Journal of Bangladesh Institute of Planners ISSN 2075-9363
Vol. 12, 2019 (Printed in June 2020), pp. 33-43, © Bangladesh Institute of Planners

Potential Amplifiable Areas in Dhaka City for Seismic Hazard

Masudur Rashied*
Md. Akter Mahmud**

Abstract

After 1990s the population of Dhaka accelerated rapidly due to its economic and political influence with many other pull factors. Historically, the city grew along with the shore of River Buriganga and its surrounding areas. Later on, the city expanded towards its north, east and south-eastern parts. A significant number of canals, khals, and water bodies are infilled with sand, especially in the peripheral areas of the city. Dhaka is one of the most seismically vulnerable cities in the world for its location since it is close to Eurasian and Indian plates. From the lithological aspect, the core city has developed on Upper and Lower Madhupur Terrace with surrounding Holocene floodplains. The soil profile of the floodplain shows the near-surface soil up to a depth of 30m mostly composed of alluvial sandy and clayey soils with a probable chance of soil amplification. The empirical correlation between Standard Penetration Test (SPT) and shear wave velocity (Vs) is a popular approach for estimating the amplification factor. This paper gathered secondary information from existing literature to illustrate the potential amplifiable areas in Dhaka city and compare it with the gradual shrinkage of water bodies for seismic hazard.

Introduction

Dhaka the capital city of Bangladesh has a long history of development. It is assumed that human settlement in Dhaka started from the 12th century before the Mughal period (Ahmed, 1986). Though, the importance of this area first acknowledged by the Mughal and established their capital city to rule this region in the early 17th century (Kabir and Parolin, 2012). After the fall of Mughal empire, The East India Company and the British Colonialism remained intake until 1947 (Hossain, 2014).Dhaka was established as the capital of East Pakistan after the British colonial period and became an attraction point for people(Ahmed et al, 2014). Dhaka hold its attraction from the post liberation war to present in an enormous way. Moreover, the landuse has changed over the time within the city due to economic and political changes (Hossain, 2014).As a consequence, different economic classes of people anchored in Dhaka city from different parts of Bangladesh, mostly in the peripheral areas (Ahsan, 1991; Rashied, 2017).

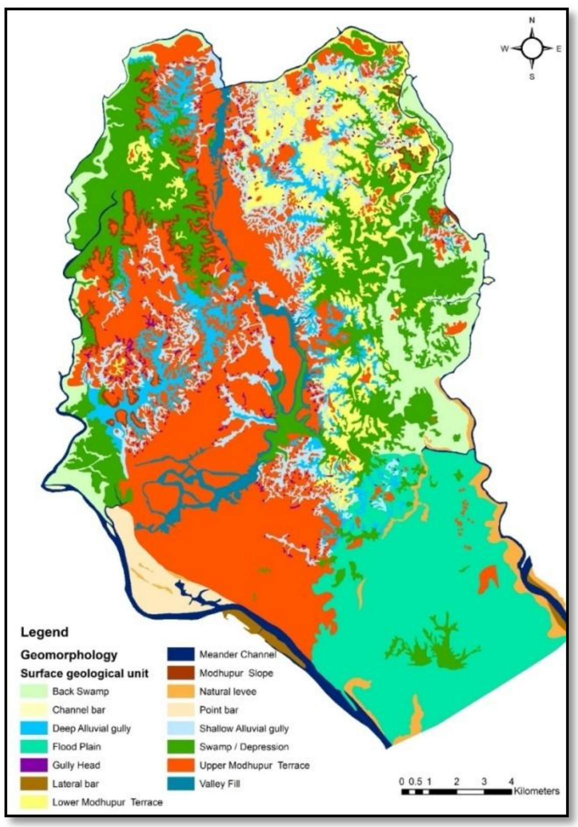
Dhaka is one of the most densely populated cities in the world. According to World Population Review 2019 over 20 million people live in this city with an area of 321 sq km. Spontaneous population growth after 1990s created a huge housing demand, as a result the peripheral areas in Dhaka city started developing. A significant number of canals, khals and waterbodies infilled with sand to reduce the excessive development pressure (Dhaka Structure Plan 2016-35). Geomorphological study of CDMP shows that Dhaka

---

* Junior Research Consultant, SATREPS-TSUIB Project, Housing and Building Research Institute, 120/3, Darussalam, Mirpur Rd, Dhaka 1216, Bangladesh. Email: masudurrashied@outlook.com

** Professor, Department of Urban and Regional Planning, Jahangirnagar University, Savar 1342, Bangladesh. Email: aktermahmud@yahoo.com

soil is mainly consist of upper and lower Madhupur Terrace with surrounding Holocene floodplains (CDMP, 2009).The terrace consist of the Pleistocene clayey soils and the floodplains are composed of alluvia sandy and clayey soils (Rahman et al., 2014). The geotechnical properties of Madhupur clay vary significantly both aerially and vertically(Islam et al., 2014). Newly developed areas in north western and eastern part of the city are developed on floodplains area. Non engineered structures, unplanned development, ignorance of following national building code, narrow roads and the huge number of populations made this city seismically vulnerable. According to Earthquake Disaster Risk Index (EDRI) parameters Dhaka is one of the top twenty high earthquake risk cities in the world (Cardona et al., 1999).Such soil properties may cause soil amplification due to ground motion. Previously many researchers from engineering and geological background worked on the geological and seismotectonic characteristics of Dhaka however, social interpretation and illustration of the potential amplifiable areas are not strongly explained in somewhat missing from urban planning perspective. This paper tried to illustrate the potential amplifiable areas in Dhaka city from urban planning perspective.

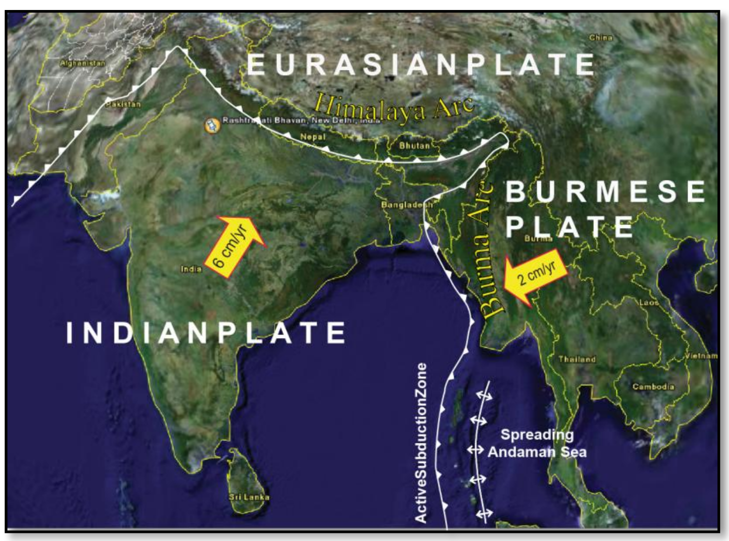


Source: CDMP, 2009

Figure 1: Geomorphological map with surface geological unit of Dhaka city

Geology and Seismotectonics of the Study Area

Dhaka is situated at the southern tip of Pleistocene terrace, the Madhupur tract, having a maximum raise of 14m and partially on the Holocene floodplains having a minimum elevation of 2m (Karim and Haider, 1999; Islam et al., 2014; Rahman et al., 2014). 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 (Figure 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 (Islam et al., 2014). It is characterized by reddish plastic clay with very fine sand particles (ibid). Second one, is the Madhupur clay that overlies the Dupi Tila formation of the Plio-Pleistocene age and composed of medium to coarse yellowish-brown sand and infrequent gravel (ibid).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 (ibid). 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, southeastern, south western and northwestern part of the city (Rahman et al., 2014).



Source: Akhter, 2010

Figure 2: Tectonic setup of Bangladesh and plate boundaries

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 (Akhter, 2010 pp: 401).The collision 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 (Curry et al., 1982; Aitchison et al., 2007; Rahman et al., 2018). Moreover, the Indian Plate is continuing its motion towards north at approximately 4-6 centimeter per year (Bilham and Hough, 2006; Akhter, 2010). Two major active tectonic belts are accountable for the large and destructive earthquake in Bangladesh, Northeast India, Nepal, Bhutan and Myanmar (Rahman et al., 2018). Moreover, the boundary between plates acts as an energy reservoir and releases its stored energy into large earthquake; such energy is generated by continuous deformation of the rock (Bilham and Hough, 2006). Bangladesh is divided into four seismic zone; where Dhaka city and its surrounding areas are situated in the seismic zone 2 with a basic seismic coefficient, Z=0.20 (BNBC, 2015). Dhaka mightencounter two potential epicenters of magnitude 6 and 7 from Madhupur and Bansi fault (Islam et al., 2014; Maitra and Akhter, 2011). 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 (Ansary et al., 2004; Akhter, 2010).

Site Amplification from Standard Penetration Test (Spt) and Shear Wave Velocity (V_s)

The characteristics of an earthquake for its seismic motion at a site are expressively affected by the presence of soil deposits (Kirar et al., 2016). In geotechnical earthquake engineering, soil dynamic properties such as density, stiffness, damping and maximum shear modules are important for the analysis of soil response (Thokchom et al., 2017). During an earthquake most damage is caused by shaking the ground, amplified by local site effects based on the soil's geotechnical properties (Badrakia, 2016). In recent years, considerable interest and research has been focused on the effect of local soil conditions on the amplitude and frequency content of earthquake motions (Ansari et al., 2004).

Shear wave velocity is the basic geotechnical function that serves as the main input of quantitative earthquake engineering and site response controller (Marto et al., 2013). It is an important parameter which represents the stiffness of soil. The shear wave velocity profile at a location is typically obtained by wave propagation analysis; however, such experiments are often not economically feasible at all locations (Kirar et al., 2016). In most site investigation, the Standard Penetration Test (SPT) is typically used. It would, therefore, be of considerable advantage to have a reliable correlation between Vs and the Standard Penetration Test Blow Count (SPT N-value) to reduce the cost of site investigations (Tumwesige et al., 2014). Several researchers have established empirical correlations between SPT-N value and shear wave velocity.

Empirical Correlation between Spt-N and V_s For Dhaka City from Existing Studies

Estimating near surface shear wave velocity (V_s) by using experimental field test is always recommended. However, from an economic point of view, experimental field test for all sites of an area is not feasible, particularly in Dhaka. Huge investment is required to execute such experiment. Many researchers suggested the alternative way i.e. the standard penetration test for an in-situ investigation of an area which is widely used for geotechnical characterization (Ansary et al, 2004; Noor and Ansary, 2015; Rahman et al, 2018).

From the study of Ansary et al. (2004), a total of 190 borehole SPT data were collected and used in that study to assess the site amplification characteristics of Dhaka city. Usual depth of those boreholes was 50ft, but some of them were upto 150 ft. Collected borehole data were converted into shear wave velocity using the relationship proposed by Ohta and Goto (1978) as shown in Table 1.

Table 1: Existing empirical correlation of different researchers between V_s and SPT-N

Authors	Shear wave velocity, V_s (m/sec)		
	All soils	Sandy soils	Clayey soils
Shibata (1970)	-	$V_s = 32 N^{0.5}$	-
Fujiwara (1972)	$V_s = 92.1 N^{0.337}$	-	-
Imai (1977)	$V_s = 91 N^{0.337}$	$V_s = 80.6 N^{0.331}$	$V_s = 102 N^{0.292}$
Ohta and Goto (1978)	$V_s = 85.35 N^{0.348}$	-	-
Imai and Tonouchi (1982)	$V_s = 97 N^{0.314}$	-	-
Seed et al. (1983)	-	$V_s = 56.4 N^{0.5}$	-
Sykora and Stokoe (1983)	-	$V_s = 100.5 N^{0.29}$	-
Fumal and Tinsley (1985)	-	$V_s = 152 + 5.1 N^{0.27}$	-
Athanasopoulos (1995)	$V_s = 107.6 N^{0.36}$	-	-
Raptakis et al. (1995)	$V_s = 100 N^{0.24}$	-	-
Kayabal (1996)	-	$V_s = 175 + 3.75 N$	-
Kiku et al. (2001)	$V_s = 68.3 N^{0.292}$	-	-
Jafari (2002)	-	-	$V_s = 27 N^{0.73}$
Hasancebi and Ulusay (2007)	$V_s = 90 N^{0.309}$	$V_s = 90.82 N^{0.319}$	$V_s = 97.89 N^{0.269}$
Hanumantharao and Ramana (2008)	$V_s = 82.6 N^{0.43}$	$V_s = 79 N^{0.434}$	-
Dikman (2009)	$V_s = 44 N^{0.48}$	$V_s = 73 N^{0.33}$	$V_s = 44 N^{0.48}$
Akin et al. (2011)	$38.55 N^{0.176} D^{0.481}$	$78.1 N^{0.116} D^{0.35}$	
Kuo et al. (2011)	$169.04+4.46N + 0.59D$		
Mhaske and Choudhury (2011)	$V_s = 72 N^{0.4}$		
Naik et al. (2014)	$V_s = 78.46 N^{0.39}$		

Source: Adopted from Rahman et al., 2018

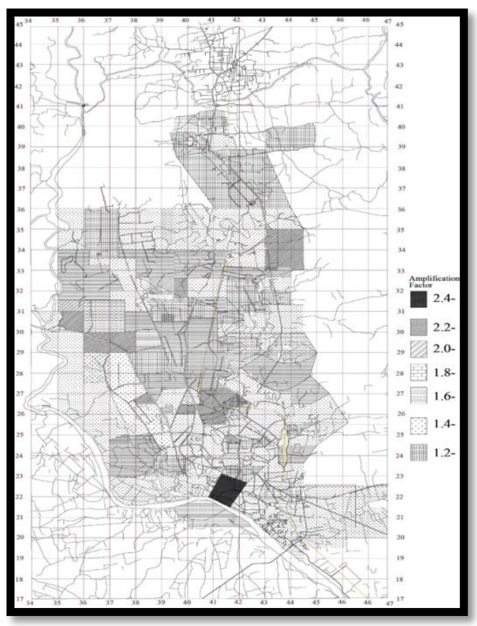
Due to the multiple reflection of shear waves in the surface layers, the effects of "Bedrock" and "Outcrop" motion on the different soil layers at the location sites were then measured using the software SHAKE. The used frequency ranges from 0 to 20 Hz frequency with a regular interval of 0.05 Hz. Energy lost due to soil layers were also under consideration by taking 2% damping ratio. Moreover, no earthquake motion was used during V_s computation in that study. In this study, the maximum depth of borehole was assumed to be the bedrock. From existing literature most of the methods used to assess the impact of local soil conditions on earthquake response are based on the assumption that the key responses in a soil deposit are triggered by upward propagation of shear waves. Hence, only shear waves (SH components) were considered in this study. This study concludes with the result that among the 190-borehole data used for this study shows the amplification factors vary from 1.2 to 2.6. Lower the amplification factor, represents stiff/hard soil and higher the amplification factor, represents soft/loose soil (Figure, 3).

Rahman et al. (2018) also perform a similar study that compares the SPT-N value with shear wave velocity to a depth of 30m at 152 sites in Dhaka City. In their study, they used the CDMP data and compare the correlation with downhole seismic (DS) method and surface wave. Multichannel Surface Wave Analysis (MASW) and Small-Scale Microtremor Measurement (SSMM) methods were used for surface wave measurement. The average shear wave velocity results of all methods vary from 127 to 320 m/s. They proposed empirical correlation between V_s and SPT for Dhaka city upto 30m of depth to derive empirical correlation for all soils, sandy soils and clayey soils. The proposed correlation between V_s and uncorrected SPT-N by using nonlinear regression of power law model are:

$$Vs = 97.3062\,N^{0.3393}\ (r = 0.7496 \text{ and } R^2 = 0.5618) \text{ for all soils}$$

$$Vs = 82.01N^{0.3829}\ (r = 0.6689 \text{ and } R^2 = 0.4474) \text{ for sandy soils}$$

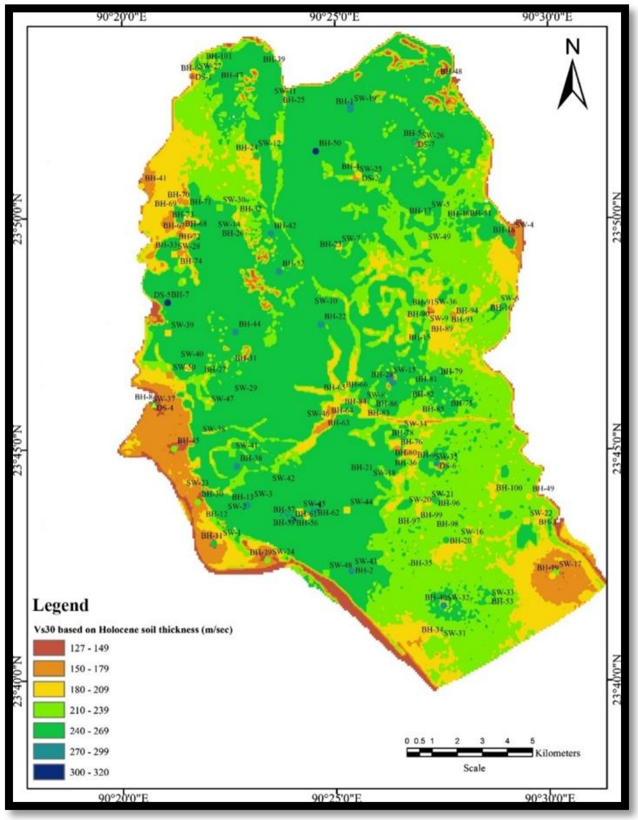
$$Vs = 139.33N^{0.5334}(r = 0.7304 \text{ and } R^2 = 0.5334) \text{ for clayey soils}$$



Source: Ansary et al., 2004

Figure 3: Seismic amplification capability map of Dhaka city

From previous studies, correlation between uncorrected SPT-N and average shear wave velocity represent better results than corrected SPT value (Table, 1). Hence, Rahman et al. also used the uncorrected SPT-N to predict the V_s. Estimating the V_s^{30} by using DS method for the correlation equation of all soils, sandy soils and clayey soils at the same borehole site and compare the result with the predicted V_s showed more or less similar results. However, at several borehole locations using different methods at the same site, the V_s^{30} results are not equal.



Source: Rahman et al., 2018

Figure 4: $V_s{}^{30}$ map of Dhaka city

Therefore, in their study, they only consider the Holocene soil for estimating $V_s{}^{30}$ for Dhaka city. The Holocene clayey and sandy soils are overlying on the Pleistocene and Plio-pleistocene clayey and sandy soils are present in the eastern, southeastern, southwestern and northwestern parts of the city. Thickness of the Holocene soil ranges from 0m to 30m and shear wave velocity ranges from 145 to 260 m/s (Figure 4). Lower value represents soft soil and higher value represents the stiff or hard soil.

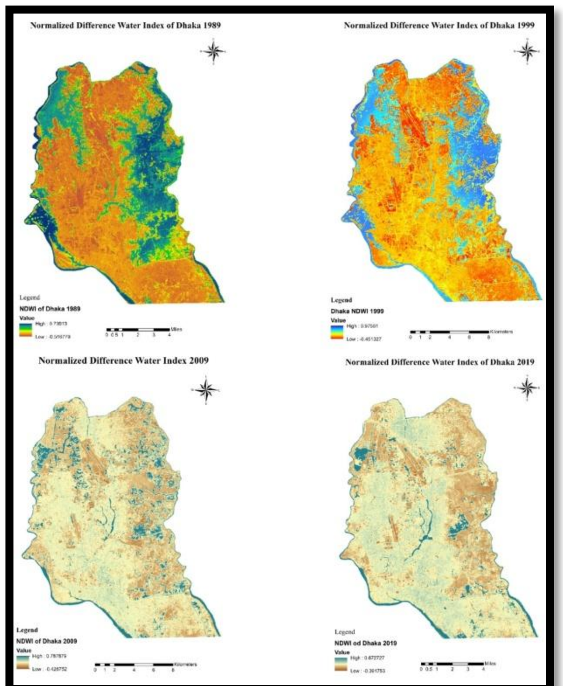
Potential Amplifiable Areas in Dhaka City

Over the time, Dhaka has developed its peripheral areas to reduce the excessive demographic pressure. A significant number of canals, khals and water bodies were infilled with sand for newer development. A simplified method is used to identify the continuous encroachment of water bodies in Dhaka city. Normalized Difference Water Index popularly known as NDWI is a remote sensing analysis method to monitor the changes of water bodies by using green and near-inferred wavelengths (McFeeters, 1996). Following equation is used on Landsat image to identify the changes of water content in Dhaka in last 30 years from 1989 to 2019.

$$NDWI = \frac{Xgreen - Xnir}{Xgreen + Xnir}$$

Here, X_{green} is the green wavelengths and X_{nir} is near-inferred rays.

Figure 5 explicitly shows that eastern, northwestern and some western part of the city were the low-lying areas which gradually infilled with sand/soil. Particularly, the eastern part of Dhaka city lost its water bodies significantly from 1989 to 2019. Bashundhara residential area, Uttarkhan, Beraid, Satarkul were depressed/flood flowing zone of Dhaka city are now fully developed. Most of the development took place in these areas during 1999 to 2009. Uttara 3rd phase, Baunia and some parts of Pallabi were also low-lying areas, which has turned into mixed residential areas. Finally, the southwestern part of Dhaka, like Mohammadpur, Hazaribagh, Kamrangirchar were also developed by sand filling.



Source: Developed by Author

Figure 5: Normalized Difference Water Index of Dhaka city (1989-2019)

In the study of Ansary et al. (2004), Lalbagh and Kotwali show the heights of amplification factor 2.4 or higher. Agargaon, Khilgaon, Sabujbagh also have the higher amplification factor 2.2 to 2.4. Rest of the city corporation area's amplification factors ranges from 1.2 to 1.8 which represent stiff to very stiff soil. On the other hand, Rahman et al. (2018) investigated only the Holocene soil i.e. the peripheral areas of the city. From their study, Uttara 3rd phase, Baunia, Pallobi are potentially amplifiable in the northern part of the city according to the V_s^{30} map and the shear wave velocity ranges from 180 to 240 m/s. In the eastern part, Bashundhara residential area, Uttarkhan, Beraid are also potentially amplifiable since the shear wave velocity ranges from 180 to 240 m/s. The southwestern part of Dhaka city, Mohammadpur, Hazaribagh, Kamrangirchar are the most vulnerable areas since the shear wave velocity ranges from 150 to 180 m/s. Similar result is shown for Matuail and Demra in the southern part of Dhaka. Figure 6 presents the amplifiable areas in Dhaka city regarding amplification factors, average shear wave velocity and reduction of water bodies to maintain the development trend.

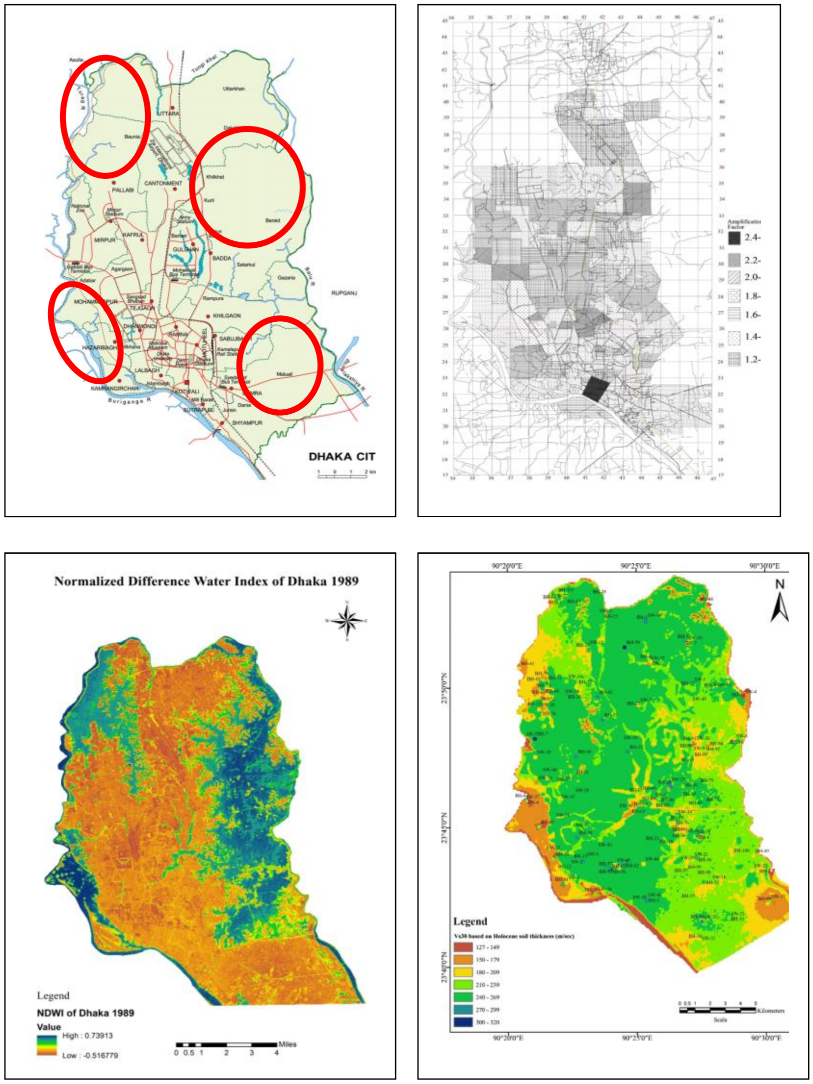


Figure 6: Potential amplifiable areas in Dhaka city from different studies.

Conclusion

Dhaka the capital city of Bangladesh is under great threat of seismic hazard due to its seismic tectonic location. For more than 100 years, Dhaka did not experience any large earthquake. The development of this city has been haphazard and unplanned. From the existing literature of subsoil investigation, it is found that the peripheral areas of the core city have the potentiality of soil amplification. Particularly, in the northwestern, eastern, southwestern and in the southeastern part of Dhaka has shown considerable risk for amplification factor. Unavailability of all necessary data and related documents has been the key constraint of this research. Thus to verify the vulnerability of Dhaka city, further research is required on-seismic geology and site response analysis. This is required for authentic and more reliable results to help in professional decision making for resilient urban development in Dhaka city.

References

Ahmed, B., Hasan, R. and Maniruzzaman, K. M. 2014. 'Urban morphological change analysis of Dhaka city, Bangladesh, using space syntax'. ISPRS International Journal of Geo-Information, 3(4), pp.1412-1444.

Ahmed, S. U. 1986. 'Dacca: A Study in Urban History and Development'. Dhaka: Curzon Press.

Ahsan, R. M. 1991. 'Changing pattern of the commercial area of Dhaka city. Dhaka Past Present and Future'. Dhaka: The Asiatic Society of Bangladesh, pp.396-414.

Aitchison, J. C., Ali, J. R. and Davis, A. M. 2007. 'When and where did India and Asia collide'? Journal of Geophysical Research: Solid Earth, 112(B5).

Akhter, S. H. 2010. 'Earthquakes of Dhaka. Environment of Capital Dhaka—Plants wildlife gardens parks air water and earthquake'. Asiatic Society of Bangladesh, pp.401-426.

Ansary, M. A., Noor, M. A. and Rashid, M. A. 2004. 'Site amplification characteristics of Dhaka city'. Journal of Civil Engineering (IEB), 32(1), pp.1-16.

Badrakia, P. 2016.'Estimation of Shear Wave Velocity Using Correlations'. International Journal of Innovative Research in Science, Vol. 5, Issue 6, June 2016.

Bilham, R. and Hough, S. 2006. 'Future earthquakes on the Indian subcontinent: inevitable hazard, preventable risk'. South Asian Journal, 12(5), pp.1-9.

Bilham, R. 2009. 'The seismic future of cities'. Bulletin of Earthquake Engineering, 7(4), p.839.

BNBC, 2015. 'Draft Bangladesh National Building Code'. Published by Housing and Building Research Institute, Dhaka, Bangladesh.

Cardona, C., Davidson, R. and Villacis, C. 1999. 'Understanding urban seismic risk around the World, a final report on the Comparative Study'. A project of the United Nations RADIUS Initiative, IDNDR, published by Geo Hazards International.

CDMP, 2009. 'Comprehensive Disaster Management Programme.' Ministry of Disaster Management and Relief, Government of Bangladesh.

Curray, J. R., Emmel, F. J., Moore, D. G. and Raitt, R. W. 1982. 'Structure, tectonics, and geological history of the northeastern Indian Ocean'. In The ocean basins and margins (pp. 399-450). Springer, Boston, MA.

Fazlul, M. and Haider, M. Z. 1999. 'Engineering Geology and Geomorphology for Ground Improvement in the Dhaka City-Tongi Area'. Forum on Urban Geology in Asia and The Pacific-1999.

Ghazi, A., Moghadas, N. H., Sadeghi, H., Ghafoori, M. and Lashkaripur, G. R. 2015. 'Empirical relationships of shear wave velocity, SPT-N value and vertical effective stress for different soils in Mashhad, Iran'. Annals of Geophysics, 58(3), p.0325.

Hossain, N. 2014. 'History of Commercial Development in Dhaka and the Spatial Significance of Spontaneous Retail Growth', IOSR Journal of Humanities and Social Science, Volume 19, Issue 11, Ver. VII (Nov. 2014), PP 66-73.

Islam, M. S., Shahin, H. M., Banik, S. and Azam, F. 2014. 'Elasto-plastic constitutive model parameters and their application to bearing capacity estimation for Dhaka sub-soil.' Journal of Civil Engineering, The Institution of Engineers, Bangladesh, Vo. CE, 42, pp.171-188.

Kabir, A. and Parolin, B. 2012. 'Planning and Development of Dhaka – A Story of 400 Years', paper presented in 15th International Planning History Society Conference, 15-18 July 2012, at Brazil.

Karim, M. F. and Rahman, M. Z. 2002. 'Possible effect of a moderate earthquake on existing infrastructures of Dhaka city: a geological-geotechnical overview'. Bangladesh J Sci Tech4(2), pp.193-203.

Kirar, B., Maheshwari, B. K. and Muley, P. 2016. 'Correlation between shear wave velocity (vs) and SPT resistance (N) for Roorkee region'. International Journal of Geosynthetics and Ground Engineering, 2(1), p.9.

Landsat Imagery from United States Geological Survey. Retrieved from https://earthexplorer.usgs.gov/

Masudur, R. 2017. 'Gender Responsive Urban Public Places in Dhaka City.' Unpublished Master's Thesis, Department of Urban and Regional Planning, Jahangirnagar University.

Maitra, M. K. and Akhter, S. H. 2011. 'Neotectonics in Madhupur tract its surroundings floodplains'. Dhaka Univ J Earth Environ Sci, 12, pp.83-89.

Marto, A., Tan, C. S. and Leong, T. K. 2013. 'Universal correlation of shear wave velocity and standard penetration resistance'. Electronic Journal of Geotechnical Engineering, 18, pp.2727-2738.

McFeeters, S. K. 1996. 'The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features'. International journal of remote sensing, 17(7), pp.1425-1432.

Papadrakakis, M., Papadopoulos, V. and Plevris, V. 2015. 'Understanding Shear Wave Velocities Correlations With N-Spt And Qc-Cpt Values'.5thECCOMAS Thematic Conference onComputational Methods in Structural Dynamics and Earthquake Engineering. Crete Island, Greece, 25–27 May 2015.

Rahman, M. Z., Kamal, A. M. and Siddiqua, S. 2018. 'Near-surface shear wave velocity estimation and V_s30 mapping for Dhaka City, Bangladesh'. Natural Hazards, 92(3), pp.1687-1715.

RAJUK (Rajdhani Unnayan Kartripakkha): Dhaka Structure Plan, 2016-2035.

Sekiguchi, T., Calderon, D., Nakai, S., Aguilar, Z. and Lazares, F. 2013. 'Evaluation of surface soil amplification for wide areas in Lima, Peru'. Journal of Disaster Research, 8(2), pp.259-265.

Shukla, J., Choudhury, D. and Shah, D. 2016. 'Estimation of shear wave velocity from SPT N-value-field assessments'. Japanese Geotechnical Society Special Publication, 2(7), pp.346-349.

Soils (A Case Study of The Earthquake Prone Area of The Albertine Graben)'. Second European Conference on Earthquake Engineering and Seismology, Istanbul, August 25-29, 2014.

Thokchom, S., Rastogi, B.K., Dogra, N.N., Pancholi, V., Sairam, B., Bhattacharya, F. and Patel, V. 2017. 'Empirical correlation of SPT blow counts versus shear wave velocity for different types of soils in Dholera, Western India'. Natural Hazards, 86(3), pp.1291-1306.

Tsai, C. C. and Kishida, T. 2015. 'Unified Correlation between SPT-N and Shear Wave Velocity for all Soil Types'.6th International Conference on Earthquake Geotechnical Engineering1-4 November 2015, Christchurch, New Zealand.

Tumwesige, R., Gidudu, A., Bagampadde, U. and Ryan, C. 2014. 'An Investigation of the Relationship Between Standard Penetration Test and Shear Wave Velocity for Unsaturated