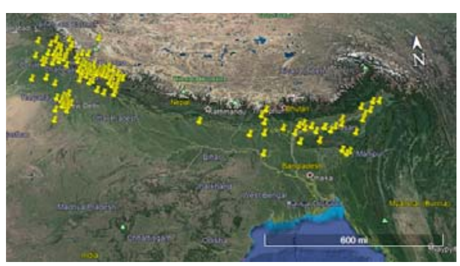
BNUS ANNUAL REPORT-2020

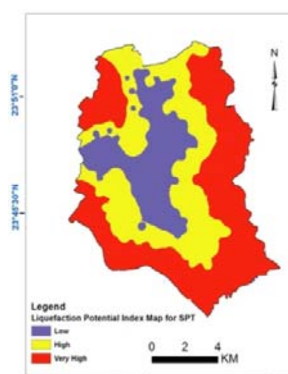
BANGLADESH NETWORK OFFICE FOR URBAN SAFETY

BUET, DHAKA, BANGLADESH

Edited By:

Mehedi Ahmed Ansary





April 2021

BANGLADESH NETWORK
OFFICE FOR URBAN SAFETY

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PART-I

CYCLONE AMPHAN, 20th MAY, 2020

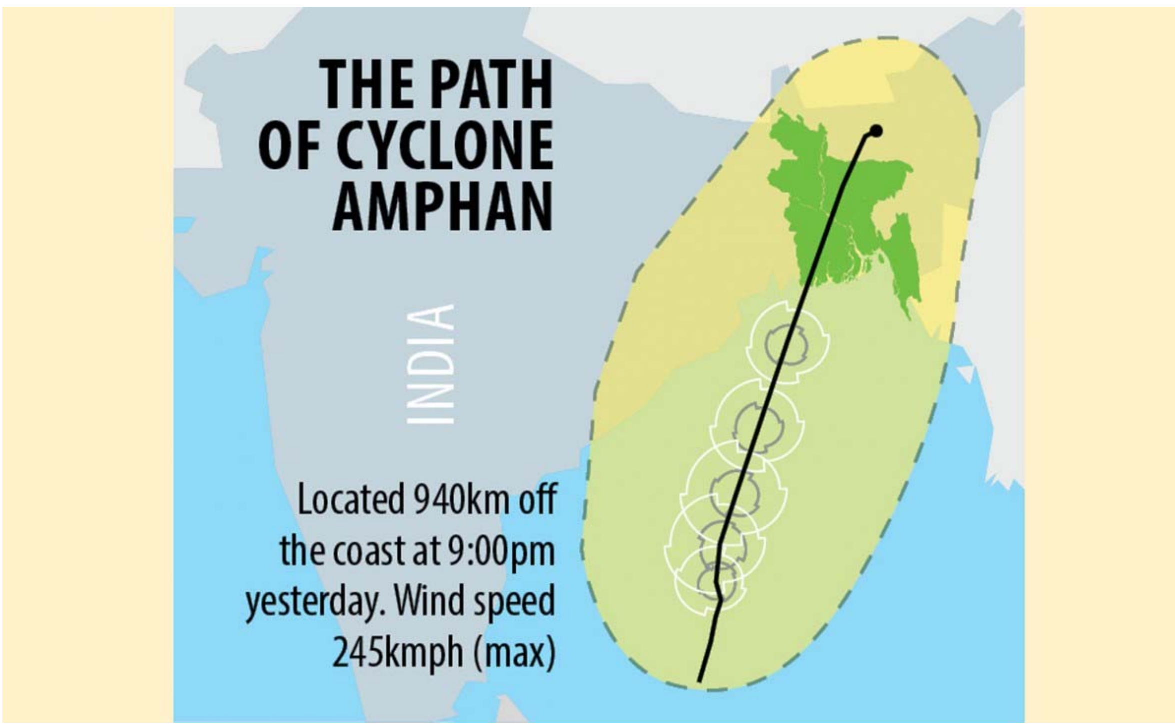
BANGLADESH NETWORK OFFICE FOR URBAN SAFETY (BNUS), BUET, DHAKA

Prepared By: Maruf Billah

Mehedi Ahmed Ansary

A powerful cyclone Amphan that tore through India's eastern state of West Bengal and Bangladesh this week causing a damage of $14 billion) to infrastructure and crops, state officials said. The two countries have lost at least 102 people in the cyclone, the most powerful in over a decade, mostly because of house collapses and electrocution. More than 3 million people were evacuated before Amphan made landfall, preventing a large number of deaths. The cyclone has affected more than 13 million people - some losing houses, crops and lands - and over 1.5 million houses have been damaged.

The cyclone also destroyed farmland in Bangladesh's low-lying coastal areas, damage that will likely endanger livelihoods,



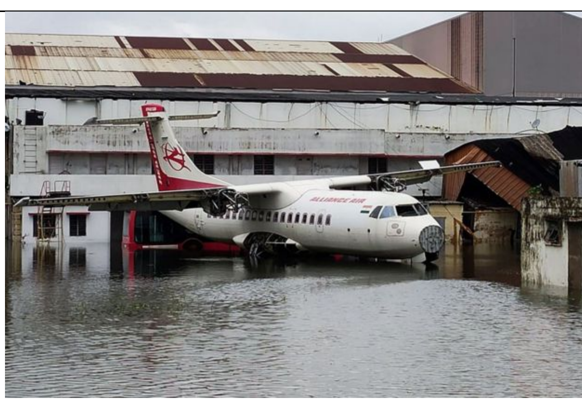
With a wind speed of up to 245kmph, Amphan (Thai word meaning ambition) was located 940km off the coast at 9:00pm on May 19. It was formed in the Bay of Bengal on May 17. GoB has 4,071 permanent shelters, where around 51 lakh people were accommodated. It took seven to eight hours to evacuate 20 lakh people from their homes and take them to the shelters.

According to the Met office, the coastal districts of Satkhira, Khulna, Bagerhat, Jhalakathi, Pirojpur, Barguna, Patuakhali, Bhola, Barishal, Laxmipur, Chandpur, Noakhali, Feni, Chattogram and their shore islands and chars have suffered the worst of the storm,









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PART-II

CPT AND SPT TESTS IN ASSESSING LIQUEFACTION POTENTIAL

BANGLADESH NETWORK OFFICE FOR URBAN SAFETY (BNUS), BUET, DHAKA

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1. INTRODUCTION

Liquefaction problem has become important when it started to affect human and social activities by disturbing the function of facilities and also after rapid urbanization by expanding the cities in reclaimed areas. Ground failures generated by liquefaction has been a major cause of damage during past earthquakes e.g., 1964 Niigata, Japan and 1964 Alaska, USA, 1971 San Fernando, 1989 Loma Prieta, 1995 Kobe, Japan and 2004 Chuetsu, Japan earthquakes. Liquefaction affects buildings, bridges, buried pipelines and lifeline facilities etc. in many ways.

The historical seismicity data and recent seismic activities in Bangladesh and adjoining areas indicate that Bangladesh is at high seismic risk. As Bangladesh is the world's most densely populated area, any future earthquake shall affect more people per unit area than other seismically active regions of the world. Bangladesh including capital city Dhaka is largely an alluvial plain consisting of fine sand and silt deposits with shallow ground water table in most places. Although the older alluvium is less susceptible to liquefaction, the deposits along the river flood plains may liquefy during a severe earthquake. Human made soil deposits also deserve attention. Loose fills, such as those placed without compaction, are very likely to be susceptible to liquefaction.

Over the past 30~40 years Dhaka city has experienced a rapid growth of urban population and it will continue in the future due to several unavoidable reasons. This high population increase demands rapid expansion of the city. Unfortunately, most parts of Dhaka city has already been occupied. As a result, new areas have been reclaimed by both government and private agencies in and around Dhaka city. In many cases, the practice for developing such new areas is just to fill lowlands of the depth 3~12m with dredged material consisting of silty sand. This causes liquefaction susceptibility for such areas.

Seed and Idriss (1971) have presented test procedures for measuring soil liquefaction characteristics as summarized in Table 1. Their proposed basic simplified method to evaluate liquefaction potential has been modified and improved by Seed et al. (1983); Youd and Idriss (2001); Boulanger and Idriss (2004); Cetin et al. (2004) as described in Table 1.

Seed et al. (1983) has evaluated liquefaction potential using field test data. They used simplified procedure for evaluating the liquefaction potential of sand deposits using data obtained from Standard Penetration Test (SPT). Field data for sites which have been known to be liquefied or not liquefied during earthquakes in the United States, Japan, China, Guatemala, Argentina and other countries have been presented to establish a criterion for evaluating the liquefaction potential of sands in Magnitude 7.5 earthquakes. Then the results of this study have been extended to other magnitude earthquakes using a combination of laboratory and field tests data.

Gratchev et al. (2006) have conducted research to investigate the liquefaction potential of clayey soils under cyclic loading. This research seeks to investigate the liquefaction of clayey soils, a phenomenon that has been the trigger for many natural disasters in the last few decades, including landslides. Research has been conducted on artificial clay-sand mixtures and natural clayey soils collected from the sliding surfaces of earthquake-induced landslides.

Robertson (2009) has developed cone penetration test (CPT) based relationships to evaluate the susceptibility to strength loss and liquefied shear strength for a wide range of soils based on case histories as stated in Table 1. The case histories has indicated that very young, very loose, nonplastic or low-plastic soils tend to be more susceptible to significant and rapid strength loss than older, denser, and/or more plastic soils. The CPT is a useful in situ test that can provide continuous estimates of the potential for flow liquefaction. For low risk projects, the CPT-based method is appropriate when combined with selective samples to confirm the soil type as well as conservative estimates of soil response. For moderate risk projects, the CPT-based method should be combined with appropriate additional in situ testing, as well as selected undisturbed sampling and laboratory testing, to confirm soil response. For high risk projects, the CPT-based method should be used as an initial screening to identify the extent and nature of potential problems has been followed by additional in situ testing and appropriate laboratory testing on high-quality samples. An advanced numerical modeling is appropriate for high risk projects where initial screening indicates a need.

The SPT based liquefaction charts are commonly been used for determining liquefaction potential. Simplified method given by Seed, Tokimatsu and Yoshimi (Y-T) and Idriss and Boulanger (2008) methods of liquefaction assessment have been analyzed by Kumar et al. (2012) as presented in Table 1. Computational methods like artificial neural network (ANN) and neuro-fuzzy technique (NF) has been also discussed as capable for liquefaction assessment using database either from SPT or CPT results. Some pertinent soil properties along with seismic characteristics may help in modeling and analyzing liquefaction potential of prone sites. The major advantage of computational methods is the ability to associate both SPT and CPT indicator properties for better engineering judgment to evaluate site dependent liquefaction.

Sesov et al., (2012) has presented (Table 1) that the investigations and results on the evaluation of the potential of liquefiable soil layers at location where new industrial complex has been planned to be built in southern part of Republic of Macedonia. Investigations combine the results from different in-situ methods, site response analysis and laboratory cyclic triaxial undrained tests. For the purpose of the new industrial complex which has been planned to be built at, first preliminary evaluation of the liquefaction potential has been done with SPT and CPT methods. Results have indicated that for the soil layers where cyclic resistance ratio is lower than the expected cyclic stress ratio might behave as liquefiable. Soil samples have been taken from the boreholes of the site and cyclic undrained triaxial tests have been done.

Guettaya et al. (2013) has presented a case study of liquefaction potential assessment for the foundation of an earth dam in Tunisia. An emphasis has been made on the exploration of geotechnical conditions and the interpretation of field tests (SPT and CPT) and the results have been collected before and after soil densification using the vibro-compaction technique. The SPT resistance values has been increased on average from 12 to 25 blow counts/0.3m, and the CPT resistance has been increased on average from 8MPa to 14MPa. Before vibro-compaction, the factor of safety (FS) against liquefaction fell below 1.0, which means that the soil is susceptible for liquefaction. After vibro-compaction the values of FS exceed the unit which justified the liquefaction mitigation efforts in dam foundation.

Ecemis and Karaman (2014) has performed (Table 1) a set of four high-quality field tests at 20 different locations on the Northern coast of the Izmir Gulf: (1) piezocone penetration test (CPTu), (2) pore pressure dissipation test (PPDT), (3) direct push permeability test (DPPT), and (4) standard penetration test (SPT). The total sounding depth for each test is about 15 m. Uncertainties prevail at the current liquefaction screening method based on the cone penetration test (CPT) as to whether the existence of fines increases liquefaction resistance or decrease cone penetration resistance. Field-based data have been used to evaluate the effects of non-/low plastic fines on liquefaction resistance at the current CPT-based liquefaction assessment method. The liquefaction resistance of sands and silty sands has been reinterpreted from the current CPT-based liquefaction assessment method. The trend, which presents the change of liquefaction resistance with fines content at the same relative density, has been compared with the available laboratory-based data in the literature.

Ndoj et al., (2015) have evaluated the liquefaction, based on the data collected by Piezocone Test (CPTU) and Standard Penetration Test (SPT) as shown in Table 1. These data have been used to evaluate the liquefaction for a case study, in a coastal area of Albania, located in from Lalezi Bay to Hamallaj area, near Durresi city, where several residential buildings and resorts useful during the summer season are foreseen to be built. The site investigation has been carried out with 8 CPTU tests until a maximal depth of 20 m. According to this study, in this area sands, gravelly sands, silty sands and clays are present. The water level is located very close to ground surface, at around 0.5 - 2.0 m under the ground surface. The highest moment magnitude registered in this area is 6.2 and it belongs to Durresi city, for the earthquake happened in December 1926. CPT based method show that all the soils have been classified as “like sands”, below the water level where the liquefaction may occur. Also the SPT based method show that the liquefaction may occur in these soils, but the thickness of liquefiable layers of soils is small.

Konni (2015) has been taken a live project having offshore artificial island of 84 km offshore and an attempt has been made to assess compaction levels achieved for offshore artificial islands. Subsequently, liquefaction potential has been evaluated based on SPT, N and CPT data as summarized in Table 1.k). According to the test result it has been found that CPT appears to be better suited to liquefaction assessment than SPT because it is more standardized, reproducible, and cost-effective and yields a continuous penetration record with depth. CPT can be quickly and economically identify the thick and thin liquefiable soil, which is cost-prohibitive in SPT test.

During the recent devastating earthquakes in Christchurch, many residential houses have been damaged due to widespread liquefaction of the ground. In-situ testing has widely been used as a convenient method for evaluating liquefaction potential of soils. Cone penetration test (CPT) and standard penetration test (SPT) are the two popular in situ tests which are widely used in New Zealand for site characterization. Mirjafari et al., (2016) has conducted the Screw Driving Sounding (SDS) test in Christchurch, a correlation has been developed between tip resistance of CPT test and SDS parameters for layers consisting of different fines contents. As SDS method is simpler, faster and more economical test than CPT and SPT, it can be a reliable alternative in-situ test for soil characterization, especially in residential house constructions as shown in Table 1.

Huang and Yu (2017) have evaluated three procedures for liquefaction potential based on in situ. Procedure one is the assessment of “triggering” (initiation) of soil liquefaction. Soil type is very important for assessment of this initiation. Clay content, liquid limit, and water content has been used to evaluate the potential initiation of soil liquefaction. Procedure two is the assessment of liquefaction resistance based on in situ tests. The methods that has been used to evaluate liquefaction are the standard penetration test (SPT), cone penetration test (CPT), dynamic cone penetration test (DPT), Becker penetration test (BPT), and shear wave velocity (VS) test. The liquefaction resistance has been obtained by calculating the penetration resistance in empirical equations. Procedure three is assessment of the site liquefaction index and deformation of liquefiable sites. In this procedure, the depth and thickness of the liquefiable soil layer has been considered. Finally, the site liquefaction potential has been calculated by integrating all test points. Assessment of soil seismic deformation also been introduced.

Hoque et al., (2017) has presented (Table 1.m) evaluation and comparative analysis of liquefaction potential from Standard Penetration Test (SPT) and Cone Penetration Test (CPT) based deterministic relationships. Both methods have significant relative advantages, and can often be optimal when used in combinations. In this research, four pairs of SPT and CPT tests have been carried out at the river bank of Jamuna, Bangladesh and each pair of test has been conducted as close as possible.

The goal of this paper is to estimate the earthquake induced liquefaction potential of selected reclaimed areas of Dhaka city and develop liquefaction potential (LPI) map based on CPT and SPT

2. EVALUATION OF LIQUEFACTION SUSCEPTIBILITY

2.1 Evaluation Based on SPT N-Value

The most common index properties for estimating liquefaction strength is the N-value obtained from the standard penetration test. The standard penetration test (SPT) consists of driving a thick-walled sampler into the granular soil deposit. The measured SPT N-value (blows per foot) is defined as the penetration resistance of the soil, which equals the sum of the number of bows required to drive the SPT sampler over the depth interval of 15 to 45 cm (6 to 18 in).

SPT test is probably the most widely used field test in the Bangladesh as well as in the world. This is because it is relatively easy to use, the test is economical compared to other types of field testing, and the SPT equipment can be quickly adapted and included as part of almost any type of drilling rig.

The most comprehensive liquefaction data catalogs are based on Standard Penetration test (SPT) blow counts (SPT N). Starting in the 1970's, Seed and his colleagues worked to develop a reliable method for assessing liquefaction potential based on SPT data. Their framework for SPT-based assessments of liquefaction potential has been developed in a series of papers that includes Seed and Idriss (1971); Seed and Idriss (1982); Seed et al. (1983)significant contributions have been also made by Tokimatsu and Yoshimi (1983) as summarized in Table 1. This research culminated in the liquefaction criteria published by Seed et al., (1985) as described in Table 1.

The empirical chart published by Seed et al. (1983) is based on a standardized SPT blow count, (N1)60 and the cyclic stress ratio (CSR).To get (N1)60, the measured NSPT corrected for the energy delivered by different hammer systems and normalized with respect to overburden stress. Boundary curves separating nonliquefied from liquefied soils, in terms of CSR and (N1)60have been conservatively drawn to nearly all observed cases of liquefaction in the data catalog. Three separate boundary curves have been presented for clean to silty sands. To consider the effects of earthquake magnitude on the duration of strong shaking, magnitude scaling factors has been specified. Over the last few decades, the empirical method given by Seed et al. (1983), sometimes referred to as the "simplified procedure", has been widely used for evaluating soil liquefaction potential in all around the world.

2.2 Evaluation Based on CPT

For estimating liquefaction potential by in-situ test other than the SPT, the most advanced ones are those using cone penetration resistances. The idea for the cone penetration test is similar to the SPT except that instead of driving a thick-walled sampler into the soil, a steel cone is pushed into the soil. The force required to move the cone into the extended position divided by the horizontally projected area of the cone is defined as the cone resistance, qc. For liquefaction analysis, the cone penetration test value qc is corrected for the vertical effective stress. A major advantage of the cone penetration test is that by using the electric cone, a continuous subsurface record of the cone resistance qc can be obtained. This is in contrast to the SPT, which obtains data at intervals in the soil deposit. Disadvantage of the CPT are that soil samples cannot be recovered and special equipment is required to produce a steady and slow penetration of the cone.

The Cone Penetration test (CPT) yields a continuous profile of penetration resistance and is thus well-equipped for detecting thin, liquefiable layers within a larger, stable soil deposit.

3. SELECTED AREAS FOR THE RESEARCH

Total ten areas of the Dhaka city have been selected for this research. The main targeted areas have been reclaimed lands since some of these lands have been found to be susceptible to liquefaction (Hore, 2013). The reclaimed areas are Bramangaon, Ashian City, Badda, Banasree, Gabtoli, Kawran Bazar, Purbachal, United city, Uttara and Kamrangirchar. Figure 1 shows the selected study areas. The study area is located between the latitude 23°35´N-23°54´N and the longitudes 90°19´ E-90°30´E. the expansion of the city is restricted by the Buriganga River in the south, Turag River in the west and Balu River in the east. The city lies on the lower reaches of the Ganges Delta (Rahman et al., 2011) as described in Table 1.

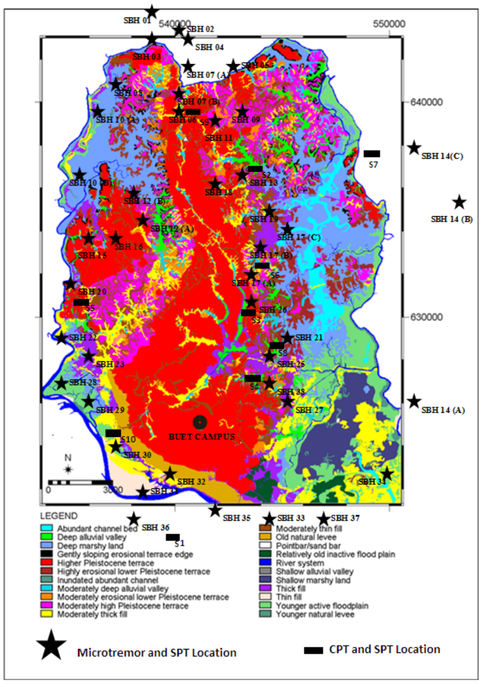
3.1 Geology of Dhaka

Geological evolution of the Bengal Basin starting from Upper Paleozoic time when Gondwana land break up and collision the Indian plate with the Asian plate and sedimentary cover of the basin with a maximum thickness of 20 km includes three major lithostratigraphic units separated by three major unconformities. Most of the authors have the opinion about the Madhupur tract is the tectonic uplifted surface. Fergussion (1963) believes that the Madhupur tract is the recent uplifted surface due to the 1762 earthquake. Dhaka city is situated in the southern half of the Madhupur Tract and Floodplain area with southern river system.

Table 1 Summary of previous works

No.	Reference	Summary
a.	Seed and Idriss (1971)	a) Significant factors affecting the liquefaction potential of sands during earthquake b) variable field data concerning the liquefaction or non-liquefaction behaviour of sands during earthquakes and compared with evaluations of performance using the simplified procedure.
b.	Seed et al. (1983)	a) Evaluating the liquefaction potential of silty sand deposits (Field data for liquefied or not liquefied during earthquakes in the United States, Japan, China, Guatemala, Argentina, and other countries) using data obtained from standard penetration tests has been reviewed. b) Evaluated the possible magnitude of pore water pressure generation during earthquake shaking. c) evaluating the liquefaction resistance of soils by static cone penetrometer, shear wave velocity, and electrical measurements
c.	Youd and Idriss (2001)	a)In 1996 a workshop sponsored by the National Center for Earthquake Engineering Research (NCEER) was convened by Professors T. L. Youd and I. M. Idriss with 20 experts to review developments over the previous 10 years. b) The following topics have been reviewed and recommendations developed: (1) criteria based on SPT tests; (2) criteria based on CPT tests; (3) criteria based on shear-wave velocity measurements; (4) use of the Becker penetration test for gravelly soil; (4) magnitude scaling factors; (5) correction factors for overburden pressures and sloping ground; and (6) input values for earthquake magnitude and peak acceleration.
d.	Cetin et al., (2004)	a)New correlations for soil liquefaction, b) new correlations are-accumulation of an expanded database (field performance case histories); factors affecting interpretation of SPT data; factors affecting site-specific earthquake ground motions; d) improved methods for in situ cyclic shear stress ratio c)this paper helps to develop magnitude-correlated duration weighting factors, adjustments for fines content, and corrections for overburden stress.
e.	Robertson (2009)	a) Analyzing some case-histories of cone penetration test-based relationships to evaluate the susceptibility to strength loss and liquefied shear strength for a wide range of soils.
f.	Idrissand Boulanger (2008)	a)Fundamentals of liquefaction behaviour for the development and limitations of various engineering analytical procedures; b) methods for liquefaction analysis and use of factors of safety in engineering practice, c) mitigation strategies, and methods for ground improvement; d) Cyclic softening of saturated clays for potential performance of cohesive fine-grained soils.
g	Kumar et al.,(2012)	a) Assessment of liquefaction of soils both in conventional and computational (ANN, NF) methods, using database either from SPT or CPT results.
h.	Sesov et al. (2012)	a)At southern part of Republic of Macedonia the evaluation of the potential of liquefiable soil layers has been done where new industrial complex has been planned to be built, b) assessment of liquefaction hazard at the location with medium to high seismicity and heterogeneous soil condition, c) potential of liquefaction in complex geological condition with high degree of soil heterogeneity.
i.	Ecemis andKaraman (2014)	a)Evaluate the effects of non/low plastic fines on liquefaction resistance at the current CPT liquefaction method. b) Examines the effects of the coefficient of consolidation or drainage characteristics of fine soils (cone penetration resistance)c) coefficient of consolidation depends on fines content and the relative density of the soil d) investigates the contribution of fines content (< 30% by weight) on the liquefaction resistance of soils at different relative densities e) Fines content (>30% by weight) and/or high plasticity of fines can cause additional complications.
j.	Ndoj et al. (2015)	a)CPTU tests (8) at a depth of 20 m, b) soil profiles contain sands, gravelly sands, silty sands and clays b) evaluation of liquefaction in a coastal area of Albania based on the data collected by Piezocone Test (CPTU) and SPT.
k.	Konni (2015)	a)Liquefaction potential has been evaluated based on SPT, N and CPT data in a live project (having 84km offshore artificial island), b) studied the reliability of the data for the liquefaction assessment.
l.	Mirjafari et al. (2016)	a)Correlation developed between tip resistance of CPT test and SDS parameters for soil of different fines contents at Christchurch (New Zealand), b) a chart was proposed which relates the cyclic resistance ratio to the appropriate SDS parameter.
m.	Hoque et al. (2017)	a)Evaluation and comparative analysis of liquefaction potential from SPT and CPT (four pairs) based deterministic relationships which carried out along the river bank of the Jamuna river, Bangladesh (About 85 km from Dhaka city).
n.	Seed and Idriss (1982)	In this paper, the following areas have been covered: a) Liquefaction analysis for the methods for evaluating the potential for under ground motion during earthquake. b) Liquefaction behaviour for a common understanding of the development and limitations of various engineering analytical procedures under ground motion.
o.	Tokimatsu and Yoshimi (1983)	a) Field performance of sandy soil deposits during past earthquakes has been conducted with special emphasis being placed on SPT N-values and fines content, b) field relationship between adjusted dynamic shear stress ratio and normalized SPT N-values together with laboratory tests on undisturbed sands indicate that (1) sands containing more than 10% fines has much greater resistance to liquefaction than clean sands having the same SPT N-values, (2) extensive damage would not occur for clean sands with SPT N_1-values greater than 25, silty sands containing more than 10% fines with SPT N_1-values greater than 20, or sandy silts with more than 20% clay, and (3) sands containing gravel particles seem to have less resistance to liquefaction than clean sands without gravel having the same SPT N-values. c) an improved empirical chart separating liquefiable and non-liquefiable conditions is presented in terms of dynamic shear stress ratio, SPT N-values, fines content, and shear strain amplitude.
p.	Seed et al., (1985)	a)To clarify the meaning of the values of standard penetration resistance used in correlations of field observations of soil liquefaction with values of N_1 measured in SPT tests b) Liquefaction resistance curves for sands with different $(N_1)60$ values and with different fines contents have been proposed.
q.	Rahman et al., (2011)	Dhaka city, the soul of Bangladesh is highly vulnerable to the earthquake disaster (caused liquefaction) due to high density of population, unplanned infrastructure and close proximity with India and Myanmar's active seismic area, poor economic condition, poor emergency preparation and recovery capability.
r.	WASA, (1991)	a) The changing trend of wetlands makes the drainage system of Dhaka City vulnerable and creating water logging problems and b) Land filling and encroachment is the main reasons for shrinking of the wetlands in the city.
s.	Morganand McIntire (1959)	Geological condition of Bengal Basin, East Pakistan and India has been investigated in this research paper. Two areas of Pleistocene terrace border the Bengal basin on the east and west and flank Tertiary and older hills of India. Two large inliers of Pleistocene sediments within the basin are surrounded by Recent flood-plain deposits of the Ganges and Brahmaputra rivers and their combined deltaic plain.
t.	Robertson(1990)	a) A new system has been proposed based on normalized CPT data, b) new charts are based on extensive data (from a 300 m deep borehole with wire-line CPT) available from published and unpublished

Regional elevation of the area gradually declines towards Buriganga River on the south and the elevation ranges from 10m to 17m but is generally around 14m above mean sea level. Geologically Dhaka city belongs to Bengal Foredeep and is situated in the Pleistocene uplifted block (Madhupur Tract) within the passive margin surrounded by subsiding floodplains bounded on the west by a series of NW-SE trending en-echelon faults including the Dhamrai, Maijail and Kaliakoir ones (WASA, 1991; Morgan and McIntire,1959) as summarized in Table 1.r) and s) . Land surface is covered by gray floodplain and non-Cretaceous floodplain soils. Stratigraphically, Old Dhaka is characterized by hundreds of meters thick unconsolidated sequence of fluvio-deltaic deposits many composed of gravels, sands, silts and clays of Plio-Pleistocene age. In this paper, subsoil characteristics of two sites (namely Bramangaon and Ashian City have been elaborated.



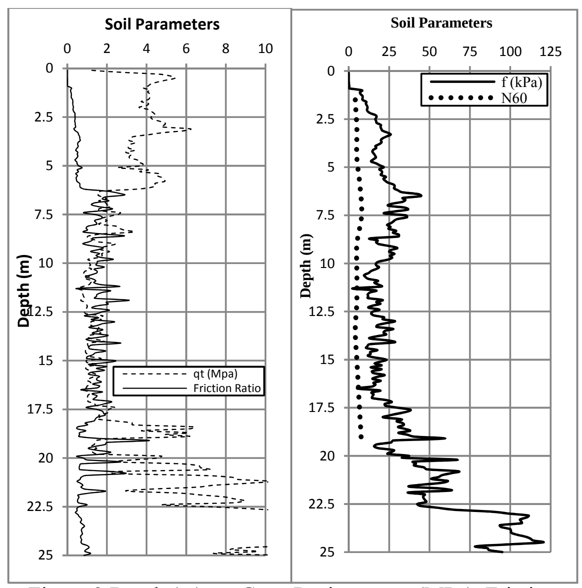


Figure 2 Depth (m) vs. Cone Resistance q_t (MPa), Friction (kPa), N_{60} and Depth vs. friction ration (kPa) at Bramangaon

Figure 1: Geological Map showing study areas of Dhaka city.

3.2 Sub- Soil characteristics of Bramangaon

This site has been situated in southeast part of Dhaka city. It is a private land development project where main filing has been done by dredged river sand. The depth of filling of fine sand is 5.0 m from existing ground level. The clayey silt layer exists from 5.0 m to 6.5 m from EGL. After that 1.5 m is sandy silt layer. Then 12.0 m is clayey silt. The uncorrected SPT N value of filling fine sand varies from 4 to 5. The SPT N value of clayey silt layers varies from 5 to 8. The maximum value of SPT N is 8. The minimum value of SPT N is 4. From the CPT test, the cone resistance varies from 0.51 to 16.78 MPa. The average value of cone resistance is 3.88 MPa. Friction varies from 0 to 120.2

kPa. The average value of Friction is 30.79 kPa. Friction ratio varies from 0 to 4.13. The average value of Friction ratio is 1.11.The SPT N values of the boreholes have been shown in the Table 2. Figure 2 shows Depth (m) vs. Cone Resistance qt (MPa), Friction (kPa), N60 and Depth vs. friction ration (kPa) at Bramangaon. From the CPT test, the cone resistance varies from 0.51 to 16.78 MPa. The maximum value of cone resistance is 16.78 MPa. The minimum value of cone resistance is 0.51 MPa. The average value of cone resistance is 3.88 MPa. Friction varies from 0 to 120.2 kPa. The average value of friction is 30.79 kPa. Friction ratio varies from 0 to 4.13 kPa. The average value of Friction ratio is 1.11 kPa. Results from grain size analysis of the soil samples have been presented in Table 2. The mean grain size (d50), fine content (Fc) of filling sand varies 0.16 to 0.17 mm, 20 to 21% respectively. The mean grain size (d50), fine content (Fc) of silt is 0.046 mm, 71% respectively. Table 3 shows Probable soil classification using CPT data (Robertson, 1990) (as shown in Table 1) at Bramangaon.

Table 2 SPT N value and grain size analysis at Bramangaon

Depth(m)	Description of Soil	SPT N Value	F_c (%)	d_{50} (mm)
1.5	Filling Sand	4	20	0.17
3		5		
4.5		5		
6	Clayey Silt	7	71	0.046
7.5	Sandy silt	8	51	0.076
9	Clayey Silt	5	71	0.046
10.5		5		
12		5		
13.5		4		
15		5		
16.5		6		
18		7		
19.5		8		

Table 3 Probable soil classification using CPT data (Robertson, 1990) at Bramangaon

Depth Range (m)	I_c Range	Probable Soil Classification
0-3	0.82-1.52	Sand
3-6	1.22-1.92	Sand
6-9	1.77-2.82	Sand/Silt
9-12	2.34-3.24	

3.3 Sub-Soil Characteristics of Ashian City

This site has been situated in Northern part of Dhaka city. The depth of filling of fine sand is 3.5 m from existing ground level. The silty clay layer exists from 3.5 m to 12.5 m from EGL. After that 4.5 m is fine sand layer. Then 3.0 m is silty clay. The uncorrected SPT N value of filling fine sand varies from 4 to 5. The SPT N value of silty clay layers varies from 3 to 7. The maximum value of SPT N is 42. The minimum value of SPT N is 3. Figure 3 shows Depth (m) vs. Cone Resistance qt (MPa), Friction (kPa), N60 and Depth vs. friction ration (kPa) at Asian City. From the CPT test, the cone resistance varies from 0.195 to 7.805 MPa. The average value of cone resistance is 1.78 MPa. Friction varies from 0 to 233.9 kPa.

The average value of Friction is 31.21 kPa. Friction ratio varies from 0 to 6.35 kPa. The average value of Friction ratio is 1.29 kPa.

SPT has been conducted in the area following procedure described in ASTM D1586. The SPT N values of the boreholes have been shown in the Table 4. The graph between depth vs N value has been shown in Figure 3.

The graph between depth vs friction and cone resistance have been shown in Figure 3. From the CPT test, the cone resistance varies from 0.195 to 7.805 MPa. The maximum value of cone resistance is 7.805 MPa. The minimum value of cone resistance is 0.195 MPa.

Results from grain size analysis of the soil samples have been presented in Table 4. The mean grain size (d50), fine content (Fc) of filling sand varies 0.16 to 0.17 mm, 20 to 21% respectively. The mean grain size (d50), fine content (Fc) of clay varies 0.002 to 0.003 mm, 94 to 96% respectively. The mean grain size (d50), fine content (Fc) of sand is 0.16 mm, 21% respectively. Table 5 shows the probable soil classification using CPT data (Robertson, 1990) at Ashian City.

4. LIQUEFACTION POTENTIAL ANALYSIS BASED ON SPT AND CPT

The main objective of this study is to present the liquefaction potential of the selected reclaimed areas. Soil characteristics of the selected reclaimed areas have been determined by field and laboratory tests. Test results have been presented earlier. Liquefaction potential has been estimated using two methods based on CPT (Robertson, 2009) and SPT (Seed et al; 1983) data. The results of these estimations have been presented.

5. GROUND MOTION AND EARTHQUAKE IN AROUND DHAKA CITY

In this research, the value of amax has been taken as 0.15g as Dhaka city exist in the zone 2 of seismic zonation map of Bangladesh (BNBC, 1993). Other researchers (Ansary and Rashid, 2000) also used similar values of amax for the similar purpose as given in Table 1. Though at present the value of amax is being update by various researchers and agencies from 0.15 to 0.2. But it has not been taken to the consideration for this study since it has not been incorporated to BNBC yet. Earthquake ground motion has been influenced by a number of factors. Most important factors are moment magnitude, epicenter distances, local soil conditions, earthquake sources, etc. In Seed-Idriss simplified procedure moment magnitude (Mw) input parameter is also important correction factor. From Table 6, it is seen that ranges of Mw at nearby faults from Dhaka varies 7.5~8.5. However, this value cannot be considered directly for Dhaka since those faults are at quite distant places from Dhaka. Due to non-availability of attenuation law and suitable correlations between distance and ground motion characteristics for Dhaka, the design moment magnitude has been taken 7.5 for this study, which is the lowest value in Table 6.

Bangladesh covers one of the largest deltas and one of the thickest sedimentary basins in the world. According to the report on time predictable fault modeling (CDMP, 2009), earthquake and tsunami preparedness component of CDMP have identified five tectonic fault zones which may produce damaging earthquakes in Bangladesh. These are Madhupur fault zone, Dauki fault zone, plate boundary fault zone -1, plate boundary fault zone -2, and plate boundary fault zone -3. Among these, Madhupur fault zone has been considered as a source of damaging earthquake near Dhaka in this study.

6. LIQUEFACTION POTENTIAL INDEX (LPI) ANALYSIS

Liquefaction potential based on CPT (Robertson, 2009) and SPT (Seed et al; 1983) data have been estimated. Liquefiable zone is where FS<1, on the other hand non liquefiable zone is where FS>1. The liquefaction analyses results for 10 different locations as described earlier have been presented in Table 7.

Liquefaction potential index (LPI) has been estimated using Iwasaki et al. (1982) based on CPT data and is shown in Figure 4. The lowest Liquefaction Potential Index (LPI) value for CPT has been found at Kawran Bazar which is 3 and highest value at Bramangaon which is 21. The Liquefaction Potential Index (LPI) ofother sites like Badda, Gabtoli, United City, Ashian city, Uttara, Kamrangirchar, Banasree and Purbachal are 10, 10, 11, 13, 16, 16, 18 and 18 respectively. Based on Liquefaction Potential Index (LPI) for CPT test results, the Dhaka city has been divided in to three zones according to Iwasaki et al. (1982) named low, high and very high as presented in Table 1). The low liquefaction zone has been found at the center position of the study area and spread along the north south direction. The high liquefaction zone has been found in the outer periphery of the study area.

Liquefaction potential index (LPI) has also been estimated using Iwasaki et al. (1982) based on SPT data and is shown in Figure 5. The lowest liquefaction value for SPT has been found at Kawran Bazar which is 1 and highest value at Purbachal which is 28. The Liquefaction Potential Index of other sites like Badda, Gabtoli, United City, Ashian city, Uttara, Kamrangirchar, Banasree and Bramangaon are 10,16, 7, 9, 9, 18,14 and13 respectively. Based on Liquefaction Potential Index for SPT test results, the Dhaka city has been divided in to three zones according to Iwasaki et al. (1982) named low, high and very high. The low liquefaction zone has been found at the center position of the study area and spread along the north south direction. The high liquefaction zone has been found in the outer periphery of the study area.

These results are supported by the Geological Map presented in Figure 1 and past study by Ansary and Rahman (2013) where microtremor survey has also been carried out as described in Table 1.

The similarity of liquefaction potential index map based on CPT (Figure 4) and SPT (Figure 5) data is that for both the cases, low liquefaction zone has been found at the center position of the study area and spread along the north south direction. The very high liquefaction zone has been found in the outer periphery of the study area. CPT based method also show very high liquefaction zone in Northern and North-Western part of Dhaka. High liquefaction zone area is relatively larger for SPT based map.

7 CONCLUSIONS

In this research liquefaction potential have been evaluated using procedures based on both SPT and CPT. SPT based evaluation has been carried out by Seed-Idriss Simplified Procedure. Cone Penetration Test (CPT) based evaluation has been carried out by the methods proposed by Robertson. Results of Liquefaction Potential slightly vary in the two methods. One of the reasons of this variation may be due to the process of data collection. SPT N value has been obtained at each 1.5 m interval. On the other hand CPT value has been collected at each 0.01 m interval. This yields a more reliable and continuous CPT data than SPT. Some certain zone of liquefaction which cannot be recognized by SPT clearly has been identified by CPT test results. According to the zonation map of Dhaka city based on Liquefaction Potential Index (LPI),the low potential zone has been found along the center and north south alignment. The high and very high liquefaction zone has been found in the outer periphery of the study area.

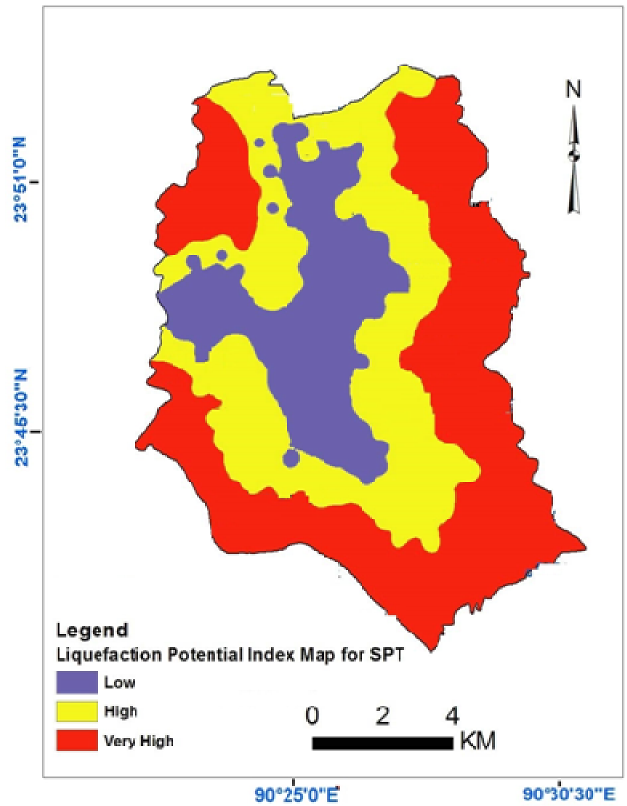


Figure 5: Liquefaction potential index Map based on SPT data

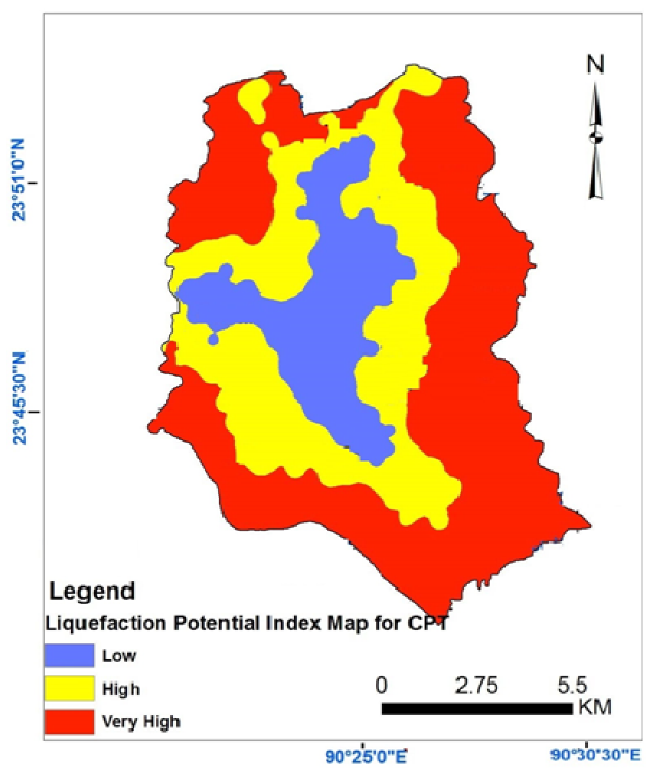


Figure 4: Liquefaction potential index Map based on CPT data

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PART-III

WEBINAR ON EXPERT CONSULTATION ON BUILDING EARTHQUAKES RESILIENT COMMUNITIES AND SOCIETIES FOR BANGLADESH: SHARING EXPERIENCES AND LESSON LEARNED FROM EARTHQUAKES AROUND THE WORLD

A Celebration of the United Nations International Day on Disaster Reduction

Tuesday, 13 October 2020

BANGLADESH NETWORK OFFICE FOR URBAN SAFETY (BNUS), BUET, DHAKA

Prepared By: **Mehedi Ahmed Ansary**

On the day of International Day on Disaster Reduction, Centre on Integrated Rural Development for Asia and the Pacific (CIRDAP) in collaboration with Bangladesh University of Engineering and Technology (BUET), organized a webinar on Tuesday 13th October, 2020. The webinar is entitled "**Expert Consultation on Building Earthquakes Resilient Communities and Societies for Bangladesh: Sharing Experiences and Lesson Learned from Earthquakes around the World**". Experts from Bangladesh, Thailand and U.S.A. joined this webinar to discuss this highly burning issue – Earthquake risks – and it's after effects on the planet and the general people on the world.

Introduction

1. Director General (DG) CIRDAP Dr. Cherdsak Virapat welcomed all participants. He informed that the date of 13 October is an important day for Thailand as the country commemorates the passing of the late King Bhumibol Adulyadej, the Father of the Nation in 2016. . For honoring the King, all the participants were requested to stand up for the Royal Anthem.
2. Dr. Virapat then proceeded by giving opening address of the webinar and provided his message for the International Day for Disaster Risk Reduction. He called for immediate global attention on disaster risk reduction by mean of hazard vulnerability assessment, disaster early warning, mitigation, preparedness and response. He expected that the meeting will identify strategic actions, measures and pilot implementation of end-to-end earthquake risk reduction systems for Bangladesh. Each participant was asked to introduce oneself. Then, Dr. Virapat invited Prof. Mehedi Ansary, BUET to provide background and aims of the meeting.
3. Prof. Ansary acknowledged CIRDAP for collaboration with BUET in organization of this webinar. He briefly addressed the past earthquakes occurred in Bangladesh as follows.

Professor Mehedi Ansary

4. Prof. Ansary showed some graphs on the earthquakes of Bangladesh as this is a moderately seismic country in the world. Several past earthquakes have occurred in Bangladesh and surrounding region in the last several hundred years. Among these earthquakes, the 1762 Arakan, 1869 Cachar, 1885 Bengal, 1897 Indian, 1918 Srimangal, 1930 Dhubri, 1934 Nepal, 2015 Nepal Earthquakes are well known in Bangladesh. The 1897 Indian Earthquake located in Assam, has caused massive destruction to structures in Dhaka City killing 1542 people in the region (Oldham 1899). He also showed some old photographs regarding the damage of 1897 great Indian (AKE M. 8.1) and 1918 Srimangal earthquake (7.6), which showed destruction of the buildings and land.

5. Prof. Ansary pointed out that at that time only 90,000 people lived in the Dhaka city out of them 1542 were killed. Today, almost 20 million people live in Dhaka city, and also there are around 2 million buildings here so that it can be imagined that what will be the casualty if the same earthquake happens today. Prof. Ansary also shared that no large earthquake has occurred here for the last few decades, so the people have become complacent.

Dr. Walter D. Mooney

6. Dr. Mooney gave his speech on Indonesian Palu and Sulawesi earthquakes which occurred on September 28, 2018. This earthquake caused Tsunami and also ground shaking created lots of destruction on the areas. Dr. Mooney showed the 5 –year period of Indonesian seismicity (2015-2020). Not only Tsunami but also the Palu earthquake generated ground shaking, landside and liquefaction which was un-anticipated. Most of the emergency warning centres were also destroyed due to this earthquake and also the ground shaking stayed for a long time.
7. Due to the earthquake, the death toll was high with the confirmed death of 3,400 people. Dr. Mooney described the enigmatic source of Tsunami and quantifying damage facilitates informed decisions on seismic building design. He said it will not matter how strong a building is built if the foundation is weak. The key points of the Palu earthquake is that Tsunami waves was there for several minutes after the main shock. And another point is that the maximum tsunami inundation was 469 m.
8. Dr. Mooney also presented some of the images of the Palu earthquakes in the city regarding mass destructive buildings, roads, houses and bridges with intensity and severity levels. There is severe liquefaction in three areas – Balaroa, Petobo and Jonooge-Sidera.
9. In the end of his presentation, Dr. Mooney shared the recovery plan

   Recovery Plan 1:

   - Not allowed to build any settlements within 100 m of the coast.
   - Areas with high risk pf liquefaction to be converted to public places.
   - Local living in “high risk” zones are being rehoused to “low risk” areas.

   Recovery Plan 2:

   - 1,100 new houses built in “safe zones”
   - Mangrove and sea wall being assessed for coastal protection
   - BMKG working collaboratively with the USGS to improve efficiency of Tsunami warning system.

   Prof. Ansary discussed and gave his opinion on the presentation of Dr. Mooney that the Palu city is not densely populated as Dhaka city given the fact that death toll and causes. Dr.

Mooney responded that this city is much higher than the Switzerland in population but obviously lower than Dhaka city. He also said that at present they changed their land use policies because of the earthquake. But it's very difficult to relocate or gave up the land in the offshore because it the matter of people's land ownership and livelihoods.

Prof. Tavida Kamolvej

10. Prof. Tavida Kamolvej, Dean of Political Science, Thammasat University, Thailand presented on lesson learned from disasters.
11. Prof. Kamolvei emphasized more to lesson learned, awareness and education training about the earthquake more than the technicality of it. How are we doing about the safety of the people? What measures did the governments take for this? Are people aware enough about the consequences of earthquake? Do they have enough knowledge about post disaster risk reductions measures and others?
12. She focused on the shared risk big data and communication amongst nations, and on the risk governance.
    - Degree of uncertainty and nonlinearity still there.
    - There are compound hazards and trans border still.
    - Structural and non-structural measures for disaster risk reductions cannot be same for every sector of the people. Combination of both is important and need balance between the two.
    - Transboundary and different level of capacity and literacy are required.
    - Research and development on possible risks and measures are required.
    - Different vulnerabilities from capacity and competency.
    - Political commitment and priority must be given.
    - Public and private investment should be allocated in the disaster risk reduction. And 1% of the national budget must be allocated for the post disaster measures. Everyone always talks about the pre-disaster measures not post-disaster risk reduction measures.
    - Self-sustained emergency management with reverse risks and adaptive risk governance is required.
    - Policy sandbox and institutional innovation are needed. Translations of institutional design/measures to local mechanism are needed for the community people. It is difficult to change the mindset of the people so that we need to focus more on for increasing technical capacity.
    - Balanced risk and economic loss in recovery is needed. (with a combination of pre-designed measures, policy alternative simulation and institutional changes).

- After Dr. Tavida's presentation, Prof. Ansary commented that it is very difficult to change the political will and institutional changes are needed. He pointed out that knowledge of people is power.
- Dr. Tavida stressed that communication at the community level helped make risk reduction measures more practical than the national level measures. Participatory action research is required for this. Academics and local people – this combined team of these two groups – can be useful through pilot project on the disaster risk reductions measures or post – disaster phases.

13. Prof. Ansary presented some of the work slides of Bangladesh Earthquakes and Risk Assessment of Dhaka, Bangladesh on behalf of **Dr. Fouad Bendimerad, EMI, U.S.A.** This presentation showed about the risk assessment of building collapse due to distance earthquake outside the Dhaka city.
    - Recent incidents at Shakharinazar in 2004, Collapse of 9 storied building Rana Plaza in April, 2013 are described. In every building collapse tragedy, 80% of the people is rescued by local community people rather than fire brigades and other defense people.
    - One of the world bank funded assessment study on the proposed earthquake scenario in Dhaka which is developed by Earthquakes & Megacities Initiatives (EMI), U.S.A showed that because of the earthquake 6 billion dollar will be direct loss. Nearly 200 thousand people will die and nearly 300 thousand people will be injured. More than 5.3 million people will be displaced person in need of access to basic social services.

Open discussions

At the open discussion, Dr. Virapat gave a Mock scenario questions to everyone about what are lessons learned from earthquakes happen in different countries, what are local capacity requirements on end-to-end early warning and mitigation systems. What will be practical measures and action plan in response to an incoming earthquake for Bangladesh.

Dr. Tavida Kamolvej: In reply to these questions, Dr. Tavida responded that to communicate with earthquake is very much difficult than other disasters. If an autonomy is established, she would want to build an earthquake resistant building and in the risk prone area instead of trying to change political thoughts which is very difficult. Also a learning center with data regarding earthquake can be built closer to the epicenter kind of area to educate the community and people. This center will have warning of aftershock and record or predict about the destructions. It is not possible to help people by forecasting about the earthquake beforehand. However, this learning and education will teach the community what to do after the earthquake. With this learning center, government can also be aware or learnt about the investment, what kind of balance between structure and non – structured measurement, Community capacity, etc. And this building can be used as a shelter for a short period of time. Basically, this building will be an example of safety for the community people beforehand of the earthquake. Those places which are already being destroyed and have destruction, to communicate with the people of those areas to prepare for the next one will be less difficult. But those areas which are not suffered or observed the earthquake yet will be difficult. Because most of the people will not understand the future risks of the earthquake that you are forecasting.

Dr. Ansary discussed that by showing and experiencing the incidents especially with the fire incidents then people can easily relate to that. This is due to the fact that during the last few years several fire incidences in Dhaka killed several hundred people as well as damaged several multi-storied buildings. If fire incidents and earthquake can work together, people will understand. But creating awareness to the people only about the earthquake, it will be very difficult to work. People need some example – like since there is no earthquake in the last decades but there are lots of fire incidents – people can relate because the fire incidents are still burning in their minds.

Dr. Tavida then asked the question regarding the recent event of Indonesian tsunami to Dr. Mooney. She asked that is it possible to forth sight the different kind of source of risks or have pre-design of every possible risks from disasters based on the geo data and other techniques. And relating to the Dr. Tavida's query, Mr. Tomasi asked about the indigenous people of Indonesia and their knowledge whether it exists or not?

Dr. Walter Mooney: There are too many earthquakes with the faults around the world. The main issue is the more responsibility needs to be pushed down to the local level for all these agencies. The field staff/people always depends or waits for the instruction from the headquarters – the local people are identifying the vulnerable structure and also not sending the recommendations back to the headquarters. There is a lack of empowerment in the local level for example in Indonesia there are 10 warning centers/bureaus at the local level in different places. But every bureaus always look at the Jakarta and waits for the instruction but it should be other way around, these local bureaus should tell the headquarter about what they need? It is a big problem of a human organization for reducing the risks and also saving the lives.

Prof. Ansary suggested to start communicating with Director General (DG) of Department of Disaster Management (DDM), Bangladesh. Or the secretary of the disaster management about the EMI CVMP produced the risk of map of earthquake of Dhaka city.

Prof. Helal Uddin of Director Research:

Prof. Helal pointed out on the earthquake impacts on the country economy. Since the capital stock of Bangladesh is more than trillion dollar and Dhaka city contributes around 40% of our GDP which is a huge amount. So, Dhaka is being the most popular city and exposed to the earthquake, economic development and growth will be tremendously affected by indirect loss incurred by any earthquake. indirect cost. It will be seriously damaging effect to the Bangladesh's economy. This figures and statistics is needed to place before government.

In Bangladesh, the earthquake is in nowhere in the priority of the government. Agreeing with Dr. Tavida that one tsunami change the public sector priority in Indonesia, the common and general people should be aware of more about the earthquake rather than constantly going back to the government in Bangladesh – make general people aware about the severity of earthquake – Once general people makes the earthquake as a popular demand, then government will give priority. After that this future risks can be calculated or for casted about the disaster. Through some projects, this awareness amongst people about earthquake can be possible – they can learn and apply the measurements and at the same time with this government will also be attracted.

Mr. Tinnakorn Tatong: Earthquake cannot be predicted but still the good data base is needed for kind of predicting about where it is going to happen. Which magnitude it is going to be? Then we can go to the government – pursuing government is clearly a management issue. Government always have to make priority about each sectors such as COVID 19 is a big issue. So, government will prioritize this pandemic more than the earthquake. For every projects, the big data of Earthquake is more needed.

Closing Remarks

With the open discussions amongst the participants the webinar ended on 12 p.m. by the closing remarks of DG CIRDAP Dr. Virapat. On behalf of CIRDAP, he thanked all the experts and participants for sharing their views on the issue of earthquake. The ideas that we are generating that how we are going to mitigate the risks and problems due to the earthquake which may happen in Bangladesh or anywhere in the world. CIRDAP and Prof. Ansary have already submitted a project proposal on the earthquake and natural disaster resilience in Chittagong city to European Union Horizon 2020 fund and hoping that next year EU will approve the fund for this project. Again, thanking all the participants for celebrating the international day of disaster risk reductions, DG CIRDAP closed the webinar.

Experts and Partcipants of the Webinar:

Experts

1. Prof. Mehedi Ansary, Department of Civil Engineering, BUET
2. Dr. Walter Mooney, United States Geological Survey (USGS), U.S.A.
3. Prof. Tavida Kamolvej, Dean, Faculty of Political Science, Thammasat University, Thailand
4. Mr. Tinnakorn Tatong, Department of Mineral Resources, Ministry of Natural Resources and Environment, Thailand

CIRDAP

1. Dr. Cherdsak Virapat, DG, CIRDAP
2. Prof. Helal Uddin, Centre on Integrated Rural Development for Asia and the Pacific (CIRDAP)
3. Mr. Tomasi V. Raiyawa, Strategic Planning Officer, CIRDAP
4. Mr. George C. Babu, Programme Officer, CIRDAP
5. Dr. Usharani Boruah, Head of Librarian, CIRDAP
6. Ms. Hurain Jannat, Communication Officer, CIRDAP

PART-IV

STRONG GROUND MOTION IN BANGLADESH AND NORTH-EAST INDIAN REGION FROM 2005 TO 2017 AND ITS PREDICTION OF ATTENUATION DATA DURING FUTURE EARTHQUAKES

BANGLADESH NETWORK OFFICE FOR URBAN SAFETY (BNUS), BUET, DHAKA

Prepared By: **Tanzila Tabassum**

Mehedi Ahmed Ansary

1 Introduction

Over the last few decades, the world has experienced numerous devastating earthquakes (Sieh et al., 2008). As a result of these devastating earthquakes, severe structural damages are occurring in densely populated areas and increasing loss of human life (Doğangün, 2004). Mechanisms of earthquakes and seismic ground motions are continually advancing (Bolt, 2004). To understand and interpret earthquakes and earth structures, more observation stations need to be established for monitoring high quality seismic data. When enough effective earthquake data are available, statistical analysis of these data could be carried out to better understand the wave propagation. Earthquake magnification due to the local site condition and distance from the focus, play an imperative role in predicting seismic hazards of structures (Idriss, 1991; Singh, 1998; Liao, 2013).

Ground-motion prediction equations (GMPEs) are function of magnitude, distance, site class, scaling of ground-motions etc.(Bradley, 2010; Atkinson and Adams, 2013). The amplitudes of strong ground motions decay (attenuation) with increasing distances from the source of earthquakes (Minzheng, 1984; Boore and Atkinson, 2008). Previous literatures relied on earthquake intensity in predicting models (Murphy and O'brien, 1977; Malone and Bor, 1979; Ambraseys, 1985). However, Cornell et al. (1979) proved that, earthquake intensity had poor correlations with acceleration. Consecutively, Hasegawa et al. (1981) converted earthquake intensity data into equivalent strong motion data e.g. acceleration and velocity. They also described the potential importance of these strong ground motion parameters for developing response spectra. Boore and Atkinson (2008) predicted ground motion equations for spectral periods between 0.01s and 10.0s. They have analyzed peak ground acceleration (PGA), peak ground velocity (PGV) for the prediction analysis. However, they have not incorporated peak ground displacement (PGD) for analysis as PGD is too sensitive to the low-cut filters. According to their research, PGD might influence the data processing system. Their study recommended to use response spectra (acceleration or velocity) at long periods instead of PGD. Moreover, Dino Bindi et al. (2014) investigated ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped pseudo-spectral acceleration (PSA) at spectral periods up to 3.0 s. This research only considered the spectral ordinates within the usable frequency band and have the function of the low-cut frequency. Joyner and Boore (1981) analyzed strong-motion data to derive new attenuation relations for peak horizontal acceleration and velocity for the earthquake of close distances. Whereas, Bommer and Akkar (2012) predicted ground motion prediction equations considering source-to-site distance metrics and used regression analysis to calibrate the equations.

Sabetta and Pugliese (1996), Abrahamson and Silva (1997) also established different predictive attenuation relationships for different regions which were functions of magnitude, distance and soil sites. Defining these functions and using them in a consistent manner is very important for prediction of attenuation models (Chen and Faccioli, 2008). In this research, the predicted peak ground parameters are expressed as a function of moment magnitude, distance (e.g. hypocentral distance) and site category (rock and firm soil). Early studies often measure the distance decay with respect to epicentral or hypocentral distance (Dino Bindi et al., 2014). These distance matrices can severely affect the prediction models (Bommer and Akkar, 2012). Some researchers also considered the coupled effect of these parameters in their studies (Qiwen et al., 1986; Fukushima and Tanaka, 1990; Hwang and Huo, 1997).

This study includes 1608 records with three-component digital seismograms recordings both from the North-East Indian and Bangladesh region. In this research, the data collected from IMD has been extracted by Seismosignal software and multi stage regression method has been used to calibrate the ground motion prediction equations proposed by Joyner and Boore (1981) and Bommer and Akkar (2012) model. The advantages of these two models are the motivation of behind opting them. These two studies had the benefit of analyzing earthquake ground motion without any bias of considered parameters. Predicted models from Joyner and Boore (1981) and Bommer and Akkar (2012) are based on geometrical spreading and anelastic attenuation as well as can retain magnitude-independent shape curves. Joyner and Boore (1981) model had the benefit that it decouples distance dependence of the acquired data from the magnitude dependence. Whereas Bommer and Akkar (2012) model show the relationship associated with magnitude and distance for available ground motion data. This research includes two GMPEs derived from the same dataset to demonstrate and observe the potential difference and effect on the prediction equation for different soil sites.

In this study, the predicted ground shaking amplitudes, e.g. acceleration; velocity, and acceleration response spectrum (ARS) and velocity response spectrum (VRS) for 0.3s, 1.0s and 2.0s are expressed as a function of magnitude, hypocentral distance and site category. Similar studies have been performed for different dataset by some authors (Joyner and Boore, 1982; Ansary and Yamazaki, 1998). Ground-motion prediction equations (GMPEs) based on peak ground motions, spectral values and attenuation relationships has been used for this research work. (Seed et al., 1976; Ansary and Yamazaki, 1998). Residual values (model errors) for predicted equations have also established in this research (Anderson and Lei, 1994; Boore and Atkinson, 2008). Predicted models have been also compared with the previous work done by other authors (Minzheng, 1984; Fukushima and Tanaka, 1990; Cui et al., 2006).

2 Recorded Database

The database consists of total 160 earthquakes with around 1608 three-component (North-South, (NS), East-West (EW) and Vertical) seismic recordings from North-East Indian Meteorological Department (IMD) network of instruments. Figure 1 shows the locations of the instruments established by IMD. This database contains acceleration values within 1000 km of the fault from earthquakes. The amplification of ground motions due to the local site condition plays an important role in seismic damage (Mohraz, 1976; Bommer and Akkar, 2012). The stiffness of soil site is expressed by the time average shear wave velocity in the upper 30 m of soil deposits and was initiated in the early 1990s (Nakamura, 1989; Borcherdt, 1994; Boore and Atkinson, 2008) by assigning a range of V_{S30} to different site categories e.g., NEHRP categories (Crouse and McGuire, 1996). Soils having shear wave velocity between 700 m/s to 1620 m/s are characterized as rock sites (soil type A). Furthermore, the range of shear wave velocity between 375 m/s to 700 m/s and 200 m/s to 375 m/s are categorized as soft rock (soil type B) and firm soil (soil type C), respectively. Table 1 shows the summary of the data used in this study. This can be observed that, bulk of the data are from soil type A and C, which range from rock to firm soil; very few data were from soil type B (soft rock).

Table 1 Summary of data used for the attenuation study

No. of earthquakes	160
No. of records	536
No. of total three component data	1608
No. of recording stations	163
Magnitude range	2.3 – 7.8
Minimum intensity (larger of two horizontal components)	PGA $\geq$ 0.438 cm/s^2
Soil Type A (Rock) 700< Vs_{30} <1620 m/s	273 records
Soil Type B (Soft Rock) 375 < Vs_{30} <700 m/s	63 records
Soil Type C (Firm) 200 < V_{s30} < 375 m/s	200 records

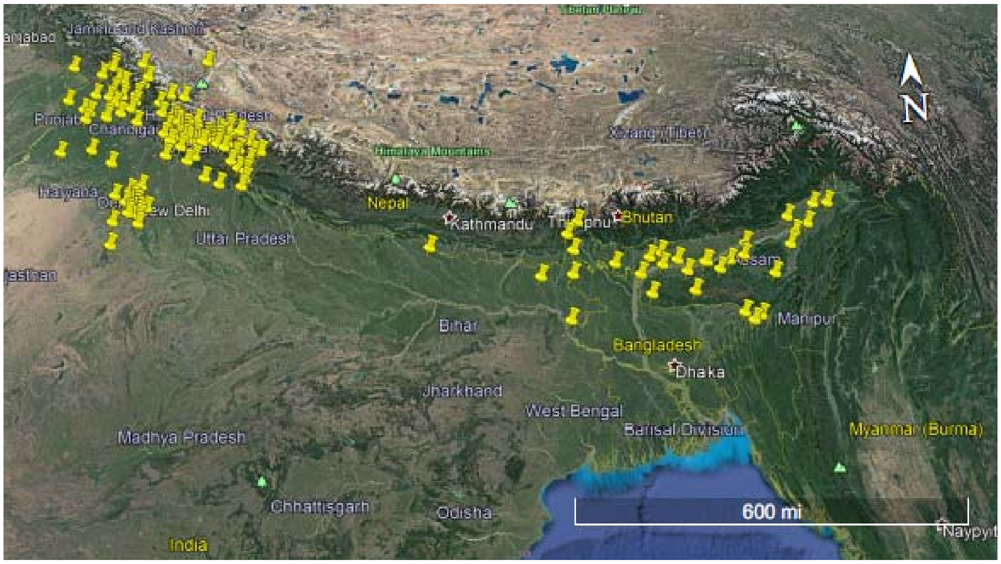


Fig. 1 Map showing the locations of the instruments covered by the IMD

3 Attenuation Model and Predictive Equations

Peak ground motion attenuation models have been usually presented by logarithmic type of empirical equations (Trifunac, 1976; Joyner and Boore, 1981; Sabetta and Pugliese, 1996; Abrahamson and Silva, 1997; Boore et al., 1997; Bommer and Akkar, 2012). All the attenuation theories and research achievements are mainly based the observations and data recorded by the stations during earthquakes. Therefore, the number of data available is very important to develop the ground motion attenuation relationships.

The predictive relationships are usually expressed as ground motion parameters, e.g. PGA, PGV, ARS, VRS in a functional form (Boore and Atkinson, 2008; Dino Bindi et al., 2014). The functional forms of the predictive relationships are usually selected to reflect the mechanical properties of the ground motions as close as possible minimizing the number of empirical coefficients and allowing greater confidence in application of the predictive relationships to seismic parameters, e.g. magnitude, distance, site conditions etc. (K. W. Campbell, 1985).

The general functional form of attenuation relationship for any type of soil can be presented by the expression:

$$f(Y) = a + f_1\,(M) + f_2\,(r) + f_3\,(\log r) \pm \sigma \qquad (1)$$

Where, Y = Ground Motion (acceleration, velocity, response spectrum)

a = Regression Constant

M = Moment Magnitude

r = Hypocentral Distance (km) = $\sqrt{epicentral\ distance^2 + depth^2}$

σ = Standard Error

Final functional form for modelling the ground motion attenuation equations for any type of soil can be represented as following:

$\log Y = b_1 + b_2\, r + b_3 M + b_4 \log r \pm \sigma$ (Joyner and Boore, 1981) (2)

$\log Y = b_1 + b_2\, M + b_3 M^2 + (b_4 + b_5 M) \log r \pm \sigma$ (Bommer and Akkar, 2012) (3)

In order to determine the coefficients and standard deviation in equation (2) and (3), multiple regression method is used with variable soil type (Joyner and Boore, 1981, 1982; Graizer and Kalkan, 2007; Idriss, 2008; Bommer and Akkar, 2012). Attenuation model is essential for ground motion attenuation relationships. The standard deviation of the regression analysis result of a proper and suitable attenuation model should be as small as possible. For making the predictive models acceptable and reliable, resulting equations should be consistent with data as much as possible (Somerville et al., 1997; Graizer and Kalkan, 2007).

3.1 Regression coefficients

GMPEs based on peak ground motions and spectral values are presented in this paper IMD strong ground motion (SGM) data recorded from 2005 to 2017. To determine the coefficients of attenuation equations, two attenuation models proposed by Joyner and Boore (1981); equation (2) and Bommer and Akkar (2012); equation (3) are used in this study to fit the SGM data. This study predict PGA, PGV, ARS and VRS spectral ordinates at response periods for 0.3s, 1.0s, and 2.0s. as a function of moment magnitude (M), hypocentral distance and site class. Usually, response spectrum periods less than 0.3s are indicated as short periods. Periods between 0.3s to 2.0s are specified as intermediate and greater than 2.0s are expressed as long periods (Joyner and Boore, 1982). Joyner and Boore (1982) explain that, spectral values for period less than 0.3s can generate slight de-amplification at the soil sites. Intermediate periods e.g. between 0.3s to 2.0s can avoid the errors associated with the amplifications of soils and scaling effects. Several earlier studies also explain that, response spectrum equations predicted for periods between 0.3s to 2.0s, can result in a consistent manner (Joyner and Boore, 1982; Bozorgnia and Niazi, 1993; Wilson and Lam, 2003).

Tables 2 and 3 show coefficients determined by multistage regression analysis for rock and firm soil sites respectively for Joyner and Boore (1981) GMPEs whereas, Tables 4 and 5 show coefficients determined by multistage regression analysis for rock and firm soil sites for Bommer and Akkar (2012) GMPEs. Here, b_1, b_2, b_3, b_4 are the coefficients for the independent variables, σ is standard deviation (lesser value indicating good model) and correlation factor R^2 (higher value indicating good correlation between the parameters). As there are only 63 records for soft rock sites (Table 1), the analysis of soft rock soil sites has been excluded in this research.

Table 2 Regression coefficients for peak ground motions and spectral values using Joyner and Boore (1981) GMPEs for rock sites (Soil Type A)

Y	b_1	b_2	b_3	b_4	σ	R^2
$PGA_{max,h}$	0.80532	0.00030	0.36134	-0.92616	0.37057	0.35008
$PGA_{max,v}$	0.70752	0.00033	0.38629	-1.06121	0.40904	0.36024
$PGV_{max,h}$	0.23332	0.00025	0.28093	-0.64941	1.26125	0.02363
$PGV_{max,v}$	0.29710	0.00037	0.24754	-0.75369	1.25565	0.02544
$PGA_{res,h}$	0.88098	0.00028	0.36346	-0.91552	0.37306	0.34561
$PGV_{res,h}$	0.30098	0.00025	0.28609	-0.64690	1.26213	0.02390
ARS_h (0.3s)	-1.97543	0.00032	-0.13774	0.57342	0.52654	0.18665
ARS_h (1.0s)	-2.36232	0.00006	-0.10470	0.69627	0.54808	0.19524
ARS_h (2.0s)	-2.13429	0.00033	-0.14379	0.64215	0.53334	0.21353
VRS_h (0.3s)	-2.32579	0.00012	0.06316	0.18016	1.35363	0.01386
VRS_h (1.0s)	-1.60392	0.00004	0.05702	0.01944	1.34169	0.00253
VRS_h (2.0s)	-1.43951	-0.00011	0.08796	-0.02869	1.34631	0.00275
ARS_v (0.3s)	-2.48720	0.00000	-0.08348	0.61952	0.66552	0.12431
ARS_v (1.0s)	-2.22717	0.00002	-0.05987	0.43130	0.64645	0.07373
ARS_v (2.0s)	-2.39968	-0.00012	-0.10277	0.66317	0.60647	0.13431
VRS_v (0.3s)	-2.19324	0.00024	-0.00951	0.13308	1.31757	0.00906
VRS_v (1.0s)	-1.55553	0.00025	0.02355	-0.09257	1.34334	0.00234
VRS_v (2.0s)	-1.21549	0.00041	0.09624	-0.36059	1.36968	0.00598

Table 3 Regression coefficients for peak ground motions and spectral values using Joyner and Boore (1981) GMPEs for firm soil (Soil Type C)

Y	b_1	b_2	b_3	b_4	σ	R^2
$PGA_{max,h}$	0.63296	-0.00062	0.43518	-0.84747	0.30658	0.49519
$PGA_{max,v}$	0.56545	-0.00067	0.41255	-0.85580	0.34536	0.44610
$PGV_{max,h}$	0.55935	0.00012	-0.23624	0.51760	1.30931	0.01283
$PGV_{max,v}$	0.60381	0.00045	-0.30737	0.45938	1.30335	0.02197

$PGA_{res,h}$	0.72201	-0.00064	0.43682	-0.83985	0.29974	0.50658
$PGV_{res,h}$	0.62698	0.00011	-0.22759	0.49924	1.30802	0.01225
ARS_h (0.3s)	-3.13749	-0.00052	0.07768	0.70577	0.59477	0.17871
ARS_h (1.0s)	-3.01049	-0.00062	0.09620	0.62204	0.57714	0.15254
ARS_h (2.0s)	-2.81744	-0.00039	0.06788	0.58105	0.59339	0.13916
VRS_h (0.3s)	-1.57219	0.00059	-0.62886	1.46261	1.38130	0.09570
VRS_h (1.0s)	-0.68733	0.00076	-0.63600	1.19174	1.37277	0.08472
VRS_h (2.0s)	-0.25837	0.00061	-0.59675	0.99466	1.36563	0.06784
ARS_v (0.3s)	-2.98277	-0.00054	0.09208	0.55851	0.67368	0.10135
ARS_v (1.0s)	-3.57852	-0.00132	0.13989	0.82195	0.63922	0.16144
ARS_v (2.0s)	-3.47533	-0.00105	0.07258	0.89599	0.64865	0.15442
VRS_v (0.3s)	-2.56279	0.00005	-0.64273	1.84534	1.38835	0.10536
VRS_v (1.0s)	-1.25212	0.00092	-0.55499	1.06735	1.37557	0.07851
VRS_v (2.0s)	-0.78463	0.00073	-0.58880	1.05993	1.37838	0.07146

Table 4 Regression coefficients for peak ground motions and spectral values using Bommer and Akkar (2012) GMPEs for rock site (Soil Type A)

Y	b_1	b_2	b_3	b_4	b_5	σ	R^2
$PGA_{max,h}$	0.01572	0.12328	0.07870	0.36183	-0.24825	0.36744	0.36340
$PGA_{max,v}$	0.01549	0.12000	0.07856	0.18590	-0.23509	0.40893	0.36297
$PGV_{max,h}$	0.60494	-0.35371	0.11282	0.39446	-0.20777	1.26228	0.02566
$PGV_{max,v}$	1.44156	-0.67949	0.13472	0.16065	-0.16841	1.25704	0.02692
$PGA_{res,h}$	0.10633	0.10592	0.08287	0.40495	-0.25719	0.36880	0.36286
$PGV_{res,h}$	0.68015	-0.35456	0.11351	0.40195	-0.20816	1.26321	0.02587
ARS_h (0.3s)	-0.77177	-0.34989	-0.01495	-0.23223	0.18542	0.52222	0.20325
ARS_h (1.0s)	-1.78714	-0.06227	-0.03513	0.01048	0.14537	0.54709	0.20153
ARS_h (2.0s)	-1.21176	0.11363	-0.10098	-0.97367	0.35719	0.52387	0.24439
VRS_h (0.3s)	0.30639	-0.50732	-0.00638	-1.18072	0.30220	1.34715	0.02690
VRS_h (1.0s)	-0.03879	-0.23158	-0.01388	-0.90128	0.20141	1.34069	0.00773
VRS_h (2.0s)	0.31509	-0.25365	-0.00460	-0.98732	0.19011	1.34541	0.00778
ARS_v (0.3s)	-0.40104	-0.29914	-0.05029	-0.96401	0.33373	0.65031	0.16776
ARS_v (1.0s)	-1.00245	-0.14135	-0.04011	-0.62087	0.22441	0.64084	0.09389
ARS_v (2.0s)	-1.44359	0.17819	-0.10198	-0.91591	0.32913	0.59674	0.16555

VRS_v (0.3s)	0.45172	-0.92082	0.06362	-0.47733	0.14840	1.31341	0.01897
VRS_v (1.0s)	0.62426	-0.90209	0.08907	-0.20249	0.04036	1.34194	0.00811
VRS_v (2.0s)	0.86310	-0.67402	0.05193	-0.76169	0.12701	1.37029	0.00878

Table 5 Regression coefficients for peak ground motions and spectral values using Bommer and Akkar (2012) GMPEs for firm soil (Soil Type C)

Y	b_1	b_2	b_3	b_4	b_5	σ	R^2
$PGA_{max,h}$	-0.21224	0.61269	0.01595	-0.25977	-0.16759	0.31216	0.47932
$PGA_{max,v}$	-0.42053	0.75202	-0.00915	-0.49652	-0.12559	0.34930	0.43628
$PGV_{max,h}$	-1.39360	-1.20635	0.26292	4.58270	-0.79111	1.29721	0.03593
$PGV_{max,v}$	-0.85807	-1.24603	0.22804	3.89521	-0.63607	1.29756	0.03559
$PGA_{res,h}$	-0.14321	0.61198	0.01749	-0.22437	-0.17393	0.30550	0.49004
$PGV_{res,h}$	-1.34040	-1.18048	0.26038	4.55703	-0.78734	1.29607	0.03516
ARS_h (0.3s)	-2.79298	0.18648	-0.01987	0.28340	0.03770	0.60092	0.16592
ARS_h (1.0s)	-2.60069	0.12248	-0.00349	0.35801	-0.00206	0.58558	0.13203
ARS_h (2.0s)	-2.42870	0.18662	-0.02730	0.05313	0.06976	0.59730	0.13223
VRS_h (0.3s)	-1.80672	-1.50317	0.16374	3.53395	-0.35805	1.38191	0.09952
VRS_h (1.0s)	-0.79252	-1.62982	0.17719	3.36354	-0.36335	1.37372	0.08813
VRS_h (2.0s)	-0.89564	-1.62035	0.20816	3.79156	-0.49874	1.36347	0.07553
ARS_v (0.3s)	-2.93939	0.58434	-0.08220	-0.45564	0.15258	0.67651	0.09846
ARS_v (1.0s)	-5.14879	0.89017	-0.04817	0.97874	-0.14065	0.65152	0.13334
ARS_v (2.0s)	-4.54408	0.43679	0.00066	1.39851	-0.18783	0.65994	0.12928
VRS_v (0.3s)	-3.60777	-1.16205	0.14115	4.03399	-0.42556	1.38770	0.11076
VRS_v (1.0s)	-1.51042	-0.91665	0.05468	1.87134	-0.07897	1.38462	0.07110
VRS_v (2.0s)	-1.40231	-0.98178	0.08031	2.33904	-0.18845	1.38474	0.06766

Here, subscript '*h*' and '*v*' denotes values for horizontal and vertical component and '*res*' denotes for residual value.

3.2 Attenuation Models

By multiple regression analysis for all earthquake data (536 records) the predicted attenuation model correspond to authors are given below:

$log\ A_{max,h} = 0.45612 - 0.00027*r + 0.39353*M - 0.73977*log\ r \pm 0.3547\ \sigma$ (Joyner and Boore, 1981) (4)

$$\log A_{max,h} = 0.12628 + 0.44816*M + 0.00922*M^2 + (-0.47679 - 0.07301*M) \log r \pm 0.3552\ \sigma$$

(Bommer and Akkar, 2012) (5)

The standard deviation for equation (4) is ± 0.3547 and for equation (5) is ±0.3552; which are satisfactory. Whereas, the correlation factors are 0.3461 and 0.3456, respectively. From the standard deviation and correlation values it is evident that, both models are satisfactory for all earthquake data records (536 records). Both Fig. 2 and 3, solid line represents the mean value of equation (4) and (5) respectively where the value of σ is zero.

3.2.1 Peak ground acceleration with respect to hypocentral distance

The attenuation relationship developed by K. Campbell (1994) and Boore and Joyner (1982) are recommended for predicting acceleration in horizontal direction (A_H). The coefficients in this relationship were determined from regression analysis. The distribution of the recordings with respect to magnitude and hypocentral distance were plotted in Fig. 2 and 3 according to local site conditions.

Inspection of Fig. 2 and 3 reveal that there is a correlation between magnitude and distance, which may induce bias to the magnitude and hypocentral coefficients b_2 and b_3 in equation (2) for Joyner and Boore (1981) and coefficients b_2, b_3 and b_5 in equation (3) for Bommer and Akkar (2012). However, because there are many earthquakes with only a few records in our data set, instead of grouping together the data belonging to the same earthquake, the data have been divided into three soil classes e.g. soil type A, B and C (Table 1); based on the shear wave velocity at 30 m depth of the related event. Herak et al. (2001) also predicted earthquake attenuation equation for different soil sites. Figures 2 and 3 demonstrate strong correlation between magnitude and hypocentral distance with a coefficient of 0.4999, and 0.6617 respectively for rock site (soil type A) and firm soil (soil type C). Soil type A includes total 273 sets and type C includes 200 sets of data.

Predicted equations for horizontal and vertical component of the earthquake ground motions after regression method according to soil sites and corresponding authors are given below:

Rock sites (Soil Type A)

Joyner and Boore (1981)

$$\log A_{max,h} = 0.80532 + 0.00029*r + 0.36134*M - 0.92616*\log r \pm 0.3705\ \sigma \quad (6)$$

$$\log A_{max,v} = 0.70752 + 0.00033*r + 0.38629*M - 1.06121*\log r \pm 0.4090\ \sigma \quad (7)$$

Bommer and Akkar (2012)

$$\log A_{max,h} = 0.01572 + 0.12328*M + 0.07870*M^2 + (0.36183 - 0.24825*M) \log r \pm 0.3674\ \sigma$$

(8)

$log\ A_{max,v} = 0.01549 + 0.12000*M + 0.07856*M^2 + (0.18590 – 0.23509*M)\ log\ r \pm 0.4089\ \sigma$ (9)

Firm soil (Soil Type C)

Joyner and Boore (1981)

$log\ A_{max,h} = 0.63296 - 0.00062*r + 0.43518*M – 0.84747*log\ r \pm 0.3066\ \sigma$ (10)

$log\ A_{max,v} = 0.56545 - 0.00067–r - 0.41255*M – 0.85580*log\ r \pm 0.3454\ \sigma$ (11)

Bommer and Akkar (2012)

$log\ A_{max,h} = -0.21224 + 0.61269*M -0.01595*M^2 + (-0.25977–0.16759*M)\ log\ r \pm 0.3122\ \sigma$ (12)

$log\ A_{max,v} = -0.42053 +0.75202*M -0.00915*M^2 + (-0.49652 – 0.12559*M)\ log\ r \pm 0.3493\ \sigma$ (13)

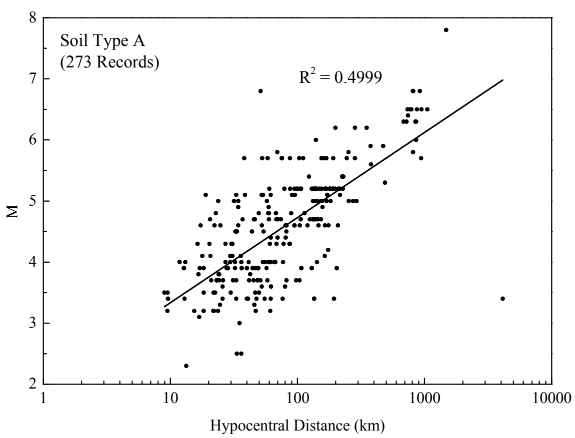


Fig. 2 Distribution of recordings in the PGA database as a function of magnitude, distance for rock site: soil type A

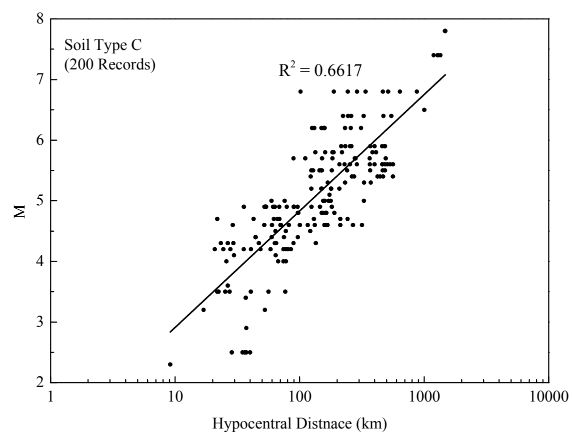


Fig. 3 Distribution of recordings in the PGA database as a function of magnitude, distance for firm soil: soil type C

Figures 4 and 5 describe the attenuation curves according to equations (6-7) and (10-11) for rock and firm soil respectively that correspond to Joyner and Boore (1981) model. First row indicates the magnitude interval 4.5 ≤ M ≤ 5.5, where the mean magnitude is 5. Second row shows magnitude interval of 5.6 ≤ M ≤ 6.5 and the mean magnitude is 6. The bottom row denotes the magnitude interval of 6.5 ≤ M ≤ 7.8 where the mean magnitude is 7. Left column shows the peak horizontal acceleration (maximum one of the two horizontal component) and right column shows the vertical component. The mean magnitude is expressed as a solid bold line. Short and long dashed lines bound ±lσ and ±2σ intervals, respectively. The multiple correlation coefficient of equation (6) and (7) is high: 0.35 for horizontal component and 0.36 for vertical component, respectively. Standard error σ is 0.3705 for horizontal component and 0.4090 for vertical component. For equation (10) and (11), the multiple correlation coefficient is also very high: 0.50 for horizontal component and 0.45 for vertical component, respectively. Standard error σ is 0.3066 for horizontal component and 0.3454 for vertical component. Similar results have also presented by (Herak et al., 2001).

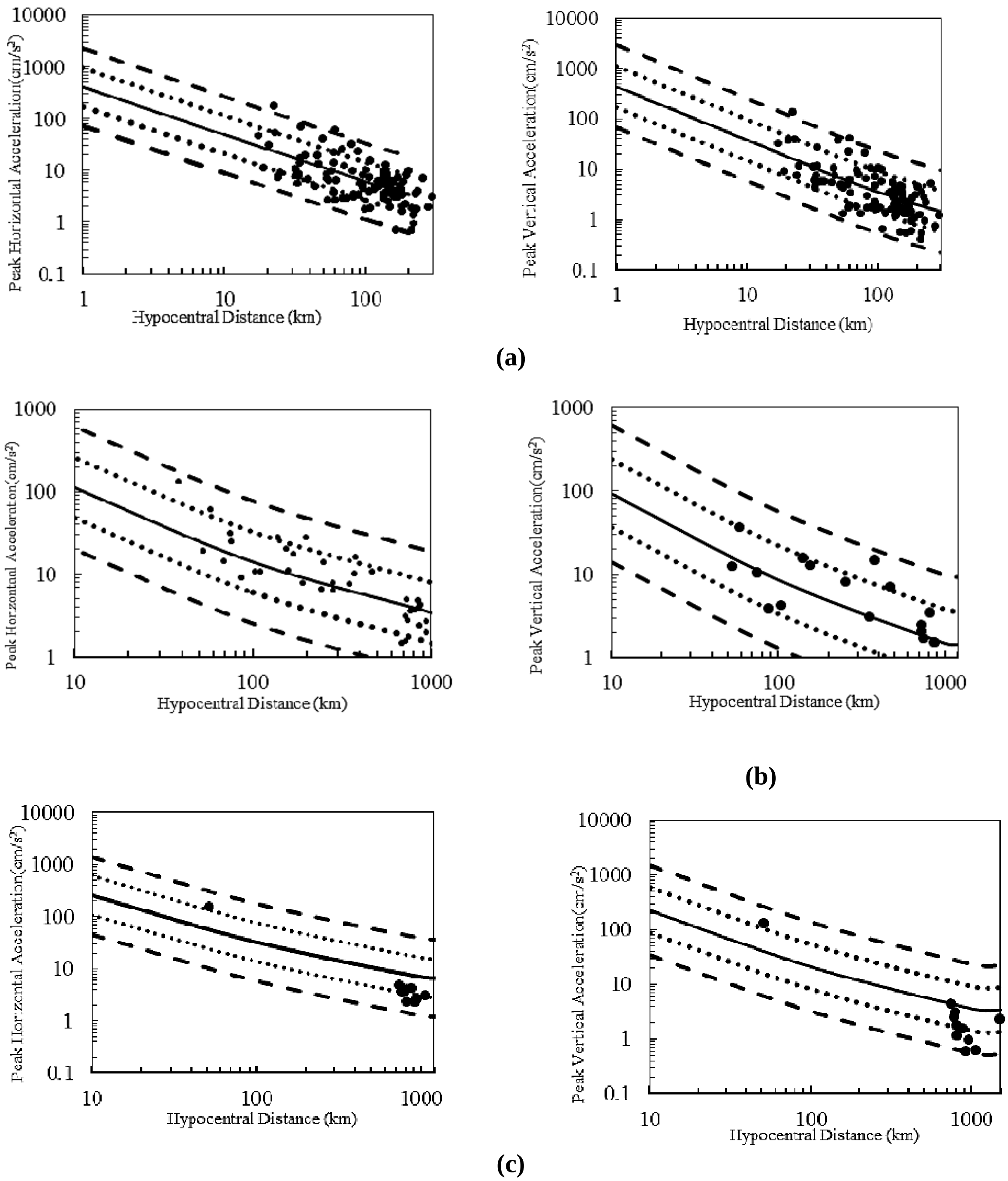
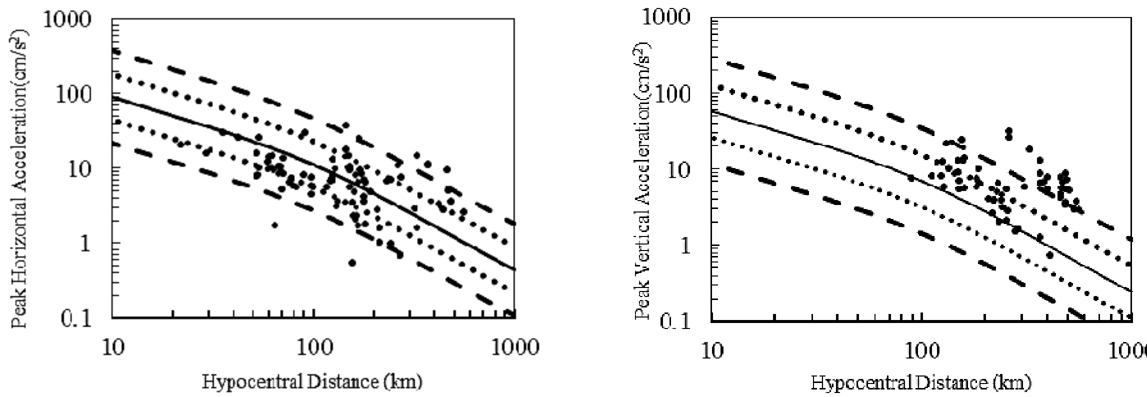
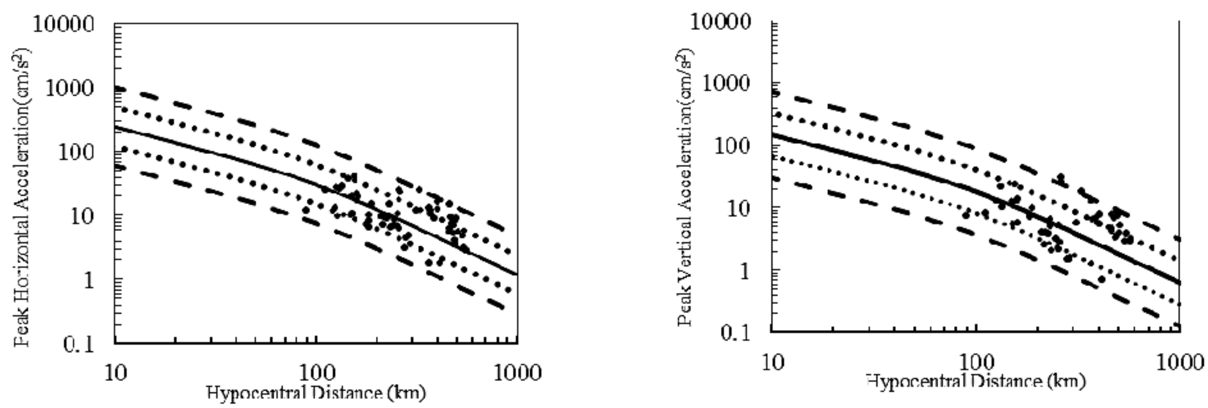


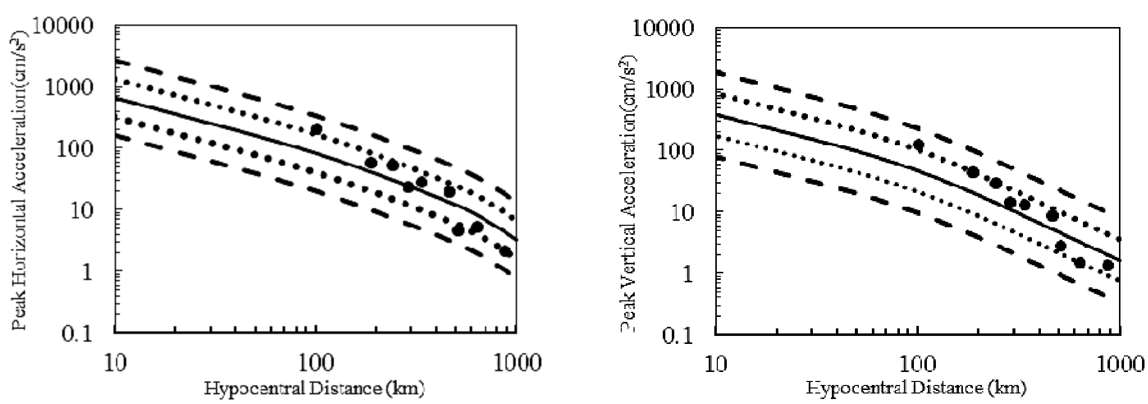
Fig. 4 Comparison of peak horizontal acceleration with predicted ones for earthquakes for soil type A



(a)



(b)



(c)

Fig. 5 Comparison of peak horizontal acceleration with predicted ones for earthquakes for soil type C

From Fig. 4 (a), it can be perceived that for magnitude range 4.5 to 5.5, most of the points lie between the ±lσ range, which demonstrates that the predicted results are consistent with the observations. However, for Fig. 4 (b), the data set are little bit biased in ±1σ for vertical component of peak acceleration whereas for the peak horizontal acceleration it shows most of the points lie in +lσ range. For magnitude range 6.5 to 7.8 in Fig. 4 (c) it is evident that, the data set is biased in -1σ to -2σ range for both acceleration component e.g. horizontal and vertical. This is because lack of the data set in the magnitude range of 6.5 to 7.8.

From the result of Fig. 5 (a), it can be seen that for magnitude range 4.5 to 5.5, most of the points lie between the ±lσ range for horizontal component of peak acceleration, but massively biased to +2σ and more for vertical component. Which demonstrates that the predicted results are consistent with the observations for horizontal component but not for the vertical one. Since Fig. 5 (b), the data set are within the range of ±2σ for both component of peak acceleration, which demonstrates that the predicted results are consistent with the observations. For magnitude range 6.5 to 7.8 in Fig. 5 (c) it is evident that, the data set is within ±1σ range for both acceleration component e.g. horizontal and vertical. It expresses a good correlation between the predicted and observed values for attenuation models.

This research includes total 216 records of magnitude from 4.5 to 5.5, 112 records of magnitude from 5.6 to 6.5 and only 33 records of magnitude from 6.5 to 7.8.

3.3 Decay of Predicted Acceleration

As the hypocentral distance of the earthquake increases, the predicted peak horizontal and vertical acceleration also decreases (Anderson and Lei, 1994). Thus, the predicted maximum acceleration is a function of hypocentral distance. From Fig. 6, it is perceived that for a fixed earthquake magnitude e.g. M = 6; the peak horizontal acceleration is dominant for Bommer and Akkar (2012) attenuation model than Joyner and Boore (1981) model and the peak value of acceleration is more for firm soil and less for rock site. Thus, the predicted values for firm soil sites are always lager than those from rock sites for given conditions. This is due to amplification effect of local site condition. The shapes of the curves do not depend on the magnitude, indicating the magnitude independence of the distance decay. Anderson and Lei (1994) also had similar results. Anderson and Lei (1994) described that peak horizontal and vertical acceleration had very weak tendency to decrease with magnitude. It is evident from Fig. 6 that the decay curves are steeper for Bommer and Akkar (2012) model indicating faster decay of the model. This decay is related to the higher frequency content in the ground motions. However, the reason needs further investigation.

Similarly, Fig. 7 shows that, for a fixed earthquake magnitude e.g. M = 6; the peak vertical acceleration is larger for Bommer and Akkar (2012) attenuation model than the other one and the peak value of acceleration is more for firm soil and less for rock site. This scenario is acute for smaller hypocentral distance.

3.4 Predictive Equations with Respect to Residuals, Distance and Magnitude

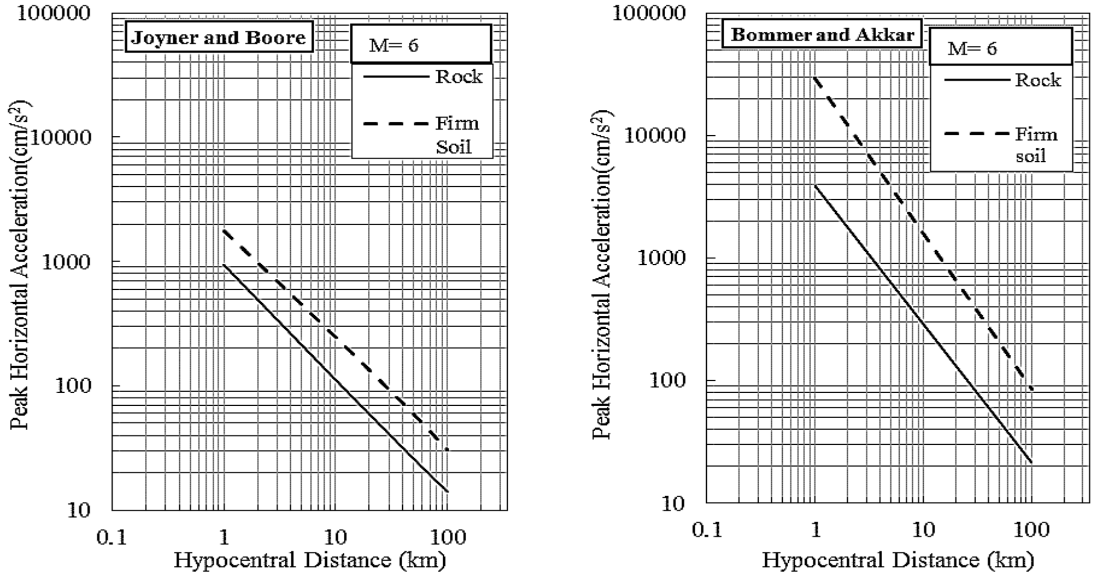
The residuals represent the deviations of the predicted values from the observed values. It can be defined as:

$$residual = log_{10} \left(\frac{Y_{observed}}{Y_{predicted}}\right) \quad (14)$$

Where, $Y_{observed}$ is the observed value recorded, e.g. peak ground motion acceleration, while $Y_{predicted}$ represents the value predicted by the empirical attenuation equations accordingly. The residual can describe the extent to which the predicted values are consistent with the recorded values, representing the reliability and applicability of the empirical predictive equations. The plots of the residuals with respect to magnitude or distance can show the description of the results. If no trend is apparent in the residual points, the predictive equations are satisfactory, vice versa. The residual plots could be seen hereafter.

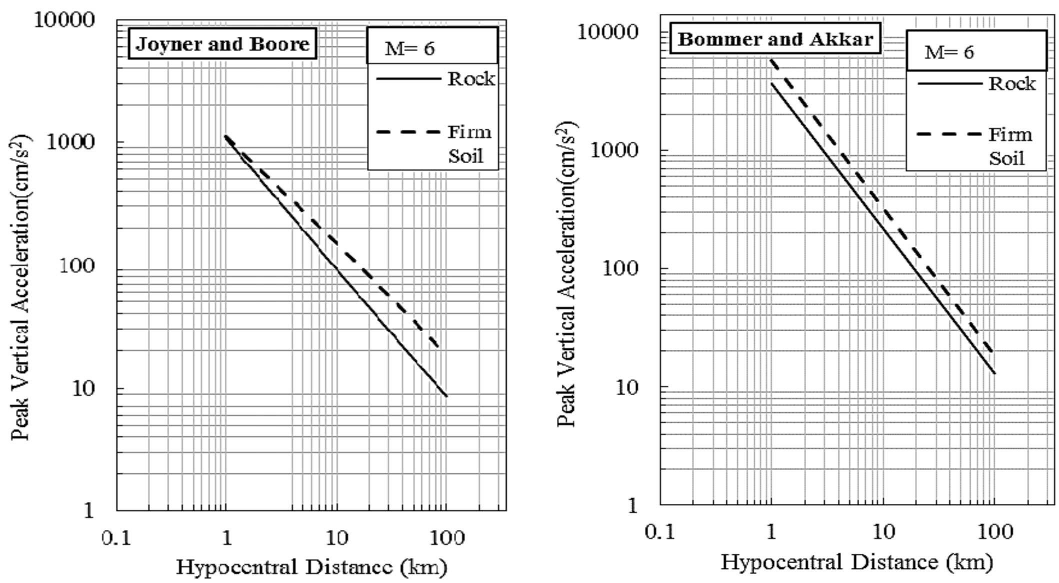
The ratios of observed and predicted model (residuals) for rock and firm soil sites according to equation (6) (Joyner and Boore, 1981) and equation (8) (Bommer and Akkar, 2012) are shown in Fig. 8 and 9 respectively, as a function of hypocentral distance (a) and magnitude (b). These results show no bias or singularity with distance and magnitude. These indicate that, residuals of the peak horizontal acceleration are independent of hypocentral distance and magnitude. Along with, Fig. 8-9 show that most of the data are within its one standard deviation of ±0.3705 and ±0.3674 respectively, indicating good correlations of residuals with magnitude of the earthquakes and distance. Though, for hypocentral distance, the data are seen scattered whereas for magnitude showing regular tendency.

Residuals distribution of firm soil sites by equation by (Joyner and Boore, 1981) and equation (12) (Bommer and Akkar, 2012) are shown in Fig. 10 and 11 as a function of hypocentral distance (a) and magnitude (b). The results show no distance dependence of residuals for any of the component, even for large distances. Residuals are also not magnitude dependent. Nevertheless, most of the data are within its one standard deviation ±0.3066 (Fig. 10) and ±0.3122 (Fig. 11) indicating good correlations of residuals with magnitude of the earthquakes and distance. These results are also supported by previous studies (K. W. Campbell, 1981; Herak et al., 2001; D Bindi et al., 2006).



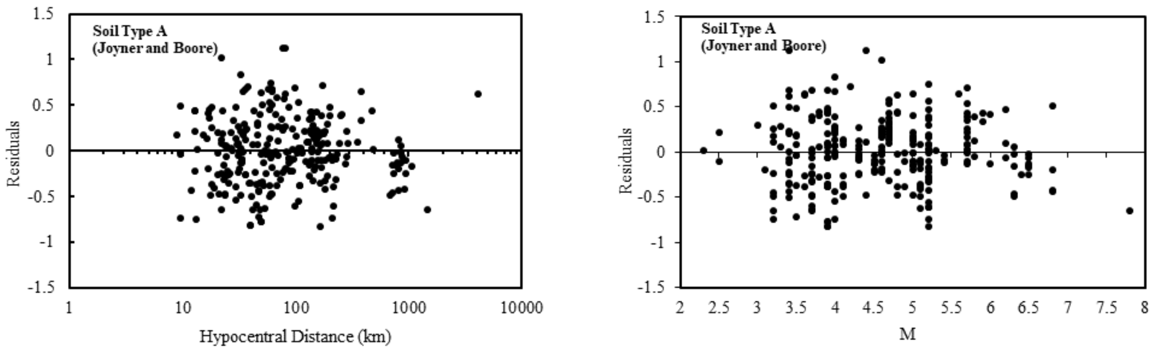
(a) **(b)**

Fig. 6 Comparison of peak horizontal acceleration with local site conditions and distance predicted by the attenuation relationship recommended by Joyner and Boore (1981) (a); Bommer and Akkar (2012) (b)



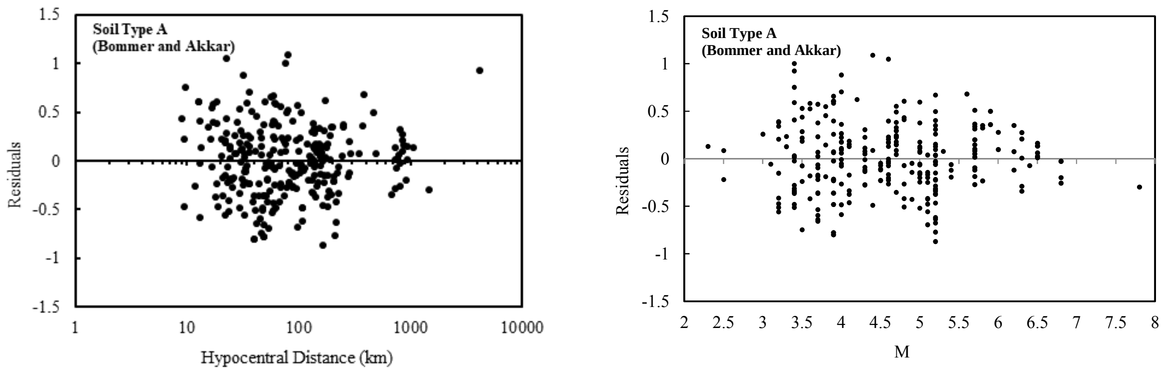
(a) **(b)**

Fig. 7 Peak vertical acceleration with local site conditions and distance predicted by the attenuation relationship recommended by Joyner and Boore (1981) (a); Bommer and Akkar (2012) (b)



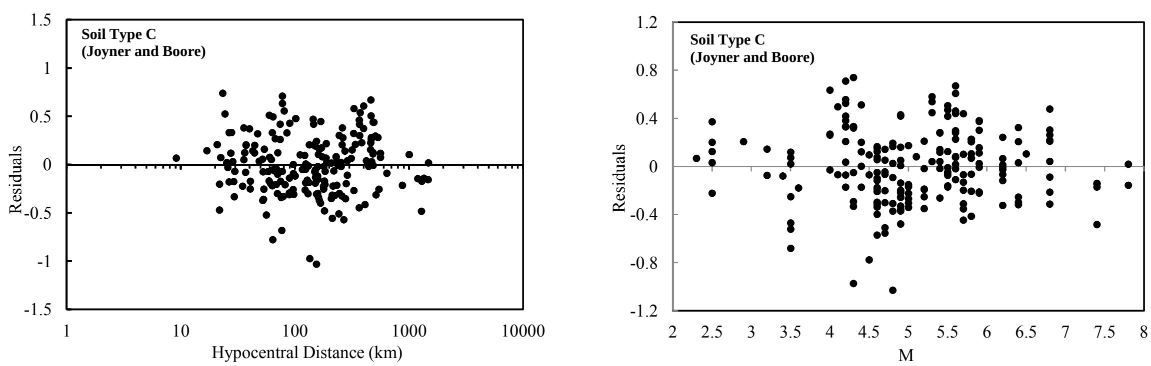
(a) **(b)**

Fig. 8 Peak horizontal acceleration ratios between observed values and predicted ones for rock site by equation (6) Joyner and Boore (1981) as function of hypocentral distance (a) and magnitude (b)



(a) **(b)**

Fig. 9 Peak horizontal acceleration ratios between observed values and predicted ones for rock site by equation (8) Bommer and Akkar (2012) as function of hypocentral distance (a) and magnitude (b)



(a) **(b)**

Fig. 10 Peak horizontal acceleration ratios between observed values and predicted ones for firm soil by equation (10) Joyner and Boore (1981) as function of hypocentral distance (a) and magnitude (b)

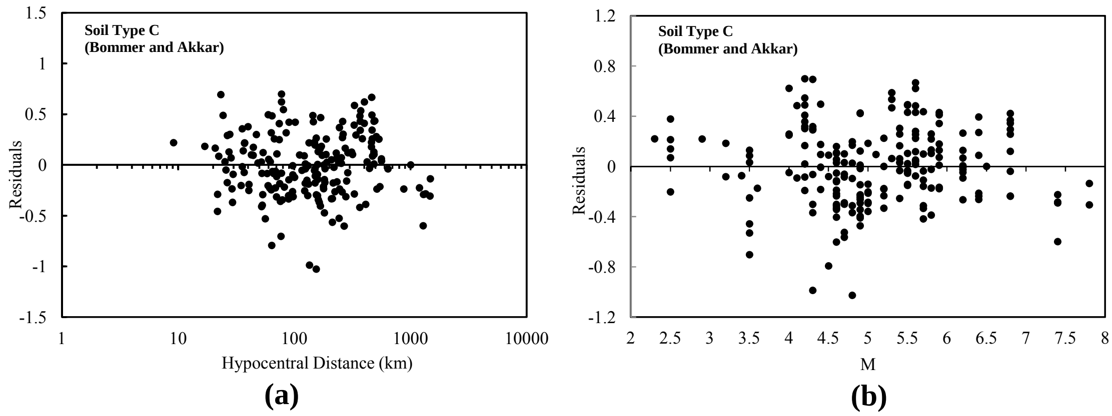


Fig. 11 Peak horizontal acceleration ratios between observed values and predicted ones for firm soil by equation (12) Bommer and Akkar (2012) as function of hypocentral distance (a) and magnitude (b)

3.5 Predictive Equations with Respect to Residuals and Log-Normal Plot

The residuals of horizontal as well as vertical component are distributed approximately log-normally for different soil types. For the horizontal components of acceleration, firstly, the peak of the two horizontal components (East-West and North-South) has been taken for the analysis and then the same analysis is performed for the resultant of the two components. Similar study has also been conducted by some authors (Boore and Joyner, 1982; Anderson and Lei, 1994; Herak et al., 2001).

Figures 12-13 show the distribution of residuals according to equations (6) and (8) respectively. They are distributed approximately log normally with slight asymmetry showing longer tails on the positive side for Joyner and Boore (1981) model as well as in negative side for Bommer and Akkar (2012) model. This is most probably caused by site amplification at some stations and balanced by a larger than expected number of residuals in the first negative and positive class, respectively. Peak acceleration residuals with log-normal distribution are shown in Fig. 14-15 according to equations (10) and (12). Similar slight asymmetry is observed with positive and negative tails respectively for Fig. 14-15. These have been balanced by a larger than expected number of residuals in the first negative class for Fig. 14 and larger residuals in the first positive class for Fig. 15.

3.6 Comparisons of Peak Ground Acceleration with Other Studies

A comparison of Joyner and Boore (1981) and Bommer and Akkar (2012) prediction model has been shown in Fig. 16 for rock and firm soil sites. These two models function quite different for same data set and condition. Figure 16 (a) compare the dissimilarity of equations (6) and (8) that is for rock site explaining that, the deviation of ground acceleration increases with the increased magnitude. There is no difference between the two models for small magnitude of earthquake e.g. M = 5. The largest deviation between the curves corresponds to a factor of 10 which is greater than standard deviation of the data about the regression line. As there are similarity of the absolute predictions, there are no fundamental differences in the shape of the curves. Thus, shape of both models is constrained to be independent of magnitude. Figure 16 (b) shows the comparison of attenuation curves of equations (10) and (12) for firm soil site. The deviation of ground acceleration increases with the increased magnitude which was seen same for rock site. However, the largest deviation between the curves exceeds 33 percent in logarithm scale. The reason may be Bommer and Akkar (2012) model has much dependency on magnitude parameter.

Attenuation predictive equations obtained in this study have been compared with other regression equations. According to the study of Cui et al. (2006), the predictive equations for Yunnan area could be expressed as:

$$\log (A_h) = 3.5549 + 0.2881*M + (-2.7317 + 0.0889*M) \log (D + 13) \pm 0.5314\ \sigma \qquad (15)$$

Where, A_h represents the horizontal predictive accelerations in cm/s^2, D is epicentral distance in kilometers, and M is magnitude.

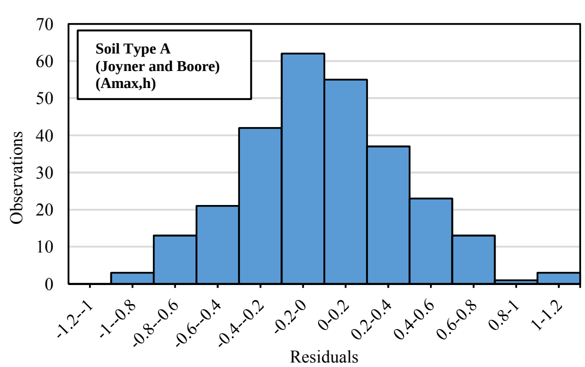


Fig. 12 Distribution of residuals of the logarithm of peak acceleration with log-normal distributions for horizontal component for rock sites (soil type A) according to equation (6)

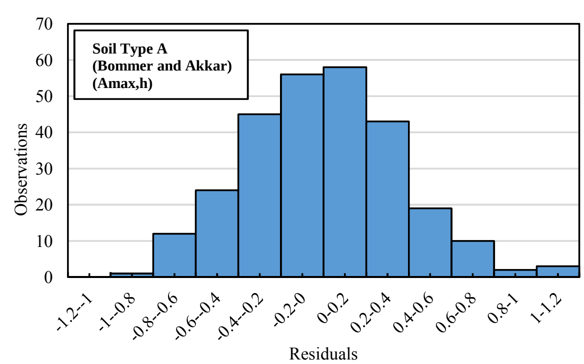


Fig. 13 Distribution of residuals of the logarithm of peak acceleration with log-normal distributions for horizontal component for rock sites (soil type A) according to equation (8)

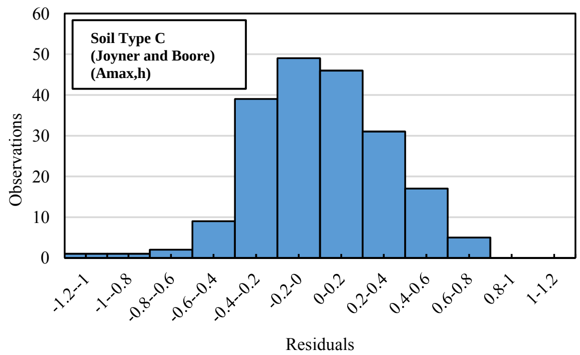


Fig. 14 Distribution of residuals of the logarithm of peak acceleration with log-normal distributions for horizontal component for firm soil site (soil type C) according to equation (10)

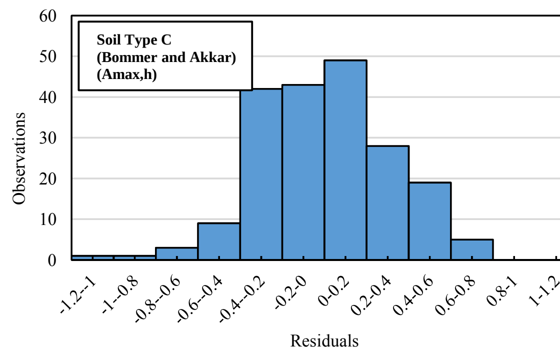


Fig. 15 Distribution of residuals of the logarithm of peak acceleration with log-normal distributions for horizontal component for firm soil site (soil type C) according to equation (12)

According to Fukushima and Tanaka (1990), the resulting attenuation relation in Japan is,

$$log\ A = 0.41*M - log\ (R+0.032*10^{0.41M}) - 0.0034*R+1.30 \quad (16)$$

Where, A is the mean of the peak acceleration from two horizontal components at each site in cm/s^2, R is the shortest distance between site and rupture surface in kilometer and M is the surface wave magnitude.

The following equation is proposed by Hu and Zhang (1984) and widely used in attenuation research in China,

$$log\ (a_{max}) = 1.71 + 0.657*M - 2.18\ log\ (D_{ep} + 30) \pm 0.47\ \sigma \quad (17)$$

Where, a_{max} is the maximum acceleration from two horizontal components at each site in cm/s^2, D_{ep} is the epicentral distance and M is the magnitude.

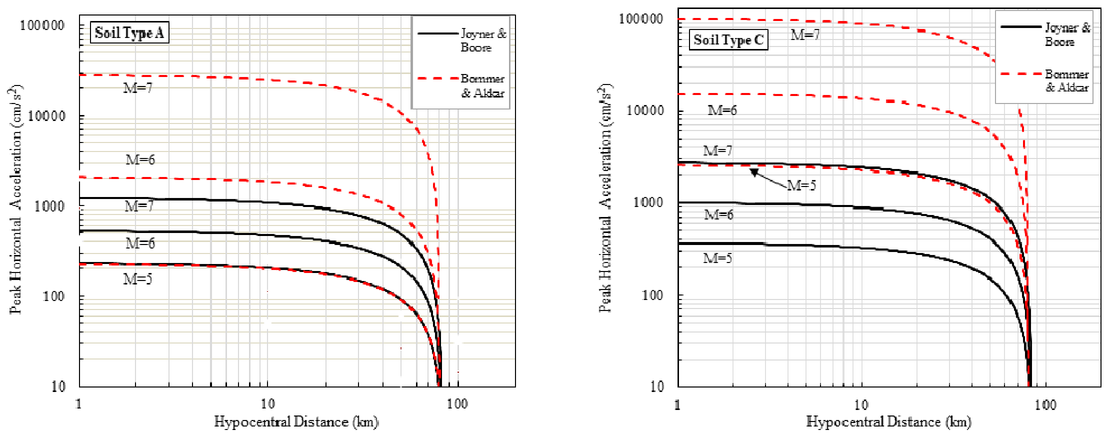
Figure 17 illustrates the comparison between the predicted horizontal component values from equations (15-17) and this study equation (6) for Joyner and Boore (1981) model. This comparison is performed assuming the magnitude of M = 6.0. Following conclusions can be made from this section:

(i) All attenuation curves are very close and have the consistent decay trend. The results obtained from other authors are lower than this study at larger distance. It is because other studies may have simulated results. Simulative recordings need digitalization and different kinds of correction, but the digitalization may introduce long period error which will control the ground motion values at the long period. In the correction of simulative recording the most important step is filtering to remove the long period error. However, filtering will inevitably influence the ground motion at long period, as a result, will underestimate the PGA. The data sets used in this study are direct acceleration recordings (extracted by Seismosignal software), without filtering, which are very proper for study on PGA.

(ii) Within small distances, at 1 km, the predicted values from Cui et al. (2006), Fukushima and Tanaka (1990), Hu and Zhang (1984) are lower than this study. But as the distance increases from 4 km to 70 km, the predicted value from this study decreases than the other research.

(iii) At distances such that 10 km to 100 km, the predicted values from Hu and Zhang (1984) and this study are approximately close.

(iv) If a site is relatively far away (more than 50 km) from the source, predictive peak acceleration from this research is smaller. The design may not be much conservative.



(a) **(b)**

Fig. 16 Comparison of attenuation curves for peak horizontal acceleration by Joyner and Boore (1981) (solid lines) with the 50 percentile curves by Bommer and Akkar (2012) (dashed lines) for rock site (a) and for firm soil site (b)

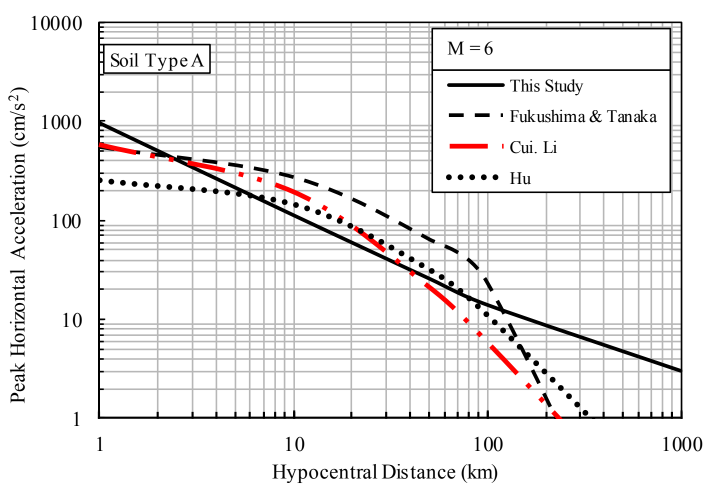
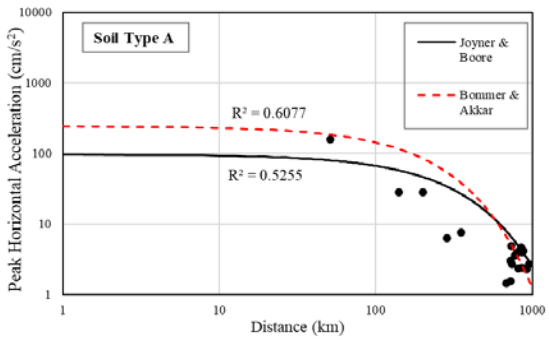
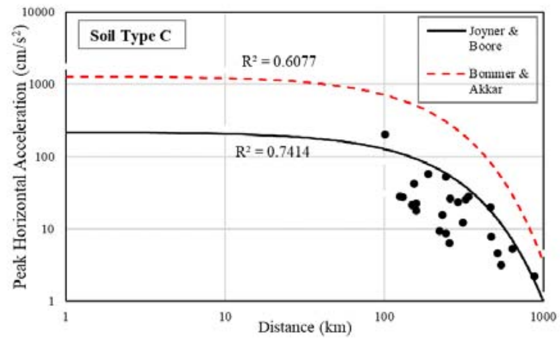


Fig. 17 Comparison of predicted horizontal PGA attenuation curves with respect to distance, M=6.0 for rock site



(a)



(b)

Fig. 18 Comparison of predicted PGA values for a M = 6.0 earthquakes between Joyner and Boore (1981) and Bommer and Akkar (2012) for rock (a) and firm soil sites (b)

Figure 18 shows comparison of predicted PGA values for magnitude 6 earthquake using Joyner and Boore (1981) (equations 6 and 10) and Bommer and Akkar (2012) (equations 8 and 12) GMPEs at various distances for rock as well as firm soil sites. From this Fig. 18, it can be stated that rock site data fits relatively well with Bommer and Akkar (2012) GMPE whereas firm soil site data fits well with Joyner and Boore (1981) GMPE.

4 Conclusions

This study deals with the data collected from North-East Indian region and Bangladesh to derive the ground motion attenuation relationships. The predicted equations are expressed in terms of PGA, PGV, ARS and VRS for both horizontal and vertical direction. In this study, predicted attenuation models are represented with respect to hypocentral distance and magnitude. These results are consistent with the data from other authors having relatively low standard deviation. This study states that, the predictive attenuation values for firm soil sites are larger than those of rock sites under the same conditions for a given earthquake event. Rock sites data fit relatively well with Bommer and Akkar (2012) model whereas firm soil sites data fit satisfactorily with Joyner and Boore (1981) model. The amplification effect of soil is demonstrated in this research. Attenuation curves are magnitude-independent, indicating the magnitude will not change the shapes of the curves. Adding to it, residuals are distributed approximately log-normally. There is no distance and magnitude dependence of residuals for rock or firm soil sites for both models. Furthermore, the curves for predicted peak acceleration, are decaying with distance almost linearly in the proper coordinate scales. However, the predictive equations are sometimes governed by the hypocentral distance. This study considers hypocentral distance instead of the station-to-fault distance. This might be the a shortcoming inducing scattered data points in the models. Another limitation of this research is, it does not incorporate any physical model and thus not permit extrapolation beyond the range of obtained dataset. However, when the strong ground motion data over the entire observed area becomes plentiful, this limitation will become less critical. For better interpretation of earthquakes data more observation stations need to be established for obtaining high quality seismic data. The comparison of this study with other literatures done by authors' shows consistency of the obtained results.

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PART-V

PEOPLE'S AWARENESS, KNOWLEDGE AND PERCEPTION INFLUENCING EARTHQUAKE VULNERABILITY OF A COMMUNITY: A STUDY ON WARD NO. 14, MYMENSINGH MUNICIPALITY, BANGLADESH

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1 Introduction

Earthquake is considered as one of the most deadly natural hazards (Choudhury et al. 2016; Jimee et al. 2012). In recent years, the world has witnessed devastating nature of earthquakes destroying major cities and large-scale havoc in the surrounding environ- ment (Choudhury et al. 2016; Goda et al. 2015). Apart from casualties, it results in exten- sive damage of physical and social infrastructures, disruption of life-sustaining facilities, destruction of economic structure, etc. (ADPC 2002; Shinozuka et al. 1998; Alam et al. 2008). Studies in different countries over the years conclude that such impact of earthquake varies greatly in different countries and even in different localities in a country despite being exposed to similar intensity earthquake (Brouwer et al. 2007; Gallopín 2006; Smit and Wandel 2006). The most significant reason behind such difference is the variation in vulnerability of different community. Hence, it can be said that although inhabitants of hazard prone areas are at higher risk due to their potential exposure, their vulnerability may vary greatly for their complex contexts (Cutter et al. 2003; Morrow 1999; Tapsell et al. 2010). So, for effective disaster risk reduction and management as well as building long□ term resilience against future shocks, understanding of the root causes of vulnerability is vital (Calgaro and Lloyd 2008). The vulnerability of different areas is guided by disparity in rapid urbanization, population growth, migration and unplanned development (CDMP 2014; Flanagan et al. 2011; Singh et al. 2014). In addition to these factors, the complex contexts of local people are also considered very important, which varies significantly from community to community (Morrow 1999; Murphy 2007; Paton and Johnston 2001). These complex contexts include but not limited to personal contexts (age, gender, educa- tional qualification, economic condition, asset ownership status, race, ethnicity, etc.), social capital (household relation, social network, duration of stay in the locality, etc.), power structure, and people's awareness, knowledge and perception about the risk (hazard and vulnerability), etc. (Dynes 2002; Mechanic and Tanner 2007; Morrow 1999; Moser 1998; Murphy 2007; Shi et al. 2018). All these contexts as a whole give rise to vulnerability (Cutler et al. 2018; Flanagan et al. 2011; Gallopín 2006; Rufat et al. 2015; Singh et al. 2014; Tapsell et al. 2010).

At any extent of disaster, local people in the community are the one who suffer most and they are in the frontline to respond the disastrous condition. Due to unpredict- able nature in the event of an earthquake, predicting and mitigating the exposure of the people to the hazard is beyond control. But, the vulnerability of the community can be addressed through understanding their complex contexts leading to the vulner- ability. Moreover, the community people can be integrated in the process of disaster management. This should include the coping and survival strategies to face or respond to the circumstances immediately after an earthquake before the appearance of addi- tional help (Habiba and Shaw 2012; Habiba et al. 2013). Utilizing local resources, capabilities and knowledge also reduce the cost of disaster risk reduction dramatically (Maskrey 2011; Yodmani 2001). In the process of reaching consensus and achieving acceptability, their involvement is essential (Bendimerad 2003). Thus, at present, dis- aster risk reduction and management is inclining more and more to community-based approaches (Allen 2006). Community-based disaster management (CBDM) is consid- ered a more effective tool for disaster management nowadays in this regard (Maskrey 2011; Rahman et al. 2018a, b, c; Yodmani 2001). CBDM is a bottom-up disaster man- agement approach where community people play the central role to assess their own vulnerability to hazards, and develop strategies and resources necessary to manage the vulnerability accordingly (prevention, mitigation, adoption, coping, preparedness, response, rescue, relief and recovery) utilizing their own physical and social resources (Pandey and Okazaki 2005; Shaw and Okazaki 2004). Effective and efficient adoption and implementation of CBDM greatly depends on the active participation of commu- nity people. Such participation again depends on the complex contexts of local people which again varies from community to community (Bendimerad 2003).

Among different complex contexts mentioned earlier, people's awareness, knowl- edge and perception of risk is most significant because these conditions indicate their capacity to realize as well as utilize their own social, physical and psychological assets, thereby leading to effective participation in and implementation of CBDM (Bankoff 2013; Paton and Johnston 2001). Hence, Ainuddin and Routray (2012) and Paton and Johnston (2001) concluded that vulnerability of a community depends on awareness, knowledge as well as perception. Though these factors are interdependent, there is a distinction among the degree of awareness, knowledge and perception. This distinction may give rise to their vulnerability. Again other complex contexts of local community people like personal contexts and social capital have significant influence on hazard awareness, knowledge and perception of people (Ainuddin and Routray 2012; Alam 2016; Anderson-Berry 2003; O'Sullivan et al. 2013; Paton et al. 2001; Roder et al. 2016).

Several studies have been carried out on hazard awareness, knowledge and percep- tion of people. Table 1 shows summary of the literature on hazard awareness, knowl- edge and perception with respect to hazard(s) considered, country of study and major findings or focus. From the table, it can be observed that these studies focused on either of the awareness, knowledge and perception, or on combination of awareness and perception, awareness and knowledge, knowledge and perception, etc. Again, these researches focused on influence of these factors on different aspects of vulnerability. But none of these studies focused on understanding the distinction among people's hazard awareness, knowledge and perception, how other complex contexts of people may influence these factors, and how they influence on the vulnerability of a community as a whole.

Bangladesh lies in a moderately seismic-prone region signifying potential exposure to earthquake (Akhter 2010; BNBC 1993; BNBC draft 2019). It is positioned at the junction of three plates which results in the generation of active faults (Akhter 2010). Historical evidence points to major earthquakes within or close to the country (Bilham et al. 2001; Islam et al. 2011; Sarker et al. 2010). Several researches have been carried out in Bangladesh on earthquake. These studies mainly focus on hazard assessment (Carlton et al. 2018; Islam et al. 2011; Sarker et al. 2010), vulnerability assessment (Das et al. 2018; Jahan et al. 2011; Mazumder et al. 2018; Rahman et al. 2018a, b, c; Rahman et al. 2015), risk assessment (Boni et al. 2017), damage assessment (Ansary et al. 2000), management (Biswas et al. 2018; Rahman et al. 2018a, b, c), etc. Very few studies focused on hazard awareness, knowledge and perception in Bangladesh (Table 1).

This study aims to explore different dimensions of people's awareness, knowledge and perception influencing vulnerability of a community to earthquake. In this regard, the objectives of this research are firstly to understand the existing condition and dis- tinction among people's earthquake awareness, knowledge and their actualized percep- tion in relation to their personal contexts and social capital in a community in Bangla- desh and secondly to explore how such distinction influences earthquake vulnerability of the community.

1.1 Vulnerability

Vulnerability has been defined in different studies differently. Birkmann et al. (2013) sum- marized the definition based on review of different studies, where vulnerability is defined as "… the propensity of exposed elements such as physical or capital assets, as well as human being and their livelihoods, to experience harm and suffer damage and loss when impacted by single or compound hazard events…". In this research, a framework has been proposed to frame vulnerability, risk and societal response called MOVE framework (Methods for the Improvement of Vulnerability Assessment in Europe). Though the frame- work is developed based on European context, the concept of vulnerability is universal and is applicable in other countries with consideration and adjustment on the basis of local con- texts. According to this framework, vulnerability depends on hazard (potential occurrence of natural, socio-natural or anthropogenic event), exposure (elements at risk), susceptibility or fragility (conditions of elements at risk leading to suffer harm), resilience or response capacity (existing capacity) and adaptive capacity (capacity to improve in future). All these components lead to increase or reduce vulnerability of a community.

Table 1 Summary of the literature on hazard awareness, knowledge and perception

Focus	Hazard(s) considered	Country of study	Major focus or findings
Hazard awareness	Overall	Canada	O'Sullivan et al. (2013) identified situational awareness as an important factor to foster adaptive responses to disasters in Canada through community-based participatory approach (focus group discussion)
	Flood Drought	Indonesia India	Isa et al. (2018) and Jülich (2018) concluded in their researches that among other factors people's awareness subject to past disasters greatly influence resilience against natural hazards at local level
Hazard knowledge	Overall	Papua New Guinea, and Philippines	Kelman et al. (2012) showed potential of indigenous knowledge for contributing in disaster risk reduction
	Earthquake	Iran	Taghizadeh et al. (2012) studied knowledge, attitude and practice of Tehran's inhabitants for earthquake and related determinants
	Coastal disasters	Germany, UK, Italy, Portugal, Sweden, France, Bulgaria, and Spain	Barquet and Cumiskey (2018) addressed the impact of integrating scientific knowledge with stakeholders' knowledge to implement different disaster risk reduction measures
Hazard perception	Overall	Australia	Morrissey and Reser (2007) addressed psychological perspective of individual and community about natural disasters in Australia, which includes perceptions, responses, preparedness and planning
		USA	Flint and Luloff (2005) advanced a community-based approach incorporating vulnerability, risk perception, and the capacity for local action in a framework for understanding community response to risk
			Cutter et al. (2008) and Paton et al. (2001) described community risk perception as one of the factors in predicting community resilience to natural disasters
	Earthquake	Bangladesh	Rahman et al. (2018a, b, c) analyzed the factors influencing the perceptions of and vulnerability to an earthquake disaster in Dhaka, Bangladesh
			Paul and Bhuiyan (2010) examined seismic risk perception among residents of Dhaka City and investigate their levels of earthquake preparedness

Table 1 (continued)

Focus	Hazard(s) considered	Country of study	Major focus or findings
	Flood	Bangladesh	Paul and Hossain (2013) studied people's perception about flood disaster management in Bangladesh
			Rahman (1996) studied peoples' perception and response to flooding in Bangladesh
	Landslide	Italy	Pedoth et al. (2018) considered risk perception as awareness of risks associated with the area people live in, knowledge about past hazard events or personal experience of them, and perceived probability of future events
	Flood and landslide	Taiwan	Ho et al. (2008) examined influence of type of disaster (flood or landslide) and victim characteristics on risk perception
	Cyclone	Bangladesh	Islam et al. (2004) studied perception of coastal people in Bangladesh about their response to broadcast media for cyclone warning and disaster mitigation
	Coastal disasters	USA	Goidel et al. (2019) studied perception of local residents regarding the resilience of their local communities in USA
			Cope et al. (2018) and Cutler et al. (2018) investigated the effect of different individual and geographic level social, economic and biophysical influences on perceived household preparedness and coping capacity for disaster
	Climate change and induced disasters	Ghana	Samaddar et al. (2018) explored the relationship between trust, risk perception, and the acceptance of preventive actions in Northern Ghana
		Pakistan	Bott (2016) analyzed perception of stakeholders about the nexus between environmental risks and migration, and its influence on adaptation outcomes in Pakistan
	Heat wave	USA	Cope et al. (2018) and Cutler et al. (2018) investigated the effect of different individual and geographic level social, economic and biophysical influences on perceived household preparedness and coping capacity for disaster

Table 1 (continued)

Focus	Hazard(s) considered	Country of study	Major focus or findings
	Volcano	New Zealand	Cutter et al. (2008) and Paton et al. (2001) described community risk perception as one of the factors in predicting community resilience to natural disasters
	Hurricane	USA	Eisenman et al. (2007) studied the experience of Hurricane Katrina evacuees to better understand factors influencing evacuation decisions in impoverished, mainly minority communities that were most severely affected by the disaster. The authors found that perception of people greatly influence evacuation decisions
Hazard awareness and perception	Earthquake	Pakistan	Ainuddin and Routray (2012) aimed to propose a community resilience framework for an earthquake prone area in Baluchistan based on the findings of an extensive research carried out on vulnerability and resilience assessment. In this framework, the authors identified that risk awareness and perception can affect the community vulnerability to a considerable level. The results also reveal that risk perception is basically subjective and strongly influenced by socioeconomic characteristics (age, education, and income), awareness and understanding, coping and preventive mechanism with resilience capacity
		Japan	Shaw et al. (2004) studied impact of earthquake experience and education on awareness and perception
	Drought	Bangladesh	Habiba et al. (2012) studied farmer's perception and adaptation practices to cope with drought in Bangladesh.
Hazard awareness and knowledge	Overall	Australia	Teo et al. (2018) carried out comparative study of low socioeconomic (LSE) and non-LSE population groups to identify key disaster knowledge sources and how it shapes levels of disaster awareness
Hazard knowledge and perception	Earthquake	Australia	Hurnen and McClure (1997) studied effect of increased earthquake knowledge on perceived preventability of earthquake damage
		Israel	Soffer et al. (2011) determined the relationship between demographic and educational parameters in terms of the perceived threat, perceived coping, knowledge and mitigation of earthquakes in Israel

1.2 Disaster awareness, knowledge and perception influencing vulnerability

There are many studies on people's hazard awareness, knowledge and perception which are summarized in Table 1. Nonetheless, none of these literature has compared these concepts. Table 2 shows the indicators which have been considered in different literature to under- stand people's hazard awareness, knowledge and perception accordingly. From the table, it can be observed that the indicators of awareness are somewhat overlapping either with knowledge or perception. Such overlapping indicates that the interdependence in the nature of the concepts of awareness, knowledge and perception. But the fact is that these three concepts though are interdependent, do not reflect same concept.

Hazard awareness indicates whether people are aware of the hazard and corresponding risk or not. Among different awareness indicators, claim of the people about their hazard awareness is important because they are considered to be more willing to become informed through actively seeking the knowledge (Anderson-Berry 2003; Samaddar et al. 2015). Awareness influences people to develop adaptive and coping capacity utilizing their own physical and psychological assets and thereby leads to community resilience at the local levels (Ainuddin and Routray 2012; Bankoff 2013; Habiba et al. 2012; Isa et al. 2018; Jül- ich 2018; O'Sullivan et al. 2013). It is a critical factor to efficiently implement mitigation and disaster preparedness measures (Anderson-Berry 2003; Bendimerad 2003; Cumiskey et al. 2018; Shaw et al. 2004; Teo et al. 2018). It maximizes empowerment and reduces the potential for feelings of helplessness and vulnerability (Back et al. 2009; Bendime- rad 2003). Thereby, awareness enhances appropriate response (Anderson-Berry 2003; O'Sullivan et al. 2013; Teo et al. 2018). These facts lower the community vulnerability to a considerable level (Ainuddin and Routray 2012; Isa et al. 2018).

Such awareness does not necessarily mean possession of scientific hazard knowledge (Kruse et al. 2018). People may be aware of hazard but may not have proper knowledge. It is evident from the study of (Anderson-Berry 2003) that "…Campaigns were effective in raising community awareness of storm surge, although, it did not generally improve residents understanding of this hazard…". From Table 2, it can be observed that explor- ing individual's knowledge about natural hazards has been considered important because such knowledge increases the ability to assess risks (Soffer et al. 2011). In contrary, lay- person knowledge leads to poor judgments and decisions (Flint and Luloff 2005). Source of knowledge is important because if an individual trust the knowledge source, then the acceptability of risk reduction measures increases (Samaddar et al. 2018). Again, direct experience of past disaster increases hazard knowledge (Alam 2016). For infrequent disas- ters like earthquake, most people may not have direct experience in their lifetimes. There- fore, researches considering this factor may have to rely on experience of small disasters or different disasters

(Becker et al. 2017). Appropriate hazard knowledge motivates people to participate in different training programs effectively (Becker et al. 2017; Roder et al. 2016). Thus, hazard knowledge enhances people's coping capacity as well as their willingness to take risk mitigation and preparedness approaches (Alam 2016; Anderson-Berry 2003; Becker et al. 2017; Roder et al. 2016; Soffer et al. 2011; Taghizadeh et al. 2012). Conse- quently, they are more likely to response appropriately, take part in disaster management activities and thereby reduce casualty (Roder et al. 2016; Soffer et al. 2011).

Based on the awareness and hazard knowledge, people make their perception (Ainud- din and Routray 2012; Bankoff 2013; Becker et al. 2017; Kruse et al. 2018; Pedoth et al. 2018; Roder et al. 2016). People having perfect understanding about the hazard and its potential impacts and risks at the local and community levels are more likely to have clear perception (Ainuddin and Routray 2012). People remembering past disaster experience are more likely to perceive an event more probable (Alam 2016; Paton et al. 2001; Roder et al. 2016). Such perception may or may not be based on reality. In contrary, having appro- priate awareness and adequate knowledge may not lead to appropriate adaptation, prepar- edness and response behavior, because such behavior depends on the perception people develop through processing and internalizing the knowledge (Anderson-Berry 2003; Bott 2016). According to (Anderson-Berry 2003) "…If perceived risk is a true reflection of the actual risk associated with a particular hazard, then mitigation strategies, warning com- pliance and response preparedness are likely to be appropriate and vulnerability can be minimized…". Therefore, risk perception is considered important as well as a challenge to make the risk reduction initiatives successful (Ainuddin and Routray 2012; Bendimerad 2003; Ho et al. 2008; Paton et al. 2001). In this regard, several studies have considered different attributes to study perception of local people about hazard, which are shown in Table 2.

Suitable risk perception leads to effective adoption of mitigation, coping, adaptation and preparedness actions (Ainuddin and Routray 2012; Alam 2016; Anderson-Berry 2003; Bott 2016; Habiba et al. 2012; Ho et al. 2008; Morrissey and Reser 2007; Paul and Bhui- yan 2010; Samaddar et al. 2018). Having appropriate risk perception may not always lead to appropriate response, because appropriate response depends on participation in training, drill and practices (Goidel et al. 2019). But training programs are more successful if peo- ple perceive the importance and need (Anderson-Berry 2003). Thus, realistic perception improves actual behavior and thereby ensures appropriate response (Ainuddin and Routray 2012; Anderson-Berry 2003). Again, participation of local people in the local disaster management process for effective and efficient adoption and implementation of CBDM greatly depends on their perception (Bendimerad 2003). Community people can join in such process as a member in formal local disaster management committee for decision making purpose at the event of an emergency (Fernandez et al. 2006; Mathbor 2007; Wang and Wan Wart 2007). They can also participate in various disaster management activities during pre- and post-disaster periods as volunteers (Alexander 2010; Brennan et al. 2005; Fernandez et al. 2006; Mathbor 2007; Twigg and Mosel 2017). It depends on their will- ingness and perception about the importance of such participation (Fernandez et al. 2006;

Samaddar et al. 2015; Van Krieken et al. 2017; Wang and Wan Wart 2007). As a whole, appropriate awareness, knowledge and perception about hazard leads to reduced vulner- ability and vice versa (Paton and Johnston 2001; Paton et al. 2001; Rufat et al. 2015).

1.3 Personal contexts and social capital influencing vulnerability

Personal contexts and social capital has significant influence on community vulnerability (Cutler et al. 2018; Flanagan et al. 2011; Gallopín 2006; Rufat et al. 2015; Singh et al. 2014; Tapsell et al. 2010). Personal contexts of people in a community include gender, age, educational qualification, occupation, economic condition, asset ownership status, race, ethnicity, etc. Women are more vulnerable to disasters, because they cannot respond to disaster immediately and effectively due to their responsibilities toward other members of the family (Rahman 1996; Teo et al. 2018). Children and older people are most vulnerable because they face difficulties to response immediately after a disaster due to their mobility and health issues (Ainuddin and Routray 2012; Back et al. 2009; Brunkard et al. 2008; Cut- ler et al. 2018; Doocy et al. 2013; Freeman et al. 2015; Isa et al. 2018; Jonkman et al. 2009; McGuire et al. 2007; Rahman 1996; Taghizadeh et al. 2012; Tapsell et al. 2002; Wood et al. 2010). Again, young people can greatly contribute to enhance community resilience and risk management capacity (Back et al. 2009; Freeman et al. 2015; Haynes and Tan- ner2015). Some training programs are targeted for young people at present considering the fact that it is easier to disseminate knowledge to households through them (Bendime- rad 2003; Freeman et al. 2015; Haynes and Tanner 2015). They also have wide scope to be engaged in disaster management activities through proper training (Back et al. 2009; Bendimerad 2003; Freeman et al. 2015; Haynes and Tanner 2015; Teo et al. 2018). But, decisions regarding children and young people are taken by their parents who sometimes do not acknowledge their capacities as social actors to contribute to family decision making and to demonstrate empathy for others (Freeman et al. 2015). People with higher educa- tion can search, obtain and understand the scientific complexities of hazards more easily (Anderson-Berry 2003; Ho et al. 2008). They also have more adaptive capacity and more tend to be prepared (Isa et al. 2018; Taghizadeh et al. 2012). Thereby, educated people can be more easily encouraged to participate in CBDM (Adhikari et al. 2016). Tenants stay in an area for temporary basis and therefore lack the sense of responsibility, so they are less worried about vulnerability of the area compared to owners who would stay in the area lifelong. This also leads to increased community vulnerability (Ainuddin and Routray 2012; Morrow 1999; Rahman 1996; Tapsell et al. 2002; Wood et al. 2010).

Social capital includes household relation, social interaction, duration of stay in the locality, etc., which influence capacity of individuals and community for disaster man- agement (Ainuddin and Routray 2012; Cope et al. 2018; Dynes 2002; Mechanic and Tanner 2007; Morrow 1999; Moser 1998; Murphy 2007; Shi et al. 2018; Tapsell et al. 2010). People living in a locality for longer duration (either in dwelling or in the area generally) are assumed to have strong sense of belonging to the place and community bonding, as well as better knowledge about the area (Anderson-Berry 2003; Goidel et al. 2019; Roder et al. 2016; Rufat et al. 2015; Taghizadeh et al. 2012; Teo et al. 2018). Thereby, based on common interests and experiences, people in a community form relationship and lead to increased interaction (Anderson-Berry 2003). Enhancement of social capital by improving social interaction leads to increasing preparedness, adaptive and coping capacity, and resilience to hazards (Cope et al. 2018; Murphy 2007; Paton et al. 2001; Pedoth et al. 2018; Rufat et al. 2015). Through social interaction, people can share information and offer and receive support in warning period or at the event of a disaster (Anderson-Berry 2003). Strong social bond absorbs the stress and thereby helps people to respond appropriately (Shaw et al. 2004; Smit and Wandel 2006). Community having strong bond can also recover fast supported by collective decision making (Murphy 2007). Thus, social bond effectively reduces individual and household vulnerability (Anderson-Berry 2003).

2 Methodology of the research

2.1 Study area selection

Mymensingh municipality is situated in Mymensingh district of Dhaka division on the west bank of Old Brahmaputra River which lies in high earthquake prone zone in Bangla- desh (BBS 2011; BNBC 1993; BNBC draft 2019; Sarker et al. 2010). From the history of earthquake damage in the study area, it is evident that the city was significantly damaged by the Great Indian Earthquake of June 12, 1897, with 8.1 magnitude (Sarker et al. 2010). The earthquake also changed the main flow of the Brahmaputra River shifting about 62 miles (100 km) west which co-sided west of the greater Mymensingh region (Goswami and Das 2002). Considering the potential exposure of Mymensingh municipality to earth- quake, this municipality has been considered for this research. For the purpose of this study, one among the 21 wards of the municipality (ward is the smallest administrative unit in a municipality in Bangladesh) has been selected as the study area, which is Ward no. 14. It has been considered as a case study in this research considering two points: Firstly, this research aims to study at local level considering one smallest administrative unit at a time, and secondly, the study area will represent the other wards of Mymensingh municipality. Figure 1 shows location of the study area.

Table 2 Indicators considered in different literature to understand people's hazard awareness, knowledge and perception

Components	Indicators	References
Awareness	Acknowledgment of the awareness of hazard	Gallopín (2006), Habiba et al. (2012), Isa et al. (2018)
	Acknowledgment of the risk in the area	Shaw et al. (2004)
	Awareness about history of past disasters	Jülich (2018), O'Sullivan et al. (2013)
	Awareness about preparedness and coping measures	Ainuddin and Routray (2012)
	Awareness about adaptation techniques	Habiba et al. (2012), Teo et al. (2018)
	Awareness about hazard resilient design of houses and important facilities	Ainuddin and Routray (2012)
Knowledge	Knowledge and understanding about the hazard	Alam (2016), Anderson-Berry (2003), Eisenman et al. (2007)
	Source of knowledge and understanding about the hazard	Anderson-Berry (2003), Eisenman et al. (2007), Hurnen and McClure (1997), Jimee et al. (2012), Roder et al. (2016), Teo et al. (2018)
	Past experience or knowledge about historical disasters	Alam (2016), Anderson-Berry (2003), Eisenman et al. (2007), Pedoth et al. (2018), Roder et al. (2016), Shaw et al. (2004), Taghizadeh et al. (2012)
	Response during past disaster experience	Shaw et al. (2004)
	Knowledge about preparedness measures	Alam (2016), Taghizadeh et al. (2012)
	Knowledge about possible immediate response	Alam (2016), Anderson-Berry (2003), Eisenman et al. (2007), Roder et al. (2016), Soffer et al. (2011), Teo et al. (2018)
	Knowledge about disaster management organizations at the community	Alam (2016)
Perception	Perception about risk of the area	Ainuddin and Routray (2012), Alam (2016), Anderson-Berry (2003), Habiba et al. (2012), Ho et al. (2008), Paul and Bhuiyan (2010), Pedoth et al. (2018), Rahman (1996), Roder et al. (2016), Soffer et al. (2011)
	Reasons behind the potential risk of the area	Anderson-Berry (2003), Habiba et al. (2012), Roder et al. (2016)
	Perception about risk of their building	Ainuddin and Routray (2012), Roder et al. (2016)
	Reasons behind the potential risk of their building	Anderson-Berry (2003), Roder et al. (2016)
	Perception about preparedness	Goidel et al. (2019), Paul and Bhuiyan (2010), Rahman (1996), Roder et al. (2016), Soffer et al. (2011)
	Perception about issues and problems associated with preparedness	Ainuddin and Routray (2012), Anderson-Berry (2003)
	Perception about immediate response	Rahman (1996)
	Perception about effectiveness of disaster management in the area	Paul and Hossain (2013)
	Willingness to take action to reduce risk (spend for retrofitting)	Shaw et al. (2004)

The study area covers an area of 0.54 square kilometer with 12,142 population and 22,485 per square kilometer population density. The ratio of male and female population is 47.06 percent and 52.94 percent, respectively. The total number of households in the area is 2194, and average family size is 4.5 (BBS 2011). The primary occupations of people in the study area are service (80.6%), agriculture (11.7%) and industry (7.6%). Major land use of the study area includes residential, health facility and mixed use (BBS 2011). There are 1611 buildings consisting of 735 pucca structures (URM and RCC buildings) and rest semi-pucca, kutcha and under-construction buildings (Field survey 2017).

2.2 Data collection

2.2.1 Secondary data collection

For the purpose of this study, the GIS database of Ward no. 14 of Mymensingh Municipal- ity was collected from Urban Development Directorate (UDD) (UDD 2015). The GIS data- base includes area boundary, land use, buildings and road network of the area. The Com- munity Series of Statistics of the study area (2011) was collected from Bangladesh Bureau of Statistics (BBS) (BBS 2011). These data were collected to understand basic profile of the study area and to consider as the basis for primary data collection.

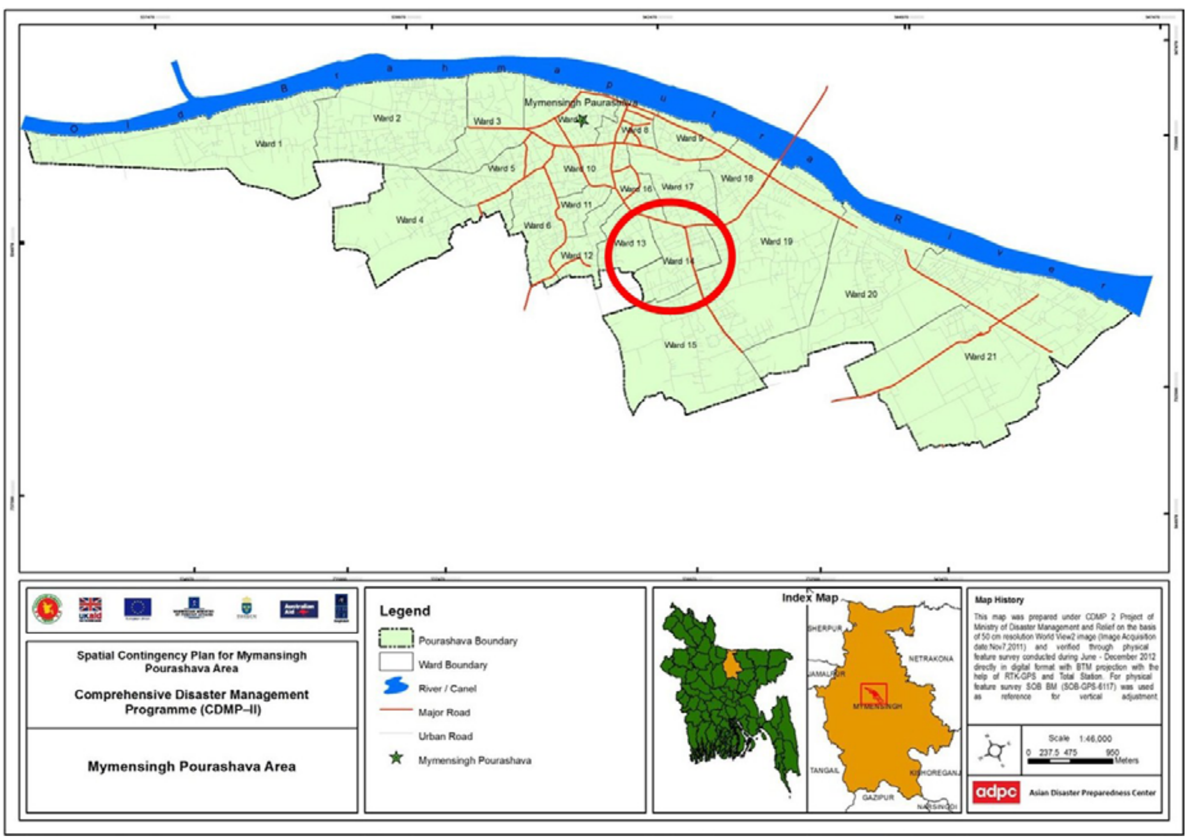

Fig. 1 Location of the study area Ward no. 14, Mymensingh Municipality, Bangladesh. *Source*: Adapted from UDD (2015)

2.2.2 Primary data collection

It is already known that the study area is at risk of exposure to earthquake. But, the earthquake vulnerability of an area may differ due difference in susceptibility (or fragil- ity) of its different elements at risk. In case of earthquake, such variation may occur due to difference in soil condition and different physical features of buildings in the area. To comprehend physical earthquake vulnerability of the study area, geological data were collected through borehole test at twelve locations and micro-tremor test at eight loca- tions to understand liquefaction susceptibility of the soil in the study area which may happen due to an earthquake. To know about earthquake vulnerability of the buildings in the study area, Rapid Visual Screening (RVS) Method was used to collect data on condition of 735 buildings in the study area including all pucca (URM and RCC) struc- tures (FEMA 154 2002).

For the purpose of the study, face-to-face household questionnaire survey was con- ducted in the study area. The sample size for the questionnaire survey was 700 house- holds including owners (430 households) and tenants (270 households). Separate build- ings were selected for owners and tenants, so that 700 pucca buildings among 735 could be covered. Here, sample size for owners is about 1.6 times of that of tenants. So while selecting sample, two buildings in a row were considered for owner's household questionnaire survey and then one for tenant's household questionnaire survey. Thus, repeating this process, 700 household samples were selected through systematic random sample selection method. For the purpose of sample selection in this method, the GIS database of buildings in the study area was utilized. This survey was conducted parallel to the building vulnerability assessment survey. The survey team consisted of three members—two from the locality and one from BUET to. Thus, consistency and reliabil- ity of the data was ensured through integration of local people in the surveying process.

For household questionnaire survey, firstly a draft questionnaire was prepared based on review of literature on disaster awareness, knowledge and perception. The question- naire firstly included questions to collect basic demographic and economic data of all the members of the households surveyed. The variables for this purpose included gender, age, educational qualification, occupation and disability. For the purpose of this research, the questionnaire consisted of five sections: awareness, knowledge, perception, personal con- text and social capital. Table 3 shows the factors considered under each section with corre- sponding questions and type of response collected. After preparation of draft questionnaire, pilot survey of five households in the study area was conducted in April, 2017. Based on the pilot survey, the questionnaire was finalized. The final household questionnaire survey was conducted in the May–June 2017. Thereby, basic demographic and economic data of all the members of 700 households were collected consisting of 2630 persons, and research related data were collected from the respondents considering that the 700 respondents represent 700 families, respectively.

2.3 Data preparation and analysis

To understand actual vulnerability of the study area, firstly the physical earthquake vulner- ability profile was developed. It included assessment of liquefaction susceptibility in the study area using the collected geological data through borehole and micro-tremor tests. Earthquake vulnerability of all the buildings (735 pucca structures) in the study area was assessed based on seismic design criteria through RVS method on the basis of collected building condition data. Moreover, road network in the area was analyzed based on the col- lected GIS data (road shape file) to understand whether the roads are suitable for disaster management after an earthquake. Here, the assumption is that higher proportion of roads with sufficient road width (minimum 12 ft for movement of both way traffic) is suitable for response, rescue and evacuation after an earthquake.

The database of all the collected household questionnaire survey data was prepared in statistical analysis software SPSS 21. After that, the data were analyzed using MS-Excel 2013 and SPSS 21. Firstly, the social profile of the households in the study area was devel- oped based on collected data of 700 sample households consisting of 2630 persons. The analysis for the purpose of the research was done based on response of 700 respondents considering that these respondents represent their households. To understand relation among different variables, descriptive statistics and contingency tables or cross-tabulation to display the bivariate frequency distribution of variables were analyzed. To analyze asso- ciation (strengths and weaknesses) of these relations, Goodman–Kruskal's gamma (G) coefficient was computed and interpreted accordingly.

In this research, impact on vulnerability was analyzed utilizing the MOVE framework proposed by Birkmann et al. (2013), because this framework analyses vulnerability, risk as well as societal response which is also the basis of analysis in this research. Accord- ing to this framework, vulnerability depends on hazard (potential occurrence of natural, socio-natural or anthropogenic event), exposure (elements at risk), susceptibility or fragil- ity (conditions of elements at risk leading to suffer harm), resilience or response capacity (existing capacity) and adaptive capacity (capacity to improve in future). Here, the general hazard and social profile of the area portray the exposure and susceptibility or fragility.

On the other hand, difference among awareness, knowledge and perception influenced by personal contexts and social capital portray resilience or response capacity and adaptive capacity of local people.

3 Results and discussion

3.1 Actual physical earthquake vulnerability profile of the study area

It is evident from the review of historical earthquake analysis of Mymensingh municipality that the area is at high vulnerability for exposure to potential earthquake. However, from the study of geological data in the study area, it has been found that the soil in area is not susceptible to liquefaction. Again, from the earthquake vulnerability assessment of the buildings in the study area based on seismic design criteria through RVS method, it has been found that about 37% buildings are vulnerable to earthquake. Thus, these buildings are susceptible to damage if exposed to an earthquake. Among the total building stock in the study area, about 58% buildings have been developed before the year 2000. It repre- sents that a significant portion of the area is newly developed. Although road network cov- ers 21.8% of total land area, most of the roads are very narrow in the study area. The width of the roads varies from 1.5 to 12 ft (Field survey 2017). Most of these roads are only accessible through walking, cycle, motorcycle or one-way rickshaw/van due to their width. Only a very few roads including the major thoroughfare (Dhaka-Mymensingh Highway) are accessible for vehicles in both way directions. All these conditions represent that the study area is highly vulnerable for potential earthquake.

3.2 Social profile of the households in study area

The 700 households surveyed in the study area consist of 2630 persons. Table 4 shows overall social profile of these people. Gender distribution of male and female among the population is almost equal. Moreover, about 14% of the people are children (younger than 10 years), about 6% are elderly people (elder than 60 years), and about 0.34% (10 out of 2630 people) are physically disabled. These people are considered as 'vulnerable group' at the occurrence of any disaster and would need assistance for evacuation from the affected areas (Hemingway and Priestley 2006; Lord et al. 2016; McGuire et al. 2007). So special attention will be required for these persons in the study area after an earthquake. Major-ity of the people in the study are young and middle aged (54%). Most of them are liter- ate, with 29% people having education level graduation or above which is much higher in Bangladesh context. One-third of the people is student. These people can be utilized to ensure effective development of awareness, knowledge and perception about earthquake in the study area effectively. They can also implement and directly participate in the CBDM process in the study area successfully with appropriate training.

3.3 Awareness and knowledge about earthquake

Among 700 surveyed respondents, 85% claimed to be aware of earthquake. Table 5 shows the sources from which these respondents could learn about earthquake, the knowledge they possess about earthquake and immediate response, and their past experi- ence of earthquake. From the table, it can be observed that majority of these respondents learned about earthquake from electronic media, such as television, radio, etc. This find- ing is compliant with the findings from other researches (Becker et al. 2017; Eisen- man et al. 2007; Hurnen and McClure 1997; Jimee et al. 2012; Pedoth et al. 2018; Teo et al. 2018). Only 9% respondents have attended earthquake-related program. Thus, it can be said that very few earthquake-related programs were organized in the area where very few respondents participated. On the other hand, 12% respondents learned about earthquake from their neighbors. This finding is consistent with that of Cumiskey et al. (2018); Eisenman et al. (2007); Teo et al. (2018), who concluded that knowledge about hazard is also passed from one person to other through social interaction.

Among the respondents, only about 44% respondents have appropriate (though not scientific) knowledge about earthquake. About 12% respondents think that earthquake is only the movement of buildings, which reflect their lack of knowledge about earth- quake. In case of knowledge about immediate response, from Table 5 it can be observed that about 88% respondents think that they should move to a safe place immediately during an earthquake including moving up to the roof top of a building or getting down from the building, which is not appropriate response. Though about 9% respondents claimed to know about earthquake through attending earthquake-related program, only 5.4% respondents have appropriate knowledge about immediate response, and only 1.9% respondents could respond appropriately during their experience of past earthquake.

Here, worth mentioning is the fact that about 32% respondents panicked and showed no response.

Table 6 shows association of respondents' actual response during past earthquake expe- rience and their knowledge about earthquake and immediate response during an earth- quake. Actual response during past earthquake does not have any significant relation with respondents' knowledge about earthquake ($G = 0.107$, $p > 0.05$) but has weak and significant relation with their knowledge about immediate response during an earthquake ($G = 0.371$, $p < 0.05$). Thus, people's lack of knowledge about appropriate response is reflected by their inappropriate response during past earthquake experience or not remem- bering the event.

In the study area, there is a Ward Disaster Management Committee (WDMC) which is a government committee at ward level for disaster management. When respondents were asked about whether they know about the WDMC in their area, unfortunately about 84% respondents stated that they do not know about it. So there is a lack of communication between the authority and the inhabitants of the area.

3.4 Perception about earthquake

Only 44% respondents perceive their area to be vulnerable to earthquake. Figure 2 shows reasons of earthquake vulnerability of the area in ranked order according to the respond- ents. The respondents mentioned geographic location, unplanned establishment of build- ings and high density of development in the area as prime reasons for vulnerability of their area. Though for the purpose of this research, earthquake vulnerability of the buildings was assessed, the results were not shared with the respondents. In such condition, only 26% respondents perceive the building they are residing into be vulnerable to earthquake. Fig- ure 3 shows reasons of earthquake vulnerability of the buildings in ranked order according to the respondents, and Table 7 shows association of the perception with different factors. Old buildings and defective construction practices have been identified as the most impor- tant reasons for perceiving their building to be vulnerable to earthquake. The perception is strongly and significantly associated with year of construction ($G = 0.468$, $p < 0.05$). The buildings constructed before 1995 are considered as most vulnerable by the respondents compared to newly constructed buildings. Thus, people's perception is compliant with real- ity regarding age of the building. When compared with the perception of the respondents about earthquake vulnerability and the actual earthquake vulnerability (according to RVS) of their building, it has been found that even though 37% buildings in the study area are actually vulnerable to earthquake, only 26% respondents think that their building is vul- nerable for damage due to potential earthquake. Only 10% respondents from vulnerable buildings think that their building is vulnerable. The association is weak and insignificant ($G = 0.017$, $p > 0.05$). When both of the perceptions of respondents about area and building vulnerability to earthquake have been compared, it could be observed that most of the resi- dents (46%) think that neither the area nor their building are vulnerable, with strong and significant association ($G = 0.462$, $p < 0.05$). Such conditions reflect that the residents' lack of clear perception about their earthquake vulnerability.

To reduce earthquake vulnerability of the buildings, retrofitting is necessary which depends on the willingness of the building owner to invest for this purpose. Table 8 shows the comparison of the building owners' willingness to invest for retrofitting their building. About 39 owners perceive that their buildings are vulnerable, but they are not willing to invest money to strengthen their buildings. It can also be seen that 162 own- ers who do not perceive their building vulnerability are also unwilling to invest money. Again, 70 owners whose buildings are actually vulnerable are not willing to invest for reducing vulnerability of their buildings. On the other hand, 152 owners whose build- ings are actually not vulnerable are willing to invest money for strengthening buildings if necessary. Thus, perception or actual building vulnerability do not reflect owners' willingness to invest for retrofitting their building ($G = 0.124$, $p > 0.05$ and $G = 0.069$, $p > 0.05$, respectively).

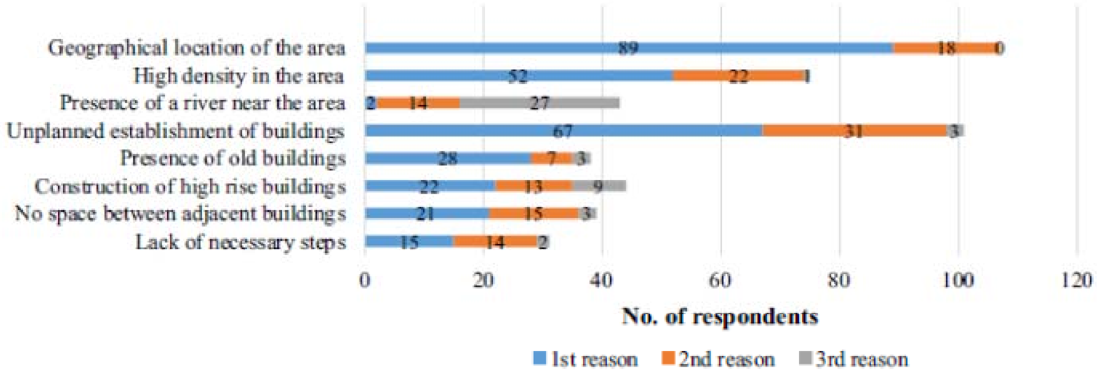

Fig. 2 Ranked reasons of earthquake vulnerability of the area according to the respondents. *Data Source*: Field survey (2017)

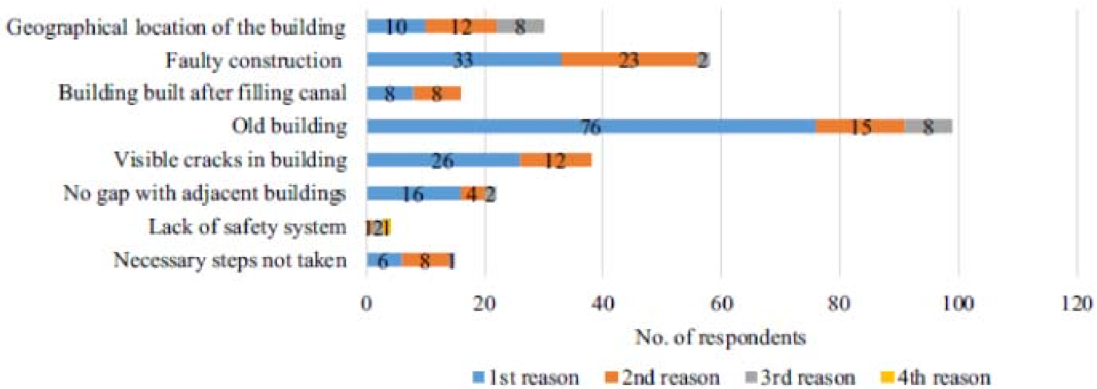

Fig. 3 Ranked reasons of earthquake vulnerability of the buildings according to the respondents. *Data Source*: Field survey (2017)

About 67% of the respondents expressed their willingness to get involved in the dis- aster management process as volunteer. Table 9 shows the distribution of the mentioned duties ranked by the respondents willing to get involved in the disaster management pro- cess as volunteer. Most respondents have given priority to rescue mission and showed interest to participate in this operation. According to their preference, these willing peo- ple can be utilized for implementation of CBDM in the study area. Table 10 shows the association of the respondents' willingness to participate in the disaster management process in the study area as volunteer with their perception about earthquake vulner- ability of the area, where weak but significant association can be observed ($G = 0.274$, $p < 0.05$). Thus, their willingness to participate in CBDM is influenced by their perception about the earthquake vulnerability of their area, which reflect the influence of their perception on their decision.

3.5 Distinction among awareness, knowledge and perception about earthquake

Table 11 shows association of the respondents' awareness, knowledge and perception about earthquake. From the table, it can be observed that the earthquake awareness of the respondents has significant association with their knowledge. It is very strongly associ- ated with their knowledge about earthquake ($G = 0.928$, $p < 0.05$), weakly associated with their knowledge about immediate response during an earthquake ($G = 0.369$, $p < 0.05$), and moderately associated with their past earthquake experience ($G = 0.433$, $p < 0.05$). That is, the lack of knowledge leads to the lack of awareness. But here the alarming fact is that though 85% respondents claimed to be aware of earthquake, 41.4% and 80% of them have inappropriate or no knowledge about earthquake and immediate response during an earth- quake, respectively, and about 83.1% of them could not respond appropriately or could not recall their past earthquake experience. Overall, it can be said that although there is significant relation among awareness and knowledge, awareness does not necessarily mean having appropriate knowledge or does not necessarily ensure appropriate response.

Awareness also has significant association with respondents' perception about earth- quake vulnerability of the area and their willingness to participate in the disaster manage- ment in the study area as volunteer, but the association is insignificant for their percep- tion about earthquake vulnerability of their building ($G = 0.221$, $p > 0.05$). Awareness is strongly associated with respondents' perception about earthquake vulnerability of the area ($G = 0.622$, $p < 0.05$) and moderately with their willingness to work as volunteer ($G = 0.588$, $p < 0.05$). Thus, most of the aware people perceive their area to be vulnerable and are willing to work as volunteer. This finding is consistent with other literature who found association of awareness with their perception (Ainuddin and Routray 2012; Bankoff 2013; Morrow 1999; Wood et al. 2010). But, they are indifferent about the vulnerability of their building or in other sense, vulnerability of their own ($G = 0.221$, $p > 0.05$.) This find- ing is consistent with that of Paul and Bhuiyan (2010) who stated that people believe that they or their property would not experience damage at the event of a disaster.

Perception of respondents about earthquake vulnerability of the area is weak but sig- nificantly related to their knowledge about earthquake ($G = 0.345$, $p < 0.05$). This finding is consistent with the findings of Alam (2016); Flint and Luloff (2005); Roder et al. (2016); Soffer et al. (2011), who concluded that hazard knowledge has greater influence on people's hazard perception. In contrary, there is no significant association between people's per- ception about earthquake vulnerability of their building and their knowledge about earth- quake ($G = 0.101$, $p > 0.05$). Thus, people develop their perception based on knowledge, but when it comes to their own vulnerability, then they remain indifferent about it. This finding is consistent with that of B. K. Paul and Bhuiyan (2010) who stated that people believe that they or their property would not experience damage at the event of a disaster.

Again, willingness of the respondents to work as volunteer has no significant relation with either of their knowledge about earthquake or earthquake response ($G = 0.071$, $p > 0.05$ and $G = -0.025$, $p > 0.05$, respectively). But such willingness is weak but significantly related to their past earthquake experience ($G = 0.220$, $p < 0.05$). Overall, it can be said that earth- quake knowledge has little influence on people's actual preparedness behavior, which is consistent with Anderson-Berry (2003) who concluded that hazard knowledge does not necessarily translate into appropriate preparedness and adaptation behaviors.

3.6 Relation of awareness, knowledge and perception about earthquake with personal context and social capital

Tables 12, 13, 14 and 15 show association of the respondents' awareness, knowledge and perception about earthquake with their personal contexts including gender, age, education level and building ownership status, respectively. It is evident Table 12 that the associa- tions of respondents' gender with their earthquake awareness and knowledge are very weak as well as insignificant representing similar level of knowledge and awareness among male and female respondents. This finding contradicts with that of Teo et al. (2018), who con- cluded that level of awareness varies among male and female residents. In case of percep- tion, respondents' gender has very weak and no significant relation with their perception about earthquake vulnerability of the area ($G = 0.093$, $p > 0.05$). This finding complies with that of Roder et al. (2016), stating that men and women feel the danger at the same level. On the other hand, perception about earthquake vulnerability of the building the respond- ents are residing is lower among male respondents though the association is weak and sig- nificant ($G = -0.225$, $p < 0.05$). Again, willingness to work as volunteer for disaster man- agement is moderately and significantly associated with gender ($G = 0.486$, $p < 0.05$). Male respondents are more willing compared to female respondents to work as volunteer. It is also evident in the research of Soffer et al. (2011) who found that men are more confident to respond than female. Table 13 shows that the associations of respondents' age with their earthquake awareness, knowledge as well as perception are very weak as well as insig- nificant representing similar level of awareness, knowledge and perception among different age group of the respondents. This finding contradicts with that of Ho et al. (2008); Roder et al. (2016) who stated that older people have greater perception compared to younger.

Table 14 shows that awareness, knowledge and perception of the respondents about earthquake differs with their education level. Awareness of the respondents about earth- quake, knowledge about earthquake and their past earthquake experience, and perception about earthquake vulnerability of the area have negative very weak but significant asso- ciation with education level ($G = -0.199$, $p <$

0.05; G = − 0.183, $p < 0.05$; G = − 0.183, $p < 0.05$; G = − 0.199, $p < 0.05$, respectively). Willingness to work as volunteer has nega- tive weak but significant association with their education level (G = − 0.270, $p < 0.05$). It represents that educated people are more aware as well as have better knowledge and per- ception about earthquake. This complies with the findings of other studies (Cutler et al. 2018; Habiba et al. 2012; Shaw et al. 2004; Soffer et al. 2011; Taghizadeh et al. 2012; Teo et al. 2018). In contrary, the association of respondents' education level is very weak and insignificant with their knowledge about immediate response and perception about build- ing vulnerability.

From Table 15, it can be observed that respondents' building ownership status has very weak but significant association with their earthquake awareness (G = 0.197, $p < 0.05$). Thus, owners are more aware of earthquake. Despite this fact, respondents' perception about earthquake vulnerability of their building and their willingness to work as volunteer are negatively and significantly related to ownership, where the relations are very weak and weak, respectively (G = − 0.16, $p < 0.05$ and G = − 0.250, $p < 0.05$ correspondingly). Thus, despite having better awareness, owners are in denial of the vulnerability of their building and are not willing to work as volunteer. In contrary, tenants have better perception about vulnerability and willingness to get involved in disaster management regardless of having lower awareness. Ownership has very weak with no significant association with knowl- edge (about earthquake, immediate response and past experience) and perception about earthquake vulnerability of the area (G = 0.033, $p > 0.05$; G = 0.030, $p > 0.05$; G = − 0.152, $p > 0.05$; and G = − 0.091, $p > 0.05$, respectively). This finding contradicts with other researches who found that tenants stay in an area for temporary basis so they are less wor- ried about vulnerability of the area compared to owners who would stay in the area lifelong (Ainuddin and Routray 2012; Morrow 1999; Rahman 1996; Tapsell et al. 2002; Wood et al. 2010).

Tables 16 and 17 show association of the respondents' awareness, knowledge and percep- tion about earthquake with their social capital including social interaction and duration of stay of respondents in the study area, respectively. From the analysis, it has been found that about 75.8% respondents in the study area discuss about earthquake with their acquaintances, especially with their family members (69.28%). Only 27.86% respondents discuss with the local people, whereas 25.43% respondents discuss with other building users. Mainly female, middle-aged and literate people take part in such discussions. When this social interaction of respondents has been compared with their awareness, knowledge and perception about earthquake, it has been found that respondents' social interaction has significant association with their earthquake awareness, knowledge as well as perception, except for their knowl- edge about immediate response during an earthquake (G = 0.205, $p > 0.05$). Social interaction has very strong relation with respondents' awareness (G = 0.818, $p < 0.05$), moderate relation with earthquake knowledge (G = 0.459, $p < 0.05$), weak relation with past earthquake experi- ence ($G = 0.250$, $p < 0.05$), moderate relation with perception about earthquake vulnerability of the area ($G = 0.431$, $p < 0.05$), weak association with perception about earthquake vulner- ability of their building ($G = 0.293$, $p < 0.05$), and moderate association with respondents' willingness to participate in disaster management as volunteer ($G = 0.512$, $p < 0.05$). Thus, respondents who interact more with their acquaintance are more aware, have more appropri- ate knowledge and have better perception about earthquake. This finding is consistent with that of other researches (Cope et al. 2018; Rufat et al. 2015; Smit and Wandel 2006).

From the analysis, it has also been found that about 40% respondents have been living in the study area for more than 20 years, whereas only about 6% of them have been living in this area for less than a year. Based on findings from other researches, it is expected that people living in a locality for longer duration have strong sense of belonging to the place and community bonding as well as better knowledge about the area which in turn lead to better hazard perception and effective participation in local disaster management (Teo et al. 2018; Wang and Wan Wart 2007). But in this study it has been found that respondents' duration of stay in the study area has very weak as well as no significant influence on their social interaction, and awareness, knowledge and perception about earthquake. Both new and old residents have similar social interaction, and they have expressed analogous aware- ness, knowledge and perception about earthquake.

3.7 Influence of awareness, knowledge and perception about earthquake on vulnerability of the area

Tables 18 and 19 show influence of general physical and social profile of the area and awareness, knowledge and perception of respondents about earthquake on the vulnerability of the area. From Table 18, it can be observed that the study area is vulnerable to earth- quake due to the hazard, exposure and fragility of local people. From Table 19, it can be observed that the difference found among people's earthquake awareness, knowledge and perception influences their existing response capacity as well as adaptive capacity. Such influence impacts on vulnerability of the study area reducing in some case and increas- ing in some other. Aware people are capable of accepting the risk. But with inappropriate knowledge, they are unable to understand the risk leading to poor judgments and deci- sions regarding earthquake management and inappropriate response leading to increased casualty. Moreover, people develop their perception based on their awareness and to some extent based on earthquake knowledge. Thus, misconception leads to wrong perception about earthquake. Most of the people are also not capable of accepting and understand- ing their own vulnerability. The WDMC can co-ordinate the disaster management in the study area. But with the lack of communication between the authority and the inhabitants, WDMC will fail to do so. All these scenarios lead to reduce response capacity and resil- ience of local people in the study area. People with inappropriate knowledge may not feel the urge to attend training programs and take necessary actions. Again, people without having proper perception will not participate in different training programs willingly. Thus, adaptive capacity of local people in hampered. All these factors lead to increasing their earthquake vulnerability. On the other hand, aware people can also be easily encouraged to participate in different training programs. People have greater trust on electronic media and also have good social interaction which can be utilized in the future for knowledge and capacity building for disaster management in the future. The building owners can be guided to invest for reducing the fragility of their building accordingly. People are willing to work as volunteer based on their past earthquake experience irrespective of the knowl- edge they possess. These people can be involved in CBDM in the study area. The WDMC can take necessary measures in this regard for future capacity building.

4 Conclusion

This research is intended to understand existing condition and difference among people's awareness level, knowledge and perception as well as their underlying personal and social contexts influencing earthquake vulnerability of a community in Mymensingh, Bangladesh.

Majority of the respondents stated that they are aware of earthquake. These people are expected to be capable of accepting the risk. On the other hand, aware people can also be easily encouraged to participate in different training programs. The main source of their knowledge is electronic media. Very few people attended earthquake-related pro- gram representing infrequency in organization and lack of participation in such programs. Respondents could also learn about earthquake from their neighbors. The trust of people in these sources can be utilized in the future for knowledge and capacity building for disaster management in the future. Unfortunately, a significant portion of the respondents do not have appropriate knowledge about earthquake and its immediate response. Moreover, the respondents attending earthquake-related programs do not possess appropriate knowledge regarding immediate response. Such finding reflects that even the few earthquake-related programs were not effective to train the people about appropriate response during an earth- quake. With inappropriate knowledge and misconception, people are unable to understand the risk leading to poor judgments and decisions regarding earthquake management and inappropriate response leading to increased casualty. This is reflected by their inappropri- ate response during past earthquake experience or not remembering the event. Moreover, people with inappropriate knowledge may not feel the urge to attend training programs and take necessary actions. The analysis shows that the lack of knowledge leads to lack of awareness. But though a significant portion of the respondents claimed to be aware, majority of them do not have appropriate knowledge about earthquake and the immediate response. Thus, knowledge of the respondents about earthquake and immediate response do not comply with their stated awareness. This awareness and knowledge of people in the study area are not related to respondents' gender or age. But educated people are more aware and have better knowledge.

Despite the inconsistency between earthquake awareness and knowledge, people develop their perception based on their awareness and to some extent based on earthquake knowledge. They have strong perception about earthquake vulnerability of the area as well as the building they are residing in. Such perception is higher among educated people irre- spective of their gender and age. But the perception is inconsistent with the actual build- ing vulnerability. Thus, misconception and inappropriate knowledge lead to wrong percep- tion about earthquake. Most of the people are not capable of accepting and understanding their own vulnerability and thereby avoiding necessary actions to address the vulnerability. Again, such denial is higher among male respondents and owners irrespective of their age or education level. People without having proper perception will not take the risk seriously and thereby will not feel the urge to participate in different training programs willingly. Major portion of the owners are willing to invest for retrofitting and thereby strengthening their building, though such willingness is not guided by their perception or actual vulner- ability of their building. It will be easier to motivate the owners to strengthen their build- ing where necessary. In contrary, as owners are developing their perception without prop- erly understanding the vulnerability, at the time of execution they may not act accordingly though they have expressed their willingness to do so.

There is WDMC for disaster management at local level in the study area which can co-ordinate the disaster management in the study area and can take necessary measures for capacity building. But with the lack of communication between the authority and the inhabitants, WDMC will fail to do so. Though most of the respondents do not know about the presence of WDMC in their area, majority of them are willing to get involved in dis- aster management process in the area as volunteer. Aware people and people remembering past earthquake experience showed more willingness in this regard, where knowledge has no significant influence on such perception. Male and educated respondents especially who are living in the area as tenants are more willing to participate in disaster management. These people can be involved in CBDM in the study area.

For addressing the difference among earthquake awareness, knowledge and perception of local people and thereby reducing their vulnerability, different initiatives for awareness raising and knowledge sharing will have to be taken. In this regard, the findings of this study should be considered. Electronic media, training programs and social network can be utilized further because people are used to and already have trust in these sources. Innova- tive and informative programs can be designed to be telecasted in electronic media. All the sources should contain appropriate information including separate training programs for awareness raising and knowledge about earthquake and associated risk; preparedness and immediate response measures, and capacity building for CBDM. Awareness raising and knowledge about earthquake and associated risk will bring out local people from their misconception, build the capacity of the people to understand their own vulnerability and thereby leading to better perception. Special attention will have to be given on building owners so that they can come out of their denial and can accept their own vulnerabil- ity. If necessary, separate training programs will have to be organized for them to build their capacity to understand the earthquake vulnerability of their buildings themselves at preliminary level. They should be able to realize the situation when they should contact experts for detailed assessment of their building. They will also have to be motivated to take necessary measures to address their building vulnerability accordingly with proper understanding and reasoning. The awareness and knowledge training program should also focus on motivating people to participate in CBDM because better awareness and percep- tion have found to lead people to higher willingness to work as volunteer. Female, less educated residents and owners are less willing to participate in disaster management. Additionally, young people are more energetic and enthusiastic, and they are asset for a locality. So, special focus will have to be given on female and young people to motivate their participation in this regard. Hands on training and drill programs should be organized at local level to ensure effective preparedness and immediate response. If people attend this program after the first one, then they will be able to learn and grab the preparedness and response measures effectively with proper reasoning supported by their appropriate knowledge. Planning will have to be done to effectively implement CBDM in the study area considering peoples' preference of duty. Training programs will have to be organized for capacity building of the willing people to work as volunteer according to their preferred duty. Such consideration of preference will ensure their effective participation in CBDM.

These initiatives are not enough to achieve the goal if people do not participate here effectively. Participation of all gender, age and education group of people irrespective of their building ownership status should be ensured. From the analysis, it has been found that willingness to participate is influence by peoples' awareness and perception. So peo- ple will have to be motivated at first to attend the training programs on awareness raising and knowledge about earthquake and associated risk. In light of appropriate awareness and knowledge, people will be motivated to participate in training programs on earthquake pre- paredness and response, and capacity building for CBDM. As educated people in the study area have been found to be more aware, have better perception, have higher willingness to work as volunteer and can readily understand the information, they can be utilized here to motivate local people to participate. Moreover, young people can also be utilized here. Such motivation can be done utilizing the social interaction among the residents which has been found very effective in the study area. Moreover, training of trainer's method can be utilized here for capacity building at local level utilizing their own resource. In this regard, educated and young people in the study area may be given training at first and then they can be utilized in different training programs as trainer. This will in turn increase acceptability among local people motivating them to participate in the training programs. To effectively implement CBDM in the study area, capacity of the WDMC will have to be strengthened to establish link and communication with local people and organize earthquake-related training programs themselves at local level without outside help or intervention.

This study brings out that people's awareness, knowledge and perception about earth- quake has significant impact on vulnerability of a community. Without consideration of these contexts, different measures may fail to reduce vulnerability of a community due to the lack of relevance, applicability or acceptance. Therefore, it is necessary to understand the context of local people's awareness, knowledge and perception about the hazard in a community. This research can be utilized as a guideline for this purpose in other areas of the country, as well as in other countries with necessary adjustment and modification considering local context.

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PART-VI

ANALYSIS AND SEISMIC RETROFITTING PROCEDURE OF UNREINFORCED MASONRY BUILDING-A CASE STUDY

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Introduction

In the context of structures of Bangladesh masonry structures, comprise a good portion of the total buildings built in the twentieth century. Majority of the unreinforced masonry structures still standing today were built in the Pakistan period (1949-1971). At that time any sort of national building regulations or provisions of seismic codes did not properly exist. Owing to the tectonic framework and existence of three major active fault lines within the country (Raihanul et al, 2016) and being the most densely populated region in the world, Bangladesh is in imminent threat of seismic hazard in a catastrophic scale. Due to the structural inadequacy and existence in a country vulnerable to seismic hazard, these non-engineered structures may sometimes turn out to be real life incarnations of death traps. The present use of these masonry structures as government offices, headquarters, factory units, religious centers and even residential quarters increases the risk of damage and casualties in case of a seismic event. So, engineering assessment of these structures with properly developed procedures along with required retrofitting and rehabilitation is a dire need.

For Unreinforced Masonry structures the load bearing walls are subjected to gravity loading and lateral loading (in case of wind and earthquake). In addition to compressive stresses due to gravity loading, the walls also must experience shear stresses due to both gravity and lateral load. While exposed to strong earthquakes, creation of tensile and shearing stresses in the walls of masonry buildings is the primary cause of damage suffered by these structures. To ensure minimum casualties in an earthquake either the seismic demand on the structure has to be reduced by including additional shear walls, infill walls, steel bracing, base isolation devices or by retrofitting (i.e. Ferro-cement, RC overlay, RC jacketing) of all the structural members concerned (load bearing walls, beams, slabs etc). The primary objective is to increase its seismic resistance to a defined performance level as per the design code's (BNBC 1993) requirement so that the probability of total failure/collapse remains out of the equation. These procedures are largely based on academic studies carried out by researchers. For example, Gorai and Maiti (2016) presented various techniques for strengthening damaged structures. Jadhav and Patil (2012) investigated a 60 years old RC water tank and its structural members which had reinforcement corrosion and deteriorating concrete and those were repaired using reinforced cement grouting and polymer mortar. Chaturvedi and Patel (2016) observed improved behavior of RC jacketed beams in terms of deflection and strength. Seleem et al (2003) evaluated the static response of beams retrofitted with U shaped RC jackets in terms of strength, stiffness and composite action. The test result indicated a vital effect of the presence of stirrup in the concreting jackets in enhancement of both stiffness and ultimate load capacity of the retrofitted beam. Surface roughness is a vital determinant in retrofitted beam performance level. Cheong and MacAlevey (2000) observed differences in behavior of jacketed beam whose interface was fully and partially roughened. RC jacketed beams showed significant improvement in flexure capacity and mechanical behavior, compared to ordinary reinforced beams of the same dimension, even though cores of the jacketed beams were damaged (Fatih, 2004). Shehata et al (2009) investigated the impact of shear stud in strengthening existing beams by addition of high strength concrete layers. As per studies by Sachin and Urmil (2012), use of shear connectors and bonding agent paired with micro-concrete is much more efficient, compared to other jacketing alternatives, in enhancing the performance level of beams.

One method of retrofitting of the masonry walls is 'Ferro-cement lamination', which, on infilled masonry changes the shear dominated failure to flexure failure. Under lateral cyclic loading, an effective mesh reinforcement of 0.16% increases the lateral strength, initial stiffness and energy dissipation approximately by two folds (Sen et al, 2019). The composites ductile strength is dependent on the effective volume fraction, mesh type and its orientation within the matrix (Prawel and Reinhorn, 1982). Ferro-cement overlay having wire mesh oriented at 45° had the highest ultimate capacity compared to other orientations. But in perspective of strength to cost ratio wire mesh having 0° orientation had the most economically efficient outcome (Prem et al, 2010). Under static cyclic test, this retrofitting technique increased the in-plane lateral resistance by a factor of 1.5 (Abrams and Lynch 2001). Study by Reinhorn and Prawal (1985) led to the definition of the failure mechanism. According to their research, the ferro-cement overlay either fails by diagonal tension (ductile) or de-attachment (bond failure). Bond anchors have a dominant effect on the development of these mechanism. Another effective way of increasing the shear strength of the load bearing walls to the extent that flexural failure consistently occurs is to apply a thin layer of cement plaster over high strength steel reinforcement (Sheppard and Tercelj, 1980). This improves the in-plane resistance of shear by a factor of 1.25 – 2.90 (Jabarov et al, 1980, Sheppard and Tercelj, 1980). The out-of-plane resistance is substantially improved as is the composite ductility. The improvement of strength depends on the strengthening layer thickness, cement mortar strength, reinforcement quantity and means of bonding with the retrofitted wall and the degree of masonry damage (ElGawady et al, 2004). There are several case studies reported in professional literature where reinforced plaster coatings were used to strengthen existing masonry structures (Willie and Dean, 1984, Guoliang, 1980). Ghiasi et al (2013) explained different retrofitting options for URM foundation and their applicability form a practical perspective. He strategized to rehabilitate the structure either by physical extension of the existing foundation or by improvement of subsoil layers. Apart from these, there have been several case studies leading to complete restoration of historical masonry structure based on finite element analysis and laboratory experimental data (Bozkurt et al, 2016; Hancilar et al, 2011; Sayin et al, 2019).

This study was initiated considering the vulnerability of the URM structures in case of earthquake in Bangladesh. It started with background survey and appraisal of in-built condition of the structure. The required parameters for Detailed Engineering Assessment (DEA) were assessed by conducting in-situ as well as laboratory tests. Next, Finite element analysis of the structure was done as per the field reports to analyze its response to seismic loading under the current state. Based on the numerical analysis results, laboratory tests and past researches, retrofitting techniques were designed for all the load bearing members which were found to be inadequate. Finally, the retrofitting designs were implemented which was followed by a quality control program. Though the studies conducted by researchers and professional literatures depict building retrofitting procedure, there are no comprehensive reference on unreinforced masonry structures rehabilitation. So, this study aims to serve as a representative application of research-based methodology in seismic retrofitting of URM structures in developing countries.

Methodology

Building features

A visual observation of an unreinforced masonry building having plan dimension of 31m × 10.7 m (102’ × 35’) was done to note down the existing condition of the building and some structural features to facilitate the further study. The building was constructed in 1960 and have been using as an office building. There are two identical stories from ground floor with two additional stories extension on southern (Grid A to C of Figure 3.5b) side. Some building features are summarized in Table 1.

Table 1: Building features of the studied building

Building features	Description
Floor system	Beam supported RC slab
Floor area	332 m^2 (3570 sqft) per floor
Foundation system	Wall foundation
Load bearing wall thickness	375mm on ground floor, 250mm on the other stories
Floor height	Ground floor: 4.47m (14.66 ft), Other floors: 3.20m (10.50 ft)
Construction material	Brick and reinforced concrete

Visual observation

Survey of the as-built condition of the existing structure was carried out to verify the as –built condition of the whole structure. Initial measurements were taken to prepare as-built drawings. Structural conditions of various structural members of the building were assessed during the field survey. Apparently, the structural members of the building were in a good condition. No visible signs of cracks and distress were found in the beams, load bearing walls and slabs. Some of walls on the ground floor appeared to be damp. Partition walls were found to be weak. Figure 3.1 shows the load bearing brick columns, which will be susceptible to short column failure under seismic loading.

Figure *Error! No text of specified style in document.*.**1 Load bearing brick columns**

Data collection and testing

Strength of the concrete in the existing beams and slabs has been assessed by extracting concrete core samples. Brick aggregate was used in the concrete as coarse aggregate. The compressive strength test of concrete cylindrical core was conducted according to ASTM C42. Diameter of the core sample was 68mm with minimum length/diameter ratio of 1.0. The core strength test results are summarized in Table 2. Combine failure represents the failure of both mortar and aggregate.

Table 2: Core strength test results

Sl. No.	*Location*	*Sample Identification*	*Crushing strength MPa (psi)*	*Type of failure*
1	*GF*	*GF Roof, C-1*	*11.4 (1605)*	*Combined*
2	*GF*	*GF Roof, C-2*	*11.9 (1730)*	*Combined*
3	*1st floor*	*1st floor roof C-1*	*12.1 (1750)*	*Combined*
4	*1st floor*	*1st floor roof C-2*	*8.1 (1170)*	*Combined*
5	*1st floor*	*1st floor roof C-3*	*24.5 (3550)*	*Combined*
6	*1st floor*	*1st floor Beam-1: C-1*	*21.8 (3160)*	*Combined*
7	*1st floor*	*1st floor Beam-5: C-2*	*17.7 (2570)*	*Combined*

Compressive strength test of brick was done as per ASTM C67. Two samples were collected, and compressive strength were found to be 20.75 MPa and 17.51 MPa. Brick shear test (Table 3) was done on masonry wall in order to estimate allowable shear strength Fv, which in turn was used to calculate allowable compressive stress f'm and modulus of Elasticity of masonry Em using proposed equation of Bangladesh National Building Code (BNBC 1993). Minimum shear stress was used to be in safe side. The compressive strength of brick, compressive strength of masonry and modulus of elasticity of brick were found to be 17.51 MPa, 7.5 MPa and 5625 MPa respectively. Mortar grade was M2 having mix proportion of 1:4. These values would be used for structural analysis of the masonry structure.

Table 3: Experimental data of brick shear test on masonry wall

No.	*Location*	Shear Stress, σ Mpa (psi)	Area, A_1 mm^2 (in^2)	Load, P kN (lb)
1	GF Interior wall (G/1-2)	10.34 (1500)	858 (1.33)	8.87 (1995)
2	GF Exterior Wall (K/1-2)	6.89 (1000)	858 (1.33)	5.92 (1330)

Presence of reinforcement in beams and slabs were done using Ferroscan. The determination of rebar diameter using ferroscan imaging is questionable. The standard deviations of the rebar diameter measurement results are significantly large, meaning the spread of the measurement data are scattered over a large area. (Salek, 2015). This gives the impression of unreliable measurement outcomes. So, in capacity assessment of the beam and slab, smallest possible diameter (16mm for beam, 10mm for slab) was assumed.

Ferro-scan report showed the 1st floor beams (400mm x 300mm) to have 4 tension reinforcement. As for the 2nd floor beams having cross section of 500mm x 300mm the reports showed 5 rebar in the tension zone. For analysis, the rebars were assumed to be 16mm diameter bars. Schematic diagrams of the beams are depicted in Figure 3.2. As for slab, the ferro-scan reports show, the rebars were spaced at 6" c/c in both directions. Ferroscan test results are shown in Figure 3.3.

The standard penetration test (SPT) is performed to obtain an approximate measure of bearing capacity and dynamic soil resistance. SPT value suggests that, the upper soil (up to 6.0 m depth) corresponds to very stiff cohesive soil which is suitable for moderate load bearing structures (Terzaghi and Peck, 1967). Ground water level at -5.75m EGL. Soil test results are shown in Table 4 and Table 5.

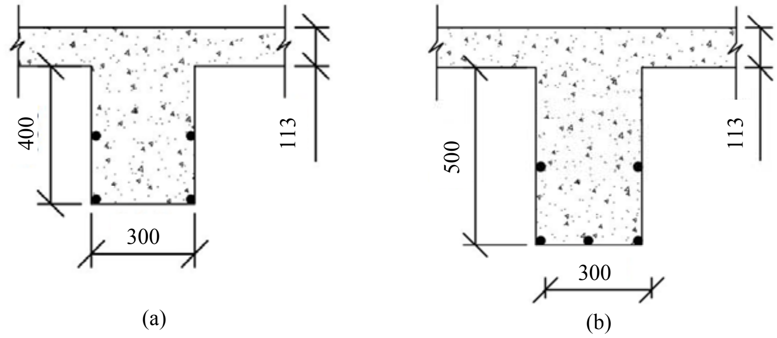


Figure *Error! No text of specified style in document.*.**2 Schematic diagram of floor beams, (a) 1st floor (b) 2nd floor**

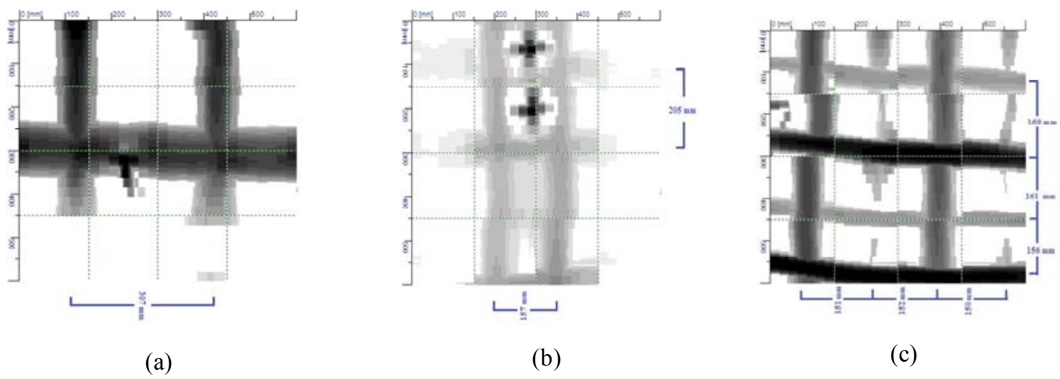


Figure *Error! No text of specified style in document.*.**3 Ferroscan of GF beam E1-E2 [(a) lateral (b) bottom] and (c) slab**

Finite element modelling

As the extreme ends of the reinforced concrete beams rested in masonry wall, they tend to behave like simply supported beams. Therefore, they are assigned hinge restraints in FE model. The slabs were modelled as shell element. The load bearing wall were modelled as membrane. Element dimensions were taken from the as-built drawing. Average compressive strength of 13.8 MPa (2 ksi) was judiciously selected for structural analysis of the building. Minimum yield strength (275.79 MPa) and tensile strength (482.63MPa) of the 40 grade rebar were taken for the analysis purpose. Seismic loading parameters e.g. zone coefficient (Z=0.15), strength reduction factor (R=6.0), importance coefficient (I=1.0), exposure category A (urban-sub urban area), wind load (V=210 Km/hr), are taken from BNBC 1993 as per site location. Site coefficient was taken 1.0 as the soil is stiff clay at foundation level. Surface area method was used for wind load analysis and maximum wind load deflection limit h/500 was taken considering 100% wind effect. The building was analyzed for gravity loads (dead and live loads) as well as code specified lateral loads. Loading used in the finite element analysis is shown in Table 6. The 3D model and the plan view of the structure is shown in Figure 3.5.

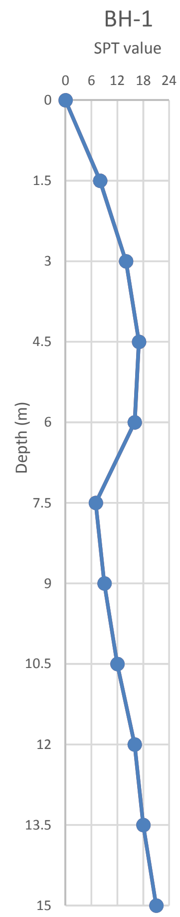
Table 4: Soil property borelog-1

Depth (m)	Soil property BH-1
1.0 - 6.0	Stiff to very stiff silty clay. (High plasticity)
6.0 - 9.0	Medium stiff to stiff, clayey silt with fine sand. (Medium compressible)
9.0 – 15.0	Medium dense, silty fine sand, trace mica

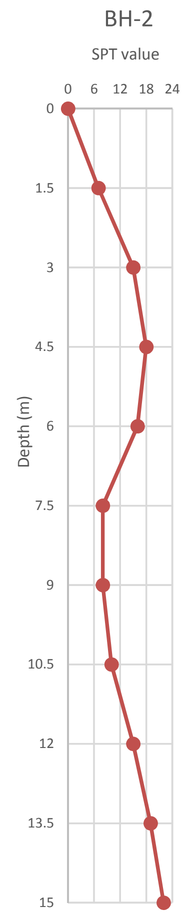
Table 5: Soil property borelog-2

Depth (m)	Soil property BH-1
1.0 - 6.0	Medium stiff to very stiff silty clay. (High plasticity)
6.0 - 9.0	Stiff, clayey silt with fine sand. (Medium compressible)
9.0 – 15.0	Medium dense, silty fine sand, trace mica

Figure **Error! No text of specified style in document.**.4
Standard penetration test on site



SPT – BH 1



SPT – BH 2

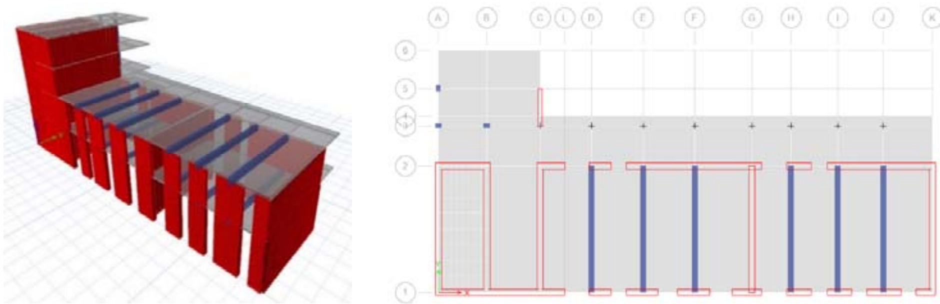
Sensitivity Analysis

Sensitivity analysis was done on the developed model to choose the optimum size and number of mesh for which results obtained will be reliable and accurate to the desired degree and at the same time, it will require optimal time to run and execute the analysis of the model. Coarser mesh produced lower stresses in the walls with respect to finer mesh. So, optimum mesh sizes were selected by trial and error considering two vital factors.

Analysis run time

Results having similar accuracy compared to those with finer mesh size.

An illustration of a small part of the wall in elevation 1 is depicted in



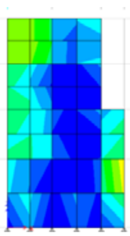
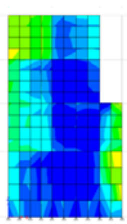
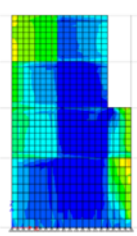
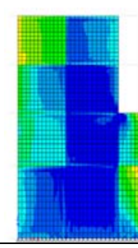
(a) (b)

Figure **Error! No text of specified style in document.**.5 Complete finite element model of URM building [(a) 3D model (b) *Typical plan*]

Table 6: Super imposed static loads

Loading type	Code specified load (kN/m^2)
Live load (office building)	2.87
Live load on porch	0.48
Live load on stairs	4.80
Internal partition wall load	1.44
Floor finish wall load	1.44

Table 7: Sensitivity Analysis of the structure

Number of shell elements	40	128	512	1152
Maximum Shear Stress for 10-inch wall	93	100	106.5	108
% change in stress	---	7.53 %	6.5 %	1.41 %
Image of a Wall				

Results and Discussion

Adequacy check of load bearing walls

The structural system of the building is primarily unreinforced masonry system resting on wall foundations. According to the BNBC 1993 guideline, Working Stress Design (WSD) method was used to access the structural adequacy of the masonry elements of the structure.

Slenderness ratio check

According to the BNBC 1993, masonry wall's slenderness ratio shall not exceed 20. The slenderness ratio of the walls of this structure falls within this limit, which can be seen, from Table 8.

Table 8: Slenderness ratio of the building

Story details	Effective height	Effective thickness	Slenderness Ratio	Comment
Ground floor	175.5 in (4.46 m)	15 in (0.38 m)	11.7	Satisfied
1st - 3rd floor	115.5 in (2.93 m)	10 in (0.25 m)	11.55	Satisfied

Maximum compressive stress (Fa) check

In unreinforced masonry structures, load-bearing walls are by far the most vulnerable element to seismic loading. These elements are primarily designed to carry vertical loads by compression. Allowable limit of axial compressive stress, Fa (Eqn 1; Eqn 4.3.1 BNBC 1993) was calculated to be 1.38 MPa (200 psi). As shown in Table 9, the load bearing walls satisfy the vertical compressive stress requirement due to service load combination (Dead+ Live).

$F_a = \frac{f'_m}{5}\left[1-\left(\frac{h'}{42t}\right)^3\right]$ (1)

Where, h' is the effective height of the wall and t is the effective thickness of the masonry wall.

Table 9: Maximum axial compressive stress generated in FEM model for load bearing walls

Wall Designation	Generated Max compressive stress MPa (psi)	Remarks (Limit state)
1A-1L	0.52-0.59* (75-85*)	Satisfied
1D-1K	0.52-0.59* (75-85*)	Satisfied
2A-2B	0.69* (100*)	Satisfied
2C-2K	0.69* (100*)	Satisfied
A1-A2	0.62 (90)	Satisfied
B1-B2	0.83 (120)	Satisfied
C1-C2	0.52 (75)	Satisfied
C4-C5	0.21* (30*)	Satisfied
G1-G2	0.34 (50)	Satisfied
K1-K2	0.41 (60)	Satisfied

*In very small portions of the wall surface the stress values have been found to be much greater than the maximum values presented in Table 9. So those small portions were neglected since these were too small compared to the whole wall surface. For example, the point of the wall at which a beam rests the compressive stress is above 120 psi, and even at some points it is greater than the allowable limit due to stress concentration. So, these points of stress concentration are to be taken into account while retrofitting of the structure.

Maximum shear stress Fv check

In seismic event, load-bearing walls are subjected to repetitive in plane and out of plane horizontal loading. Due to not having any reinforcing element they have insignificant resistance to horizontal shear stress. The allowable limit of shear stress of unreinforced masonry was calculated to be 0.069MPa (10 psi) (Eqn 2; Eqn 4.3.5, BNBC 1993 and Eqn 6.7.6, BNBC 2017).

$F_v=0.025\sqrt{f'_m}<0.40$ N/mm2 (2)

Table 10 shows the generated shear stress on the masonry wall for service load combination (Dead + Live) as well as lateral loading (Dead + Earthquake). Majority of the wall section are vulnerable to failure under horizontal shear. Figure 4.1 shows the visual representation in typical floor plan view of the adequate and inadequate walls for both the loading criteria of BNBC 1993 and 2017. The seismic forces calculated as per BNBC 2017 were much higher than those calculated as per BNBC 2006. This is because, the Response Reduction Factor (R), for load bearing unreinforced masonry structure is 1.5 in BNBC 2017 which is much less than that of BNBC 2006 (R=5). So, the allowable limit of shear stresses due to dead and seismic forces of BNBC 2017 is exceeded for all the walls. (Figure 4.1). The retrofitting was also done taking consideration into the forces of higher magnitudes (Seismic forces of BNBC 2017)

Table 10: Maximum shear stress generated in FEM model for load bearing walls

Wall Designation	Maximum shear stress D+L MPa (psi)	Remarks (Limit state)	Maximum shear stress D+EQ MPa (psi) BNBC 1993	Remarks (Limit state)	Maximum shear stress D+EQ MPa (psi) BNBC 2017	Remarks (Limit state)
1A-1L	0.07* (10*)	Satisfied	0.14 (21)	Not Satisfied	0.76 (110)	Not Satisfied
1D-1K	0.01* (2*)	Satisfied	0.03* (5*)	Satisfied	0.09 (13)	Not Satisfied
2A-2B	0.10 (14)	Not Satisfied	0.19 (27)	Not Satisfied	0.90 (130)	Not Satisfied
2C-2K	0.04* (6*)	Satisfied	0.19* (28*)	Not Satisfied	0.57 (83)	Not Satisfied
A1-A2	0.20 (29)	Not Satisfied	0.15 (22)	Not Satisfied	0.37 (54)	Not Satisfied
B1-B2	0.21 (30)	Not Satisfied	0.16 (23)	Not Satisfied	0.39 (56)	Not Satisfied
C1-C2	0.14 (20)	Not Satisfied	0.19 (28)	Not Satisfied	0.50 (73)	Not Satisfied
C4-C5	0.06* (8*)	Satisfied	0.06* (8*)	Satisfied	0.16* (23*)	Not Satisfied
G1-G2	0.09 (13)	Not Satisfied	0.15 (22)	Not Satisfied	0.43 (63)	Not Satisfied
K1-K2	0.03* (5*)	Satisfied	0.10 (15)	Not Satisfied	0.31 (45)	Not Satisfied

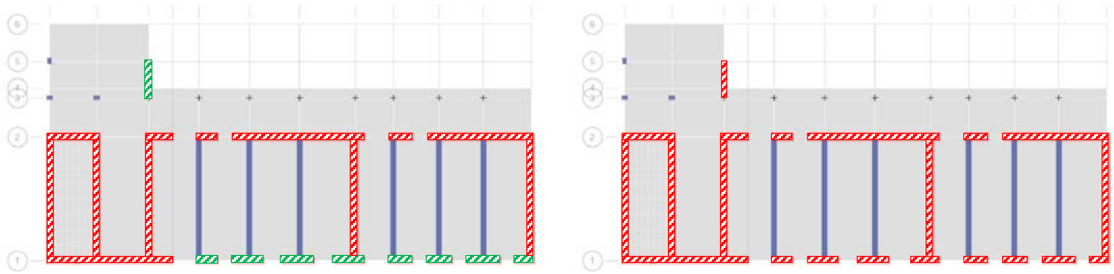


Figure 4.1:Wall condition in typical floor plan (a) BNBC 1993 EQ loading condition (b) BNBC 2017 EQ loading condition

At some small locations of the walls, actual maximum stress was found to be much greater than the tabulated maximum values (asterisk marked). This may have happened due to stress concentration at locations where beams rest on walls or at sharp corners (i.e. Window/door frames). These were discarded as they covered a negligible portion of the wall surface and were not representative of the actual maximum stress.

Adequacy check of Reinforced Concrete Members

Adequacy check of beams

The dimensions of all the beams of 1st floor (Ground floor roof) and 2nd floor (1st floor roof) are respectively 400mm × 300mm and 500mm × 300mm. The Ferro-scan test was able to determine the number and location of longitudinal bars in the beams but gave a vague idea about the exact diameter of the rebar. So, to be most conservative, 16mm diameter reinforcement bars were assumed as longitudinal bars during beam adequacy check. None of the beams were adequate to withstand the service load moment as shown in Table 11 and Table 12. The inadequacy of the all the beams was due to the combination '1.4DL + 1.7LL'.

Table 11: Analysis result of beam (1st floor)

Beam designation	Steel requirement (mm^2)		Comment
	Compression	Tension	
1D-2D	Overstressed	Overstressed	Failure – Inadequate section
1E-2E	Overstressed	Overstressed	Failure – Inadequate section
1F-2F	Overstressed	Overstressed	Failure – Inadequate section
1H-2H	Overstressed	Overstressed	Failure – Inadequate section
1I-2I	Overstressed	Overstressed	Failure – Inadequate section
1J-2J	Overstressed	Overstressed	Failure – Inadequate section

Table 12: Analysis result of beam (2nd floor)

Beam designation	Steel requirement (mm^2)		Comment
	Compression	Tension	
1D-2D	2845	1865	Failure – Inadequate reinforcement
1E-2E	2860	1883	Failure – Inadequate reinforcement
1F-2F	3011	2057	Failure – Inadequate reinforcement
1H-2H	2393	1345	Failure – Inadequate reinforcement
1I-2I	2587	1569	Failure – Inadequate reinforcement
1J-2J	2691	1688	Failure – Inadequate reinforcement

Adequacy check of columns and slabs

The design of RCC column assuming a minimum of 1% of rebar percentage was found to be adequate as per FEM analysis and the governing combination was '1.4DL + 1.7LL'.

According to the analysis, 10 mm bars placed 150 mm apart is adequate. The scan reports of the slabs suggest that rebars are spaced at around 140 mm c/c along short direction of the slabs which conforms to the structural requirement of the slab. The maximum deflection of the slabs and the minimum slab thickness were checked and found to be within the limit prescribed by the code.

Adequacy check of wall foundation

The foundation system of the building consists of wall foundation. Figure 4.2 shows the excavated foundation of exterior and interior wall, which have a depth of approximately 0.94m and 1.0m respectively. From the borelog, the top layer is found to be medium stiff to very stiff silty clay with an average SPT value of nearly 6.

(a) (b)

Figure 4.2: Foundation excavation [(a) External wall footing (b) Internal wall footing]

Undrained shear strength of clay, Cu was estimated from the SPT-N value from co-relation set by Hera et al (1974). Using Skempton's bearing capacity factor Nc = 6.7 for strip footing, the bearing capacity of the soil is estimated to be approximately 2.25 tsf. A factor of safety of 3.25 was considered for future extension. From the finite element analysis, the support reactions of the walls were found due to service gravity load which were used to find the stress on the soil to further compare it to the allowable bearing capacity of the soil. It was finally found that the provided foundation was inadequate against bearing capacity failure.

Retrofitting of structural members

Retrofitting of RC beams

Reinforced concrete structural element can lose their strength and stiffness due to repetitive dynamic loading forcing inelastic deformation, incorrect design and degradation of building materials. In this case U shaped RC jackets were used for retrofitting of RC beams. This was chosen as among other available options (externally bonded steels plates, fiber reinforced plastic (FRP), Carbon fiber reinforced polymer (CFRP)) are prone to premature de-lamination failure, due to mismatch of tensile strength and stiffness with that of RC elements. These are also quite labor intensive and costly. Table 13 and Table 14 show the governing moments in all the beams.

Table 13: Analysis result of beam (1st floor)

Beam designation	Max bending moment – kN-m BNBC 1993	Governing bending moment – kN-m BNBC 1993	Max bending moment – kN-m BNBC 2017	Governing bending moment – kN-m BNBC 2017
1D-2D	389.42	412.86	349.84	370.98
1E-2E	393.77		353.75	
1F-2F	412.86		370.98	
1H-2H	332.77		298.73	
1I-2I	356.38		320.03	
1J-2J	366.31		328.99	

Table 14: Analysis result of beam (2nd floor)

Beam designation	Max bending moment – kN-m (BNBC 1993)	Governing bending moment – kN-m (BNBC 1993)	Max bending moment – kN-m (BNBC 2017)	Governing bending moment – kN-m (BNBC 2017)
1D-2D	400.17	423.84	359.20	380.52
1E-2E	402.38		361.16	
1F-2F	423.84		380.52	
1H-2H	336.09		301.37	
1I-2I	363.64		326.22	

1J-2J	378.38	339.52

RC jacketing is done by extension of the existing beam cross section, with a new layer of high strength concrete reinforced with both shear and flexural reinforcement of 500 MPa. Shear reinforcement was designed as per IMRF requirement. For the retrofit design the effective slab thickness of 100mm was taken into account. Retrofitted extension of depth and width was taken to be 100 mm. So, the new dimensions of 1st floor and 2nd floor retrofitted beams became 600mm × 500mm and 700mm × 500mm respectively. Table 15 and Table 16 present the retrofitting design of beams.

The existing reinforcement was considered to be 40 grade 16mm diameter rebar. Only 50% of their area was considered to be effective in resisting flexural tension as these were not at the same effective depth as the newly retrofitted bar. For retrofitting of beams the concrete mix ratio was chosen as 1:1.2:1.7. 5 mm down stone chips were used as coarse aggregate and 100% Sylhet sand (F. M.=2.4) was used as fine aggregates. Super plasticizer was used as an admixture. The compression zones of the beams mostly consist of the old concrete which has a compressive strength of 13.8 MPa (2 ksi) and the newly cast concrete (〖f'〗 _c=35 MPa or 5 ksi) was mostly in the tension zone which is expected to be undergo flexural cracking. So, the concrete will contribute only in compression and thus the compressive strength was considered as 13.8 MPa (2 ksi) in retrofitting design.

Table 15: Retrofitting solution for 1st floor beam considering different material strength

Description	Code	Moment (kN-m)	*b* (mm)	*d* (mm)	f_y (MPa)	f_c' (MPa)	Rebars
1st Floor beam	BNBC 1993	412.86	500	500	500	13.79	5#7
	BNBC 2017	370.98	500	500	500	13.79	4#7

Table 16: Retrofitting solution for 2nd floor beam considering different materials

Description	Code	Moment (kN-m)	b (mm)	d (mm)	f_y (MPa)	f_c' (MPa)	Rebars
2nd Floor beam	BNBC 1993	423.84	500	600	500	13.79	4#7
	BNBC 2017	380.52	500	600	500	13.79	3#7

To facilitate the retrofitting work, at first the existing plaster was removed, and old concrete was thoroughly chiseled (fully roughened surface) before retrofitting. Air blower was used to remove dust and clean off any loose debris. U shaped stirrups (10mm diameter bars @ 100mm c/c at supports and 150mm c/c at mid span) were drilled (75mm) into the existing slab, securing it by epoxy. Longitudinal bars were placed as per design requirement. To ensure composite action between the concrete interfaces 10mm diameter @ 150mm c/c shear keys (one end hooked) were embedded alternatively (staggered pattern) into the existing beam. Embedded length was 75mm. Surface bonding reagents was applied to bind the new concrete with the existing surface. Steel shuttering and propping were set in place. For concreting, 150mm diameter holes were drilled into the top slab. Concrete strength for beam was 35 MPa which was confirmed by cylinder test with 28 days curing.

Figure 4.3 and Figure 4.4 present the beam cross section of the beam with the details of the flexural design. Figure 4.5 and Figure 4.6 show the long section of beam along with shear reinforcement.

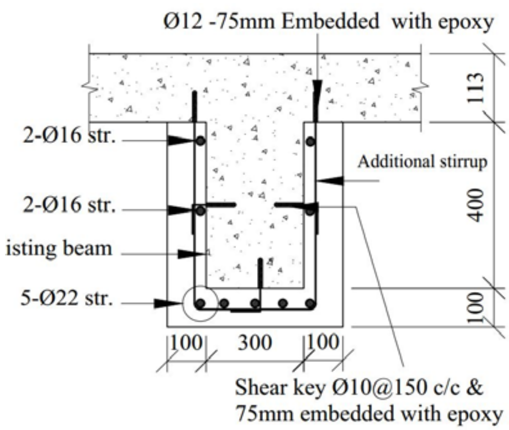


Figure 4.3: Retrofitted beam of 1st floor

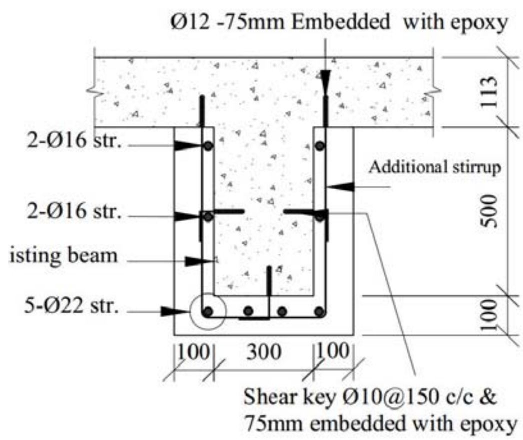


Figure 4 4*: Retrofitted beam of 2nd floor*

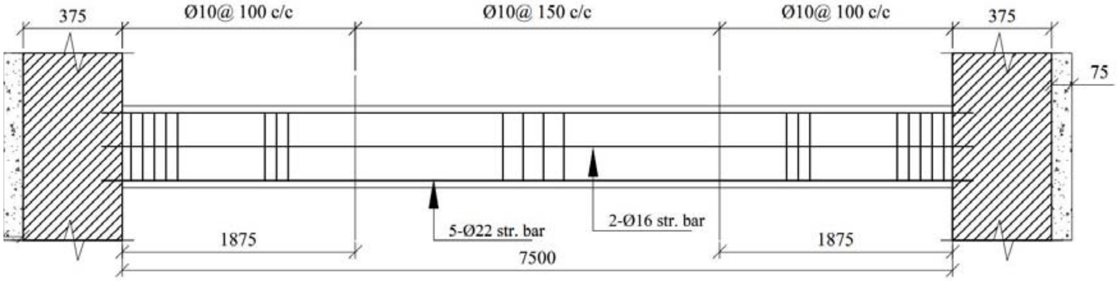


Figure 4.5: Longitudinal section of retrofitted beam of 1st floor

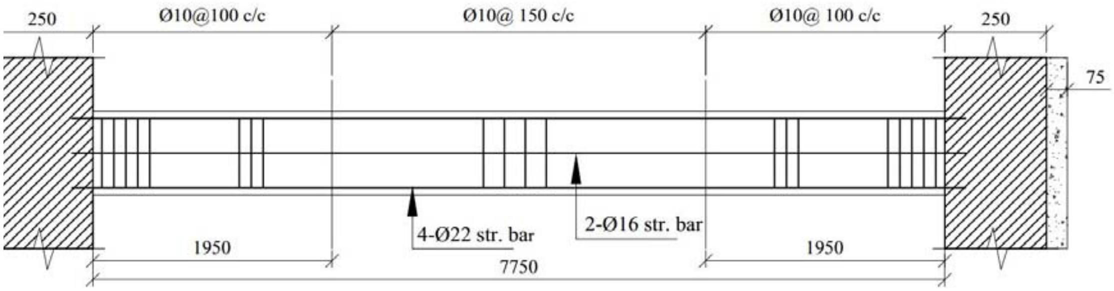


Figure 4.6: Longitudinal section of retrofitted beam of 2nd floor

Retrofitting of Masonry Walls

Two alternative methods of retrofitting of the masonry load bearing walls were proposed viz. by ferrocement overlay and by reinforced concrete jacketing. However, due to shear strength requirement of the structure for higher seismic loading of BNBC 2017, thicker ferrocement overlay with more wire meshes was found to be cumbersome for construction, for which reinforced concrete jacketing was done for retrofitting of all the walls in the existing building. Both the methods are still described in this section with short details of the procedure.

Ferrocement Overlay

One of the economically feasible retrofitting methods is ferrocement retrofitting. Ferro-cement is an orthotropic composite material having a high strength cement mortar matrix reinforced with steel wires in the form of a mesh (Horizontal/diagonal). It improves ductile strength and in-plane inelastic deformation capacity making the retrofitted structure more resilient against seismic forces. As it is cost effective and low labor intensive which make it economically feasible for developing countries. The direct tensile strength is dependent on the bonding between the existing masonry and composite layer, the reinforcement distribution within the matrix, its orientation w.r.t the load direction (Prawel and Reinhorn, 1982) and volume fraction 〖V〗_f. V_f is the ratio of volume of mesh reinforcement to the volume of composite layer (reinforcement mesh and matrix). Ferro-cement reinforced with square/rectangular mesh, the volume fraction and effective area of reinforcement were calculated using following equation mentioned in the Eqn 3 (BNBC 1993, Appendix D) -

$V_f = \frac{N\pi d_b^2}{4h} \left(\frac{1}{D_t} + \frac{1}{D_l}\right)$ (3)

Where, Dt and Dl are center to center spacing of wires aligned transversely and longitudinally in reinforcement mesh; db is diameter of the wire mesh; h is thickness of the composite layer (reinforcement mesh and matrix) and N is the number of layers of reinforcements. Effective area of reinforcement (Asi) per layer of mesh reinforcement in resisting direct tensile stress in cracked ferro-cement section can be estimated by (Eqn 4; BNBC 1993, Eqn 12.4.2, Rahman 2002) –

$A_{si} = \eta V_f A_c$ (4)

Where, η is global efficiency factor of mesh reinforcement and Ac is cross sectional area of the ferro-cement overlay. From this effective reinforcement area 〖(A〗 _si) nominal tensile resistance was determined (Eqn 5; BNBC 1993, Eqn 12.4.3). Allowable tensile stress of the wire mesh was taken to be 60% of the yield strength f_y (BNBC 1993, Art. 12.4.3.2).

$N_n = 0.6 A_{si} f_y$ (5)

A systematic procedure was proposed for the retrofitting purpose. The existing plaster of the masonry wall was chipped off up to a 20mm depth. The chipped wall was thoroughly cleaned by air blower to remove dust and loose debris of chipped bricks. For cracked masonry walls, cement slurry was applied to ensure proper bonding between the cracks. Galvanized nails were drilled in (75mm) according to design specification. Next, 5mm thick cement mortar was troweled onto the surface of masonry wall. Cement mortar was made by mixing ordinary portland cement of type I with natural river sand as fine aggregate passing through no. 4 sieve (2.36mm) having fineness modulus in range of 2.6 ~ 2.65. Mixing proportion of the mortar was 1:2.5 with water cement ratio of 0.45. This was followed by the attachment of 18 gauge (A.W.G) wire mesh having 8.5mm opening to the newly plastered masonry wall surface. The wire mesh was held in place by previously affixed 32mm nails. The nails were fixed in by epoxy in a square grid pattern (250mm c/c). As cover, a second layer of mortar with thickness of 10mm was applied on the wire mesh. In case of multiple layers of wire mesh, spacers were placed in between the reinforcement layers to control their position. Then cement mortar was passed between the 18 gauge meshes aided by a high-speed surface vibrator. The retrofitted wall was cured for 28 days with hessians. Detailing of the ferrocement design is summarized in Table 17.

Table 17: Ferro-cement retrofitting of the walls detailed design (BNBC 1993 loading)

Wall	Max. shear stress (psi)	A.G.S.	Description	Thickness	V_f	Capacity N_n (psi)
1A-1L	21	18 gauge	External side:	19mm	2.03%	31.39

2A-2B	27		2-layer wire mesh			
2C-2K	28					
A1-A2	22					
B1-B2	23					
C1-C2	28					
G1-G2	22					
K1-K2	15	18 gauge	External side:1-layer wire mesh	16mm	1.21%	15.70

Reinforced concrete retrofitting

The construction of a Ferro-cement section consisting of more than two wire mesh layers is practically cumbersome. Therefore, for high stresses where two wire meshes are not sufficient reinforced concrete jacketing of the walls can serve as a potential alternative for retrofitting. However, in this case the total shear force is to be taken by the RC section. The design of the RC section is similar to that of the reinforced concrete shear wall. Three-inch (3”) shear wall was proposed and the total shear is taken by the concrete (V_c) and the steel (V_s). This strengthening method leads to significant improvement in the shear resistance of the jacketed walls (Churilov and Jovanoska, 2013). Detailing of the reinforced concrete retrofitted wall is shown in Figure 4.7.

Same procedure was followed for the RC retrofitting purpose. This steel reinforcement was arranged as a vertical and horizontal square mesh of 10mm diameter bars, spaced at 150mm c/c (Figure 4.7). 8 mm dia shear keys were installed spanning 1000 mm in both directions. They are affixed 75mm into the surface of the exiting masonry wall by epoxy resin. Before concrete casting surface bonding reagents was applied to bind the new concrete with the existing surface. The placement and spacing of the shear keys (in case of RC jacketing) should be such that those are to be inserted in mortar joints of the masonry walls and not in bricks in order to prevent cracks in the bricks. Material properties and detailing of the reinforcement is shown in Table 18 and Table 19.

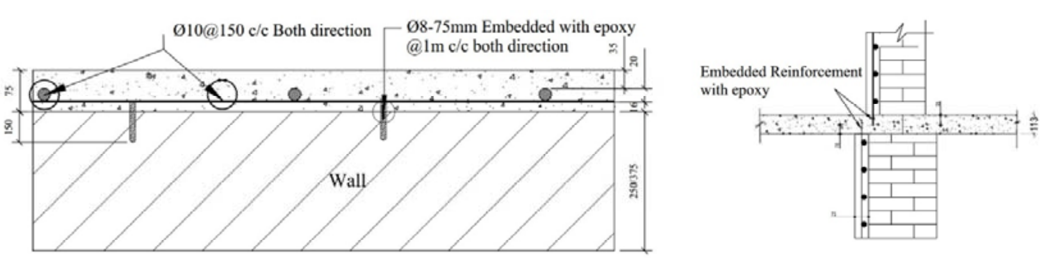


Figure 4.7: Detailing of reinforced concrete wall retrofit

Table 18: Material propertied of retrofitting materials

Material Properties	
Yield strength of steel deformed bar:	500 MPa
Compressive strength of concrete:	34.5 MPa

Concrete mix ratio:	1:1.2:1.7
Coarse aggregate:	5mm down stone chips
Fine aggregate:	100% Sylhet sand as fine aggregate
Admixture:	Super plasticizer

Table 19: Reinforced concrete overlay design requirement (BNBC 2017 loading)

Wall	Max. shear stress (psi)	V_u (lb/in)	Reinforcement Detailing	Final Design details
1A-1L	110	1100	#3 @ 187.5 mm c/c	#3 @ 6 inch c/c i.e. 10 mm @ 150 mm c/c Vertical and Horizontal direction
2A-2B	130	1300	#3 @ 187.5 mm c/c	
2C-2K	83	830	#3 @ 262.5 mm c/c	
A1-A2	54	540	#3 @ 462.5 mm c/c	
B1-B2	56	560	#3 @ 437.5 mm c/c	
C1-C2	73	730	#3 @ 312.5 mm c/c	
C4-C5	23	230	#3 @ 2525 mm c/c	
G1-G2	63	630	#3 @ 375 mm c/c	
K1-K2	45	450	#3 @ 612.5 mm c/c	

Retrofitting of Footing

After retrofitting, the building will be vertically extended upto 4 story. So, from a full 4-story finite element model, vertical reactions, F_z at the supports (along base of the wall) for unfactored gravity loads were extracted. With these, the additional load of the 3-inch RC jacket and wall footing below grade were added to find the total vertical load per unit length of the wall footing. Then it was converted to stress and compared to the allowable capacity (3.1 tsf for a factor of safety equal to 4) of the soil. Major portion of the existing wall footing was found to be inadequate against bearing capacity failure.

The most cost effective and viable retrofitting option is lateral extension of the entire strip of foundation. This was used to determine the required amount of extension to the footing width to comply with the allowable bearing capacity of 3.08 tsf.

Table 20: Required horizontal extension of strip footing

Elevation	Wall	Load per unit	Extension on Each	Governing

		length (kN/m)	Side (mm)	Extension (mm)
1	1A-1L	188.3	60.9	
	1L-1K	177.1	42.4	
2	2A-2B	283.6	219.9	
	2C-2K	250.0	163.8	
A	A1-A2	189.4	62.8	225 mm on each side
B	B1-B2	192.8	68.4	
C	C1-C2	205.8	90.2	
G	G1-G2	171.2	32.5	
K	K1-k2	164.4	21.2	

Table 20 shows the required extension for each wall. Horizontal extension was done in two increments. The retrofit stripes were casted using reinforced concrete, which was merged with the external 75mm thick retrofitted RC jacket above EGL.

Figure 4.8 shows the details of retrofitted strip footing. Baseline - existing ground level: As reinforcement 12 mm diameter L shaped bars were placed vertically along with straight horizontal bars at an equal spacing of 250 mm in both directions.

The reinforcement of the walls (for RC jacketing) are continued to the foundation. On the other side rebars are provided as temperature and shrinkage reinforcement.

At its base 2-12mm diameter horizontal rebar were used as corner reinforcement. These were set along the length of the strip foundation with shear key holding them in place. 12mm diameter shear key at 250mm spacing were used with an embedded length of 75mm. The shear keys were drilled in and fixed by epoxy.

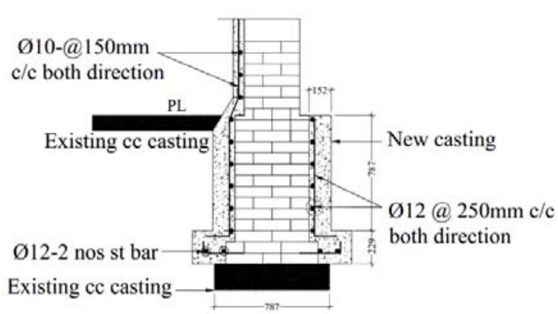


Figure 4.8: Strip footing detailing

Conclusion and Recommendation

To summarize, we can conclude that a case study has been presented here where a masonry building was selected for study. The detailed engineering assessment of the building was conducted as per the national building code which was followed by the retrofitting of the whole structure as required. The following points from the whole study are primarily outlined.

The stresses on the load bearing walls were investigated for the seismic loading of the both the versions of the national building code (BNBC 1993 and BNBC 2017) and it was found that the stress due to the loading of BNBC 2017 was much higher than that of BNBC 1993 due to a low response modification factor, R for masonry load bearing walls in BNBC 2017 compared to the 1993 version.

Alternative methods of retrofitting were proposed for the load bearing walls where it was also recommended that for higher stresses the ferrocement jacketing was not feasible for construction due to the requirement of more than two layers of wire mesh. For these cases, Reinforced Concrete Jacketing of the masonry load bearing walls turns out to be a handy solution to withstand high shear stress due to lateral load and at the same time it will contribute in resisting the gravity loading along with the existing wall.

The retrofitting of the inadequate beams was done by Reinforced concrete jacketing which increased the depth and the reinforcement of the beams resulting in increased flexural strength.

The sizes of the base of the wall footing were increased to reduce the stress under footing and keep it below the bearing capacity of the soil.

In case of newly cast concrete in walls, beams and footings for retrofitting, the shear keys were installed in all member to ensure load transfer between the existing and the newly built structural portions.

Thus, this study is expected to provide elaborate details of the assessment of the age-old masonry structures by Finite Element Analysis as well as the design and procedures of the required retrofitting of all the structural components involved.

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BANGLADESH NETWORK OFFICE FOR URBAN SAFETY

PART-VII

INTEGRATION OF EARTHQUAKE RISK SENSITIVITY IN LANDUSE PLANNING: AN APPROACH FOR AN AREA UNDER DEVELOPMENT AT LOCAL LEVEL

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1. Introduction

Earthquake is one of the most destructive natural hazards which occur less frequently than floods, but can affect much larger areas and can have long-lasting economic, social, and political effects (Akhter, 2010; Erdik, 2006; World Bank & EMI, 2014). In recent decades, earthquake risk in cities have increased due to the high rate of urbanization, unplanned growth, faulty land-use planning, poor construction practice, inadequate infrastructure and services provision and environmental degradation, which is again compounded due to unplanned urbanization and development in high-risk zone (Erdik, 2006). It is evident from the experiences of historical earthquakes in different countries that, the occurrence of an earthquake cannot be prevented but proper risk reduction and management measures can reduce the risk and consequences of this devastating event. In Japan, earthquake destruction especially during the Great East Japan Earthquake in 2011 could be reduced significantly compared to its magnitude through disaster risk reduction and management initiatives (Mimura et al., 2011; WBI, 2012). A good lesson learned from the comparative analysis of Haiti and the Chile earthquakes in 2010 reveals that, although the Chilean earthquake was 31 times stronger and released about 178 times more energy (need to check??) than the Haiti earthquake, the smaller quake produced more extensive damage in Haiti due to lack of disaster risk reduction and management initiatives (Bapat, 2010; Bárcena et al., 2010; DesRoches et al., 2011; Wayman, 2010).

In recent years, Risk-sensitive Land Use Planning (RSLUP) is getting significant importance among different approaches for disaster risk reduction and management. Landuse planning is a complex process to rationalize and regulate activities of individuals and groups in order to promote the sustainable use and development of land embracing both the natural and the built environment (WBI, 2006b). Sound and equitable landuse planning and management is very effective approach to ensure sustainable natural hazard mitigation to ensure lower disaster losses of human life, physical, environmental and institutional assets (Becker & Johnston, 2002; Becker et al., 2013; Fat-Helbary et al., 2004). Therefore in the process of landuse planning, consideration of disaster risk reduction and management is very important along with social, economic and environmental requirements of a society (WBI, 2006b). In general, the process of mainstreaming disaster risk management parameters in land use planning is termed as RSLUP. RSLUP promotes urban growth without generating new risks, helps identify and mitigate the root causes of disaster like those entrenched in existing land development practices, modifies and reduces vulnerable conditions of people and places, preempts disaster damage before it happens rather than cleaning up after, reduces vulnerability and losses of people and increases their ability to recover and hasten the process of reconstruction and rehabilitation (Godschalk et al., 1998; WBI, 2006e; World Bank & EMI, 2014). Hence RSLUP can play a significant role to reduce earthquake damage effectively (Olshansky, 2001).

RSLUP is more effective for application at local level as it can address the local issues in detail (Bendimerad & von Einsiedel, 2010; Erdik & Durukal, 2008; Fat-Helbary et al., 2004; Motamed et al., 2012). Application of RSLUP also depends on the state of development in an area. It is most convenient to apply RSLUP while planning for development in a new area (WBI, 2006e). In contrary, in case of developed area, the scope of RSLUP is very limited where some strategies for improvement or redevelopment can be proposed (WBI, 2006e, 2006f). In an area at development phase there is scope to apply RSLUP, but is challenging to some extent. It can be done through proper correction and modification of the proposed plan (Fat-Helbary et al., 2004). Therefore, study on RSLUP in an area under development at local level is necessary.

Numerous studies have been carried out in different countries on RSLUP, e.g. New Zealand (Becker & Johnston, 2002; Becker et al., 2013), Egypt (Fat-Helbary et al., 2004), Iran (Motamed et al., 2012), Taiwan (Hung et al., 2013), China (Kim & Rowe, 2013), India (Kamat, 2015), Nepal (EMI, 2010), Istanbul (Erdik & Durukal, 2008; Ilkisik et al., 2013; WBI, 2006d), Philippines (Bendimerad & von Einsiedel, 2010; Reyes, 2004; WBI, 2006a), etc. Burby, Deyle, Godschalk, and Olshansky (2000); and Hudson (2011) focused on implementation of RSLUP through policy initiatives by local, federal as well as state governments. Çabuk (2002); Wang (2012); and Hofer, Marquis, Veith, and Ceci (2013) studied and proposed approaches for RSLUP. Erdik and Durukal (2008); Becker and Johnston (2002) and Becker et al. (2013) investigated the integration of earthquake hazards in landuse plans and policy statements at the national level. Kim and Rowe (2013) and Kamat (2015) tested the effectiveness of integrating risk sensitivity in urban master plans to limit future development in disaster-prone areas considering earthquake as well as other hazards at the regional level. Bendimerad and von Einsiedel (2010); EMI (2010); Fat-Helbary et al. (2004); Hung et al. (2013); Motamed et al. (2012); Reyes (2004) integrated earthquake risk sensitivity in landuse planning at the city level. But none of the researches focused on earthquake RSLUP of an area under development at local level.

In this background this research aims to understand earthquake risk sensitivity of a landuse plan of an area at development phase at local level and to formulate RSLUP strategies to be incorporated in the landuse plan addressing the risk sensitivity.

2. Methodology of the study

2.1 Selection of the study area and reference area

The historical trend of seismicity and some recent tremors occurred in Bangladesh and adjoining areas indicate that the country is at high risk of exposure to potential earthquake (Akhter, 2010; European Commission, 2017; Kamal, 2013; Roy, 2014). Dhaka, the capital city of Bangladesh is experiencing unplanned land-use without disaster risk consideration, and violation of building codes and by-laws (Hasnat & Hoque, 2016; World Bank & EMI, 2014). Such rapid and uncontrolled urbanization is increasing the vulnerability of populations and infrastructure (CDMP, 2009b; UDD & ADPC, 2016; World Bank & EMI, 2014). Therefore different national and international studies have identified Dhaka to be highly vulnerable to earthquake (Davidson & Shah, 1997; Davidson et al., 2000; Kamal, 2013; RADIUS, 2000). Considering the earthquake vulnerability of Dhaka city, several researches have been carried out focusing on earthquake risk assessment and management (Ahmed et al., 2012; Ansary et al., 2004; Jahan, 2010; Rahman et al., 2012; Rahman et al., 2015; Sadat et al., 2010). Several initiatives have been taken by the Government of the Republic of Bangladesh (GoB) for integrating risk sensitivity in landuse planning process for sub-districts and municipalities, Mymensingh Town, and Rajshahi Metropolitan area (RDA, 2019; UDD, 2011, 2013; UDD & ADPC, 2016). But none of the researches focused on earthquake RSLUP in Bangladesh.

The URMT is one of the township projects initiated by Capital Development Authority (RAJUK) (RAJUK, 2016). The purpose of such housing projects are to reduce the pressure of population in Dhaka city; maintain the balance of environment by proper urbanization; reduce the existing acute problem of housing; expand civic facilities; development of new township and expansion of economic facilities; and solve future housing demand (RAJUK, 2016). The URMT project was planned to be developed in three phases (i.e. 1st, 2nd and 3rd). Among them, the first phase was started in 1966 and completed by around 1992. Immediately after the completion of first phase, the second phase was initiated and was completed by around 1998. It consists of 1.77 square km land and is divided into four sectors (i.e. 11, 12, 13 and 14). Under the project area, 5152 housing plots were allotted. Among them about 1000 plots are still vacant (Field survey, 2016). Thus till date 80% development of buildings has been completed in the area.

At present, the third phase of URMT is under development process (RAJUK, 2010, 2016). It is located in northern part of Dhaka Metropolitan area, which has been identified as highly earthquake prone area (EMI, 2014). The project area of the study area includes around 9.11 square kilometer land. It is divided into four sectors, i.e. 15, 16, 17 and 18. Additionally, separate area is selected for commercial purpose designated as “Central Plaza”. Figure 1 shows the sectors in the study area. The four sectors are further divided into 40 neighborhoods. According to the present development trend in Bangladesh, the current land development projects of public agencies are allocating a part of the projects for multistoried apartment block housing schemes (Shamsuzzaman, 2014). Consistent with this trend, gross area of 0.87 square kilometer of land in the study area is allocated for multi-storied apartment buildings titled “Uttara Apartment Project”, which is designated in sector 18. Based on the size of apartments to be provided, the sector is divided into three blocks (Block A, B, and C) according to the proposed plan.

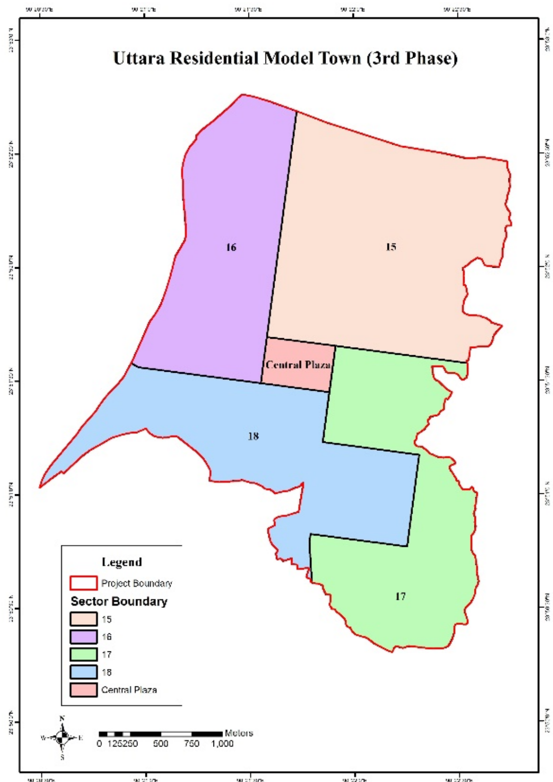
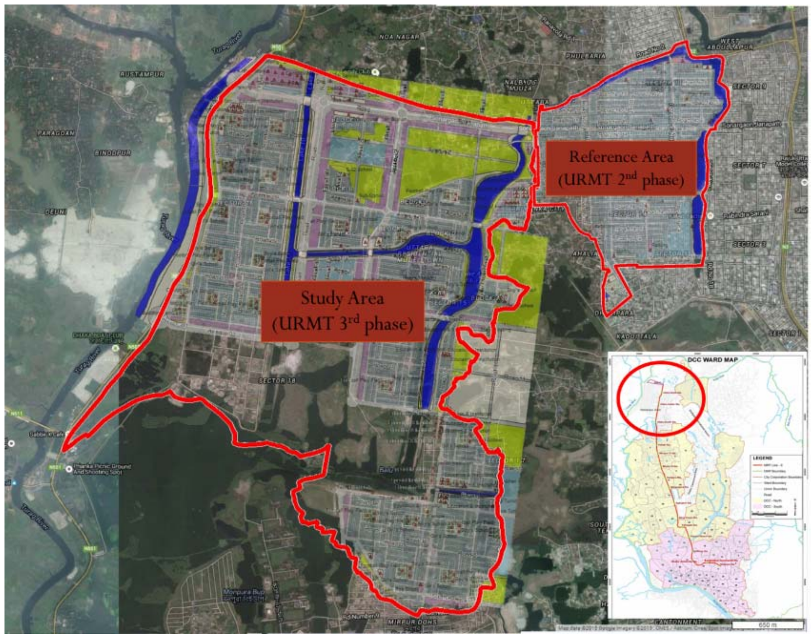


Figure 1: Sectors in the study area (URMT 3rd phase)

According to RAJUK (2016), land development works in the study area has mostly been completed. About 92% of site development work has already been done and about 70% road construction work has already been completed. The construction of apartment buildings in Block A (Sector 18) is at the final phase and these apartments have already been allocated. Dhaka Electricity Supply Co. (DESCO) is doing the electrification work of the project area as deposit work who will take necessary action to connect and supply of electricity as per allotter's demand. Electric poles have already been partially installed in all sectors. Dhaka WASA will execute the work of water supply in the study area as deposit work and construction of deep tube well and pipeline network will start soon. Gas line installation work will be executed with the consultation with TITAS Gas Company. Remaining work is in progress. So, still there is scope to reduce earthquake risk in this area through revision of the landuse plan integrating RSLUP strategies. Considering these conditions, third phase of URMT has been selected as the study area for this research.

To understand the earthquake risk of the study area, it is necessary to study the development trend (consistency of landuse with proposed plan and trend of building height) and earthquake vulnerability of the building stocks. But the study area selected for this research is at development phase. Therefore, it is necessary to select a recently developed area assuming that similar development will take place in the study area, considering it as the reference area for this research. For this purpose, the second phase of URMT has been considered as the reference area in this research. Figure 2 shows satellite image of the study area (URMT 3rd phase) and the reference area (URMT 2nd phase) along with their location in Dhaka city in the inset. From the figure it can be observed that the study area and the reference area are located in the north-western part of Dhaka city.



Source: Google Satellite Image (2016) and RAJUK (2016)

Figure 2: Satellite image and location of the study area (URMT 3rd phase) and the reference area (URMT 2nd phase)

2.2 Data collection and processing

Necessary data required for this research have been collected from secondary and primary sources. Landuse map of the study area (Third Phase of URMT) and reference area (Second Phase of URMT) have been collected from RAJUK (RAJUK, 2010, 2016). The GIS shapefiles of geomorphology and suitability of structures considering the geomorphic unit of Dhaka Metropolitan area have been collected from Geological Survey Of Bangladesh (GSB) (GSB, 2016). Furthermore, the map of Detailed Area Plan (DAP) for Dhaka Metropolitan area has been collected from RAJUK (RAJUK, 2011). From these collected resources, data of the study area have been extracted for this research.

Primary data have been collected mainly from the reference area (Second Phase of URMT) to understand development trend and earthquake vulnerability of the building stocks. The time frame of the surveys has been September 2016 to December 2016. To understand development trend in the reference area, a field survey has been carried out to collect data regarding present landuse, vacant plots and building information (building use and number of storey). To assess earthquake vulnerability of buildings in the reference area, a survey has been conducted for sample buildings. Total number of buildings in the reference area is 3,777 [4152??] (Field survey, 2016). To conduct the survey, a sample size of 360 buildings has been taken considering the confidence level at 95% and confidence interval at five. Samples have been chosen in the reference area through stratified random systematic sampling in two steps. At first step, samples have been distributed in the reference area according to the proportion of buildings in each of the four sectors. At the second step, samples in each of the four sectors have been distributed on the basis of the proportion of buildings according to plot size and number of stories. To ensure even distribution of the samples in the reference area, sample buildings have been chosen from each of the road segments in the sectors accordingly. After selection of sample buildings in the reference area, a sidewalk survey with visual inspection and limited data collection has been utilized to collect building-related information for earthquake vulnerability assessment.

2.3 Assessment of earthquake risk sensitivity of the landuse plan of the study area

The study area is at the risk for exposure to potential earthquake (EMI, 2014). So to formulate earthquake RSLUP strategies to be integrated in the landuse plan of the study area, it has been necessary firstly to understand its risk sensitivity. The evaluation has been done on the basis of some risk sectors or risk themes. Risk sectors or themes are distinctly manageable clusters of probabilities and vulnerabilities for which a coordinated approach action is necessary through exploration of risk factors in each sector (WBI, 2006f). World Bank and EMI (2014) has proposed some risk themes and their corresponding risk factors in Risk-Sensitive Land Use Planning Guidebook for Dhaka city under Bangladesh Urban Earthquake Resilience Project. Considering the context of this research and the status of development of the study area, eight of the risk themes and their corresponding risk factors have been selected. The landuse plan of the study area has been analyzed from the perspectives of these risk themes and corresponding factors to understand it's risk sensitivity to earthquake. Table 1 shows risk themes, risk factors and corresponding methodology for analysis of earthquake risk sensitivity of the landuse plan of the study area. Need to mention Table 2 somewhere???

Table 1: Risk themes, risk factors and corresponding methodology for analysis

Risk themes	Risk factors	Methodology
1. Macro-form risks	1.1 Development and settlement pattern in the highhazard-prone zone	Landuse plan of the study area.
	1.2 Connectedness to the rest of the city	Primary road network in the study area for disaster management with support from the city center.
2. Risks in urban texture	2.1 Availability of resources	Natural resources in the landuse plan of the study area. For utilization in emergency.
	2.2 Interconnectedness in the area as means of escape and access to rescue and relief	Internal road network and width in the study area for means of escape and access to rescue and relief after an earthquake.
	2.3 Width of roads	
3. Risks in land-use incompatibilities	3.1 Landuse incompatibilities in the plan	Allocation of land for different use as well as their comparative placement in the plan of the study area with respect to classification of landuse zones as per Table 2. To reduces risk and ensure effective disaster management.
	3.2 Consistency of development with the landuse plan in reference area	Assessment of present landuse with respect to plan in the reference area (Second Phase of URMT) based on collected primary data. To ensure execution of the plan accordingly.
4. Risks in hazardous uses	4.1 Hazardous landuse (LPG and petrol stations, chemicals, explosives, power plant, etc.) and landuse within 200m radius around them	To avoid secondary hazards (explosion, fire, pollution, etc.), development within 200-meter radius of the hazardous uses should be restricted (Argo & Sandstrom, 2014; Brender, Maantay, & Chakraborty, 2011; MfE New Zealand, 2002). Analysis was done by creating buffers of 200-meter around the hazardous uses in the landuse plan of the study area using "Create Buffer" tool in ArcGIS 10.3.1.
5. Special risk areas	5.1 Geomorphologic condition	Soil condition for development in the study area. Soil unsuitable for development lead to greater damage after an earthquake.
	5.2 Designated water bodies and flood flow zones and corresponding landuse in plan	Condition of water bodies and flood flow zones in the landuse plan of the study area with respect to the proposal in Detailed Area Plan (DAP) by RAJUK (RAJUK, 2011). If not preserved, it increases risk for exposure to liquefaction and flood.
6. Risks in building stocks	6.1 Vulnerability of building stocks in reference area	Preliminary building vulnerability assessment in the reference area (Second Phase of URMT) based on collected primary data (Discussed in the next section).
7. Open space scarcity risk	7.1 Interconnectedness and adequacy of open space (park, play-fields, green space, car-park, etc.)	Open spaces in the landuse plan of the study area with respect to Private Housing Project Land Development Rule, 2004 (MoHPW GoB, 2004), requirement to be used for evacuation space (one square meter space per person) (CDMP, 2009a; Xu, Okada, He, & Hatayama, 2006) and interconnectedness among them.
8. Risks in critical facilities	8.1 Adequacy of critical facilities (health, education, community centers, fire service stations, etc.)	Educational facility, community centers, government offices, religious facilities, etc. in the landuse plan of the study area with respect to Private Housing Project Land Development Rule, 2004 (MoHPW GoB, 2004) and requirement to be used for evacuation space (one square meter space per person) (CDMP, 2009a; Xu et al., 2006). Health facilities in the landuse plan of the study area with respect to Private Housing Project Land Development Rule, 2004 (MoHPW GoB, 2004) for emergency response after an earthquake. Fire service station in the landuse plan of the study area considering 3-kilometer service area around a station (Tishi, 2015). Analysis was done by creating buffers of 3-kilometer around the hazardous uses in the landuse plan of the study area using "Create Buffer" tool in ArcGIS 10.3.1.

Table 2: Classification of landuse zones

Zone	Permitted use	Conditional use	Restricted use
Residential	Residence	Small business shops (e.g. confectionary shop, corner shop)	Commercial; Industrial; Any type of polluting activities
Commercial	General merchandise store (e.g. food market, books and office supplies, etc.)	Light industries with limited manpower or types	Residence; Educational (e.g. school, college, etc.)
Industrial	Heavy, medium and light industries	Commercial with limited categories	Residence; Educational (e.g. school, college, etc.)
Educational	School; College; University	Student dormitory	Commercial; Industrial; Residential
Agriculture	Agriculture; Forestry; Gardening	Fisheries; Livestock	Commercial; Industrial; Residential
Open space (recognized formal areas)	Park; Playground; Lake; Zoo	Temporary structures with light activities	Commercial; Industrial; Residential
Mixed use	Combination of residential, commercial, offices, etc.		Industrial
No development zone (hazard-prone)	Temporary use, e.g. agriculture, gardening, forestry	Temporary structures with light activities	Commercial; Industrial; Residential
Urban reserve (risk-prone area)	Existing uses with no further extension	Improvement of existing structures	Any type of new construction

Source: Adapted from UDD and ADPC (2016)

2.4 Preliminary building vulnerability assessment in the reference area

After an earthquake, impacts in urban areas are greater due to the collapse of buildings. Vulnerable buildings increase the risk of damage and loss. Earthquake vulnerability assessment of building stocks is a very difficult and time-consuming process. Preliminary inspection or simplified assessment procedures require limited engineering analysis based on information from visual observations and structural drawings or on-site measurements to get a gross impression about the structure requiring. Among different methods for preliminary earthquake vulnerability assessment of building stocks, Federal Emergency Management Agency- Rapid Visual Screening (FEMA-RVS) (Level I) and Turkish Simple Survey Procedure (Level I) are the most commonly used (FEMA, 2015; Sucuoğlu & Yazgan, 2003a, 2003b; Sucuoğlu et al., 2007). Considering the suitability, several studies have utilized these methods for preliminary earthquake vulnerability assessment of buildings (Kumar et al., , 2017; Srikanth et al., 2010). These have also been utilized in some studies in Bangladesh (Alam et al., 2008; Jahan, 2010; Rahman et al., 2015; Sadat et al., 2010; Sarraz et al., 2015). Therefore, to get a simplified image of building vulnerability in the reference area, preliminary inspection has been carried out in this research.

For FEMA-RVS, the data collection form for moderate seismic zone was utilized as Dhaka falls in the moderate seismic zone (BNBC Draft, 2020). The building attributes observed are: number of storey, building type, vertical irregularity and plan irregularity (FEMA, 2015). Vertical irregularity is identified if one part of the building expands vertically than the other part leading to shift in centroid resulting in reduction of its strength to hold the building during an earthquake (FEMA, 2015). Deviation of building floor plan from a rectangular plan is called plan irregularity, which leads to irregularities in stiffness and strength distributions of buildings increasing the risk of damage during strong ground excitations (FEMA, 2015; Jahan, 2010). Based on collected attributes, building vulnerability scores of sample buildings were calculated through modification of the basic structural hazard score by adding (or subtracting) score modifiers related to observe performance attributes. After that, the buildings have been categorized into five grades based on their corresponding RVS scores reflecting likely seismic damage as per European Macro Seismic Scale (EMS-98) (Table 3).

Table 3: Different damage grades corresponding to RVS scores of buildings

RVS score (S)	Grade	Explanation	Likely damage
S<0.3	**1**	Negligible to slight damage: No structural damage, slight non-structural damage	Fine or hairline cracks in plaster over frame members, walls at the base, or partitions and infills. Fall of small pieces of plaster or loose stones from upper parts of buildings in very few cases.
0.3<S<0.7	**2**	Moderate damage: Slight structural damage, moderate non-structural damage	Cracks in columns and beams of frames, structural walls, or partition and infill walls. Fall of brittle cladding and plaster, mortar from the joints of the wall panel.
0.7<S<2.0	**3**	Substantial damage: Moderate structural damage, heavy non-structural damage	Cracks in columns and beam-column joints of frames at the base and at joints of coupled walls. Large cracks in partition and infill walls. Failure of individual infill panels or non-structural elements (partitions, gable walls etc.). Roof tiles detach. Spalling of concrete cover, buckling of reinforced bars.
2.0<S<3.0	**4**	Heavy damage: Moderate structural damage, heavy non-structural damage	Large cracks in structural elements with compression failure of concrete and fractures of reinforcement bars. Bond failure of bars, tilting of columns. The collapse of a few columns or of a single upper floor. Serious failure of walls. Partial structural failure of roofs and walls.
S>3.0	**5**	Destruction: Very heavy structural damage	The collapse of ground floor parts (e.g. wings of the building). Total or near total collapse of a building.

Source: Adapted from (FEMA, 2015; Jahan, 2010)

The building attributes observed for Turkish simple survey are: number of storey, presence of a soft storey, presence of heavy overhangs, presence of short column, possible pounding between adjacent buildings, and apparent building quality (Sucuoğlu & Yazgan, 2003a, 2003b; Sucuoğlu et al., 2007). If a building has a floor which is open in character (for parking garages, retail space or simply a floor with a lot of windows) making it 70% less stiff than the floors above it, then it is considered as a soft storey building. Soft storey lead to lesser opportunities to install shear walls to distribute lateral forces resulting in reduction of capacity to cope with the lateral forces caused by the swaying of the building during a quake (Sucuoğlu & Yazgan, 2003a, 2003b; Sucuoğlu et al., 2007). Heavy overhang is observed in the form of heavy balconies or over hangings floors in buildings shifting the mass center upwards and giving rise to increased seismic lateral forces and overturning moments during earthquakes (Ozcebe et al., . Apparent building quality can be judged by observing the material and workmanship quality and the care given to its maintenance, where it is assumed that buildings with poor apparent building quality possess weak material strengths and inadequate detailing (Sucuoğlu & Yazgan, 2003a, 2003b; Sucuoğlu et al., 2007). Structural columns which are short in length relative to other columns on a particular storey of buildings are considered short columns, which may fail during an earthquake either by being crushed due to compression or by bending due to their greater stiffness (Sucuoğlu & Yazgan, 2003a, 2003b; Sucuoğlu et al., 2007). Pounding between two adjacent buildings is one of the main causes of building damages in an earthquake, which occurs when the separation distance between adjacent buildings is not large enough to accommodate the relative motion during earthquake events (WBI, 2006f).

In Turkish simple survey method, three types of building vulnerability assessment scores have been developed for three seismic intensity zones in terms of probable Peak Ground Velocity (PGV), i.e. Zone I (60<PGV<80), Zone II (40<PGV<60), and Zone III (20<PGV<40) (Sucuoğlu & Yazgan, 2003a, 2003b; Sucuoğlu et al., 2007). Dhaka falls in Zone II (BNBC, 1993), which has been followed in this research. Based on the vulnerability parameters of sample buildings in the reference area obtained from survey, the vulnerability scores have been calculated by adding (or subtracting) them accordingly (Sucuoğlu & Yazgan, 2003a, 2003b; Sucuoğlu et al., 2007). After that, the buildings have been categorized into four damage states based on their corresponding Turkish simple survey scores reflecting likely seismic damage (Table 4).

Table 4: Possible damage states corresponding to Turkish simple survey scores

Turkish simple survey (Level 1) score	Damage State	Likely damage
>=100	None	No visual sign of damage
80-100	Light	Hairline incline or flexural cracks in the wall. Flaking of plaster.
50-80	Moderate	Concrete sealing. Cracking in walls and joints between panels.
0-50	Severe or Collapse	Wide and through cracks in the wall. Crushing of walls or out of plane toppling of walls. Local structural failure and local or total collapse.

Source: (Sucuoğlu & Yazgan, 2003a, 2003b; Sucuoğlu et al., 2007)

After score calculation, building vulnerability components and vulnerability have been analyzed through frequency distribution and correlation testing in SPSS 17 and Microsoft Excel 2013. Correlation among the vulnerability components and vulnerability have been carried out using non-parametric Spearman's rho technique because they are discrete ordered data.

2.5 Formulation of earthquake RSLUP strategies

After assessment of risk sensitivity of the landuse plan of the study area, the earthquake RSLUP strategies to be incorporated in the landuse plan have been formulated. For this purpose, firstly, review of the strategies have been done from different literature. After that key informant interviews have been carried out to understand their expert opinion in this regard. While interviewing the experts, findings from earthquake risk sensitivity of the landuse plan of the study area have been explained to give them a brief understanding about the purpose of the interview. Based on literature review and findings from the key informant interviews, earthquake RSLUP strategies to be incorporated in the landuse plan have been formulated addressing the risk sensitivity accordingly.

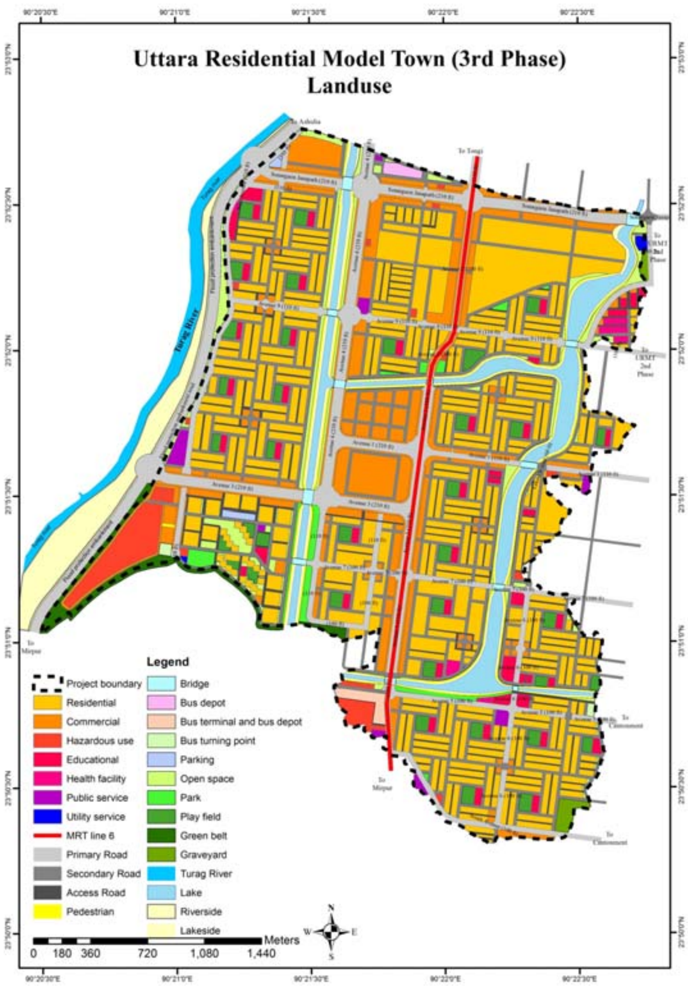
3. Earthquake risk sensitivity of the landuse plan of the study area

The earthquake risk sensitivity of the proposed landuse plan of the study area is described as per the risk themes in the following sections.

3.1 Macro-form risks

Figure 3 shows the landuse plan of the study area proposed by RAJUK. The landuse in the study area has been planned considering grid pattern. Here different uses have been allocated by RAJUK on the basis of 'Private Housing Land Development Rule, 2004' (MoHPW GoB, 2004) to ensure minimum land for urban community facilities in the area which will improve the living quality (Shamsuzzaman, 2014). The proposed density of the study area is 300 persons per acre and projected total population to be accommodated within its area is around 0.65 million people (Shamsuzzaman, 2014).

Among different uses shown in Figure 3, most significant uses of total area are road network (33.73%), residential (33.39%) and commercial (11.81%). Mainly five categories of residential landuse have been proposed including residential plots, public residential high-rise apartment, private residential housing apartment, government staff housing, and accommodation for urban poor. The commercial landuse in the area includes central business district (CBD), plaza, warehouse and kitchen market for the study area as a whole, commercial plots (along the primary roads surrounding the neighborhoods), and neighborhood shops, centers and plaza at neighborhood level to maintain hierarchy of commercial use. Rest of the uses include communication (road network), hazardous uses, critical facilities (educational, health and public service), utility service, and water body and open space. From the overall landuse allocation in the plan of the study area, it can be said that the allocated uses are suitable for earthquake risk management but these uses should be resilient to earthquake



Source: Adapted from RAJUK (2010)

Figure 3: Landuse plan of the study area

.From the analysis of road network, it could be found that, there are mainly twelve primary roads in the study area connecting it with the city. In addition to the primary roads, there is the western Dhaka flood protection embankment road constructed on the east bank of the Turag river, which is located at the west side of the study area. Additionally, the proposed route of Metro Rail Transit (MRT) line six is going through the study area. Table 5 shows the primary road segments connecting the study area with the rest of the city along with their width, connectedness, and direction.

Table 5: Primary road segments connecting the study area with the city

Primary road segment name	Road width	Connectedness	Direction
Sonargaon Janapath	210 ft	Flood protection embankment – URMT 2nd phase	East - West
Avenue 1	110 ft to 210 ft	Avenue 4 - URMT 2nd phase	East - West
Avenue 2	100 ft	Avenue 3 -Ashulia and Tongi	North-South
Avenue 3	100 ft to 210 ft	Flood protection embankment - Avenue 2 - Mirpur	East - West
Avenue 4	210 ft	Avenue 3 -Ashulia and Tongi	North-South
Avenue 5	100 ft	Avenue 3 - Cantonment	East - West

Avenue 6	100 ft	Avenue 7 - Avenue 5 - South Avenue	North-South
Avenue 7	100 ft	Avenue 3 - Cantonment	East-West
Avenue 8 and Avenue 9	110 ft	West Avenue - Avenue 4 - Avenue 2 - URMT 2nd phase	East-West
West Avenue	110 ft	Avenue 3 -Ashulia and Tongi (Parallel to Flood protection embankment road)	North-South
South Avenue	100 ft	Avenue 3 - Avenue 6 - Cantonment	East-West
Flood protection embankment road	200 ft	Ashulia - Mirpur	North-South
MRT line 6	Metro rail	Uttara - Mirpur - Farmgate - Karwan Bazar - Shahbag–Motijheel	North-South

From Figure 3 and Table 4, it can be observed that in the east-west direction the primary road network connects the study area with URMT Second Phase and channel the traffic towards flood protection embankment road. Again in the north-south direction, there is only two continuous primary road network including flood protection embankment road and MRT line six. Among them, MRT line six has limited points of access with fixed stations. Avenue 4 connects the area with Ashulia in the north direction, but it is not continuous in south direction. Thus, at the time of emergency situation, there will be excessive pressure on flood protection embankment road. Furthermore, there are some points of intersection where bottlenecks are created due to change in road width. All these factors will hamper the response, rescue, and relief after an earthquake with support, control and guidance from the city center.

3.2 Risks in urban texture

The roads in the landuse plan of the study area are arranged in a grid pattern, where road width varies between 20 ft. to 210 ft. (Figure 3). There are three hierarchies of roads including access road (connecting the plots and different landuse: width varying from 20 ft. to 50 ft.), secondary road (connecting different neighborhoods: width varying from 60 ft. to 70 ft.) and primary road (connecting secondary roads and city center: width varying from 100 ft. to 210 ft.). Along with roads for vehicular movement, there are provisions for walkways beside the lakes which also act as a buffer between the lakes and the residential areas. Moreover, there are twelve bridges over the lakes proposed in the plan to connect the roads over water bodies without interrupting them.

From the analysis of the internal road network and their width, it can be concluded that the proposed grid patterned road network ensures interconnectedness within the study area (Dill, 2004). Additionally, the widths of the proposed roads are sufficient for emergency movement within the area. This will further confirm means of escape and access to rescue and relief after an earthquake. Though the internal road network is well connected with sufficient road width, some roads are planned over lakes connected by bridges and culverts. If any of them are damaged, then it will create interruption of vehicle movement and thereby cause more congestion. The interconnected lakes and walkways along them can also be utilized as an alternative to road transport. It will reduce some pressure on road network at the time of emergency. These waterbodies can be utilized as a source of water at the time of emergency for different purposes.

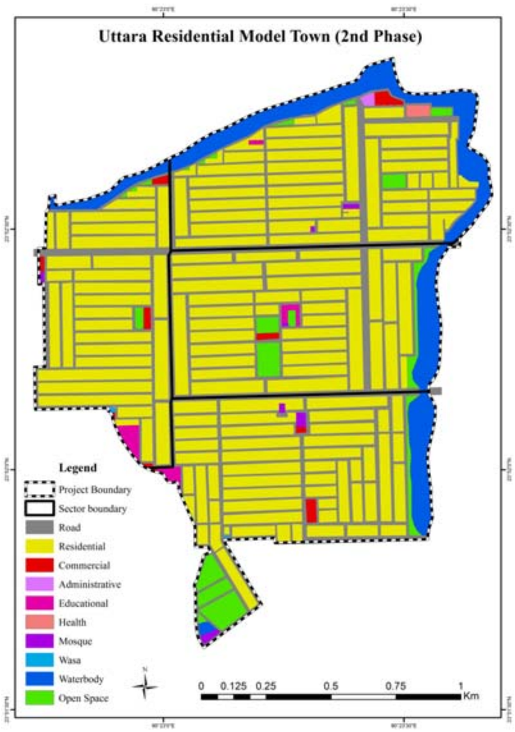
3.3 Risks in landuse incompatibilities

The study area has been divided into four sectors which have been further arranged into 40 neighborhoods. The neighborhoods have been planned consisting of residential plots, commercial plots, educational and recreation facilitates. For major commercial uses, a central plaza has been proposed and the plots along the primary roads have been designated for commercial purposes. Additionally, other uses (e.g. bus depots, parking facility, waste management facility, power grid, etc.) have been kept outside the neighborhoods. Thus, the landuse in the study area has been planned considering compatibility among different uses.

Consistency of the development with proposed plan has been analyzed in the reference area. From the analysis it could be observed that landuse of about 7.73% plots have been changed by plot owners. Most significant change is conversion of residential plots into commercial use, that of residential and commercial to educational. Figure 4 shows consistency of the development with proposed plan in the reference area showing proposed landuse and existing landuse. From this analysis it can be said that the landuse is changing violating the proposed one. If similar trend continues in the study area, then it will increase risk of the area to earthquake.

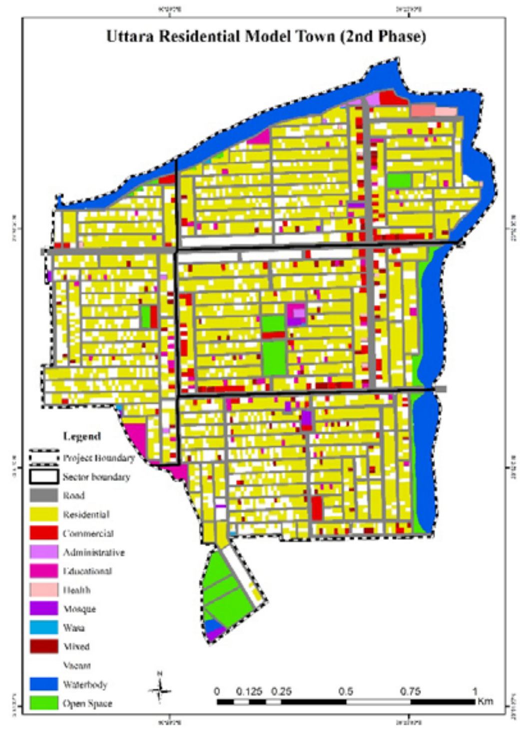
3.4 Risks in hazardous uses

In the study area, hazardous landuse comprise of 2.25% of total area. There are together nine proposed gas stations and petrol pumps, collectively six power and substations proposed, MRT depot, provision for waste management and recycle area in 0.13 square kilometer land, and a water treatment plant with an area of 0.03 square kilometer. Figure 5 shows location of these hazardous uses and landuse within 200-meter buffer area surrounding them in the study area. From the map, it can be observed that there are residential, commercial, educational and public services within the buffer area which represents a higher risk of these areas to the earthquake. Additionally, a portion of the MRT line six lies within the buffer area which represents greater risk.



Source: RAJUK (2016)

Figure 4a: Proposed landuse



Source: Field Survey (2016)

Figure 4b: Existing landuse

Figure 4: Consistency of the development with proposed plan in the reference area

3.5 Special risk areas

Figure 6 shows the geomorphology of the study area including geomorphologic composition and the suitability for construction on the analyzed on the basis of geomorphologic composition by GSB. From the figure, it is visible that major portion of the study area (about 67.1%) consist of floodplain, marshy land and depression, and Madhupur terrace. Therefore, about 71.21% of the study area comprise of very weak foundation condition for which specialized foundation design is required, 17.58% is in weak foundation condition for which pile foundation is required, and 11.21% is suitable for all kind of infrastructure.

In consistent with this analysis, the soil test in MRT depot located in the study area by Dhaka Mass Transit Company Ltd. (DMTCL) found that the soil condition is unfit for erecting necessary infrastructures including MRT workshops, administrative building, washing plant and rolling stocks. Thus, a project for land development of MRT depot located in the study area has already been implemented by Dhaka Mass Transit Company Ltd. (DMTCL) costing around 560 million BDT to make around 50 acres of land fit for taking load of infrastructures for 100 years (from 2016 to 2018). According to DMTCL, dynamic compaction and sand piling compaction have been done through compaction of land with sand and soil layer by layer (DMTCL, 2018). Thus, the geomorphic condition increases risk of landuse in the study area.

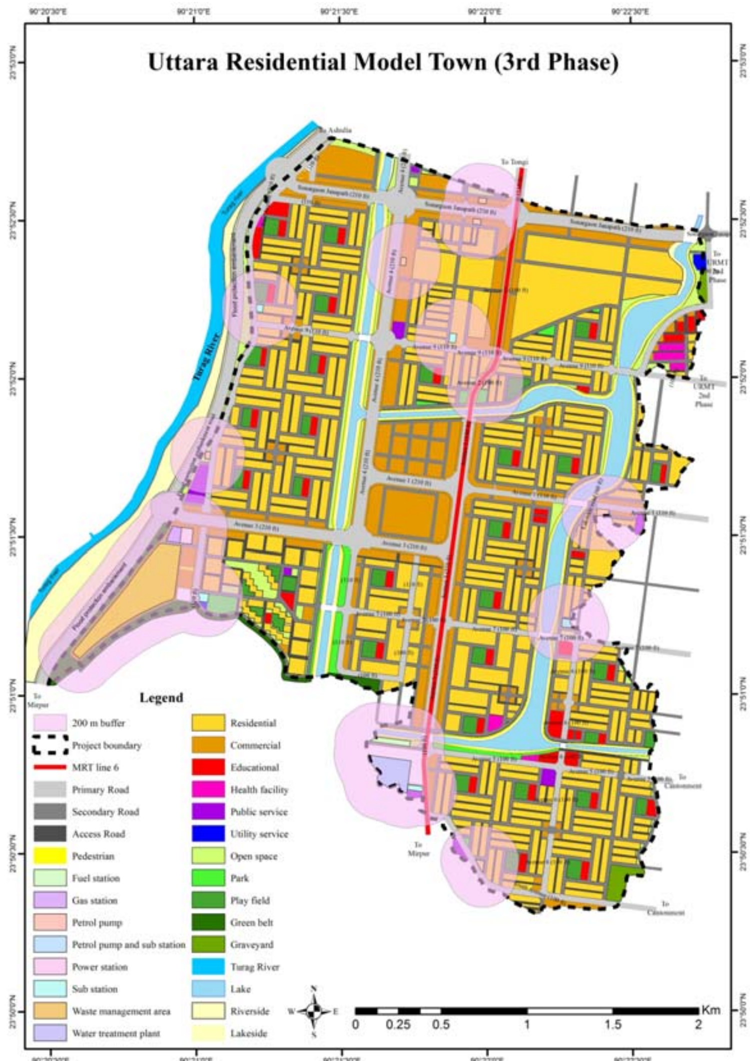
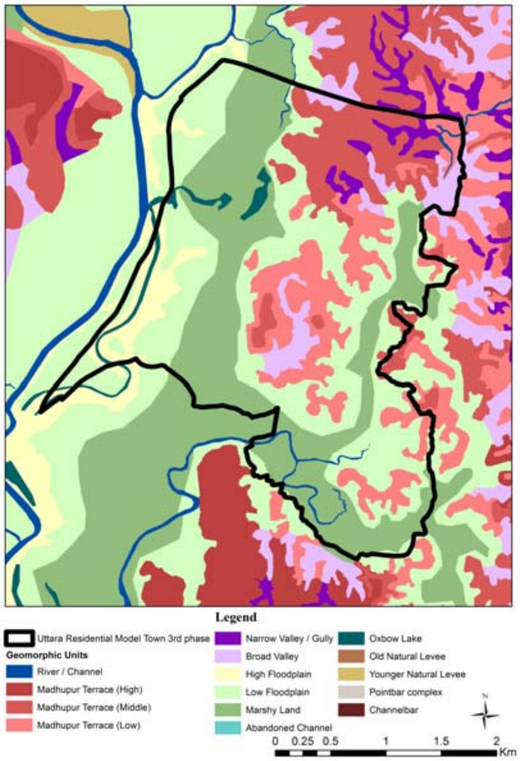


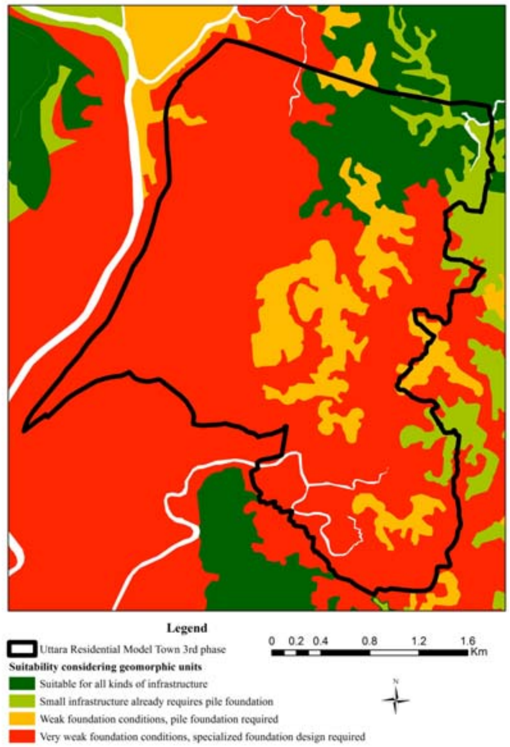
Figure 5: Location of hazardous uses and surrounding landuse in the study area

From the analysis of waterbodies in the landuse plan of the study area, it can be observed that there are interconnected lakes proposed to be preserved by RAJUK comprising of about 7.67% of total study area. Though the amount of water bodies proposed to be preserved seems to be suitable to address the risk, while comparing with the proposal of DAP it has been found that some waterbodies proposed in DAP to be preserved have not been preserved. Figure 7 shows the water bodies in the study area designated in DAP but not addressed in the proposed landuse plan. Thus, all the designated water bodies have not been addressed in the proposed plan which may have entailed increased vulnerability to earthquake hazard in those areas. Thus it may increase risk of landuse to earthquake.



Source: GSB (2016)

Figure 6a: Geomorphologic composition



Source: GSB (2016)

Figure 6b: Suitability for construction considering geomorphic composition

3.6 Risks in building stocks

Earthquake risk in building stocks of the reference area (Second Phase of URMT) was assessed assuming that similar situation would appear in the study area if development trend remains same. Majority of the buildings in the reference area are RCC with very few masonry buildings. Height of the buildings range from one storied to 11 storied. About 70% of them are 6-storied. The reason is that, till 2006 the building height was restricted up to six storey by the government due to its close proximity from the airport. After 2006 the restriction was withdrawn. In 2008 the “Dhaka Mahanagar Building (Construction, Development, Protection and Removal) Rule 2008” was amended which regulated building construction by Floor Area Ratio (FAR) (MoHPW GoB, 2008). This enabled construction of high rise buildings maintaining FAR ratio. Thus, after 2008 rate of construction of high rise buildings in the area increased. Figure 8 shows the distribution of buildings with respect to number of storey in the reference area.

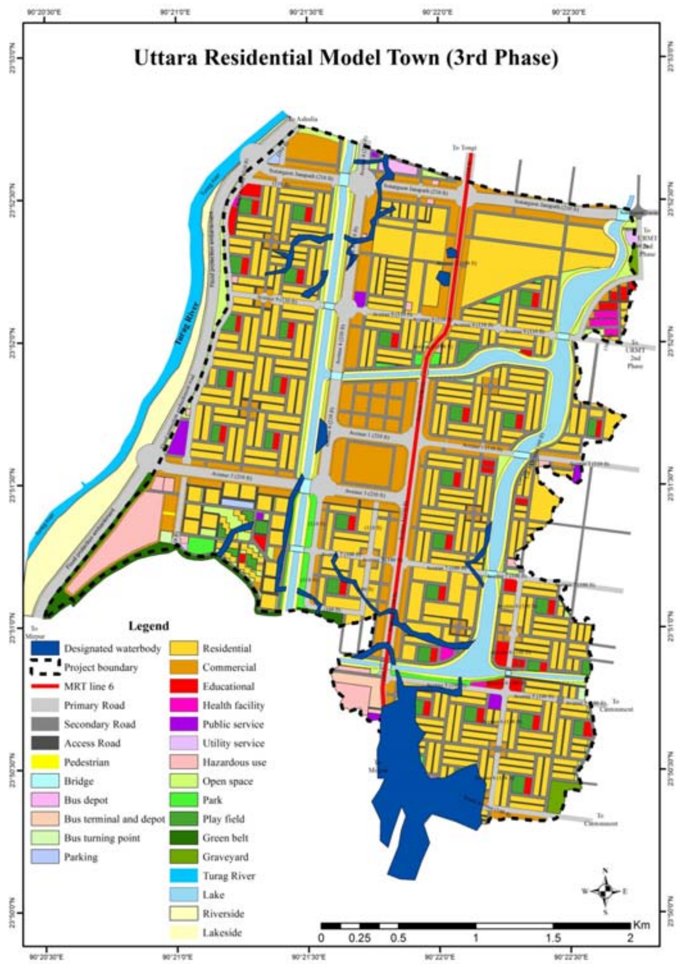


Figure 7: DAP designated water bodies not addressed in the proposed plan of the study area

All of the plots in the reference area are regular shaped (rectangular). But most of the buildings have extended portions for veranda as well as irregular shape or extended portions to enhance architectural beauty. These practices have led to the problem of vertical irregularity, plan irregularity as well as heavy overhang. Thus, among the sample buildings in the reference area, 85% buildings have problem of severe vertical irregularity, 76.1% of the buildings have heavy overhang problem and about 64.4% of the buildings have problem of plan irregularity. These problems also increase mass of buildings leading to vulnerability. Around 84.7% have the problem of soft storey as the ground floors of these buildings are used for car parking. Very few buildings in the reference area have problem of short column (16.4%) and none of the buildings have pounding effect. The reason behind such finding is that all of the buildings in the reference area have minimum gap with other surrounding buildings as per requirement (MoHPW GoB, 2008). The buildings in this area have mostly been built after the year of 2000. So apparent quality of most of the buildings are good (24.2%) or moderate (57.2%). In most cases existing earthquake-resistant building codes were not applied. Figure 9 shows distribution of buildings in the reference area with respect to building vulnerability through RVS method and Turkish simple survey method respectively. From the analysis it can be observed that major portion of the sample buildings is highly vulnerable to earthquake. Thus the overall scenario of building stocks in the reference area is not in a good condition from the earthquake vulnerability perspective, where the most important vulnerability factors are vertical irregularity, soft storey, heavy overhang and plan irregularity.

Figure 8: Buildings with respect to number of storey in the reference area

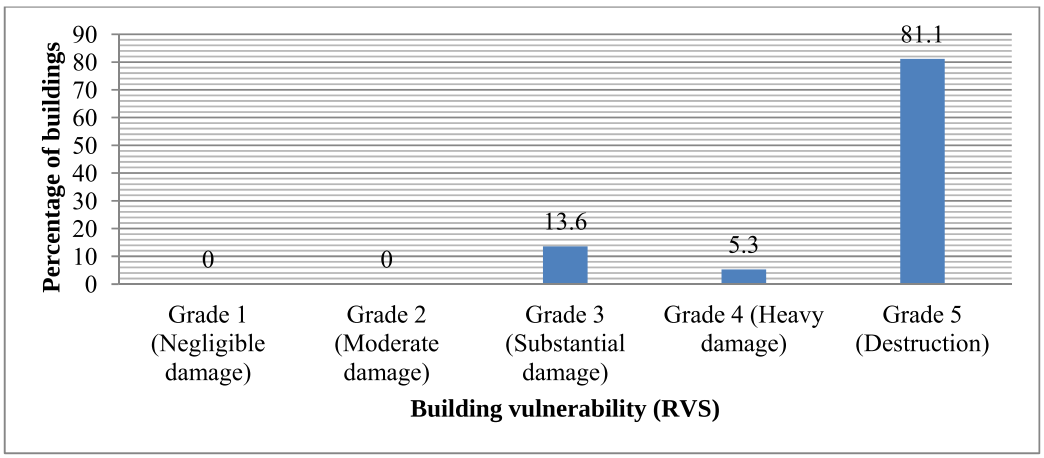


Figure 9a: RVS method

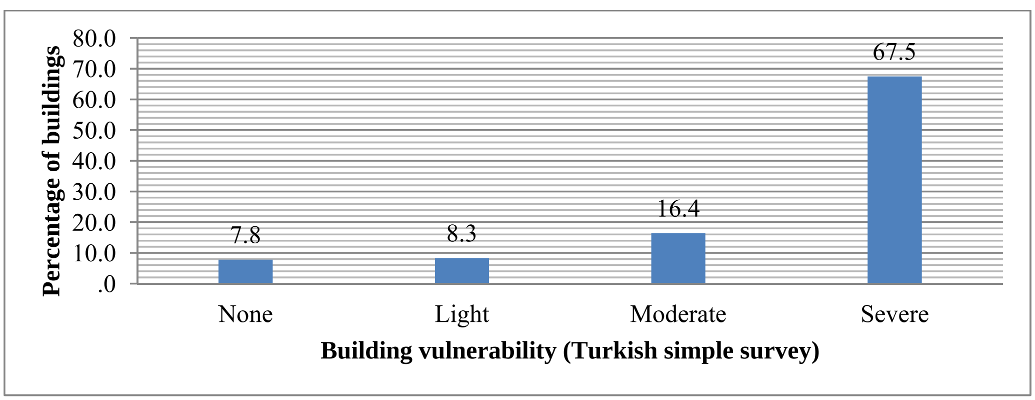


Figure 9b: Turkish simple survey method

Figure 9: Distribution of buildings with respect to building vulnerability in the reference area

Table 6 shows the correlation between the building vulnerability and their vulnerability components in the reference area. Short column and pounding effect do not have significant effect on building vulnerability or other components. So these two factors have been removed from correlation analysis. From the table, it can be observed that there is a very strong-significant relation between buildings' soft storey and vertical irregularity reflecting that buildings with soft storey also have vertical irregularity. Again, buildings' vulnerability according to RVS method is very strong-significantly related to vertical irregularity and soft storey, and according to Turkish simple survey method is strong-significantly related with number of stories, vertical irregularity, plan irregularity and soft storey. Thus the most significant factors influencing building vulnerability are vertical irregularity and soft storey. Additionally, buildings' vulnerability according to RVS method and Turkish simple survey method is strong-significantly related to each other, meaning that the findings from assessment through two methods are consistent.

Thus, the analysis of building vulnerability to the earthquake in the reference area represent that, most of the buildings are highly vulnerable to earthquake. The most important building vulnerability factors are vertical irregularity, soft storey, heavy overhang and plan irregularity. Among them influence of vertical irregularity and soft storey on vulnerability are most significant. Such condition has been arisen due to building construction violating building codes and regulations mostly focusing on beautification. If the similar trend continues in the study area, then similar vulnerability of buildings to the earthquake will result in there.

3.7 Open space scarcity risk

In the study area, about 7.69% area (0.7 square km) is designated as open spaces in the proposed plan, including 12 parks, 36 playfields, two graveyards, 0.05square km green belt, and 0.26 square km open space. The playfields are evenly distributed in all of the neighborhoods adjacent to the educational facilities. The parks are mostly located along the lakes. The green belt is located along south-eastern sides of Sector 18 to separate the waste management plant, water treatment plant and the neighborhoods from the water retention area located at the southern portion of the area.

Considering the projected total population for the study area (about 0.65 million), 0.53 square km land is required for playgrounds and parks, whereas the available space is 0.39 square km area as per Private Housing Project Land Development Rule, 2004 (MoHPW GoB, 2004). According to Xu et al. (2006)and CDMP (2009a), the evacuation spaces do not provide long time shelter and therefore a minimum per capita space (one square meter space per person) is required for the victims of an earthquake. Thus, the open spaces in the study area altogether have the capacity to accommodate about 0.7 million people for evacuation at the response phase of an earthquake, whereas the projected population for the study area is around 0.65 million. So it can be said that the parks and playfields are not sufficient as per requirement of the standard, but altogether they are sufficient to serve the area at the time of emergency. The open spaces are evenly located and well connected by road networks, and the parks along the lake are connected by walkways, which is suitable for emergency response after an earthquake.

3.8 Risks in critical facilities

In the study area, the critical facility comprises of 3.39% of total area, which includes educational, health and public service facility. Considering the projected total population for the study area (0.65 million), required space for educational facilities is 0.44 square km area whereas the available space as per landuse plan is 0.22 square km area (including schools, educational institutions, and special institutions). Moreover, there are three religious facilities comprising 0.03 square km area whereas the requirement as per standard is 0.1 square km. Therefore, provided educational and religious facilities are not sufficient to serve the area. From evacuation perspective though open spaces in the study area are sufficient, the additional evacuation space may be required to combat the situation supporting surrounding areas where educational and religious facilities in the area may serve the purpose.

The health facilities proposed in the study area includes one hospital block and a club with 0.03 square km area which is sufficient as per the standard. But the facility is located at the north-western corner of the study area which may not be accessible by all the residents of the study area after an earthquake. There are two fire service stations in the landuse plan of study area. Considering 3 km service area, it can be observed that two fire stations are sufficient to serve the area at the event of emergency response after an earthquake. Additionally, there are two police stations and one RAJUK site office in the landuse plan of study area. These are approximately centrally located, which can be utilized to coordinate earthquake management activities in the study area.

4. RSLUP strategies to be incorporated in the proposed plan of the study area

From the analysis it can be said that, though there are positive aspects of the landuse plan of the study area, the risk issues affect the earthquake risk sensitivity of the plan adversely. Therefore, these issues are necessary to be addressed accordingly. The most fundamental approach in RSLUP is to simply avoid proposing a development on lands that have seismic hazard and subsurface structures, which is executable at planning phase and for areas land values are comparatively low (Fat-Helbary et al., 2004; UDD & ADPC, 2016). But for the areas with high man to land ratio and high land values, such approach may prove to be unsustainable. Burby et al. (2000) explained the tradeoffs while prioritizing the RSLUP strategies for adoption as:

"…Some emphasize long-range strategies, while others react to current development proposals. Some try to reduce development in hazardous areas, while others accept such development but focus on site and building design to reduce vulnerability. Some redirect public investment, but most seek to regulate or influence private development. Some are regulatory, and others are voluntary…"

Hence, formulation of RSLUP strategies depends on risk sensitivity of landuse plan as well as the local context of the area to be considered. Therefore, based on the analyzed risk sensitivity, RSLUP strategies to be incorporated in the landuse plan of the study area reflecting the risk sensitivity were formulated based on literature review and key informant interview. The formulated strategies are discussed in the following sections.

4.1 Spatial strategies to revise the landuse plan

Based on the findings from analysis, some unavoidable revision of the landuse plan of the study area are necessary to reduce the earthquake risk.

4.1.1 Promote mixed-use development

From the analysis of the risks in landuse incompatibilities it has been found that the landuse proposed in the plan of the study area is compatible. But at present, mixed-use development is increasing day by day whether planned or not. Moreover, from disaster management perspective, mixed-use development is encouraged to increase self-sufficiency of a local entity, reduce dependency on the city and thereby reduce dependency on connectivity with rest of the city (UDD, 2013). Thus to avoid spontaneous development and guide the trend, mixed-use development should be promoted in the study area. In such development, corresponding building construction rules and regulations should be followed accordingly (WBI, 2006b, 2006e).

4.1.2 Road widening and extension

From the analysis of the macro-form risks it has been found that connectedness of the primary roads in the study area are insufficient in the north-south direction and there are bottle-necks at some intersections due to inconsistent road width, which may hamper the connection of the area with the city. To address these issues, some of the primary roads should be extended at the southern portion of the study area and some road should be widened. Figure 10 shows the proposed locations where road widening initiative should be implemented and arrow sign represents the road segments which should be extended in the study area. To implement these proposals, RAJUK can make necessary corrections in the landuse plan. If the adjacent plots have already been allocated, then initiative should be taken to acquire the required land (Burby et al., 2000; EMI, 2010; Reyes, 2004; UDD, 2013). Tax incentive can be provided for owners leaving space for this purpose (EMI, 2010; Mitchell & Myers, 2013).

Figure 10: Proposed locations for road widening and extension in the study area

4.1.3 Preservation of the waterbody proposed in DAP

From risk in special areas in the landuse plan of the study area it can be observed that some of the DAP designated water bodies have not been addressed in the proposed plan. The DAP (1995-2015) should be strictly followed. Even if the smaller portions cannot be revived, the greater waterbody designated in the DAP should be preserved accordingly. For this purpose, necessary measures should be taken to make to make change in the landuse plan of the study area designating the waterbody.

4.1.4 Community level parking facilities to discourage soft-storey

Risks in building stocks reflect that one of the possible major causes for building vulnerability which may arise in the study area is soft storey due to open space at ground floor for parking purpose. To discourage soft-storey in buildings due to building level parking, alternative community level parking facilities should be provided, e.g. common parking space at neighborhood, multistory parking facility, etc. For this purpose, the neighborhood level commercial spaces can be utilized.

4.1.5 Relocation of petrol pump

Analysis of risks in hazardous uses reflects that a portion of the MRT line six lies within 200 m buffer area of hazardous uses. This petrol pump should be relocated to a safer location. Moreover location of petrol pump filling station should be decided based on the guidelines (Biswas & Hossain, 2016; BPC, 2014).

4.1.6 Additional provision for health facility

Risks in critical facilities revealed that there is only one large health facility which is not sufficient for emergency situation. Moreover, it is located at the north-eastern corner of the study area. So additional health facilities should be provided at different locations of the study area. Considering the existing landuse, health facilities can be provided in the central plaza, CBD as well as at some of the central commercial spaces of the neighborhoods. This will ensure sufficient facility as well as proper distribution of health facilities in the study area.

4.2 Earthquake resilient planning of hazardous uses

From the analysis of risks in hazardous uses it has been found that there are several hazardous uses in landuse plan of the study area. Moreover, there are residential, commercial, educational and public services within 200 m buffer area of these hazardous uses. As the area is at development phase where many of the plots have been sold, so it is difficult to relocate the hazardous uses in the area. Again, from macro-form risks perspective, MRT line going through the study area along with a MRT depot is positively influencing its connectivity with the city which is also hazardous. Despite having positive impact, the presence of the MRT line and the depot poses threat for secondary hazard in the study area after an earthquake.

Considering all these facts, earthquake resilient planning and design of these hazardous landuse should be done as per international standards (MfE New Zealand, 2002; MIACC, 1995; UNECE, 2017). A buffer area or green belt should be provided around these uses to protect the surrounding area from its effect. A proper management plan should be developed to ensure safe handling and management of hazardous materials (biological, solid, chemical, etc.) especially at the MRT depot, waste management area and water treatment plant in the study area with specialized and modern equipment and techniques considering disaster resilience. Environmental pollution should be regulated for these hazardous uses by environmental protection legislations in Bangladesh (MoEF GoB, 2002a, 2002b).

4.3 Building height restriction to control density and prevent resonance during earthquake

After making necessary corrections in the landuse plan of the study area integrating earthquake risk sensitivity in it, some strategies will have to be taken to manage the development accordingly considering risk sensitivity. As the area is at risk for potential earthquake, the development in the area will have to be managed to control density and thereby reduce risk of potential damage. The projected population density for the study area is 300 persons per acre which was decided on the basis of standard. From the analysis of risks in building stocks it could be observed that majority of buildings in the reference area are 6-storied. But at present the trend for construction of high rise building is increasing. If this trend continues in the study area, then density may cross the estimated density limit. Therefore, the estimated density should be maintained through height restriction considering soil condition (Bendimerad & von Einsiedel, 2010; EMI, 2010; Reyes, 2004; UDD, 2013; WBI, 2006b, 2006e; World Bank & EMI, 2014).

Buildings and earth, all have natural periods, where hard bedrock has higher frequencies than softer sediments. If the period of ground motion matches the natural period of a building, it will undergo resonance with the largest oscillations possible (IRIS, 2018). It multiplies the frequency during an earthquake causing greatest damage. Analyzing the destruction caused by the earthquake of 19 September 1985 in Mexico City, Flores, Novaro, and Seligman, (1987) concluded that based on soil condition, severe damage of buildings were occurred due to soil-building resonance effect for specific building height. Similar results have been explored from the experience of seismic sequence in Molise (Italy) in 2002, by Mucciarelli et al. (2004). Thus, certain building height for certain soil condition causes resonance during an earthquake increasing building damage. This height can be calculated using following equations as per BNBC Draft (2020) considering that at resonance period of building and soil becomes equal.

Period of building, TB = N/10 second; [Here, N= No. of storey]

Period of soil, TSoil = 4H/Vs30 seconds; [Here, H = Thickness of soil layer and

Vs30 = Average shear wave velocity for top 30m of soil]

Building height above or below this specified height is considered safe. Therefore, to prohibit resonance of buildings in the study area during an earthquake and thereby reducing risk of building damage, building height with possibility of resonance should be determined for each plot through soil test. After that allowable height range should be considered plot wise. This determined building height should be utilized to restrict building height for controlling density and preventing resonance during earthquake.

4.4 Earthquake resilient design and construction

Earthquake resilient landuse plan is not enough to address the risk alone, if the buildings are not constructed following earthquake resiliency then the casualty, damage and loss would increase after an earthquake. Especially damage or collapse of critical facility buildings would result in failure in disaster response and management after an earthquake. Analysis of risks in building stocks reveals that most of the buildings in the reference area are vulnerable to earthquake, where the major causes are vertical and plan irregularity, soft storey, and heavy overhang. Such condition has been arisen due to building construction violating building codes and regulations mostly focusing on beautification. If the similar trend continues in the study area, then similar vulnerability of buildings to the earthquake will result in the study area. Again, from the analysis of risks in urban textures it has been found that internal road network in the study area is well connected with sufficient road width, but there are several bridges connecting the roads over lakes. If any of them are damaged, then it will create interruption of vehicle movement and thereby cause more congestion. Failure in MRT line would not only interrupt disaster management but also pose great risk of secondary hazard. Similarly, failure in hazardous uses would lead to secondary hazards. Additionally, special risk areas analysis shows that the geomorphic condition increases risk of landuse in the study area.

Therefore, earthquake resilient construction methods will have to be followed for designing and executing all sorts of construction as per BNBC as well as Building Construction Regulation (BNBC, 1993; BNBC Draft, 2020; MoHPW GoB, 2008). Prior to designing and construction, soil test should be done. Based on soil analysis, height restriction for buildings should be determined through soil analysis. Required designs should be done to ensure soil compactness accordingly. Where necessary, compactness of soil should be ensured through foundation, soil treatment, piling and other suitable approaches. Additionally, according to Newton's law of force, force of earthquake on a building, $F=ma$; [Here, m = building mass, a = acceleration of earthquake]. Thus force of earthquake increases due to increased mass of buildings. Hence, ornamental extensions of buildings for beautification leading to plan irregularity, vertical irregularity and heavy overhang should be prohibited. Additionally, buildings should be constructed using materials reducing building mass and thereby reduce impact of earthquake. For this purpose, researches should be conducted to invent low mass durable building material. Consideration of all these factors while designing and executing construction would lead to earthquake resiliency.

4.5 Policy initiatives to execute earthquake resilient landuse plan and construction

Earthquake resilient landuse plan would fail to achieve the goal if they are not executed accordingly. Risks in land-use incompatibilities discloses that the landuse is changing violating the proposed plan in the reference area. Again, analysis of risks in building stocks reveals that most of the buildings in the reference area are vulnerable to earthquake, which has been arisen due to building construction violating building codes and regulations mostly focusing on beautification. If the similar trend continues in the study area, then it will result in increased earthquake risk. Therefore, policy initiatives will have to be taken to execute earthquake resilient landuse plan and construction accordingly.

An effective approval system for landuse and building design approval should be developed, where landuse and building design approval certificates should be issued by respective authorities endorsing compliance with landuse plan and BNBC ensuring earthquake resiliency (BNBC, 1993; BNBC Draft, 2020). Without having such certificates, one should not be able to proceed for construction. If any of the owners require financial assistance for earthquake resilient building construction, risk financing should be introduced (Baur & Parker, 2015; OECD, 2018; RMS, 2018; World Bank Group & GFDRR, 2015).

Additionally proper monitoring system should be developed (Bendimerad & von Einsiedel, 2010; EMI, 2010; Reyes, 2004; WBI, 2006c, 2006f; World Bank & EMI, 2014). It should be performed continuously at regular interval for confirming efficiency and continuity, which can be done at three phases of construction, e.g. pre-construction phase (to ensure certification of approval for consistent landuse and resilient building design by endorsed design and construction farms or technical persons); during-construction phase (landuse and building construction by endorsed workers and monitoring as per approval); and post-construction phase (yearly, half-yearly, or semi-yearly monitoring landuse and building as per approval at regular interval and prohibit any unauthorized alteration). Moreover, monitoring should ensure preservation of other landuse in the area accordingly preventing any sort of encroachment and alteration. Here special attention should be given on hazardous uses, open spaces, waterbodies, roads and pedestrian walkways.

To reduce pressure on the central system as well as strengthen and increase efficiency, the monitoring system should be decentralized at community level involving local co-operatives and volunteers, with support from technical institutions (e.g. engineering universities, diploma institutions, etc.). Online record keeping and monitoring system should be developed for easy monitoring of unauthorized building design change as well as to ensure transparency and accountability (WBI, 2006c; World Bank & EMI, 2014). Capacity of the related persons for approval and monitoring should be developed through proper training. Moreover, proper training and endorsement system should be promoted for the design and construction farms, technical persons and workers (mason, bar binder, etc.) for earthquake resilient building construction.

Landuse change without approval, and building construction without design approval or violation from approved design should be considered illegal. In such case, there should be the provision of penalty for violation (Bendimerad & von Einsiedel, 2010; WBI, 2006c; World Bank & EMI, 2014). Liability of design and construction farms or technical persons for their design as well as workers for construction should be increased. In case of violation, provision for the reduction of rating or suspension of license should be developed. Tax incentive can be provided for compliance with proposed landuse and approved design. In contrary heavy tax penalty (e.g. double tax) can be imposed for non-compliance (EMI, 2010; Mitchell & Myers, 2013).

4.6 Planning for disaster management

In addition to resilient landuse planning and its appropriate implementation strategies, planning for disaster management should be done utilizing the local resources accordingly and appropriately. Where necessary, additional supports should be provided.

In the landuse plan of the study area there are several hazardous landuse, which can be witnessed from risks in hazardous uses. Therefore, appropriate planning should be done for management of secondary hazards. Central control panel at one point or some secondary control panels at several points of the study area should be planned and established for electricity and gas supply. This will enable to immediately switch off the supply in the area during an earthquake and thus avoid secondary hazards in the study area from explosion. Firefighting facilities should be preserved in the buildings, e.g. hose pipe, fire extinguisher, sprinkler, etc. to immediately combat fire and reduce dependency on Fire Service and civil Defense (FSCD). Risks in urban texture brings out that there are interconnected lakes in the landuse plan of the study area which can be utilized for different purposes of disaster management. The usability of water bodies as source of water for firefighting and other purposed should be ensured through installation of pumps at different points. Additionally, the lakes should be cleaned at regular interval.

The interconnected lakes can also be used for waterway as an alternate to roadways. If promoted appropriately, the lakes can connect the study area with northern portion of the city, and URTM 2nd phase and Cantonment at eastern direction. Thus, the waterway will be able to ensure internal connectedness in the study area as well as connection of the study area with other parts of the city. Thereby, the macro-form risk of the area that is insufficient connectedness in the north-south direction can be overcome to some extent. To support waterways, parking facilities should be provided at different points beside waterbodies to park the car and use waterways and thereby establishing a link between road and water transport network. Helicopter support and arrangement of helipad should be provided at open spaces as an alternative way for rescue and relief operations in the study area with outside support (Bozorgi-Amiri et al., 2017; Caprì et al., 2009; Ozdamar, 2011).

Again, risks in urban texture shows that the internal road network is well connected with sufficient road width. But to ensure internal connectivity of the study area for internal response, rescue and relief activities, uninterrupted movement of emergency vehicles after an earthquake should be safeguarded. In this regard a traffic management plan should be prepared regulating direction of traffic movement in the access roads in the study area, e.g. one-way or two-way traffic flow (Barrett et al.,2000; Liu et al., 2007; Madireddy et al., 2011). Additionally, to discourage people from using vehicle for evacuation after an earthquake, it is necessary to provide proper and uninterrupted pedestrian movement facility in the study area (Reyes, 2004; WBI, 2006e). An evacuation plan should be prepared for the study area to ensure proper response in the study area after an earthquake (Argyroudis, Pitilakis, & Anastasiadis, 2005; Bendimerad & von Einsiedel, 2010; Reyes, 2004; Xu, Okada, et al., 2008; Xu et al., 2006; Xu, Okada, Takeuchi, & Kajitani, 2007). A dumping ground for debris accumulation should be planned so that even if some portion of the roads get blocked by debris, they can be removed immediately to ensure continuity of the internal roads, especially evacuation route.

Open space scarcity risk reveals that the open spaces in the study area are sufficient, evenly distributed and well connected. These open spaces should be maintained at regular interval to ensure their cleanliness, environment and usability as evacuation space. For this purpose, proper and regular monitoring, inspection and management plan should be prepared. Public toilet should be provided in the open spaces, which can also be used at the event of emergency. According to analysis of risks in critical facilities, there are several centrally located government facilities in the landuse plan of the study area which can be utilized for coordination of earthquake management. The coordination center should be equipped with necessary facilities and equipment to be used for a response to an earthquake, e.g. search and rescue equipment, dry foods, and water, tents, medicines, etc. Management capacity in the open spaces, disaster shelters and critical facilities should be developed to shift rapidly to emergency performance. Disaster management related legislations should be followed properly to ensure proper earthquake management in the study area (MoDMR GoB, 2012, 2015, 2017, 2019). Communication among different stakeholders in the study area should be established for proper co-ordination after an earthquake (MoDMR GoB, 2019).

4.7 Preparedness of local people

Appropriate execution of the earthquake risk sensitive landuse plan in the area would mostly depend on acceptability by the people living in the area. If they can perceive the importance, then acceptability would increase. Again such perception can be improved through proper awareness. Therefore, the earthquake risk-sensitive landuse plan of the study area should be disseminated among the plot owners of the study area to make them understand about the risk (WBI, 2006f; World Bank & EMI, 2014). Different awareness raising and training initiatives should be taken to improve understanding of the local people about earthquake preparedness, importance of landuse compliance and importance of constructing earthquake resilient buildings (Saito, 2007; WBI, 2006f). This would increase household level preparedness of the community for earthquake, and also encourage them to construct their building ensuring compliance with proposed landuse and earthquake resilience.

Based on the above discussion, Table 7 summarizes the RSLUP strategies corresponding to the risk themes and risk factors as well as the positive and negative aspects found from the risk sensitivity analysis of landuse plan of the study area.

5. Conclusion

This research proposes a methodology to develop RSLUP strategies for earthquake to be integrated in the landuse plan at local level for an area under development through analysis of risk sensitivity of the plan and addressing them accordingly. From the analysis it can be said that earthquake risk sensitivity was not considered or integrated in the proposed landuse plan of the study area. Moreover, from the development trend in the reference area (URMT second phase) it could be observed that landuse changes without approval and the building are not constructed considering structural resilience. If similar trend of development continues in the study area, then it will result in increased earthquake risk sensitivity leading to greater damage after an earthquake. Based on findings from risk sensitivity analysis of landuse plan of the study area, RSLUP strategies have been proposed on the basis of literature review and expert opinion. The strategies include spatial change in the landuse plan to address earthquake risk, earthquake resilient planning and construction ensure earthquake resiliency in built environment, policy initiatives to execute the plan accordingly and, planning strategies to ensure appropriate disaster management, and finally awareness raising activities to ensure acceptability of the RSLUP strategies by local people.

In this research the study area considered has been in the development phase. So, for analysis of risk sensitivity in terms of consistency of development with proposed landuse and risk in building stock, a reference area has been selected in this research assuming that similar development will take place in the study area if the current trend of the reference area continues. In reality, the development trend may vary. While assessing risk sensitivity of landuse plan of the study area, risk in life-lines could not be considered in this research because the layout of life-lines of the study area was not available. Additionally, in this research earthquake and its secondary hazards have been considered, but other hazards (e.g. flood) could not be incorporated considering the scope of this research.

Despite having the limitations, this research will guide policymakers to understand risk sensitivity of the proposed landuse plan of URMT (Third phase). This will guide them to take necessary steps to integrate the proposed strategies to reduce earthquake risk and thereby increase earthquake resilience of the study area. This research can also be replicated in other areas of Bangladesh as well as in other countries with necessary modification considering local perspective and other hazard scenarios.

This research brings out the great scope for reduction of earthquake risk through integration of risk sensitivity in landuse planning by theme-based assessment and strategy development. It brings out that for integrating earthquake RSLUP strategies in landuse plan effectively, assessment of risk sensitivity of the plan is a must. Such analysis is more effective at local level as detailed local level analysis brings out the actual scenario more accurately. Thus it enables development of RSLUP strategies with more relevance and effectiveness. This research will guide policymakers to understand the importance and application of RSLUP and thereby take necessary for this purpose to increase earthquake resiliency of an area. In future, researches should be carried out to assess risk sensitivity of landuse considering multiple hazards. Moreover, similar research should be carried out to integrate RSLUP strategies in developed areas because the scenarios and approach would be different for such areas.

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PART-VIII

ASSESSMENT OF RIVER BANK EROSION AND CHANNEL SHIFTING OF PADMA RIVER USING MULTITEMPORAL SATELLITE DATA AND GIS TECHNIQUE

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1. Introduction

The rivers have played a significant role in the lives and living of people in Bangladesh. Rivers are highly sensitive to environmental conditions. Alluvial channels can respond or readjust at a range of rates to the variations caused by water and sediment inputs, active tectonics and human activities at a range of spatial and temporal scales. Any changes, whether natural or anthropogenic, can initiate a departure from a state of dynamic equilibrium This may, in turn, result in channel instability causing changes in channel form and pattern. For Bangladesh, changes in frequency, magnitude and depth of flooding are very important. On average, 21% of the area of the country (31,000 km2) gets inundated by floods annually and 21% of the population (assuming uniform population distribution) is vulnerable to annual flooding and, in exceptional cases, more than 60% of the country or 70 million people are affected by flooding. In 1987, 1988 and 1998, Bangladesh experienced three extreme floods, leaving trails of devastation and human misery.

The Ganges is one of the major and dynamic rivers in the world originating in the Gangotri glacier of the Himalayan (Hossain et al. 2005). The river is named Padma where it enters Bangladesh territory . The river traverses through India nearly 2150 km (km) and in Bangladesh is nearly 366 km (Hossain et al. 2005). In Bangladesh the Padma River is joined by the mighty Jamuna (Lower Brahmaputra) near Rajbari and meets with the Meghna at Chandpur (Allison 1998). The Padma–Meghna–Jamuna river systems supply every year about 1.2 billion tons of sediments from Himalaya and distribute this within the Bangladesh delta (Kudrass et al. 1998). Coleman 1969) also mentioned that every year about 2.5 billion tons of sediments are discharged by these river systems in Bangladesh. This high sediment discharge naturally exerts an effect on the sedimentation rates in the rivers (Anon 2014; Anon 2015; Khan 2015). The Padma River left the signature of its dynamism in the surroundings of the present course. Over time the river changes course with bank erosion and leaves the sediments in the older course. Due to bank erosion and shifting, neighboring communities and individuals had to relocate to new areas every few years as they lose their properties (Elahi et al. 1991; IRIN 2008; Islam and Rashid 2011). Some people have had to migrate several times. Bangladesh has a unique hydro-geological setting and deltaic floodplain which is jointly formed by the deposition of the Ganges (Padma), Brahmaputra (Jamuna) and Meghna River. Because of the geo-morphology near Padma River location, river morphology, and the monsoon climate render Bangladesh highly vulnerable to natural disasters, primarily, floods, cyclones and bank erosion. Bank lines of the Padma River are particularly unstable. The Padma is wide with major erosion occurring along the left bank near Harirampur upazila of Manikganj district, where an acute erosion problem exists (Banglapedia 29/01/2015). Most recently, the right bank of the Padma has also come under threat of extreme erosion, particularly in Naria upazila of Shariatpur district. Victims have to live under the open sky as their dwellings were washed away by river waters. Croplands have also been washed away. However, in the present paper, an attempt has been made to monitor and map the bank erosion and accretion of the Lower Padma river. The better understanding of such erosion-accretion processes, as well as techniques to detect such changes, are very useful for planning and management of the floodplain environment of the Padma river. There is the availability of satellite image data at various spatial and temporal resolutions provides tremendous opportunity to monitor river bank erosion and deposition processes. This study report the overall scenario of the affected area of Lower Padma comparing past forty years of data of erosion and accession of Lower Padma River. This report has been developed based on the assessment of this massive disruption districts near to Lower Padma with the assist of Geographic Information System (GIS), and on field validation with transect walk. Here, GIS and RS methods had been used to analyse satellite image data.

1.1 Literature Review

1.1.1 River Bank Erosion

River bank erosion is important geomorphologically in effecting changes in the river channel course and in development of the flood plain. These are amongst the most dynamic elements of the landscape and thus an understanding of the processes is fundamental to our explanation of the development of fluvial features. River erosion is also important economically due to the loss of farm land and the undermining of structures adjacent to the river channel.(Journal of Hydrology, 42 (1979)

Erosion is a geomorphic process that detaches and removes material (soil, rock debris, and associated organic matter) from its primary location by some natural erosive agents or through human or animal activity. (Woodward, J. and Foster, I.A.N., 1997)

River bank erosion is important geomorphological changes in the river channel course and in development of the flood plain. These are amongst the most dynamic elements of the landscape and thus an understanding of the processes is fundamental to our explanation of the development of fluvial features. River erosion is also important economically due to the loss of farm land and the undermining of structures adjacent to the river channel; this problem is often underestimated in Britain. Relatively few detailed studies of the processes of bank erosion have been made until recently, but these have shown the considerable activity of rivers including several in Britain (Wolman, 1959; Twidale, 1964; Walker and Arnborg, 1966; Lewin, 1972; Hill, 1973; Knighton, 1973; Mosley, 1975).

In a study on river bank erosion along the left bank of the mighty Padma River in the Charghat and Bagha Upazilas of Rajshahi District has been assessed using temporal Landsat imageries and socioeconomic approaches. Remote sensing data analysis indicates that about 7297 hectare bank areas have been eroded during last 40 years since 1975. In 2015, erosion poses high threat to the Pakuria and Gargari Unions that is estimated 5392 hectare comprising 74% of the total eroded area. Excessive sedimentation within the channel and change in thawed as well as flow directions due to the adverse effects of the Farakka barrage are the main causes of the left bank erosion. Based on the social survey findings, about 79% of the respondents found river bank erosion, while 69% of them thought river course changing, 55% observed less water flow during summer and 45% realized flood are the major disasters in the area. Most of the respondents (97%) mentioned that river bank erosion have affected their daily life and livelihoods. About 84% of the sampled population opined that they lost homestead and operated lands due to the bank erosion (Md. Shareful H., S. Mahmud-ul-islam and Md. Sultan-Ul-Islam)

Knowledge of rates of erosion is fundamental to full interpretation of the landscape, especially in evaluation of the time period required for development of particular features and in assessment of the influence of climatic, geological and environmental conditions (Brunsden, D., and Kesel, R.).

River bank erosion occurs primarily through a combination of three mechanisms: mass failure, fluvial entrainment, and subaerial weakening and weathering. Subaerial processes are often viewed as 'preparatory' processes, weakening the bank face prior to fluvial erosion. Within a river basin downstream process 'domains' occur, with subaerial processes dominating the upper reaches, fluvial erosion the middle, and mass failure the lower reaches of a river (Pauliner R. Couper and Ina P. Maddock)

Many of these problems are associated with sampling both in space and time and are exacerbated by a lack of standardization of terms and methods which makes comparison and accumulation of data difficult. Measurement of river bank erosion has the advantage that the process is relatively rapid compared with many other geomorphological processes but this enhances its importance in interpretation of landscape change. Knowledge of rates of bank erosion is also of value in investigation of the effects of human activities on channel processes and in short-term prediction of erosion and planning of erosion control (Hooke, J.M., 1980).

1.1.2 GIS and RS

A geographic information system (GIS) is a system designed to capture, store, manipulate, analyze, manage, and present all types of geographical data. The key word to this technology is Geography – this means that some portion of the data is spatial.

Remote Sensing (RS) instruments are acquiring the data by scanning the Earth surface. Different types of scanning systems are using in Remote Sensing for acquiring the data. A scanning system collecting data over a various wavelengths but not continuous is referred as Multi spectral scanning system.

The River bank erosion mostly occurs when the river is flooded or soon after the flood. Besides river bank erosion is occurring at Padma River throughout the year. It is a natural geomorphic process or disturbance that shapes the land. Satellite remote sensing provides frequent synoptic view of an area and comprises comprehensive information about the earth surface. Great number of earth observing satellites orbits around the globe to provide high resolution spatial and temporal data of earth surface. Landsat is among the most widely used satellite, somewhat in light of the fact that it has the longest time series of data in currently available satellites.

GIS and RS are important tools which can aid in identifying river changes and bank erosions situations. A study on Jamuna River was taken with GIS and RS for the measurement by Imran Khan, Muneer Ahammad and Shiblu Sarker Postgraduate Student, Department of Water Resources Engineering, Bangladesh University of Engineering and Technology for river bank erosion analysis.

In a study on the Brahmaputra River characterized by frequent bank erosion leading to channel pattern changes and shifting of bank line The study is aimed at quantifying the actual bank erosion/deposition along the Brahmaputra River within India for a period of eighteen years (1990-2008) (Sarkar, A., Garg, R.D. and Sharma, N.).

In a study it was identified that, Analysis of a series of Landsat images, between 1973 and 1992, revealed the dynamic nature of the river bank and riverine islands over that period, including channel migration, movement and widening, submergence, erosion and accretion of riverine islands. Within the study period, the erosion rate in the Brahmaputra–Jamuna River is 160 m per year, indicating the severity of erosion hazard along the river(Khan, N.I. and Islam, A., 2003).

1.1.3 SPSS

SPSS Statistics Base forms the foundation for many types of statistical analyses, allowing a quick look at data and its easy preparation for analysis. Easily build charts with sophisticated reporting capabilities, formulate hypotheses for additional testing, clarify relationships between variables, create clusters, identify trends and make predictions.

SPSS Advanced Statistics makes analysis and conclusions more accurate when working with complex relationships in data, it offers powerful and sophisticated and multivariate analysis techniques.

SPSS Categories provides tools to obtain clear insight into complex categorical, numerical and high-dimensional data. Understand which characteristics consumers relate most closely to your brand, or determine customer perception of your products compared to others. SPSS Decision Trees helps you better identify groups, discover relationships between them and predict future events through the exploration of results and visual determination of how your model flows. Create visual classification and decision trees directly within the Statistics suite of products and present results in an intuitive manner.

Correlation Regression

Correlation and Regression are the two analysis based on multivariate distribution. A multivariate distribution is described as a distribution of multiple variables. Correlation is described as the analysis which lets us know the association or the absence of the relationship between two variables 'x' and 'y'. On the other end, Regression analysis, predicts the value of the dependent variable based on the known value of the independent variable, assuming that average mathematical relationship between two or more variables (Bland, J.M. and Altman, D.G., 1994).

Standard Deviation

The standard deviation (SD, also represented by the lower case Greek letter sigma σ or the Latin letter s) is a measure that is used to quantify the amount of variation or dispersion of a set of data values. To calculate the standard deviation of a data set first need to calculate the mean of the data set. If the data set is considered as x the mean is,

Mean, $\overline{x} = \Sigma(x)/n$; n is the number of distribution.

Standard Deviation, $Sx= \Sigma (x-\overline{x}) ^2/n$;

Correlation Coefficient

The linear correlation coefficient r, which is a numerical measure of the strength of the association between two variables representing quantitative data. Using paired sample data, the value of r is use to conclude that there is (or is not) a linear correlation between the two variables (Dakhil, N.K. and Abdullateef, A., 2016).

If the two data set are x and y and the means are $\overline{x}$ and $\bar{y}$ and standard deviation are Sx and Sy, then

Correlation Coefficient, $r=1/ (n-1)*Sx*Sy*\Sigma ((x-\overline{x})*(y- \bar{y}))$

Linear Regression

Algebraically describes the relationship between the two variables x and y. The graph of the regression equation is called the regression line (or line of best fit, or least-squares line). (Bland, J.M. and Altman D.G.,1994). There are three types of linear regression, they are

1. Simple Linear Regression

$\hat{y} = b0+ b1x$

2. Multiple Linear Regression

$\hat{y} = b0+ b1x1+ b2x2+.....+ bnxn$

3. Polynomial Linear Regression

$\hat{y} = b0+ b1x1+ b2x2^2+.....+ bnxn^n$

The regression equation expresses a relationship between x (called the explanatory variable, or predictor variable, or independent variable) and (called the response variable or dependent variable). The preceding definition shows that in statistics, the typical equation of a straight line "y = mx + b" is expressed in the form,

$\hat{y} = b0 + b1x$; Where, b0 is the y-intercept and b1 is the slope.

The slope b0 and y-intercept b1 can also be found using the following formulas.

$b0 = \bar{y} - b1\,\bar{x}$

$b1 = r*(Sy/Sx)$, Here r is the Correlation Coefficient of the distributed data;\

1.2 Problem Statement:

For decades, the Padma River has meandered, twisted, and weaved in different shapes through central Bangladesh. Each zigzag and turn tells a geologic story of the region, such as a large flooding event or the opening of a nearby dam. These events can lead to intense erosion along the banks of the river, displacing farms, homes, and even lives. Every year, hundreds (sometimes thousands) of hectares of land erode and fall into the Padma River. Since 1967, more than 66,000 hectares (256 square miles) have been lost—roughly the area of Chicago. (World of Change: Padma River - NASA Earth Observatory)

In general, bank erosion is greatest on the outside of the river bends, where several processes can influence the land deterioration: changes in river flow, land masses moving downslope, and vegetation wearing away where the river meets the land. Erosion rates vary over time with the magnitude of the flood flow and the type of bank material. In 1998, a large flood rose over these banks, exacerbated by the opening of the Farakka barrage (dam) in India. The Padma also has a large sand-bed, which is easily erodible. From 1998-1999, the erosion rate peaked at 3,120 hectares (12 square miles) per year.

In recent Padma has been experienced massive river erosion. Padma River was in a rising trend and speedy current is engulfing houses and establishments rapidly near areas to the Lower Padma. The extreme erosion patterns have two main causes. First, the Padma is a natural, free-flowing river with little bank protection, other than some occasional sandbags to protect buildings. Over the years, researchers have observed an increase in the river's sinuosity and braiding. Second, the bank sits on a large sand bed that can be eroded quickly (World of Change: Padma River - NASA Earth Observatory)

The erosion swallowed houses, schools, dams, roads, business establishments, mosques. The residents of riverbank are going through days of fear of further erosion while several more houses are still at greater risk Locals have started demonstrating for government action to tackle erosion by the Lower Padma.

Meanwhile, the two-storied building of the Upzilla Health Complex, which was over 500 meters away from the bank a couple of months ago, is being devoured now. Over 4,000 families have become homeless and many affluent farmers broke during the same period.

2. DATA AND METHODOLOGY

2.1 Approach of the Study

This chapter provides insight on how the research has been conducted. This chapter deals with discussions on research methodology, sampling techniques and data collection process. It also addresses the research investigation by highlighting the discussion of semi-structured interviews. The research has been conducted following a methodology with conformity to the scopes and objective of the study. The methodology is described in detail as below in figure 2.1.

Figure 2.1: Methodology Flow Chart

2.2 Study Area Selection:

This study concentrates the Padma river is located in Bangladesh, is 120 km long and its width varies from 4 to 8 km (Chowdhury 2003). The study area (Fig. 2.2) embraced the confluence points of the Padma-Jamuna at Goalanda, Rajbari and the Padma-Meghna at Matlab, Chandpur. The study area which lies between the latitude 23°50'–23°13'N and longitude 49°43'–90°39'E, and it passes through the Chandpur, Dhaka, Faridpur, Madaripur, Manikganj, Munshiganj, Rajbari and Shariatpur districts. The Padma river is characterized by Ganges river system. The annual average discharge is 35,000 m3 and the average width of the river is 10.3 km (CEGIS 2010).

2.3 Data Acquisition

2.3.1 Primary Data

To conduct this research, the necessary data were mainly collected from satellite image analysis. The research methods adapted in this study is analytical in nature because the study tries to find out trend of river bank shifting, erosion and deposition of Padma River in selected districts Chandpur, Dhaka, Faridpur, Madaripur, Manikganj, Munshiganj, Rajbari and Shariatpur districts were selected as study area because these districts cover distinct length of Padma River from both sides. Major reasons behind the selection of these districts as study area are—these districts are located on the bank of Padma River. River bank shifting and channel migration is very rapid in this area and finally majority portion is being eroded and newly deposited. An initial field survey was taken too Sariatpur District and Harirampur Union to verify current situation of Lower Padma River Bank and a site investigation was taken.

2.3.2 Secondary Data

The Remote Sensing (RS) and Geographic Information System (GIS) methods and other statistical data techniques have been used for the assessment of river bank erosion-accretion and identification of bank line shifting pattern of the Padma river. The remote sensing techniques provide a great possibility to analyze the environmental processes in local or global scale. Landsat images with their 30 m resolution are suitable among others for land cover mapping and change monitoring.

Identification of the channel migration pattern of rivers from satellite images of different years using GIS and Remote Sensing technology is found very much useful for studying the fluvial geomorphology of a river. For the purpose of this study the dry season satellite images from 1988 to 2018 have been collected. The details of these images are shown in (Table 2.1). Bank lines of these years were digitized from the geo-referenced satellite imageries using the ARC GIS and erosion-accretion pattern due to the lateral movement of the active river channel have been estimated using the GIS software. Along with these, all the major channels of the Lower Padma River were also digitized to show the channel migration pattern of this highly morphologically active river.

Two bands as band 3 and band 6 from LANDSAT 8 and LANDSAT 7 Images and band 2 and band 5 from oldest LANDSAT 5 TM were taken To maintain the similarity of spatial resolution and maximum band configuration among all the images. Some important articles have accessed from CEGIS library. Other secondary data sources include BBS, Banglapedia, news articles, published works and various online sources. The data also collected from various kinds of university journals and unpublished research papers, related books and web sites.

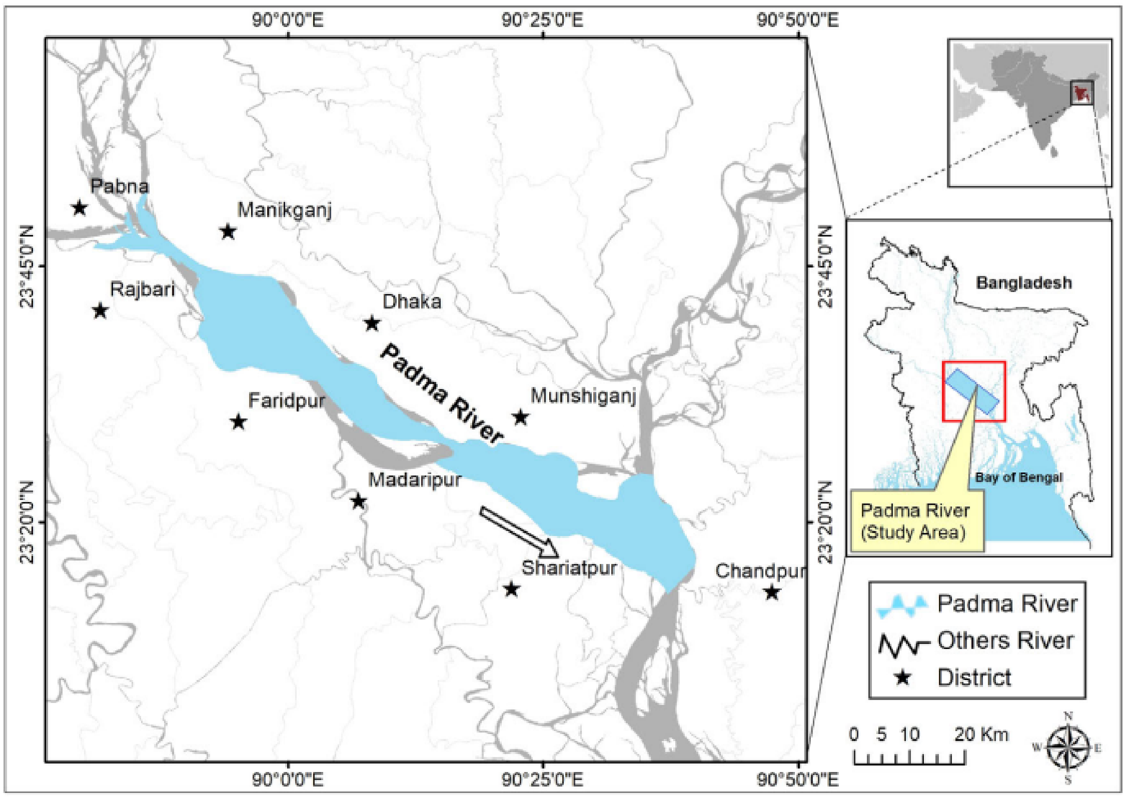


Figure 2.2: Lower Padma River Area

Table 2.1: List of LANDSAT Images Data Set

Image Year	Satellite	Path/Row	Acquisition Date	Land Cloud Cover	Scene Cloud Cover	Ground Resolution	Source
1988	LANDSAT_5	137/044	1988/11/01	16	15	30m x 30m	
1989	LANDSAT_5	137/044	1989/11/20	0	0	30m x 30m	
1990	LANDSAT_5	137/044	1990/12/09	3	3	30m x 30m	
1991	LANDSAT_5	137/044	1991/11/26	0	0	30m x 30m	
1992	LANDSAT_5	137/044	1992/11/12	0	0	30m x 30m	
1993	LANDSAT_5	137/044	1993/11/15	1	1	30m x 30m	

1994	LANDSAT_5	137/044	1994/12/04	0	0	30m x 30m	
1995	LANDSAT_5	137/044	1995/11/21	0	0	30m x 30m	
1996	LANDSAT_5	137/044	1996/12/25	0	0	30m x 30m	
1997	LANDSAT_5	137/044	1997/11/26	18	17	30m x 30m	
1998	LANDSAT_7	137/044	1998/12/22	0	0	30m x 30m	
1999	LANDSAT_7	137/044	1999/11/24	0	0	30m x 30m	
2000	LANDSAT_7	137/044	2000/11/26	0	0	30m x 30m	
2001	LANDSAT_7	137/044	2001/11/29	2	2	30m x 30m	
2002	LANDSAT_7	137/044	2002/11/16	0	0	30m x 30m	USGS
2003	LANDSAT_7	137/044	2003/11/19	0	0	30m x 30m	
2004	LANDSAT_7	137/044	2004/12/07	0	0	30m x 30m	
2005	LANDSAT_7	137/044	2005/12/10	0	0	30m x 30m	
2006	LANDSAT_7	137/044	2006/12/13	0	0	30m x 30m	
2007	LANDSAT_7	137/044	2007/12/16	3	3	30m x 30m	
2008	LANDSAT_7	137/044	2009/01/19	0	0	30m x 30m	
2009	LANDSAT_7	137/044	2009/12/21	0	0	30m x 30m	
2010	LANDSAT_7	137/044	2010/11/06	5	5	30m x 30m	
2011	LANDSAT_7	137/044	2011/11/09	0	0	30m x 30m	
2012	LANDSAT_7	137/044	2012/11/11	0	0	30m x 30m	
2013	LANDSAT_8	137/044	2013/12/24	0.08	0.07	30m x 30m	
2014	LANDSAT_8	137/044	2014/11/25	0.01	0.01	30m x 30m	
2015	LANDSAT_8	137/044	2015/12/30	8.2	8.07	30m x 30m	
2016	LANDSAT_8	137/044	2016/11/30	0.08	0.07	30m x 30m	
2017	LANDSAT_8	137/044	2017/11/01	4.04	6.88	30m x 30m	
2018	LANDSAT_8	137/044	2018/12/22	0.08	0.07	30m x 30m	

In this study Modified Normalized Difference Water Index (MNDWI) were investigated from the aspect as land cover types of water body (W) (Ex: figure 2.3).

Two bands as band 3 and band 6 from LANDSAT 8 and LANDSAT 7 Images and band 2 and band 5 from LANDSAT 5 were taken for the study for river presentation with converting the satellite data into raster data of water body showing the channel patterns of the study area using MNDWI method given in the figure 2.4.

Cracking point

Cracking point is the value for separating the water body from the raster data. For every images the cracking point variant from every year. The value was measured from the comprising field survey and google earth map by calculating the water body parameter.

Figure 2.3: Landsat Imagery Data

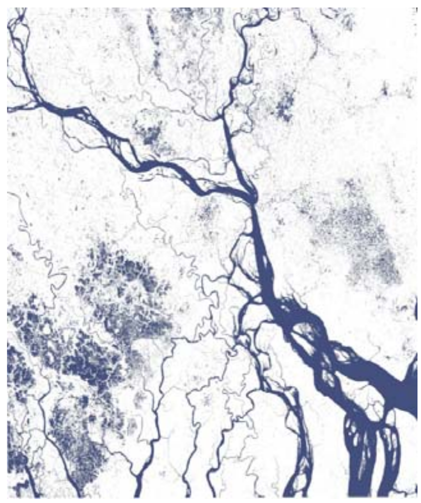


Figure 2.4: Converted into Raster Data with MNDWI

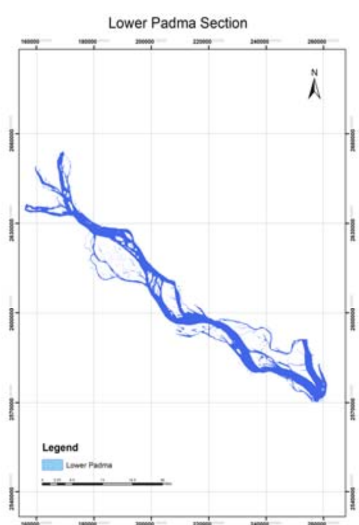


Figure 2.5: Lower Padma Section

The overlaid bank line gave the overall the rate of erosion and accretion, islands area and bank line shifting pattern of the Padma river from 1988 to 2018. Comparing the image vector data from different periods, were defined the changes of the river channel position over different time series. The results revealed the places where erosion and accretion occurred during each period and outputs were mapped. Bankline shifting was measured taking 24 cross-sections with 5 km intervals along the river. Each sectioned were differently named considering from alphabet “A” to “V” in figure 2.5. Using GIS tools each sections were calculate to render width of each sections given in the figure 3.3.

RESULTS AND DISCUSSIONS

2.1 Shifting nature of the Padma River channel

Satellite imagery shows how the river has been transforming in shape, size, and location from 1988 to 2018. The images above were acquired by the Thematic Mapper on Landsat 5 (1988) and the Operational Land Imager on Landsat 8 (2018). All images were acquired in January and February, during the dry season. Shifting nature of the Padma River in our study area is a common fluvio-geomorphic phenomenon which can be observed in any part of the rivers. The historical channel alignment is shown in Figure 3.1. The figure clearly shows the dynamic braided nature of the Padma River. Over the time period, the channel pattern becomes highly irregular and changes abruptly. The shifting of bank line from 1988 to 2018 on both banks along the Padma river was measured through 24 cross- sections at an interval of 5 km along the river and the results are presented in Figure 3. Analysis of the satellite images of the research area showed that the highest amount of erosion of land observed in the left bank along the section K from 1994–2005 near Munshiganj district and in the right bank along the section F from 2005–2018 near Faridpur and Madaripur districts. The maximum amount of accretion of land was established in the left bank along the section O near Shariatpur district and in the right bank along the section L near Madaripur district from 1994–2005. On the other hand a generalized output of the river bank line for the year 1988 and 2018 is shown in Figure 3.2. From these figure near Manikganj there is tendency of the channel to move towards the right bank. However near Madaripur and Shariatpur the channel is moving towards the left bank side and then takes more of a straight shape to Chadpur.

The changes in patterns of channel of Lower Padma River are very frequent. In general, bank erosion is greatest on the outside of the river bends, where several processes can influence the land deterioration: changes in river flow, land masses moving downslope, and vegetation wearing away where the river meets the land. The middle sections of the Padma River tend to experience low rates of erosion. Arcmap 10 was used for erosional and depositional pattern, channel bar development, and bankline shifting analysis. Assessment of erosion and deposition of both banks, polygons of two particular years were taken (superimposing) using the union method of Analysis tool. Channel bar development, its statistics, width of the river at different times, and statistics of the bankline shifting were calculated by using Microsoft Office Excel 2007 and Arcmap 10. The channel widths from both banks of this river at different times of different cross sections were measured perpendicular to the two banklines at the same fixed geographical points by using the measure tool in Arcmap 10.

24 cross sections were drawn in different parts of the river course (Fig. 3). The river width's standard deviations (SD) were calculated for different times on the basis of river widths at different cross sections (Fig 3.3) The river center points from both banks of this river at different times of different cross sections were pointed out perpendicular to the two banklines at the same fixed geographical points by using the line construction tool in Arcmap 10 (Fig. 3). On the basis of these center points, river center lines at different times were drawn (Fig. 3) to delineate the shifting of center lines of the river to both banks at different times.

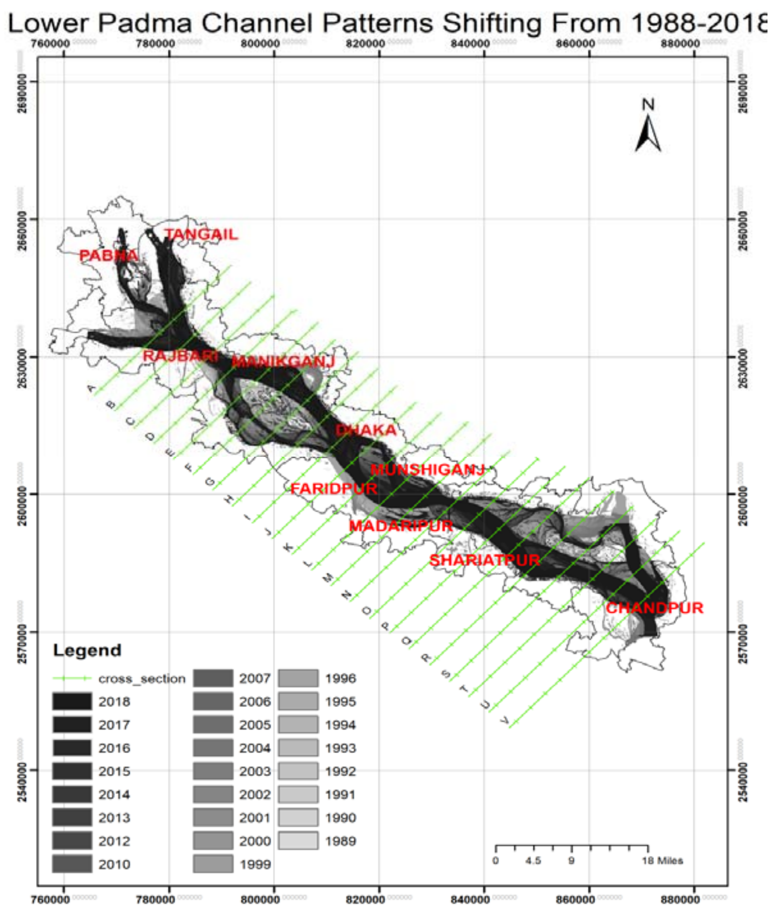


Figure 3.1: Channel Shifting of Padma River from 1988 to 2018

The shifting is represented within five years intervals in figure 3.2. From this figure picture A shows the differences of lower Padma Channel pattern from 1988 to 1993, in the figure B channel pattern change is showed from 1994 to 1997, in figure C the channel changes from 1998 to 2003 is represented, in figure D channel changes from 2004 to 2008, in figure E channel changes from 2009 to 2013 and in figure changes of channel from 2014 to 2018 is represented.

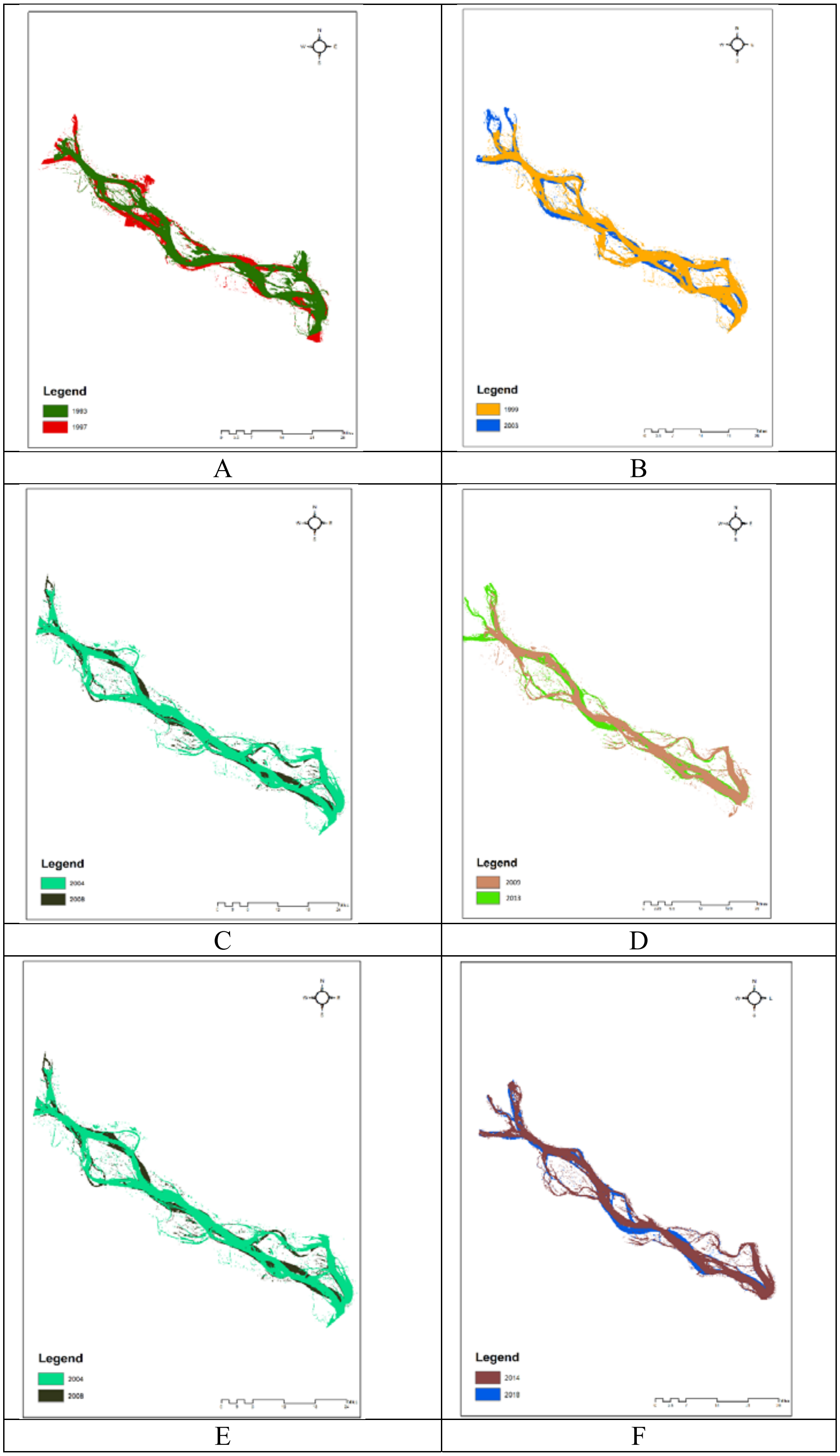


Figure 3.2: Channel shifting within 5 years intervals from 1988 to 2018

During the period from 1988 to 1993 and 1994 to 1997 the eroded lands were about 43.4 km2 and 49.8 km2 at a rate of about 10.86 km2 and 12.45 km2 year−1 . The erosion rate was increased on the left bank, while on the right bank the situation was more or less similar in respect of earlier period. Afterwards, during the period from 1998 to 2003 and 2004 to 2008 the erosion was dramatically decreased on both banks. About 15.62 km2 and 91.41 km2 of lands were eroded on the left and right banks, respectively, at a rate of about 1.04 km2 and 6.10 km2 year−1.IN 2009 to 2013 the erosion rate remain same. Consequently, from 2014 to 2018, the erosion was again increased on both banks of the river, while on the right bank the increasing rate was more than on the left bank. About 7.25 km2 and 30.69 km2 of lands were eroded on the left and right banks, respectively, at a rate of about 2.42 km2 and 10.23 km2 year−1 . Over the past 30 years, about 132.6 km2 and 245.7 km2 lands eroded on the left and right banks, respectively, at a rate of 4.82 km2 and 8.19 km2 year−1. Therefore, erosion was higher on the right bank than on the left bank over the past 30 years. During that period about 11 km2 and 37.90 km2 lands also accreted on the left and right banks, respectively, at a rate of 0.28 km2 and 0.95 km2 year−1. In the same period about 20.88 km2 and 107.19 km2 lands again redeposited on the left and right banks, respectively. The study also discloses that the erosion rates were not always same on both banks of the river. Sometimes erosion was more prominent on the left bank when the situation was reverse on the right bank. Saleem et al. (2019) also indicated that erosion and deposition vary both spatially and temporally on both banks of the Lower Padma River.

2.2 Backline Migration and Erosion Assessment

The satellite images from 1988 to 2018 have been visually interpreted to identify river width and bankline migration of the Lower Padma River at different times (Figs. 3.3). The river width has been measured perpendicular to the two banklines at the same fixed geographical points. 24 cross sections have been drawn in different parts of the river course. These are A - V (Fig. 3.3)

In cross section “A to E” the width of the river follows an increasing trend from 1988 to 1999, and after that it was a decreasing trend. But the overall trend is a decreasing one at a rate of 0.018 km per year (Fig. 3.3). . In case of cross section “F to H” the width of the river continuously follows an increasing trend at a rate of about 0.26 km year−1 (Fig. 9). In cross section “I to K” the river width follows increasing trend from 1988 to 1999, and after that it was a decreasing trend . However, the overall trend is an increasing one at a rate of 0.03 km year−1 (Fig. 3.3). In cross section “L to O” the river width was also gradually increased from 1988 to 1999, and after that it has been decreased. But in the overall result, the width of the river in this section has been increased at a rate of 0.05 km year−1 (Fig. 3.3). In cross sections "p and Q" the river width was increased from 1988 to 1999 but after that slightly decreased. In cross sections "R to V" the widths of the river have been gradually increased from 1988 to 2018 at a rate of 0.11, 0.10 km year−1 , respectively (Fig. 3.3). The analysis shows that the average width of the river follows an increasing trend from 1988 to 1999, but after that it was a decreasing one from 1999 to 2014 and again increased from 2014 to 2018 . As a whole, the river width shows an increasing trend at a rate of 0.083 km year−1 over the past 30 years . The river width's standard deviations (SD) have been calculated for different times on the basis of river widths at different cross sections (Table 10). The SD indicates that the river width at different parts of its course were not same.

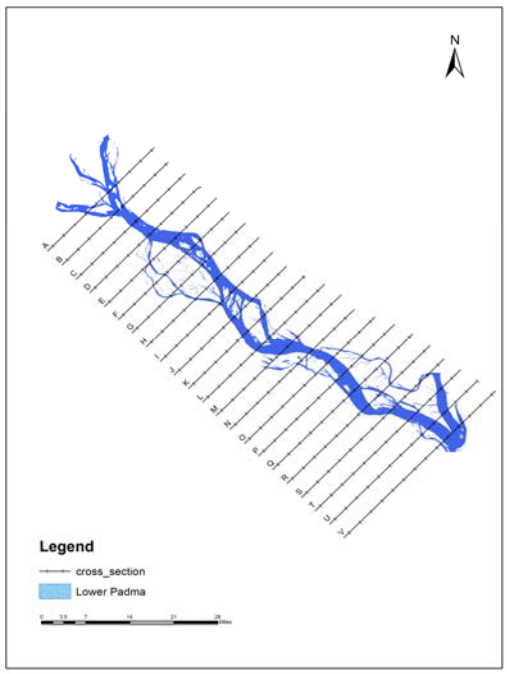


Figure 3.3: Sectioning Lower Padma Naming Acceding A-V

The historical bank line movement of the Padma River is shown in Figure 3.5. An interesting thing visible from this figure as well as from table 1 of appendix is that the average width of the Padma River is showing an increasing trend. To verify this observation the average width of the river for all the available satellite images were determined using the digitized bank lines. A plot was prepared showing the changing width of the Padma river which is shown in Figure 3.4. The figure clearly shows the increasing and decreasing average width of the river.

In the figure x axis represents the increasing intervals of time period of 30 years from 1988 to 2018 considering one unit as one year and y axis represents the average width of Lower Padma River.

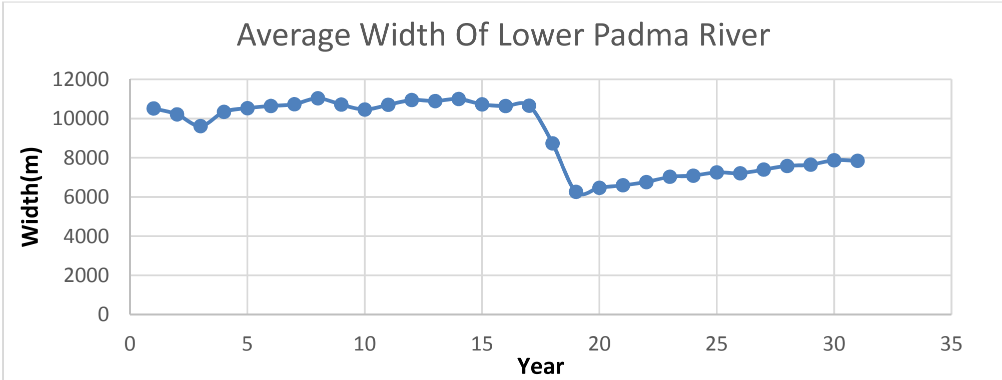


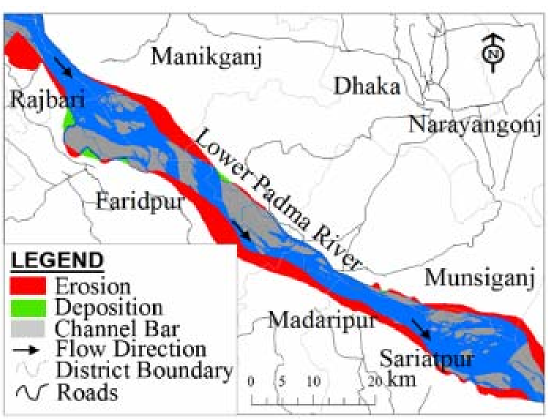
Figure 3.4: increasing and decreasing average width of the lower Padma River

In figure 3.6 the variation in erosion and accretion amount of section A to V are given from 1988 to 2018. In the chart the sections are defined in variant colors and positive results in y axis are representing the erosion amounts and the negative results explains the accretions represented in the figure 3.6, as well as Table 2 and 3 define the amount of erosion and accretion in individual section.

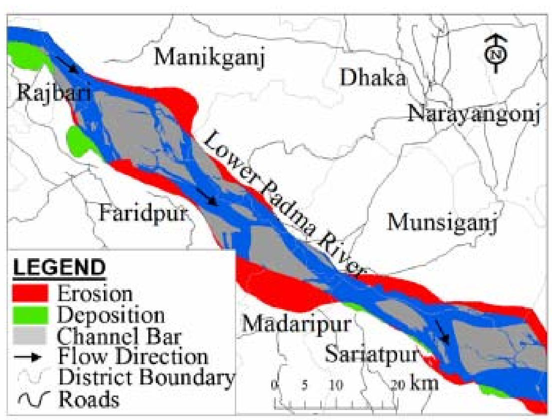
From the bar chart the erosion and accretion can be explained throughout the year from 1988 to 2018 and erosion is much frequent in every year. Erosion occurs in every year with a severe amount but 1990, 1995, 2003 and 2007 at section A, D and L had the major impacts on Padma for channel shifting and river path changes.

And also can be noticed that the accretion amount was not too regular but the changes of 1988,1990,1996,1997,2003,2005,2006 were also contribute a huge impact on channel pattern shifting.

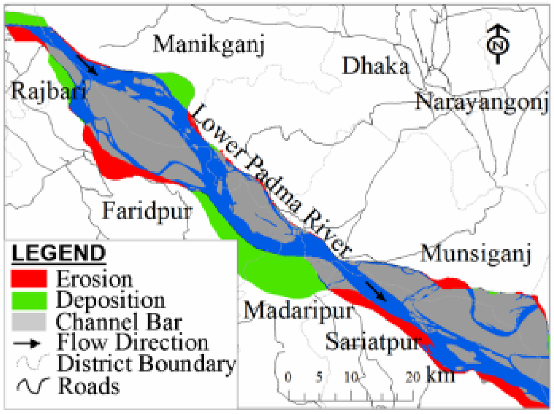
Considering the low amount of accretions all over the years in 1990, 2005 and 2006 at section E, F and S to V can be seen from the bars a huge amount of accretion occurred during these time period (figure 3.6). In these periods some huge areas of land increased due to the lack of river flow resulting decreasing the river widths with a severe amount.



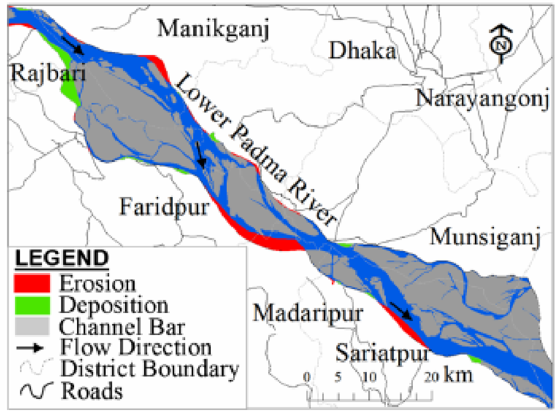
A



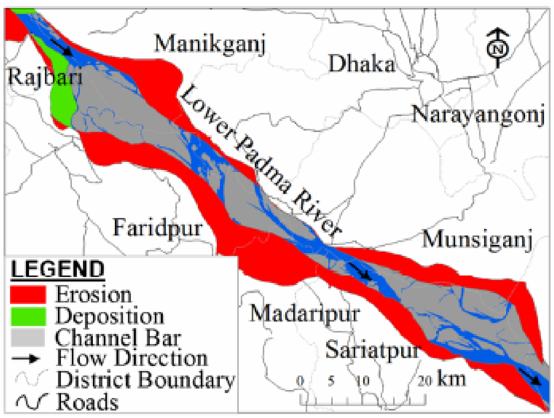
B



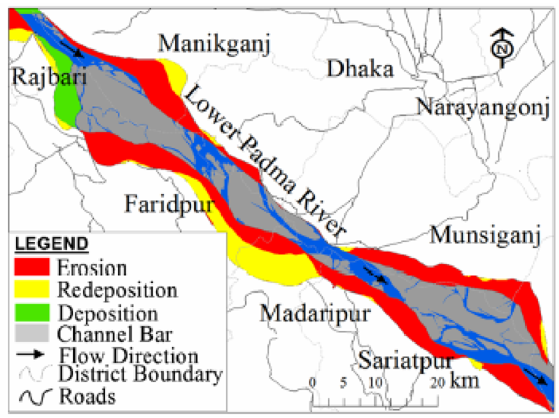
C



D



E



F

Figure 3.5:Erosion and Deposition map of the Lower Padma River in Different Time Duration: A (1988-1993), B(1994-1997) ,C(1998-2003), D(2004-2008), E(2009-2013), F(2014-2018)

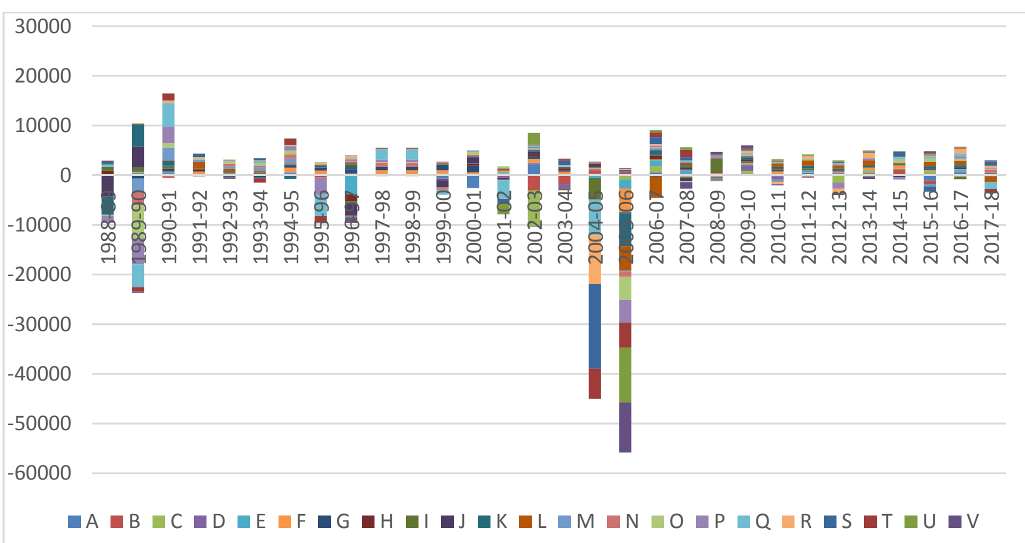


Figure 3.6: Erosion and accretion amount chart of every sections from 1988 to 2018

4.1 Conclusion

Bangladesh is predominantly a riverine country where river bank erosion is an annual disastrous phenomenon, especially in the Padma river, erosion-accretion is a common and very frequent event. The channel and bank line pattern of the Padma river changes continuously. The present study shows that satellite data like Landsat can be successfully used to monitor river bank erosion-accretion using the application of RS and GIS with multi-temporal satellite images. It has been revealed that sharp changes in river channel erosion/accretion in recent years resulting in considerable formation and loss of lands and represents the retrospective scenario of the Lower Padma river. The geomorphological formation and the physical dynamics of the Lower Padma is subject to runoff from the highest and most tectonically active mountain range in the world, the Himalayas. These young alpine mountains are naturally subject to severe erosion. Subsequently the Padma River carries a very heavy sediment load. The combination of large and variable discharges of water and sediment is responsible for the Lower Padma's braided pattern. Braided rivers are characterized by unstable bank lines and rapid rates of lateral movement. Spatial-temporal analysis of various data sets reveals that very high rates of erosion can occur over periods of 1 year or a few years, but the same patterns of erosion are not sustained for many years at the same location and they do not occur at all locations simultaneously. Similarly, low rates of erosion have been identified in some parts of the river, but the duration of low rates of erosion is short. Over the whole river, it is found that riverine islands most often persist from 1 to 7 years, but 30% have lasted for 14 years or more. The analysis provided the opportunity to predict bank erosion rates over time and space, as well as in physical direction. It was found that erosion and accretion was more dominant in the middle part of the river. Results of this study revealed that erosion and accretion were more pronounced in the right bank than that of the left bank. This finding could be used to measure or estimate the vulnerability of the protection measures already in place, estimate potential erosion loss of mainland area, and estimate the population at risk. River bank erosion is treated as one of the foremost natural disasters responsible for poverty in Bangladesh due to the enormous destruction of resources and displacement of large numbers of the population. The hazard also has an impact on unemployment levels in rural Bangladesh. This study shows the urgency of giving regular wake-up calls to the people concerned under potential threat of river bank erosion through a warning system and the need to adopt possible strategies that may assist in mitigating the human suffering and adverse socio-economic impacts of these recurring natural events.

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BANGLADESH NETWORK OFFICE FOR URBAN SAFETY

PART-IX

GIS-BASED LANDSLIDE SUSCEPTIBILITY MAPPING USING ANALYTICAL HIERARCHY PROCESS (AHP) IN BAGHAICHHARI UPAZILA, RANGAMATI

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Mehedi Ahmed Ansary

Introduction

Landslides represent a major threat to human life, properties, infrastructures, and natural environments in most mountainous regions of the world. Statistics from the Centre for Research on Epidemiology of Disasters (CRED) (Brussels, Belgium) show that landslides are responsible for at least 17% of all fatalities from natural hazards worldwide (Lacasse and Nadim, 2009) landslide is recognized as a disaster in mountainous region and responsible for huge social and economic losses. Particularly, earthquake-induced landslides are significant threats for the inhabitants of mountain areas in terms of casualties, infrastructure damages, and destruction of property (Keefer 1984). The landslide is a common natural phenomenon which a slope collapses abruptly due to weaken self-retain the capability of the earth under the influence of the gravitational force. It causes for the orientation of bedding planes, slope steepness, water and drainage, soil composition, vegetation, joints and fractures and by the sudden tremors (Islam and Rahman 2014). Some other reasons that contribute to the slope failure are the high shear stress, lack of lateral support or removal of support, weathering and low intergranular force due to seepage pressure (Islam and Rahman 2019).

Bangladesh is highly vulnerable to various types of natural hazards and disasters (Rabby, Hossain, and Mahbub, 2019). Chittagong Hill Tracts (CHT), in particular, are mainly prone to landslides in Bangladesh (Rabby and Li 2019). Heavy rainfall during the monsoon is the main triggering event for landslides in the region (Khan et al. 2012). Global climate change has exacerbated the extreme and prolonged rainfall, resulting in landslides with increased frequency in recent times (Ahmed and Dewan 2017; Ahmed et al. 2018: Abedin et al. 2020). The active seismic zones, high steep slopes, unfavorable geological conditions make the hilly part of Chittagong specially Rangamati is one of the most hazard prone areas in Bangladesh. Besides, the role of people in causing the hillslope instability is unprecedented, which is manifested through a housing development on the hillslope, hill-cutting, increased population pressure, deforestation, unsustainable agricultural practices, urban development, and weak governance (Ahmed 2015; Rahman et al. 2017) (11,12). More than 350 people have died as a result of landslides in Chittagong in the last three decslams (Islam and Islam 2017). Despite casualties, damages, and environmental degradation caused by landslides, no sufficient conservation efforts and hazard mitigation programs have been conducted in these areas due to weak institutional capacities. Various studies on landslide prediction and reduction in landslide damage have been performed. Some other reasons that contribute to the slope failure are the high shear stress, lack of lateral support or removal of support, weathering and low intergranular force due to seepage pressure (Islam and Islam 2017). A series of landslide in the Rangamati area in the recent years indicated that there was a progressive time of occurrence between two consecutive landslides. A total of 118 people, including five army men, were killed in Rangamati, which was hit hardest by the landslides in 14 June, 2017. Baghaichhari is a upazila of Rangamati district, this upazila is highly vulnerable to landslide because of its geographic features. Moreover, the rapid population growth and eventually rapid urbanization fosters, unplanned land use practices and obviously illegal hill cutting which is the collective facts for enhancing the vulnerability of landslides in this locality. In recent years, landslide hazard analysis and risk assessment have become a major subject in landslide studies and consequently, much of the recent progress has been in these areas. In particular, the application of information and geospatial technologies such as remote sensing and geographic information systems (GIS) has greatly contributed to landslide hazard assessment studies over recent years.

Landslide hazard assessment, including hazard investigation and analysis, refers to identifying and quantitatively describing the potential landslide hazards, and consequently, evaluating the probability of occurrence of landslides within a specified period of time. Because landslide hazards have important spatial components related to the initiation of the hazard and the areas affected by landslides (van Westen et al., 2008). Landslides cause soil erosion, land degradation, and loss of ecosystem integrity as well as substantial damage to the property, infrastructure, agriculture, economic development, and human lives (Guzzetti et al. 2012; Pourghasemi and Rahmati 2018; Yilmaz 2009; Chen et al. 2017). Given its significance, researchers, policymakers, and disaster management planners have become interested in understanding the probability of landslides that are likely to occur in a region– known as landslide susceptibility – so that strategies could be developed to reduce future risks and damages. Landslide susceptibility assessment, which shows the probability of landslides over an area, is critical to minimize the losses and deaths caused by the landslide. Landslide susceptibility mapping is essential to mitigate landslide disasters, and a landslide inventory is the first step toward susceptibility assessment (Rabby, Hossain, and Mahbub, 2019). The landslide susceptibility mapping is a useful technique in identifying the most susceptible areas of a region. The empirical observation of which is essential for science-based ecosystem management, land use planning, and disaster mitigation strategies (Ahmed 2015; Lei, Chen, and Pham 2020). Usually, the landslide susceptibility maps have been inaugurated using different GIS based methods and statistical analysis, such as the analytical hierarchy process (AHP), frequency ratio, bivariate, multivariate, Logistics regression, fuzzy logic, and artificial neural network (Matori, Basith et al. 2012). Landslide susceptibility can be investigated using quantitative and qualitative methods. Quantitative methods determine the mathematical relationship between landslides' occurrences and their associated predisposing factors (Althuwaynee, O.F and Pradhan, 2014). Quantitative methods can be categorized as deterministic and probabilistic methods. In a deterministic approach, a slope safety factor, defined as the ratio of shear strength to shear stress, is commonly used to determine an area's landslide susceptibility (Cheng, Peng and Hong 2019). This approach is suitable for small areas due to the challenge of measuring the safety factor over a large area (Merghadi and Abderrahmane, 2020). Qualitative methods depend on expert knowledge and judgment. Qualitative methods include field geomorphological analysis and index-based approaches, namely, the Analytical Hierarchy Process (AHP) and Weighted Linear Combination (WLC) (Vakhshoori and Zare 2016; Yilmaz, I 2010). In this study, analytical hierarchy process (AHP) is used for landslide susceptibility mapping. The method selection for landslide susceptibility mapping depends on the scale of analysis, cost, the timeline of the project, and the inventory data. Away from the influence of aforementioned major factors on the spatial distribution of landslides, rainfall, slope, lithology, aspect, land use and land cover (LULC) are also a significant factor in the landslide susceptibility assessment. However, high-resolution satellite data and GIS have also gained significant importance for construction of thematic data layers used to produce the valid susceptibility mapping. The production of landslide susceptibility map describes the prone area where landslide may occur in the future. Therefore, the susceptibility maps of the area are very important for effective management of landslide hazards and future planning. Considering the extreme causalities occurred in recent time in the Hill tracts, especially in the Baghaichhari Upazila, Rangamati region due to landslide, this study aims to produce a landslide susceptibility map for Baghaichhari upazila by integrating Frequency Ratio (FR) method and Analytical Hierarchal Process (AHP) method. This study also aims to identify the high susceptible road of this upazila using GIS and remote sensing technique.

Problem statement

Landslides are a common problem in the Chittagong hill districts (CHD) of Bangladesh. CHD is broadly classified into two major groups, urbanized hill districts (includes Chittagong and Cox's Bazar) and indigenous hill districts (includes Bandarban, Khagrachari and Rangamati). Although landslide disasters were infrequent in densely populated Bangladesh in the past, increasing human activities such as hill cutting for residential development has resulted in many landslides (Bayes 2010). The recent trend of spontaneous urbanization in the hills (i.e., covering approximately 10% of the total land area of Bangladesh) and the resulting impact of landslides on hilly communities indicate a sharp escalation of landslide disaster risks in Bangladesh (Ahmed and Rubel 2013; BUET-JIDPUS 2015; Ahmed and Dewan 2017). Landslide refers to the movement of debris, rocks, and soil under the influence of gravity 1 It is a common phenomenon in mountainous areas (Roy, J.; Saha, S. 2019) and accounts for 9% of the world's disasters (Galli, M.; Ardizzone, F. 2008). Landslide causes damage to infrastructure, human fatalities, and economic losses (Cipolla, F.; Sebastiani, C. 2004). Two types of factors, predisposing and triggering ones. Predisposing factors create suitable conditions for landslides, whereas triggering factors initiate the landslides (Guzzetti, F. 2012). The predisposing factors of landslides include slope, elevation, aspect, curvature, geology, and land use/land cover (Ahmed, B. 2017)

After the recent landslide occurrence of 2017, landslide susceptibility mapping of the Rangamati district has become indispensable to identify the future landslide hazard-prone areas. Rangamati, which is well known as indigenous hilly district (B. Ahmed 2017) suffered highest negative consequences in its history, as the disaster claimed lives of 152 people in total, severely destroying 6,000 dwellings, roads, telecommunication system, and power supply, along with an economic loss of about USD 223 million 12 The study area of this research is Baghaichhari Upazila of Rangamati district that is consist of hill tracks and mountains. The roads here are incurved in the hills of Rangamati. Sajek valley is a critical point of this study area having a reputation of uprising tourist attraction. During season the human load along with live load of transportations endanger the stability of the hill curved road and the slope of the mountain at higher elevation. Steep slopes, water saturation, geometry, land cover and previous landslides all play an influential role in landslide in Baghaichhari Upazila. Also having all the predisposing factors in play, the live load of tourist along with their heavy transport acts as another triggering factor as severe as the earth quack and heavy rainfall. So, keeping the importance of the study area in mind it is very clear that landslide susceptibility mapping of this hill track area of Baghaichhari upazila is essential and critical points are to be marked and monitored to avoid any type of accidental losses of human lives or properties.

The devastating impact of the landslides can be reduced by taking appropriate mitigation measures after identifying the susceptible hazardous areas. Landslide susceptibility mapping involves the determination of the spatial extent of a particular type of landslides, its volume, and the probability of its occurrence over a period of time and space (R. & W. C. Soeters 1996) So using landslide inventory, gradient, slope, land cover data etc. this study has a determination to develop high landslide prone area susceptibility map.

Review of some literature

Landslides are one of the most significant natural damaging disasters in hilly environments (Ayala et al. 2006). Social and eco-nomic losses due to landslides can be reduced by the means of effective planning and management (Rajakumar et al. 2007). Land-slide hazard assessment is generally based on the concept that ‘the present and the past are keys to the future’. This is why, most landslide hazard analyses take into account an up-to-date land-slide inventory that represents the fundamental tool for identifying the hill-slope instability factors in triggering landslides (Lee and Sambath 2006).

n Bangladesh landslide events mainly occur in the hilly parts of Chittagong Division. Chittagong is the largest port and second largest city of Bangladesh and plays a substantial role in the economic development of Bangladesh. Locational advantages and opportunities lead to rapid urbanization and compact urban form (Rahman, 2012). Landslides have occurred frequently in Chittagong city due to extreme rainfall. The devastation aggravates with weak geological structure, unplanned and erratic use of hills and settlement development. The unplanned and haphazard urbanization (Rahman et al., 2012), land-cover change, coupled with the increased intensity and frequency of heavy rainfall, is causing landslides in Bangladesh. Land cover changes (e.g., urbanization, deforestation) cause large variations in the hydro-morphological functioning of hill-slopes, affecting rainfall partitioning, infiltration characteristics and runoff production (Chau et al., 2004). Many urban dwellers and their livelihoods, quality of life, property and future prosperity are being continuously threatened by the risks of rainfall triggered landslides (Ahmed et al., 2014a). The development authority of Chittagong has identified 30 risky hills (Chakraborty and Uddin, 2014) among 88 hills of 18304 acre (Chisty, 2014). More than 10,000 people are currently living in such vulnerable areas. People are living at the toe and on the slopes of hills with high risk of landslides and associated damage (Mia et al., 2016) (36). Many devastating landslides occurred in these hills in recent past. Landslides triggered by heavy rains in Chittagong claimed at least 185 lives in the last few years.

Landslide is a term generally used to describe the downward movement of a portion of a hill slope containing soil, rock, and organic materials under the effects of gravity and also the landform that results from such movement (Highland et al., 2008). Landslide inventory can be seen as datasets of multiple events which may include but are not limited to landslide locations, date of landslide, type of the landslide, potential causes, and damage information (Hervás, 2013). A past disaster event can be seen as an opportunity to learn the lesson to enhance future disaster mitigation capacity (Rahman and Kausel, 2012). Thus, it is important to have a critical evaluation of past landslides to understand the causes and issues related to these events. Landslide inventory is one of the most important data for many landslide studies such as susceptibility mapping (Ahmed, 2015; Cardinali et al., 2006). landslide hazard zonation (Anbalagan et al., 2015), slope instability recognition (Soeters and van Westen, 1996), spatial distribution of mass movement. This kind of information can also be useful for urban land-use planning (Rahman and Islam, 2013).

Various geo-structural as well as causative-factor based approaches are already available for landslide susceptibility zoning. But Geographic Information System (GIS) modelling of landslide phenomena has taken precedence in recent time. Geospatial technologies like the use of GIS, Global Positioning System (GPS), and Remote Sensing (RS) are useful in the hazard assessment, risk identification, and disaster management for landslides. GPS is a space-based global navigation satellite system which provides the information of position and time anywhere in the world in all weather conditions (Akbar and Ha 2011). Previous studies showed the application of GPS for mapping and identifying landslide zones. GIS is used for data collection, storage, and analysis of processes where geographic information is involved. The use of GIS for land-slide mapping is common in various studies. Remote sensing is the science in which information is acquired about the surface of earth without physically being in contact with it. RS is also used for monitoring and mapping of landslides (Akbar and Ha 2011). Mapping the areas that are susceptible to landslides is essential for proper land use planning and disaster management for a particular locality or region. Throughout the years, different techniques and methods have been developed and applied in the literature for landslide susceptibility mapping. Landslide susceptibility maps can be produced using both the quantitative or qualitative approach (Park et al. 2013).

Qualitative methods simply portray the hazard zoning in descriptive terms (Guzzetti et al. 1999). But because of the developments in computer programming and geospatial technologies, quantitative techniques have become popular in recent decades. Moreover, it incorporates the causes of landslides (instability factors) and probabilistic methods (Bai et al. 2010).

There are mainly four methods available to map landslide susceptibility, namely landslide inventory based probabilistic, deterministic, heuristic, and statistical techniques (Guzzetti et al. 1999). Within these techniques, the probabilistic and statistical methods have been commonly used in recent years. These methods have become more popular, assisted by GIS and RS techniques (Lee and Sambath 2006). The probabilistic (non-deterministic) models like frequency ratio, bivariate analysis, multivariate analysis, and Poisson probability model (Bui et al. 2013) are more frequently used to determine the landslide susceptibility zones (Zêzere et al. 2008)

This method is also known as landslide inventory and provides a spatial distribution of existing landslides represented on a map either as the affected area (polygon) or as point events (Wieczoreck 1984 & 1987).

Disadvantage: it does not relate landslides to their causative factors

Advantage: it is economic and can cover a large area

Map Combination

The map combination approach is a simple procedure that combines different thematic maps based on the knowledge of the expert. This approach involves the following steps (Soeters & van Westen 1996): the Selection and mapping of landslide controlling parameters.

Thematic data layer preparation with relevant categories of the parameters.

Assignments of weights and rankings to parameters and their categories respectively.

Integration of thematic data layers. Preparation of landslide susceptibility map showing different zones.

Disadvantage: It strongly depends on expert knowledge and therefore can inherit human error and bias judgment.

Advantage: It is simple as compared to the other methods, which normally use complex equations

Quantitative Approach

Probabilistic

Approach This approach compares the spatial distribution of landslides in relation to different causative factors. It is based on the Bayesian probability. Some models based on this approach include conditional probability model, Weight of evidence method, certainty factor method under favorability mapping model, etc.

Disadvantages: It requires known landslide points as an input data set and can over estimates if the number of known landslide points is too much. Therefore, random selection of the landslide point that would be used is crucial.

Advantages: The fact that it uses known landslides points makes it the most
suitable model for landslide susceptibility mapping, as landslide studies are based on the assumption that future landslides will occur under similar circumstances as historic landslide.

Multivariate

Statistical

Analysis

Multivariate approaches consider relative contribution of each of the thematic data layer to the total susceptibility within a defined area. The procedure involves several important steps (Aleotti & Chowdhury 1999):

Identification of percentage of landslide affected areas in each pixel and their classification into stable and unstable zones.

Preparation of an absent/present matrix of given category of a given thematic layer.

Multivariate statistical analysis and reclassification of the area based on the results and their classification into susceptibility classes.

Moreover, GIS-based Multi Criteria Decision Analysis (GIS-MCDA) provides powerful techniques for the analysis and prediction of landslide hazards. GIS-MCDA belongs to heuristic analysis. These include the Analytic Hierarchy Process (AHP), the Weighted Linear Combination (WLC), the Ordered Weighted Average (OWA), etc. (Feizizadeh and Blaschke 2013). Analytic Hierarchy Process (AHP) is used to complete the study.

Remote Sensing and GIS for landslide susceptibility mapping

Techniques for landslide mapping have changed little, in principle, over the past few decades even when newer data sources become available (Sarkar & Kanungo 2004). Landslides are most often detected and mapped by a combination of interpretation of air photos or multispectral digital imagery and selected ground verification information (Roering & McKean 2004), and is often based on "professional judgment" (Wieckzorek 1984). There has been a drastic increase in magnitude and frequency of natural disasters around the globe but at the same time there has been improvements in the technical capabilities to mitigate them. The increased efficiency of computers has created opportunities for detailed rapid analysis of natural hazards. The acquisition of information through remote sensing and spatial data analysis using GIS has improved the capabilities of geo-informatics in the field of disaster management (Dahal et al. 2007). The following section describes some of the GIS techniques and remote sensing tools that have been used for landslide susceptibility mapping and early warning.

GIS modeling for Landslide Susceptibility Mapping –

Landslide hazard is normally depicted on maps which show spatial distribution of hazard classes. The development of these maps requires knowledge of the processes active in the area being studied (geological, hydrological, land-cover, and morphological factors), as well as triggering mechanisms leading to the occurrence of landslides (e.g., rainfall and seismicity) (Kanungo et al. 2009). Landslide hazard maps typically aims to predict where failures are likely to occur without any clear indication of when they are likely to occur. However, the focus on time-based modelling techniques have proved to be useful for providing landslide hazard information needed for planning and protection purposes (e.g., Brunettii et al. 2010). Geographic information systems and the selection of parameters that are deemed to influence landslide occurrence in a certain area and the consequent preparation of corresponding thematic data layers are crucial components of models for landslide susceptibility mapping (Sarkar & Kanungo 2004). The parameters that are generally deemed to govern instabilities include geology, geomorphology, land use, climatic conditions, hydrology, vegetation and geohydrology (Dahal et al 2007). These factors can vary both locally and/or regionally. The derivation of landslide susceptibility maps involves the combination and integration of spatial information on these factors to provide an indication of the areas where the combination of factors is such that they create an environment conducive to landslide occurrence.

Different approaches have been used to weight landslide controlling parameters and to model landslide susceptibility maps. The choice of the appropriate technique strongly depends on the nature of the problem, the observation scale and data availability (Temesgen et al. 2001, Lee, Choi. & Min

2004, Sarkar & Kunongo 2004). Landslide susceptibility mapping approaches can be grouped into two broad categories; qualitative and quantitative (Glade & Crozier 2005). In the qualitative approach, a lot of subjectivity is introduced in preparation of various thematic data layers contributing for landslide occurrences, which are integrated in a GIS to create a landslide susceptibility map of the area (Kanungo et al. 2009). The quantitative approach focuses on developing the ways of quantifying the relative importance of various causative factors (Kanungo et al. 2009).

Digital Elevation Model

DEMs are considered one of the basic data sources for three-dimensional modeling of the Earth's topography (Mutluoglu, O 2010) and also suitable to provide a snap shot of landscape along with the available features having the elevation values (Toz, G.; Erdogan, M. 2008). DEMs have been defined as digital representations generated with elevation values at the equal grid intervals of the terrain (Yakar, M 2009; Li, X 2017; USGS; Taud, H. 1999). The United States Geological Survey (USGS) has also defined these models as a digital cartographic representation method for the elevation of the terrain at regularly spaced intervals x and y directions using z (elevation) values referenced to a common vertical datum. Open source DEMs have replaced higher-resolution elevation models in a few applications, however, they are not feasible in applications that demand high accuracy. The accuracy of a DEM is always dependent on the quality of the field survey data collection methods (Wang, T. 2015), and these include contour insertion/plotting, scanning quality, digitization accuracy, map scale, and interpolation techniques.

Landslide inventory

Landslide susceptibility mapping is essential to mitigate landslide disaster, and landslide inventory is the first step towards the susceptibility assessment (Guzzetti et al. 2012). Since landslides generally occur in existing slide areas, it is vital to know the locations of occurred landslides, size of landslides, and their-related geomorphological factors (Chen et al. 2017) Landslide inventory is a dataset of various information associated with landslides, including the absolute and relative location, date, type, size, distribution, casualties, and causes of landslides (Guzzetti et al. 2012). Several methods have been used for landslide inventory mapping, including field mapping and visual interpretation of aerial and satellite images (Rabby and Li 2019). The first step of landslide inventory is to map the exact location of landslides and then to construct the dataset of landslides (Galli et al. 2008). A good landslide inventory is shareable with broad scientific community and stakeholders (Guzzetti et al. 2012).

Landslide controlling parameters

The identification of historic landslides and the analysis of the conditions leading to those landslide events is critical when attempting to identify landslides controlling parameters (Campbell 1975; Clerici, Perego, Tellini, Vescovi 2002; Morton, Alvarez, Glade 2005). The parameters affecting landslide occurrences can be broadly grouped into two categories (1) preparatory factors, which make the area susceptible to slope failure and (2) triggering factors, which sets off the movement (Crozier & Michael1986).

The parameters that affect an area's susceptibility to landslide include (1) geology, (2) geomorphology (3) human activities (4) and landcover (Wu & Siddle 1995; Atkinson & Massari 1998; Sidle et al; Sarkar & Kanungo 2004; Dahal et al. 2007)

Hence, in landslide hazard assessment practice, the term "landslide susceptibility mapping" is addressed without considering the variable factors in determining the probability of occurrence of a landslide event (Dai et al. 2001). The investigation of triggering mechanisms such as earthquakes and rainfall are critical but determining the magnitude and temporal behavior of these parameters and how it relates to landslide susceptibility has proved to be challenging (Sarkar & Kanungo 2004).

The following sections describe some of the controlling parameters affecting landslide development. These factors have been subdivided into three categories, each contributing to a separate category of landslide causative factors (preparatory parameter or triggering mechanism). They are:

Static factors – These factors are those that are unlikely to change within a short period of time like geology, the geomorphology, the soil type and depth and the vegetation type – these define the landslide preparatory factors.

Variable factors – These are the highly variable factors that can vary seasonally to daily including vegetation health (NDVI) and productivity and soil water contents – these contribute to both preparatory factors and triggering mechanisms.

Triggering mechanisms – These are the mechanisms that, when both static and variable conditions are favorable for landslide occurrence, will cause a landslide. Potential triggering mechanisms include high intensity rainfall events and/or seismic activity. The premise behind the subdivision lies in the fact that the static factors will define the area's susceptibility to landslide occurrence (Dahal et al. 2007).

Geology

The geology of an area is a critical parameter controlling the occurrence of landslides and various studies have used geology as a parameter when modeling landslide susceptibility maps (e.g., Dahal et al. 2007; Temesgen et al. 2010; Singh et al. 2011). Different lithologies have different chemical and physical properties leading to different susceptibility to mass movement. For example, different rock types have different hydrological properties i.e., transmissivity, hydraulic conductivity and permeability (Varnes 1984). These properties play a significant role on slope instabilities during rainfall events. Hence shales and siltstones are considered to be more susceptible to slope instability, while sandstones and conglomerates are regarded to have moderate to low susceptibilities to landslide occurrence (Singh et al. 2011). The sequence of the stratigraphy can also determine the stability of the area. One such example is a sequence that consists of an impermeable layer on the bottom, which is overlain by a permeable layer. Such a sequence would have higher potential to saturate with water during rainfall events, resulting in a higher susceptibility to landslide occurrence. Additionally, the presence of dykes and sills are of importance since they could have weakening effects on the lithologies (Singh 2009). The combination of rock types and structures in an area will dictate the resistance to weathering and erosion processes and ultimately, landslide susceptibility (Singh et al. 2011).

Geomorphology

The geomorphology of any landslide prone area has been found to be the most important controlling parameter by several authors (Sarkar & Kanungo 2004). Information on the geomorphology, including slope, aspect and profiles can be derived from digital elevation models of the area of interest using GIS techniques. Slope is the most substantial parameter influencing landslide development. On a slope of uniform isotropic material, increased slope correlates positively with increased likelihood of failure (Chauhan et al. 2010). In order to assess the contribution of various slope gradients to the development of landslides, it is necessary to know the spatial distribution of the slope categories, which can be obtained from a DEM (Dai & Lee 2002). The other important geomorphologic parameter is relative relief. Landslides generally occur in high relative relief areas. The relief of the area is defined as the difference between maximum and minimum elevation values within the area. This parameter can be computed using DEM (Chauhan et al. 2010). Aspect is one of the most important parameters as it directly and indirectly influences the area's susceptibility to slope failure.

Landcover

While landcover is not strictly "static" it is regarded to be relatively stable over the course of few months. It does not change daily just like rainfall and vegetation. Landcover can be defined as the observed physical and biological cover on the earth's surface. Glade (2002) concurs that vegetation cover is an important factor influencing the rate of surface runoff, which enhance chances of landslide occurrence. For instance, barren slopes are more likely to have landslide occurrence. In contrast vegetative areas tend to reduce the action of rainfall thereby preventing the erosion due to the anchorage provided by the tree roots (Gray & Leiser 1982; Greenway 1987) In general, sparsely vegetated areas are associated with higher runoff during rainy seasons when compared to densely vegetated areas. Similarly, the type of vegetation would have an impact on slope stability (i.e., forested areas are expected to be more stable than grassland). Different soil types have different properties such as grain size, porosity, transmissivity and hydraulic conductivity, therefore different soils have diverse influence on susceptibility to slope failure. An increase in absorbed moisture is a major factor in the decrease in strength of cohesive soils (Zhou 2006); Dahal et al. (2007) have also emphasized the importance of soil type as a parameter when modeling landslide susceptibility maps using the weight of evidence method. It has also been noticed that soil depth between 0.5-2 meters have maximum susceptibility to landslide (Dahal et al. 2007). It is therefore important to input soil depth as a static parameter when modeling a landslide susceptibility map.

Anthropogenic influences

Human-induced changes can affect an area's susceptibility to landslides and must be understood when assessing landslide potential of an area. Examples of such activities are road-cuts, deforestation, mining artificial vibrations, and cutting of slope toe during construction. One of the controlling factors for the stability of slopes is road construction activity (Dahal et al. 2007). Road cuts in mountainous areas can make the area susceptible to slope instability. The increase in moisture content in the soil or changing the form of a slope can increase the area's susceptibility to landslide (Garland & Olivier 1993). Development activities such as cutting and filling along roads and the removal of forest vegetation are also capable of greatly altering slope form and ground water conditions and therefore increasing the susceptibility to landslide occurrence (Swanson & Dyrness 1975). These altered conditions may significantly increase the degree of landslide hazard present (Sidle, Pearce & O'Loughlin 1985). Trees act as natural anchors during rainy seasons, and therefore reduce the effect of rainfall on erosion (Gray & Leiser 1982). Deforestations therefore can cause an area to be more susceptible to slope failure, during rainy seasons.

Variable factors

Vegetation

As mentioned previously, the vegetation in an area has a significant impact on slope instability and various studies have emphasized the significance of vegetation on slope failure (Gray & Leiser 1982; Greenway 1987; Styczen & Morgan 1995). However, it is not only the vegetation type that governs landslide susceptibility, but also the health and productivity of vegetation at a specific time. The effect of vegetation on slope stability appears to be complex in that, depending on local conditions of soil depth, soil type, slope and vegetation, a vegetation cover in some ways definitely promotes stability and in other ways it may not. In a review of behavior of vegetation on slope stability, (Prandini et al. 1977) makes the following points regarding the beneficial effects of forest cover: as a whole forest cover reduces the action of climatic agents on natural mass, in a manner favorable to slope stability by: (1) Intercepting and protecting the mass from the action of sunshine, winds and rains, (2) Retaining a considerable amount of rain water by wetting the large surface made up of leaves, branches, and trunks and eliminating the water as a vapor, (3) Eliminating, as a vapors, a large amount of water from the ground by means of evapotranspiration, and (4)Vegetal debris on the forest floor immobilizes a large amount of water and cuts down on runoff and erosion. When identifying conditions leading up to landslide events, the identification of the vegetative conditions prior to landslide occurrence can be performed. In this regard, landslides may occur preferentially in areas with little vegetation or in areas where vegetation is stressed due to drought or disease.

Triggering mechanisms

Rainfall

Rainfall is a trigger for several landslides around the globe (Iverson 2000; Cardinali et al 2005). Water is recognized to be a factor almost important as gravity in slope instability (Varnes 1984). Landslides triggered by rainfall are caused by the buildup of water pressure into the ground (Cambell 1975; Wilson 1989). Iverson (2000) has also linked slope failure and landslide motion to groundwater pressure heads that change in response to rainfall. (van Schlkwyk & Thomas 1991) have argued that prolonged precipitation events associated with high intensity rainfall are often the trigger for landslides. High intensity and short rainfall duration can trigger mostly shallow landslides and debris flows in relatively high permeability soils (Corominas & Moya 1999; Corominas 2000). Whereas long rainfall periods characterized by low to moderate average rainfall intensity can initiate shallow and deep-seated landslides in low permeability soils and rocks (Cardinali et al 2005).

Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is due to Saaty (1980) and quite often is referred to, as the Saaty method. The AHP model, developed by Saaty in the early 1970s, is a kind of multi-criteria decision-making (MCDM) process that can be used to examine complicated technological, economic, and social-political matters (Saaty 1977; Saaty and Vargas 1991). The process involves pair-wise comparisons of decision variables (e.g., objectives, alternatives). In the construction of a pair-wise comparison matrix, each factor is rated against every other factor by assigning a relative dominance value between 1 and 9 to the intersecting cell (Dai et al. 2001). In addition, the measure of inconsistency can be used to successively improve the consistency of judgments. The consistency index (CI) of a matrix of comparisons is

$$CL = (\lambda\_max-n)/(n-1)$$

where km axis the largest or principal eigenvalue of the matrix, and n is the order of the matrix (Saaty 1977)

The consistency ratio (CR) is obtained by comparing the CI with the appropriate value in a set of numbers in which each is an average random CI derived from a sample of randomly generated reciprocal matrices using the scale 1/9,1/8...,1....,8,9:

$$CR = CI/RI$$

where RI is the average of the resulting CI depending on order of the matrix given by (Saaty 1977). A CR above 0.1 indicates an inconsistent treatment of particular factor ratings, necessitating revision of the judgments in the matrix (Saaty 1977; Dai et al. 2001). In general, the AHP calculates the relative weights for each determinant based on a questionnaire survey; these weighs are used to generate a pair-wise comparison matrix. However, we used the method of (Wu 2002), who reported that the weights for the spatial variables in the multi-criteria evaluation (MCE) were difficult to determine accurately and comprehensively. These issues arise from the process of obtaining weights in the MCE. As a solution, (Wu 2002) proposed the use of a LR procedure.

Methodology

Study Area

The Rangamati district an area of 6116.19 km2, is situated in the southeast of Chittagong Hill Tracts (CHT) (Rangamati Hill District Council 2011). The study area Baghaichhari is one of the Upazilas of Rangamati district. Baghaichhari Upazila (Rangamati district) area 1868.80 sq km, located in between 23°04' and 23°44' north latitudes and in between 92°05' and 92°24' east longitudes. It is bounded by Tripura and Mizoram (India) on the north, langadu and barkal upazilas on the south, Mizoram (India) on the east and dighinala upazila on the west. Baghaichhari Upazila is divided into Baghaichhari Municipality and eight union parishads: Amtali, Baghaichhari, Bongoltali, Khedarmara, Marisha, Rupokari, Sajek, and Sharoyatali. The union parishads are subdivided into 19 mauzas and 303 villages. (District Statistics 2011)

The study area consists of 78519 populations; male 42056, female 36463; Muslim 18310, Hindu 4316, Buddhist 1142, Christian 54717, others 34 and a population density of 44 per km2 (BBS 2011). The biggest union of Baghaichhari upazila is Sajek. Sajek Valley is an emerging tourist spot in Bangladesh situated among the hills of the Kasalong range of mountains in Sajek union, Baghaichhari Upazila in Rangamati District. The valley is 1,476 feet (450 m) above sea level.

The average elevation of the study area is 70.39 m above sea level. The study area experiences a tropical monsoon climate as the country is in a tropical monsoon region with warm temperatures, intense rainfall, frequently excessive humidity, and noticeable wide seasonal variations (Abedin et al. 2020). The average annual rainfall is around 2539.19 mm with humidity level 71.6%, and the average annual temperature ranges from a highest of 36.5°C to a lowest of 12.5°C (BBS 2011; Abedin et al. 2020). April is the warmest month in the Rangamati district with an average maximum temperature of 33°C and January is the coldest month with an average maximum the temperature of 25.7°C (Khatun et al. 2016). Due to the tropical monsoon climate, 80% of the rainfall in the study areas occurs during the monsoon (June-October) season (BBS 2011). This Upazila is formed of tertiary and quaternary sediments. Seven geological formations: Dihing and Dupi Tila undivided, Bokabil, Bhuban, Tipam Sandstone, Valley Alluvium and Colluvium, Dihing, and Girujan, clay are seen in the study area (Haque et al. 2018). Among these geological formations, areas under Bhuban and Bokabil formations are especially prone to landslides due to the alternating layers of sandstone and shale (Haque et al. 2018). Moreover, anthropogenic activities and the resultant excessive rainfall during the monsoon season exacerbate the situation (Islam 2008) In Bangladesh, land use is usually influenced by climate, physiography, and levels of the land (Brammer 2002; Abedin et al. 2020). The study area is dominated by vegetation cover followed by water bodies and bare land. Bare lands being exposed for a long time are susceptible to slope failure because of erosion and weathering process (Haque et al. 2018). As the study areas are frequently rugged, they can neither be used as built-up nor agricultural areas. However, all the built-up cases, hill forest and vegetation cover primarily changed to bare land and then to a built-up area (Ahmed and Dewan 2017; Abedin et al. 2020). Analysis of the land use and land cover changes in the study area over time exhibited an increase in vegetation, bare land, and built-up area and a substantial decrease in water bodies (Abedin et al. 2020).

Approach of the Study

This chapter provides insight on how the research has been conducted. This chapter deals with discussions on research methodology, sampling techniques and data collection process. It also addresses the research investigation by highlighting the discussion of semi-structured interviews. The research has been conducted following a methodology with conformity to the scopes and objective of the study. The methodology is described in detail as below in figure 2.

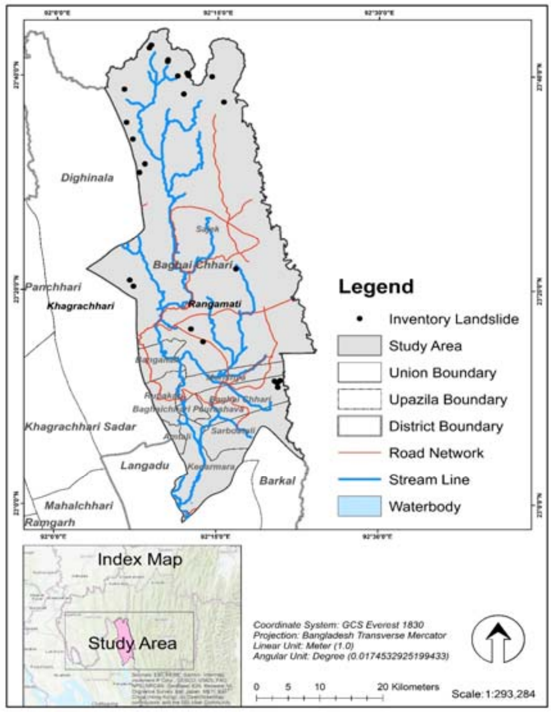

Figure 1: Study area map (Baghaichhari upazila)

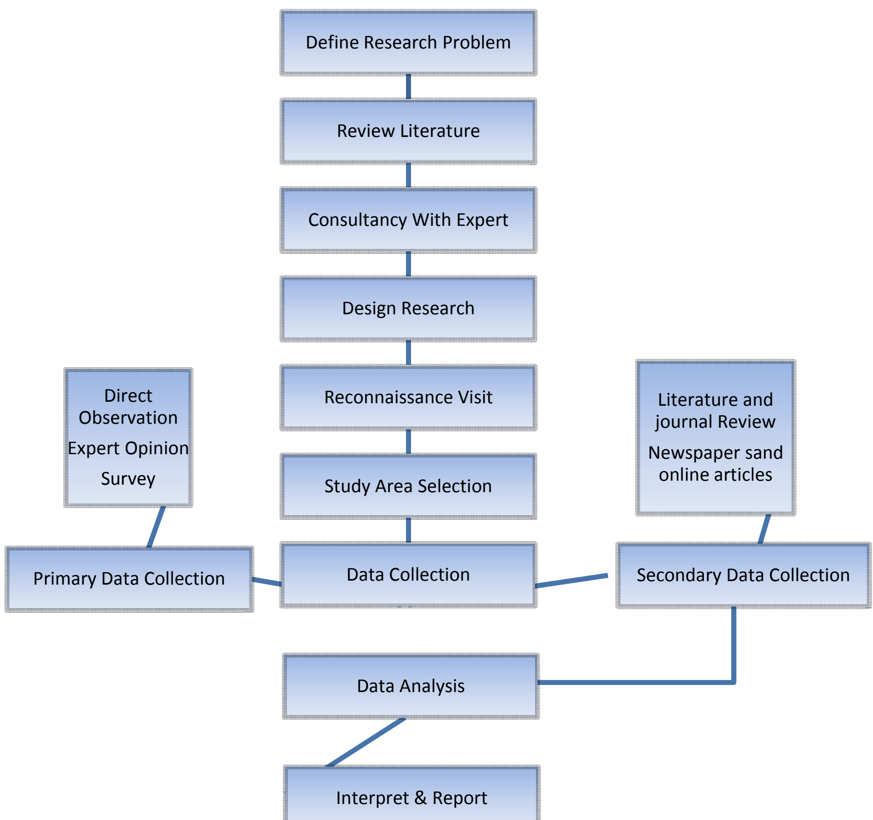

Figure 2: Approach of the study

Data Acquisition

Primary Data

The primary data source of this research is the field survey conducted on landslide prone area of Baghaichhari upazila. Field study was conducted in order to compile digital and hardcopy including geospatial data, reports and all kind of background information relevant for the analysis, such as occurrence dates of rainfall events, as well as landslides.

Secondary data

The remote sensing techniques provide a great possibility to analyze the environmental processes in local or global scale. Landsat images with their 30 m resolution are suitable among others for land cover mapping and change monitoring.

Secondary data was collected for interpreting and analyzing the information to produce a landslide susceptibility map. USGS, ALOS are the sources of Landsat image. Also, different necessary data was collected from another sources. They are – BUET ZIDPAS- 2016; CDMP-11,2012; NASA-DATABASE,2019

Table 21: Data collection source

Information	Baghaichhari upazila
DEM	In the middle filled with SRTM 30m pixel size. It was used to get the layers of Slope Angle, Slope Aspect, Elevation, and Flow Accumulation.
Land-use map	Shapefile (polygons). With 18 classes. Cover the whole Upazila. It helps to include quarries, roads and buildings.
Geology map	Shapefile (polygons) with 5 units. No structural information (faults, folds, etc.). Cover the whole upazila. Re-digitized
Geomorphology map	DEM Interpretation was made. With a total of 6 units
Existing Landslide inventories	Jpg image without attributes. It was digitized as a point based landslide inventory, placing points on the scarps of the landslides.
Hydrology	Shapefile (lines) with rivers and streams, cover the whole upazila gathered from DEM using SWAT model.
Road network	Shapefile (lines), cover the whole upazila
Other Data	Shapefile with road-cuts, Shapefile with Cliffs. Interpreted from the DEM.

Satellite images were downloaded for analyzing the data.

Table 22: Image collection source

Image Year	Satellite	Path/Row	Acquisition Date	Land Cloud Cover	Scene Cloud Cover	Ground Resolution	Source
2020	SRTM	136/44	2020/02/18	0	0	30*30	ALOS
2020	SRTM	136/44	2020/02/24	0	0	30*30	

Data-base preparation

All the information collected, was checked, selected, and modified in order to have it the most complete possible, in the same GIS format, and in the same coordinate system. This process included digitizing landslide inventories, modifying the existing maps (land-cover, geology, soils) in order to improve them, and generation of new maps that could be useful on the analysis as flow accumulation, slope angle, slope aspect, elevation, stream network, stream network distance, road network distance, etc. Finally, all DEM derivative maps as well as distance maps, had to be classified before using them in the model, to accomplish this, for Baghaichhari upazila using the point-based landslide inventories, it was analyzed how many landslides were per value of each factor map

The landslide susceptibility map quality depends on the quality and selection of the landslide inventory and predisposing factors (Reichenbach, P.; Rossi, M.; Malamud, B.D. 2018). The location, types, size, and causes of landslides are stored in a landslide inventory (Guzzetti, F). The selection of predisposing factors depends on the scope and availability of the data and the timeline and cost of the project (Guzzetti, F 2002; Cardinali, M.; Galli, M. 2006; Rossi, M.; Valigi, D. 2009; Wang, Q. 2017). Method and mapped in full scale to determine most vulnerable area in the study area of this research.

Landslide inventory

The landslide inventory was prepared using the combination of Google Earth and field mapping. (Köppen, W.P. 2020; Guzzetti, F 2009) This inventory includes 24 major landslide locations from 2000 to 2020 that were mapped in Google Earth and also collected information from field work. Field mapping was used to map landslides that occurred inaccessible areas including near the roads and settlements. In contrast, Google Earth mapping was used to map landslides in remote areas, including forests.

Elevation

Elevation controls temperature and vegetation. Generally, the occurrences of landslides increase with the increase of elevation before reaching a threshold elevation, where the landslide probability reduces due to rock and soil characteristics and other geotechnical parameters (Guzzetti, F.; Guzzetti, F 2009). For calculating elevation two Shuttle Radar Topography Mission (SRTM) images were downloaded from ALOS. Next step is to remove the background from those images. Then put those images on ArcGIS and use mosaic to new raster tool. By reclassing on 5 classes make the elevation information suitable for AHP calculation.

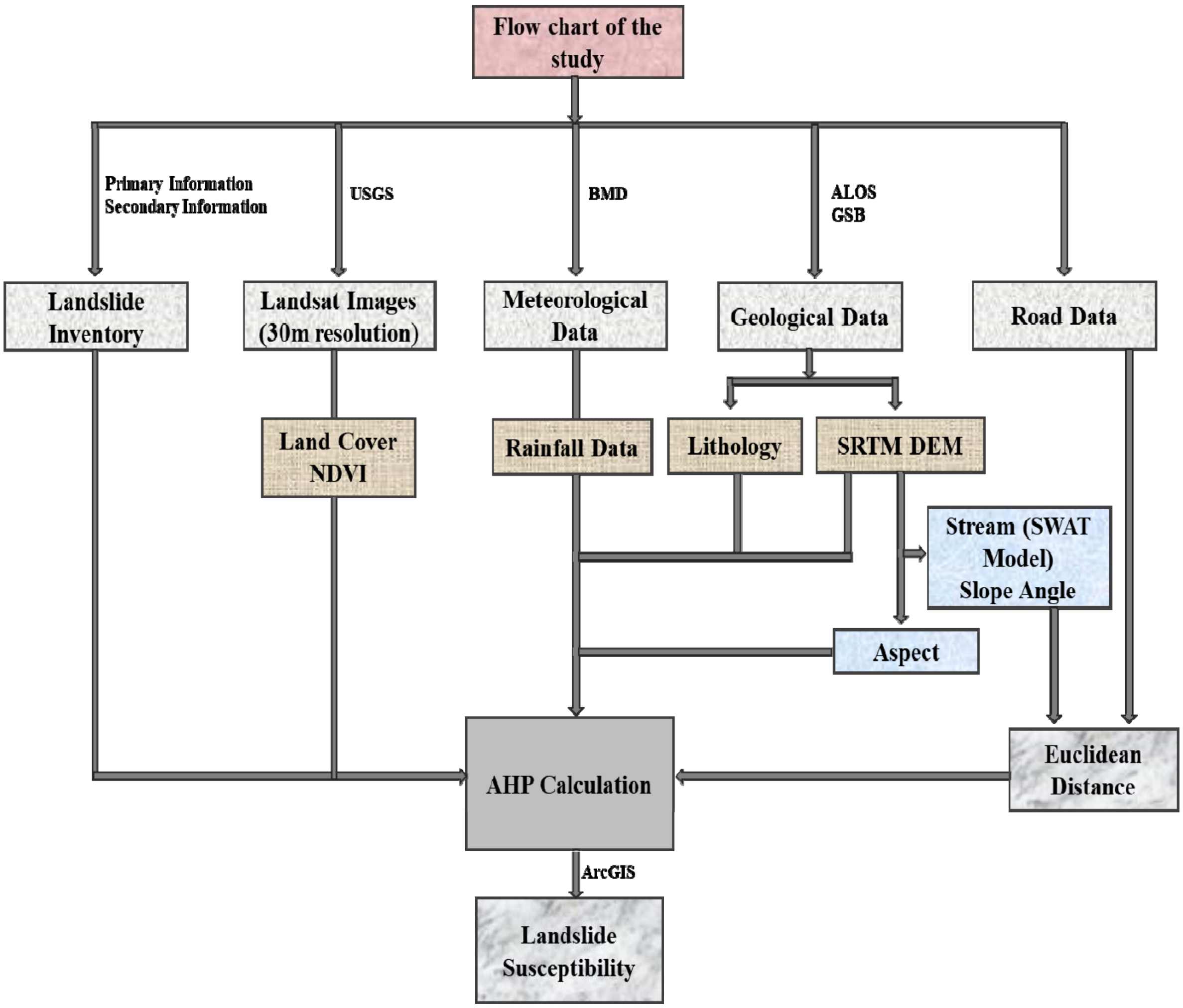

Figure 3: Methodology flowchart

Rainfall

The annual rainfall data from Chittagong Regional Stations of the Bangladesh Meteorological Department (BMD) were used to analyzing rainfall data. Last 30 years (1989-2019) data were used for analyzing annual rainfall data. Then put those data on ArcGIS and use idw tool to create a rainfall prediction surface map. Annual average rainfall data was calculated by using pivot table in excel.

Slope

The slope is another important predisposing factor. Landslides do not occur on a gentle slope, as the shear stress is low (Yilmaz, I. 2010). The steeper the slope is, the higher the probability of landslides (Chen, W. 2017) The slope raster was derived from the ASTER DEM in ArcGIS. By using special analysis tools on ArcGIS create a slope map. The slope raster was then divided into five classes, <10^0, 10-20^0, 20-30^0, 40-50^0, >50^0

Aspect

The aspect is the orientation of the slope (Calista, M.; Miccadei, E. 2019, Chen, W. 2017). The disintegration and deterioration of materials on a slope depend on the aspect because it affects rainfall and wind (Roy, J. 2019). The aspect raster was derived in ArcGIS and used special analysis tools then was divide into nine classes.

Distance to roads

LGED road layers was taken for analyzing road data. Then road layer intersects by study area using ArcGIS. Distance based factors were derived in ArcGIS and Create ring buffer for <10m, 10m, 20m, 50m. By using polygon to raster tool make the road lines.

Distance to stream

Distance based factors were derived in ArcGIS and SWAT model was used to create stream distance. Then this study area was extracted by mask. Create ring buffer for <10m, 10m, 20m, 50m. By using polygon to raster tool make the stream lines.

Lithology

Lithology is one of the most important predisposing factors of landslides ((Calista, M.; Miccadei, E. 2019, Chen, W. 2017). The slope stability depends on the strength of the rocks, which depends on the local lithology. Bangladesh geological data downloaded from Participatory Agency Service Agreement (PASA) under the Department of Energy, USA. Then use polygon to raster tool for creating lithological map.

NDVI

The Normalized Difference Vegetation Index (NDVI) is an index widely used to represent vegetation and plant health (Chen, W. 2019; Islam, M.A.; 2020; Huete, K.A.; 2002). Vegetation coverage protects land from erosion and landslides because the root system binds to soil and protects soil from wasting during rainfall (Chen, W. 2019) The NDVI was derived from Landsat 8 level 2 imagery of 11 March 2020 based on -

NDVI=(IR-R)/(IR+R)=((Band 5-Band 4))/((Band 5+Band 4)), ……………………………… 1

where IR is the infrared band and R is the red band. The NDVI ranges from -1 to 1; moderate to high NDVI (0.2–0.8) indicates vegetation and forests, a negative value usually indicates water bodies, and a low positive value (0.2 and below) represents bare land and urban areas (Chen, W. 2019; Pradhan B 2014)

Analytic Hierarchy Process (AHP) method

Analytic Hierarchy Process (AHP) is used for producing the landslide susceptibility map. AHP gained wide application in site selection, suitability analysis, regional planning, and landslide susceptibility analysis (Ayalew et al., 2005)

For calculating in AHP, it is important to identify the static, variable & triggering factors of landslides. Elevation, Rainfall, Slope, Aspect, Distance to road, Distance to stream, Lithology, NDVI, Land cover are the parameters these were calculated for producing landslide susceptibility map. In pair-wise comparison matrix, it's compulsory to choose whether elevation is very much more important, rather more important, and as important, and so on down to very much less important, than rainfall. Same judgement goes for every parameter. Each of these judgments is assigned a number on a scale. One common scale (adapted from Saaty) is the one shown in Table 4.

Table 23: Common scale of AHP method

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two factors contribute equally to the objective.
3	Somewhat more important	Experience and judgment slightly favor one over the other.
5	Much more important	Experience and judgment strongly favor one over the other.
7	Very much more important	Experience and judgment very strongly favor one over the other. Its importance is demonstrated in practice.
9	Absolutely more important	The evidence favoring one over the other is of the highest possible validity.
2, 4, 6, 8	Intermediate values	When compromise is needed
Reciprocals of the above numbers		For inverse comparison

List of random index value –

Table 24: Random index value

N	2	3	4	5	6	7	8	9
RI (n)	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Step 1

Pair-wise comparison matrix – This is the first step for analytical hierarchy process. Pairwise comparison generally is any process of comparing entities in pairs to judge which of each entity is preferred, or has a greater amount of some quantitative property, or whether or not the two entities are identical. In this matrix, it is compared whether rainfall has more importance than elevation in landslide occurrence. Same comparison goes for every factors.

AHP pairwise comparison, Construct a pairwise comparison matrix.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdot\cdot & a_{1n} \\ a_{21} & a_{22} & \cdot\cdot & a_{2n} \\ \cdot\cdot & \cdot\cdot & \ddots & \cdot\cdot \\ a_{n1} & a_{n2} & \cdot\cdot & a_{nn} \end{bmatrix}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

where n denotes the number of parameters and aij refers to the comparison of parameter i to parameter j with respect to each criterion. The nine-point scale, shown in Table 4, can be used to decide on which element is more important and by how much.

- **Step 2**

AHP synthetization - Divide each entry (aij) in each column of matrix A by its column total. The matrix now becomes a normalized pairwise comparison matrix,

$$A' = \begin{bmatrix} \frac{a_{11}}{\sum_{i\in R} a_{i1}} & \frac{a_{12}}{\sum_{i\in R} a_{i2}} & \cdot\cdot & \frac{a_{1n}}{\sum_{i\in R} a_{in}} \\ \frac{a_{21}}{\sum_{i\in R} a_{i1}} & \frac{a_{22}}{\sum_{i\in R} a_{i2}} & \cdot\cdot & \frac{a_{2n}}{\sum_{i\in R} a_{in}} \\ \cdot\cdot & \cdot\cdot & \ddots & \cdot\cdot \\ \frac{a_{n1}}{\sum_{i\in R} a_{i1}} & \frac{a_{n2}}{\sum_{i\in R} a_{i2}} & \ddots & \frac{a_{nn}}{\sum_{i\in R} a_{in}} \end{bmatrix}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

where R denotes the set of landslide susceptibility mapping requirements, that is, R ¼ {1; 2; . . .; n}.

- **Step 3**

Compute the average of the entries in each row of matrix A' to yield column vector,

$$C = \begin{matrix} c_1^1\ k \\ \vdots \\ c_1^1\ k \end{matrix} \begin{bmatrix} \frac{\frac{a_{11}}{\sum_{i\in R} a_{i1}} + \frac{a_{12}}{\sum_{i\in R} a_{i2}} + \ldots + \frac{a_{1n}}{\sum_{i\in R} a_{in}}}{n} \\ \vdots \\ \frac{\frac{a_{n1}}{\sum_{i\in R} a_{i1}} + \frac{a_{n2}}{\sum_{i\in R} a_{i2}} + \ldots + \frac{a_{nn}}{\sum_{i\in R} a_{in}}}{n} \end{bmatrix}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

Where $c_1^1 k$ denotes the relationship weightings between critical weight and normalize pair-wise matrix.

Step 4

AHP consistency verification Multiply each entry in column i of matrix A by c_1^1 k. Then, divide the summation of values in row i by c_1^(1) k to yield another column vector,

$$C' = \begin{matrix} c'^{1}_{1\,k} \\ \vdots \\ c'^{1}_{1\,k} \end{matrix} = \begin{bmatrix} \frac{c^1_{1k}a_{11} + c^1_{2k}a_{12} + \cdots + c^1_{nk}a_{1n}}{c^1_{1\,k}} \\ \vdots \\ \frac{c^1_{1k}a_{n1} + c^1_{1k}a_{n2} + \cdots + c^1_{nk}a_{nn}}{c^1_{1k}} \end{bmatrix}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

where C' refers to a weighted sum vector.

- **Step 5**

Compute the averages of values in vector to C' yield the maximum eigenvalue of matrix A,

$$\lambda_{\max} = \frac{\sum_{i \in R} C'^{1}_{ik}}{n}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

- **Step 6**

Compute the consistency index,

$$CI = \frac{\lambda_{max} - n}{n-1}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

- **Step 7**

Compute the consistency ratio,

$$CR = \frac{CI}{RI(n)}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

where RI(n) is a random index of which the value is dependent on the value of n, shown in Table 5. If CR is greater than 0.10, then go to step 1 again.

Result and Discussion

Landslide inventory

It is very important to determine the location and area of the landslide correctly when preparing the landslide susceptibility maps. Landslide inventory maps can be prepared in different formats according to the size of the area, the data obtained from the land, the quality of this data and the scale of the study. These maps can be produced by gathering the information related with the landslides or by analyzing the data from remote sensing.

In this study, primary field survey was held to collect information about landslide of this Baghaichhari upazila and also obtained information from Baghaichhari upazila office. Secondary data is collected from ALOS as SRTM image (30*30) m

Landslide inventory helps to identify the previous landslide location which will help to prepare the landslide susceptibility map. By this inventory map it can be known that which area is vulnerable to landslide disasters by showing the historical landslides. In the inventory map of this study area identifies 24 major landslides of Baghaichhari upazila. In which 20 landslides were occurred in Sajek union. Sajek is the biggest union of Baghaichhari upazila and contains highest level of mountains. Most of the major landslides determined had occurred as a result of the heavy rainfalls. Some of the landslides occurring in previous years were not determined because dense plant cover had grown over the landslide areas in the short period of 1–2 years, and the landslide area had begun to be converted to agricultural use.

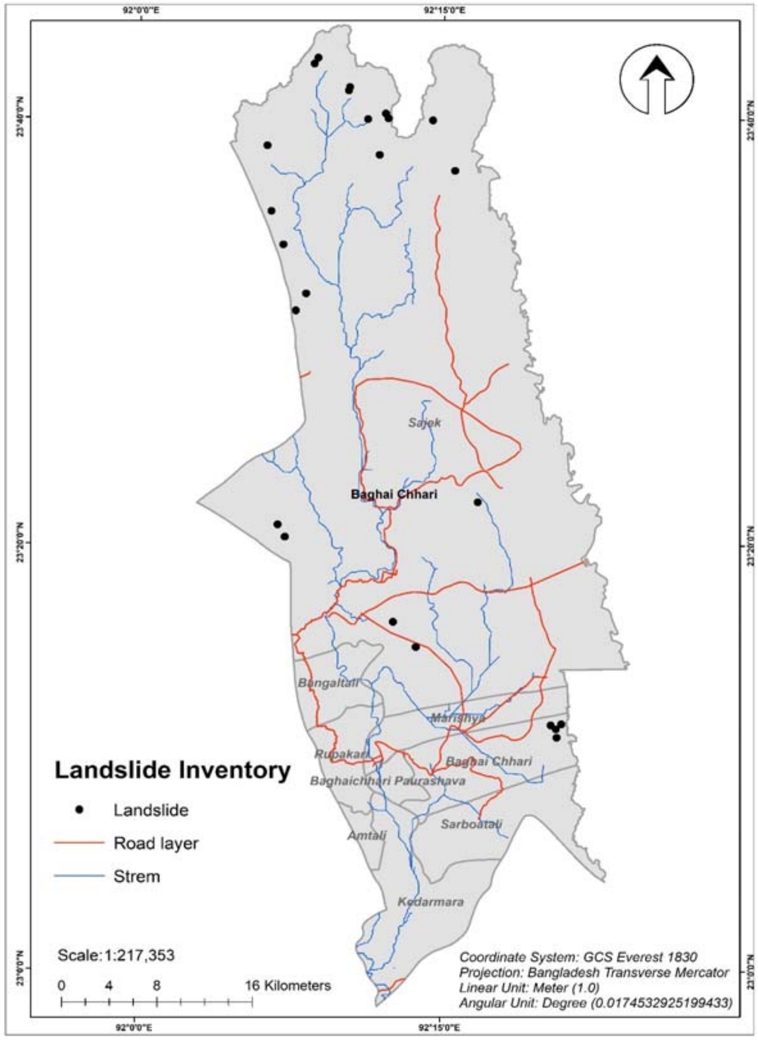

Figure 4: Inventory map (Baghaichhari Upazila)

Elevation

A change in elevation can bring changes in geomorphology, vegetation, and rate of erosion in an area and thus alters the landslide susceptibility (Chen, W. 2017). We derived elevation from SRTM, ALOS and divided them into six classes. They are- 0-84m, 85-140m, 140-200m, 200-300m, 300-450m, 450-730m. Landslide susceptibility for each elevation is analyzed (figure-6) this analysis shows that the higher the elevation (m), more susceptible for landslide. The highest elevation 450-730m is very high susceptible for landslide hazard.

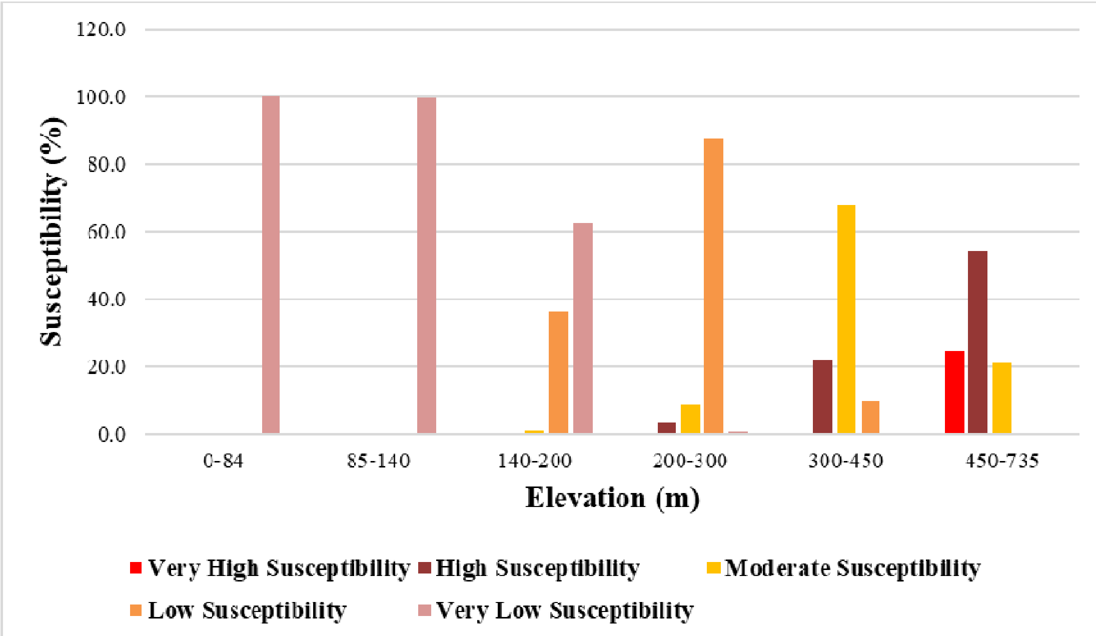

Figure 5: Elevation & Susceptibility

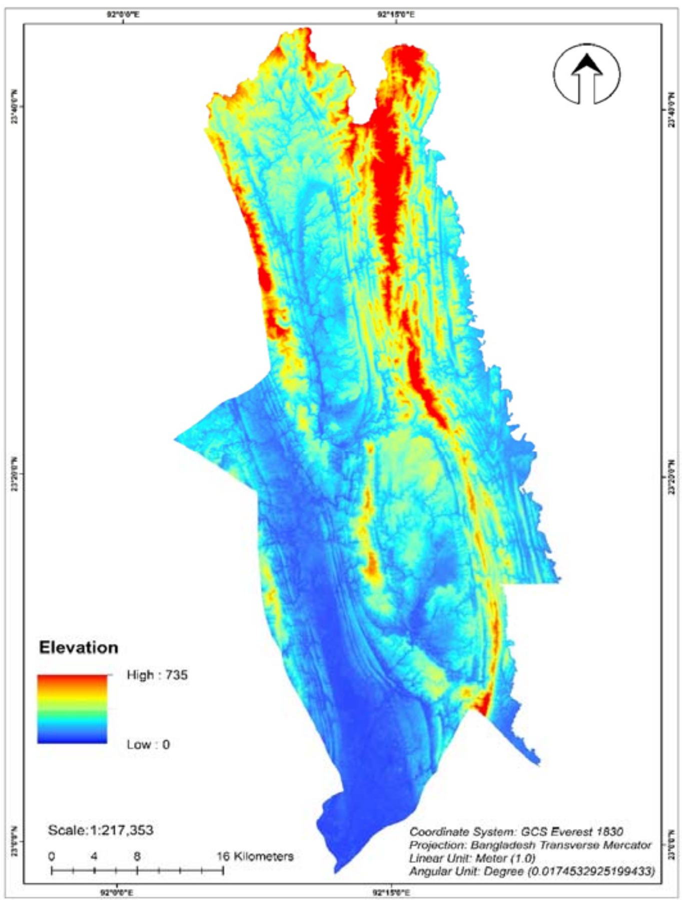

Figure 6: Elevation map (Baghaichhari Upazila)

Slope

The main parameter of the slope stability analysis is the slope angle (Lee and Min, 2001). Because the slope angle is directly related to the landslides, it is frequently used in preparing landslide susceptibility maps (Clerici et al., 2002; Saha et al., 2002; Cevik and Topal, 2003; Ercanoglu et al., 2004; Lee et al., 2004a; Lee, 2005; Yalcin, 2005). The slope map of the study area was divided into six slope categories. ArcView 3.2 analysis was performed to discover in which slope group has the high susceptibility to landslide. The area percentage in each slope group class is presented in (figure-7). The susceptibility rate for each slope class is presented in (figure-8) This figure indicates that the high susceptibility for landslides at a slope angle of less than 40°.

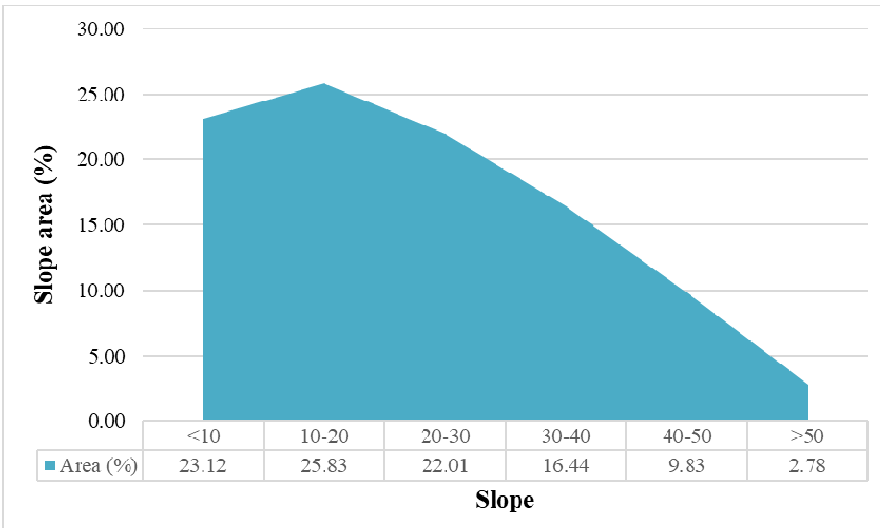

Figure 7:Slope area

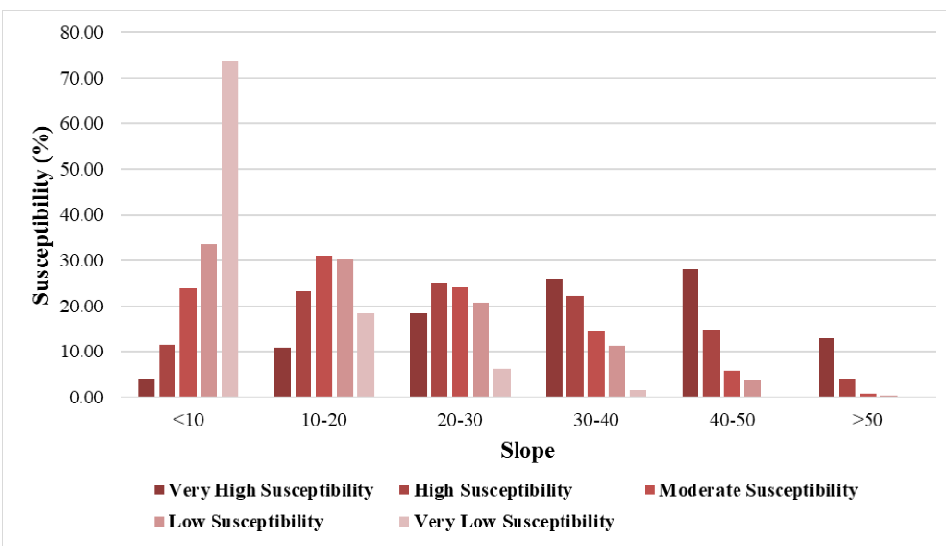

Figure 8: Slope and Susceptibility

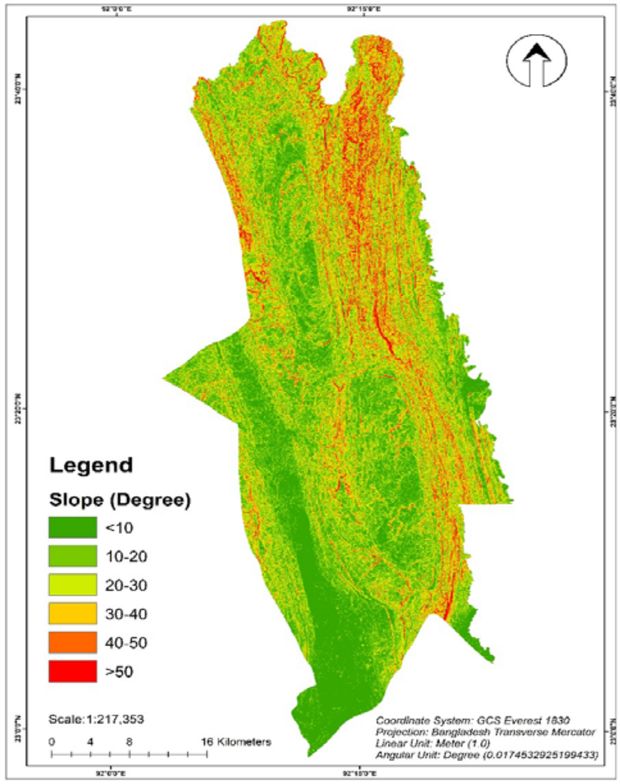

Figure 9: Slope (Baghaichhari Upazila)

Lithology

The main source of data related to the geomorphology of an area of land is determined by the lithologic properties of that land (Dai et al., 2001). The landslide phenomenon, a part of the geomorphologic studies and research, is related to the lithological properties of the material of the land. In the study area, the rock outcrops had decomposed at different degrees from the effects of physical and chemical factors. The degree of lithological types was determined by using the ArcGIS 10.6 software. Firstly, this analysis shows the lithological types and areas covered by this lithological type (figure - 12). As a result of the analysis performed according to the lithological types and landslide inventory of different units, it was verified that approximately 80% of the landslides occurred in Boka Bill formation and 20% of the landslide occurred in Bhuban formation (figure-10). This analysis also shows that now some areas of Boka bill formation has the very high susceptibility (`15.72%) and other some areas of this formation have high susceptibility to landslide (30.50%) (table-6) According to the landslide inventory, maximum major landslides were occurred in the Boka Bill formation. And also, this study shows that some areas which contains Boka Bill formation still has the highest susceptibility of landslide in Baghaichhari upazila.

Table 7: Landslide susceptibility for different lithological types

lithological Types	Very High Susceptibility	High Susceptibility	Moderate Susceptibility	Low Susceptibility	Very Low Susceptibility	Inventory
Dihing and Dupi Tila Formation	0.00	0.00	0.00	0.00	0.00	0.00
Boka Bil Formation	15.72	35.97	37.37	10.9	0.00	79.17
Bhuban Formation	10.18	28.48	30.61	30.44	0.30	20.83
Tipam Sandstone	0.06	1.08	3.19	81.18	14.49	0.00
Valley Alluvium and Colluvium	0.00	0.00	0.00	9.43	90.57	0.00
Lake	0.00	0.00	0.00	0.00	100.00	0.00

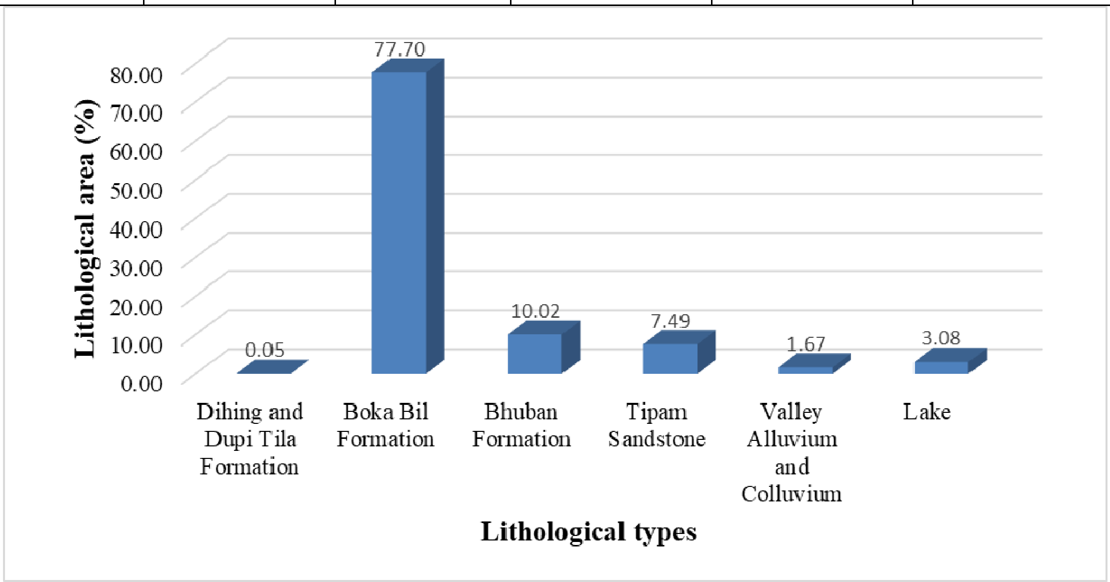

Figure 10: Lithological types

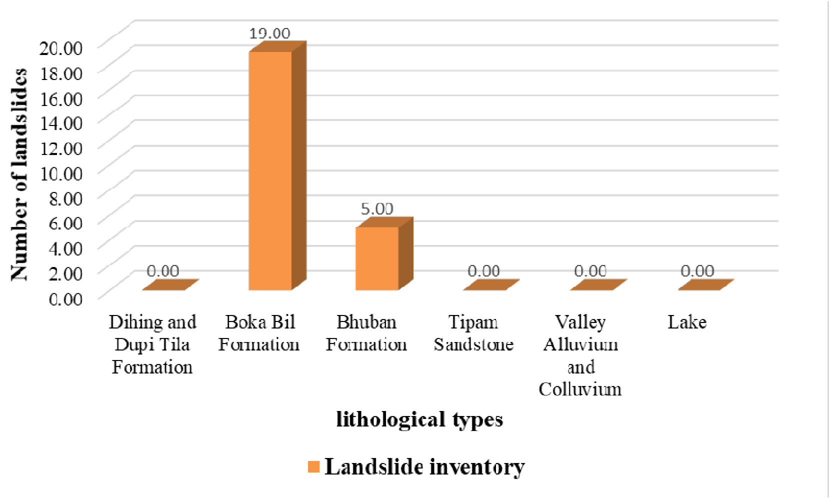

Figure 11: Lithological types and inventory

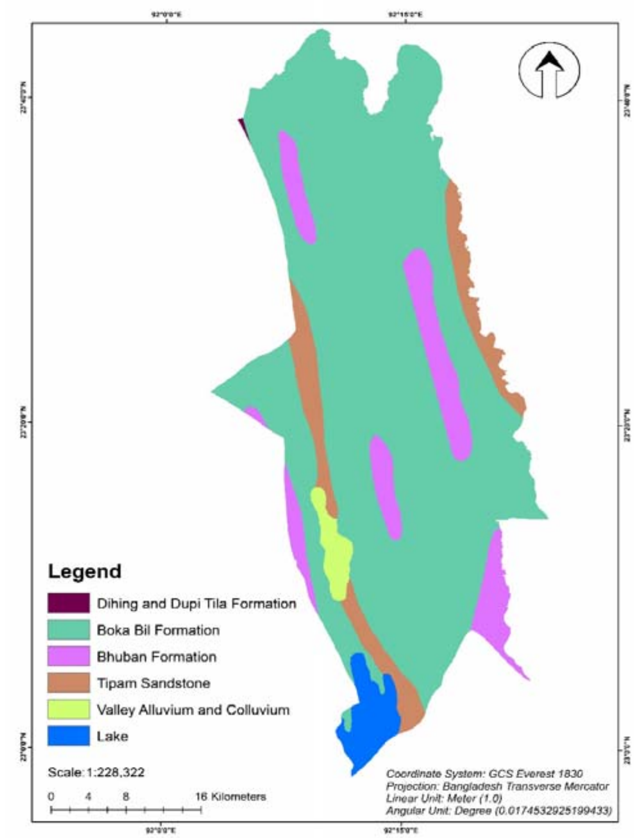

Figure 12: Lithology map (Baghaichhari upazila)

Rainfall

The average precipitation is high in the study area compared to the normal range of precipitation. Since the soil movements are influenced by numerous parameters, however, scientific and technical studies (e.g., (Xie, Esaki et al. 2004, Chang, Chiang et al. 2008, Pradhan and Lee 2010) suggest that rainfall is one of the important triggering factors that causes landslides. The effect of rainfall infiltration on slope could result in the changing soil suction and positive pore pressure, as well as raise the soil's unit weight, reducing anti-shear strength of rock and soil (Wilson and Dietrich 1987, Premchitt, Brand et al. 1994, Iverson 2000, Hengxing, Chenghu et al. 2003). The main causes of such phenomenon seem to be prolonged rainfall events of medium intensity or extreme intensity. 40 years (1979-2019) Rainfall data from Bangladesh Meteorological department (BMD) show that the lowest average annual rainfall (About 5870 mm/yr) in the study area is greater than the average rainfall of the country (1030 mm/yr). Moreover, frequency of rainfall in the past decades evident the influence of landslide by rainfall. However, rainfall distribution within the study area is unique. Almost 60% area of the study is poured with more than 2500 mm rainfall annually, which seems a leading factor of landslide. Most of the landslide movements were reported in the study area during monsoon rainfall. The rainfall in the Sajek union of the study area has higher precipitation than the rest of the areas. GIS data analysis indicates that the highest annual average rainfall about 7909 mm/yr and the lowest annual average rainfall about 5870 mm/yr. This rainfall rate is far higher than the average rainfall in Bangladesh.

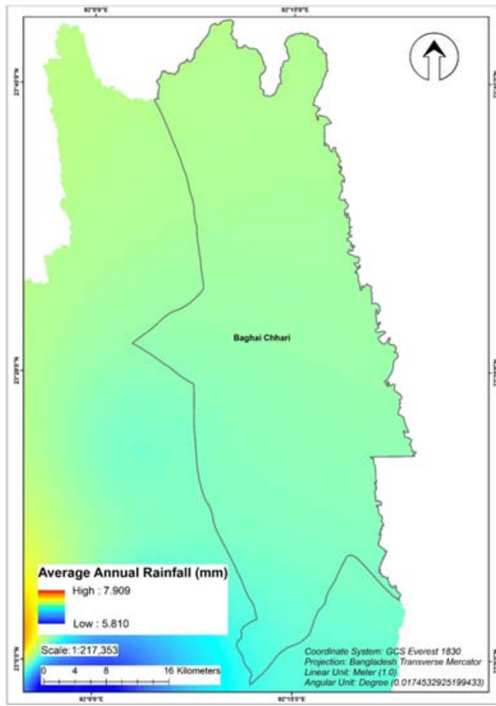

Figure 13: Rainfall rate map (Baghaichhari upazila)

Aspect

Like slope, aspect is one of the important factors in preparing landslide susceptibility maps (Guzzetti et al., 1999; Nagarajan et al., 2000; Saha et al., 2002; Cevik and Topal, 2003; Ercanoglu et al., 2004; Lee et al., 2004a; Lee, 2005). Aspect related parameters such as exposure to sunlight, drying winds, rainfall (degree of saturation), and discontinuities may control the occurrence of landslides (Dai et al., 2001; Cevik and Topal, 2003; Suzen and Doyuran, 2004; Komac, 2006). In this study, the aspect map of the study area was produced to show the relationship between aspect and landslide. Aspect regions are classified according to the aspect class as flat (−1°), north (0°–22.5°), northeast (22.5°–67.5°), east (67.5°–112.5°), southeast (112.5°–157.5°), south (157.5°–202.5°), southwest (202.5°–247.5°), west (247.5°–337.5°) Some analyses were performed using aspect and landslide inventory maps to determine the distribution of landslides, according to the aspect class, and the percentage of landslide susceptibilities in aspect class. (table - 7) This analysis also shows the area of each aspect class in the study area. (figure-14)

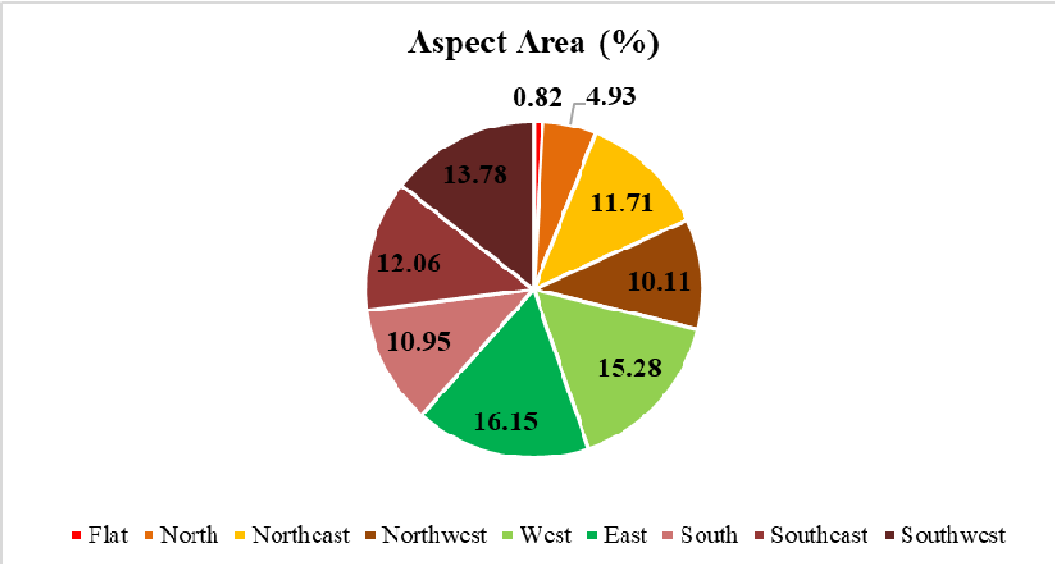

Figure 14: Aspect Area

Table 8: Aspect and percentage of susceptibility

TYPE	Very High Susceptibility	High Susceptibility	Moderate Susceptibility	Low Susceptibility	Very Low Susceptibility
Flat	0.07	0.82	8.94	15.53	74.64
North	9.26	27.50	36.46	20.83	5.95
Northeast	9.15	29.71	32.83	22.66	5.66
East	8.46	32.71	29.94	23.79	5.09
Southeast	7.59	31.86	29.59	25.34	5.62
South	7.17	30.93	31.72	24.78	5.41
Southwest	10.38	32.52	32.41	20.21	4.48
West	12.56	32.14	33.90	17.18	4.22
Northwest	12.01	29.54	35.17	18.00	5.28

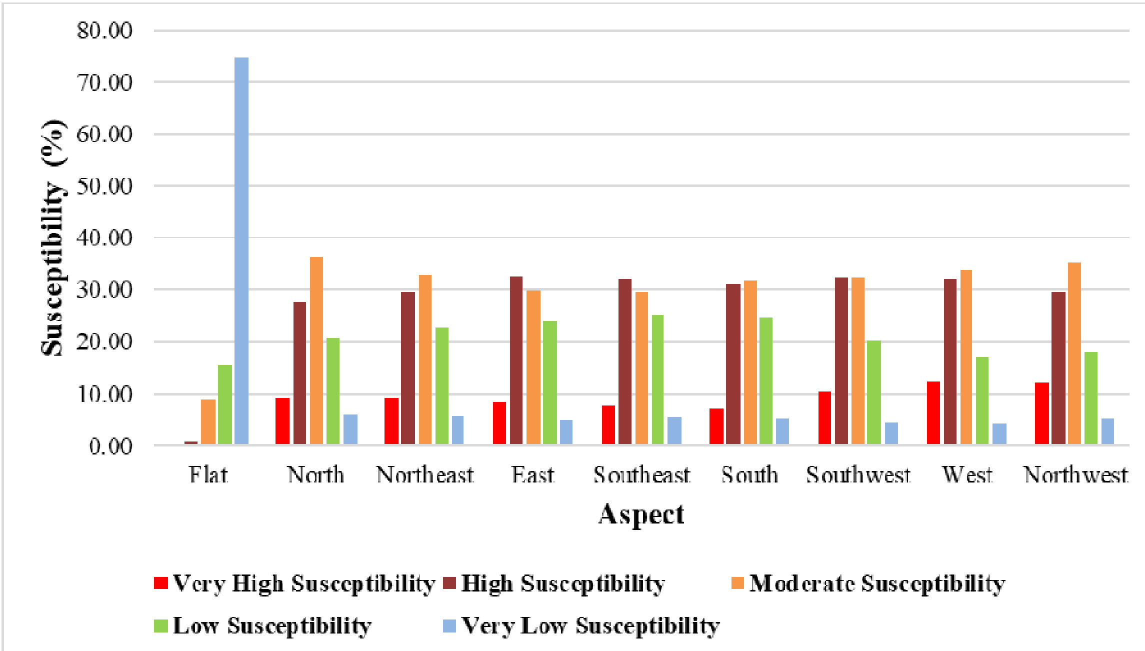

Figure 15: Susceptibility and Aspect

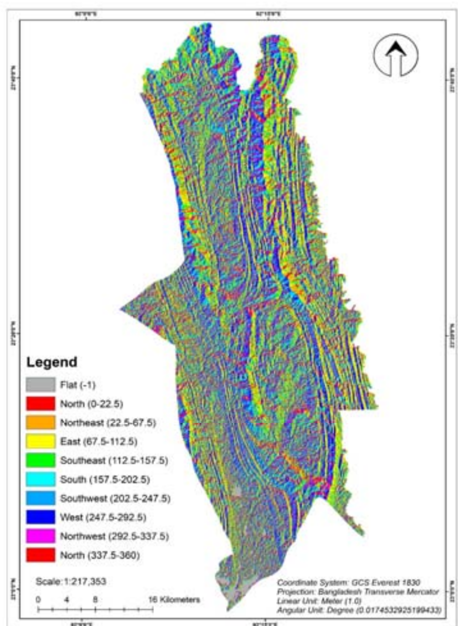

Figure 16: Aspect map (Baghaichhari Upazila)

Land cover

From the analysis of GIS (Fig.-20), it is revealed that maximum part of the upazila is covered by dense hill forest. Only 2.02% of the total area is covered by water. Here, population density is lower than other upazilas of Rangamati. Though this upazila has less population but because of densely hill forest this upazila is highly vulnerable to landslide hazards. Baghaichhari upazila has 1.94% settlement, 36.82% vegetation (garden, agricultural land, shrub field etc.) and rest of the area 59.22%

hilly forest area (figure- 18) landslide inventory shows that among major 24 landslides 17 landslides occurred in hilly forest area and 5 landslides occurred in agricultural land. (figure - 17) From the analysis it also showed that the percentage of landslide susceptibilities of each land use and land cover factors. (table-8)

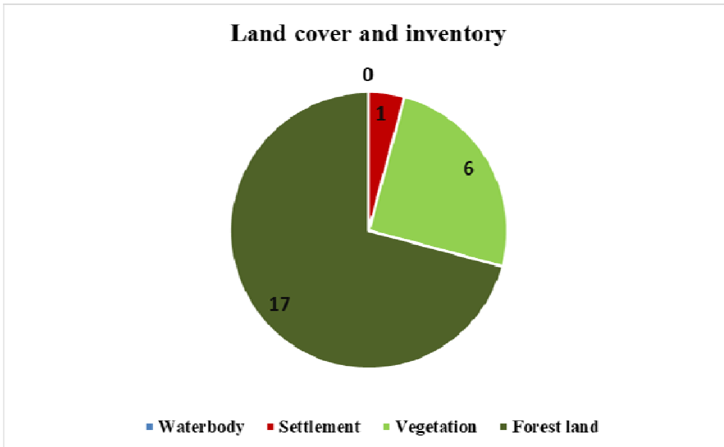

Figure 17: Landcover and Inventory

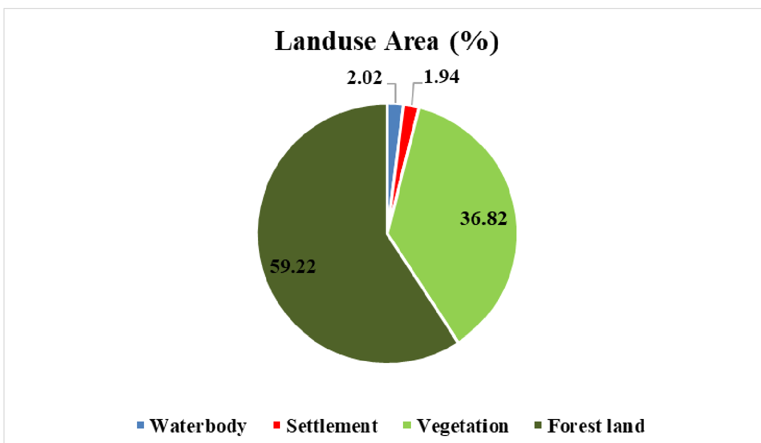

Figure 18: Landcover area

Table 9: Landcover and susceptibility

Landcover type	Waterbody	Settlement	Vegetation	Forest land
Very High Susceptibility	0.67	1.85	7.71	11.27
High Susceptibility	4.91	5.44	25.91	35.73
Moderate Susceptibility	20.78	45.11	34.98	30.64
Low Susceptibility	21.68	22.84	21.57	21.43
Very Low Susceptibility	51.96	24.76	9.82	0.93
Inventory	0.00	4.17	25.00	70.83

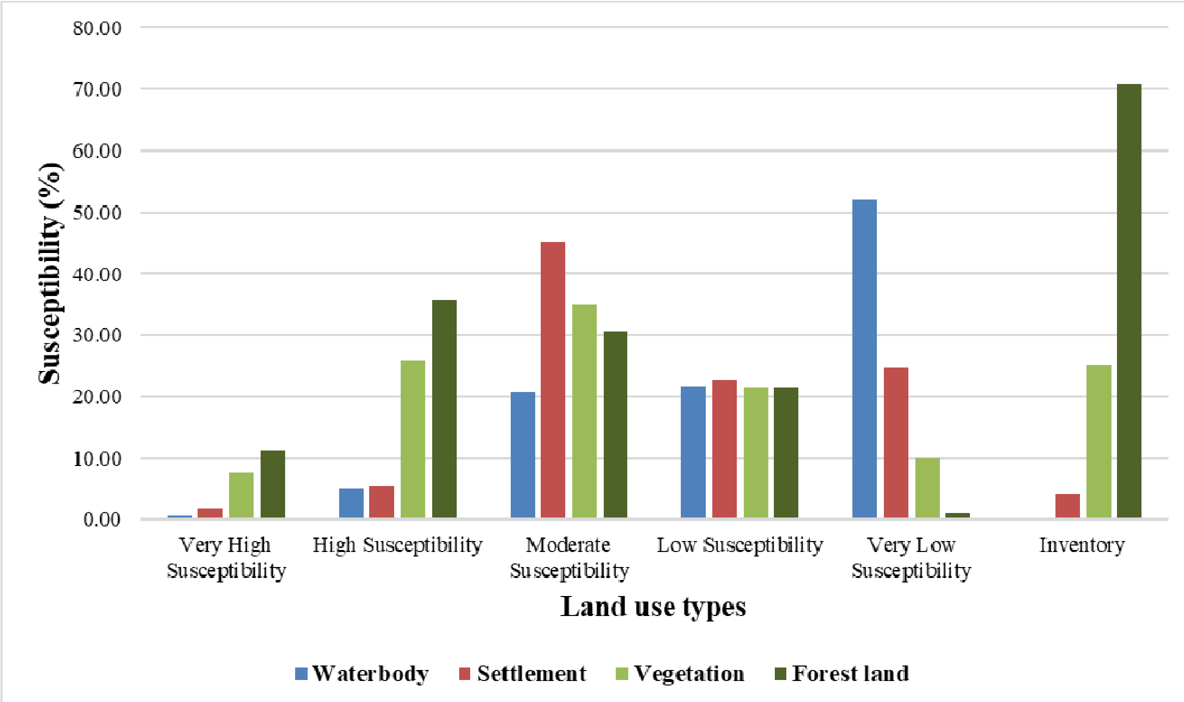

Figure 19: Landcover and Susceptibility

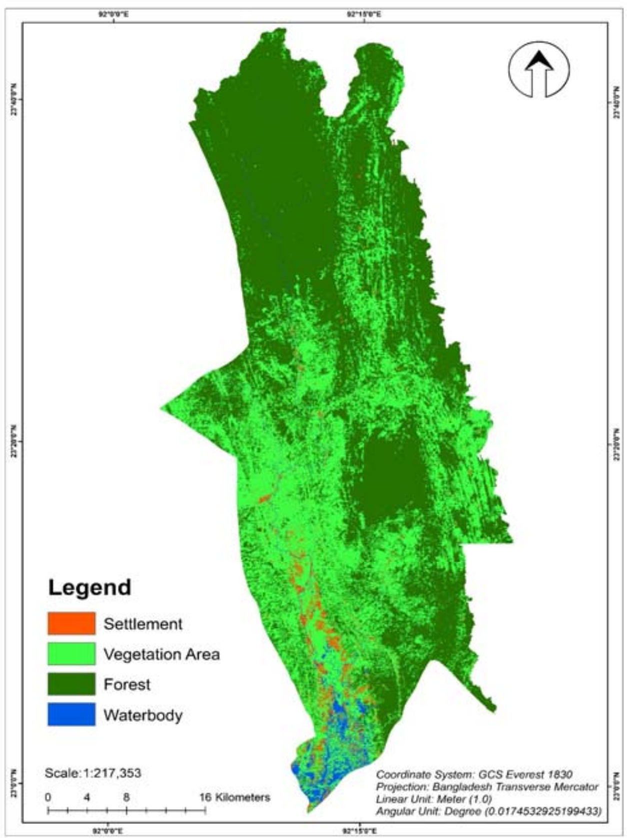

Figure 20: Landcover map (Baghaichhari Upazila)

Normalized Difference Vegetation Index (NDVI)

NDVI indicates the growth of vegetation and biomass of an area (Roy, J.; Saha, S. 2019) Generally, the probability of the occurrence of the landslide on the naturally vegetated surface is lower than the bare lands (Chen, W. 2017) The NDVI was derived from Landsat 8 level 2 imagery of 11 March 2020 based on Equation 1:

$$NDVI = ((IR-R))/((IR+R))$$

$$= ((Band\ 5-Band\ 4))/((Band\ 5+Band\ 4))$$

where IR is the infrared band and R is the red band. The NDVI ranges from -1 to 1; moderate to high NDVI (0.2–0.8) indicates vegetation and forests, a negative value usually indicates water bodies, and a low positive value (0.2 and below) represents bare land and urban areas (Chen, W. 2019; Pradhan B 2014). This study area's NDVI ranges from {(-0.05) – 0.46} which indicates that this area consists of vegetation, forests, settlements and also water bodies.

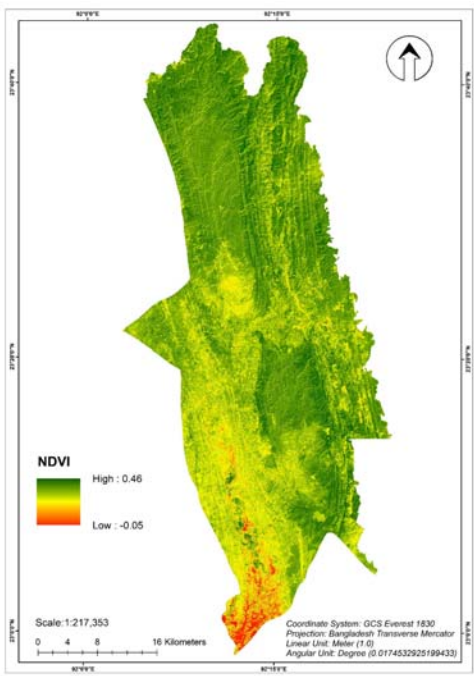

Figure 21: NDVI map (Baghaichhari Upazila)

Distance to stream

An important parameter that controls the stability of a slope is the saturation degree of the material on the slope. The closeness of the slope to drainage structures is another important factor in terms of stability. Streams may adversely affect stability by eroding the slopes or by saturating the lower part of material until resulting in water level increases (Gokceoglu and Aksoy, 1996; Dai et al., 2001; Saha et al., 2002; Cevik and Topal, 2003; Yalcin, 2005). A thorough field investigation should be carried out to determine the effects of streams on the slope. ArcGIS 10.6 is used for analyzing the stream data. Four different buffer areas were created within the study area to determine the degree to which the streams affected the slopes. Four buffer areas are <10m, 10-20m, 20-50m, >50m (Figure 22)

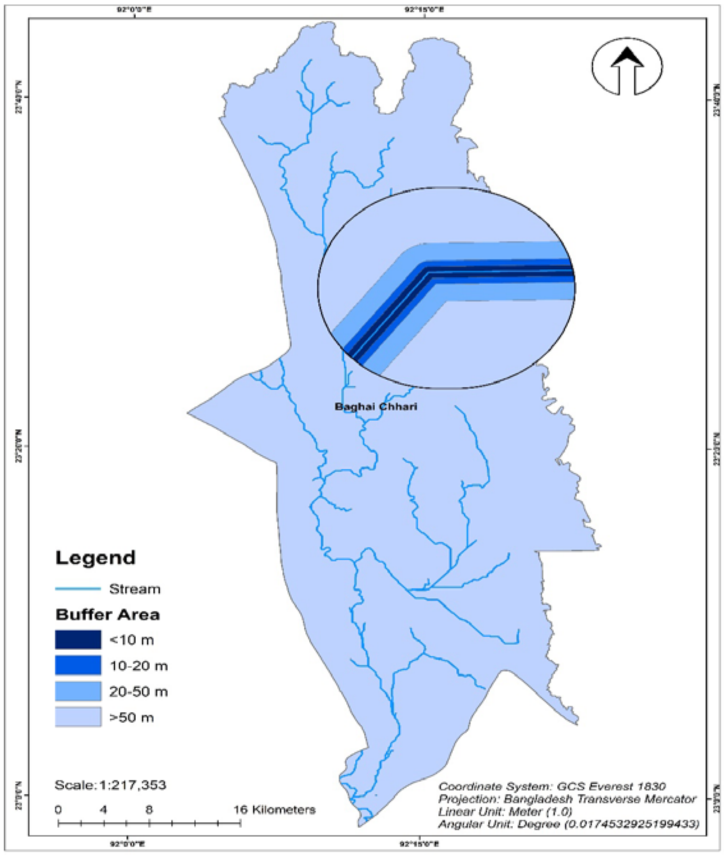

Figure 22:Distance to stream map (Baghaichhari Upazila)

Distance to roads

Similar to the effect of the distance to streams, landslides may occur on the road and on the side of the slopes affected by roads (Pachauri and Pant, 1992; Pachauri et al., 1998; Ayalew and Yamagishi, 2005; Yalcin, 2005). Distance from the road networks is one of the most critical factors. A road constructed beside slopes causes a decrease in the load on both the topography and on the heel of slope. The undercutting of slopes during road construction and the vibration created by vehicles damages the slope stability (Kanwal, S.; Atif, S.; Shafiq, M. 2017). As a result of an increase in stress on the back of the slope because of changes in topography and decrease of load some tension cracks may be created. On the slope of the hill that is balanced before the road is constructed, instability may be observed because of negative effects such as water ingress. In fact, during the field studies, landslides resulting from road construction work were detected. We used the Euclidean distance tool in ArcGIS 10.6 to derive the distance of landslides from the targeted road feature. Four different buffer areas were created on the path of the road to determine the effect of the road on the stability of slope. The landslide percentage distribution was determined according to the degrees of distance to the road achieved by comparing the map of the distance to the road and the landslide inventory. Four different road buffer areas are <10m, 10-20m, 20-50m, <50m (figure)

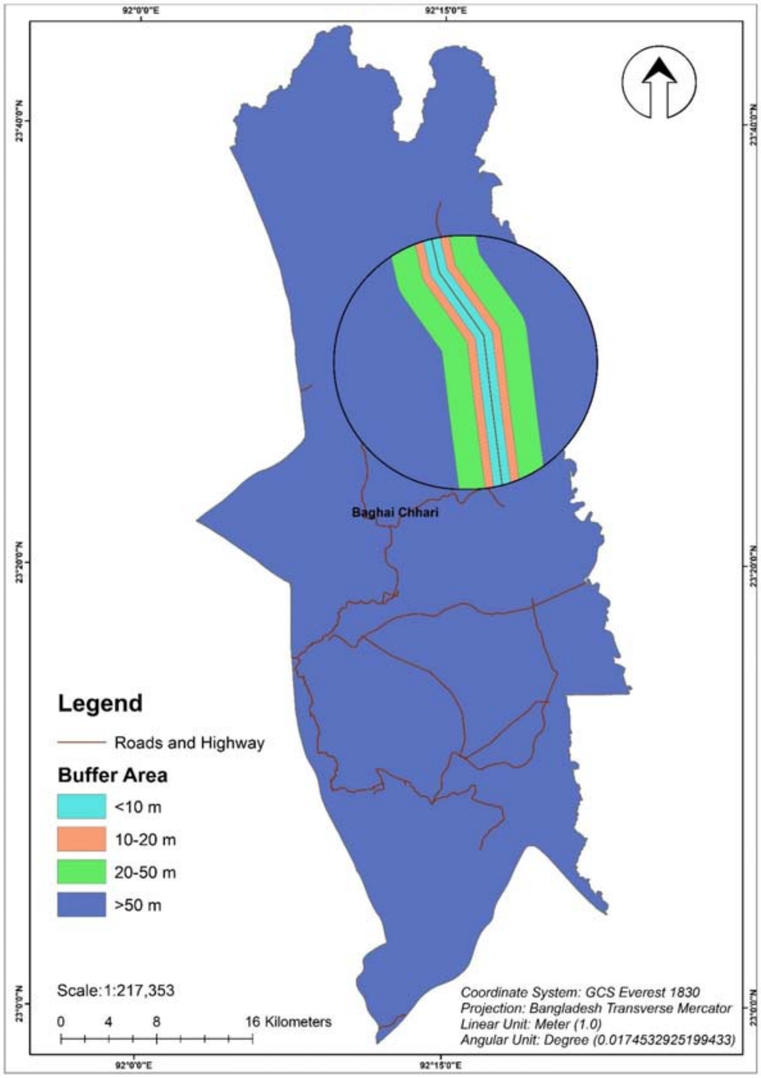

Figure 23:Distance to road map (Baghaichhari Upazila)

Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process is a theory of measurement for dealing with quantifiable and intangible criteria that has been applied to numerous areas, such as decision theory and conflict resolution (Vargas, 1990). AHP is a multi-objective, multi-criteria decision-making approach which enables the user to arrive at a scale of preference drawn from a set of alternatives. AHP gained wide application in site selection, suitability analysis, regional planning, and landslide susceptibility analysis (Ayalew et al., 2005). To apply this approach, it is necessary to break a complex unstructured problem down into its component factors; arrange these factors in a hierarchic order;

assign numerical values to subjective judgements on the relative importance of each factor; and synthesize the judgements to determine the priorities to be assigned to these factors (Saaty and Vargas, 2001). In the construction of a pair-wise comparison matrix, each factor is rated against every other factor by assigning a relative dominant value between 1 and 9 to the intersecting cell (table 3) When the factor on the vertical axis is more important than the factor on the horizontal axis, this value varies between 1 and 9. Conversely, the value varies between the reciprocals 1/2 and 1/9. In these techniques, firstly, the effects of each parameter to the susceptibility of landslides relative to each other were determined by dual evaluation in determining the preferences in the effects of the parameters to the landslide susceptibility maps. Normally, the determination of the values of the parameters relative to each other is a situation that depends on the choices of the decision-maker. However, in this study, both the comparison of the parameters relative to each other and the determination of the decision alternatives, namely the effect values of the sub-criteria of the parameters (weight), were based on the comparison of landslide inventory maps constructed using aerial photos with the other data layers. Consequently, the weight values were determined accurately for the real land data in this study, spatial databases were used, obtained as a result of the field, laboratory and office studies carried out to create landslide susceptibility maps. The analysis of data layers converted to a raster data model was completed by determining their weights in terms of both data layers and sub-criteria, in consequence of the calculation carried out according to the AHP. As a result of these analyses, the landslide susceptibility map was produced for the Ardesen region (susceptibility map). For all the models, where AHP was used, the CR (Consistency Ratio) was calculated. The models with a CR greater than 0.1 were automatically rejected. With the AHP method, the values of spatial factors weights were defined. Using a weighted linear sum procedure (Voogd, 1983) the acquired weights were used to calculate the landslide susceptibility models. In this method, elevation, slope, rainfall, lithology, NDVI and aspect are found to be important parameters for the study area, whereas distance to road, distance to stream, land cover is low.

Pair-wise comparison matrix

From equation 2, the pair wise comparison matrix for analytical hierarchy process is calculated.

Table 25: Pair-wise comparison matrix

Types	**Elevation**	**Rainfall**	**Slope**	**Lithology**	**Distance to Road**	**Distance to Stream**	**Land Cover**	**NDVI**	**Aspect**
Elevation	1.00								
Rainfall	0.50	1.00							

Slope	0.50	2.00	1.00						
Lithology	0.33	0.33	0.50	1.00					
Distance to Road	0.14	0.20	0.14	0.20	1.00				
Distance to Stream	0.20	0.17	0.17	0.20	0.50	1.00			
Land Cover	0.17	0.17	0.20	0.14	3.00	0.50	1.00		
NDVI	0.14	0.20	0.20	0.17	1.00	2.00	3.00	1.00	
Aspect	0.17	0.14	0.17	0.25	5.00	2.00	2.00	2.00	1.00

Normalized pair-wise matrix

From equation 3, by AHP synthetization a normalized pair-wise matrix can be calculated.

Table 26: Normalized pair-wise matrix

Types	**Elevation**	**Rainfall**	**Slope**	**Lithology**	**Distance to Road**	**Distance to Stream**	**Land Cover**	**NDVI**	**Aspect**
Elevation	0.32	0.32	0.41	0.30	0.20	0.17	0.19	0.25	0.23
Rainfall	0.16	0.16	0.10	0.30	0.14	0.20	0.19	0.18	0.27
Slope	0.16	0.32	0.21	0.20	0.20	0.20	0.15	0.18	0.23
Lithology	0.11	0.05	0.10	0.10	0.14	0.17	0.22	0.22	0.16
Distance to Road	0.05	0.03	0.03	0.02	0.03	0.07	0.01	0.04	0.01
Distance to Stream	0.06	0.03	0.03	0.02	0.01	0.03	0.06	0.02	0.02
Land Cover	0.05	0.03	0.04	0.01	0.09	0.02	0.03	0.01	0.02
NDVI	0.05	0.03	0.04	0.02	0.03	0.07	0.09	0.04	0.02
Aspect	0.05	0.02	0.03	0.03	0.14	0.07	0.06	0.07	0.04

Critical weight value
From equation 4, critical weight value for each parameter is calculated.

Table 27: Critical weight value

Parameters	Elevation	Rainfall	Slope	Lithology	Distance to Road	Distance to Stream	Land Cover	NDVI	Aspect
Criteria Weights	0.266	0.190	0.207	0.140	0.031	0.032	0.033	0.042	0.058

AHP consistency verification
From using equation 5, weighted sum value for each parameter is calculated.

Table 28: AHP consistency verification

Parameters	Elevation	Rainfall	Slope	Lithology	Distance to Road	Distance to Stream	Land Cover	NDVI	Aspect
Weighted Sum Value	2.703	2.014	2.137	1.432	0.294	0.312	0.323	0.408	0.570

Maximum eigenvalue calculation
Now Compute the averages of values to yield the maximum eigenvalue of pairwise comparison matrix. By using equation 6, λ_{max} is calculated.

$$\lambda_{max} = 9.9553$$

Consistency Index
Consistency Index (CI) is calculated from equation 7,

$$CI = \frac{\lambda_{max} - n}{n-1}$$
$$= 0.119412055$$

Here, λmax = 9.9553 and n refers to the number of parameters is used for this calculation. In this calculation we used 9 parameters such as, elevation, rainfall, slope, lithology, aspect, NDVI, distance to stream, land cover and distance to road. So, in this calculation n = 9

Consistency Ratio
By using equation 8, consistency ratio is calculated.

$$CR = \frac{CI}{RI\ (n)}$$
$$= 0.082353141$$

Here, CI is calculated in previous step. There are 9 parameters so, n = 9 and RI refers to a random index of which the value is dependent on the value of n, shown in Table 5. If CR is greater than 0.10, then go to step 1 again. The models with a CR greater than 0.1 were automatically rejected. From this study, CR is calculated 0.0824. so, we can say that this model calculation went successful.
Areas susceptible for landslide hazard is calculated by using ArcGIS 10.6 software. (table-13) This study shows that 9.55% area is very high susceptible, 30.88% high susceptible, 32.33% moderate susceptible, 21.51% low susceptible and 5.72% very low susceptible to landslide hazard. (figure-24) Landslide susceptibility map shows the susceptible areas. (figure-25) Sajek union is the highest susceptible union. Landslide susceptibility map is created by performing AHP method on ArcGIS 10.6

Table 29: Susceptible area

Type	Area_km
Very High Susceptibility	151.8777
High Susceptibility	490.9158
Moderate Susceptibility	513.8973
Low Susceptibility	341.9559
Very Low Susceptibility	90.8928

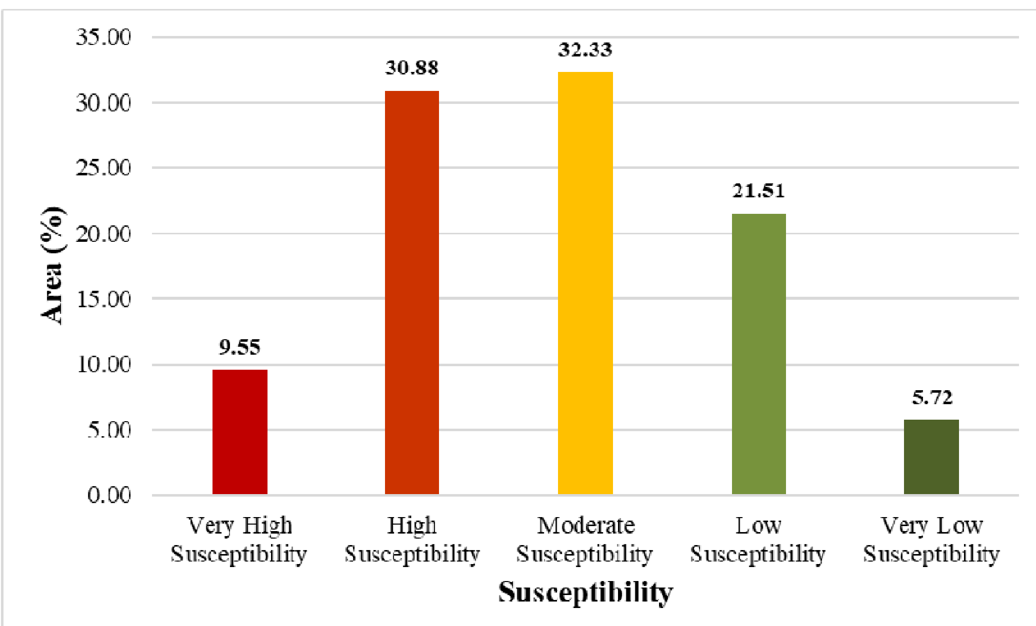

Figure 24: Landslide susceptibility

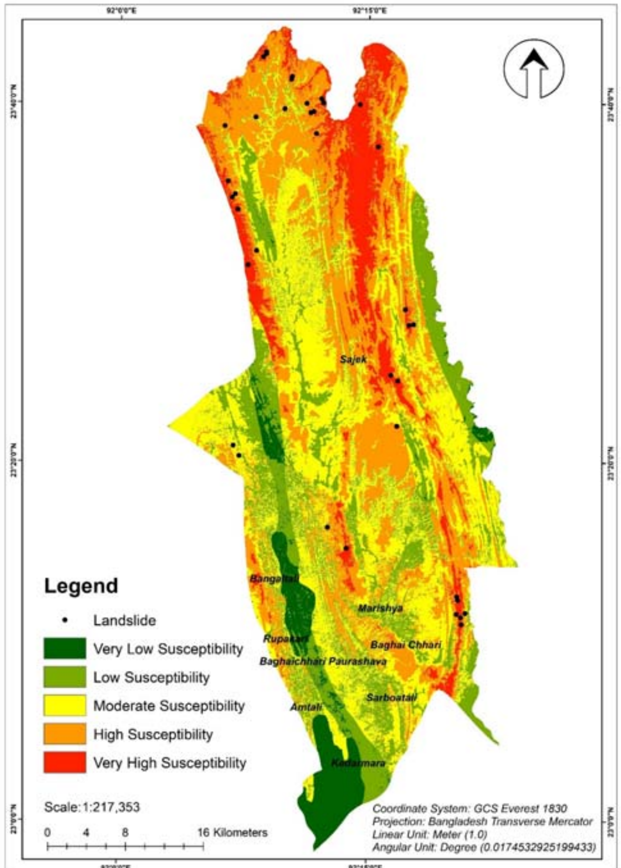

Figure 25:Llandslide susceptibility map (Baghaichhari Upazila)

Susceptibility analysis for roads and unions of Baghaichhari upazila

Hill track roads are steeper in inclination unlike roads in plain area. The roads are constructed through hilly area cutting down the hillsides. As a result, the hill track roads have a common property to have steep elevation and sharp bunking through such loose soiled hill paves. In this study 5 major vulnerable roads are taken under analysis. Five major roads are Baghai Hat - Sajek Road, Dighinala (Bagaihat) - Marisha Road, Khagrachhari - Sajek Road, Old Longkar - New Juppai Road, Sajeck Baghaihat FRB - Bhuachari via Machalong bazar. Among all the roads in Baghaichhari upazila, Old Longkar – New Juppai road and Baghai hat – Sajek road are most critically constructed road with all the possible vulnerabilities. These roads have highest landslide susceptibility than others. (table-15)

In recent time Sajek valley is being one of the most popular tourist spots and there is only one possible road to go there. This road is fully constructed alongside with hilly areas. This road is subjected to overload of tourist with their transports. As a result, the failure of this is highly suspected.

Road length of vulnerable portion of these five major roads is calculated by using ArcGIS 10.6 (table 14). Landslide susceptibility roads are shown in the map which is also made by ArcGIS 10.6 (figure 26). Susceptibility rate of these five roads is calculated and showed the percentage of very high susceptibility to very low susceptibility. (table 15)

Table 14 - road length

Road Name	Road Length
Baghai Hat - Sajek Road	5.19346304
Dighinala(Bagaihat) - Marisha Road	19.38636941
Khagrachhari - Sajek Road	13.85070199
Old Longkar - New Juppai Road	7.418
Baghaihat FRB - Bhuachari via Machalong Bazar	29.08282667

Figure 6: Susceptible road

Roads	Very High Susceptibility	High Susceptibility	Moderate Susceptibility	Low susceptibility	Very Low Susceptibility
Baghai hat – Sajek Road	16.89	55.97	27.13	0.00	0.00
Dighinala (Baghaihat) – Marisha Road	6.89	66.04	10.23	10.79	6.05
Khagrachhari – Sajek Road	0.00	16.86	45.44	36.78	0.91
Old Longkar – New Juppi Road	49.94	43.60	6.46	0.00	0.00
Baghai Hat FCB – Bhuachari via Machalong Bazar	8.04	25.12	42.56	24.28	0.00

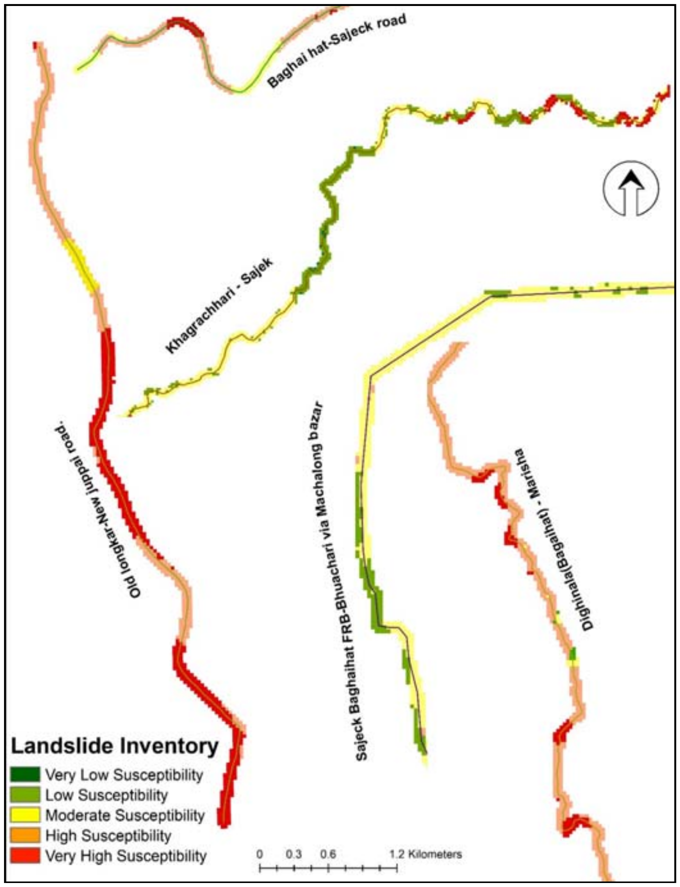

Figure 26: Susceptibility for 5 major roads

The study area, Baghaichhari Upazila is divided into Baghaichhari Municipality and eight union parishads: Amtali, Baghaichhari, Bongoltali, Khedarmara, Marisha, Rupokari, Sajek, and Sharoyatali. The union parishads are subdivided into 19 mauzas and 303 villages. (District Statistics 2011)

The susceptibility rate for these unions is calculated (table-16). This calculation shows that Sajek union has the highest susceptibility of landslides. As Sajek is the biggest union in Baghaichhari upazila and contains highest amount of hilly forest, maximum major landslide inventory is found in the Sajek union. 11.76% areas of Sajek union are very high susceptible to landslide. Baghaichhari, Bongotoli, Marisha and Sharoyatoli union also contains hilly areas and some major landslide inventory was found there. Because of urbanization, hill cutting and heavy rainfall this unions (3.13-3.98) % areas pose very high susceptibility of landslide. but among all the unions, Sajek has the highest susceptibility.

Conclusion

Understanding the processes that lead to land sliding and the effort for subsequent susceptibility mapping provides fundamental knowledge about the evolution of landscapes, and lays the foundation for hazard management and the creation of safety measures. Based on this idea, this study has presented the results of a comprehensive research on landslide controlling parameters and landslide susceptibility mapping in Baghaichhari upazila, Rangamati. In this region, landslides occurred regularly after heavy rainfall. This is because; the topography and lithological materials are eminently suitable for the creation of landslides. It is known that the role of rainfall as a triggering mechanism of landslides is strongly influenced by the landscape dynamic and geology. In Baghaichhari upazila, rough landscapes and heavy rainfall are common, hill cutting often have the potential for initiating slope failures. Susceptible stratigraphy and lithological too, contribute greatly to the occurrence of landslides in the region. With conditions conducive to the development of slope instability having existed in several areas, there was a demand to conduct landslide susceptibility mapping. This study focused on the Baghaichhari upazila, the highest hill track region of country and also contains highest level of rainfall. Sajek valley is situated in this upazila which is 1460m above from sea level. This is mainly because of the problems inherited from landslide inventory maps and the absence of universal guidelines to select causal factors. In this study, the landslide inventory map was prepared in such a way that it included major landslides. Besides, it also considered that lithology, slope gradient and land cover of materials as parameters important for susceptibility mapping. There was an attempt to differentiate the concepts of landslide susceptibility mapping. Various methods are available for landslide susceptibility mapping. In this study, AHP method is used for landslide susceptibility mapping. This study found that Sajek union is most susceptible to landslides and old longkar to new juppi road is the most vulnerable road to landslides.

This study has several limitations. We did not include some critical soil-related factors like soil permeability and soil moisture content due to data unavailability. Secondly, the geological map used in this study had a very coarse resolution compared to other causal factors, and it was a very simplified map as well. This study is performed with a few major landslide inventories. Future studies can include soil-related causal factors and assess whether they improve the accuracy of the maps. Also, future research could include as many as landslide inventories found there, this will help to get improve result than this. The more representative inventory will help to show better landslide susceptibility map of this study area. Moreover, this study recommends future research to evaluate the applicability and performance of other advanced analytical hierarchy method for landslides susceptibility mapping in the study area.

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