Geomorphological approach for seismic microzoning within Dhaka city area, Bangladesh

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Abstract: In a study, Cardona *et. al*, 1999, interpreted the highest Earthquake Disaster Risk Index (ERDI) for Dhaka, among twenty other cities in the world. In this study, a seismic microzoning of ground shaking was conducted for Dhaka city area, the capital of Bangladesh using available data to diminish the seismic risk of the city. As seismic microzoning accounts for the response of near surface sedimentary deposits, and geomorphology reflects the surface geology, the responses of an earthquakes ground shaking are evaluated based on geomorphic units. The geomorphic map has been prepared using almost pre-urban aerial photographs of 1954. The ground modifications by urbanization are delineated till 2002 using high-resolution satellite images as well as borehole information. This information was then integrated into a geomorphic map. To determine the soil response, 187 microtremors are recorded on all geomorphic units and horizontal-to-vertical (H/V) spectral ratio technique of Nakamura (2000) has been applied to calculate fundamental period and amplification factor of the sites. By averaging the H/V spectral ratios, Representative Spectral Signature (RSS) has been developed for each geomorphic unit. Considering the altitudes, the building stock in Dhaka has been differentiated into four groups: low, moderately intermediate, intermediate and high rise buildings. Their fundamental modes of vibration correspond with 0.2-0.5, 0.5-0.8, 0.8-1.4 and 1.4-2.0 seconds respectively. The hazard potentials have been ranked into low, moderately low, moderate and high based on the amplification factors of different soil, as, 1-2, 2-3, 3-5, and >5 respectively measured from RSS. The ground shaking microzoning developed for the building stock demonstrates that the buildings between 9-14 storeys are at elevated risk, which spatially covers one-third of the study area. In combating seismic risk, incorporating the findings of microzoning in the design of new constructions and fixing retrofitting in the existed vulnerable structures is highly recommended.

Résumé: Dans une étude, Cardona et Al, 1999, ont interprété l'index le plus élevé de risque de désastre de tremblement de terre (ERDI) pour Dhaka parmi vingt autres villes dans le monde. Dans cette étude, microzoning séismique de la secousse de la terre a été conduit pour le secteur de ville de Dhaka, le capital du Bangladesh en utilisant des données disponibles pour diminuer le risque séismique de la ville. Pendant que microzoning séismique rend compte la réponse des dépôts et de la géomorphologie sédimentaires extérieurs proches reflète la géologie extérieure. Les réponses de l'des tremblements de terre rectifiés secousse sont évaluées ont basé sur les unités géomorphiques. La carte géomorphique a été préparée en utilisant les photographies aériennes presque pré-urbaines de 1954. Les modifications au sol par urbanisation sont tracées jusqu'à 2002 images satellites à haute résolution employantes aussi bien que l'information de forage. Cette information a été alors intégrée dans une carte géomorphiqu. Pour déterminer la réponse de sol, 187 microtremors sont enregistrés sur toutes les unités géomorphiques et (H/V) la technique spectrale horizontal-à-verticale de rapport de Nakamura (1989) a été appliquée pour calculer le facteur fondamental de période et d'amplification des emplacements. En faisant la moyenne des rapports spectraux de H/V, la signature spectrale représentative (RSS) a été développée pour chaque unité géomorphique. Vu les altitudes, les stocks de bâtiment dans Dhaka ont été différenciés dans quatre groupes : bas, bâtiments modérément intermédiaires, intermédiaires et hauts d'élévation. Leurs modes fondamentaux de vibration correspondent à 0.2-0.5, 0.5-0.8, 0.8-1.4 et 1.4-2.0 seconde respectivement. Les potentiels de risque ont été rangés dans bas, modérément bas, modéré et la haute basée sur les facteurs d'amplification du différents sol, as, 1-2, 2-3, 3-5, et 5 respectivement mesurés à partir de RSS. La terre secouant microzoning développé pour les stocks de bâtiment démontrent que les bâtiments entre 9-14 étages sont au risque élevé, qui couvre dans l'espace un tiers du domaine d'étude. En combattant le risque séismique, on le suggère fortement d'incorporer les résultats de microzoning dans la conception de l'adaptation ultérieure de nouvelles constructions et de réparation dans les structures vulnérables existées.

Keywords: geological hazards, earthquakes, geomorphology, seismic response, seismic risk, geographic information systems

INTRODUCTION

Examining the strong seismic events, such as, Kanto (1923), Fukui (1948), Nigata (1964) and Hongo-ken Nanbu (1995) in Japan, Michoacan, Mexico (1985), Loma Prieta, USA (1989) earthquakes, researchers revealed a close relationship between the distribution of damages and that of near-surface impedance contrasts. These contrasts, such as those arising from unconsolidated soil and sediment deposits, can significantly affect the frequency-amplitude content and duration of earthquake ground motion. In response to these developments, several attempts have been made to identify and appraise site-based seismic hazards and to represent them in the form of different level of zoning maps. Zoning mapping considering the site-effects of surface geology in detailed scale for code-based structural design is known as seismic microzoning. The microzoning map is extensively used for urban landuse planning and mitigation measures for the earthquake safety of existing structures and facilities.

The best procedure for determining the site-based seismic response of a particular location is to observe the ground motion during an actual event. This can be done either strong or weak motion, by direct comparison of a sediment site to a reference site located on competent ground or by regression analysis of earthquake data. To achieve site response survey for microzoning in a reasonable period of time, this approach is practical only in regions such as California and Japan, where the rate of seismicity and signal-to-noise levels are high. It is therefore desirable to develop alternate methods of characterizing site amplification in high noise urban environments and in region where the level of seismicity is low.

One such alternate approach, which involves determining the soil response is the borehole/geophysical method. But, this method involves high cost and consumes time, and hence is less suitable for microzoning purpose. In these conditions, alternative sources of the excitations have to be sought, such as explosions, aftershocks, microseisms and microtremors. Among theses alternative sources, the use of microtremors, an idea pioneered by Kanai (1954), turns into one of the most appealing approaches in site effects studies, due to its relatively low economic cost, and the possibility of recordings without strict spatial or time restrictions (Rodriguez & Midorikawa, 2002). Although the use of microtremors in site response estimates has long been very controversial in other parts of the world except Japan, its use received renewed attention after the Guerreoro-Michigan event of 1985, where it appear clear that the ground response information provided by the microtremor was consistent with strong motion observations. Considering both the increased importance on microzoning and site effects after the damage observations in recent earthquakes, such as, Mexico 1985, Spitak 1988, Loma Prieta 1989, Kobe 1995, Tiwan, 1999, and the limited number of resources available for such studies in developing and moderate seismicity countries as well, this low cost convenient technique attracted many new users.

Techniques of microtremors have been used basically in four different ways in site response estimations: absolute spectra, horizontal-to-vertical (H/V) spectral ratio with respect to reference and non-reference site and velocity structure inversion through array recordings. The first three directly provide some information on the site response while the fourth one is geophysical exploration technique, leading only indirectly to site response estimates. The H/V spectral ratio technique proved potential after revision and improvements made by Nakamura and Uneo (1989) and Nakamura (2000) who proposed a quasi-transfer function calculation model. In H/V spectral ratio technique, the ground responses are calculated in terms of predominant period and amplification factors. Some experimental investigations (Lachet and Bard 1995, Lermo and Chavez-Garcia 1993) have validated the H/V spectral ratio technique in determining the predominant period of the ground. Predominant period indicates the frequency of the spectrum under which the near-surface soft sediment amplifies the earthquake ground motion, often referred as the site effects. The degree of damage caused by earthquake shaking is larger when the predominant period of the sites appears near the period of the structure.

Previous workers (Matsuoka and Midorikawa, 1995; Fukuwa, Arakawa & Nishizaka, 1998) postulated that geomorphological map units explicit the promising results to figure-out the response governed by the near-surface sedimentary deposits. Based on Japan Metrological Agency's (JMA) strong motion records, Yamazaki et al (2000) established that the combined use of geomorphological land classification and surface geology yield the best estimate of site amplification ratio.

A recent study conducted by Cardona, Davidson & Villacis (1999) on twenty cities of the world shows Dhaka appears to have one of the highest values of earthquake disaster risk index (EDRI) mainly due to its inherent vulnerability of building infrastructures, high population density and poor emergency response and recovery capacity. Moreover, rapid urbanization and recent increased seismic activities in the region have increased the awareness and necessity of the detailed oriented seismic hazard study of the mega-city Dhaka. So, in this article, an attempt made to estimate the seismic response for the microzoning of the ground of the Dhaka city area based on the geomorphic soil classification. No such study has been carried out for Dhaka city area so far. The microtremor technique has been employed to quantify the response of ground motion during earthquake for each geomorphic soil unit. The study area is (Figure 2) located between longitude 90^{0} $19^{/}$ 10.37"E and 90^{0} $31^{/}$ 1.61"E and latitude 23^{0} $40^{/}$ 49.9"N and 23^{0} $54^{/}$ 46.5"N encompasses Dhaka Metropolis and its vicinity covering an area of 305 km^2 within four river system, namely, Buri-Ganga, Turag, Tangi and Balu which have been flowing in the south, west, north and east sides respectively. In order to prepare a microzoning map to figure-out the structures, vulnerable for seismic hazard of the area of investigation, the following steps are taken as shown in the Figure 1:

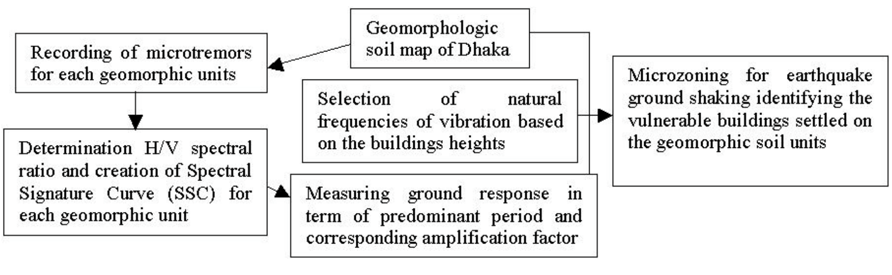

Figure 1. Flow diagram indicates the procedures adopted in this study

Both the polygon and point data have been stored, classified and integrated using GIS operation.

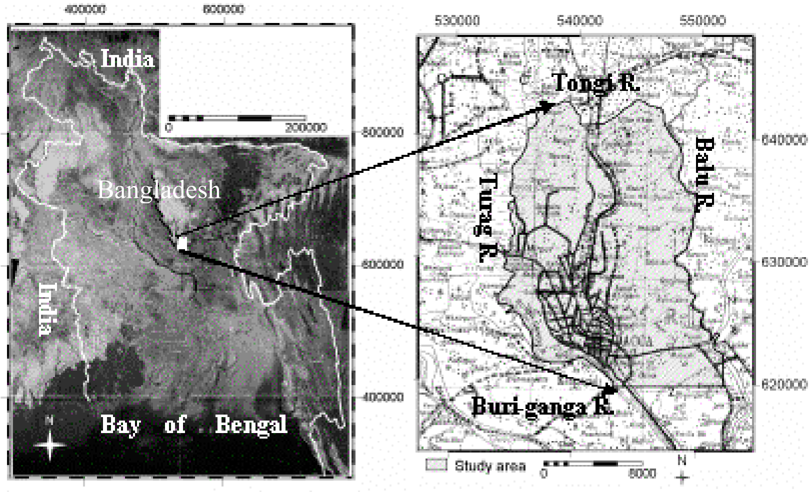

Figure 2. White polygon in the left image and grey area within the arrow in the right illustrate the area of investigation

GEOMORPHIC-SOIL MAP OF DHAKA

Kamal and Midorikawa (2004) delineated the geomorphology of Dhaka city area, differentiating the ground of the city into seventeen geomorphic units using aerial photographs (1954, 1•40000). These geomorphic units represent the soil conditions or surface geology of Dhaka with minor anthropogenic modifications. It has been observed that the city has been expanding rapidly even in the low-lying geomorphic units by fill practices for urban growth from 1960. In the study, the satellite images of Landsat ETM+ bands 5, 4 and 3 and IRS-1D PAN acquired in February 2002 and 2000 respectively are used to delineate the fill sites, so far emplaced on the low-lying geomorphic units, in order to show the urban growth settled on fill-sites. They also classified the fill-sites into four classes based on the thickness of fills. In order to collect the fill-thickness, the boreholes and old topographic map prepared in 1961 are used. Later on, the classified fills are integrated with the pre-urban geomorphic- soil units as shown in Figure 3. This geomorphological map also illustrates the urban sprawl on the low-lying geomorphic units until 2002. As surface sedimentary deposits amplify the seismic waves and geomorphological map units represent the surface geology, these detailed delineated geomorphic units are used to estimate the seismic response of the ground.

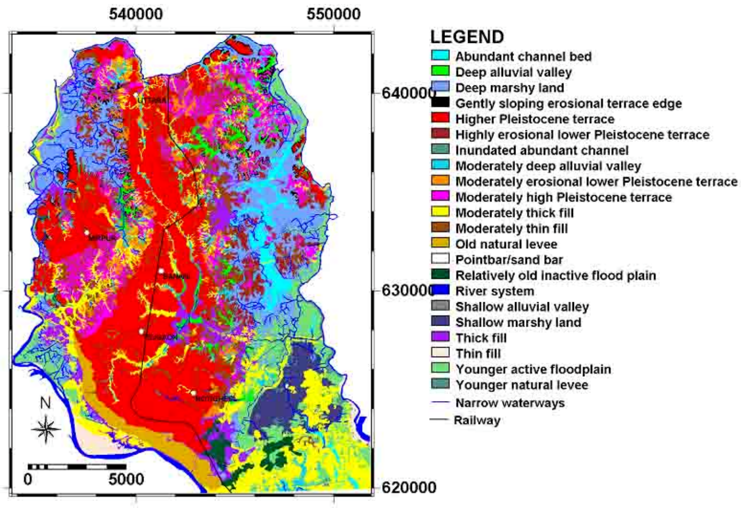

Figure 3. Geomorphological map of Dhaka city area with the information of fill thickness

MICROTREMOR MEASUREMENT AND ANALYSIS PROCEDURES

Microtremors acquisitions are performed using portable microtremor equipment (velocitimeter) named as GEODAS (Geophysical Data Acquisition System) made by Butan Service Co., Japan. The sampling frequency for all the measurements has been set at 100 Hz. The single velocity sensor used can measure simultaneously three components of vibration for a site: two horizontal (NS and EW) and one vertical (UD). The natural period of the sensor is 2 second. The potential frequency response range for the sensor is 0.1–20 Hz. A global positioning system (GPS) has been used for recording the coordinates of each observation site. One hundred and eighty six microtremor records have been recorded systematically for all the geomorphic units. Microtremors have been registered in both the fill and non-fill sites of the low-lying geomorphic units, which comprise 65% area of investigation. The recorded number of microtremors registered for near surface sediment response analyses on each geomorphic unit is shown in Table 1.

Table 1. Recorded microtremors for the geomorphic units

Geomorphic units	Records on fill-sites	Records on fill- sites of low-lying geomorphic units	Records on non-fills of low-lying geomorphic units	Total records
Higher Pleistocene Terrace (HPT)	34			34
Moderately Higher Pleistocene Terrace (MHPT)	10			10
Moderately Erosional Pleistocene Terrace (MEPT)	13			13
Highly Erosional Pleistocene Terrace (HEPT)		10	4	14
Erosional Terrace Edge (ETE)		4	4	8
Old Natural Levee (ONL)	8			8
Younger Natural Levee (YNL)		5		5
Old Inactive Floodplain (OIF)	5			5
Point Bar (PB)		5		5
Younger Floodplain (YF)		9	3	12
Deep Marshy land (DML)		11	4	15
Shallow Marshy Land (SML)		3	2	5
Deep Alluvial Valley (DAV)		9	4	13
Moderately Deep Alluvial Valley (MDAV)		11	3	14
Shallow Alluvial Valley (SAV)		13	2	15
Inundated Abundant Channel (IAC)			3	3
Abundant River Bed (ARB)			3	3
River System (RS)			5	5
Microtremores records for all geomorphic units	70	80	37	187

Micotremors have been recorded three times in each site for the duration of 82 seconds. Three noise-free portions having 20.48s have been selected from each record for spectral analysis. Steps employed for spectral analysis are given below:

(1**) Fourier transformation:** Firstly, Fourier spectra of the selected segments of two horizontal and the vertical components are calculated using the Fast Fourier Transform (FFT) algorithm. As the Fourier spectra of the two horizontal components looked alike, their horizontally combined spectra were calculated to obtain the maximum Fourier amplitude spectrum as a complex vector in the horizontal plane, while the UD component provided the vertical motion spectra.

(2) **Smoothing of the spectra:** Secondly, digital filtering has been employed on the combined horizontal and vertical spectra applying a logarithmic window [5, 12] with a bandwidth coefficient equal to 15. This filtering technique is applied to reduce the distortion of peak amplitudes.

(3) **Calculation of transfer functions**: The smoothed combined horizontal spectrum are divided with the vertical spectrum using equation 1 given below, which provided the soil response in term of amplified periods of the investigated portions (20.48s) of records.

$$R\,(f) = \sqrt{\;FNS(f)\;*\;FEW(f)\;}\;/\;FUD(f) \qquad (1)$$

where R(*f*) is the horizontal to vertical spectral ratio and F_{NS}, F_{EW} and F_{UD} is the Fourier amplitude spectra in the NS, EW and UD directions respectively.

(4) **Normalizing the data set**: After obtaining the H/V spectra of the three segments, the average of the spectra are obtained as the H/V spectrum for a particular site as a relatively non-biased response. The peak period of the H/V spectrum plot shows the predominant period as well as amplification factor of the site.

Figure 4 illustrates the above-mentioned steps using a microtremor record measured on the Higher Pleistocene terrace. From the tri-axial waveform W, three noise-free portions A, B, C having 20.48s are selected for analysis. In the plots A(*f*), B(*f*), and C(*f*), the horizontal to vertical motion Fourier spectra are observed after smoothing by logarithmic window (width coefficient b=15). In these graphs, H(*f*) represent horizontal fourier spectra whereas V(*f*) represent vertical fourier spectra. The plots D, E and F represent the soil response functions by dividing the H(*f*) with V(*f*). The red curve of graph G represents relatively unbiased horizontal-to-vertical (H/V) spectral ratio after averaging D, E and F. The circle on the red curve represents predominant period, which is around 1.0s, and the corresponding amplification factor is around 2.5. Thus, all the recorded 187 microtremors have been analyzed to obtain the predominant periods and corresponding amplification factors of the sites.

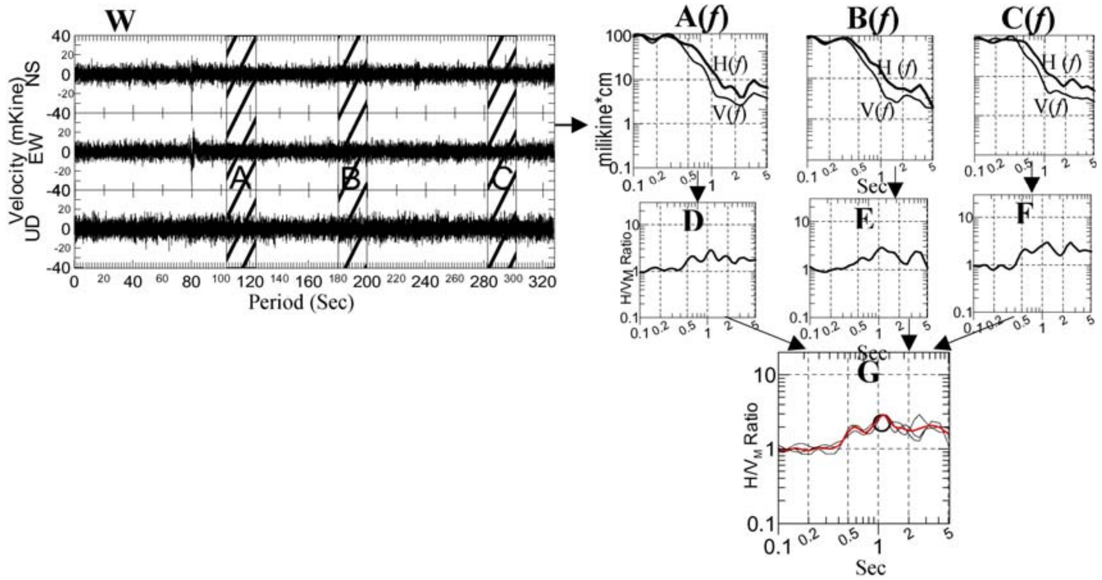

Figure 4. Different steps to determine the soil response in term of predominant period and amplification factor from a microtremor record

DETERMINATION OF REPRESENTATIVE SPECTRAL SIGNATURE (RSS) THE GEOMORPHIC UNITS

In order to investigate the overall shape and trend of the horizontal-to-vertical (H/V) spectral ratio curves for each geomorphic unit, all the curves belonging of a geomorphic unit are overlaid in a plot. For instance, the plot "*a*" of Figure 5 represents the overlay of horizontal-to-vertical (H/V) spectral ratio curves belonging to the geomorphic units, namely, Higher Pleistocene terrace and Deep Marshy land. Since, Deep Marshy land used to experience fill practice for infrastructural set-up, so, microtremor has been registered on both fill and virgin ground of this geomorphic unit. The H/V spectral ratios of fill sites are represented by the curve of light grey colour whereas the black curves represent the non-fill/virgin ground.

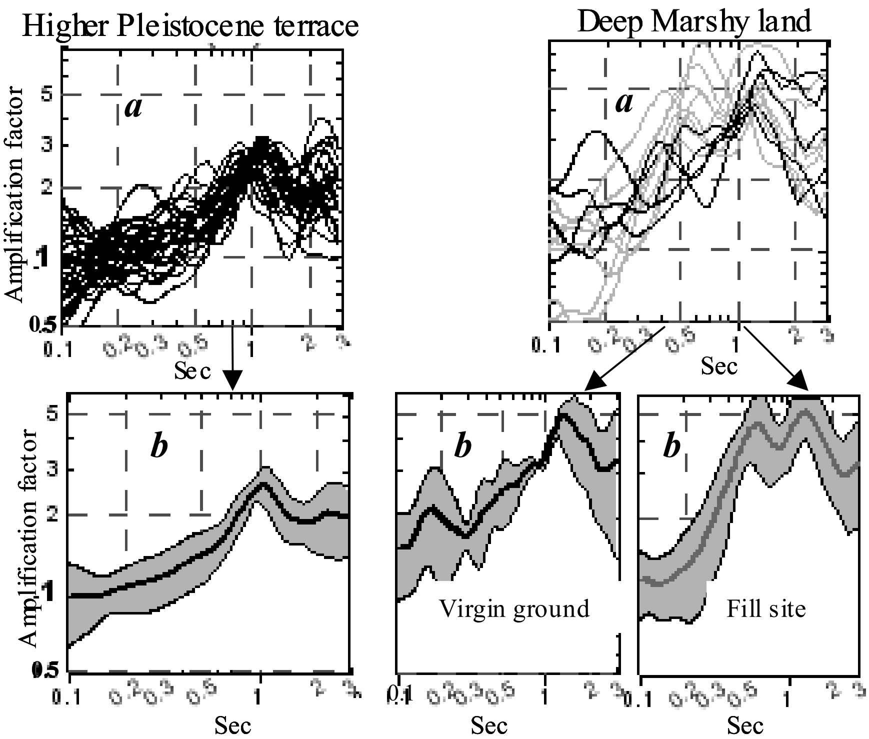

Figure 5: Overlay of all horizontal-to-vertical (H/V) spectral ratio curves and corresponding Representative Spectral Signature (RSS) of the Higher Pleistocene terrace and Deep Marshy land.

By averaging H/V spectral ratio curves, the impact of soil response with in a geomorphic units due to some spatial variations in the soil profiles are minimized and the Representative Spectral Signature (RSS) curve with standard deviation of each geomorphic unit are prepared as shown in Figure 5*b*. The combined shape and amplified periods of RSS of a geomorphic unit reflect relatively non-bias seismic response under dynamic load. Thus, the RSS curves of all geomorphic units are prepared and the soil response of each geomorphic unit is measured in term of predominant period and amplification factor, which is shown in Table 2. In the table, two or three modes of amplified periods are observed in some low-lying geomorphic units. The amplified periods have been classified into short, intermediate and long periods differentiating the amplified range of frequency into 0.1-0.75, 0.75-1.4 and 1.4-2.0 seconds.

Table 2. Soil response of each geomorphic unit in term of predominant period and amplification factor with STD

Geomorphic Units	Short P. Period (M±STD)	Inter. P. Period (M±STD)	Long P. Period (M±STD)	Amp. (M±STD): Short P. period	Amp. (M±STD): Inter. P. period	Amp. (M±STD): Long P. period
Higher Pleistocene terrace		1.02±0.12			2.7±0.40	
Moderately Higher Pleistocene Terrace		1.08±0.06			3.52±0.37	
Moderately erosional Pleistocene terrace		1.20±0.08			4.30±0.29	
Moderately thick fill: Highly Erosional Pleistocene terrace	0.40±0.09	1.0±0.13	1.60±0.14	3.30±1	4.30±0.46	3.72±0.53
Nonfill: Highly Erosional Pleistocene terrace		1.10±0.10			4.70±0.20	
Moderately thin fill: Erosional Terrace Edge		1.1±0.11	1.9±0.09		4.20±0.40	4.4±0.25
Nonfill: Erosional Terrace edge		0.9±0.12	1.7±0.0		4.50±0.25	4.25±0.53
Old Natural Levee		1.20±0.12			3.55±0.22	
Thin fill: Younger Natural Levee		1.03±0.12			5.20±0.60	
Old Inactive Floodplain		0.78±0.02	1.7±0.24		3.0±0.18	3.74±0.18
Thin fill: Point Bar		1.05±0.12			5.25±0.39	
Moderately thick fill: Younger Floodplain	0.30±0.08	1.20±0.18		2.7±0.50	5.40±1.0	
Non-fill: Younger Floodplain		1.07±0.03			5.30±0.65	
Thick fill: Deep Marshy Land	0.50±0.12	1.25±0.11		4.70±1.04	5.20±0.94	
Non-Fill: Deep Marshy Land	0.35±0.16	1.15±0.30		3.20±0.28	5.60±1.50	
Moderate fill: Shallow Marshy Land	0.36±0.06	1.15±0.35		4.75±0.50	4.5±0.86	
Moderately thick fill: Shallow Marshy Land	0.32±0.06	1.01±0.28		3.85±1.15	4.33±0.58	
Thick fill: Deep Alluvial Valley	0.47±0.10	1.06±0.10		3.90±0.66	5.25±0.42	
Non-fill: Deep Alluvial Valley	0.40±0.15	1.28±0.09		3.30±0.57	4.80±0.79	
Moderately thick fill: Moderately Deep Alluvial Valley	0.50±0.08	1.2±0.16		3.4±0.63	5.40±0.70	
Non-fill: Moderately Deep Alluvial Valley	0.54±11	1.2±0.11		2.85±0.46	4.80±0.32	
Moderately thin fill: Shallow Alluvial Valley		1.13±0.14		4.1±0.15		
Non-fill: Shallow Alluvial Valley		1.20±0.20		4.20±0.42		
Thick fill: Inundated Abundant Channel		1.25±0.09		5.03±0.72		
Thick fill: Abundant River Bed	0.60±0.14			5.75±0.54		
Thick fill: River System		0.85±0.07		5.16±0.26		

P.: Predominant; Amp.: Amplification; (M±STD): Mean and Standard Deviation, Inter.: Intermediate

Different modes of amplified periods are caused due to the presence of different impedance contrast in near-surface soft sedimentary layers. In some low-lying geomorphic units, amplified short periods indicate the plane of impedance contrast between fill deposits and original ground of those geomorphic units.

MICROZONING FOR EARTHQUAKE GROUND SHAKING OF DHAKA CITY AREA

Earthquake microzoning is a procedure for estimating the seismic hazard from ground shaking and related phenomena by taking into account the effects of local site conditions. Seismic microzoning maps are detailed maps that identify the relative potential for ground disruption during an earthquake in different areas. Such maps are essential tools for effective earthquake emergency and related landuse planning. Ground shaking, the definitive characteristics of earthquakes, is a seismic hazard that causes damage to structures directly, by vibration, or indirectly, by inducing other seismic hazards, such as, liquefaction or landsliding. The practical value of microzoning is the identification of sites where buildings of certain classes will be at elevated risk. Therefore, to develop an effective microzoning map, there needs to be an understanding of the interactions of the soil of the sites and buildings settled on those sites. The responses of the soil under dynamic load have calculated using microtremor data in term of fundamental period and corresponding amplification factor. The degree of damage caused by an earthquake shaking is larger when the fundamental frequency of the building coincides with the amplified frequency of the sites. The fundamental frequency is related with the height of the building. Therefore, the height of the building is the most important criteria for site-based seismic hazard study. During 1985 Michoacan, Mexico, earthquake (M=8), despite the epicentral distance of 350 kilometres, most of the 18-22 storey buildings of the Mexico City lakebed zone suffered severe structural damage. During 1999 Chi-Chi (Taiwan) earthquake (M=7.6), despite Taipei city being located 130 kilometers away from epicenter area, many low rise (around 480) buildings were damaged though only three tall buildings collapsed. The damage pattern of 1886 Charleston earthquake showed that in the places where the dynamic site periods determined by SHAKE were similar to the natural building periods, double resonance (i. e., resonance of the soil column given the earthquake motion frequency, may have occurred in addition to resonance of the buildings having a natural period similar to the dynamic site period) has occurred which caused greater damage. To determine the natural frequency of the buildings in Dhaka, the empirical relationship (Day, 2001) that the natural period of a building in seconds is approximately equal to the number of stories divided by 10 (rule of thumb) as shown by the equation below, is used in this study:

$$T_b = N/10 \qquad (2)$$

where, Tb= vibration period of the buildings and N= Number of story/height of the buildings. According to this equation, for instances, the fundamental frequency of a 10 storey building is 1 second.

Based on the simultaneous consideration of the predominant/dynamic period estimated for the geomorphic-soil units as shown in Table 2 and the fundamental frequency of the building clusters (according to equation 2), four different height of buildings are taken into consideration for earthquake microzoning mapping of Dhaka city area. The fundamental period of the buildings cluster are shown differentiating them into four bandwidths as given below:

1) Band 1: 0.2-0.5 seconds comprise low-rise building between 2-5 storeys height.

2) Band 2: 0.6-0.8 seconds comprise moderately intermediate rise buildings between 6-8 storeys height.

3) Band 3: 0.9-1.4 second, comprise intermediate height buildings between 9-14 storeys height and

4) Band 4: 1.5-2 second, comprise relatively high- rise buildings between 15-20 storeys height.

The ground amplification factors under certain frequencies, of the soil subjected to seismic load, are estimated for each geomorphic unit from the Representative Spectral Signature (RSS) value as shown in Table 2. The higher the amplification factors of a soil type under a certain frequency of seismic wave, the higher the degree of hazard for the structures of that frequency. Therefore, the ranks of the seismic hazard have been differentiated into four classes based on the amplification factors within these bandwidths which are given in the Table 3.

Table 3. Ranking of microzoning ground shaking hazard based on amplification factors

Amplifications	Ranks
1.0-2.5	Very low Hazard
2.5-3.5	Low Hazard
3.5-4.5	Moderate Hazard
4.5-7	Relatively High Hazard

Thus, the geomorphic units are classified based on the seismic response (amplification factor as shown in Table 2) into four microzoning maps, which illustrate the spatial distribution of vulnerable buildings within Dhaka city area. The microzoning maps for low-rise, moderately intermediate rise, intermediate rise and high-rise buildings are shown in Figure 6 (*a*, *b*, *c*, and *d*).

CONCLUSIONS

It is well documented that the near surface sediments significantly amplify the earthquake ground motions, often known as site effects. The evaluation of the local site conditions and the estimation of their influence on earthquake ground motion is the main purpose of a microzoning, which has an important implication in urban landuse, planning and mitigative measures for the earthquake safety of the existing structures.

The microzoning maps of Dhaka city area demonstrate that the intermediate rise buildings of 9-14 storey in height, which spatially cover 100 km^2 out of 305 km^2 of the study area, are at elevated vulnerability. Other than, higher Pleistocene terrace, moderately high Pleistocene terrace, moderately erosional lower Pleistocene terrace, old natural levee and old inactive floodplain, almost all of the rest of the geomorphic units represent high vulnerability for 9-14 storeys buildings. The high-rise buildings between 15-20 storeys are exposed to moderate vulnerability in most of the geomorphic units. The moderately intermediate rise buildings of 6-8 storeys are highly vulnerable in the fill sites of deep marshy land and deep alluvial valley. The rest of the geomorphic units pose moderately low, to low vulnerability for 6-8 storeys buildings. The low-rise buildings of 2-5 storeys are at low vulnerability within Dhaka city area, and are relatively safe to withstand strong ground motion provided the soil behaves linearly under dynamic load. It is observed that the geomorphic units of higher Pleistocene terrace, moderately high Pleistocene terrace, old natural levee and old floodplain are consistent enough to resist the potential amplification of seismic wave that caused damage to certain structures.

The findings of this study recommend not constructing certain storey buildings, which posses elevated vulnerability in certain geomorphic-soil units. In order to combat the seismic hazard, there need to take urgent retrofitting measures to the vulnerable structures within Dhaka city area. Moreover, the authors would like to suggest imposing height restrictions in the existing city building code.

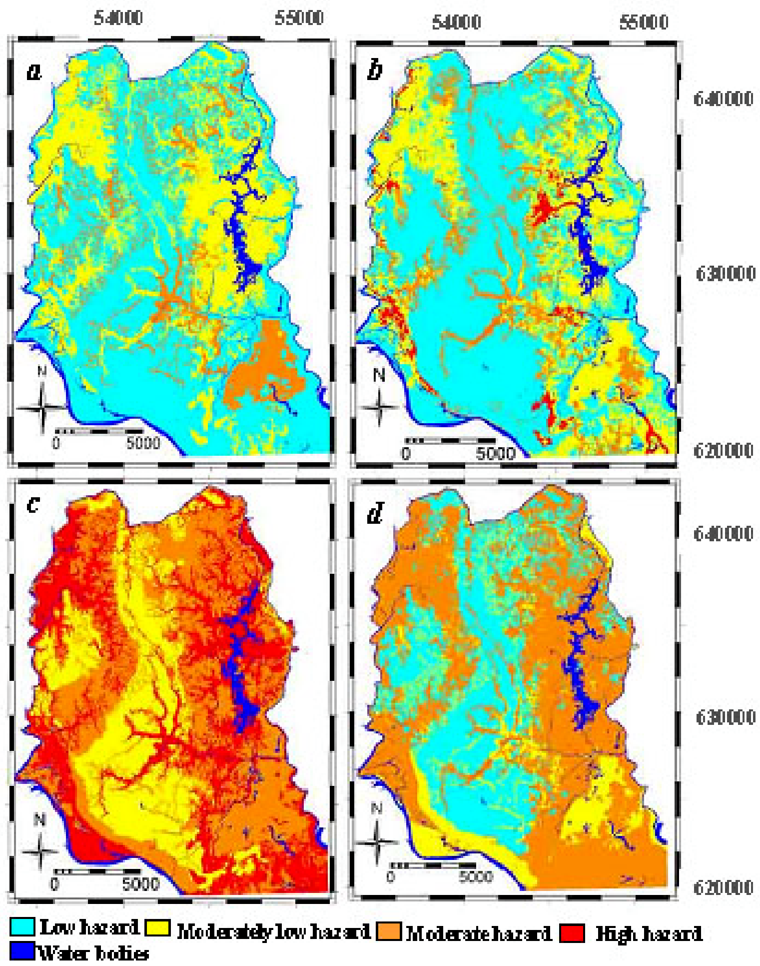

Figure 6: In the Figure "*a"* represent the vulnerability for 2-5 storeys buildings, *"b"* represents vulnerability for 6-8 storeys buildings, *"c"* represents vulnerability for 9-14 storeys buildings and *"d"* represents vulnerability for 15-20 storeys buildings.

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