescent Society	7.3	4.8	2.0	1.6
21	Bangladesh Water Development Board	7.2	4.8	1.9	1.6
22	Tekpara Govt. PS	5.7	4.1	3.2	2.1
23	Ghonarpara, Near Kaderia Non-Govt. PS	7.3	4.8	2.2	1.7
24	Mosjid Compound, Ice Factory Road	3.8	2.8	2.8	2.1
25	Ramkrisna Shebasram, Baiddorghona	5.3	3.3	2.4	1.6
26	Primary Education Officers' Compund	11.2	4.3	2.4	1.5

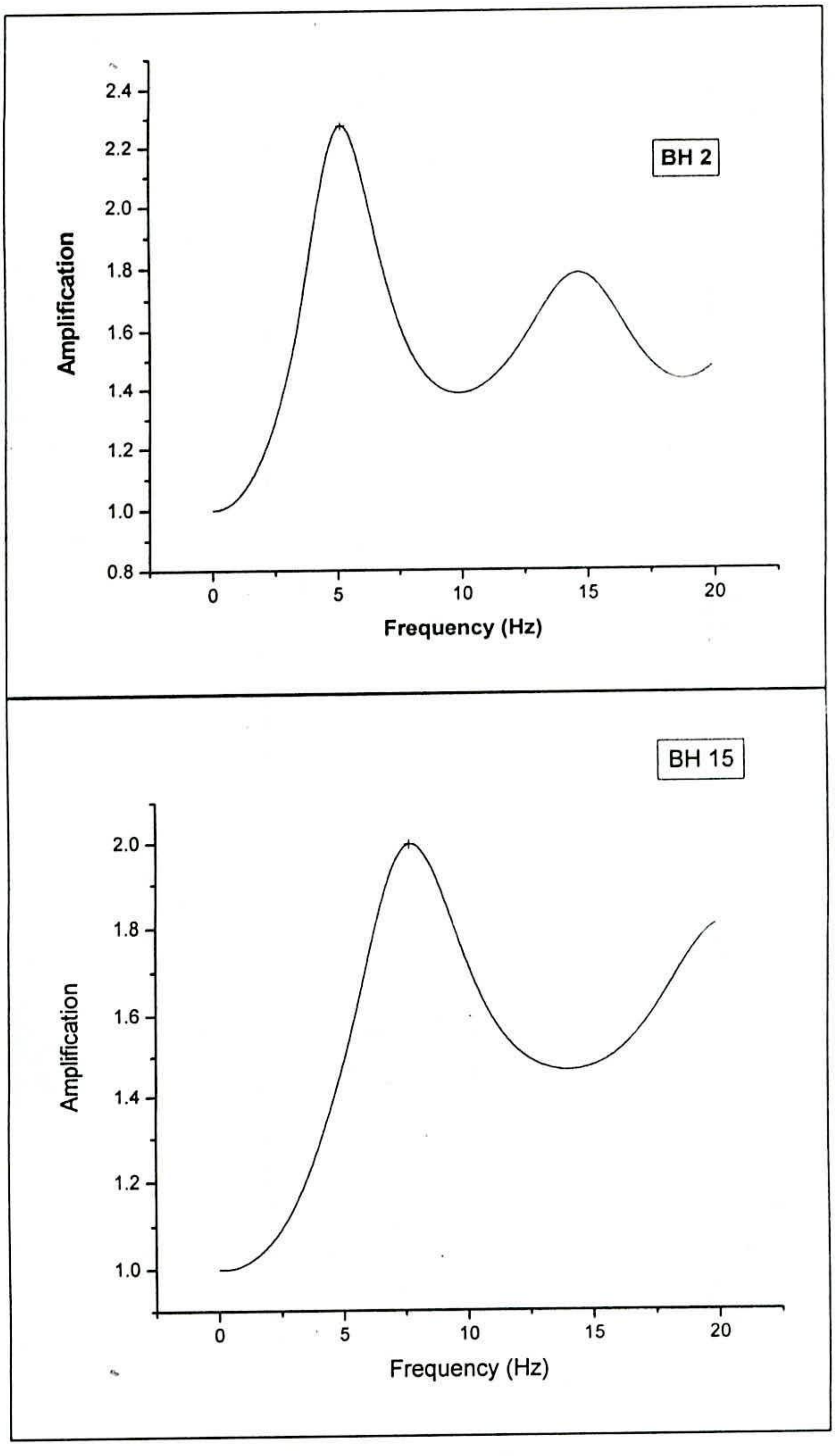


Figure 4.7: Typical Plots of transfer functions for two different boreholes conducted at the study area

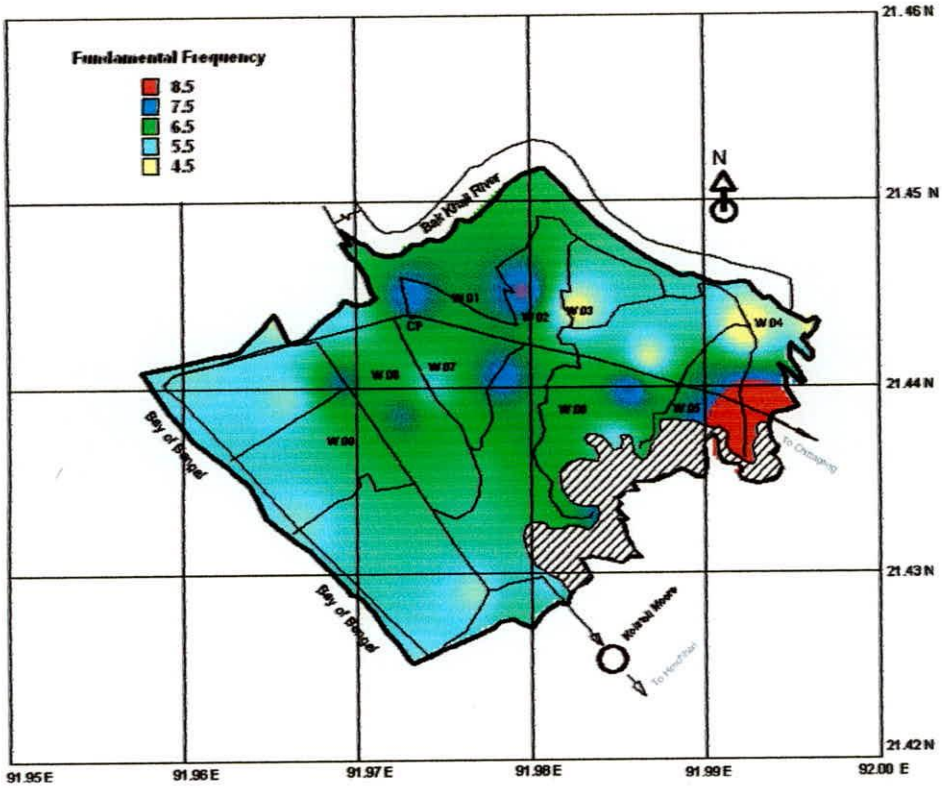


Figure 4.8: Microzonation map based on fundamental frequencies considering extreme condition

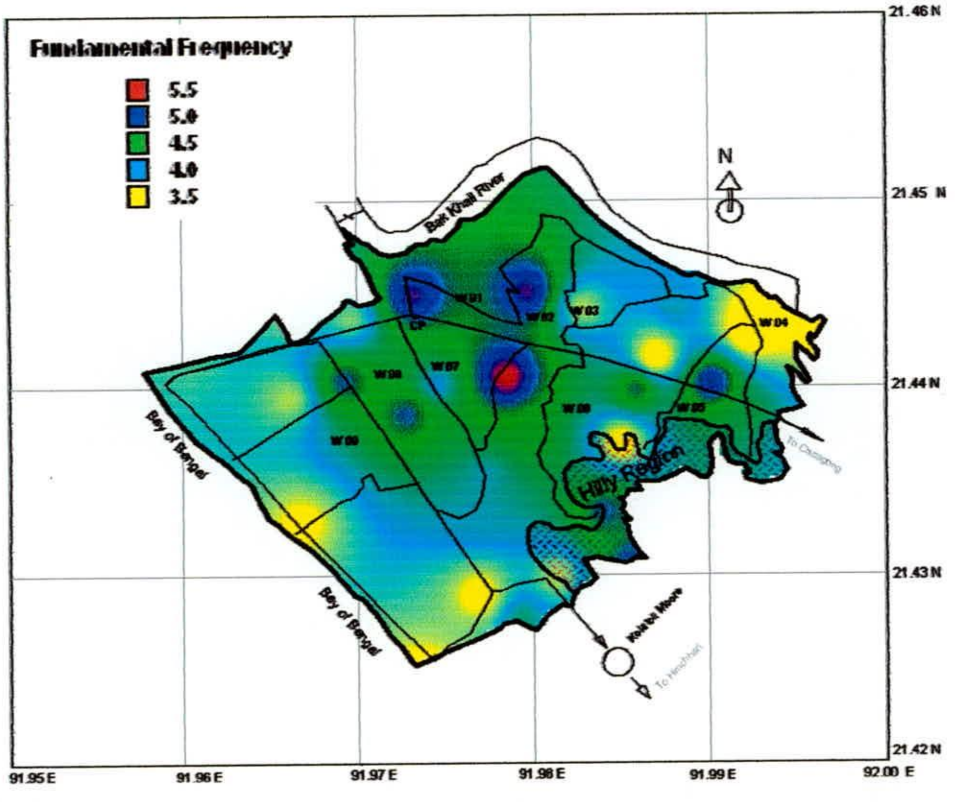


Figure 4.9: Microzonation map based on fundamental frequencies considering AHSA

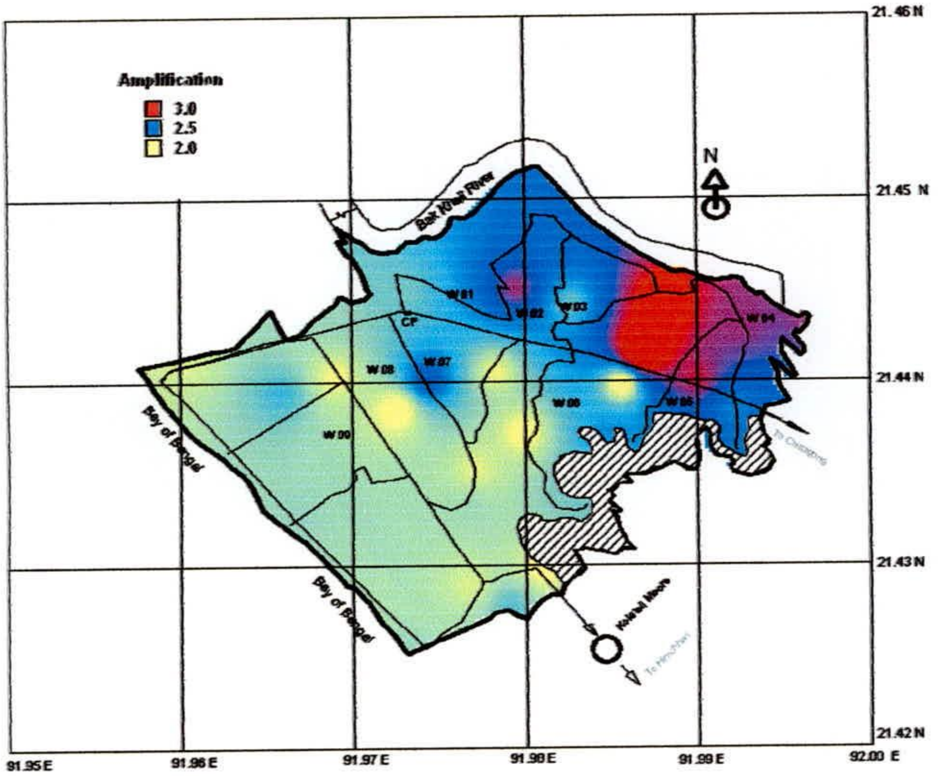


Figure 4.10: Microzonation map based on maximum amplification considering extreme condition

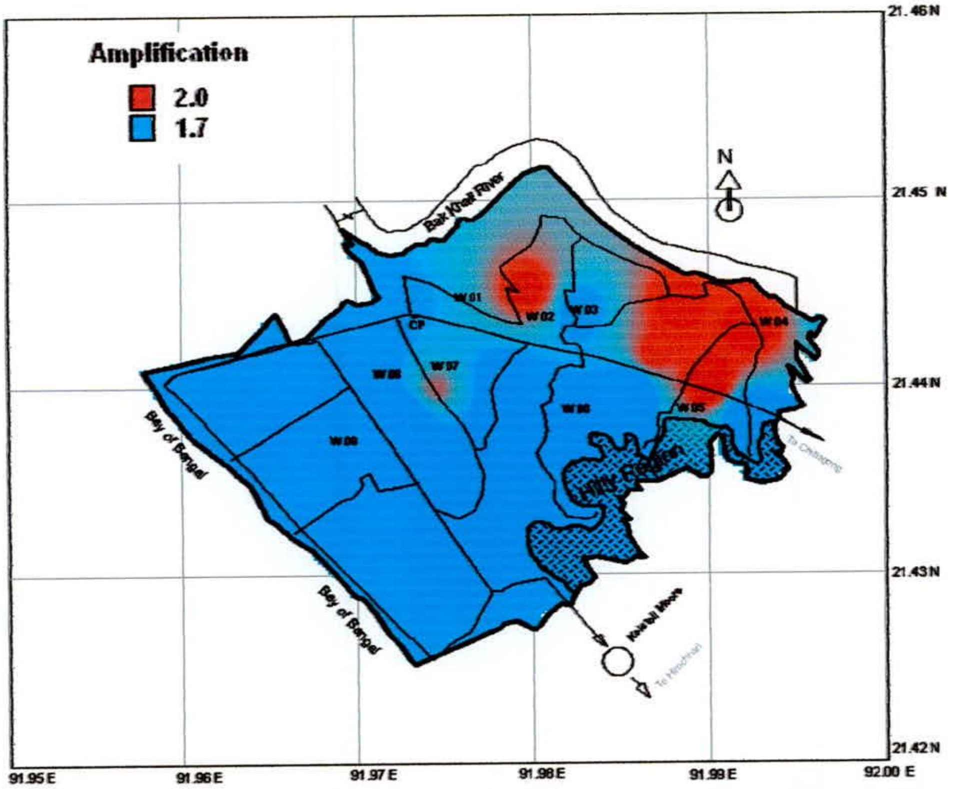


Figure 4.11: Microzonation map based on maximum amplification considering AHSA

4.4.2 Liquefaction Analysis

From the site amplification study, the average amplification factor was found to be 2.3 and 1.7 respectively for extreme and average conditions. The rock level PGA for return period of 200 years was estimated as 0.18g. Thus the surface level PGAs calculated by multiplying the rock level PGA with amplification factor were 0.41 g at extreme condition and 0.31 g considering AHSA. These PGAs were used in liquefaction analyses for the two cases. Figure 4.12 shows the flow chart for liquefaction potential analysis for the study area. Since the largest earthquake magnitude has been considered as 7.5, the relevant Magnitude Scaling Factor (MSF), as shown in Table 2.8, was selected as 1.0. Particle diameter data for a particular depth of soil was obtained from grain size distribution curves (Appendix E) which were used to find out the CRR values from curves (Figure 2.24). Borehole data from 26 points in Cox's Bazar municipal area were stored in MS Excel Worksheets. All the boring data include SPT N- values measured at 1.5 m interval. To consider the worst condition ground water table have been assumed at a depth of 1.5 m. The liquefaction resistance factor, F_L, for the top 20 m of soil, and the resulting liquefaction potential, I_L for the 26 sites were calculated. The flow chart of liquefaction analysis used in this study is shown in Figure 4.12. Result of Liquefaction potential was provided in a tabulated form in Table 4.3. The computed results (Table 4.3) from the liquefaction potential analysis were exported to a GIS environment and plotted on the Cox's Bazar district map dividing the study area into different zones according to the ranges of liquefaction potential index values (Table 2.9). Thus microzonation maps were developed for liquefaction potential for the two conditions which have been shown as Figure 4.13 and Figure 4.14. Microzonation maps were also developed based on the surface PGA (Figure 4.16 and Figure 4.17) expected to be experienced by the area based on the surface PGAs calculated for different sites.

Table 4.3: Liquefaction Potential Indices for different Locations of Cox's Bazar Municipal area

Sl No.	Location	Liquefacion (Extreme)		Liquefacion (Average)	
1	Diabetic Hospital Cyclone Shelter	43	high	20	high
2	Baharchhara High School	102	high	38	high
3	Shaibal Hotel Water Tank	141	high	74	high
4	Golf Field Laboni Moore	43	high	9	moderate
5	Shamudra Bilash, Middle Saikat Para	89	high	37	high
6	Baharchhara Gol Chattar Field	82	high	54	high
7	Cox's Bazar Nursery	25	high	8	moderate
8	Cox's Bazar KG & Model High School	81	high	35	high
9	Fulbagh, Rice Market Road	0	No	0	No
10	Tekpara, Near Pond	0	No	0	No
11	Rumaliar Chhra, HSA Road	0	No	0	No
12	Bibekanondo Bidya Niketon, Ghonarpara	0	No	0	No
13	76/A, Kalatoli-3	52	high	29	high
14	Cox's bazar Press Club	56	high	37	high
15	Central Govt. PS cum CS	4	low	1	low
16	Peskarpara Govt. PS cum CS	31	high	30	high
17	Kosturaghat Govt. PS	16	high	12	moderate
18	Kolatoli World Vision MCS	27	high	11	moderate
19	Baitus Sharaf Jameya Mosque	5	low	0	No
20	Bangladesh Red Crescent Society	4	low	1	low
21	Bangladesh Water Development Board	3	low	0	No
22	Tekpara Govt. PS	0	No	0	No
23	Ghonarpara, Near Kaderia Non-Govt. PS	41	high	29	high
24	Mosjid Compound, Ice Factory Road	128	high	100	high
25	Ramkrisna Shebasram, Baiddorghona	115	high	94	high
26	Primary Education Officers' Compund	20	high	13	moderate

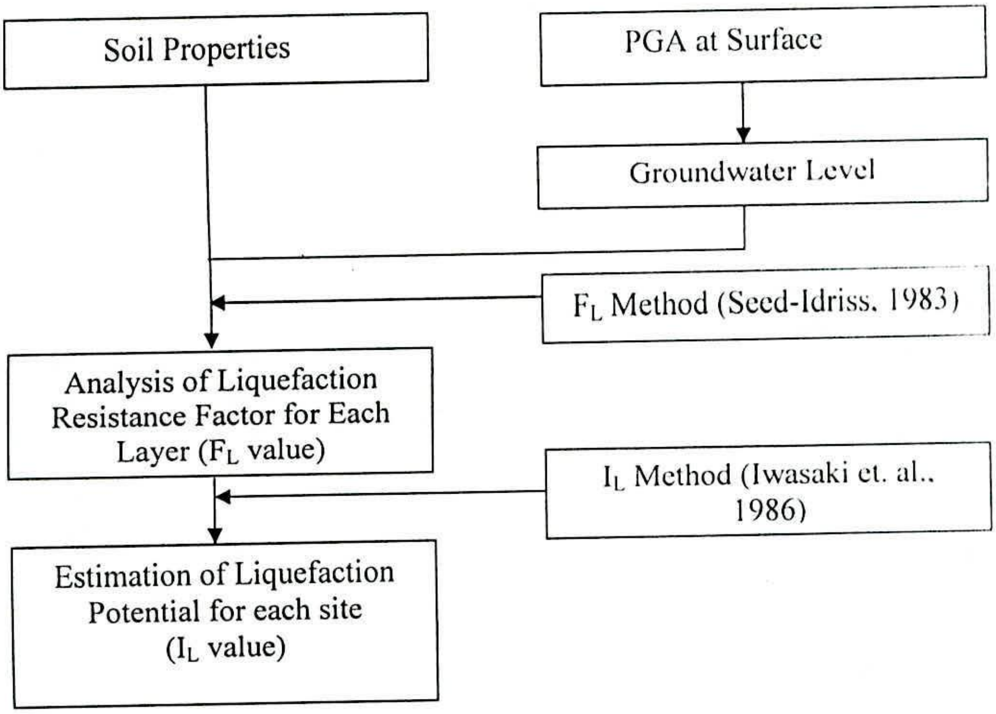


Figure 4.12: Flow chart of Liquefaction Analysis of the study area

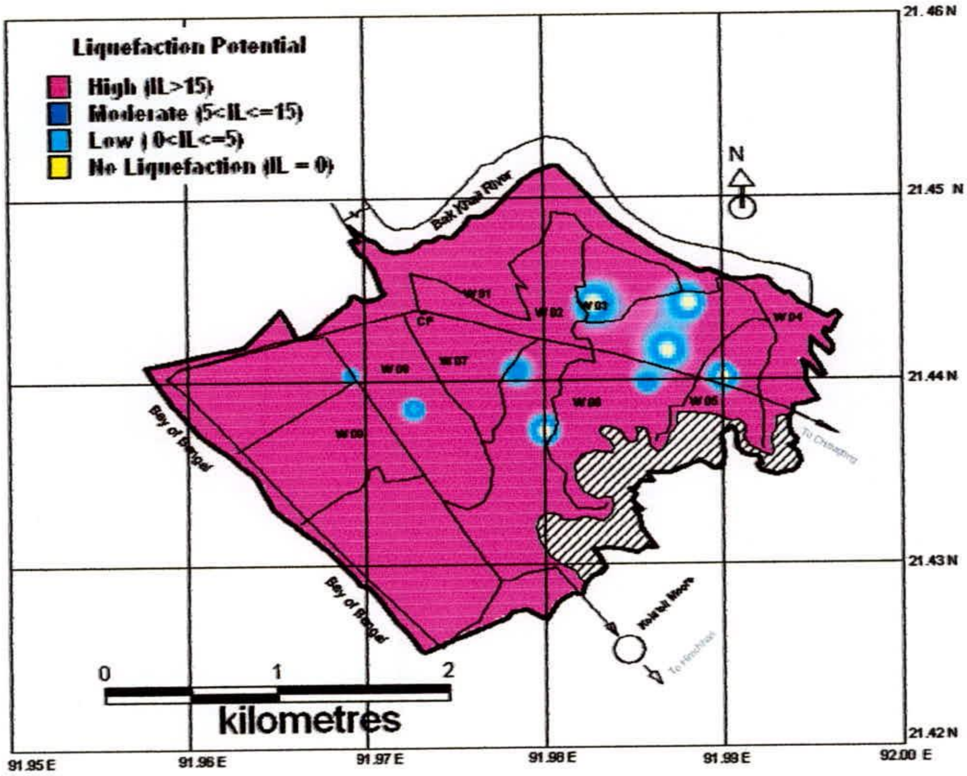


Figure 4.13: Microzonation map based on liquefaction potential considering extreme condition

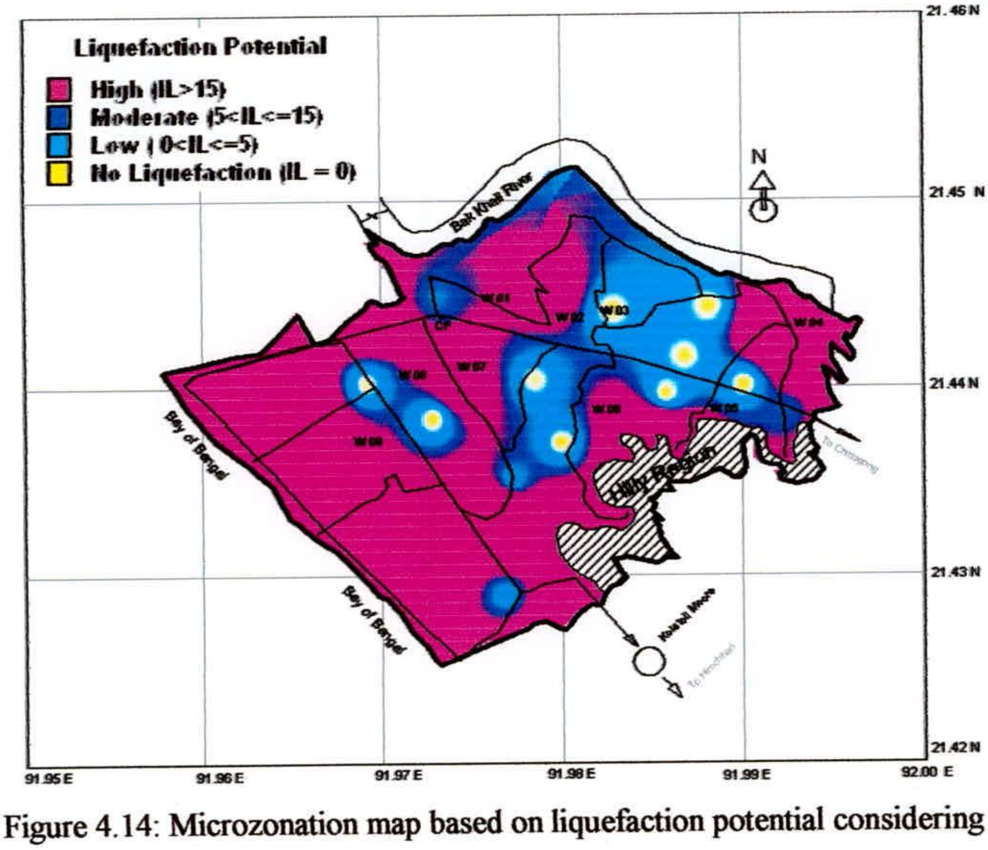


Figure 4.14: Microzonation map based on liquefaction potential considering AHSA

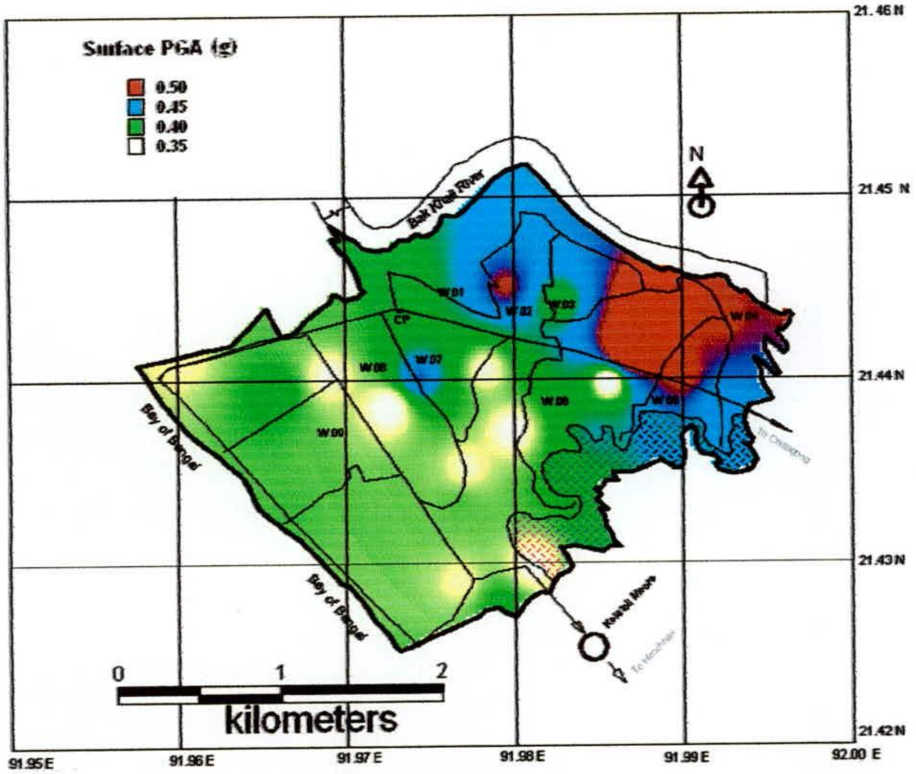


Figure 4.15: Map showing regional distribution of surface PGA considering extreme condition

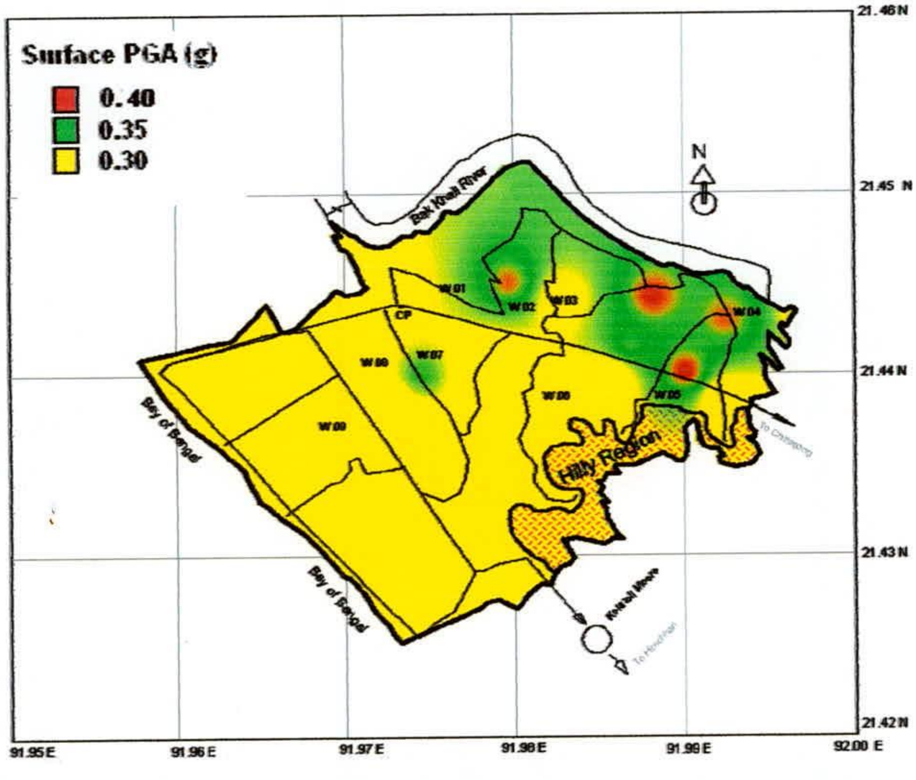


Figure 4.16: Map showing regional distribution of surface PGA considering AHSA

4.4.3 Landslide Potential Analysis

The overall stability failure mechanism is development of slip circles resulting in a deep sliding surface. This is a conventional soil mechanics stability problem. Pre-existing slip planes within the soil, cracker material can have a significant effect on slope stability. Stability analysis is carried out to evaluate the factor of safety against bearing capacity failure.

The program used for stability analysis is XSTABL, which is a fully integrated slope stability analysis program. XSTABL performs two dimensional limit equilibrium and analysis to evaluate the factor of safety for a layered slope using the simplified Bishop Method. The strength parameters of the slope and foundation materials required for the analyses could be obtained from consolidated undrained direct shear tests performed on soil samples. The minimum values of undrained cohesion (c_u) and undrained angle of internal friction (ϕ_u) were used in the slope stability analyses. The values of c_u and ϕ_u used in all the analyses have been provided in Appendix I. The location of the water table in all the slope sections was assumed to be well below the toe of the slopes. The height of the slope was considered as 30 m (100 ft) which was observed from field survey as the average height of the hills of Cox's Bazar. Generally the slopes were found to be 60° to 80°. Considering human activities and ongoing hill cutting activities the average slope of the hills were assumed to be 70°. From the analyses it was observed that only single data contained the representative value of 'satisfactory' Factor of Safety (Table 2.11, Chapter 2) and the rest were 'unsafe' (Table 2.11). Thus the landslide potential was categorized as 'high' and 'low' for Factor of Safety being greater than or equal to 1.2 and less than 1.2 consecutively. The corresponding Factor of Safety values have been exported to GIS and plotted on the Cox's Bazar municipality range. Thus the microzonation map based on landslide potential was developed which is shown as Figure 4.15.

Table 4.4: Summary of Landslide Potential Analysis

Sl No.	**Sample**	**Factor of Safety**
1	Hill behind P.T.I High School	1.44
2	Ghonarpara Hill	0.31
3	Light house Hill	0.69
4	Kolatoli Bypass Hill	0.68
5	Boiddorghona Hill	0.30
6	Kolatoli Saikat Para	0.58
7	Bus Terminal Hill	0.72
8	Khaja Monjil, Pahartoli	0.33
9	Circuit House Hill	0.60
10	Ghonerpara Road (M r. Subrata's House)	0.30
11	Boillarpara Temple Hill	0.31

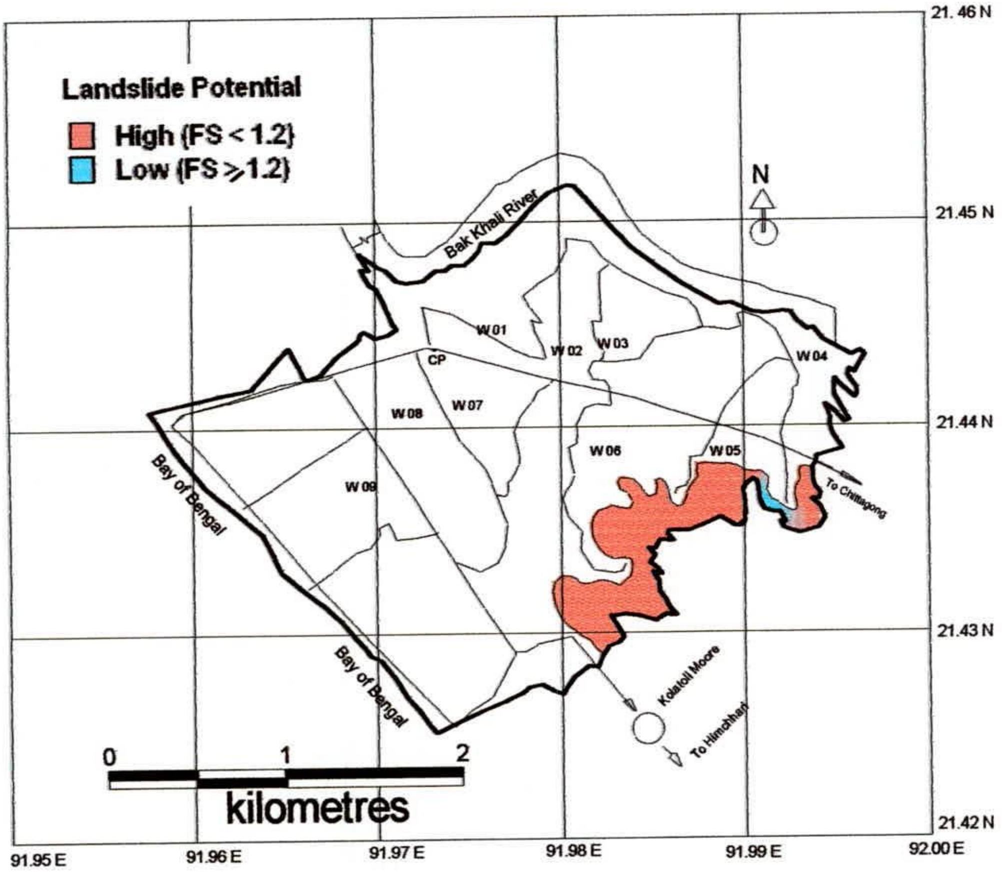


Figure 4.17: Microzonation map based on landslide potential in Cox's Bazar Municipal area

4.5 Seismic Hazard Integration

The most important endeavor of this study is the estimation of seismic hazards linked with the local site attributes of soil amplification, liquefaction, and landslide and then integrating them in such a manner so that a reflection of probable actual disaster consequences can be represented. It is not feasible to resolve how much of the potential hazard is discretely attributed by each local site effect. consequently the ultimate regional seismic hazard distribution is established on a weighted average combination of the hazards related with each effect.

4.5.1 Integration of Site Effects in the GIS Environment

Since every analysis region is different; the quantification of the secondary site effects and the weighting scheme for combining the various seismic hazards is considered to be heuristic, based on judgment and expert opinion about the influence of local site conditions in the region and the accuracy of the available geologic and geotechnical information. Figure 4.18 shows the flow chart for developing combined seismic hazard maps.

The rock level ground shaking in the region was determined as 0.18g. This PGA was considered as constant since the study area is small. The seismic intensity is basically a subjective one, based on the human sensations or damage during an earthquake. It was assumed that the final combined seismic hazard would be quantified in terms of Modified Mercalli Intensity (MMI) (Appendix K). The equation used here to convert PGA to intensity is developed by Trifunac and Brady (1975) and is given by Equation 4.12.

For the extreme condition the regional distribution of ground shaking hazards (MMI_{GS}) considering 2.0, 2.5 and 3.0 times amplification of the PGA were calculated and presented as Figure 4.19 (a) to 4.19 (c) and 4.20. The MMI scale is subjective and assigned as integer values, therefore the MMI_{GS} values are rounded to the nearest 0.5

Figure 4.13 shows the regional distribution of liquefaction potential in the study area categorized as "high" and "low". Figure 4.17 shows the qualitative description of landslide hazard in the region. For simplicity, areas were designated as having "high" and "low" landslide potential. The following heuristic rules are used to quantify the seismic hazards due to liquefaction and landslide:

MMI_{LIQ} / MMI_{LAN} $= MMI_{GS} +2$ (For region designated as "high")

MMI_{LIQ} / MMI_{LAN} $= MMI_{GS} +1$ (For region designated as "moderate") and otherwise

MMI_{LIQ} / MMI_{LAN} $= 0$

The rules for combining the various hazards are based on expert opinion (after Stephanie and Kiremidjian, 1994) about the relative accuracy of the hazard information and the behavior of the local geology. For this study, it is assumed that the ground-shaking hazard is the most accurate followed by liquefaction and landslide.

For this study, the possible combinations and their assumed weights are shown in Table 4.5. The final combined hazard (MMI_F) is computed as a weighted sum of the various hazards. The weights in each rule must sum to 1.0. The additive factor in rules in Table 4.5 is to account for the increase in hazard due to two or more hazards occurring. Table 4.6 summarizes the results of the calculations for combined hazard analysis which are presented by Figure 4.21(a) to Figure 4.21 (i). Figure 4.22 shows the regional distribution of combined hazards for extreme condition developed by overlaying the maps in Figure 4.21(a) to Figure 4.21(i).

Following the similar procedure calculations were performed for combined hazard analysis considering the approach based on average horizontal spectral amplification (AHSA). The results are shown in Table 4.7. The regional distribution of combined hazards for this condition is presented in Figure 4.23.

Figure 4.24 and 4.25 show the regional distribution of the final combined seismic hazard (MMI_F) for extreme condition and considering AHSA.

Table: 4.5: Quantification rules for seismic hazard (Stephanie and Kiremidjian, 1994)

Rule	**Possible hazards**	**Weighting Scheme for Final combined Hazard (MMI_F)**
(a)	Ground shaking	$MMI_F=MMI_{GS}$
(b)	Ground shaking + Liquefaction	$MMI_F= .55\ MMI_{GS} + .45MMI_{LIQ}+.5$
(c)	Ground shaking+ Landslide	$MMI_F=.65\ MMI_{GS} + .35MMI_{LAN}+.5$

1. MMI_F= Final Combined Hazard
2. MMI_{GS}= Ground Shaking Hazard
3. MMI_{LIQ}=Liquefaction Hazard
4. MMI_{LAN}=Landslide Hazard
5. MMI_F must be less than or equal 12

4.6. Summary

This chapter deals with the seismic hazard assessment and analysis of the ground susceptibility to that. Probabilistic seismic hazard assessment methodology has been used for this purpose. Using historical seismicity records and attenuation laws of Peak Ground Acceleration (PGA), the bedrock PGA was estimated as 0.18g for magnitude 7.5 earthquake with 200 years return period. The amplification factors and corresponding fundamental frequencies for the area were estimated. The surface PGA was calculated as 0.41g and 0.31g adopting on First Peak Amplification and Average Horizontal Spectral Amplification, respectively. The liquefaction potential of the boreholes points have been assessed by inducing these PGAs. Landslide potential has been assessed using slope stability program. The results obtained from these three analyses, respective microzonation maps have been developed in GIS environment. At the end, different possible hazards have been integrated to investigate the combined effects of more than one hazard. The combined intensity distribution for the area has also been presented in zonation map. The results of the combined hazard analysis considering two conditions, extreme and AHSA, have been summarized in Table 4.8.

Table 4.6: Combination of possible hazards for Cox's Bazar Municipal Area considering extreme condition due to a scenario event equivalent to M= 7.5 Earthquake

<table>
<tr><th colspan="2">Possible Ground Shaking Hazards</th><th>Intensity (MMI_F)</th><th>Area (sq km)</th><th>Area (%)</th><th>Figure No.</th></tr>
<tr><td colspan="2">2.0 times Amplification</td><td>VIII</td><td>3.20</td><td>47.26</td><td>4.19(a)</td></tr>
<tr><td colspan="2">2.5 times Amplification</td><td>IX</td><td>2.87</td><td>42.36</td><td>4.19(b)</td></tr>
<tr><td colspan="2">3.0 times Amplification</td><td>IX</td><td>0.70</td><td>10.38</td><td>4.19(c)</td></tr>
<tr><th>Possible Hazards</th><th>Combination of Possible Hazards</th><th>Intensity (MMI_F)</th><th>Area (sq km)</th><th>Area (%)</th><th>Figure No.</th></tr>
<tr><td rowspan="6">Ground Shaking + Liquefaction</td><td>2.0 times Amplification + High Liquefaction</td><td>X</td><td>2.95</td><td>43.62</td><td>4.21(a)</td></tr>
<tr><td>2.5 times Amplification + High Liquefaction</td><td>X</td><td>2.40</td><td>35.50</td><td>4.21(b)</td></tr>
<tr><td>3.0 times Amplification + High Liquefaction</td><td>X</td><td>0.54</td><td>7.96</td><td>4.21(c)</td></tr>
<tr><td>2.0 times Amplification + Low Liquefaction</td><td>VIII</td><td>0.13</td><td>1.95</td><td>4.21(d)</td></tr>
<tr><td>2.5 times Amplification + Low Liquefaction</td><td>IX</td><td>0.06</td><td>0.93</td><td>4.21(e)</td></tr>
<tr><td>3.0 times Amplification + Low Liquefaction</td><td>IX</td><td>0.19</td><td>2.75</td><td>4.21(f)</td></tr>
<tr><td rowspan="3">Ground Shaking + Landslide</td><td>2.0 times Amplification + High Landslide</td><td>X</td><td>0.11</td><td>1.65</td><td>4.21(g)</td></tr>
<tr><td>2.5 times Amplification + High Landslide</td><td>X</td><td>0.42</td><td>6.25</td><td>4.21(h)</td></tr>
<tr><td>2.5 times Amplification + Low Landslide</td><td>IX</td><td>0.02</td><td>0.23</td><td>4.21(i)</td></tr>
</table>

Table 4.7: Combination of possible hazards for Cox's Bazar Municipal Area considering AHSA due to a scenario event equivalent to M= 7.5 Earthquake

Possible Ground Shaking Hazards		**Intensity (MMI_F)**	**Area (sq km)**	**Area (%)**
1.7 times Amplification		VIII	6.01	88.81
2.0 times Amplification		VIII	0.76	11.19
Possible Hazards	**Combination of Possible Hazards**	**Intensity (MMI_F)**	**Area (sq km)**	**Area (%)**
Ground Shaking + Liquefaction	1.7 times Amplification + High Liquefaction	X	3.51	51.79
	2.0 times Amplification + High Liquefaction	X	0.43	6.30
	1.7 times Amplification + Moderate Liquefaction	IX	1.27	18.81
	2.0 times Amplification + Moderate Liquefaction	IX	0.06	0.83
	1.7 times Amplification + Low Liquefaction	VIII	0.64	9.41
	2.0 times Amplification + Low Liquefaction	VIII	0.25	3.63
Ground Shaking + Landslide	1.7 times Amplification + High Landslide	IX	0.53	7.78
	1.7 times Amplification + Low Landslide	VIII	0.02	0.24

Table 4.8: Comparison of the results obtained as Final Combined Intensity and affected areas for different hazard combinations considering Extreme Condition and AHSA

Combined Intensity (MMI$_F$)	**Based on First Peak Amplification (Extreme Condition)**		**Based on Average Horizontal Spectral Amplification (AHSA) (Refined Condition)**	
	Possible Ground Shaking Hazards	**Area (%)**	**Possible Ground Shaking Hazards**	**Area (%)**
IX	2.5 times Amplification 3.0 times Amplification	42.36 10.38	-	-
VIII	2.0 times Amplification	47.26	1.7 times Amplification 2.0 times Amplification	88.81 11.19
MMI$_F$	**Combination of Possible Hazards**	**Area (%)**	**Combination of Possible Hazards**	**Area (%)**
X	2.0 times Amplification + High Liquefaction 2.5 times Amplification + High Liquefaction 3.0 times Amplification + High Liquefaction 2.0 times Amplification + High Landslide 2.5 times Amplification + High Landslide	43.62 35.50 7.96 1.65 6.25	1.7 times Amplification + High Liquefaction 2.0 times Amplification + High Liquefaction	51.79 6.30
IX	2.5 times Amplification + Low Liquefaction 3.0 times Amplification + Low Liquefaction 2.5 times Amplification + Low Landslide	0.93 2.75 0.23	1.7 times Amplification + Moderate Liquefaction 2.0 times Amplification + Moderate Liquefaction 1.7 times Amplification + High Landslide	18.81 0.83 7.78
VIII	2.0 times Amplification + Low Liquefaction	1.95	1.7 times Amplification + Low Liquefaction 2.0 times Amplification + Low Liquefaction 1.7 times Amplification + Low Landslide	9.41 3.63 0.24

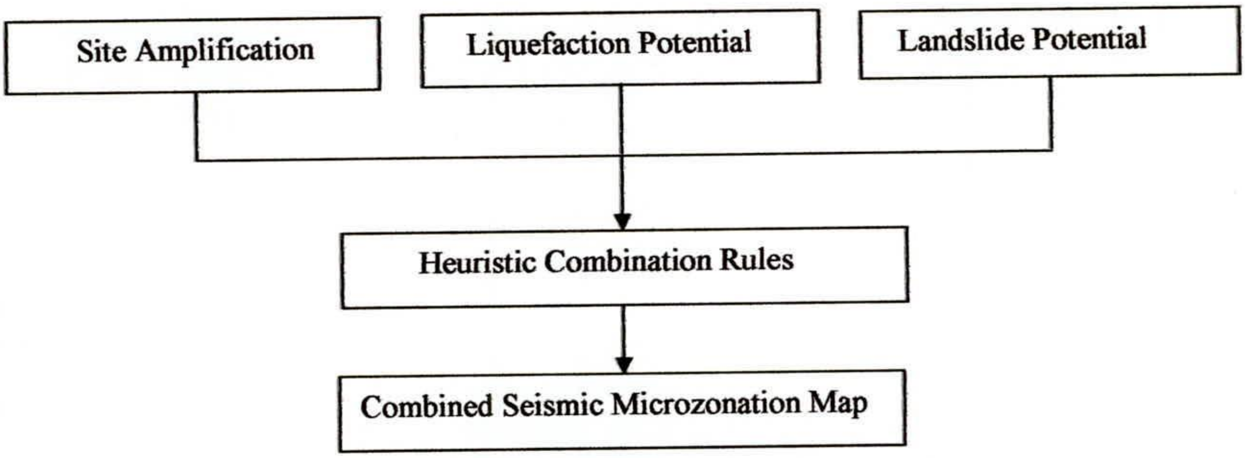


Figure 4.18: Flow chart for Combined Seismic Hazard Map

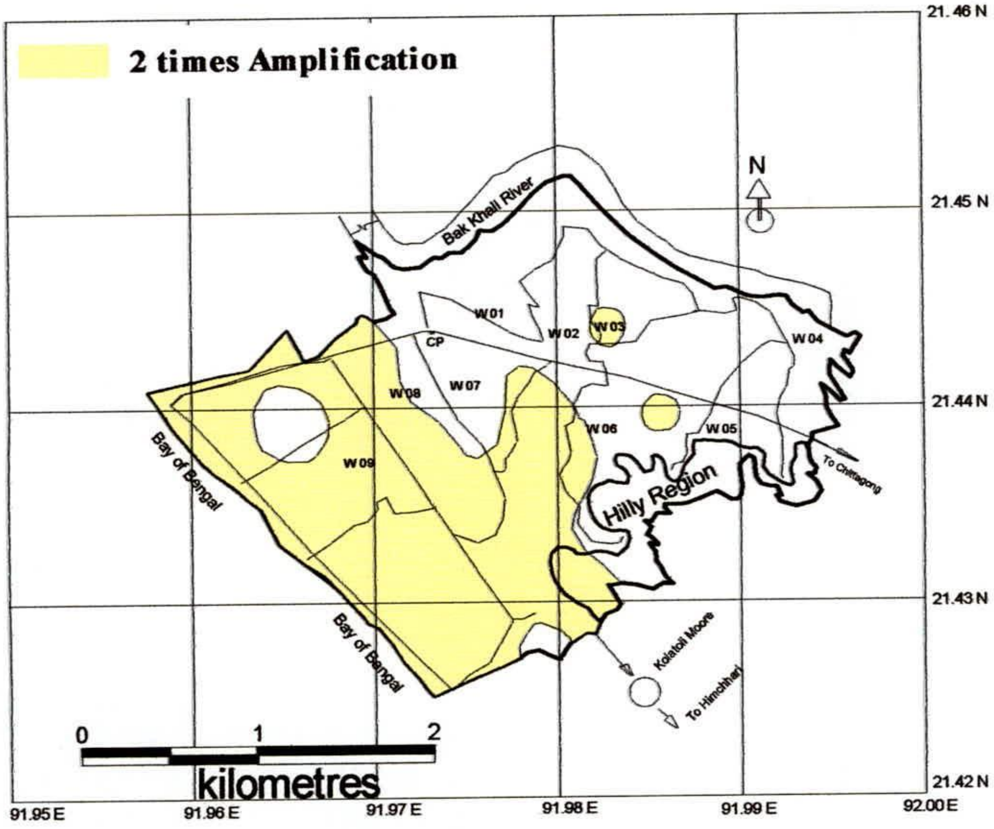


Figure 4.19(a): Map showing only 2.0 times amplification for extreme condition

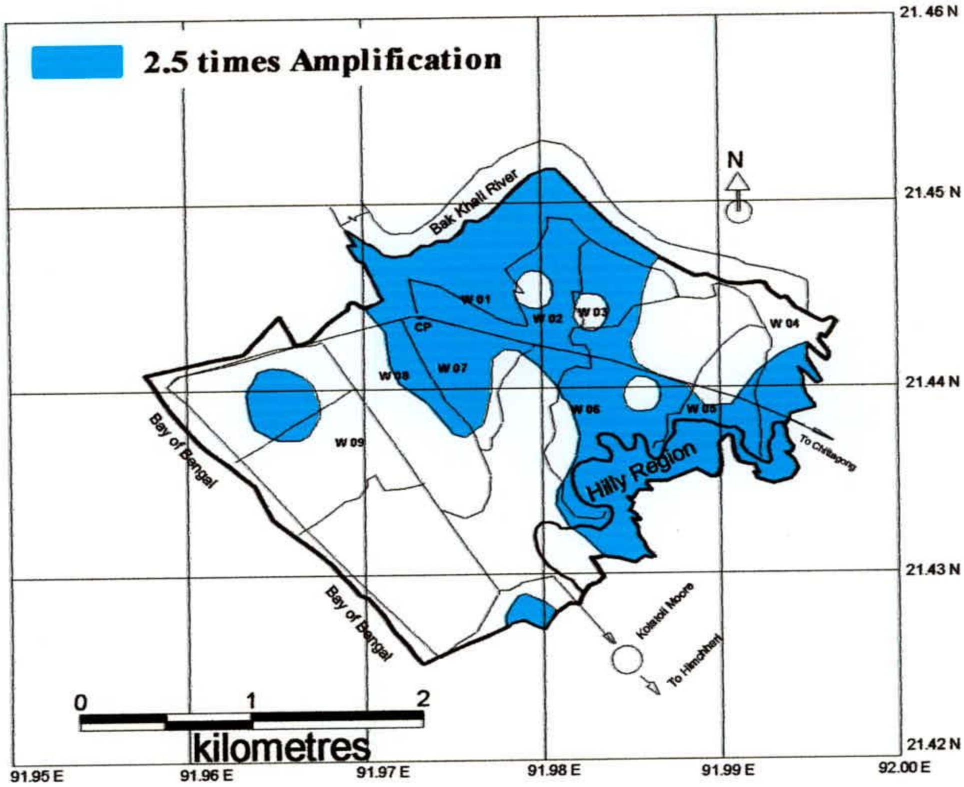


Figure 4.19(b): Map showing only 2.5 times amplification for extreme condition

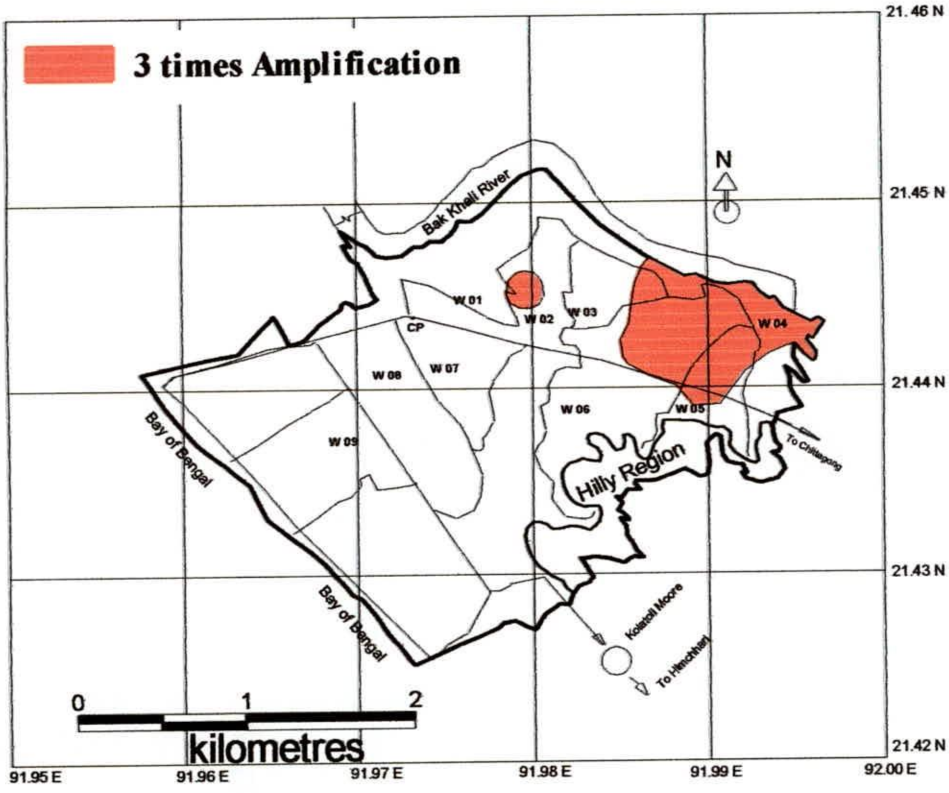


Figure 4.19(c): Map showing only 3.0 times amplification for extreme condition

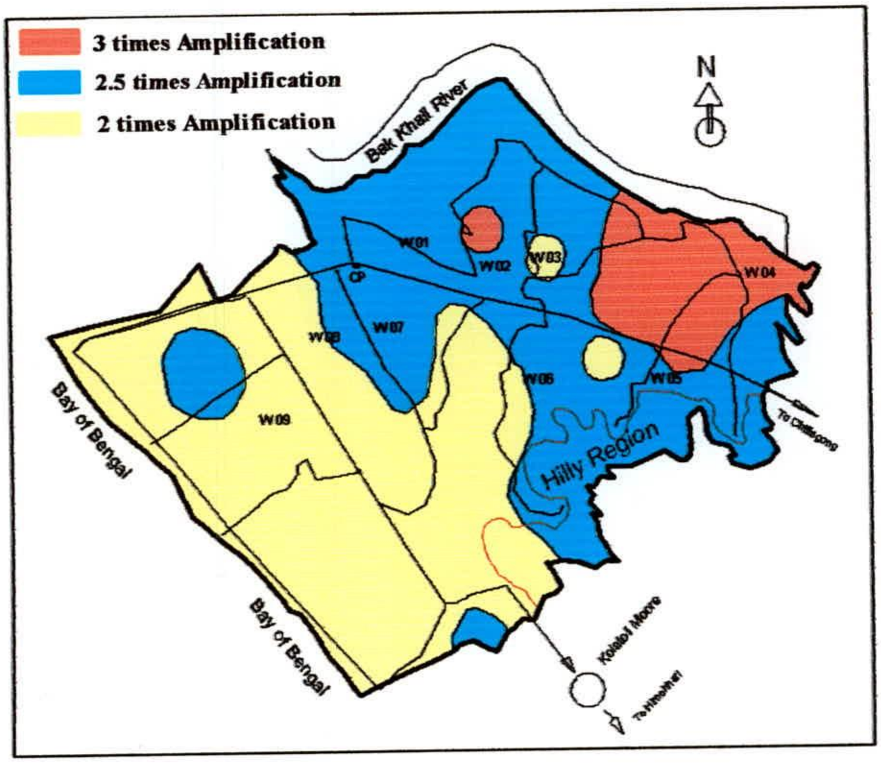


Figure 4.20: Map showing the possible Ground Shaking Hazards for extreme conditions over the area

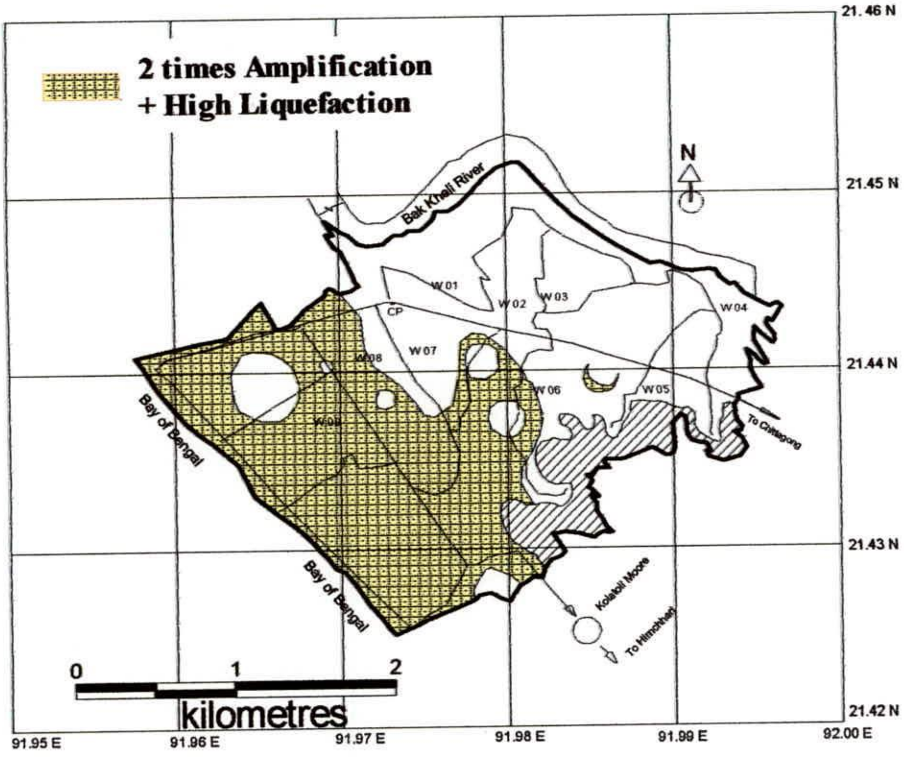


Figure 4.21(a): Map showing only 2.0 times Amplification with High Liquefaction for extreme condition

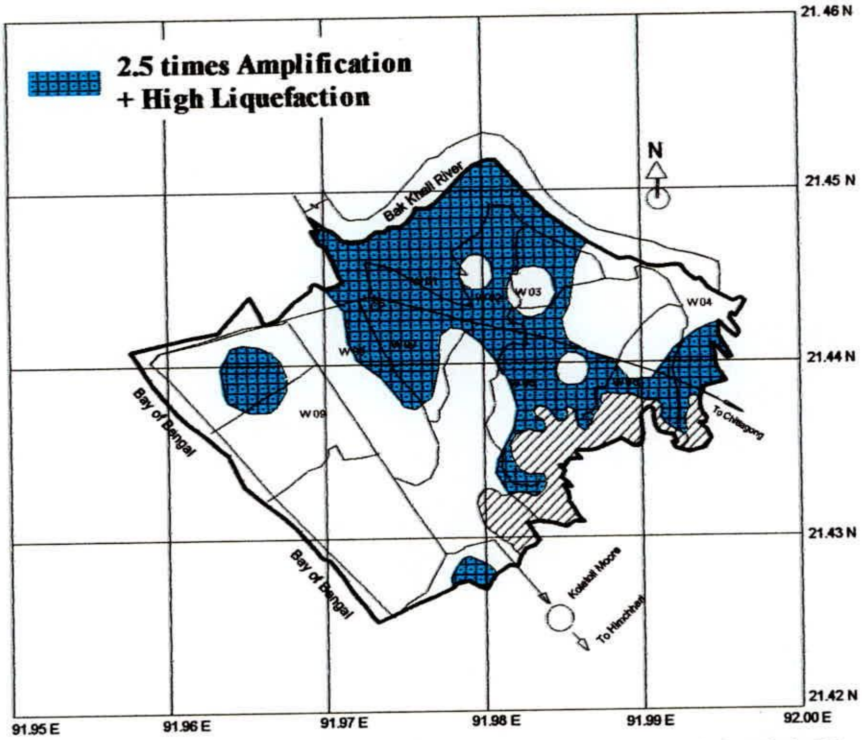


Figure 4.21(b): Map showing only 2.5 times Amplification with High Liquefaction for extreme condition

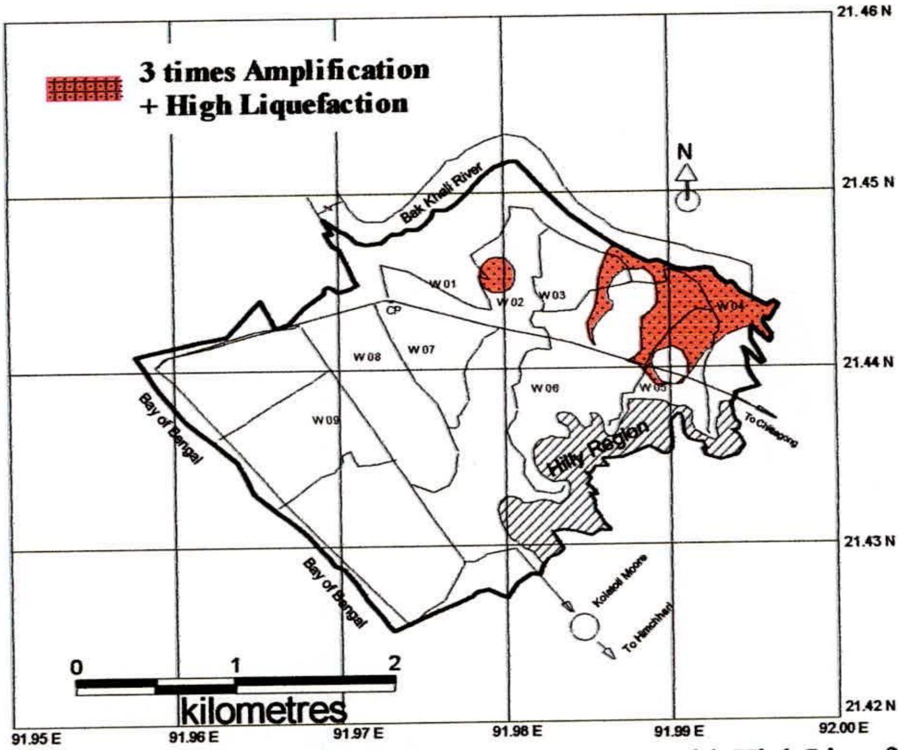


Figure 4.21(c): Map showing only 3.0 times Amplification with High Liquefaction for extreme condition

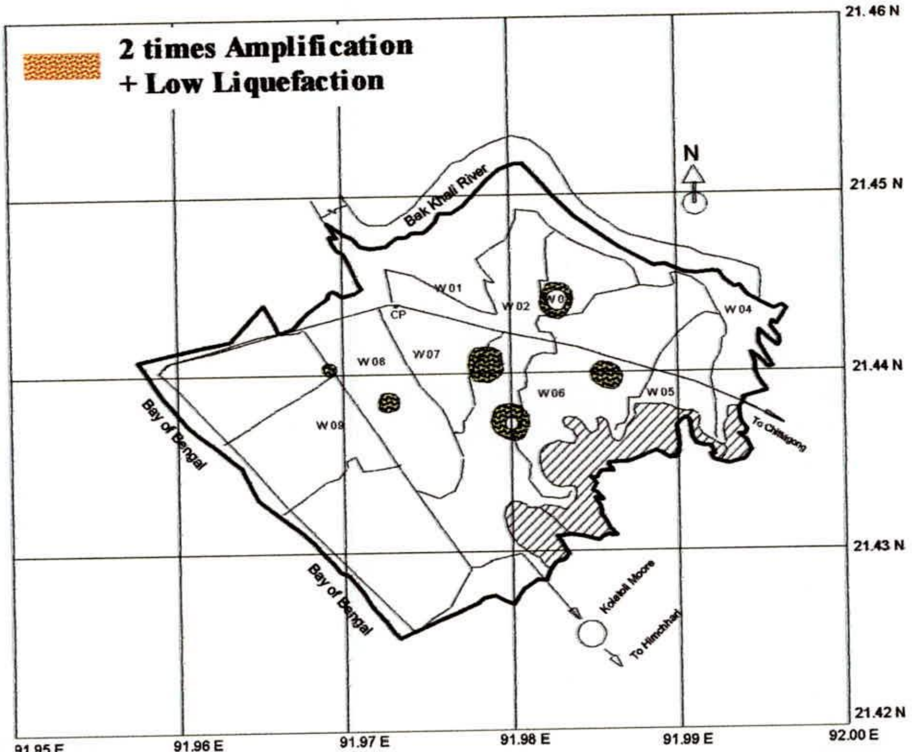


Figure 4.21(d): Map showing only 2.0 times Amplification with Low Liquefaction for extreme condition

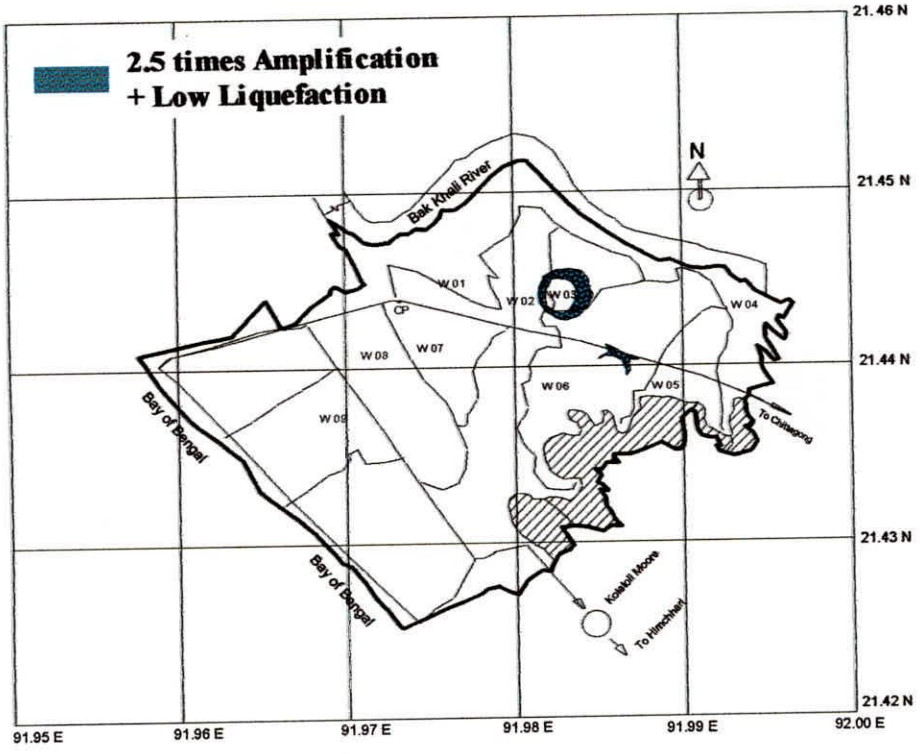


Figure 4.21(e): Map showing only 2.5 times Amplification with Low Liquefaction for extreme condition

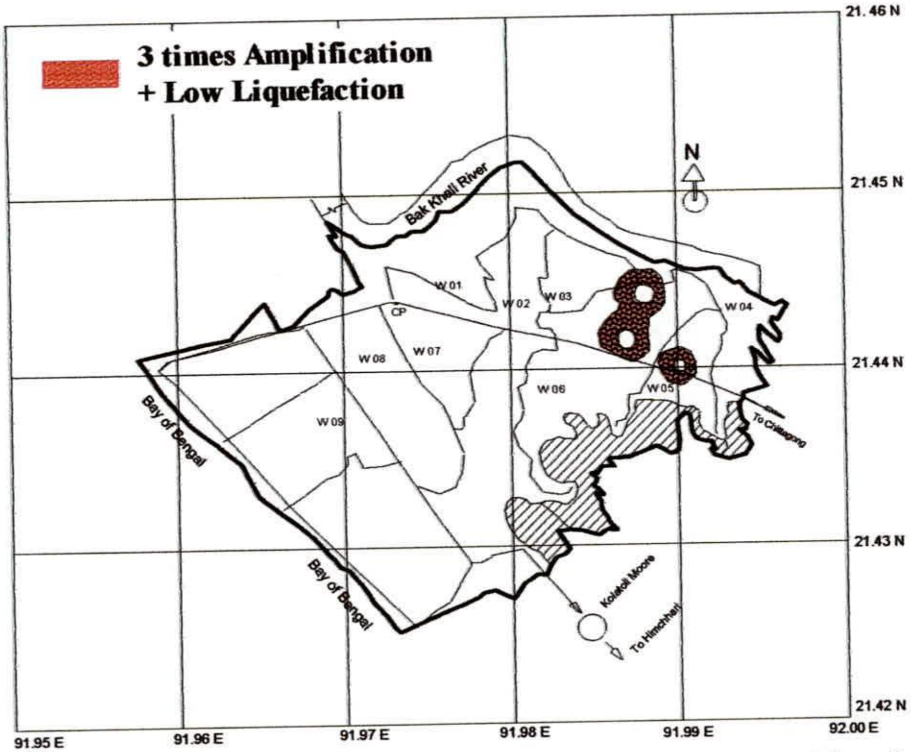


Figure 4.21 (f): Map showing only 3.0 times Amplification with Low Liquefaction for extreme condition

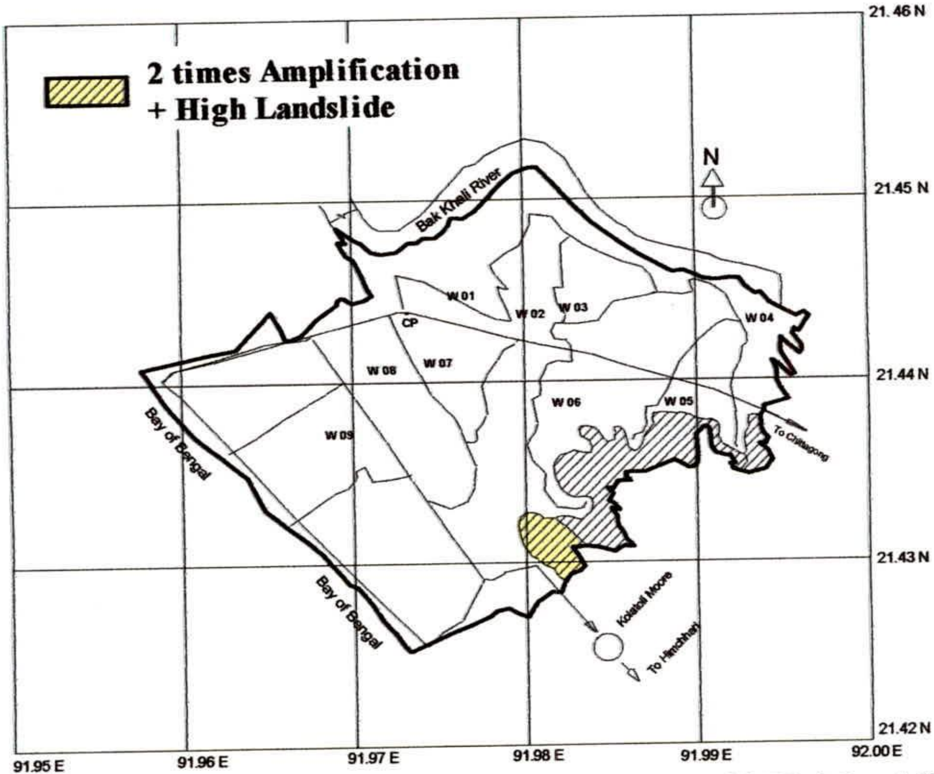


Figure 4.21(g): Map showing only 2.0 times Amplification with High Landslide for extreme condition

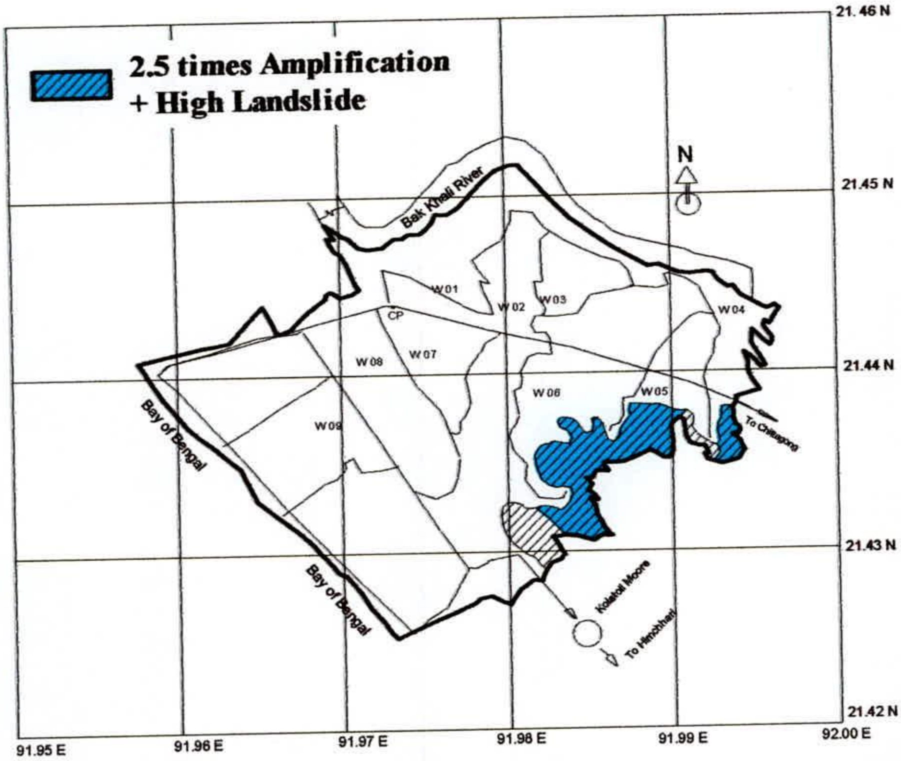


Figure 4.21(h): Map showing only 2.5 times Amplification with High Landslide for extreme condition

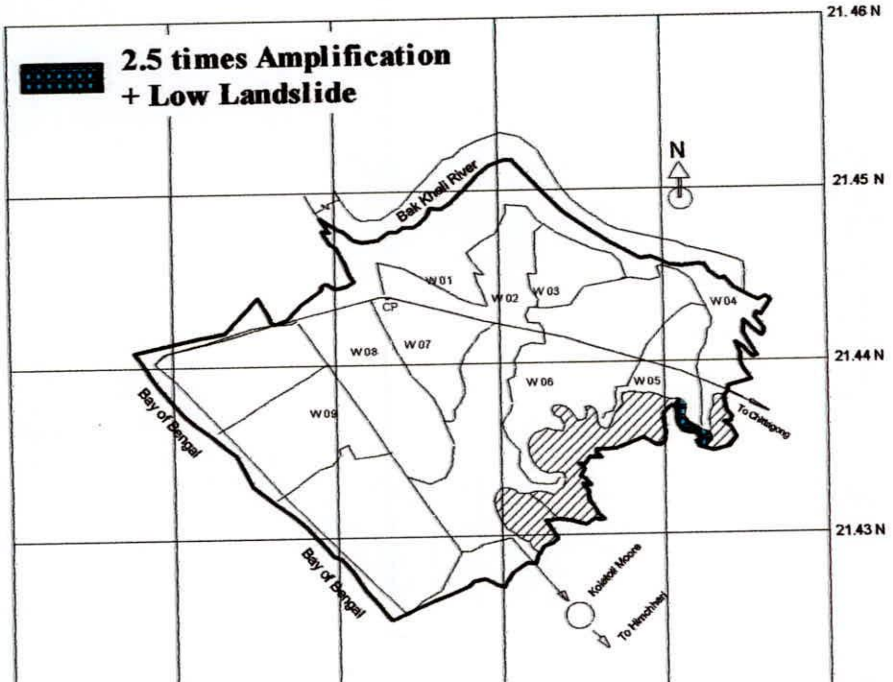


Figure 4.21(i): Map showing only 2.5 times Amplification with Low Landslide for extreme condition

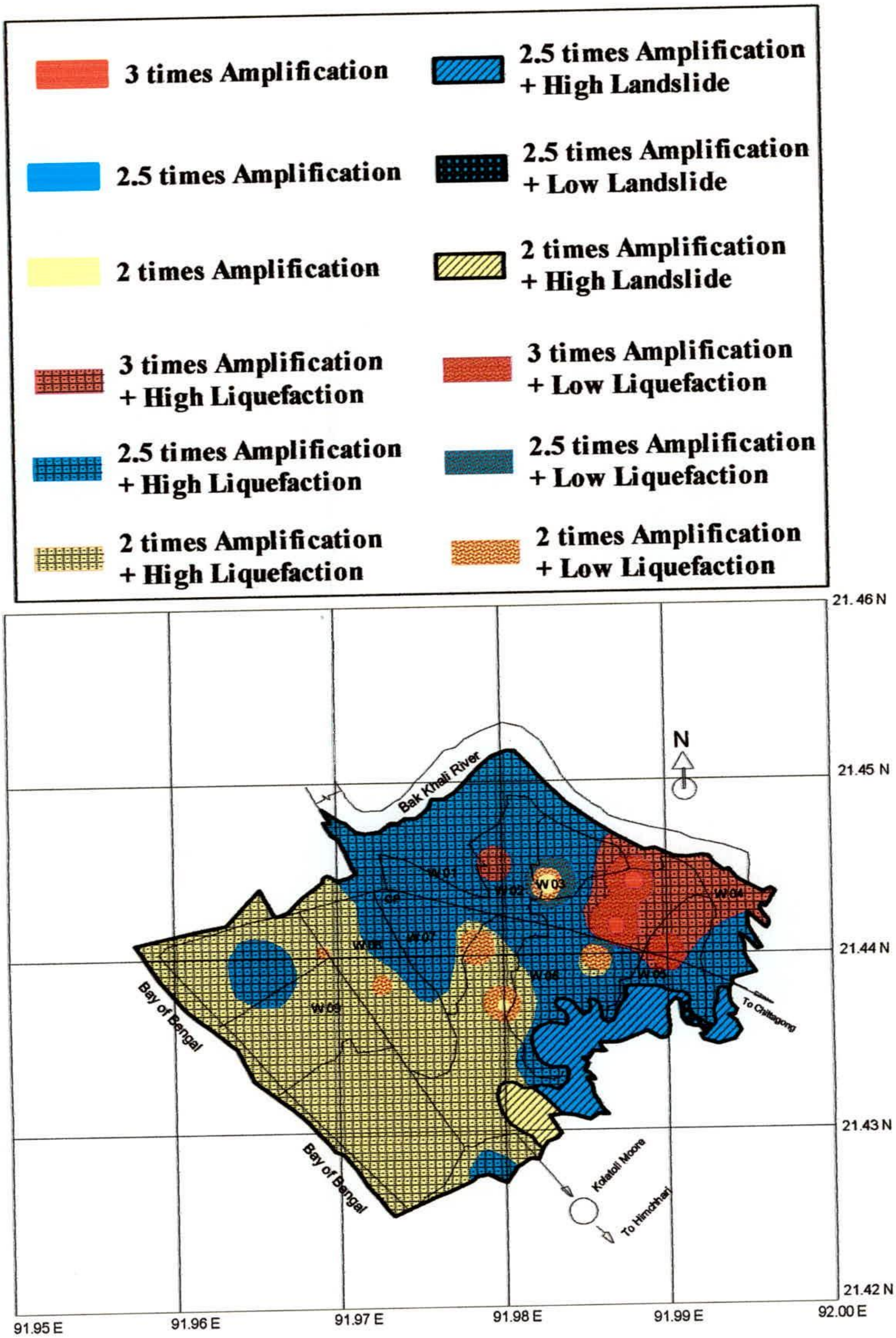


Figure 4.22: Map showing the possible hazard combinations for extreme condition

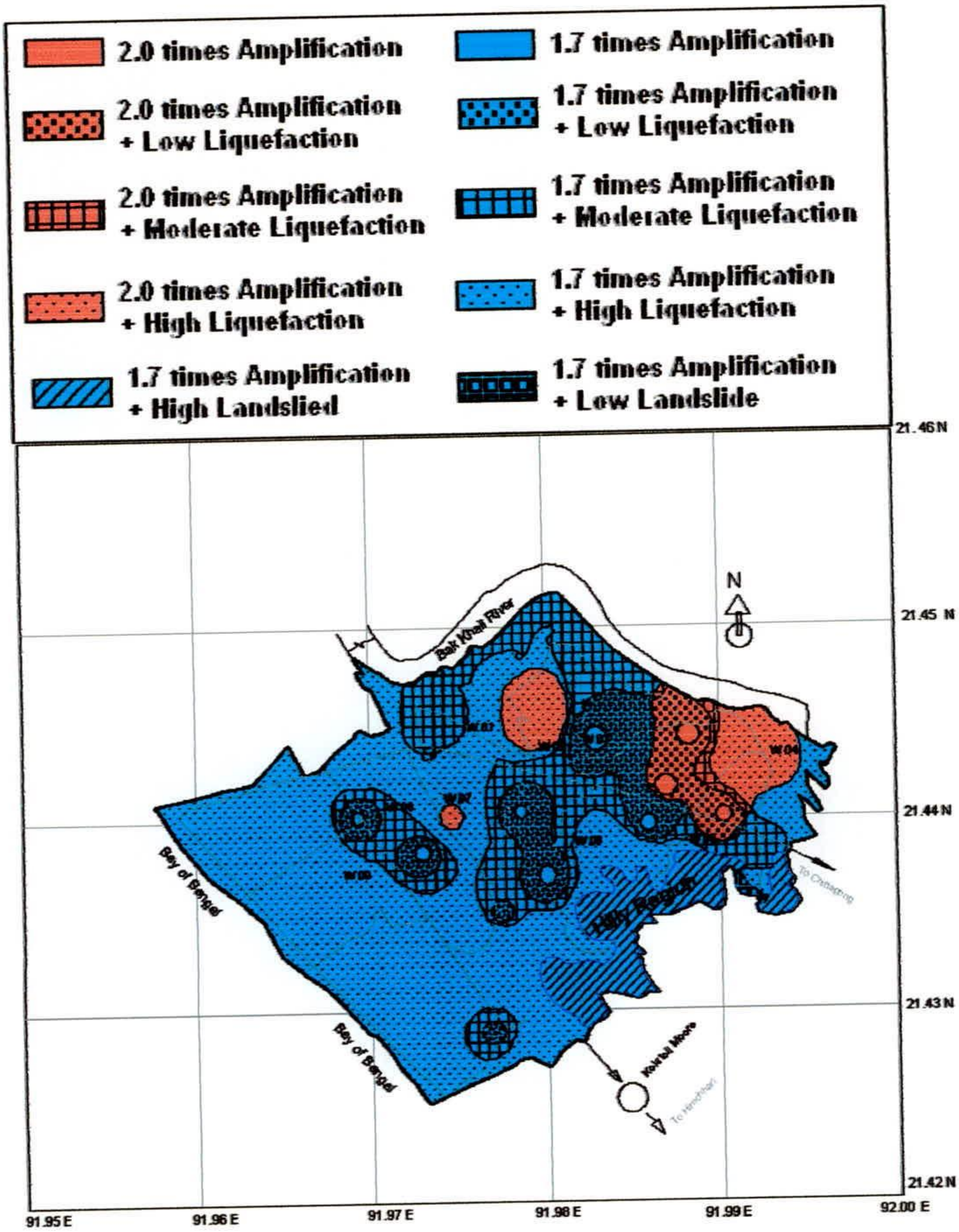


Figure 4.23: Map showing the possible hazard combinations considering AHSA

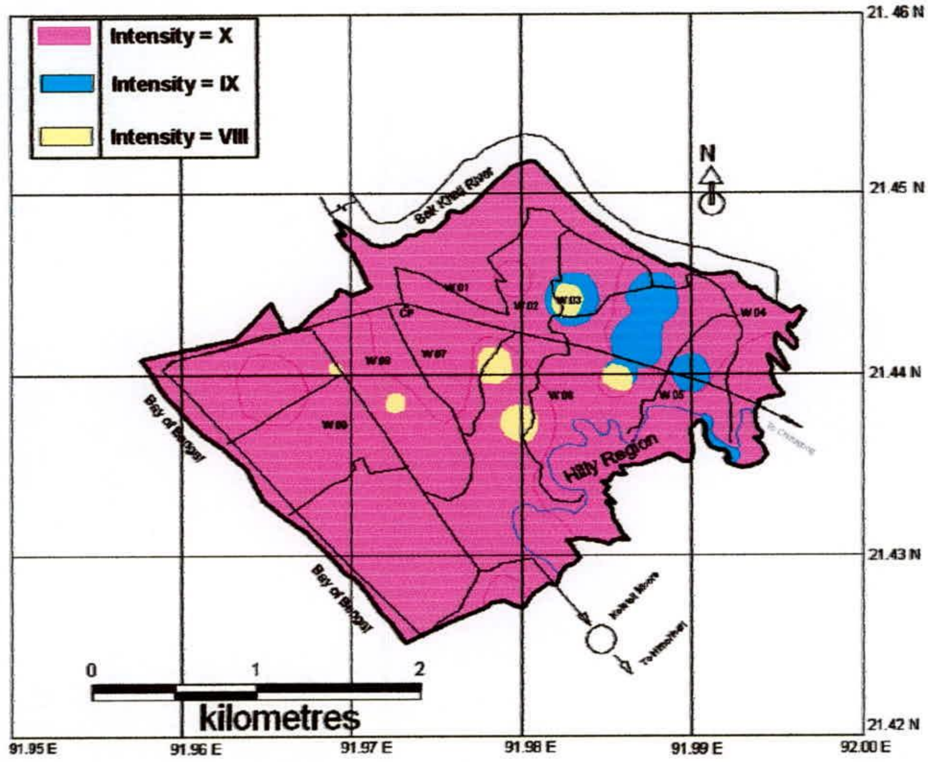


Figure 4.24: Map showing the regional distribution of combined seismic hazard (MMI_F) in Cox's Bazar Municipal Area for extreme condition

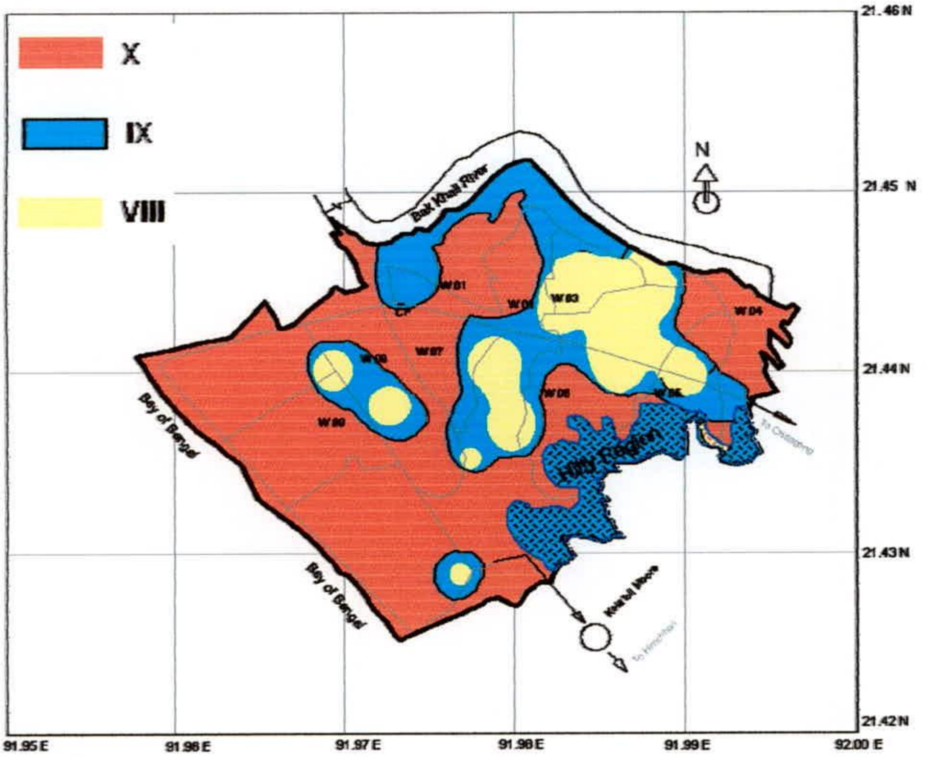


Figure 4.25: Map showing the regional distribution of combined seismic hazard (MMI_F) in Cox's Bazar Municipal Area considering AHSA

CHAPTER 5

CONCLUSIONS AND FUTURE STUDY

5.1 Conclusions

In this study, GIS has been used to develop seismic microzonation maps for the study area where primary hazards due to ground shaking and local site effects such as soil amplification, liquefaction and landslide have been considered. Prior to that, different field and laboratory tests of the soil samples collected at different depths from 26 sites and laboratory tests of soils collected from 11 hills of the study area have been performed for geotechnical characterization. Furthermore, this study introduces a methodology to combine the different hazards based on a weighted average approach. In the GIS environment, maps representing regional geologic and geographic information have been overlaid and their attributes were combined to produce intermediate maps of regional seismic hazards. This is for the first time comprehensive earthquake hazard estimation for Cox's Bazar Municipality has been carried out.

Due to an earthquake of Magnitude 7.5 with 200 years of return period around 250 km radius of Cox's bazaar Municipal Area, the rock level PGA is estimated as 0.18g. The results of the analyses for ground susceptibility can be interpreted for two different conditions.

Considering the extreme or most severe condition the rock level PGA can be amplify 2.3 times on an average in the alluvium and will gain a PGA of 0.41g in the surface. From the developed microzonation maps, it can be observed that the Southeastern end of ward no. 5 will experience the highest frequencies. Ward no. 4 consisting of East Tekpara, Rumaliarchhara and Tarabaniachhara might be affected by 3 times site amplification. Liquefaction analysis for the study area reflects that it is susceptible to very high liquefaction potential. From the borehole investigations and grain size distributions, it was observed that the soil up to 20 meter depth is mostly sandy having D_{50} ranging from 0.12 mm to 0.22 mm. It was observed that the sandy silts with trace clay, layer of silt and sand, silty sand having greater particle diameters and low to medium SPT N-values showed higher liquefaction potentials. According to the study, the landslide potential of this area is very high. Approximately 8.13% area under the municipality is hilly. The hills located in Ghonerpara, Boiddorghona, Pahartoli and Boillarpara are found to be very unstable. The combined hazard analysis shows that if the area experiences both ground shaking and liquefaction during a scenario earthquake having a magnitude of 7.5, the area can be severely affected and the intensity due to the combined effect of the hazards can be as high as X in MMI scale. The town will be highly endangered (44% area is affected) if high liquefaction associates with amplification factor as low as 2 times. On the other hand if 2.5 to 3 times site amplification occurs, still there is a high risk (MMI = IX) even in case of low liquefaction occurrence. The hilly region is highly susceptible to slope instability, moreover, 77% of the hilly region is on the risk of experiencing very high intensity (MMI = X), if 2.5 times amplification of ground shaking occurs.

Considering the average horizontal spectral acceleration (AHSA), the results are obtained for a moderate hazard condition. The average frequency expected to be experienced by the area is calculated as 1.7 and thus the surface PGA is obtained as 0.31g. Approximately 89% of the area can be affected if 1.7 times amplification of the ground shaking occurs and 11% area might be affected by 2.0 times amplification. If high liquefaction associates with round shaking amplified by of these two amplification factors the area can be affected by a combined hazard intensity of X. Similarly moderate liquefaction associates with these ground shaking hazards can cause combined hazard of intensity IX. More than 50% area can be affected if high liquefaction combines with only 1.7 times amplification of ground shaking. The entire hilly region is liable to only 1.7 times amplification. Approximately 96% of the hilly region (8% of the total area) might experience a combined intensity of IX if high landslide associates with only 1.7 times amplification of ground shaking.

The developed maps can act as a guide for the authorities at the national and regional levels in land use management, revision and enforcement of appropriate building codes and formulation of plans for mitigating measures against earthquake risk affecting the region considered.

5.2 Scope for Future Study

The study is covered with extremely wide-ranging subject; consequently several field of future study can be recognized for instance:

i. For Bangladesh, no PGA attenuation law has been developed, due to shortage of strong motion data. PGA attenuation relationships predicting strong ground motions in terms of magnitudes, distance, site geology, and other factors, using various models and data sets should be developed for the country.

ii. Study of regional tectonics with particular emphasis to locate active faults and fault plane solutions is strongly recommended. This can lead to more accurate estimation of hazardous conditions.

iii. In this study, SPT-N values were converted into shear-wave velocities using empirical correlation. Shear-wave velocities are needed to be directly estimated for different soils using cross-hole, down-hole or blasting techniques. Then correlation should be developed for the SPT-N values of local soils with shear-wave velocities.

iv. Grain Size Analysis specially, the mean particle diameter, D50 and fine contents are important data for every 1 meter depth for proper liquefaction analysis.

v. Based on soil (natural) frequency, some zones can be suggested for building height restrictions using thumb rules.

vi. Based on liquefaction potential index zones can be suggested where ground improvement is necessary.

vii. Vulnerability of landslide depends on location, land use, land cover, rainfall as well as weather, geological structure and type of human activities. These factors should be taken into consideration during landslide potential analysis.

viii. A very simplified process for integration of various sites attributes has been used in this study. Improvements are needed in the models together with the quantification of the hazards and heuristic weighted average approach. The analysis and modeling capabilities of the GIS provide an ideal environment to conduct sensitivity studies that will help to refine different hazard combination schemes.

ix. Further study can be taken by performing analysis of site amplification and calculation of transfer functions considering real earthquake strong ground motion data as input in SHAKE.

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APPENDIX – A

Earthquake Chronology of Bangladesh

1548	The first recorded earthquake was a terrible one. Sylhet and Chittagong were violently shaken, the earth opened in many places and threw up water and mud of a sulphurous smell.
1642	More severe damage occurred in Sylhet district. Buildings were cracked but there was no loss of life.
1663	Severe earthquake in Assam, which continued for half an hour and Sylhet district was not free from its shock.
1762	The great earthquake of April 2, which raised the coast of Foul island by 2.74m and the northwest coast of Chedua island by 6.71m above sea level and also caused a permanent submergence of 155.40 sq km near Chittagong. The earthquake proved very violent shake in Dhaka and along the eastern bank of the Meghna as far as Chittagong. In Dhaka 500 persons lost their lives, the rivers and jheels were agitated and rose high above their usual levels and when they receded their banks were strewn with dead fish. A large river dried up, a tract of land sank and 200 people with all their cattle were lost. Two volcanoes were said to have opened in the Sitakunda hills.
1775	Severe earthquake in Dhaka around April 10, but no loss of life.
1812	Severe earthquake in many places of Bangladesh around May 11. The earthquake proved violent in Sylhet
1865	Terrible shock was felt, during the second earthquake occurred in the winter of 1865, although no serious damage occurred.
1869	Known as Cachar Earthquake. Severely felt in Sylhet but no loss of life. The steeple of the church was shattered, the walls of the courthouse and the circuit bungalow cracked and in the eastern part of the district the banks of many rivers caved in.
1885	Known as the Bengal Earthquake. Occurred on 14 July with 7.0 magnitude and the epicentre was at Manikganj. This event was generally associated with the deep-seated Jamuna Fault.
1889	Occurred on 10 January with 7.5 magnitude and the epicentre at Jaintia Hills. It affected Sylhet town and surrounding areas.
1897	Known as the Great India Earthquake with a magnitude of 8.7 and epicentre at Shillong Plateau. The great earthquake occurred on 12 June at 5.15 pm. caused serious damage to masonry buildings in Sylhet town where the death toll rose to 545. This was due to the collapse of the masonry buildings. The tremor was felt throughout Bengal, from the south Lushai Hills on the east to Shahbad on the west. In Mymensingh, many public buildings of the district town, including the Justice House, were wrecked and very few of the two-storied brick-built houses belonging to zamindars survived. Heavy damage was done to the bridges on the Dhaka-Mymensingh railway and traffic was suspended for about a fortnight. The river communication of the district was seriously affected (Brahmaputra). Loss of life was not great, but loss of property was estimated at five million Rupees. Rajshahi suffered severe shocks, especially on the eastern side, and 15 persons died. In Dhaka damage to property was heavy. In Tippera masonry buildings and old temples suffered a lot and the total damage was estimated at Rs 9,000.

APPENDIX – B

Seismic Data around Cox's Bazar

DD-MM	Year	Latitude	Longitude	Depth, h (Km)	EQ Magnitude, M	Distance (km)
-	1664	24.00	90.00	50.00	7.80	350.05
-	1858	18.72	95.27	50.00	7.66	458.22
-	1912	21.75	96.38	50.00	7.90	456.71
10.08	1923	22.60	93.40	50.00	5.91	195.33
25.08	1927	22.00	90.00	50.00	5.56	214.04
02.01	1955	21.60	92.70	33.00	6.50	76.67
12.06	1956	22.62	93.95	50.00	6.43	242.03
12.07	1956	22.60	94.00	50.00	6.30	245.21
13.04	1959	22.00	93.30	50.00	5.90	150.07
01.01	1959	21.51	92.38	30.00	6.24	42.19
22.01	1964	22.40	93.60	50.00	5.44	198.52
06.05	1966	22.10	92.80	43.00	4.06	112.18
15.02	1967	20.33	93.99	50.00	4.91	242.83
25.01	1969	22.89	92.40	50.00	4.67	167.12
22.04	1969	23.15	92.62	50.00	4.04	201.44
-	1970	21.83	94.20	50.00	4.38	233.78
02.01	1970	21.30	93.50	50.00	4.01	158.34
01.01	1971	21.44	93.88	50.00	4.74	196.86
-	1973	20.97	93.29	50.00	4.47	145.66
02.01	1973	22.43	93.38	50.00	4.54	181.77
20.01	1974	22.80	92.90	50.00	4.57	178.67
05.04	1974	21.60	94.00	50.00	4.60	209.94
05.04	1974	21.33	93.68	50.00	4.54	176.63
23.07	1974	22.00	93.30	50.00	4.47	150.07
06.09	1975	20.20	93.50	50.00	4.54	209.93
12.05	1977	21.68	92.96	39.00	5.06	104.92
31.07	1977	20.21	93.94	50.00	4.47	245.63
28.03	1978	23.15	92.74	50.00	4.27	205.82
02.01	1978	23.47	92.85	50.00	4.00	243.06
01.01	1979	20.89	93.69	50.00	4.70	187.77
08.02	1980	21.27	93.59	50.00	4.08	167.98
01.01	1980	22.74	93.92	50.00	5.10	246.95
02.01	1980	22.06	90.94	50.00	4.17	127.76
02.01	1980	21.08	93.59	50.00	4.60	171.77
03.08	1981	20.70	93.40	50.00	4.08	168.94
01.01	1981	22.70	93.23	50.00	4.30	190.53

DD-MM	Year	Latitude	Longitude	Depth, h (Km)	EQ Magnitude, M	Distance (km)
12.03	1994	22.61	93.55	50.00	4.27	207.86
20.03	1994	23.27	93.33	50.00	4.69	246.61
21.04	1994	23.36	92.92	50.00	4.80	234.60
21.04	1994	22.08	93.22	50.00	4.59	146.66
19.05	1994	22.51	92.88	50.00	4.27	151.06
29.05	1994	20.53	94.15	50.00	4.08	247.25
29.05	1994	20.54	94.18	50.00	6.10	249.64
16.06	1994	21.60	93.33	50.00	4.38	140.92
03.08	1994	21.64	94.12	50.00	6.17	222.70
07.08	1994	21.99	92.86	16.00	5.01	109.69
17.09	1994	23.48	92.09	50.00	4.80	227.38
23.09	1994	21.85	94.05	50.00	5.01	218.99
23.09	1994	21.62	93.68	50.00	5.22	177.17
-	1994	23.20	93.15	50.00	4.17	230.00
-	1994	22.75	90.51	50.00	5.33	210.36
-	1994	22.71	92.26	50.00	5.01	144.29
01.01	1994	22.84	92.51	50.00	4.17	165.15
01.01	1994	23.11	92.32	50.00	4.38	189.17
01.01	1994	21.60	93.44	50.00	5.54	152.21
20.06	1995	22.91	93.47	50.00	4.48	224.43
15.07	1995	22.51	93.64	50.00	4.06	208.69
15.07	1995	22.57	93.77	50.00	4.27	223.50
20.07	1995	23.08	92.26	50.00	4.00	184.83
-	1995	21.83	94.07	50.00	4.38	220.59
01.01	1997	21.23	93.08	50.00	4.20	116.42
01.01	1997	22.22	92.68	50.00	5.70	113.00
02.07	1998	21.00	93.69	50.00	4.10	184.09
02.01	1998	22.30	92.75	33.00	4.00	124.48
08.02	1999	22.16	92.85	50.00	4.10	120.46
22.07	1999	21.62	91.90	10.00	4.40	21.69
03.01	2000	22.11	92.81	46.00	4.00	113.68
01.01	2000	21.70	92.86	34.00	4.60	95.59
10.07	2001	22.60	93.30	50.00	4.46	187.71
13.07	2001	20.90	93.10	33.00	4.27	130.88
-	2001	21.08	93.69	50.00	4.90	181.88
02.01	2001	22.00	94.10	50.00	5.03	227.93
02.01	2001	20.80	93.30	50.00	4.75	154.48
05.05	2002	22.58	90.93	50.00	4.30	166.89
-	2002	21.18	93.50	50.00	4.40	160.28
26.07	2003	22.89	92.33	50.00	5.50	165.40

APPENDIX – C

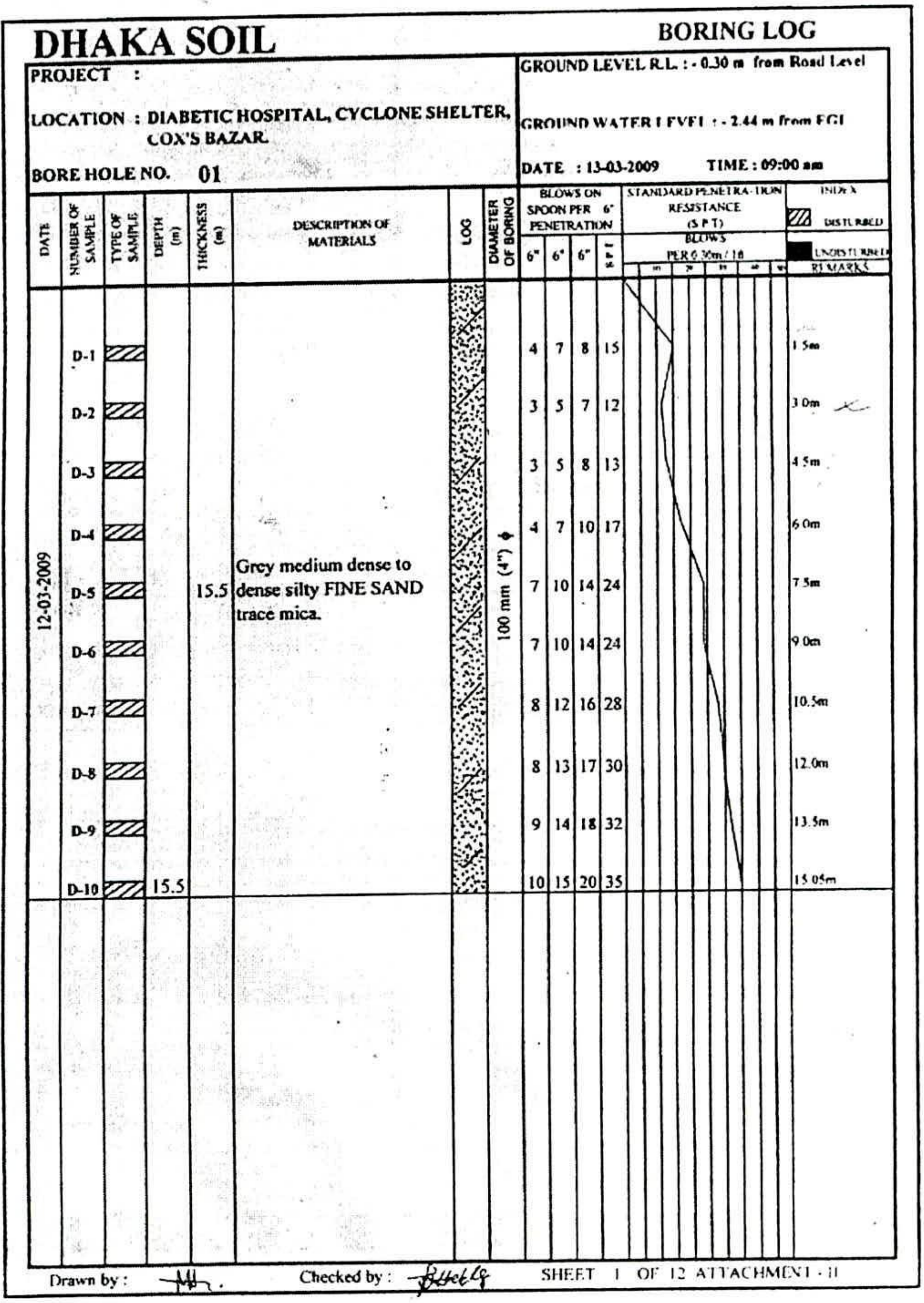
Chronology of Major Landslides

1968	At Kaptai-Chandraghona road where the protective vegetation is removed, the soil gets exposed to the monsoon rains and eroded rapidly. This resulted in landslides, and the loose soil washed down the slopes and carried by rivers into the kaptai lake. As a result, the reservoir silted up and the authorities confirmed that in its 30 years existence it had lost about 25% of its volume due to siltation.
1970	Similar event along Ghagra-Rangamati road.
1990	Occurred on May 30, 1990. Affected the link road embankment at Jhagar beel area of Rangamati district.
1997	A major landslide occurred in July 1997 at Charaipada of Bandarban. The total area affected by it was about 90,000-sq m. If such a landslide occurred in Bandarban Town and any other urban or semi-urban centre, the devastation would be tremendous.
1999	Two big landslides one in Bandarban and the other one in Chittagong occurred on 11 and 13 August 1999 respectively claiming the life of 17 people. Out of 17 fatalities, 10 were in Chittagong and the rest in Bandarban district. Heavy and incessant rainfall at that time was one of the causes of sliding. This landslide affected Lama thana and the Aziz Nagar union of Bandarban district. Aziz Nagar is almost an inaccessible rugged hilly terrain. Landslide badly affected the villages of Chittaputti, Monargiri, Meounda, Muslimpara, Sonaisari, Bazapara, Kalargiri, Maishkata, Aungratali, Chionipara, Kariungpara. The 11 August landslide was followed again on 15 August at Chittaputti area. At least 50 houses were completely vanished under the solid earth and 300 houses were partly damaged. About 283.50 ha of cultivated land, 810 ha of household garden, and 50 km unmetalled road were crushed. Road communication between Bandarban headquarters and remote thanas became snapped. Especially, Aziznagar-Bazalia road had been closed for traffic due to falling of huge mass of earth over the road at 25 places. Chittagong landslide location was at Gopaipur under Chittagong Kotwali Thana. The slides crushed two thatched houses at the foot of the hill claimed the lives of the inmates of the houses who were asleep.
2000	At least 13 people were killed and 20 injured in landslide incidents on the Chittagong University campus and other parts of Chittagong City on Saturday, the 24 June 2000. The incident was caused due to the deluge of mud and water that swamped various part of the port city amid torrential rain.

APPENDIX – D

Standard Penetration Test Data

SPT Data from Primary Sources



DHAKA SOIL

BORING LOG

PROJECT :

LOCATION : DIABETIC HOSPITAL, CYCLONE SHELTER, COX'S BAZAR

BORE HOLE NO. 01

GROUND LEVEL R.L. : - 0.30 m from Road Level

GROUND WATER LEVEL : - 2.44 m from EGL

DATE : 13-03-2009 TIME : 09:00 am

INDEX
▨ DISTURBED
■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	STANDARD PENETRATION RESISTANCE (S.P.T) BLOWS PER 0.30m / 1ft	REMARKS
12-03-2009	D-1	▨		15.5	Grey medium dense to dense silty FINE SAND trace mica.		100 mm (4") ϕ	4	7	8	15		1.5m
	D-2	▨						3	5	7	12		3.0m
	D-3	▨						3	5	8	13		4.5m
	D-4	▨						4	7	10	17		6.0m
	D-5	▨						7	10	14	24		7.5m
	D-6	▨						7	10	14	24		9.0m
	D-7	▨						8	12	16	28		10.5m
	D-8	▨						8	13	17	30		12.0m
	D-9	▨						9	14	18	32		13.5m
	D-10	▨	15.5					10	15	20	35		15.05m

Drawn by : Checked by : SHEET 1 OF 12 ATTACHMENT - II

DHAKA SOIL

BORING LOG

PROJECT :

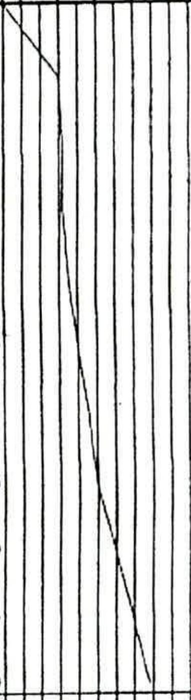
LOCATION : SHAIBAL HOTEL, NEAR WATER TANK,
COX'S BAZAR.

BORE HOLE NO. 03

GROUND LEVEL R.L. : + 0.46 m from Road Level

GROUND WATER LEVEL : - 2.5 m from FGL

DATE : 14-03-2009 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION				STANDARD PENETRATION RESISTANCE (SPT) BLOWS PER 0.30m. 1ft	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
								6"	6"	6"	SPT		
13-03-2009	D-1	▨		15.5	Grey medium dense to dense silty FINE SAND trace mica.		100 mm (4") ϕ	4	6	9	15		1.5m
	D-2	▨						4	6	10	16		3.0m
	D-3	▨						4	7	9	16		4.5m
	D-4	▨						5	8	10	18		6.0m
	D-5	▨						5	9	11	20		7.5m
	D-6	▨						6	11	12	23		9.0m
	D-7	▨						7	12	13	25		10.5m
	D-8	▨						8	13	17	30		12.0m
	D-9	▨						10	15	19	34		13.5m
	D-10	▨	15.5					11	18	21	39		15.05m

Drawn by :

Checked by :

SHEET 3 OF 12 ATTACHMENT - II

DHAKA SOIL

BORING LOG

PROJECT :

LOCATION : SAMUDRA BILASH, MIDDLE SHAIKAT PARA,
BLOCK-D, KALATOLI ROAD, COX'S BAZAR.

BORE HOLE NO. 05

GROUND LEVEL R.L. : + 0.75 m from Road Level

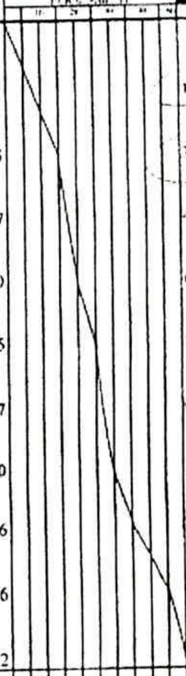
GROUND WATER LEVEL : - 3.66 m from EGL

DATE : 14-03-2009 TIME : 09:00 am

INDEX
▨ DISTURBED
■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	REMARKS
13-03-2009	D-1	▨	2.0	2.0	Light brown loose silty FINE SAND trace mica.		100 mm (4") ϕ	2	3	5	8	1.5m
	D-2	▨		13.5	Light brown medium dense to very dense silty FINE SAND trace mica.			4	6	9	15	3.0m
	D-3	▨						5	7	10	17	4.5m
	D-4	▨						5	8	12	20	6.0m
	D-5	▨						6	10	15	25	7.5m
	D-6	▨						7	10	17	27	9.0m
	D-7	▨						8	12	18	30	10.5m
	D-8	▨						10	14	22	36	12.0m
	D-9	▨						12	18	28	46	13.5m
	D-10	▨	15.5					13	20	32	52	15.05m

STANDARD PENETRATION RESISTANCE (S.P.T.) BLOWS PER 0.3m 1ft



Drawn by :

Checked by :

SHEET 5 OF 12 ATTACHMENT - II

DHAKA SOIL

BORING LOG

PROJECT :

LOCATION : COX'S BAZAR NURSERI, SIRCUIT HOUSE ROAD, COX'S BAZAR.

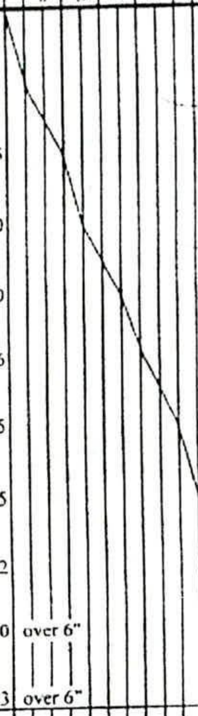
BORE HOLE NO. 07

GROUND LEVEL R.L. : - 1.0 m from Road Level

GROUND WATER LEVEL : - 2.44 m from EGL

DATE : 15-03-2009 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION				STANDARD PENETRATION RESISTANCE (S.P.T.) BLOWS PER 0.30m (1ft)	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
								6"	6"	6"	SPT	10 20 30 40 50	
15-03-2009	D-1	▨		3.5	Brown loose to medium dense silty FINE SAND trace mica.		100 mm (4") ϕ	2	2	4	6		1.5m
	D-2	▨	3.5					4	6	9	15		3.0m
	D-3	▨		12.0	Grey medium dense to very dense silty FINE SAND trace mica.			5	8	12	20		4.5m
	D-4	▨						7	12	18	30		6.0m
	D-5	▨						9	14	22	36		7.5m
	D-6	▨						12	18	27	45		9.0m
	D-7	▨						16	22	33	55		10.5m
	D-8	▨						20	30	22	52		12.0m
	D-9	▨						20	30	-	50	over 6"	13.5m
	D-10	▨	15.5					26	37	-	63	over 6"	15.05m



Drawn by :

Checked by :

SHEET 7 OF 12 ATTACHMENT - II

DHAKA SOIL

BORING LOG

PROJECT :

LOCATION : FULBAG, RICE BAZAR ROAD,
COX'S BAZAR.

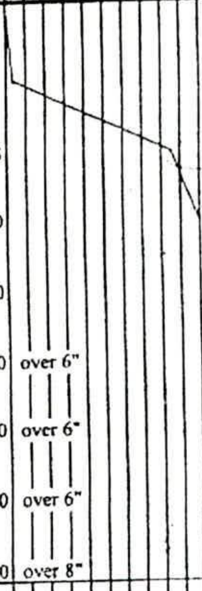
BORE HOLE NO. 09

GROUND LEVEL R.L. : - 0.0 m from Road Level

GROUND WATER LEVEL : - 3.0 m from E.G.L

DATE : 17-03-2009 TIME : 09:00 am

INDEX
▨ DISTURBED
■ UNDISTURBED



DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	S.P.T.	STANDARD PENETRATION RESISTANCE (S.P.T.) BLOWS PER 0.30m (N)	REMARKS
16-03-2009	D-1 U-1	▨ ■	2.5	2.5	Grey soft silty CLAY trace fine sand medium plastic.		100 mm (4") ⌀	1	1	1	2		1.5m
	D-2	▨		10.0	Grey dense to very dense silty FINE SAND trace mica.			10	15	28	43		3.0m
	D-3	▨						13	20	30	50		4.5m
	D-4	▨						15	25	35	60		6.0m
	D-5	▨						20	30	-	50	over 6"	7.5m
	D-6	▨						23	35	-	50	over 6"	9.0m
	D-7	▨						25	40	-	50	over 6"	10.5m
	D-8	▨	12.5					27	30	-	50	over 8"	12.05m

Drawn by : Checked by :

DHAKA SOIL

BORING LOG

PROJECT :

LOCATION : RUMALIAR CHARA, HAJI SIDDIQUIA AHMED ROAD, COX'S BAZAR.

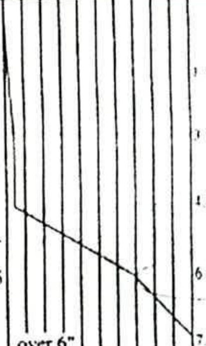
BORE HOLE NO. 11

GROUND LEVEL R.L. : - 0.61 m from Road Level

GROUND WATER LEVEL : - 2.44 m from EGL.

DATE : 18-03-2009 TIME : 09:00 am

INDEX: ▨ DISTURBED ■ UNDISTURBED

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (m)	THICKNESS (m)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	STANDARD PENETRATION RESISTANCE (SPT) BLOWS PER 0.30m / 1ft	REMARKS
17-03-2009	D-1	▨		5.5	Grey very soft silty CLAY trace fine sand medium plastic.		100 mm (4") ⌀	1	0	1	1		1.5m
	U-1	■											
	D-2	▨						1	1	1	2		3.0m
	D-3	▨	5.5					1	1	1	2		4.5m
	D-4	▨		7.0	Grey dense to very dense silty FINE SAND trace mica.			10	15	20	35		6.0m
	D-5	▨						20	30	-	-	over 6"	7.5m
	D-6	▨						25	35	-	-	over 6"	9.0m
	D-7	▨						30	40	-	-	over 6"	10.5m
	D-8	▨	12.5					37	20	-	-	over 9"	12.05m

Drawn by :

Checked by :

SHEET 11 OF 12 ATTACHMENT - II

SPT Data from Secondary Sources

DHAKA SOIL

BORING LOG

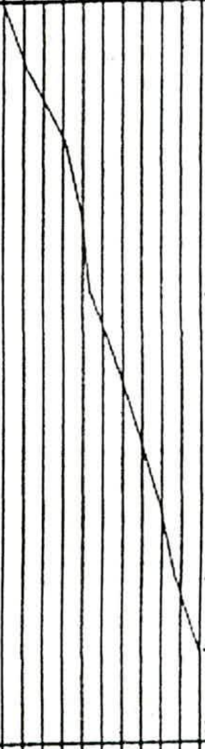
PROJECT : CONST. OF 8-STORIED SERVICE APARTMENT
LOCATION : PLOT NO. 76, BLOCK - A, KALATALI
COX'S BAZAR LIGHT HOUSE ROAD.

BORE HOLE NO. 03

GROUND LEVEL R.L. :+1'-0" from Road Level

GROUND WATER LEVEL : - 12'-0" from EGL

DATE : 12-06-2008 TIME : 09:00 am

DATE	NUMBER OF SAMPLE	TYPE OF SAMPLE	DEPTH (ft)	THICKNESS (ft)	DESCRIPTION OF MATERIALS	LOG	DIAMETER OF BORING	BLOWS ON SPOON PER 6" PENETRATION 6"	6"	6"	SPT	STANDARD PENETRA-TION RESISTANCE (S P T) BLOWS PER 0.30m / 1ft	INDEX ▨ DISTURBED ■ UNDISTURBED REMARKS
11-06-2008	D-1	▨		24.0	Light brown loose to medium dense silty FINE SAND trace mica.		100 mm (4") ϕ	2	2	4	6		5'
	D-2	▨						3	6	10	16		10'
	D-3	▨						4	8	12	20		15'
	D-4	▨	24.0					4	9	13	22		20'
	D-5	▨		27.0	Grey medium dense to very dense silty FINE SAND trace mica.			6	12	16	28		25'
	D-6	▨						8	15	19	34		30'
	D-7	▨						10	16	24	40		35'
	D-8	▨						10	18	26	44		40'
	D-9	▨						12	23	27	50		45'
	D-10	▨	51.0					12	25	28	53		50'

Drawn by : JW Checked by : SHEET 3 OF 5 ATTACHMENT - II

SHEET 2 OF 2

LOG FOR BORE HOLE # 01 (ONE)

(CO-ORDINATES : 91.9868E & 21.4729N)

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Cox's Bazar Pressclub Compound, Cox's Bazar.

METHOD OF BORING : Percussive Wash.
DIA OF BORE HOLE : 120 mm (Nominal)
DATE : 23-03-07 & 24-03-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R.L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES) 0 10 20 30 40 50	G.W.T.	SAMPLING	G_s –	w (%)	L_w –	P_w –	γ_w	γ_d	CLAY (%)	SILT (%)	SAND (%)	TYPE OF TEST	C (kPa)	ϕ	e_o	C_c	P_c (kPa)
15.0	Light grey Silty SAND with trace mica																				
				40&52 blows for 100mm penetration		D-11															
(5.7) 18.0				41&57 blows for 50mm penetration		D-12															
				72&60 blows for 75mm penetration		D-13															
20.1	Light grey SAND with some Silt & trace mica																				
21.0				52&60 blows for 100mm penetration		D-14			N	P			–	17	83						
				58&55 blows for 25mm penetration		D-15															
(2.0) 24.0				75&60 blows for 30mm penetration		D-15															
				85&55 blows for 50mm penetration		D-17															
27.0				80&60 blows for 50mm penetration		D-18			N	P			–	19	81						
28.05	Grey SILT & SAND with trace clay			43&55 blows for 75mm penetration		D-19															
30.0				45&60 blows for 75mm penetration		D-20	2.66		36	21			10	50	40						

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET).

SHEET 2 OF 2

LOG FOR BORE HOLE # 02 (TWO) ✓

(CO-ORDINATES :. 91.9904E & 21.4538N)

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Central Govt. Primary School Campus, Cox's Bazar.

METHOD OF BORING : Percussive Wash.
DIA. OF BORE HOLE : 120 mm (Nominal)
DATE : 25-03-07 & 26-03-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)
15.0 – 24.5 (9.5)	Grey to light grey SILT & SAND with laminations of silt with some clay		
24.5 – 28.0 (3.5)	Grey Sandy SILT with some Clay & occasionally laminations of silt with trace clay (occasionally)		
28.0 – 28.8 (0.8)	Grey Silty SAND with laminations of silt with trace clay		
28.8 – 30.0	Grey SILT & SAND		

Depth scale: 15.0, 18.0, 21.0, 24.0, 24.5, 27.0, 28.0, 28.8, 30.0

STANDARD PENETRATION TEST RESULTS (N - VALUES): 0 10 20 30 40 50

SUMMARY OF LABORATORY TEST RESULTS

SAMPLING	STANDARD PENETRATION TEST RESULTS (N - VALUES)	INDEX PROPERTIES									SHEAR & CONSOLIDATION CHARACTERISTICS					
		G_s -	w (%)	L_L -	P_L -	γ_w kN/m³	γ_d kN/m³	CLAY (%)	SILT (%)	SAND (%)	TYPE OF TEST	c (kPa)	ϕ (°)	e_o -	C_c -	P_c (kPa)
D-11	58,68 blows for 50mm penetration			N	P			–	60	40						
D-12	60&70 blows for 50mm penetration															
D-13	40&56 blows for 100mm penetration			N	P			–	37	63						
D-14	35&60 blows for 100mm penetration															
D-15	102 blows for 1st 125mm penetration			N	P			–	39	61						
D-16	140 blows for 1st 150mm penetration															
D-17	48&59 blows for 50mm penetration	2.67		35	18			12	58	32						
D-18	48&62 blows for 50mm penetration															
D-19	85 blows for 1st 150mm penetration			N	P			–	32	68						
D-20	110 blows for 1st 150mm penetration			N	P			–	42	58						

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

SHEET 2 OF 2

LOG FOR BORE HOLE # 03 ✓

(CO-ORDINATES :. 91.9863E & 21.4554N)

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Peshkerpara Govt. Primary School Campus, Cox's Bazar.

METHOD OF BORING Percussive Wash.
DIA. OF BORE HOLE 120 mm (Nominal)
DATE 27-03-07 & 28-03-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES) 0 10 20 30 40 50	GWT	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS: INDEX PROPERTIES G_s -	w (%)	L_w -	P_w -	γ_w	γ_d	CLAY (%)	SILT (%)	SAND (%)	SHEAR & CONSOLIDATION CHARACTERISTICS: TYPE OF TEST	c (kPa)	ϕ (°)	e_o -	C_c -	P_c (kPa)
15.0	Light grey SILT & SAND to Silty SAND																				
				75-blows for 1st 150mm pentration		D-11															
18.0				88-blows for 1st 25mm penetration		D-12															
				78-blows for 1st 100mm penetration		D-13			N	P			–	32	68						
21.0				80-blows for 1st 50mm penetration		D-14															
				110-blows for 1st 125mm penetration		D-15			N	P			–	28	72						
24.0				116-blows for 1st 100mm penetration		D-16															
				110-blows for 1st 100mm penetration		D-17			N	P			–	23	77						
27.0				97-blows for 1st 100mm penetration		D-18															
				120-blows for 1st 150mm pentration		D-19															
30.0				111- blows for 1st 150mm penetration		D-20			N	P			–	25	75						

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari

CHECKED BY : I. Ahmed

DATE : 20/05/2007

DRG. NO. :

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET).

SHEET [illegible]

LOG FOR BORE HOLE # 04

(CO-ORDINATES :. 91.9835E & 21.4532N)

CLIENT	: BUET-CDMP Partnership Project Authority	METHOD OF BORING	Percussive Wash.
PROJECT	: EARTHQUAKE ANALYSIS OF STRUCTURES	DIA. OF BORE HOLE	120 mm (Nominal)
LOCATION	: Kasturaghat Govt. Primary School Campus, Cox's Bazar.	DATE	29-03-07 & 30-03-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES)	GWT	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS														
							INDEX PROPERTIES									SHEAR & CONSOLIDATION CHARACTERISTICS					
				0 10 20 30 40 50			G_s -	w (%)	L_w -	P_w -	γ_w (kN/m³)	γ_d (kN/m³)	CLAY (%)	SILT (%)	SAND (%)	TYPE OF TEST	c (kPa)	ϕ (°)	e_o -	C_c -	P_c (kPa)
15.0	Light brown Silty SAND with some mica																				
16.0	Light grey SILT with some Sand & trace clay			60,62-blows for 75mm penetration		D-11	2.66		N	P			4	66	30						
18.0 (5.5)				57,55-blows for 50mm penetration		D-12	2.66		N	P			5	79	16						
				65,53-blows for 50mm penetration		D-13															
				61,67-blows for 50mm penetration		D-14															
21.5	Light grey SAND with some to trace silt			40,56-blows for 100mm penetration		D-15			N	P			–	14	86						
24.0				43,60-blows for 125mm penetration		D-16															
				40,63-blows for 100mm penetration		D-17															
27.0				49,63-blows for 100mm penetration		D-18			N	P			–	10	90						
				51,68-blows for 125mm pentration		D-19															
30.0				50,70- blows for 100mm penetration		D-20			N	P			–	14	86						

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET)

SHEET [illegible] OF 2

LOG FOR BORE HOLE # 05

(CO-ORDINATES :. 91.9924E & 21.4180N)

CLIENT	BUET-CDMP Partnership Project Authority	METHOD OF BORING	Percussive Wash
PROJECT	EARTHQUAKE ANALYSIS OF STRUCTURES	DIA. OF BORE HOLE	120 mm (Nominal)
LOCATION	: Kalatoli World Vision Multipurpose Cyclone Shelter compound, Cox's Bazar.	DATE	30-03-07 & 31-03-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES)	G.W.T	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS														
							INDEX PROPERTIES									SHEAR & CONSOLIDATION CHARACTERISTICS					
							G_s -	w (%)	L_w -	P_w -	γ_w kn/m³	γ_d kn/m³	CLAY (%)	SILT (%)	SAND (%)	TYPE OF TEST	c (kPa)	ϕ (°)	e_o -	C_c -	P_c (kPa)
				0 10 20 30 40 50																	
15.0		x—x																			
15.5																					
	Light grey Silty SAND to SAND with some silt & pea-gravels			44,55-blows for 75mm penetration		D-11	2.66		N	P			–	28	72						
18.0				55,60-blows for 75mm penetration		D-12			N	P			–	24	76						
				85-blows for 1st 50mm penetration		D-13			N	P			–	19	81						
				69-blows for 1st 100mm penetration		D-14															
				113-blows for 1st 125mm penetration		D-15			N	P			–	24	76						
24.0				85-blows for 1st 100mm penetration		D-16															
				90-blows for 1st 125mm penetration		D-17			N	P			–	25	75						
27.0				110-blows for 1st 125mm penetration		D-18															
				97-blows for 1st 125mm pentration		D-19			N	P			–	12	88						
30.0				120- blows for 1st 150mm penetration		D-20															

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

SHEET 2 OF 2

LOG FOR BORE HOLE # 16 ✓

(CO-ORDINATES :. 91.9805E & 21.4355N)

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Baitus Salat Jamey Mosjid Complex, South Baharchara, Cox's Bazar

METHOD OF BORING Percussive Wash.
DIA. OF BORE HOLE 120 mm (Nominal)
DATE : 23-04-07 & 24-04-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R.L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES) 0 10 20 30 40 50	G.W.T	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS: INDEX PROPERTIES G_s -	w (%)	L_w -	P_w -	γ_w	γ_d	CLAY (%)	SILT (%)	SAND (%)	SHEAR & CONSOLIDATION CHARACTERISTICS: TYPE OF TEST	c (kPa)	φ (°)	e_0 -	C_c -	P_c (kPa)
15.0	Light grey SAND with some to trace Silt			33 59-blows for 150mm penetration		D-11			N	P			–	3	97						
18.0				31 60-blows for 150mm penetration		D-12															
				33 59-blows for 150mm penetration		D-13															
				53-blows for 1st 150mm penetration		D-14			N	P			–	2	98						
				55-blows for 1st 150mm penetration		D-15															
24.0				42 55-blows for 150mm penetration		D-16			N	P			–	13	87						
				41 58-blows for 150mm penetration		D-17															
27.0				47 60-blows for 150mm penetration		D-18															
				50 40-blows for 100mm penetration		D-19			N	P			–	8	92						
30.0				53 45-blows for 100mm penetration		D-20															

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

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LOG FOR BORE HOLE # 17

(CO-ORDINATES :. 91.9738E & 21.4423N)

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION :Bangladesh Red Crescent Society Compound, Motel Road,Cox's Bazar.

METHOD OF BORING Percussive Wash
DIA. OF BORE HOLE 120 mm (Nominal)
DATE 25-04-07 & 26-04-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES) 0 10 20 30 40 50	GWT	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS INDEX PROPERTIES G_s -	w (%)	L_w -	P_w -	γ_w kN/m³	γ_d kN/m³	CLAY (%)	SILT (%)	SAND (%)	SHEAR & CONSOLIDATION CHARACTERISTICS TYPE OF TEST	c (kPa)	φ (°)	e_o -	C_c -	P_c (kPa)
15.0	Light grey Silty SAND with lumps of silt with some clay (occasionally)			35 70-blows for 100mm penetration		D-11															
17.0	Light grey Sandy SILT with trace clay																				
18.0				50 55-blows for 75mm penetration		D-12	2.66		38	21			7	64	29						
(4.5)				58-blows for 1st 150mm penetration		D-13															
				65-blows for 1st 75mm penetration		D-14															
21.5	Light grey Silty SAND with trace clay			37 58-blows for 100mm penetration		D-15	2.66		34	17			7	36	57						
(3.5)																					
24.0				52-blows for 1st 150mm penetration		D-16	2.66		38	21			7	38	55						
25.0	Light grey Sandy SILT with trace clay			40 59-blows for 75mm penetration		D-17	2.67		37	21			8	67	25						
27.0				38 58-blows for 50mm penetration		D-18															
				100--blows for 1st 150mm penetration		D-19	2.66		34	22			8	65	27						
30.0				89-blows for 1st 125mm penetration		D-20															

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET).

SHEET 2 OF 2

LOG FOR BORE HOLE # 20

(CO-ORDINATES :. 91.9836E & 21.4384N)

CLIENT	: BUET-CDMP Partnership Project Authority	METHOD OF BORING	Percussive Wash.
PROJECT	: EARTHQUAKE ANALYSIS OF STRUCTURES	DIA. OF BORE HOLE	120 mm (Nominal)
LOCATION	: Ghonapara (closed Kaderia Non-Govt. Primary School), Cox's Bazar.	DATE	02-05-07 & 03-05-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES) 0 10 20 30 40 50	G.W.T	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS																
							INDEX PROPERTIES									SHEAR & CONSOLIDATION CHARACTERISTICS					
							G_s -	w (%)	L_w -	P_w -	γ_w (kN/m³)	γ_d (kN/m³)	CLAY (%)	SILT (%)	SAND (%)	TYPE OF TEST	c (kPa)	φ (°)	e_o -	C_c -	P_c (kPa)
15.0	Light grey SAND with some Silt																				
16.0	Light grey Silty SAND with thin laminations of silt with trace clay			65-blows for 1st 150mm penetration		D-11	2.66		30	17			8	37	55						
17.4	Light grey SAND with some Silt																				
18.0				80-blows for 1st 150mm penetration		D-12		20.3	N	P	18.3	15.2	–	12	88	Q_c	3	21			
				55-blows for 1st 150mm penetration		D-13															
				60-blows for 1st 150mm penetration		D-14															
				62-blows for 1st 150mm penetration		D-15			N	P			–	13	87						
24.0				70-blows for 1st 125mm penetration		D-16															
				65-blows for 1st 150mm penetration		D-17															
27.0				69-blows for 1st 150mm penetration		D-18			N	P			–	13	87						
				77-blows for 1st 150mm penetration		D-19															
30.0				80-blows for 1st 150mm penetration		D-20															

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

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SHEET OF

LOG FOR BORE HOLE # 21

(CO-ORDINATES :. 91.9924E & 21.4463N)

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION Mosjid Compound, ICE Factory Road, Majirghat, Cox's Bazar.

METHOD OF BORING : Percussive Wash
DIA. OF BORE HOLE 120 mm (Nominal)
DATE 04-05-07 & 05-05-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES)	GWT	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS														
							INDEX PROPERTIES									SHEAR & CONSOLIDATION CHARACTERISTICS					
				0 10 20 30 40 50			G_s –	w (%)	L_w –	P_w –	γ_w kN/m³	γ_d kN/m³	CLAY (%)	SILT (%)	SAND (%)	TYPE OF TEST	c (kPa)	φ (°)	e_o –	C_c –	P_c (kPa)
15.0	Light grey SAND with trace silt & mica			15,25&35 60		D-11															
18.0				20,40&45 85		D-12			N	P			–	8	92						
18.5	Grey SILT with some Clay & Sand			16,30&40 70		D-13	2.67		43	22			14	73	13						
				20,35&51 86		D-14															
(7.5)				21,38&25-blows for 75mm penetration		D-15															
24.0				22,40&30-blows for 75mm penetration		D-16															
				30,52-blows for150mm penetration		D-17															
26.0	Light grey Silty SAND to SAND with some Silt & laminations of silt with trace clay																				
27.0				35,60-blows for 125mm penetration		D-18	2.65		N	P			6	45	49						
				44,60-blows for75mm penetration		D-19			N	P			–	10	90						
30.0				56-blows for 1st 150mm penetration		D-20															

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	**CHECKED BY : I. Ahmed**	DATE : 20/05/2007	DRG. NO. :

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SHEET 2 OF

LOG FOR BORE HOLE # 18

(CO-ORDINATES :. 91.9772E & 21.4398N)

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Bangladesh Water Development Board Compound, Cox's Bazar.

METHOD OF BORING : Percussive Wash.
DIA. OF BORE HOLE : 120 mm (Nominal)
DATE : 29-04-07 & 30-04-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R.L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES) 0 10 20 30 40 50	GWT	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS														
							INDEX PROPERTIES									SHEAR & CONSOLIDATION CHARACTERISTICS					
							G_s -	w (%)	L_w -	P_w -	γ_w kN/m³	γ_d kN/m³	CLAY (%)	SILT (%)	SAND (%)	TYPE OF TEST	c (kPa)	φ (°)	e_o -	C_c -	P_c (kPa)
15.0																					
15.5	Light grey SILT & SAND with laminations of silt with trace clay			71-blows for 1st 150mm penetration		D-11	2.65		N	P			5	43	52						
(3.5)				59-blows for 1st 100mm penetration		D-12															
18.0																					
19.0	Light grey SAND with some Silt			69-blows for 1st 150mm penetration		D-13			N	P			–	11	89						
(3.8)				75-blows for 1st 150mm penetration		D-14															
				73-blows for 1st 150mm penetration		D-15															
22.8 (1.4)	Light grey SILT with some Clay & Sand			30 55-blows for 150mm penetration		D-16	2.66		40	23			11	69	20						
24.0 24.2 (2.2)	Light grey SILT & SAND with trace clay			100-blows for 1st 150mm penetration		D-17	2.65		N	P			5	45	50						
26.4 27.0	Light grey SAND with trace silt			88-blows for 1st 150mm penetration		D-18															
				80-blows for 1st 150mm penetration		D-19			N	P			–	4	96						
30.0				77-blows for 1st 125mm penetration		D-20															

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

SHEET [illegible]

LOG FOR BORE HOLE # 19

(CO-ORDINATES :. 91.9873E & 21.4459N)

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Tekpara Govt. Primary School Campus, Cox's Bazar.

METHOD OF BORING Percussive Wash.
DIA. OF BORE HOLE 120 mm (Nominal)
DATE 30-04-07 & 01-05-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES) 0 10 20 30 40 50	G/W/T	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS														
							INDEX PROPERTIES									SHEAR & CONSOLIDATION CHARACTERISTICS					
							G_s -	w (%)	L_w -	P_w -	γ_w kN/m³	γ_d kN/m³	CLAY (%)	SILT (%)	SAND (%)	TYPE OF TEST	c (kPa)	ϕ (°)	e_o -	C_c -	P_c (kPa)
15.0	Light grey SAND with some Silt & laminations of silt with trace clay																				
				49 55-blows for 75mm penetration		D-11															
18.0				50 60-blows for 75mm penetration		D-12															
				53-blows for 1st 150mm penetration		D-13			N	P			-	17	83						
				55-blows for 1st 150mm penetration		D-14															
				60-blows for 1st 150mm penetration		D-15															
24.0				63-blows for 1st 125mm penetration		D-16															
				66-blows for 1st 150mm penetration		D-17			N	P			-	14	86						
27.0				70-blows for 1st 150mm penetration		D-18															
				67-blows for 1st 150mm penetration		D-19															
30.0				64-blows for 1st 125mm penetration		D-20															

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

LOG FOR BORE HOLE # 22 ✓

(CO-ORDINATES :. 91.9871E & 21.4398N)

SHEET 2 OF

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Ram Krishna Sheba Shram Compound, Baddayghona, Cox's Bazar.

METHOD OF BORING : Percussive Wash.
DIA. OF BORE HOLE : 120 mm (Nominal)
DATE : 06-05-07 & 07-05-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES) 0 10 20 30 40 50	G.W.T	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS														
							INDEX PROPERTIES									SHEAR & CONSOLIDATION CHARACTERISTICS					
							G_s –	w (%)	L_w –	P_w –	γ_w kN/m³	γ_d kN/m³	CLAY (%)	SILT (%)	SAND (%)	TYPE OF TEST	c (kPa)	φ (°)	e_o –	C_c –	P_c (kPa)
15.0																					
15.4	Light grey Silty SAND with trace mica																				
				50 58-blows for 100mm penetration		D-11			N	P			–	20	80						
(3.6)																					
18.0				75-blows for 1st 150mm penetration		D-12															
19.0	Light grey Silty SAND with lumps of silt with trace clay (occasionally)																				
				60-blows for 1st 150mm penetration		D-13	2.65		N	P			2	35	63						
				60-blows for 1st 150mm penetration		D-14															
(6.0)																					
				75-blows for 1st 150mm penetration		D-15	2.65		N	P			2	40	58						
24.0				69-blows for 1st 150mm penetration		D-16															
25.0	Light grey Silty SAND with laminations of silt with trace clay																				
				90-blows for 1st 150mm penetration		D-17			N	P			–	24	76						
27.0				80-blows for 1st 150mm penetration		D-18															
				87-blows for 1st 150mm penetration		D-19			N	P			–	30	70						
30.0				89-blows for 1st 150mm penetration		D-20															

End of the borehole

M. AHMED & ASSOCIATES LTD., DHAKA.

DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

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LOG FOR BORE HOLE # 30 ✓

SHEET [illegible]

(CO-ORDINATES :. 91.9925E & 21.4401N)

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Primary Education Officer's officr compound, Cox's Bazar.

METHOD OF BORING Percussive Wash.
DIA. OF BORE HOLE 120 mm (Nominal)
DATE 22-05-07 & 23-05-07

DEPTH (m) (THICKNESS)	CLASSIFICATION OF SOIL	LOG	R. L. (m)	STANDARD PENETRATION TEST RESULTS (N - VALUES)	GWT	SAMPLING	SUMMARY OF LABORATORY TEST RESULTS														
							INDEX PROPERTIES									SHEAR & CONSOLIDATION CHARACTERISTICS					
							G_s	w	L_w	P_w	γ_w	γ_d	CLAY	SILT	SAND	TYPE OF TEST	c	φ	e_0	C_c	P_c
							-	(%)	-	-	kN/m³	kN/m³	(%)	(%)	(%)		(kPa)	(°)	-	-	(kPa)
				0 10 20 30 40 50																	
15.0 15.8	Light grey SILT & SAND with lumps of silt with trace clay																				
	Grey SILT with some Clay & Sand			28,45&52-blows for 100mm penetration		D-11	2.66			24			10	78	12						
18.0				25,25&50-blows for 100mm penetration		D-12															
(7.0)				30,40&40-blows for 75mm penetration		D-13															
				24,33&50 83		D-14															
22.8				25,30&52 82		D-15															
24.0 (5.6)	Light grey SAND with some Silt and trace mica			52-blows for 1st 150mm penetration		D-16			N	P			-	15	85						
				70-blows for 1st 150mm penetration		D-17															
27.0				68-blows for 1st 120mm penetration		D-18															
27.2 (0.8) 28.0	Light grey SILT with trace clay & sand																				
	Light grey Silty SAND with trace mica & lumps of silt with trace clay			80-blows for 1st 150mm penetration		D-19	2.66		36	19			9	23	68						
30.0				77-blows for 1st 150mm penetration		D-20			N	P			-	26	74						

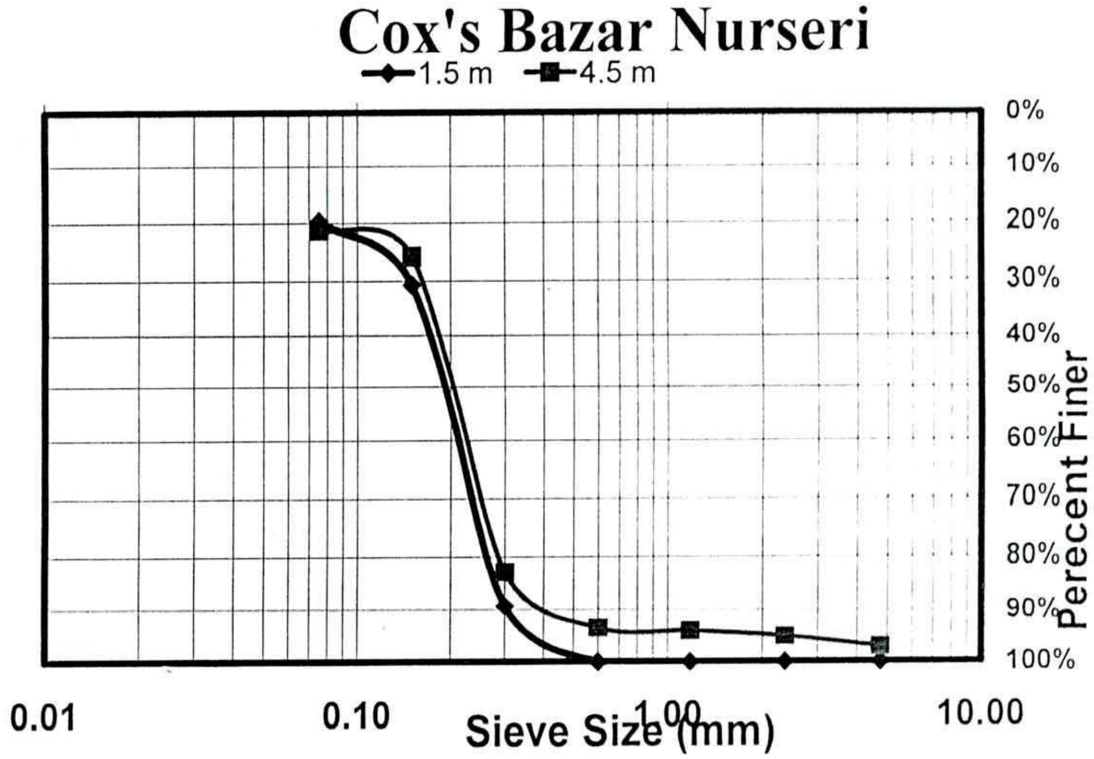
End of the borehole

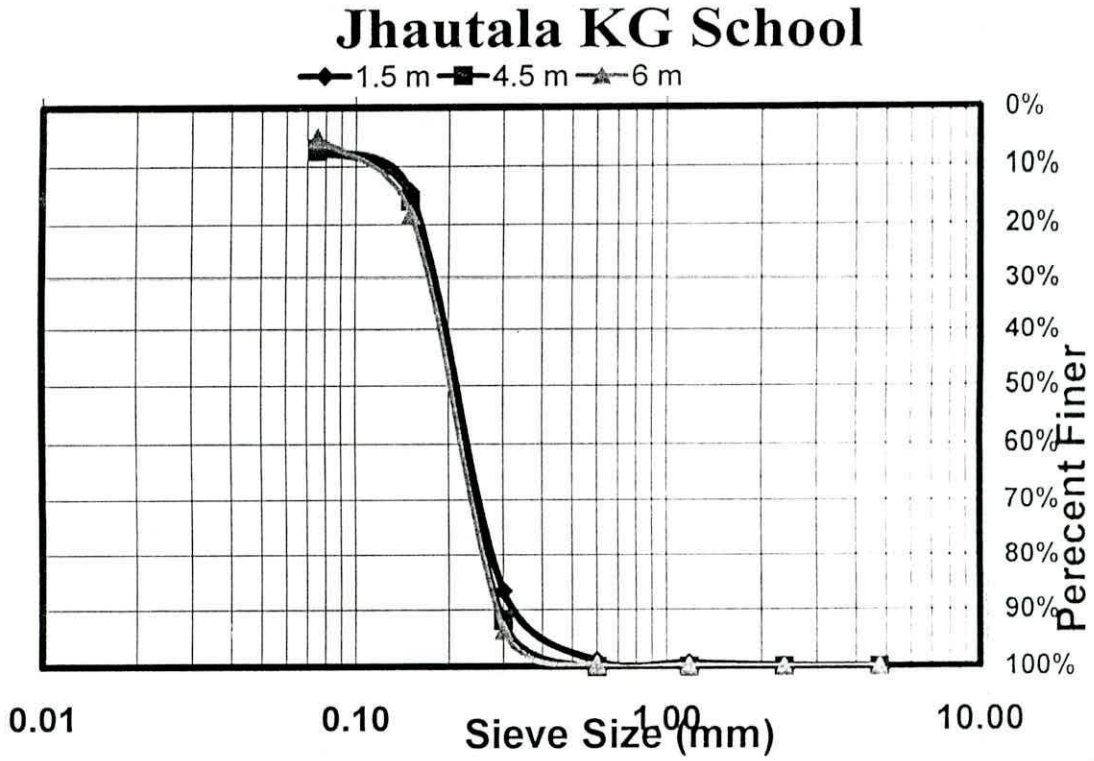
M. AHMED & ASSOCIATES LTD., DHAKA.

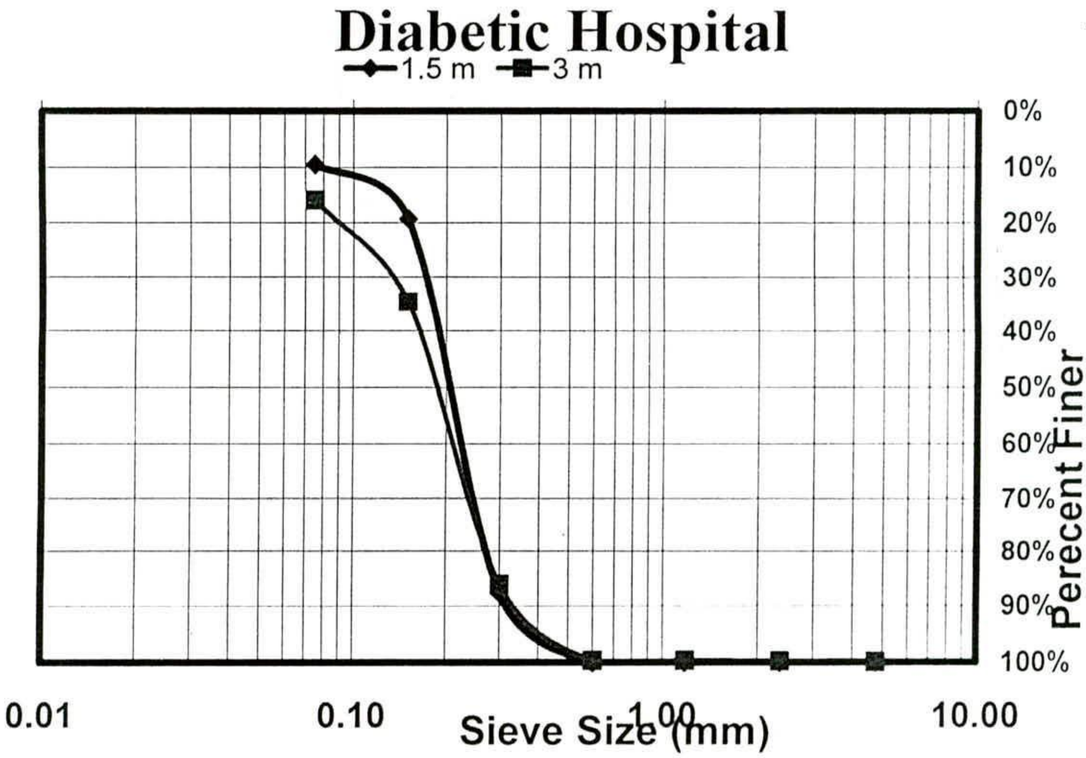
DRAWN BY : S. I. Ansari	CHECKED BY : I. Ahmed	DATE : 20/05/2007	DRG. NO. :

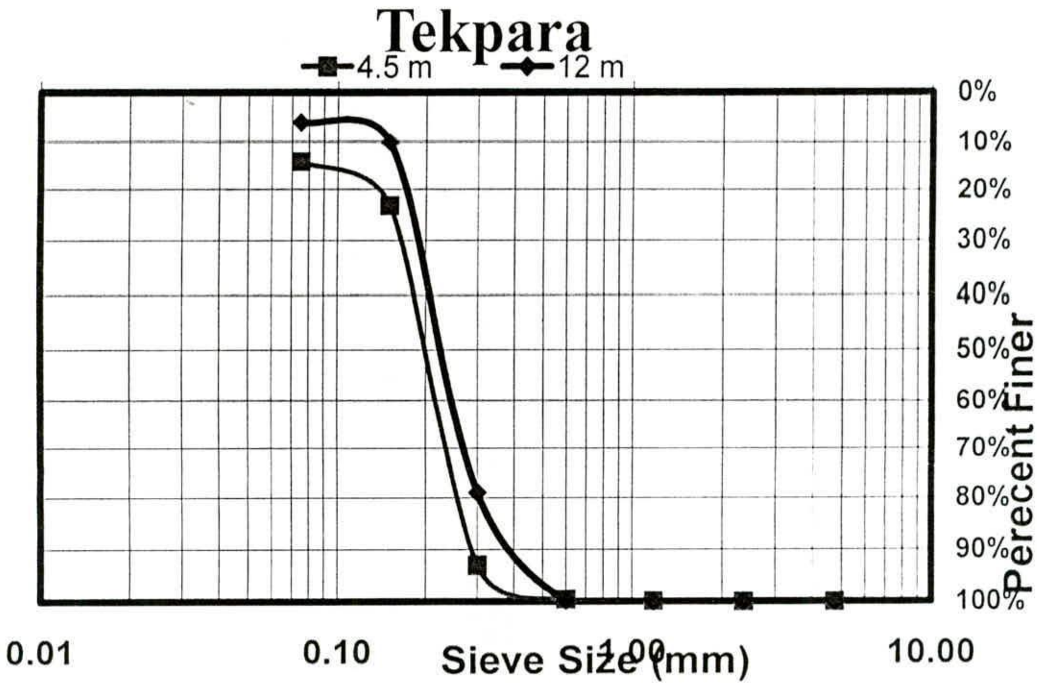
APPENDIX – E

Grain Size Distribution Data

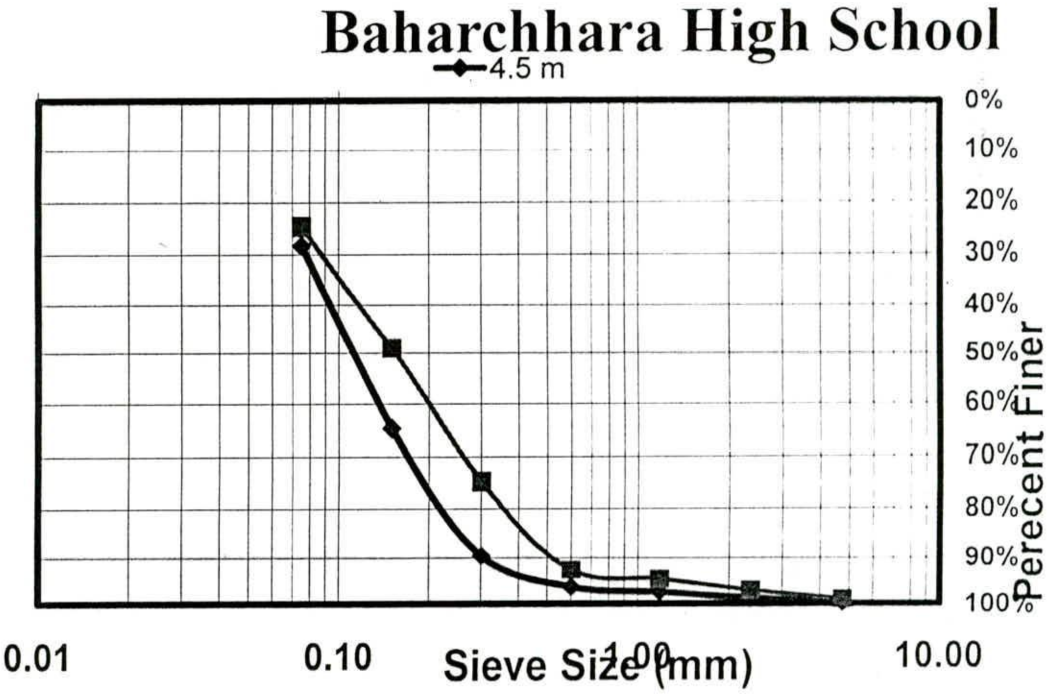

Cox's Bazar Nurseri
1.5 m
4.5 m
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Perecent Finer
0.01
0.10
1.00
10.00
Sieve Size (mm)

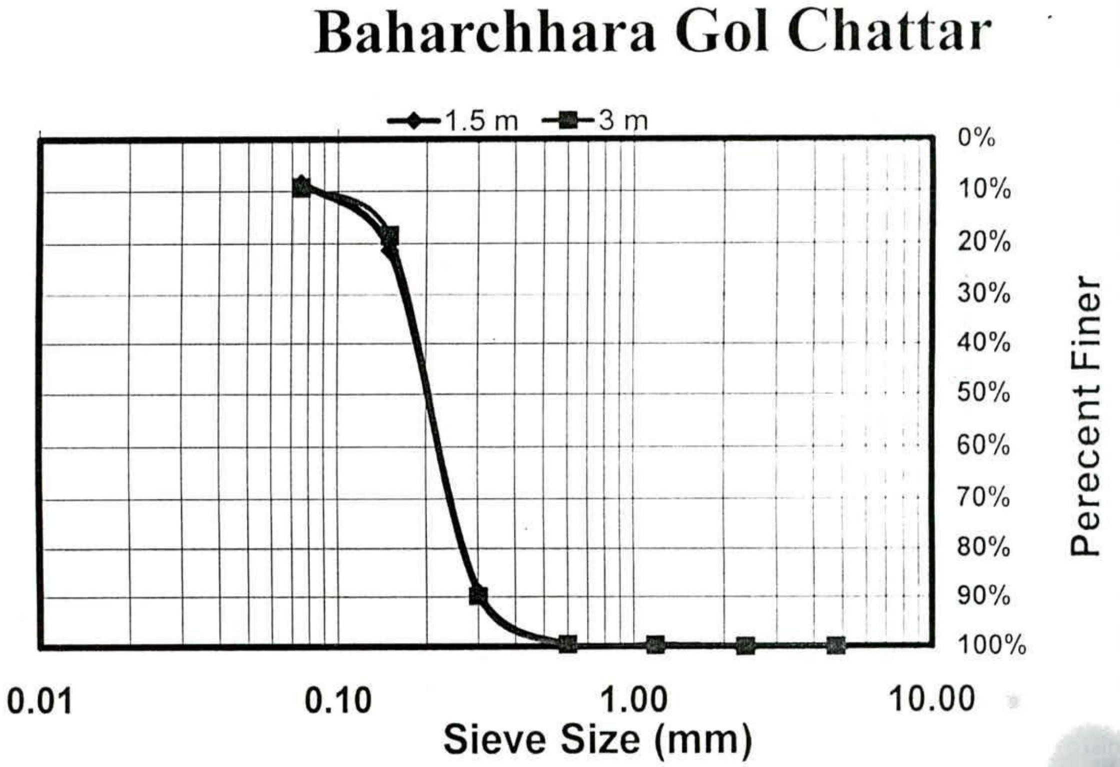

Jhautala KG School
1.5 m
4.5 m
6 m
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Perecent Finer
0.01
0.10
1.00
10.00
Sieve Size (mm)


Diabetic Hospital
1.5 m
3 m
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Perecent Finer
0.01
0.10
1.00
10.00
Sieve Size (mm)


Tekpara
4.5 m
12 m
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Perecent Finer
0.01
0.10
1.00
10.00
Sieve Size (mm)

Grain Size Distribution from Primary Source's Borehole Data

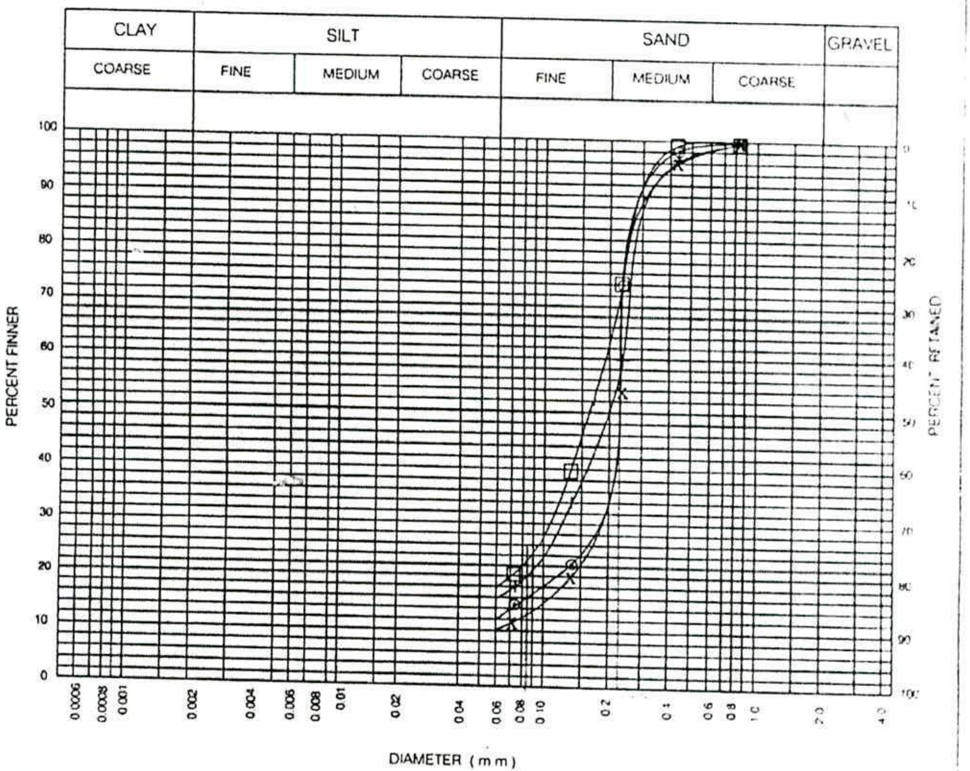




BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET)

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Central Govt. Primary School, CoX's Bazar



B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60}/D_{10}
02	D-1	1.05-1.50	-o-o-o-	-	12	88		
	D-2	2.55-3.0	-x-x-x-	-	10	90		
	D-4	5.55-6.0	⊟⊟⊟	-	16	84		
	D-5	7.05-7.5	-+-+-+-	-	14	86		

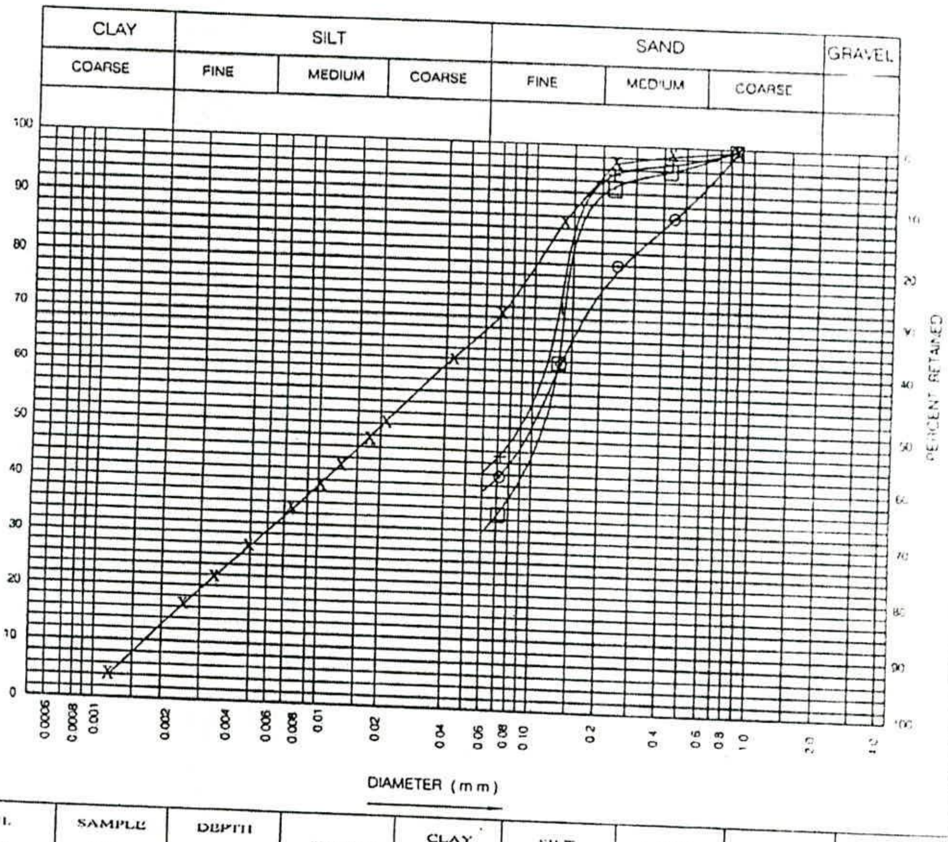
M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : H. Rahman	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No -

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET).

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Central Govt. Primary School, CoX`s Bazar



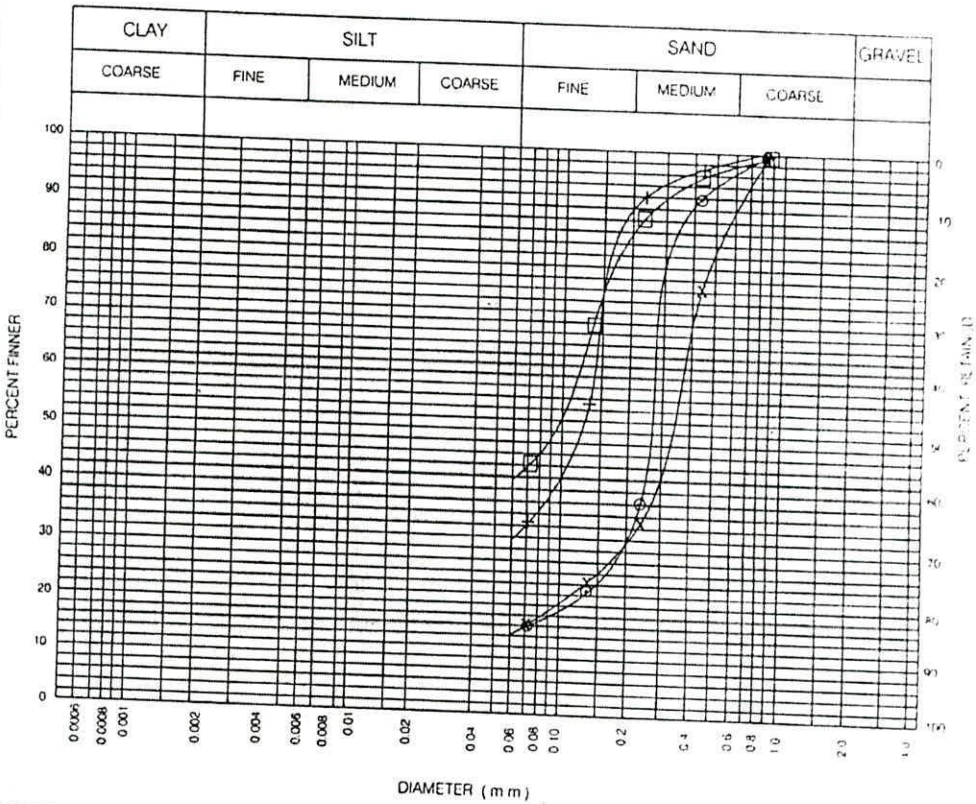
B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP GRAVITY	D_{60}/D_{10}
02	D-15	22.05-22.5	-o-o-o-	–	39	61		
	D-17	25.05-25.5	-X-X-X-	12	58	32	2.67	
	D-19	28.05-28.5	-□-□-□-	–	32	68		
	D-20	29.55-30.0	-+-+-+-	–	42	58		

M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : H. Rahman	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No :

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Peshkarpara Govt. Primary School, Cox`s Bazar



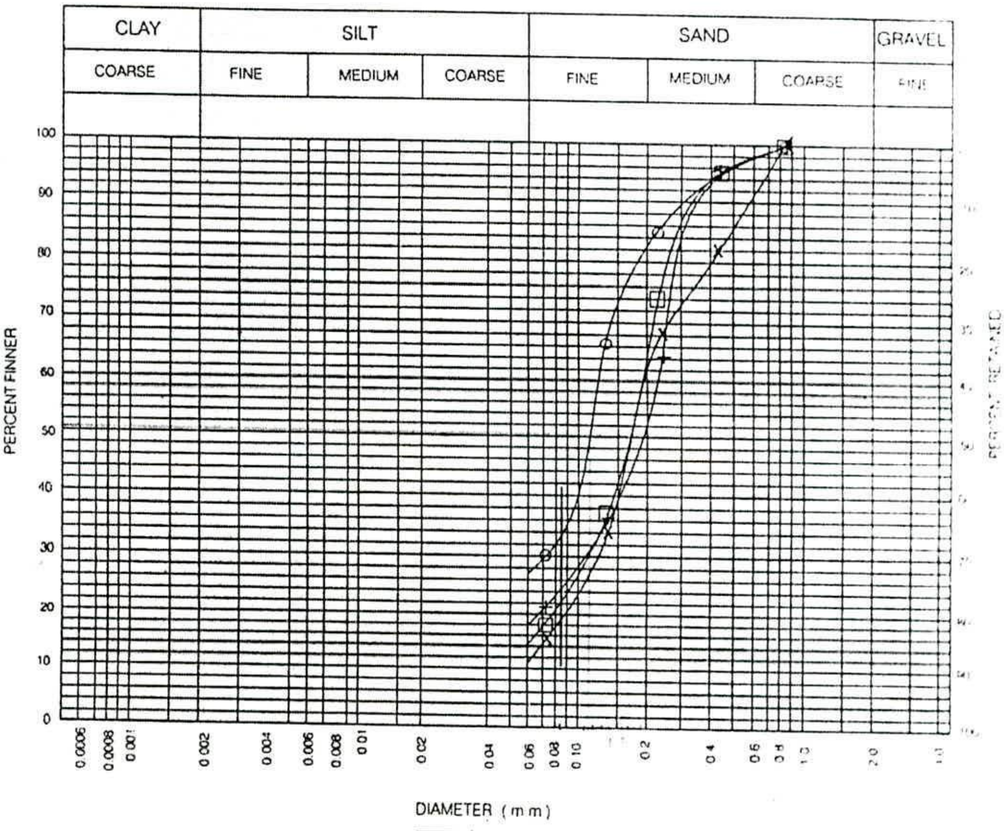
B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60} / D_{10}
03	D-5	7.05-7.5	-o-o-o-	–	14	86		
	D-6	8.55-9.0	-X-X-X-	–	14	86		
	D-9	13.05-13.50	⊟-⊟-⊟	–	42	58		
	D-12	17.55-18.0	+-+-+	–	32	68		

M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : H. Rahman	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No -

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Kusturaghat Govt. Primary School Campus, Badarmukum, Coxs Bazar.



B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D60 / D10
04	D-1	1.05-1.50	-o-o-o-	-	28	72		
	D-2	2.55-3.00	-x-x-x-	-	11	89		
	D-3	4.05-4.5	-□-□-□-	-	14	86		
	D-4	5.55-6.0	-+-+-+-	-	18	82		

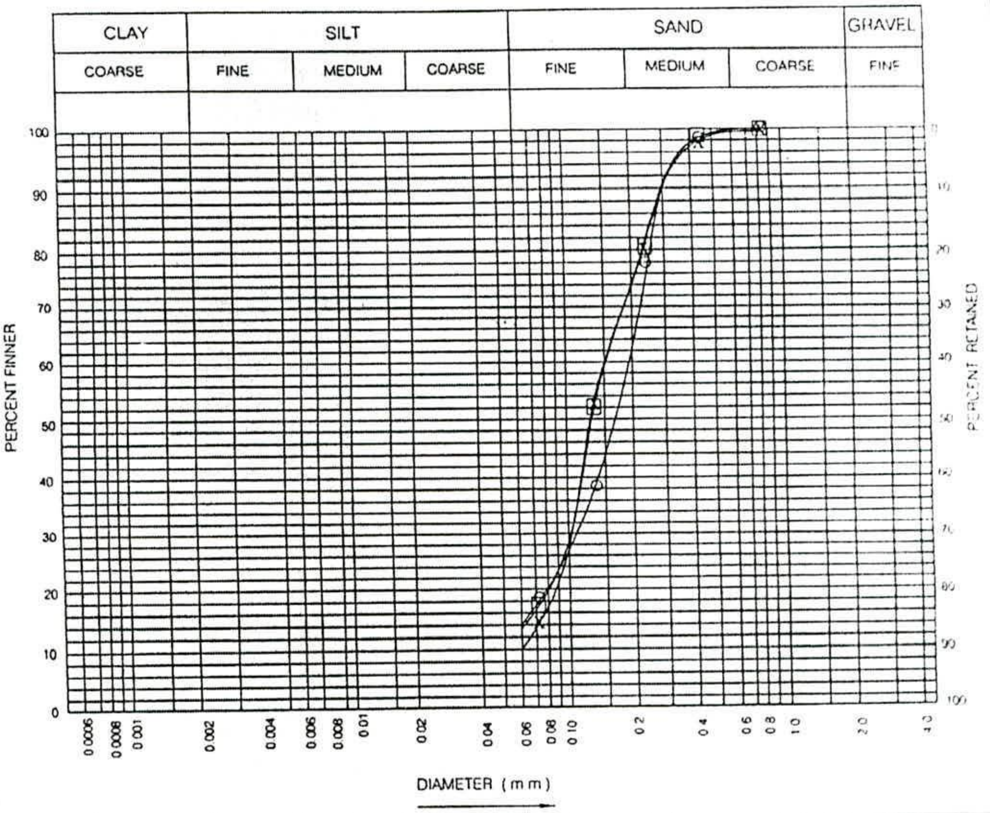
M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : H. Rahman	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET)

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Kusturaghat Govt. Primary School Campus, Badarmukum, Coxs Bazar.



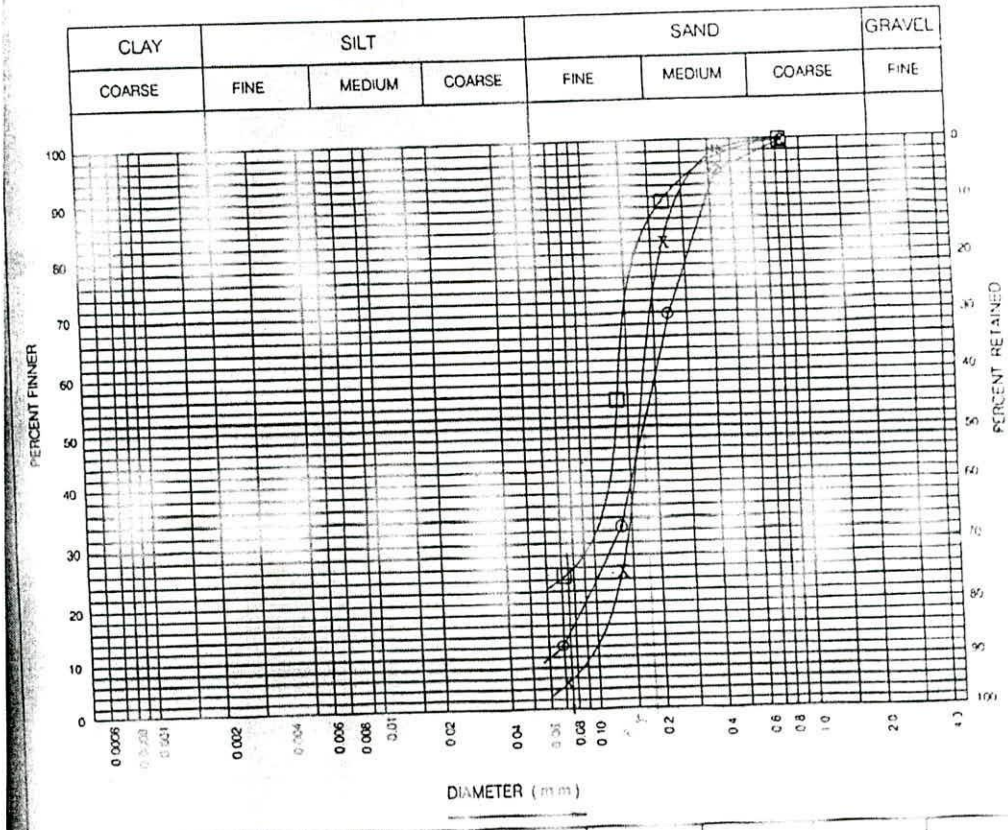
B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60}/D_{10}
04	D-15	22.05-22.5	-o-o-o-	-	14	86		
	D-18	26.55-27.0	-x-x-x-	-	10	90		
	D-20	29.55-30.0	-□-□-□-	-	14	86		

M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : H. Rahman	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg. No.

GRAIN SIZE DISTRIBUTION

CLIENT : B[illegible]MP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Baitus Salat Jamey Mosjid Complex, South Baharchara, Cox's Bazar



B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60}/D_{10}
16	D-1	1.05-1.50	-o-o-o-	–	10	90		
	D-3	4.05-4.50	-x-x-x-	–	3	97		
	D-5	7.05-7.5	-□-□-□-	–	23	77		

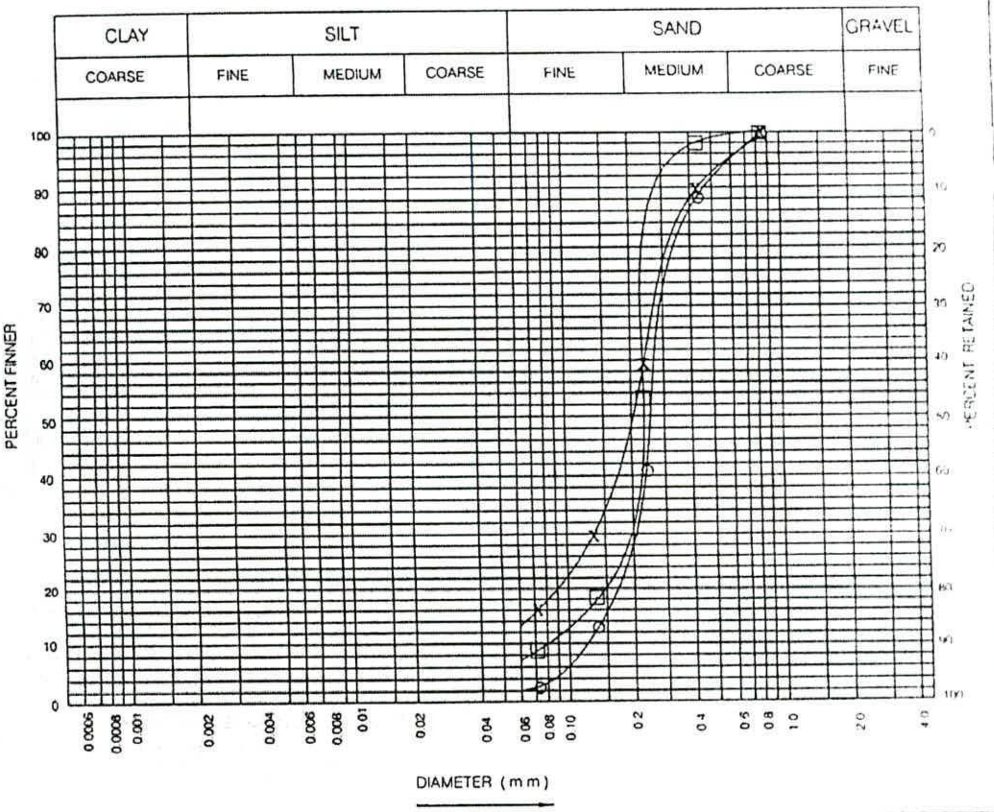
M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : S. I. Ansari	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No :

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET).

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Project Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Baitus Salat Jamey Mosjid Complex, South Baharchara, Cox's Bazar



B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60}/D_{10}
16	D-14	20.55-21.00	-o-o-o-	-	2	98		
	D-16	23.55-24.00	-X-X-X-	-	13	87		
	D-19	28.05-28.50	-□-□-□-	-	8	92		

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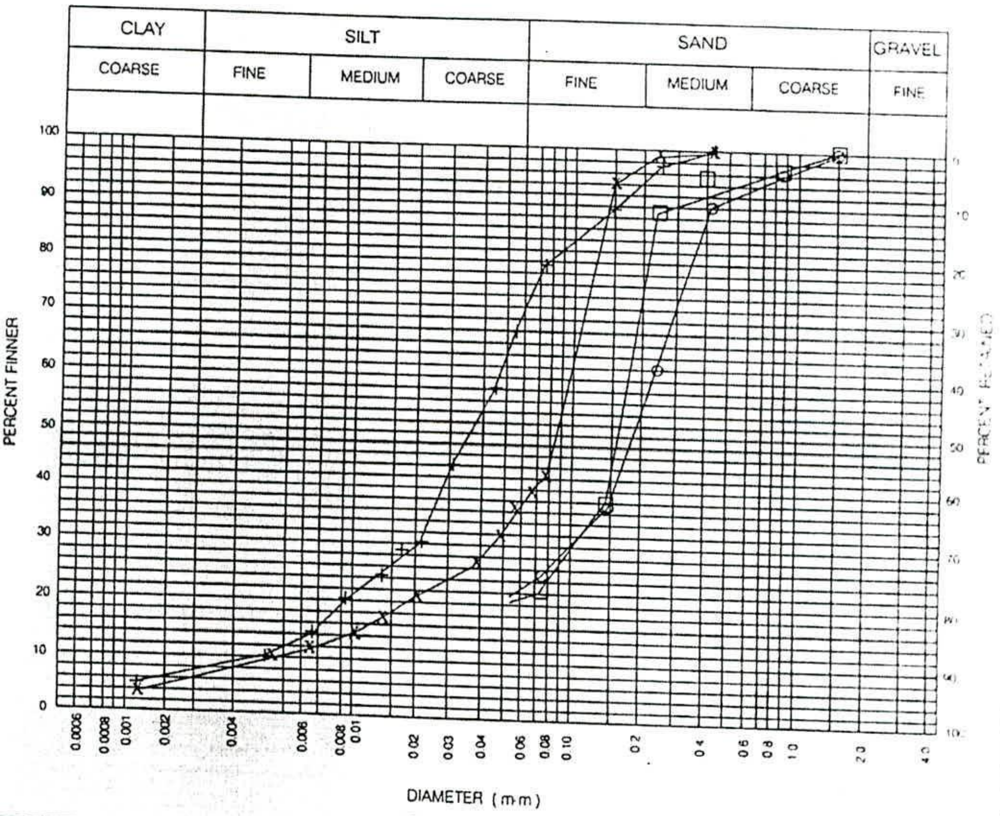
Drawn by : S. I. Ansari	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg. No -

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET).

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Bangladesh Red Crescent Society Compund, Motel Road, Cox's Bazar.



B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60} / D_{10}
17	D-6	8.55-9.00	-o-o-o-	–	23	77		
	D-9	13.05-13.50	-x-x-x-	6	34	60	2.66	
	D-10	14.55-15.00	-□-□-□-	–	21	79		
	D-12	17.55-18.00	-+-+-+-	7	64	29	2.66	

M. AHMED & ASSOCIATES LTD., DHAKA.

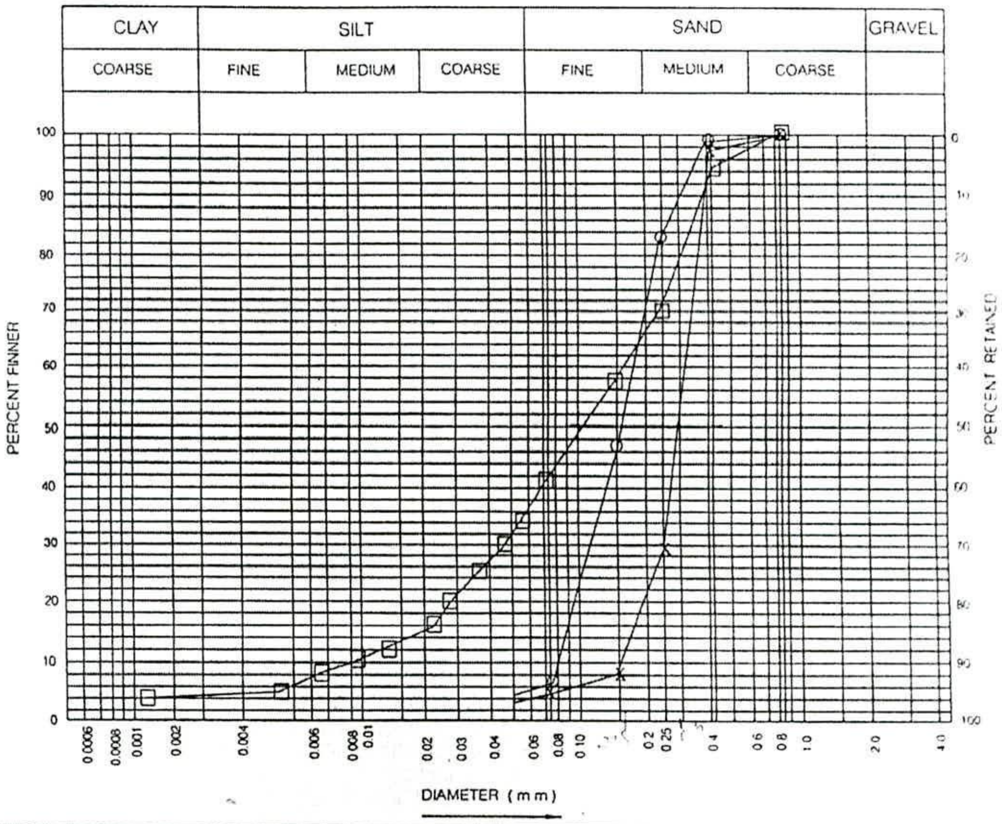
Drawn by : S. I. Ansari | CHECKED BY : I. Ahmed | Date : 22/05/2007 | Drg No :

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority

PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES

LOCATION : Bangladesh Water Development Board Compund, Cox's Bazar.



B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60}/D_{10}
18	D-1	1.05-1.50	—○—○—○—	–	5	95	–	
	D-3	4.05-4.50	—×—×—×—	–	4	96	–	
	D-6	8.55-9.00	—□—□—□—	5	32	63	2.64	

M. AHMED & ASSOCIATES LTD., DHAKA.

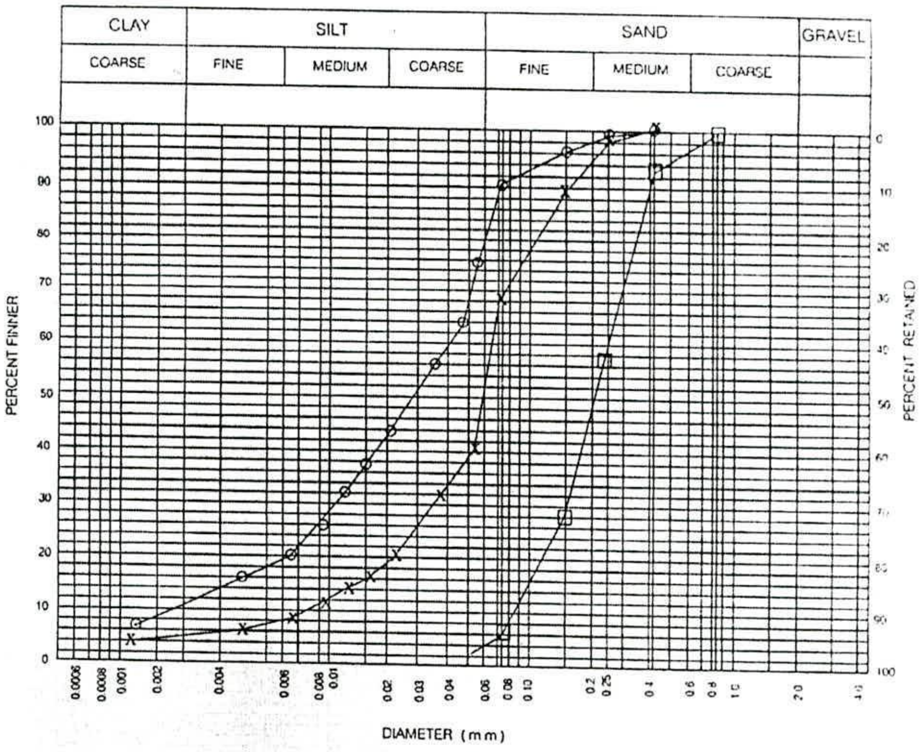
Drawn by : S. I. Ansari	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No. -

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority

PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES

LOCATION : Bangladesh Water Development Board Compund, Cox's Bazar.



B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP GRAVITY	D_{60}/D_{10}
18	D-16	23.55-24.00	-o-o-o-	11	69	20	2.66	
	D-17	25.05-25.00	-x-x-x-	5	45	50	2.65	
	D-19	28.05-28.50	-□-□-□-	-	4	96		

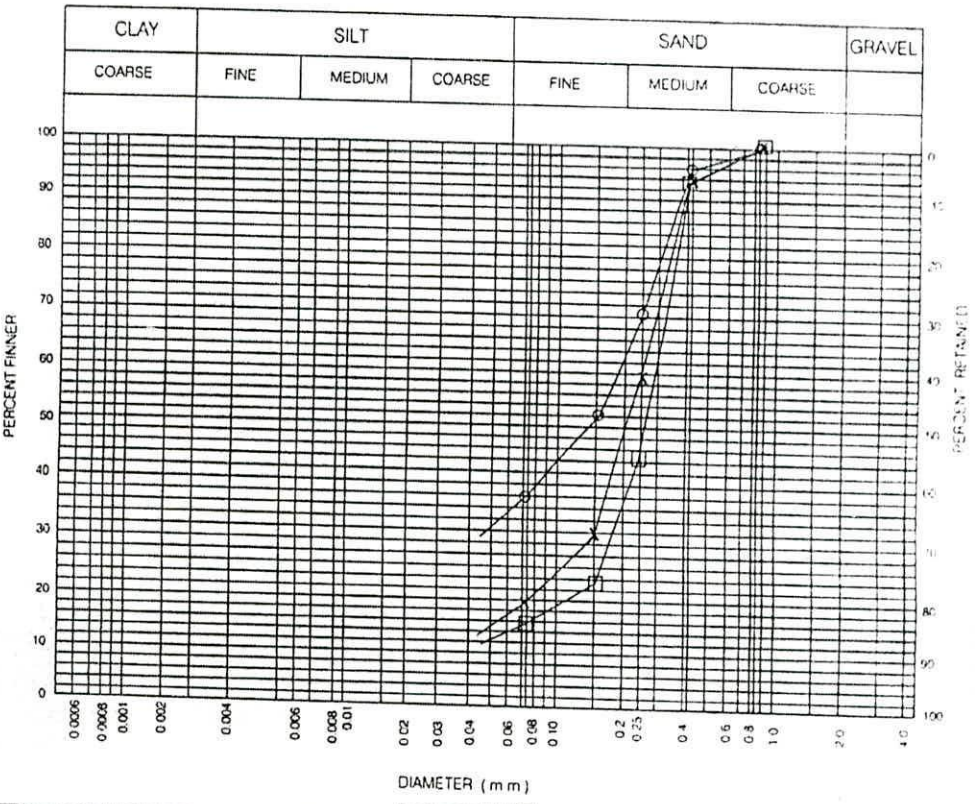
M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : S. I. Ansari	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No -

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY (BUET).

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Tekpara Govt. Primary School Campus, Cox's Bazar.



B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D60 / D10
19	D-9	13.05-13.50	-o-o-o-	-	35	65	-	
	D-13	19.05-19.50	-X-X-X-	-	17	83	-	
	D-17	25.05-25.50	-□-□-□-	-	14	86		

M. AHMED & ASSOCIATES LTD., DHAKA.

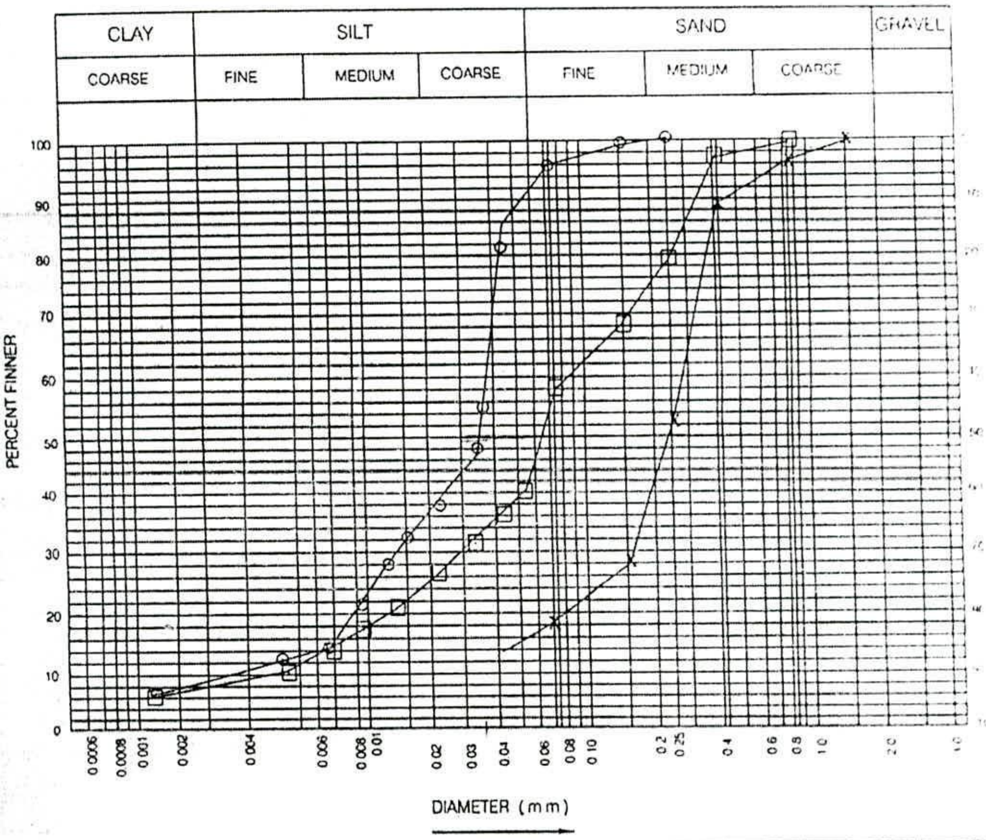
Drawn by : S. I. Ansari	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg. No

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority

PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES

LOCATION : Ghonapara (Closed Kaderia Non-Govt. Primary School) Cox's Bazar.



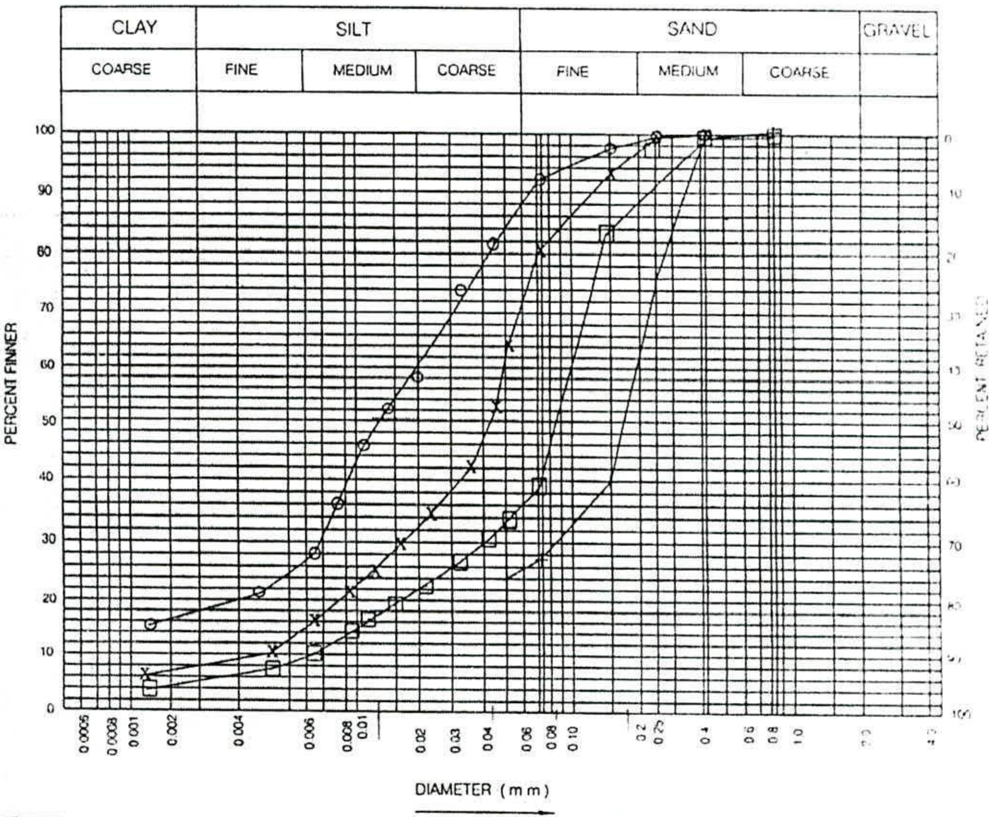
B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60}/D_{10}
20	D-6	8.55-9.00	-o-o-o-	9	83	8	2.66	
	D-8	11.55-12.00	-x-x-x-	–	17	83	–	
	D-11	16.05-16.50	-□-□-□-	8	37	55	2.66	

M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : S. I. Ansari	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No ·

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Mosjid Compound, ICE Factory Road, Mazirghat, Cox's Bazar.



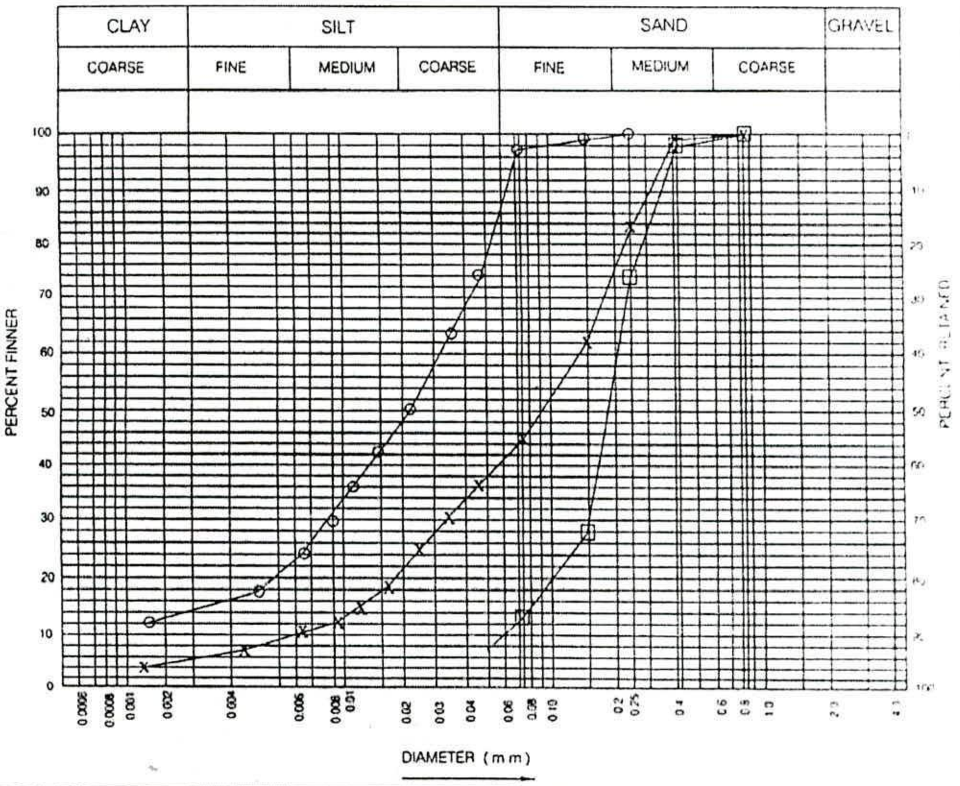
B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60} / D_{10}
21	D-1	1.05-1.50	-o-o-o-	18	70	12	2.67	
	D-2	2.55-3.00	-x-x-x-	8	63	29	2.66	
	D-3	4.05-4.50	-□-□-□-	5	31	64	2.65	
	D-4	5.55-6.00	-+-+-+-	-	26	74		

M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : S. I. Ansari	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No -

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Mosjid Compound, ICE Factory Road, Mazirghat, Cox's Bazar.



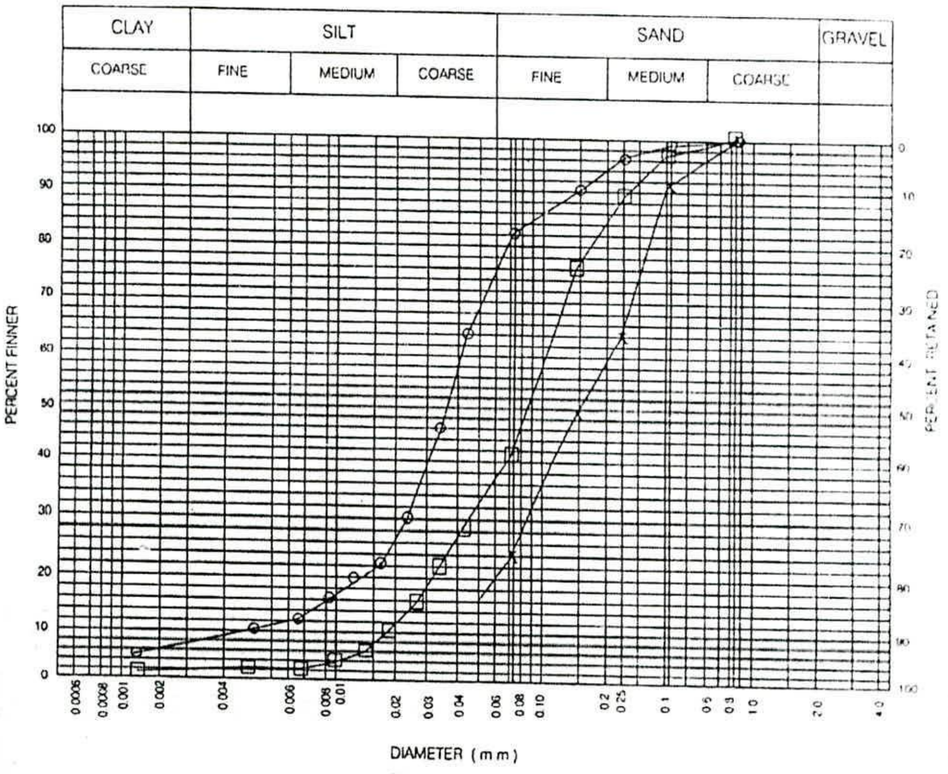
B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60} / D_{10}
21	D-13	19.05-19.50	—○—○—○—	14	73	13	2.67	
	D-18	26.55-27.00	—×—×—×—	6	45	49	2.65	
	D-19	28.05-28.50	—□—□—□—	-	10	90		

M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : S. I. Ansari	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No. -

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Ram Krishna Sheba Shram Compound, Badday Ghona, Cox's Bazar



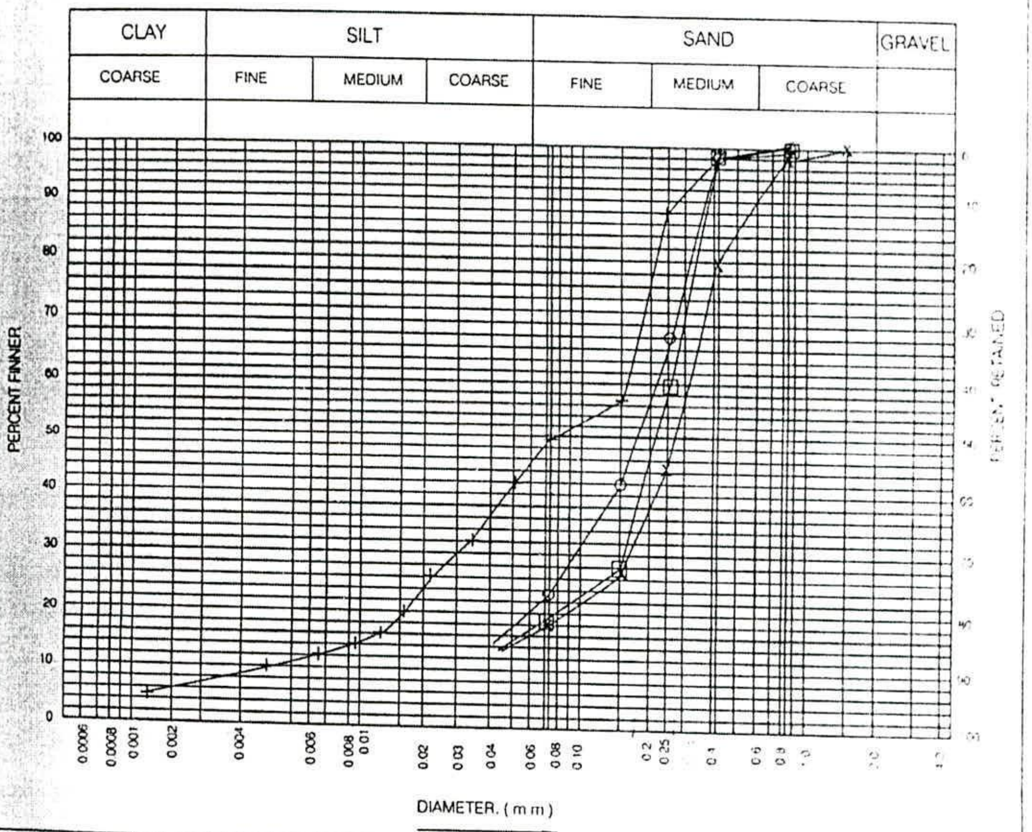
B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60} / D_{10}
22	D-9	13.05-13.50	-o-o-o-	7	67	25	2.66	
	D-11	16.05-16.50	-x-x-x-	–	20	80	–	
	D-13	19.05-19.50	-□-□-□-	2	35	63	2.65	

M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : S. I. Ansari
CHECKED BY : I. Ahmed
Date : 22/05/2007
Drg No :

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : District Officers office compound, South Romalia Chhara, Cox's Bazar



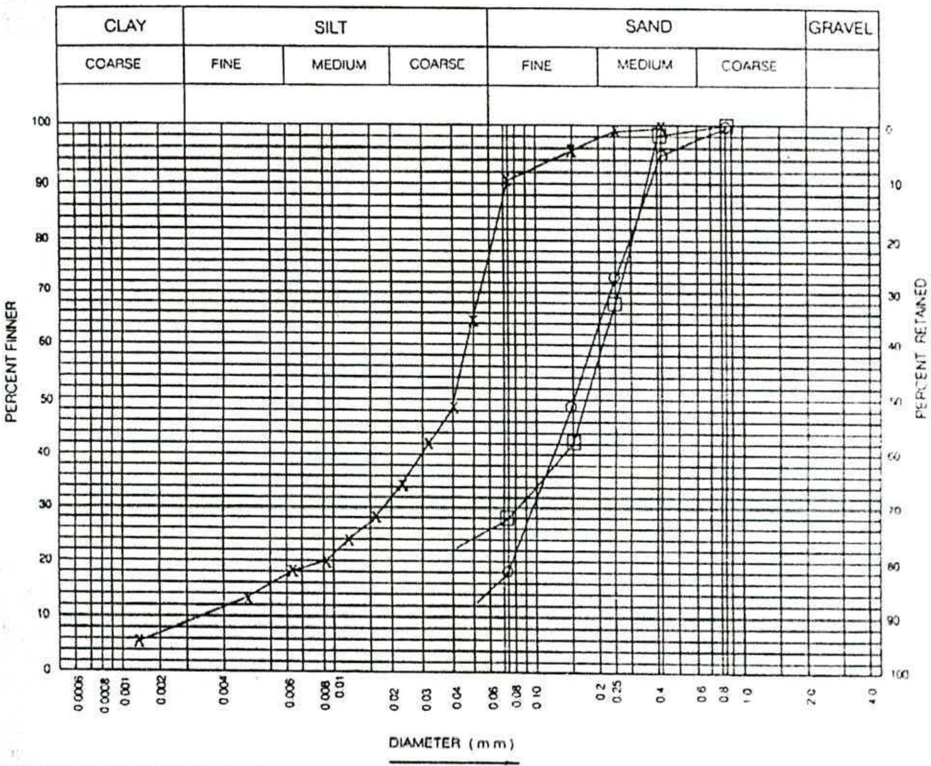
B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60} / D_{10}
30	D-1	1.05-1.50	○ ○ ○	–	20	80	–	
	D-2	2.55-3.00	X X X	–	16	84	–	
	D-3	4.05-4.50	□ □ □	–	17	83		
	D-5	7.05-7.50	+ + +	7	38	55	2.66	

M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : **S. I. Ansari**	CHECKED BY : **I. Ahmed**	Date : 22/05/2007	Drg No -

GRAIN SIZE DISTRIBUTION

CLIENT : BUET-CDMP Partnership Prpject Authority
PROJECT : EARTHQUAKE ANALYSIS OF STRUCTURES
LOCATION : Bangladesh Water Development Board Compund, Cox's Bazar.



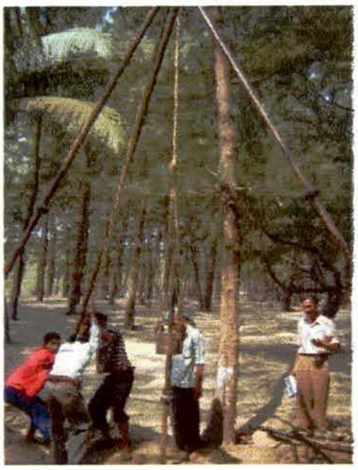
B.H. NO.	SAMPLE NO.	DEPTH (m)	SYMBOL	CLAY (%)	SILT (%)	SAND (%)	SP. GRAVITY	D_{60} / D_{10}
30	D-16	23.55-24.00	-o-o-o-	–	15	85	–	
	D-19	28.05-28.50	-x-x-x-	9	68	23	2.66	
	D-20	29.55-30.00	-□-□-□-	–	26	74		

M. AHMED & ASSOCIATES LTD., DHAKA.

Drawn by : S. I. Ansari	CHECKED BY : I. Ahmed	Date : 22/05/2007	Drg No -

APPENDIX – F

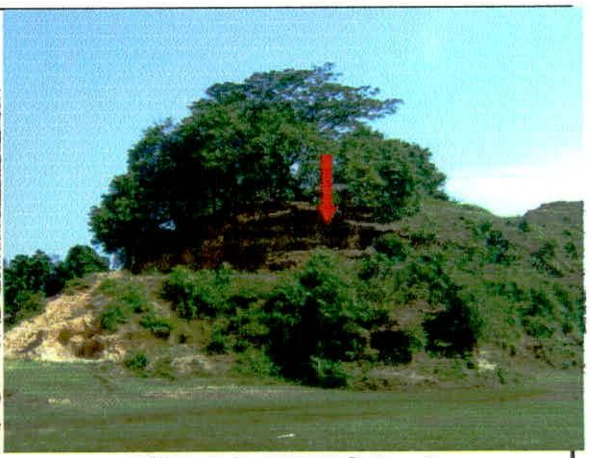
Standard Penetration Test Photographs



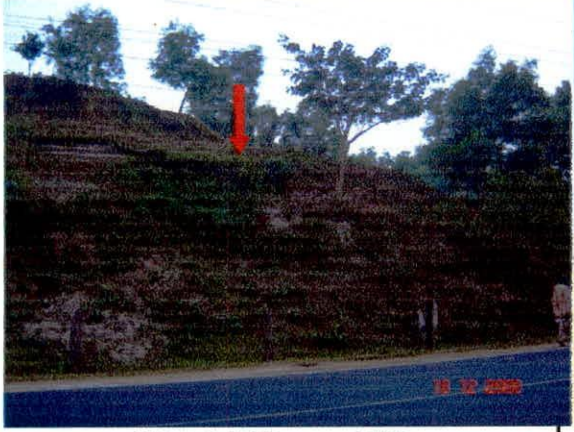
APPENDIX – G

Photographs of Landslide Sampling Locations

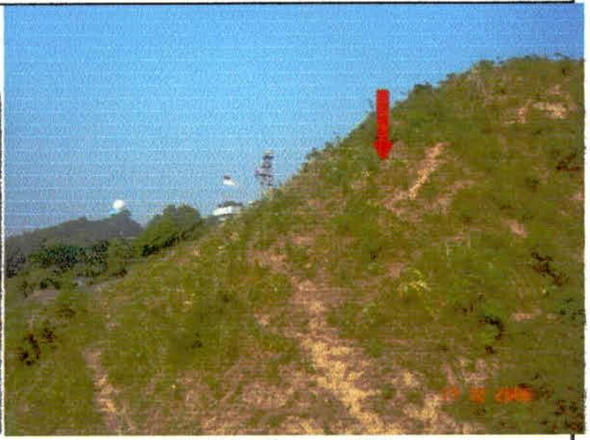
Boiddorghona Hill



Hill behind PTI School

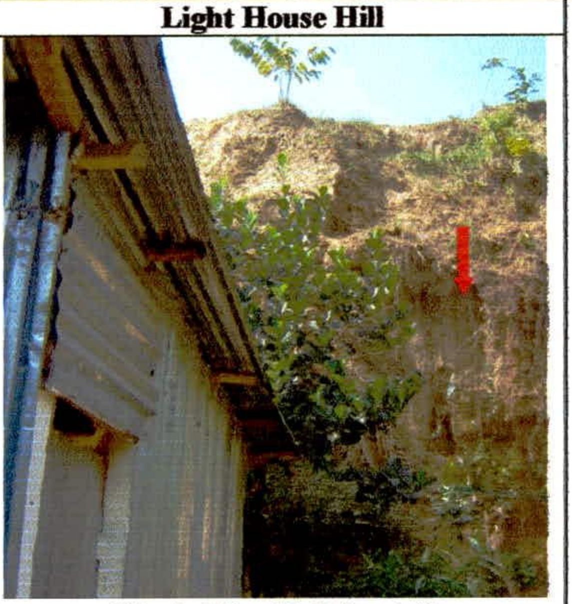


Kolatoli Bypass Hill



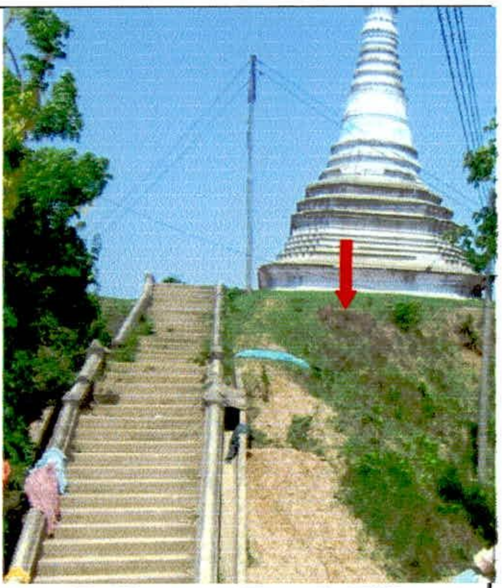
Light House Hill

Ghonarpara Hill



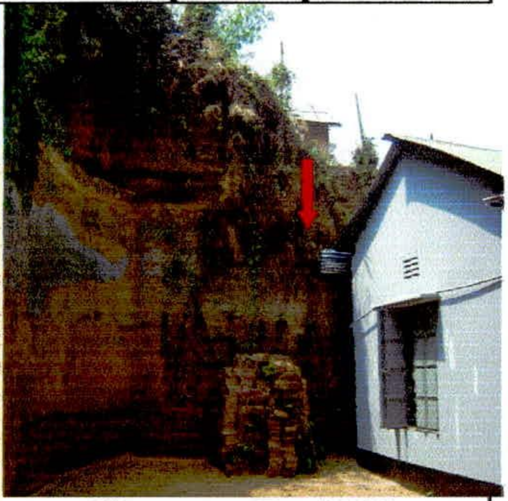
Khaja Monjil, Pahartoli

Circuit House Hill

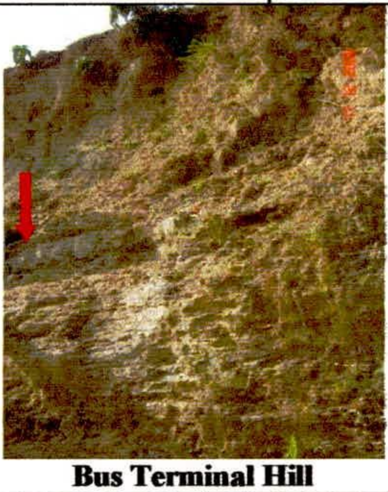


Boillarpara Temple Hill

Kolatoli Saikat Residential Area



Ghonerpara Road Hill



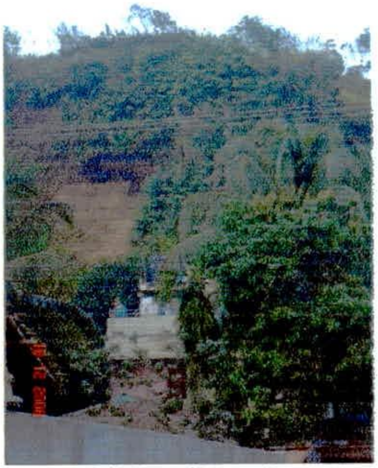
Bus Terminal Hill

↓ Sample Location

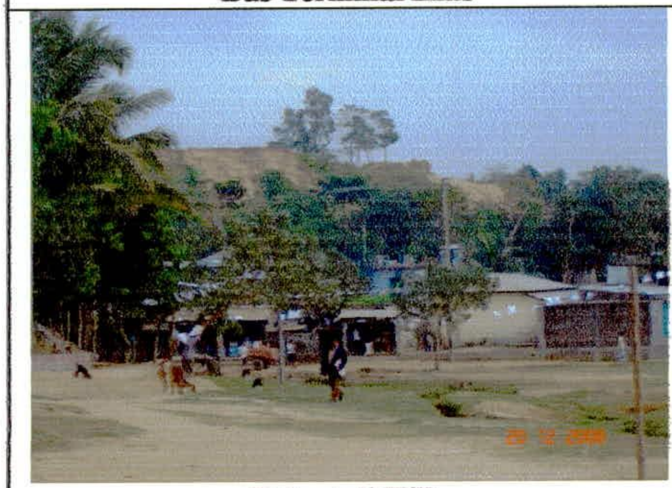
APPENDIX – H

Photographs of Hills and Landslide Potential Areas

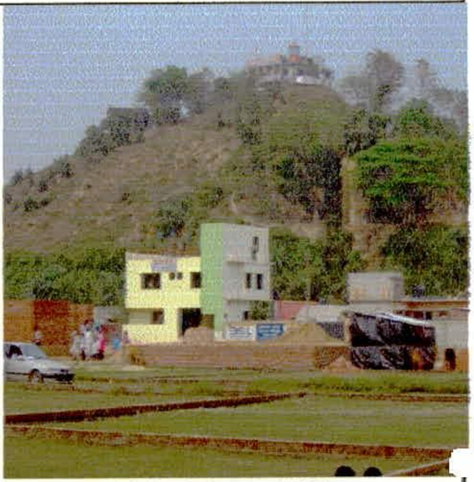
Bus Terminal Hills



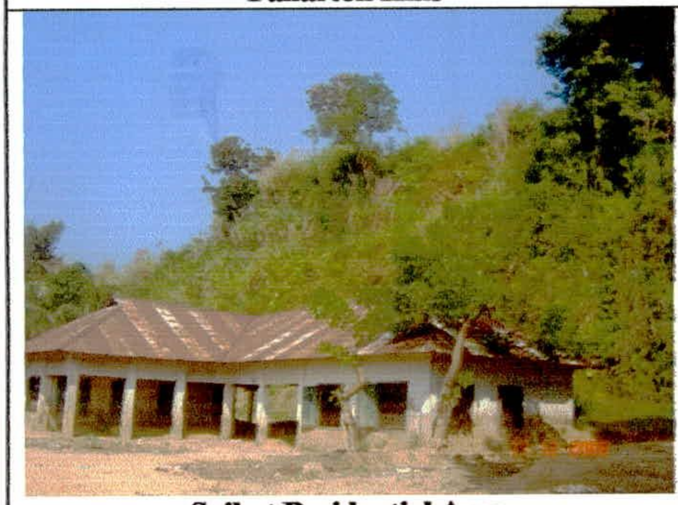
Kolatoi Road



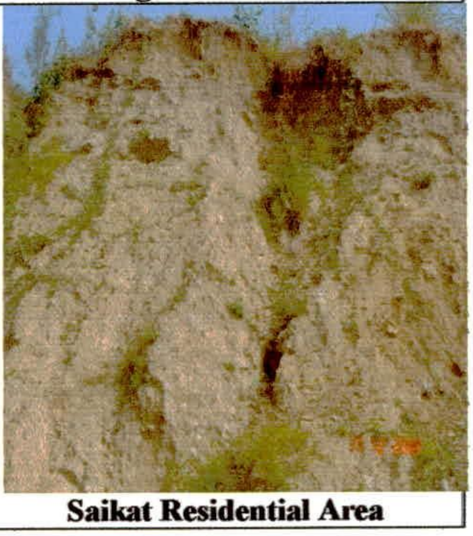
Pahartoli Hills



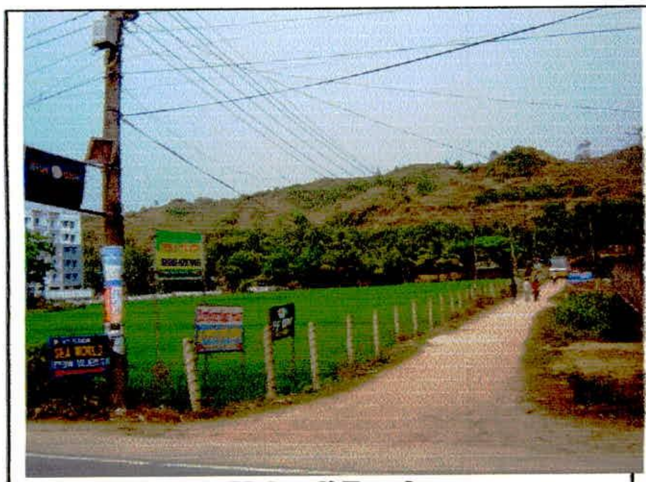
Light House Hills



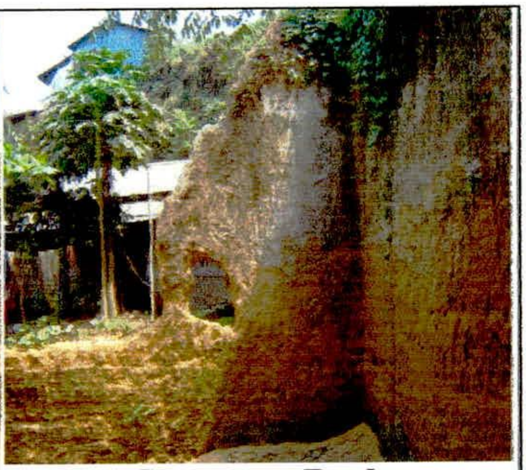
Saikat Residential Area



Saikat Residential Area

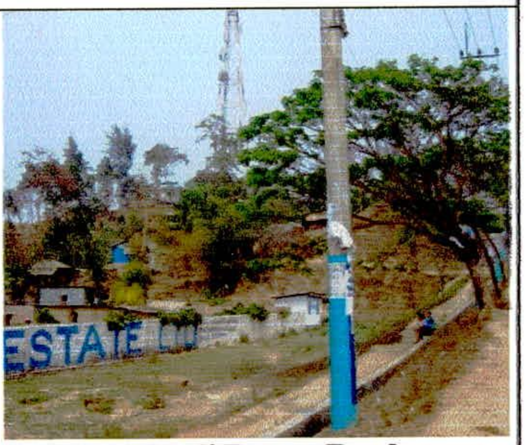


Kolatoli Road

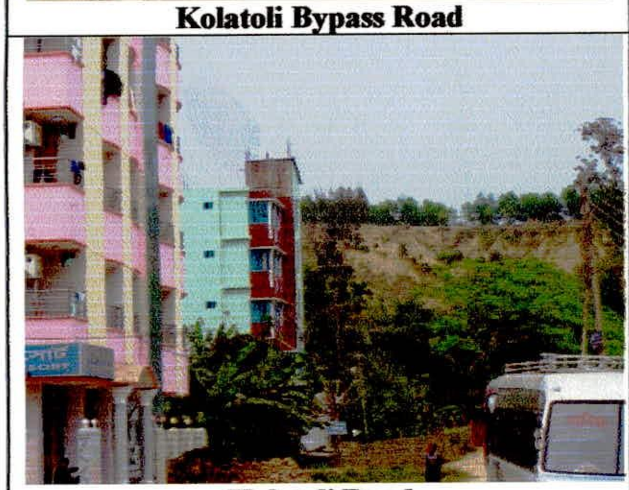


Ghonerpara Road

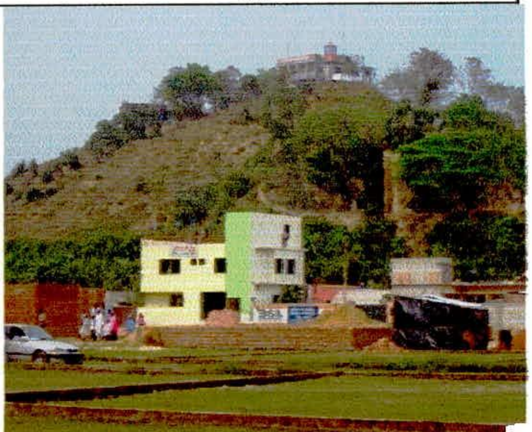
Kolatoli Bypass Road



Kolatoli Bypass Road



Kolatoli Road



Kolatoli Road

APPENDIX – I

Summary of Laboratory Test Results for Landslide Estimation

Summary of Results

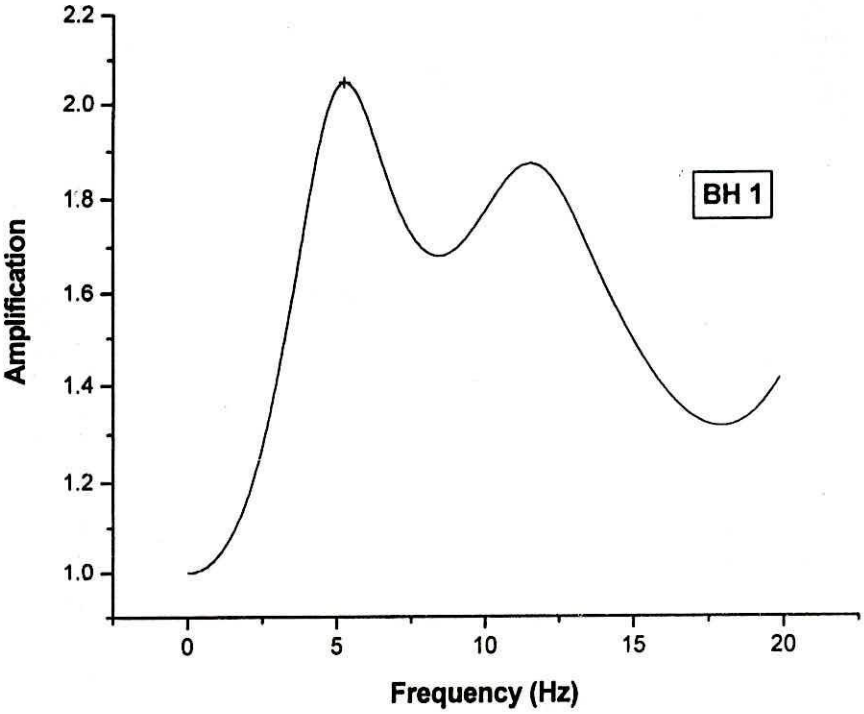
Soil Sample	Grain Size Distribution(combined) [M.I.T Classification]				Plasticity Index
	%Gravel	%Sand	%Silt	%Clay	
P.T.I High School	6	54	34.5	5.5	6.24
Ghonarpara	0.5	96.5	3	0	0
Light House Hill	1	67	29	3	0
Kolatoli Bypass	1.5	74.5	21	3	0
Boiddor Ghona	0.4	97	2.6	0.3	0

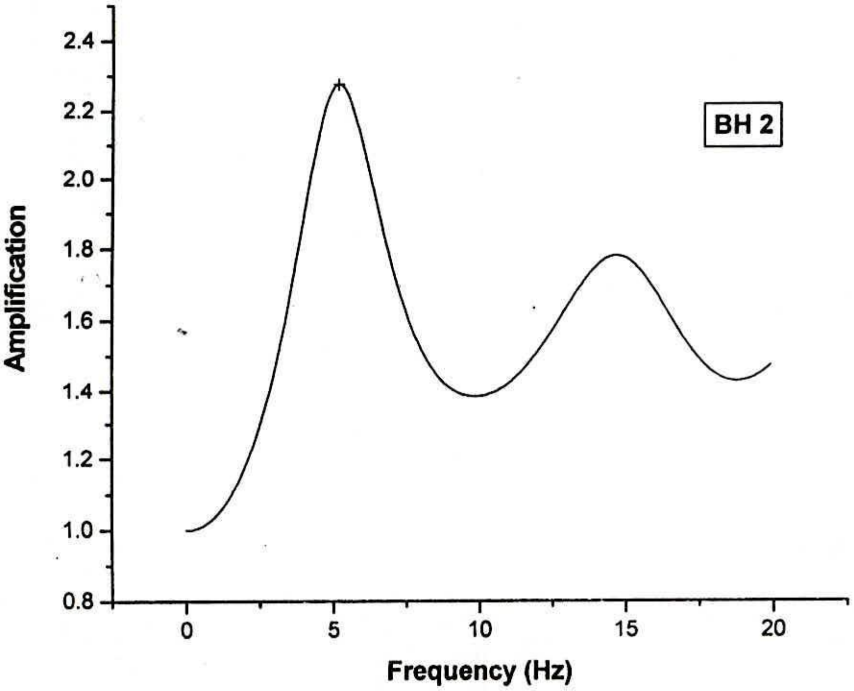
Summary of Soil Parameters for slope stability Analysis

Sample	Ysat (kN/m³)	C (kN/m²)	Φ°	F.S.
Hill behind P.T.I High School	17.3	30	36	1.44
Ghonarpara Hill	17.0	0	36	0.31
Light house Hill	17.3	8	39	0.69
Kolatoli Bypass Hill	16.8	8	38	0.68
Boiddorghona Hill	16.0	0	36	0.30

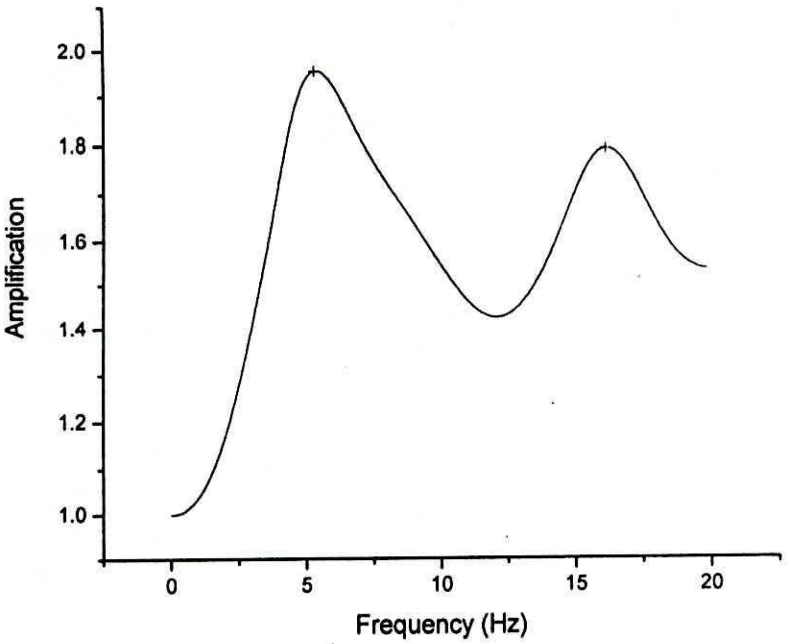
APPENDIX – J

Plot of Transfer Functions


BH 1
Amplification
2.2
2.0
1.8
1.6
1.4
1.2
1.0
Frequency (Hz)
0
5
10
15
20

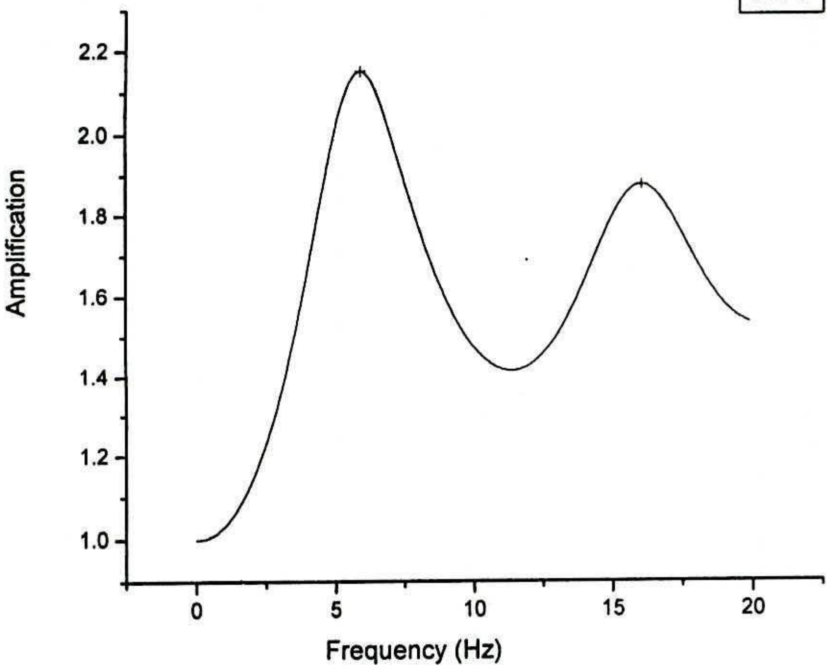

BH 2
Amplification
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
Frequency (Hz)
0
5
10
15
20

BH 5

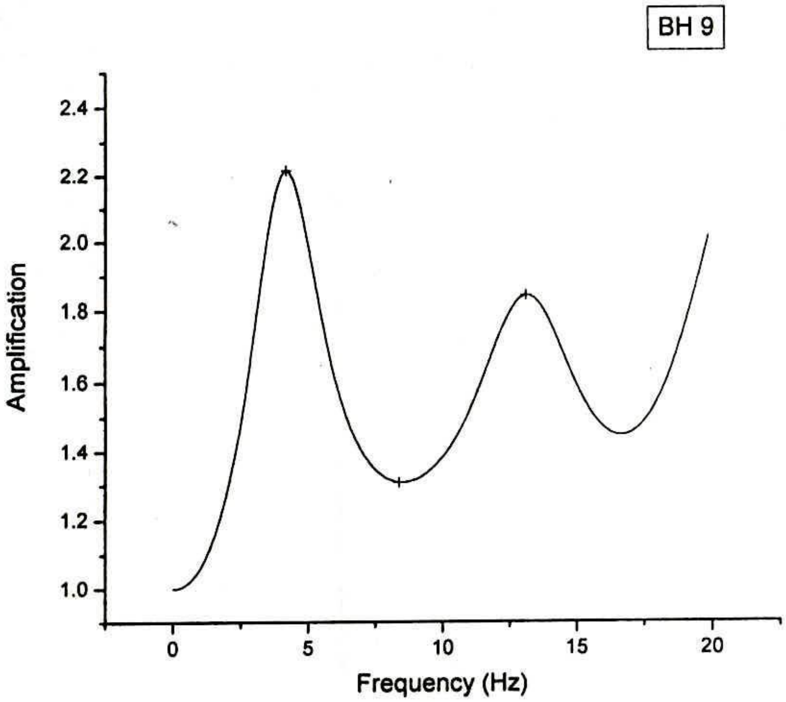


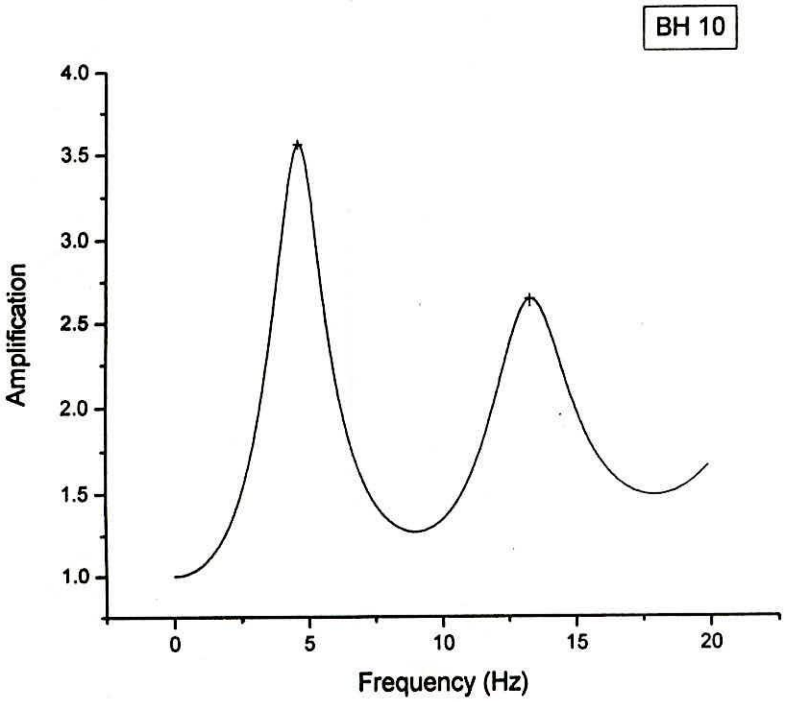
Amplification
2.0
1.8
1.6
1.4
1.2
1.0
0
5
10
15
20
Frequency (Hz)

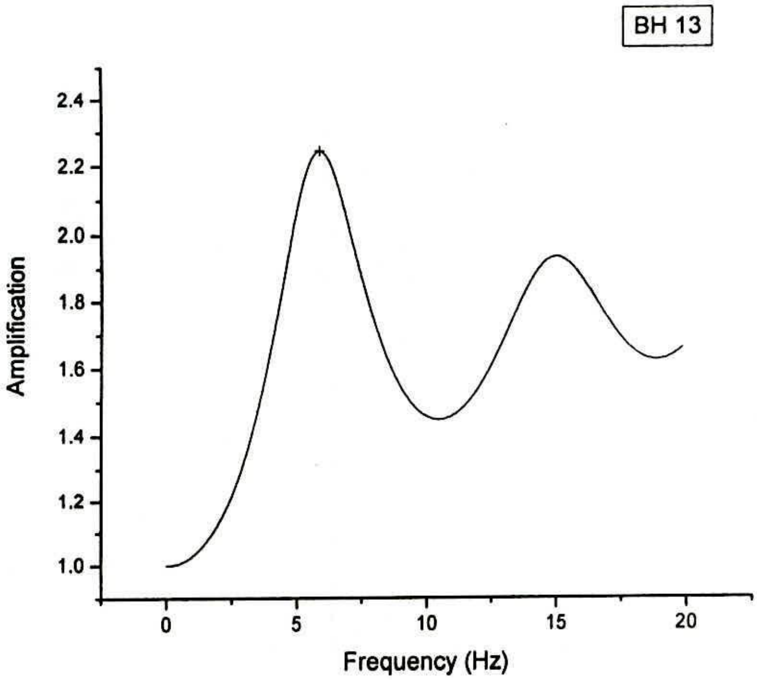
BH 6

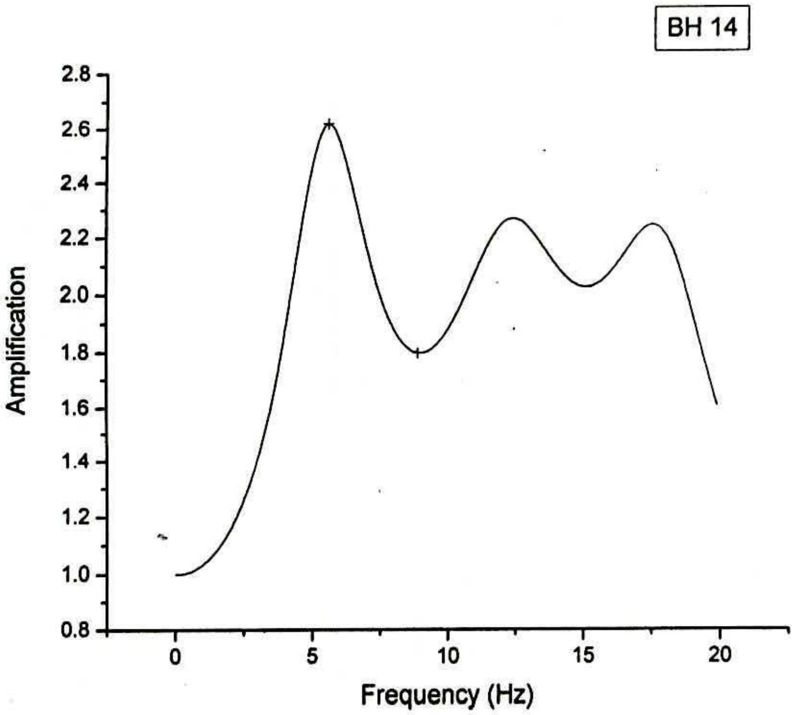


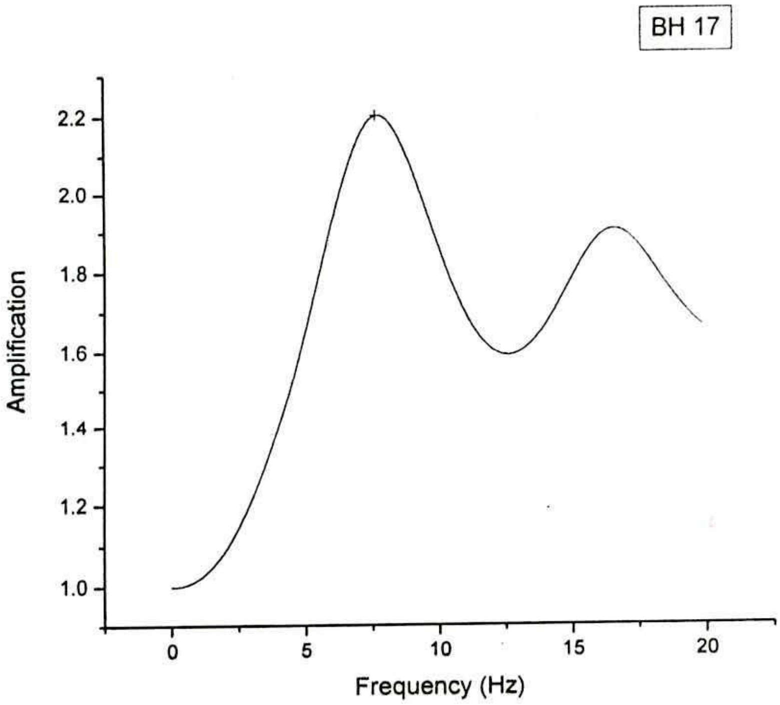
Amplification
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
5
10
15
20
Frequency (Hz)

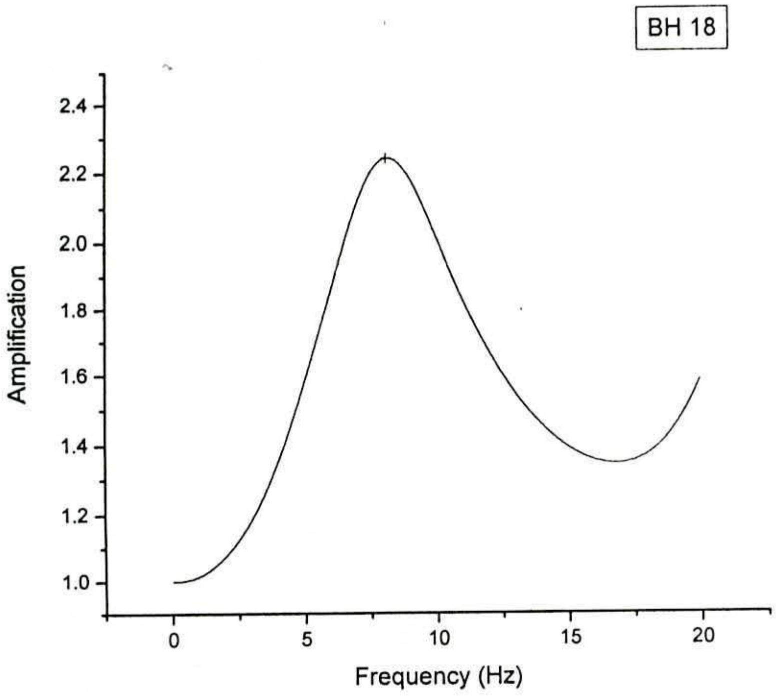

BH 9
Amplification
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
5
10
15
20
Frequency (Hz)

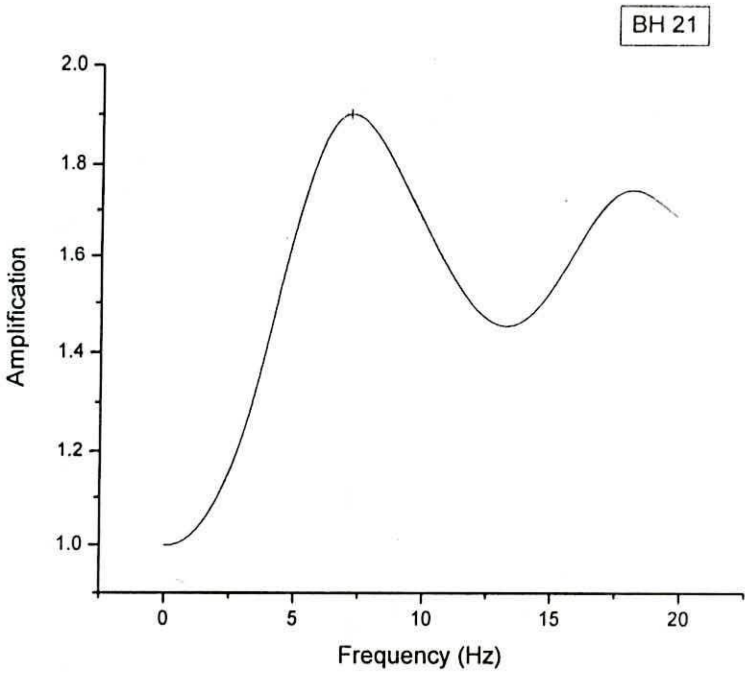

BH 10
Amplification
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0
5
10
15
20
Frequency (Hz)

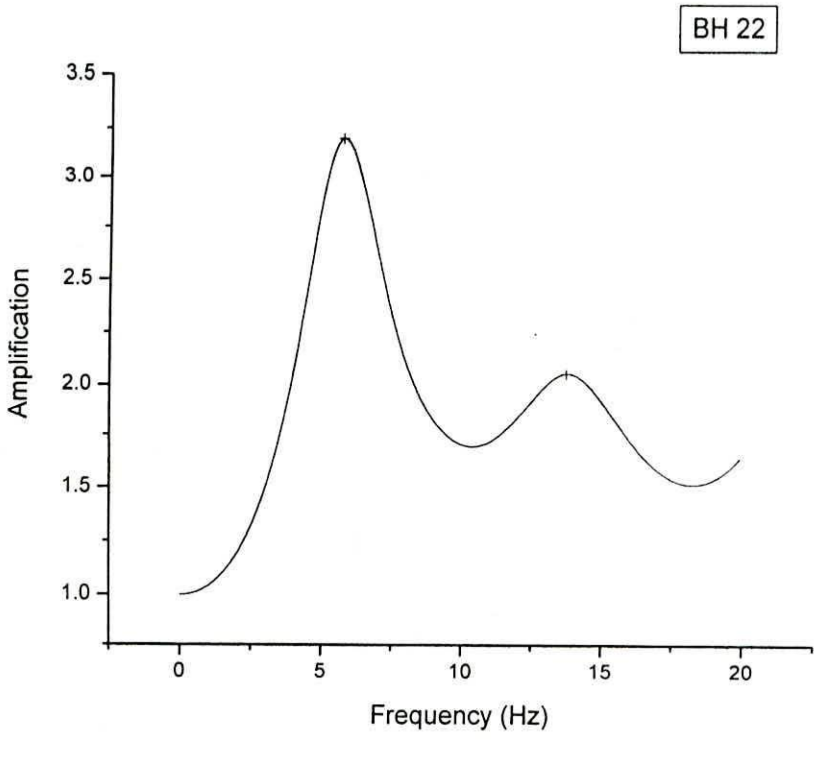

BH 13
Amplification
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
5
10
15
20
Frequency (Hz)

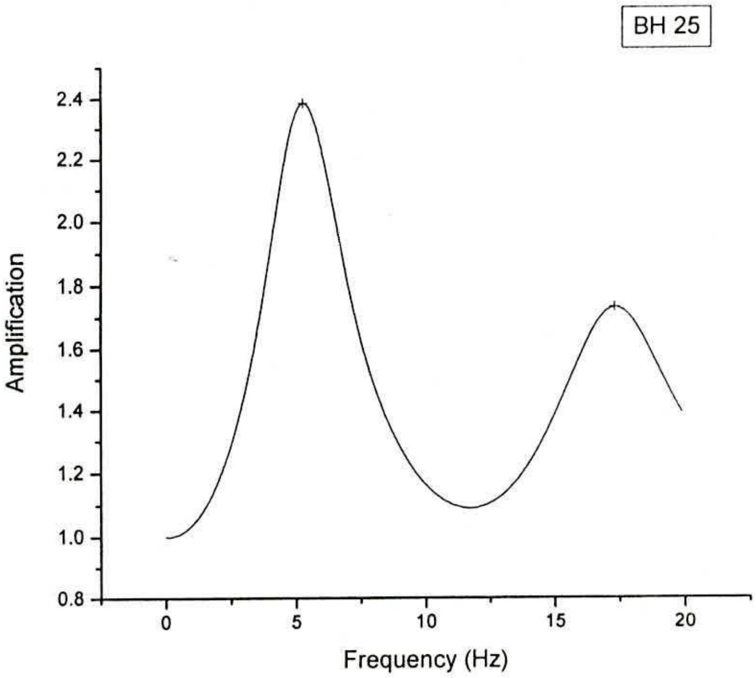

BH 14
Amplification
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0
5
10
15
20
Frequency (Hz)

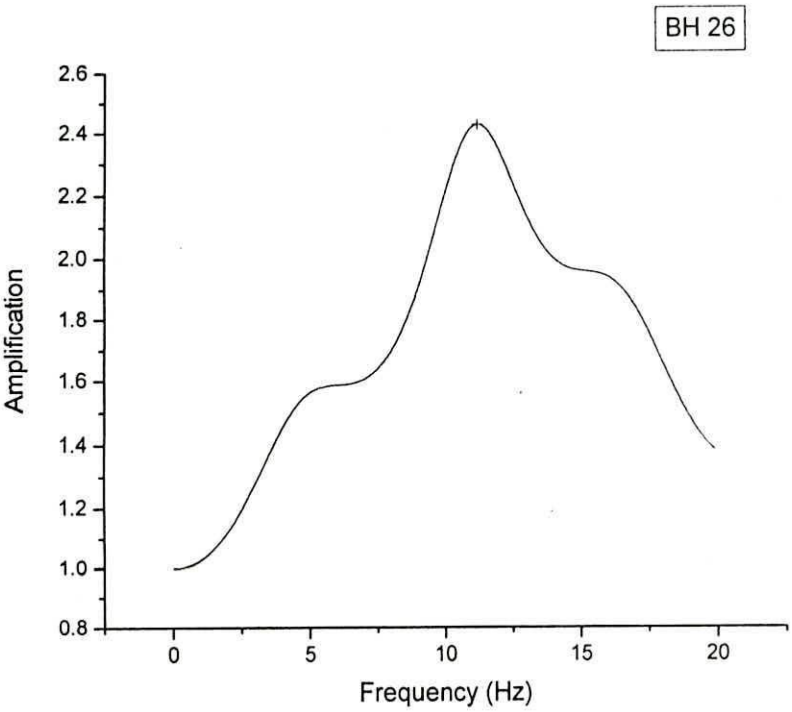

BH 17
Amplification
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
5
10
15
20
Frequency (Hz)


BH 18
Amplification
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0
5
10
15
20
Frequency (Hz)


BH 21
2.0
1.8
1.6
1.4
1.2
1.0
Amplification
0
5
10
15
20
Frequency (Hz)


BH 22
3.5
3.0
2.5
2.0
1.5
1.0
Amplification
0
5
10
15
20
Frequency (Hz)


BH 25
Amplification
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0
5
10
15
20
Frequency (Hz)


BH 26
Amplification
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0
5
10
15
20
Frequency (Hz)

APPENDIX – K

Description of MMI Scale

The effect of an earthquake on the Earth's surface is called the intensity. The intensity scale consists of a series of certain key responses such as people awakening, movement of furniture, damage to chimneys, and finally - total destruction. Although numerous intensity scales have been developed over the last several hundred years to evaluate the effects of earthquakes, the one currently used in the United States is the Modified Mercalli (MM) Intensity Scale. It was developed in 1931 by the American seismologists Harry Wood and Frank Neumann. This scale, composed of 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction, is designated by Roman numerals. It does not have a mathematical basis; instead it is an arbitrary ranking based on observed effects.

The Modified Mercalli Intensity value assigned to a specific site after an earthquake has a more meaningful measure of severity to the nonscientist than the magnitude because intensity refers to the effects actually experienced at that place.

The lower numbers of the intensity scale generally deal with the manner in which the earthquake is felt by people. The higher numbers of the scale are based on observed structural damage. Structural engineers usually contribute information for assigning intensity values of VIII or above.

			factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.
IX.	**Violent**	**Heavy Damage**	General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluvial areas sand and mud ejected, earthquake fountains, sand craters.
X.	**Very Violent**	**Extreme Damage**	Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
XI.			Rails bent greatly. Underground pipelines completely out of service.
XII.			Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.