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Application of Analytical Hierarchical Process and GIS in Earthquake Vulnerability Assessment: Case Study of Ward 37 and 69 in Dhaka City

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Abstract

Unplanned urbanization defying building codes are continuously increasing the earthquake vulnerability of citizens of Dhaka city. So, existing situation requires the assessment of earthquake vulnerability by identifying those factors contributing to vulnerability. This paper attempts to employ such assessment to identify and analyze the contribution of different factors to compare ward. 37 (Begunbari) and 69 (Nimtoli) of new and old Dhaka respectively. It applies Analytical Hierarchical Process (AHP) for determining the weight and priority of the vulnerability factors' contribution to the life of individuals. Using GIS, vulnerability index (VI) of different factors is calculated by defining an ordinal scale and overall vulnerability index maps of study areas are prepared representing the vulnerability of individual buildings. Analyses reveal that Nimtoli (mean VI is 3.06) is more vulnerable than Begunbari (mean VI is 2.77). It is also observed that soil category of Nimtoli is better than that of Begunbari but in Nimtoli about 74% buildings are old, 63% buildings are pucca and 75% buildings have less than 100 m^2 area causing to increase vulnerability.

Introduction

Earthquake is one of the most devastating natural hazards and in recent years it has become more frequent in Bangladesh including Dhaka city. Unplanned urbanization with over population density and defiance of Building codes are now increasing the vulnerability of citizens of the city against earthquake. To address these issues, vulnerability assessment against earthquake is a useful approach.

In Dhaka city, citizens and policy makers have lack of awareness about the factors that may cause vulnerability from earthquake. This paper applies the empirical results of Analytical Hierarchical Process (AHP) to reveal the contribution of different factors in vulnerability assessment against earthquake and Geographical Information System (GIS) is used to map the vulnerability of the individual buildings of Ward no. 37 (Begunbari) and Ward no. 69 (Nimtoli) of Dhaka city. This study attempts to provide useful information on the implication of planning policies.

Bangladesh is close to the meeting point of the Indian, Eurasian and Burma (Myanmar) plates. The movement of Indian and Eurasian plates has been locked at the foot of the Himalayas for many years storing strain energy. But when the lock will release, the strain

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energy will be transformed into devastating earthquake causing serious hazard over the country. The seismic zoning map divides the country into three earthquake vulnerability zones. It has been observed from the map that 43 percent areas in Bangladesh are rated high risk, 41 percent moderate and 16 percent low (Alam, 2009, September 10, p.1). According to a UN study conducted in 1999, Dhaka is the world's most earthquake vulnerable city followed by Tehran (NNN-BSS, 2010, February 24). The meteorological department detected at least 90 earthquakes that took place in Bangladesh between May 2007 and July 2008, nine of them being above 5 on the Richter scale and epicenters of 95 percent of those earthquakes being within a 600 kilometer radius of Dhaka city (Alam H. 2009, September 10, p.1).

It is obvious that the losses of life are increased due to building collapse in urban area than other factors. Many countries have reduced vulnerability by proper urban infrastructure development. The best example is Japan which experienced several strong earthquakes leaving few losses (Gharakhlou and Reveshty, 2009). So, factors regarding buildings are one of the major factors which need to be properly assessed in vulnerability assessment. In addition, if other contributing factors are properly assessed then vulnerability can also be reduced or local resilience to hazards can be improved through effective preparedness, response, recovery, and mitigation.

Recently, government has initiated the Comprehensive Disaster Management Program (CDMP) for the whole country. Under CDMP, vulnerability assessment of Dhaka city against earthquake is conducted by assessing the physical vulnerability of buildings and lifeline infrastructure and other relevant factors. Also, a contingency plan will be prepared ensuring the preparedness of citizens (Kamal, nd.). In this backdrop, this research is conducted with an objective of vulnerability assessment through developing and applying a model to earthquake hazard.

Study Methodology

The issues related to the impact of different factors on the earthquake vulnerability have been discussed in a certain number of studies. In these studies, AHP and GIS were used to assess the earthquake vulnerability based on some selected factors. For example, Reveshty and Gharakhlou (2009) stated that urban building vulnerability against earthquake is increased with the used material type of buildings, age of buildings, land use, number of floors, area of a parcel. It has been demonstrated that the region 3 of Zanjan city posses high degree of damage because of the old buildings as well as for using low quality of building materials than region 2 which shows inverse results. Aghataher *et al.* (2008) conducted a study where different factors such as: building stories, building structure types, building age and resident population were used to evaluate cities vulnerability against earthquake. These studies suggest that the effect of buildings is significant on the earthquake vulnerability assessment.

In Bangladesh, a study has been conducted based on Detailed Area Plan (DAP) of Chittagong Development Authority (CDA) presenting the seismic vulnerability assessment of "Purbo Madrabari" of Chittagong, the port city of Bangladesh. In this study, Preliminary Assessment Methodology (PAM) was used where different structural factors such as: number of stories, existence of a soft story, existence of heavy overhangs, apparent building quality, existence of short columns, pounding between adjacent buildings, topographic effects and local soil conditions were used (Alam et *al.* 2009). Jobair (2006) conducted a study on regional seismic damage assessment for the Rajshahi City using GIS, where reflection of ground shaking and the secondary site attributes of soil amplification and liquefaction are the most important features. Analyses showed that only for ground shaking, approximately 11 percent buildings had been estimated to be damaged. Again for ground shaking and liquefaction, approximately 15 percent buildings had been estimated to be damaged.

It has been observed from the previous studies that different methods can be applied in analysis of earthquake vulnerability assessment. In Bangladesh, combination of AHP method and GIS can be easily applied based on availability of GIS database. Analytical Hierarchical Process provides a useful method for estimating the contribution of different factors in earthquake vulnerability analyses. The theory of Analytical Hierarchical Process is based on multi criteria evaluation. The method is usually offered with the pair-wise comparison technique that simplifies preference ratings among decision criteria. That is, the contribution or weight of different factors on earthquake vulnerability assessment has been estimated through pair-wise comparison of the factors. Different factors or criteria regarding physical, geological, population may have relative impact on each other which increase or decrease the weight of individual factors on vulnerability assessment against earthquake that ultimately delineate the hierarchy of factors. Therefore, the hierarchy of different factors can be delineated by generating comparison matrix based on the observed results from pair-wise comparison of factors.

In the following sections, at first the results of Analytical Hierarchical Process have been applied to estimate the weights of different factors and then vulnerability has been assessed by calculating the Vulnerability Index (VI) for each building of different sub-criteria. Finally, combination of spatial and attribute data as input in GIS, the degree of vulnerability of each building element against earthquake has been measured. The vulnerability analysis of each building results in a combined output and shows the overall vulnerability of selected areas against earthquake hazard.

AHP Model for Vulnerability Assessment against Earthquake

A sample of buildings of Ward 69 (Nimtoli) and Ward 37 (Begunbari) has been selected representing Old Dhaka city and New Dhaka city respectively. The availability of GIS database has been important for conducting this work. Data has been collected from Gani Bangla Limited prepared for Detailed Area Plan and Ministry of Disaster and Relief prepared for Comprehensive Disaster Management Plan. Figure 1 shows different steps of methodology.

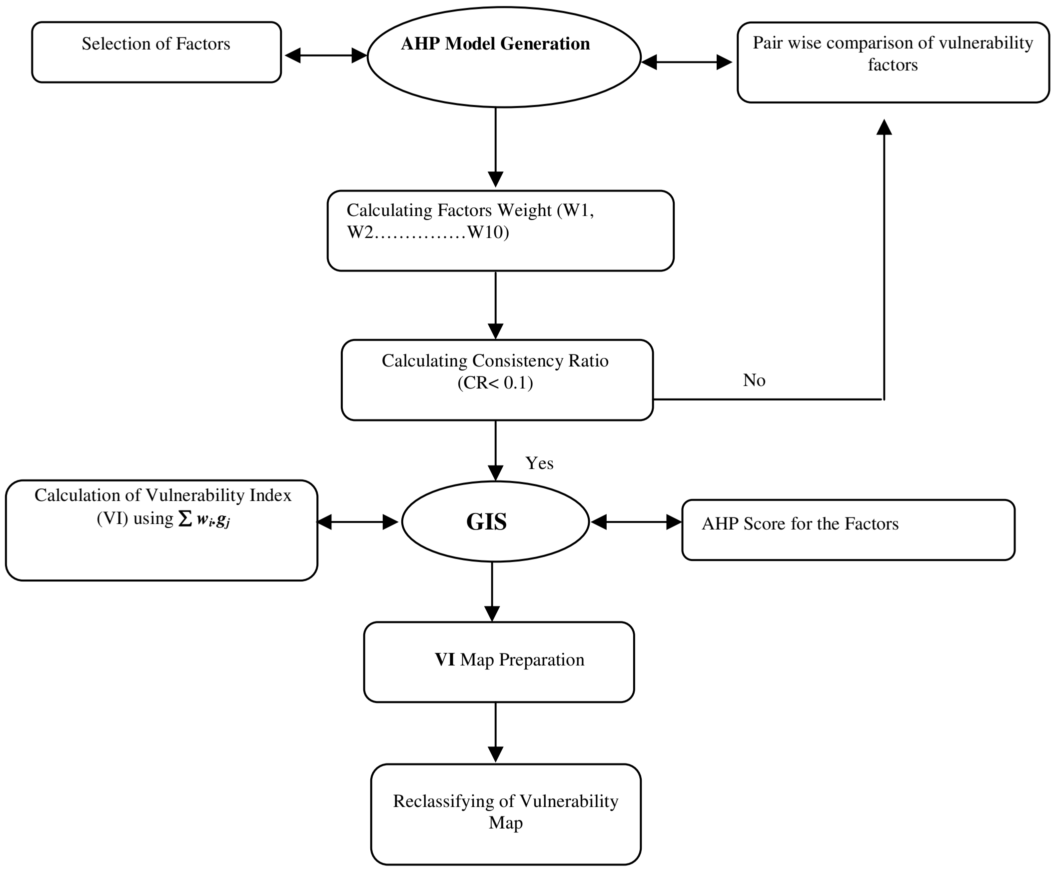


Fig. 1: Flow Chart of Study Methodology

Different spatial data has been employed for assessing the vulnerability of individual area including building type, number of floors, age of building, area of a parcel, land use, road width, open space, and soil type. Besides, non spatial data including age group and density has been also used to conduct this research. The non-spatial data has been collected from Population Census, 2001. Furthermore, the identified ten factors are categorized into four sub categories. To calculate the Vulnerability Index for each variable, these sub categories are measured in a 1-9 ordinal scale based on their frequencies and contribution to the vulnerability. Table 1 shows the factors affecting the vulnerability against earthquake.

Model Specification and Consistency

To determine the weight of every factor, they are compared together in a 1-9 ordinal scale. The results are recorded in metric n * n (in this case 10 * 10) which is called as binary comparison metric $A_{ij}= [a^{n \times n}]$. All components of the mentioned metric are positive and regarding the "reverse condition" in Analytical Hierarchy Process (if the weight of i in relation to j equals to k, the weight of j in relation to i will equal to 1/k) we will have two numerical quantity of Aij and 1/aij in every binary comparison. The nine level scales for binary comparison matrix is described in Table 2.

Table 1: Factors affecting vulnerability against earthquake along with their weight

Main Factors	Following Sub Category	Very High Vulnerability	High Vulnerability	Moderate Vulnerability	Low Vulnerability
	Weight	9	7	5	2
Building Type	Pucca	•			
	Semipucca		•		
	Tinshed			•	
	Kutcha				•
No. of Floors	6 Floor or more	•			
	4-5 Floor		•		
	2-3 Floor			•	
	1 Floor				•
Age of Building	1960-1980	•			
	1981-1990		•		
	1991-2000			•	
	2000-2010				•
Area of Parcel (m^2)	Less than 100	•			
	100 – 250		•		
	250 – 500			•	
	More than 500				•
Land use	Residential	•			
	Educational		•		
	Commercial			•	
	Mixed & others				•
Road Width	Less than 10′	•			
	10′- 15′		•		
	15′- 25′			•	
	More than 25′				•
Open Space	0.2 acre per thousand population				
Soil Type	Swamp/ Depression	•			
	Valley Fill		•		
	Alluvial Gully			•	
	Upper Modhupur Terrace				•
Density (person/ acre)	More than 600	•			
	500 – 600		•		
	250-500			•	
	250				•
Age Group	60 + yr.	•			
	Less than 15 yr.		•		
	Disable			•	
	Women				•

Table 2: Nine level scale for binary comparison of different factors

Importance	Weight
1	equal weight
2	equal – moderate
3	moderate
4	moderate – strong
5	strong
6	strong-very strong
7	very strong
8	very strong- extremely strong
9	extremely strong

Based on this nine level scale, a comparison matrix has been developed to determine the weight of each factor (Table 3). After developing a Comparison matrix, RMV for every row in the metric has been calculated by multiplying the given weight to 10 factors relative to each factor as followed, RMV = ∑ factor1*factor2*.......*factorN = 1*0.5*0.5*......*0.333 = 0.037. To calculate the unnormalized weights, the products of every row have been applied to the power of 1/n which are the number of influencing factors. Finally, to calculate the weight of factor, unnormalized weights in every row are divided by the sum of unnormalized weights. For example, Normalized Weight of factor 1, $\mathbf{W_i}$ = 0.719/11.008 = 0.065.

Table 3: Pair-wise comparison of ten vulnerability factors

Factors	1	2	3	4	5	6	7	8	9	10	RMV	Unnormal- -ized value	Normalized Value (W_i)
Building Type	1	0.5	0.5	0.333	2	2	0.333	0.5	2	0.333	0.037	0.719	0.065
No. of Floors	2	1	0.5	2	2	3	0.5	0.333	2	0.333	1.333	1.029	0.093
Age of Building	2	2	1	3	3	2	0.5	0.5	2	0.5	18.000	1.335	0.121
Area of Parcel	3	0.5	0.333	1	2	2	0.5	0.333	3	0.5	0.500	0.933	0.085
Land use	0.5	0.5	0.333	0.5	1	2	0.5	0.5	2	0.5	0.021	0.679	0.062
Road Width	0.5	0.333	0.5	0.5	0.5	1	0.5	1	2	0.333	0.007	0.608	0.055
Open Space	3	2	2	2	2	2	1	2	3	0.333	192.00	1.692	0.154
Soil Type	2	3	2	3	2	1	0.5	1	0.5	1	18.00	1.335	0.121
Density	0.5	0.5	0.5	0.333	0.5	0.5	0.333	2	1	0.333	0.002	0.545	0.050
Age Group	3	3	2	2	2	3	3	1	3	1	1944.00	2.132	0.194
Total											2173.90	11.008	1

AHP method avails to investigate the consistency of judgments to determine the significance of relative weight of factors. If A_i has weight higher than A_j and A_j has higher weight than A_k, Ai should attain higher weight than A_k. But in spite of all efforts, the people's priorities are usually discordant. Therefore, we need to find a procedure to disclose the degree of discordance in judgments (Gharakhlou and Reveshty, 2009). To determine degree of consistency in judgments consistency ratio is measured. In order to determine the consistency ratio, A_W vector is calculated by multiplying the comparison matrix with the calculated weight for each factor.

$$\begin{array}{c} 1\\2\\3\\4\\5\\6\\7\\8\\9\\10 \end{array}\begin{bmatrix} 1 & 0.5 & 0.5 & 0.333 & 2 & 2 & 0.333 & 0.5 & 2 & 0.333 \\ 2 & 1 & 0.5 & 2 & 2 & 3 & 0.5 & 0.333 & 2 & 0.333 \\ 2 & 2 & 1 & 3 & 3 & 2 & 0.5 & 0.5 & 2 & 0.5 \\ 3 & 0.5 & 0.333 & 1 & 2 & 2 & 0.5 & 0.333 & 3 & 0.5 \\ 0.5 & 0.5 & 0.333 & 0.5 & 1 & 2 & 0.5 & 0.5 & 2 & 0.5 \\ 0.5 & 0.333 & 0.5 & 0.5 & 0.5 & 1 & 0.5 & 1 & 2 & 0.333 \\ 3 & 2 & 2 & 2 & 2 & 2 & 1 & 2 & 3 & 0.333 \\ 2 & 3 & 2 & 3 & 2 & 1 & 0.5 & 1 & 0.5 & 1 \\ 0.5 & 0.5 & 0.5 & 0.333 & 0.5 & 0.5 & 0.333 & 2 & 1 & 0.333 \\ 3 & 3 & 2 & 2 & 2 & 3 & 3 & 1 & 3 & 1 \end{bmatrix} \times \begin{bmatrix} 0.065 \\ 0.093 \\ 0.121 \\ 0.085 \\ 0.062 \\ 0.055 \\ 0.154 \\ 0.121 \\ 0.050 \\ 0.194 \end{bmatrix} = \begin{bmatrix} 0.710 \\ 1.024 \\ 1.322 \\ 0.964 \\ 0.668 \\ 0.615 \\ 1.638 \\ 1.503 \\ 0.635 \\ 2.102 \end{bmatrix}$$

Then, the adaptive vector is determined by dividing the calculated numerical value of each vector by the weight of each respective factor and then multiplied by 1/n

$$= 1/10 \left[\frac{0.710}{0.065} + \frac{1.024}{0.093} + \frac{1.322}{0.121} + \frac{0.964}{0.085} + \frac{0.668}{0.062} + \frac{0.615}{0.055} + \frac{1.638}{0.154} + \frac{1.503}{0.121} + \frac{0.635}{0.050} + \frac{2.102}{0.194} \right]$$
$$= 1.278$$

To calculate the Consistency Index as deviation or degree of consistency, formula, $CI = \frac{L-n}{n-1} = \frac{11.278-10}{10-1} = 0.142$ is applied.

Knowing the Consistency Index, it is required to compare the Index value with the appropriate one which is Random Consistency Index. In this AHP model, Consistency Index (CI) = 0.142 and for n=10, Random Consistency Index (RI) = 1.49.

So, the Consistency Ratio, $CI = \frac{CI}{RI} = \frac{0.142}{149} = 0.0953$

If the value of Consistency Ratio is smaller or equal to 10%, the inconsistency is acceptable. If the Consistency Ratio is greater than 10%, we need to revise the subjective judgment. In this AHP Model, CR is estimated as 0.0953 or 9.53% indicating the consistency in judgment. Priority and weighted value of the factors are shown in Table 4.

Table 4: Priority and weighted value of the factors

Factors	Weighted value (Wi)	Priority
Age Group	0.194	1
Open Space	0.154	2
Age of Building	0.121	3
Soil Type	0.121	4
No. of Floors	0.093	5
Area of Parcel	0.085	6
Building Type	0.065	7
Land use	0.062	8
Road Width	0.055	9
Density	0.050	10

Vulnerability Index Determination

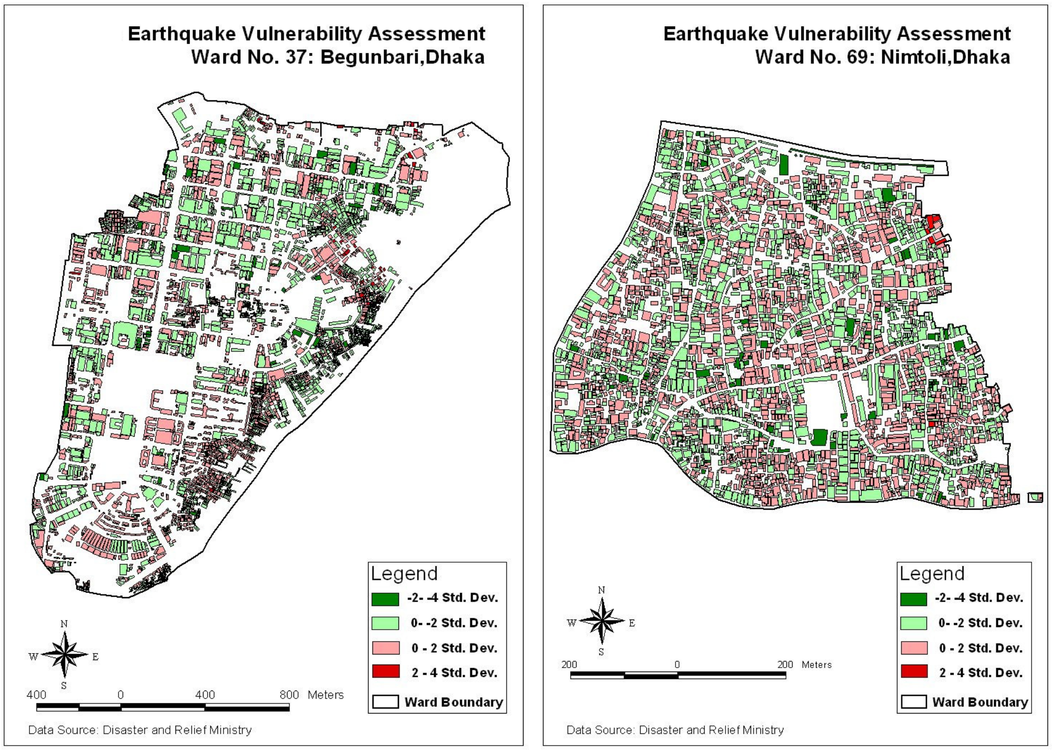
The Vulnerability Index (VI) for each building is calculated by multiplying the weight of each factor in its obtained grade from the 1-9 ordinal scale assessment. The established formula is $VI = \sum_{i-1}^{n} \sum_{j-1}^{m} w_i g_j$

Wherein W_i is the weight of the i^{th} indicator and the g_j is the j^{th} grade obtained by that factor due to its sub category from the 1-9 ordinal scale assessment. GIS has been used to calculate the VI for all of the buildings in Ward 37 and Ward 69.

Overall Vulnerability Assessment

The vulnerability index (VI) which is a relative measure of the overall vulnerability for each study area, is calculated using the abovementioned methodology. To determine the most and least vulnerable area, the VI scores are mapped based on standard deviations from the mean into four categories. Each category ranges by 2 standards deviation.

For Begunbari, the Vulnerability Index (VI) ranges from 1.04 (low vulnerability) to 4.52 (high vulnerability) with mean of 2.77 (Standard Deviation of 0.57) and for Nimtoli the Vulnerability Index (VI) ranges from 1.05 (low vulnerability) to 4.39 (high vulnerability) with mean of 3.06 (Standard Deviation of 0.46). Buildings with VI scores greater than 2 standard deviations are labeled as most vulnerable and 0 to 2 standard deviation are high vulnerable. On the other hand, Building with VI score lower than -2 standard deviations, is labeled as the lowest vulnerable and 0 to -2 standard deviation as the low vulnerable.



Source: Ministry of Flood, Disaster Management and Relief, 2010

Fig. 2: Comparing earthquake vulnerability of Ward 37 and Ward 69

Figure 2 shows the vulnerability Index map for Begunbari and Nimtoli correspondingly. In Begunbari, most of the buildings range from 0 to -2 standard deviation, i.e. those buildings have lower vulnerability. Analyses reveal that most of the buildings are new (73%), one storied (75%) and have large area of parcel (only 46% buildings have less than 100 m^2 area). On the other hand, in Nimtoli most of the buildings range from 0 to 2 standard deviations, which present higher vulnerability of the buildings. Analyses explore that most of the buildings are old (74%), of which 63% are pucca and have smaller area of parcel (75% building have less than 100 m^2 area of parcel). But few buildings have highest vulnerability as because those buildings are constructed on soil categorized as swamp/depression. In Nimtoli, though 99% buildings are constructed on Modhupur Upper Terrace, these buildings show high vulnerability rather than very high vulnerability. But comparing both maps in Figure 2, it is observed that Nimtoli is more vulnerable than Begunbari. Though soil condition of Nimtoli is better than Begunbari, Nimtoli is observed to be more vulnerable. So this study proves that unplanned infrastructure development increases the vulnerability of individuals. So, to save the city from earthquake disaster, it is necessary to develop the city in a planned way.

Conclusion

Using the proposed model of vulnerability, it can be suggested that vulnerability analysis is a multidimensional concept that helps to identify those characteristics of buildings which are responsible for earthquake disaster. From the map, those buildings are identified as the most vulnerable, and measures should be taken to protect these buildings or to prevent earthquake disaster. But in this study, social vulnerability of people can not be assessed because of the lack of data. The concept of social vulnerability helps to identify those characteristics and experiences of individuals and communities that enable them to respond to and recover from earthquake hazards. This type of study will assist the planning and development organizations become stricter in order to compel the citizens as well as developers to follow construction rules and regulation, which are not exercised at present properly. The indicators and model of this study will definitely contribute in vulnerability assessment as well as initiate mitigation efforts against earthquake of Dhaka city. It is hoped that this study will encourage other researchers to conduct further researches. This study has been conducted on two areas only representing old and new Dhaka. For a better assessment of vulnerability from earthquake in Dhaka city, the study can be conducted for the whole of Dhaka city.

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