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ANALYSIS OF GEOLOGICAL FORMATION AND SOIL CHARACTER OF DHAKA CITY TO FIND THE EARTHQUAKE VULNERABLE AREAS

M. Rashied(1), A. Mahmud(2), M. Ubaura(3)

(1) Junior Research Consultant, SATREP-TSUIB Project, Housing and Building Research Institute, Dhaka, Bangladesh. masudurrashied@outlook.com
(2) Professor, Department of Urban and Regional Planning, Jahangirnagar University, Savar-Dhaka, Bangladesh aktermahmud@juniv.edu
(3) Associate Professor, Tohoku University, ubaura@tohoku.ac.jp

Abstract

Dhaka is one of the major urban agglomerations with more than 18 million population within an area of 306 sq. km and 14th largest megacity of the world. Besides the significance as capital city, historically it has been developed as the center of administrative, economic, healthcare, education, and culture including defense headquarters. Therefore, Dhaka city continued to grow as the largest growth pole of the country with higher growth rate. During the last three decades this city has expanded mainly on the surrounding wetlands and depression areas by land filling with sand. Thus, vast amounts of land in eastern and western Dhaka city were transformed into built-up areas which were ecologically sensitive wetland and depressed areas. This paper aims to identify the earthquake vulnerable areas of Dhaka city in terms of its soil characteristics and behavior for major earthquake. Moreover, it is situated very close to Modhupur Fault and earthquake zone-2 of Bangladesh which make this city seismically more vulnerable. Soil amplification may occur during any major earthquake with liquefaction probability. Normalized difference water index (NDWI) was applied on Landsat imagery to observe the waterbodies in last thirty years to identify the gradual development of built-up areas. In addition, secondary data from various literature, articles and journal papers along with Comprehensive Disaster Management Programme (CDMP) data were analyzed to investigate the possibility of soil amplification of this city. Multichannel Analysis of Surface Wave (MASW) technique was used in geophysical investigation to determine the correlation between shear wave velocity (V_s) and SPT-N value. A non-linear regression analysis is done to predict the shear wave velocity for the top 30m depth of soil from CDMP database. This paper will come up with delineating earthquake vulnerable areas of the city which will help city planners and decision makers about framing the development policy for the future and formulating development policies to make the city resilient.

Keywords: Soil amplification, Waterbodies, Multichannel Analysis of Surface Wave (MASW), Normalized Difference Water Index (NDWI), Remote sensing, SPT-N Value.

1. Introduction

Dhaka is one of the most ancient cities in Bangladesh. Historically, the origin of Dhaka city can be identified long before the Mughal period. Some literatures showed that, human settlement in Dhaka started from the 12th century [1]. Gradually, the importance of this area was acknowledged by the Mughal and established their capital in 17th century and after the fall of Mughal empire the British regime continued to rule this region until 1947 [2][3]. After the partition in 1947, the Indian subcontinent was divided and gave birth to two new nations- India and Pakistan. Once again, Dhaka became the capital of the East Pakistan. Since then, Dhaka is developed as the center of administrative, economic, education, healthcare and culture including defense headquarters. Dhaka has earned the importance of both the historical and administrative affairs of Bangladesh.

As an attraction center for various reasons outlined above, Dhaka has attracted a significant number of people from different parts of Bangladesh to itself and created a huge demand for housing. To reduce the pressure, the peripheral areas of Dhaka started developing [4]. As a consequence, a large number of waterbodies, khals, depression areas and agricultural land transformed into build-up areas. According to Earthquake Disaster Risk Index (EDRI) parameters, Dhaka is one of the top twenty high earthquake risk cities in the world [5]. Moreover, rapid urbanization in the peripheral areas lead to unplanned development, non-engineered structures, violation of building code, poor construction and overpopulation made this city more seismically vulnerable.

For a very long time, Bangladesh did not experience any major earthquake, the last major earthquake occurred in 1897 known as 'The Great Indian Earthquake', which was one of the most devastative earthquakes in recorded history [6]. Such long gap of earthquake occurrence faded away or somewhat made people ignorant about earthquake, which negatively reflected on the build-up areas. Insufficient earthquake data have created difficulties in carrying out research work in this field. Very few related researches have hardly been found in the context of Bangladesh. The scope of this study is very limited due to data limitation. Secondary data were used to assume the soil amplification of Dhaka city. Moreover, expertise on geotech engineering is required to conduct such study. The main objective of this research is to demonstrate the probable amplifiable areas in Dhaka city in a simplified way and to stimulate geologists and geotech engineers to carry out further studies in this field.

2. Soil Formation and Geology of Dhaka City

The Geological evaluation of Bangladesh is associated with the uplift of Himalayan and outbuilding of large deltaic landmass by major river system originated from the uplifted Himalayas [7]. Thus, Bangladesh is considered the largest delta in the world [8]. The deposition through sedimentation via the major river system in not evenly distributed. The oldest deposit is the Plio-Plesitocene Barend clay, Madhupur clay and Lamaic region clay [9]. Hence, Bangladesh can be divided into three major physiographic units namely, (i) the tertiary hill formations, (ii) the Pleistocene terrace, and (iii) the recent flood plains [10]. Dhaka is situated on the southern tip of a Pleistocene Terrace, called the Madhupur Tract. Two characteristics units cover the city and its surrounding areas, namely Madhupur clay of Plcistocene age and alluvial deposits of Recent age [8][11]. The Madhupur clay is the oldest sediment of Pleistocene age and alluvial deposits of recent age. The major portion of this city is composed of upper and lower Madhupur terrace that is the high land of Dhaka. On the other hand, low land, floodplains, depression, and abandoned channels are the low-lying areas in and around the city (Fig. 1). 'The sub soil sedimentary formation up to the depth of 300m, shows three distinct types of earth matters: first one is the Madhupur clay of the Pleistocene age. It is characterized by reddish plastic clay with very fine sand particles. Second one is the Madhupur clay that overlies the DupiTila formation of the Plio-Pleistocene age and composed of medium to coarse yellowish-brown sand and infrequent gravel. And the third one is the incised channels and depression within the city are developed by recent alluvial floodplain deposits and are additional subdivided into- lowland alluvium and highland alluvium' [12]. Madhupur clay is characterized as stiff to very stiff soil that covers the central part of the city from north to south. On the other hand, Holocene Alluvium characterized from very soft to medium stiff silty clay, clayey silt and very loose to loose soil that covers the eastern, southeastern, south western and northwestern part of the city [13].

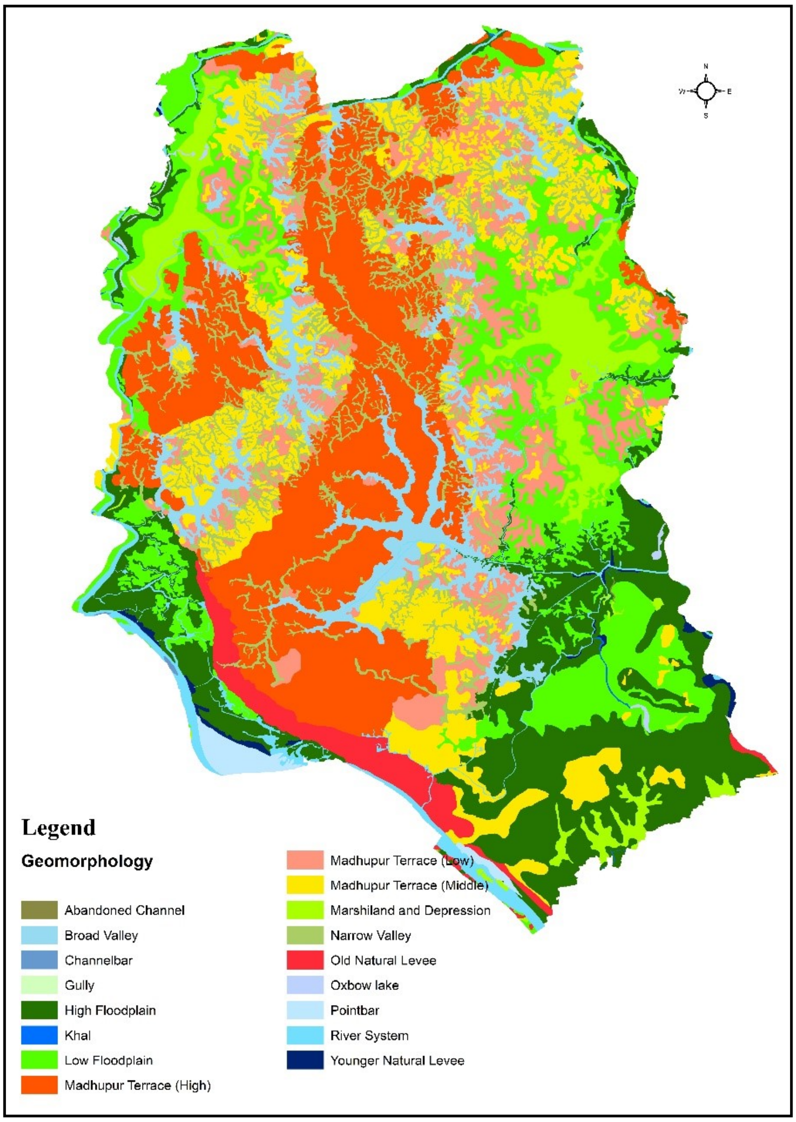

Fig.1- Geomorphological Map with surface geological unit of Dhaka City. (Source: GSB)

3. Seismotectonic of the Study Area

From the locational aspect, Bangladesh is an earthquake prone country due to its tectonic setup. It lies in the northeastern Indian plate near the edge of the Indian craton and at the junction of three tectonic plates- the Indian plate, the Eurasian plate and the Burmese microplate [6]. The impact of the Indian Plate with the Eurasian Plate in northward direction has created the Himalayan Ranges between these plates and also created the Bengal Basin in the northeastern part of the Indian Plate [13][14][15]. From literatures, it was found that the Indian Plate is continuing its motion towards north at approximately 4-6 centimeter per year approximately [6][16]. Two major active tectonic belts are responsible for large and damaging earthquake in Bangladesh, Northeast India, Nepal, Bhutan and Myanmar [13].

Bangladesh is divided into four seismic zones in the draft national building code, where Dhaka city and its surrounding areas are situated in the seismic zone 2 with a basic seismic coefficient, Z=0.20 [17]. Dhaka might encounter two potential epicenters of magnitude 6 and 7 from Madhupur and Bansi fault [12][18]. Dhaka is seismically active with multiple potential earthquake sources within 50 to 500 km distance and it is evident that the metropolis and it surrounding areas have high probability of seismic hazard [6][8]. It is perceptible from literature that, alluvium deposits usually amplify the seismic wave more than hard rock terrains during an earthquake [19]. From the geomorphological map (Fig.1), it is found that flood plain and depression areas

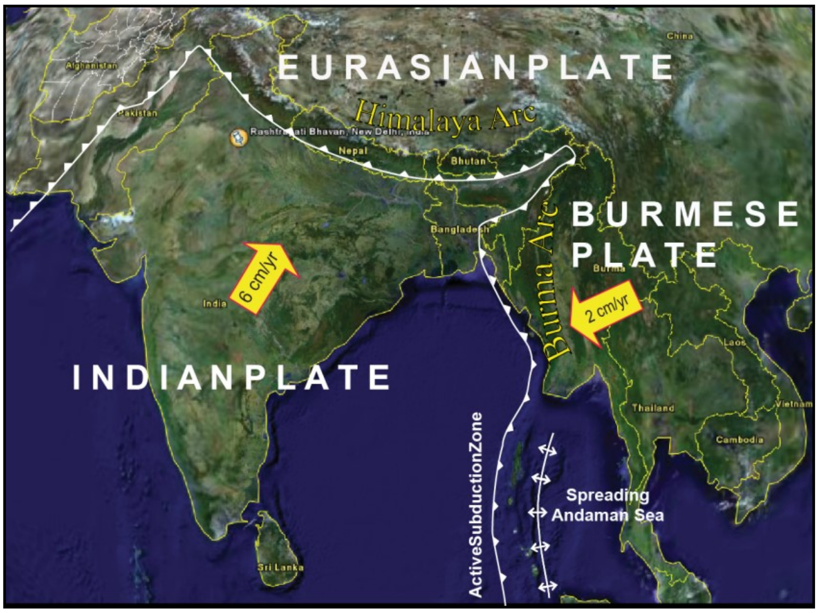

Fig.2- Tectonic setup of Bangladesh and Plate Boundaries (Source: Akhter, 2010)

surrounding Dhaka city to its peripheral areas can be subdivided into lowland alluvium and highland alluvium which indicates the probability of soil amplification of these areas.

3.1 Fault Model of the Study Area

Time predictable fault modeling for scenario earthquake was previously done by CDMP. In Fig.3, the shaded area is the surface projection of the faults and the line closest to the area indicates the intersection of the fault surface extended to the ground Surface. Table 1, shows the necessary parameters of the faults for calculating the seismic motion through the empirical attenuation relations.

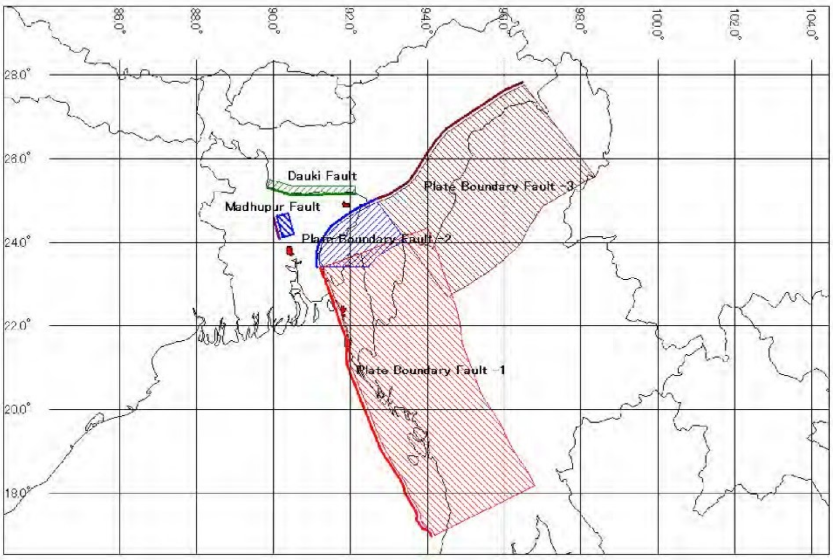

Fig.3- Scenario Earthquake Fault Model (Source: CDMP)

Table 1- Fault Parameters for Empirical Attenuation Analysis (Source: CDMP)

Fault	Mw	Depth to top of fault (km)	Dip (degree)	Down-dip rupture width (km)	Fault Type
Madhupur Fault (MF)	7.5	10	45	42	Reverse
Dauki Fault (DF)	8.0	3	60	43	Reverse
Plate Boundary Fault -1 (PBF-1)	8.5	3	20/30	337	Reverse
Plate Boundary Fault -2 (PBF-2)	8.0	3	20	137	Reverse
Plate Boundary Fault -3 (PBF-3)	8.3	3	20/30	337	Reverse

4. Data and Methodology

This study is based on secondary data sources especially, from Comprehensive Disaster Management Programme (CDMP) and also from Geological Survey of Bangladesh (GSB). Geological data was used to prepare the geomorphological map from GSB database and soil amplification factors of Dhaka city is extracted from CDMP and GSB data. Firstly, the amplification factors were calculated from empirical correlation with SPT-N value and shear wave velocity from literature. Secondly, Landsat imagery were used to analyze the normalized difference water index (NDWI) to detect the encroachment of water bodies from last 30 years and compered with geomorphological map and overlap the soil amplification map to assume the vulnerable areas in Dhaka city. A site-specific soil amplification comparison is also executed in Aftabnagar using CDMP data and GSB data to observe the difference between two data sources. Due to time constrain and limitation of resources only secondary data were used in this study.

5. Geophysical Exploration of Dhaka City

In previous study like CDMP Multi-channel Analysis of Surface Wave (MASW) was used to check the shear wave velocity (Vs) at shallower part and combined the result obtained by using Small Scale Micro-tremor Measurement (SSMM). SSMM was used to check the shear wave velocity up to 30m for reference. Finally, the average shear wave velocity for upto 30m was calculated by the following equation.

$$T_{30} = \sum \frac{Hi}{Vi}$$

$$AVS_{30} = \frac{30}{T30}$$

Where, Hi: Thickness of i layer and 30= $\sum Hi$; Vi: S-wave of i th layer.

For amplification analysis the whole Dhaka city was divided into 250 m grids and the coverage area for each grid was approximately 6 sq. kilometer. Amplification factor was calculated by PGA at the bedrock divided by PGA on surface. Shear wave velocity at the bedrock was determined at 760 m/s and bedrock was considered at 30m based on SPT-N value. Later on, interpolation method was used to assume the amplification factor for Dhaka city. The nearest fault for Dhaka city is the Madhupur fault Fig.4, shows the amplification factor for different time scale.

5.1 Normalized Difference Water Index

A simplified method is used to identify the continuous encroachment of waterbodies in Dhaka city. Normalized Difference Water Index popularly known as NDWI is a remote sensing analysis method to monitor the changes of waterbodies by using green and near-inferred wavelengths [20]. Following equation is used on Landsat image to identify the changes of water content in Dhaka last 30 years from 1989 to 2019.

$$NDWI = \frac{Xgreen - Xnir}{Xgreen + Xnir} \qquad (1)$$

Here, Xgreen is the green wavelengths and Xnir is near-inferred rays.

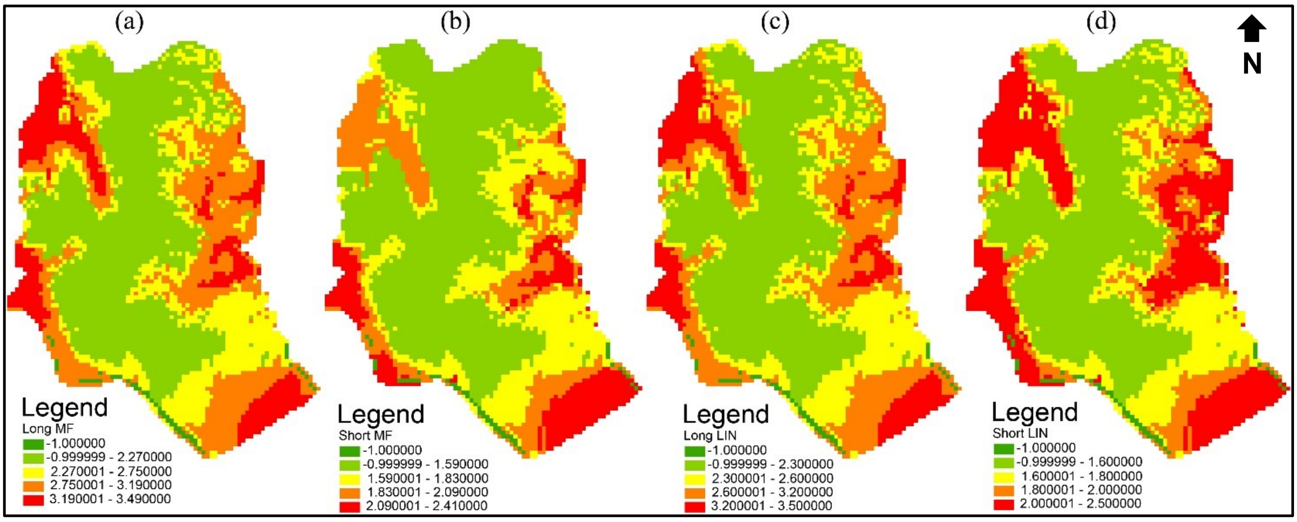

Fig.4- Amplification map of Dhaka City (a) Long MF: amplification factor of PGA and Sa (T=1 sec) for MF scenario earthquake, (b) Short MF: amplification factor of PGA and Sa (T=0.3sec) for MF scenario earthquake, (c) Long Lin: amplification factor of PGA and Sa (T=1.0sec) for other than MF, (d) Short Lin: amplification factor of PGA and Sa (T=0.3sec) for other than MF scenario earthquake. (Source: CDMP)

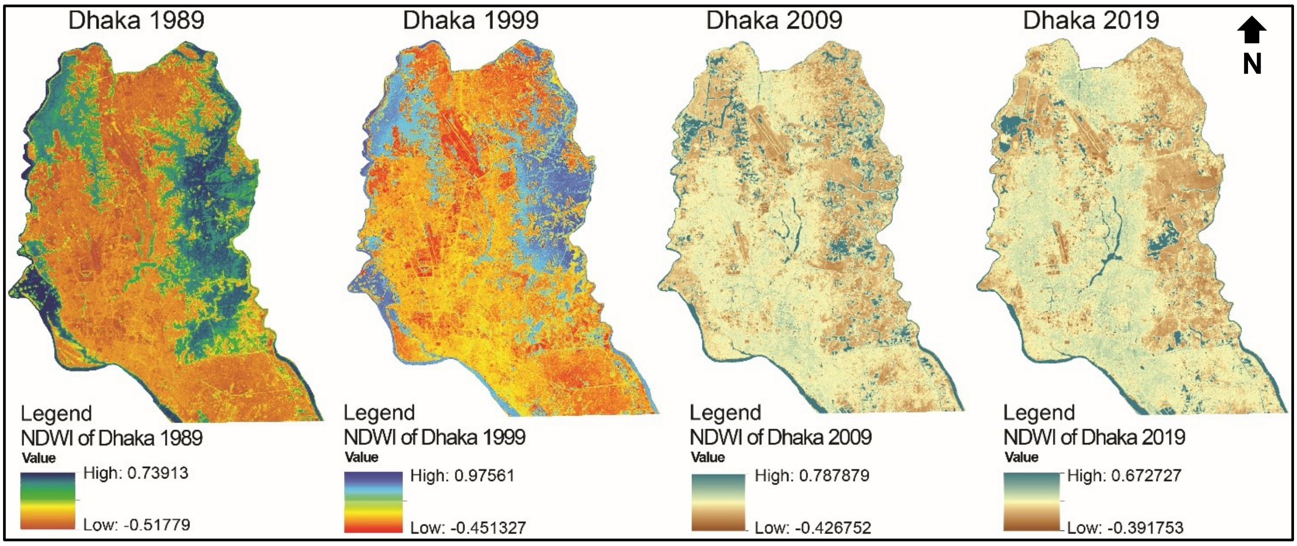

Fig.5- Normalized Difference Water Index of Dhaka city from 1989 to 2019. (Developed by Author)

Fig.5 shows that in 1989 the blue shaded areas in the eastern, northwestern, some part of the western of Dhaka city was covered by waterbodies, marshland and depression area, respectively. Over the time to accommodate the excessive population, these peripheral areas were developed by sand filling. From 1999 to 2009 water content in Dhaka city dramatically reduced. The amplification map (Fig.4) produced from the CDMP also shows that those areas are also amplifiable from different earthquake scenario.

6. Comparison of Amplification Factor

Previously, CDMP was used only 53 borehole data to predict the soil amplification of Dhaka city. Though the number of borehole data is small, different analysis methods were used to validate the data and reduce the margin of error. Later on, Geological Survey of Bangladesh did 317 boreholes in greater Dhaka city for different projects namely, Geo-Information for Urban Development Project. For this study 21 borehole data of Aftabnagar were collected from GSB. In 2018, Rahman et. al estimated the near surface shear wave velocity of Dhaka city from SPT-N data by using empirical correlation and proposed correlations between the Vs and uncorrected SPT-N by using nonlinear regression of power law model are given bellow [13].

$$Vs = 97.3062\ N^{0.3393}\ (r = 0.7496 \text{ and } R^2 = 0.5618) \text{ for all soils} \quad (2)$$
$$Vs = 82.01\ N^{0.3829}\ (r = 0.6689 \text{ and } R^2 = 0.4474) \text{ for all sandy soils} \quad (3)$$
$$Vs = 100.58\ N^{0.341}\ (r = 0.7304 \text{ and } R^2 = 0.5334) \text{ for all clayey soils} \quad (4)$$

Equation 3 and 4 were used to predict the shear wave velocity of Aftabnagar. The average depth of the borehole is 40m and the shear wave velocity for bedrock was considered 900 m/s. For simulation DEEPSOIL software was used [20]. For ground motion Chi-Chi earthquake was selected based on the soil characteristics and large number of recorded data to calculate the PGA for soil amplification.

Fig. 6- Borehole location of CDMP and GSB data and Number of boreholes.

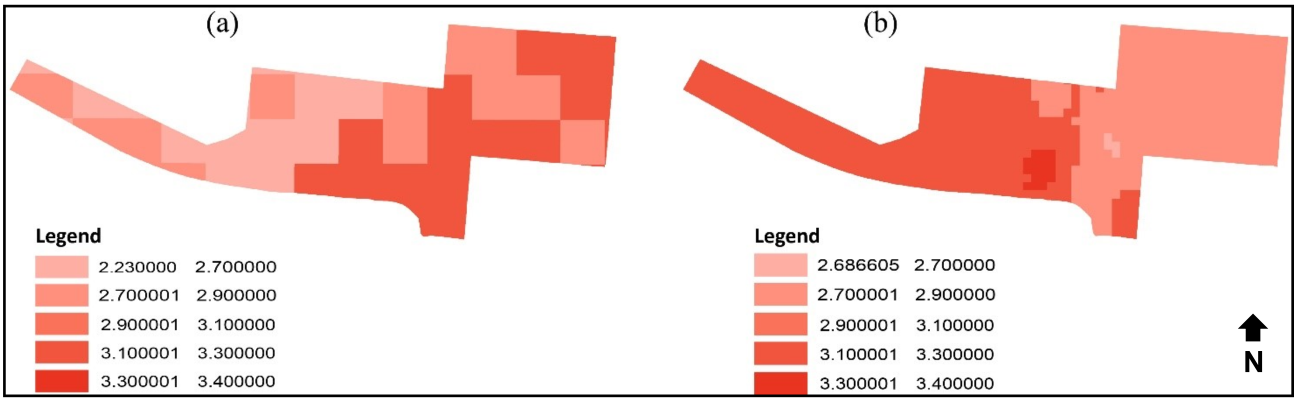

Fig. 7- Comparison of Amplification factor of Aftabnagar between (a) CDMP and (b) GSB.

Based on the 21 boreholes in Aftabnagar, Fig.7 (b) shows that the amplification factor varies from 2.6 to 3.3, where CDMP data Fig.7 (a) shows the amplification factor varies from 2.2 to 3.4. The eastern part of Aftabnagar shows the amplification factor is in between 2.6 to 2.8 and the western part is more amplifiable in Fig.7 (b). Fig.7 (a) represents the opposite scenario where, the southern and north-eastern part is more amplifiable then the western part. The result of these two different databases varies due to use different empirical correlation equations and also different ground motion. However, the variation is little if consider the number of boreholes used in CDMP. Fig.6 shows that there was only one borehole located in the east for CDMP case and interpolation method was used to cover the whole Aftabnagar area. On the other hand, 21 borehole data were used to analyze the amplification factor. From geomorphological perspective (Fig.1), the geomorphological classification of this area was dominated by high and low floodplain zone with some Lower

Madhupur Terrace. Considering the geomorphological classification with the CDMP result, a profound similarity is found. However, the geomorphological classification is determined by the surface soil and its formation and characteristics, subsoil investigation may show different results than the surface. In addition, the average depth of the GSB borehole is 40 m and the bedrock motion is considered to be 900 m/s, which could cause the variation of the amplification factors between the two databases.

7. Results and Discussion

The historical development of Dhaka can easily be identified that, it was expanded from the southern part of the city. Over the time, it was moved towards the north following the red hard soil (Madhupur Clay). Rapid urbanization creates excessive population pressure and forced to expand the city in the peripheral areas and keep developing to date. As discussed above, most of the peripheral areas were waterbodies or depressed areas which more likely to be amplified during an earthquake. CDMP study represents the amplifiable areas considering the Madhupur Fault, Plate Boundary Fault 1, 2 and 3 from different earthquake scenarios. It was found that the Madhapur Fault and Plate Boundary Fault-1 might be hazardous for Dhaka city, since the magnitude of these two faults is predicted 7.5 and 8.5 respectively. From Fig.4 it is observed that the amplification factor of PGA and Sa (T=0.3sec) for Madhupur fault might amplify the eastern, north-western, western and some southern parts of the city. The amplification factor of PGA and Sa (T=1sec) might amplify the southern, western and some parts of the eastern Dhaka. The amplification factor of PGA and Sa (T=0.3sec) other than Madhupur fault might amplify the most in the peripheral areas for plate boundary 1. From NDWI analysis it was found that the amplifiable areas from CDMP are none other than the landfilling peripheral areas in Dhaka city.

From GSB 21 borehole data were collected in Aftabnagar to analyze and compare the amplification factor with the CDMP database. The deepest borehole is 81m and it was considered as the bedrock and the lowest depth of a borehole in Aftabnagar is 39m. Among the boreholes artificial sand fill is around 4.5m to 16m. The lowest shear wave velocity among the 21 boreholes is 82 m/s and the highest shear wave velocity is 861 m/s. The shear wave velocity at the bedrock was considered 900 m/s. Whereas, in CDMP they only considered 30m depth for each borehole and under 30m depth bedrock was assumed where the shear wave velocity in the bedrock was 760 m/s. For Aftabnagar the simulation was designed based on the Chi-Chi earthquake ground motion. Aftabnagar is a private residential project with an area of 0.2 sq.km. and the area was divided into 50m grids. By using the interpolation method, the analysis was executed in ArcMap. Fig.7 shows similar amplification result with some inconsistency like the eastern part of the area is likely less amplifiable than the western part where CDMP represents the opposite. However, the area is much smaller and the amplification factors are almost the same with some variation. Nevertheless, the fact is the peripheral areas showing high amplification in both datasets.

8. Conclusion

The peripheral areas such as low-lying land and water bodies are gradually infilled with sand. These areas are likely to be amplified during earthquake for its soil formation and characteristics. From this study, it is observed that fine sand layer exists bellow 30m depth. Nonengineered buildings might be affected due to soil amplification. Construction of a building in these areas will be very expensive for pile foundation from economic point of view. Such results from subsoil investigation should incorporate in urban planning strategies. Based on the subsoil condition, the landuse plan should be updated accordingly to reduce the seismic vulnerability in densely populated areas such as Dhaka. Through the integration of such studies will strengthening the risk-sensitive urban planning to build resilient cities. Very few researchers are now working in this field. Further subsoil investigations are required in the peripheral areas of Dhaka city. Experts like, Geotech Engineers and Geologists should come forward to explore the subsoil investigation. More data are required for executing such studies. Government and policy makers should address the fact and take more initiatives for building a resilient city.

9. Acknowledgement

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10. Copyrights

11. References

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