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Understanding Spatial Variations in Earthquake Vulnerabilities of Residential Neighborhoods of Mymensingh City, Bangladesh: An AHP-GIS Integrated Index-based Approach

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Abstract: Mymensingh city is highly earthquake vulnerable due to its geological setting, existence of three faults, viz., Dauki Fault, Madhupur Blind Fault and Sylhet-Assam Fault in its close vicinity, and liquefaction susceptible soil type. Recently an attempt has been made to assess earthquake risk of the city by Comprehensive Disaster Management Programme II, of Government of Bangladesh using FEMA developed HAZUS tool which requires usage of enormous resources and expertise. Poorly resourced city planning authorities of developing countries are seldom equipped with such financial and human resources, and as a result, the inclusion of earthquake risk analysis, more specifically, information regarding spatial variations of earthquake risk is very often found missing in their physical planning exercises. This paper aims to assess the spatial variation of earthquake vulnerability of residential neighbourhoods of Mymensingh city, employing an index-based low cost approach which could provide a reasonably accurate result with minimum resource and expertise requirements. Analytical Hierarchy Process and Weighted Linear Combination are combined with a Geographical Information System to prepare a composite index considering 23 different parameters, stemming from geological, structural, socio-economic and systematic dimensions of earthquake vulnerability. The findings of the reseach show that out of 241 residential neighbourhoods of Mymensingh city, 51 are observed to be highly vulnerable, while, 123 and 67 are medium and low vulnerable respectively. Besides, the spatial distribution of earthquake vulnerable neighbouhoods in Mymensingh City, observed in the current study has also been compared with spatial distributions observed in two similar previous studies and observed found to be reasonably close. This justifies the validity of the current low cost approach for wider application in cities of resource starved developing countries.

Keywords- Earthquake vulnerability, Index, AHP, GIS, WLC, City planning and development

1. Introduction

Bangladesh, the largest delta of the world, is prone to numerous natural catastrophes due to its geographical location, and remarked as the 5th most disaster risk zone by Asia Pasific Disaster Report 2017(ESCAP,2017). Understanding the complexity of vulnerability caused by various natural disasters is the most challenging task of disaster risk reduction of an area (Alam, Chakraborty and Islam,2019). Earthquake is one of the most lethal disasters, specially in the contex of Bangladesh as the country has been shaken up by more than 250 earthquakes since her independence (Zaman et al., 2018). Tectonically, the country lies at the junction of three tectonic plates - the Indian Plate, the Eurasian Plate, and the Burmese micro-plate, which puts the country in one of the most tectonically active regions of the world (Al Zaman and Monira,2017). A recent GPS measurement of plate motions in Bangladesh combined with measurements from Myanmar and northeast India, reveal 13–17mm/yr of plate convergence on an active, shallowly dipping and locked megathrust fault underneath of Bangladesh which could unleash a 9-magnitude earthquake at any time and kill ten million people (Steckler et al. 2016). The city of Mymensingh is located in zone IV (seismic coefficient 0.36g) of seismic macro-zonation map of Bangladesh and is demarcated as one of the most earthquake-vulnerable cities of the country (BNBC, 2015). The city is seismically vulnerable due to its proximity to three major faults viz. Madhupur Blind Fault, Dauki Fault, and Sylhet-Assam Fault. Besides, liquefaction susceptible soil type covers almost 90 percent of the total area of the city which adds a new dimension to the earthquake vulnerability of the city. Not only the geological factors lying beneath the earth's surface but also factors lying above the earth surface, such as structural, socio-economic and systematic factors are making Mymensingh City vulnerable to earthquake and puts lives and assets of its citizen at risk. Mymensingh, being one of the oldest municipalities of Bangladesh, is vulnerable due to thousands of old dilapidated buildings that are at particular risk of collapse. Besides, substantial variations in socio-economic conditions among residential neighbourhoods are also observed across the city. Considering its increasing administrative importance, and economic potentials, the city has recently been elevated to the status of the 8th divisional city of Bangladesh (Alam and Haque, 2017). The city is expected to house a population of 3 million by the end of the year 2021 which would also open up possibilities of mass migration, haphazard development, and unplanned future expansions.

Residential neighbourhoods of the cities are generally highly vulnerable to earthquake due to their high spatial concentration of life and assets. Nwe and Tun (2016) examined the seismic vulnerability of Mandalay city based on land use condition and observed that residential land use type is the third seismically vulnerable land use type of a city after mixed-use (resident with a store) and commercial land use types. As an old and historic city of Bangladesh, the buildings in the residential neighbourhoods are old in Mymensingh, and substantial socioeconomic disparities among the neighbourhoods are observed. Therefore, given historical and increasing administrative importance of the city, it is crucial to assess all dimensions of earthquake vulnerabilities and their spatial distribution across the city to prioritise earthquake risk reduction strategies for the city.

2. Literature Review

2.1. Rationale

Earthquake vulnerability can be precisely assessed using HAZUS, a Geographic Information System (GIS) based multi-hazard risk assessment tool developed by the Federal Emergency Management Agency (FEMA) of the United States of America. The HAZUS methodology has capabilities to assess the spatial variations of, among others, earthquake, flood, hurricane risks through following several steps such as study region definition, hazard characterisation, and damage and loss estimation. But HAZUS cannot be readily used in other countries due to unavailability of boundary characterization function outside the USA. Therefore, it is opined that HAZUS can provide only a starting point for the development of a disaster risk assessment tool which could be used in Bangladesh considering user requirements and data availability (Sarker, Ansary, Rahman & Safiullah 2009). Another significant complexity of using HAZUS is the development of fragility function which requires a huge amount of resources, high-level of expertise and an enormous amount of data. Developing countries like Bangladesh are hardly equipped with this type of resource, data, and expertise. This paper primarily focuses on developing less resource, data and expertizes requiring methodology to assess earthquake vulnerabilities at neighborhood scale and observe their spatial distribution across the city. The developed methodology is applied to assess spatial variations in earthquake vulnerabilities of residential neighbourhoods of Mymensingh City which yielded a reasonably accurate result and ushered in the possibility of its use in planning efforts of cities having poorly resourced planning agencies in the developing counties.

1.2. Dimensions of Earthquake Vulnerability Assessment

Overall earthquake vulnerability of a neighbourhood largely depends on its structural, geological, socio-economic and systematic components. Excluding any one of these components may have severe implications in devising appropriate risk reduction strategies at the city level. Researchers all over the world are working on the evaluation of earthquake vulnerability using different methods and dimensions. Unfortunately, most of the research work on earthquake vulnerability is focused on structural component and hardly consider other dimensions of vulnerability. Sarvar, Amini, and Laleh-Poor (2011) assessed the earthquake risk of Tehran using a hybrid methodology which only considered structural dimensions of the area. Lantada, Pujades, Barbat (2004) also evaluated the seismic risk of Barcelona using the vulnerability index method and capacity spectrum-based method which had been structural vulnerability biased and excluded socio-economic dimension of the area.

Researchers such as Nath et al. (2015), Ishita and Khandakar (2010), Barbat et al. (2010), Sarris et al. (2010) also attempted to measure seismic vulnerability at different spatial scale but only considered the structural or geological dimension of vulnerability and excluded socio-economic dimension of an area. On the contrary, researchers including Armas and Gravis (2013); Martins, de Silva and Cabral (2012); Walker et al. (2014), Shirley, Boruff and Cutter (2012), Pelling (2012) in their researches highly focused on the social dimension of vulnerability of natural hazard and undervalued the other dimensions. At city scale, especially in case of cities of developing nations, it is essential to combine all dimensions of earthquake vulnerability to get a complete picture of overall vulnerability situation and its spatial implications to devise appropriate development control mechanism and resource targeting. Moreover, the studies mentioned above are not land use specific which is a major short coming for undertaking any city level land use micro-zonation, since vulnerability significantly varies with the pattern of land use also. This study endeavours to assess the land use specific earthquake vulnerability of Mymensingh City combining all dimensions of vulnerability including structural, geological, socio- economic and systematic dimensions.

1.3. Methods of Earthquake Vulnerability Assessment

While assessing overall vulnerability, it is always difficult to find an appropriate methodology since most of the contemporarily developed methods cannot integrate revealed and stated preference data at a time. The data type varies along with the vulnerability dimensions considered. Most of the structural, systematic or geological data of earthquake vulnerability are revealed preference whereas socio-economic data are both stated and revealed preference data. VahidiFard et al. (2017), Bessason and Bjarnason (2016) analysed the seismic risk of an area using time series data and damage data of previous high magnitude earthquake. Unavailability of data restricts the use of this method in developing nations like Bangladesh. Whitman et al. (1973), Braga et al. (1982), Lantada et al. (2010) used damage probability matrix to evaluate the earthquake risk which only considered the structural vulnerability and requires post-earthquake building damage statistics. Freeman et al. (1975) used the Capacity Spectrum Method (CSM) to evaluate probable seismic vulnerability by developing a capacity curve and demand curve which is a very complex methodology. Federal Emergency Management Agency (2015) has developed a method of rapid visual screening (RVS) to assess the seismic vulnerability which does not require historical or damage data of the previous earthquake but requires every detail of building stock which is very time and resource consuming. There are several other methods such as Non-linear Dynamic Analysis (Fajfar, 2000), Vulnerability Index Method (Lantada, 2010), Failure Mechanism Identification and Vulnerability Evaluation (FaMIVE) method (Formisano, Mazzolani &Indirli, 2010), etc. available for seismic damage evaluation. But all these methods are complicated, time-consuming, require high-level expertise and data support, and most importantly all of them are structural vulnerability component biased. Methods of analysis deployed in many of the reported vulnerability analysis are very complex requiring specific skill and expertise which may not be inplace for many developing countries.

Moreover, most of the reported works on earthquake vulnerability are not land use specific. Therefore, a simple but efficient methodology which can incorporate all the issues mentioned above of earthquake vulnerability assessment is needed for the use in the planning process of cities of developing nations. Multi-criteria decision making (MCDM) is the simplest and efficient methods used by researchers to integrate all dimensions of vulnerability as it can solve complex decision-making covering a wide range of choices and prioritising of decision-making alternatives (Rezaie and Panahi,2015). Analytical Hierarchy Process is the most renowned and comprehensive MCDM procedure which can integrate both stated and revealed preference data simultaneously and hierarchically solves complex decision-making issues by developing a pairwise comparison matrix. Weighted Linear Combination (WLC), another simple additive MCDM method, generally used with AHP method to get a composite score by multiplying the weight of the criteria and sub-parameters.

In this paper, spatial variations of earthquake vulnerabilities of the residential neighbourhoods of Mymensingh City have been assessed by integrating an index-based approach and GIS analysis. Analytical hierarchy process (AHP) and Weighted Linear Combination (WLC) methods have been used to develop an index combining four dimensions of vulnerability. At first, four different indices, viz., structural vulnerability index, socio-economic vulnerability index, geological vulnerability index and systematic vulnerability index are developed using expert opinions based AHP method. Then a composite index is developed using WLC method combining all four indices based on expert opinions and spatial variation of earthquake vulnerability among residential neighbourhoods of Mymensingh are analysed and visually presented in the map using GIS technology. Finally, the result obtained from this study has been compared with the previously reported assessments of the same study area done by CDMP-II and Sarker et al. (2009) using Cohen kappa statistics and confusion matrix. All results are found to be reasonably close which justifies the validity of the current approach.

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3. Methodology

3.1. Study Area

The city of Mymensingh is the oldest municipality and latest administrative division of Bangladesh, which is located in the northern part of the country (24°45' N latitude and 90°23'E longitude) on the bank of old Brahmaputra River. The city established in 1787 and became a municipality in 1869, has an area of 2.73 sqkm. has a population of 258,040 (Male-132,123, Female-125,917) and has a population growth rate of 1.82% (BBS, 2011). The city experienced earthquakes in the past including 1762 earthquake (7.5 Mw) originated from the Madhupur tract in which the course of the river Brahmaputra changed dramatically and the Great Indian earthquake of 1897 (8.7 Magnitude) in which the whole Mymensingh City was collapsed (CDMP, 2014). There are 21 administrative wards, and 241 residential neighbourhoods in Mymensingh city (**Fig. 1**), delineated based on metal space mapping during the preparation of the Mymensingh Strategic Development Plan (MSDP) sponsored by the Comprehensive Disaster Management Program (Phase-II) of the Government of Bangladesh.

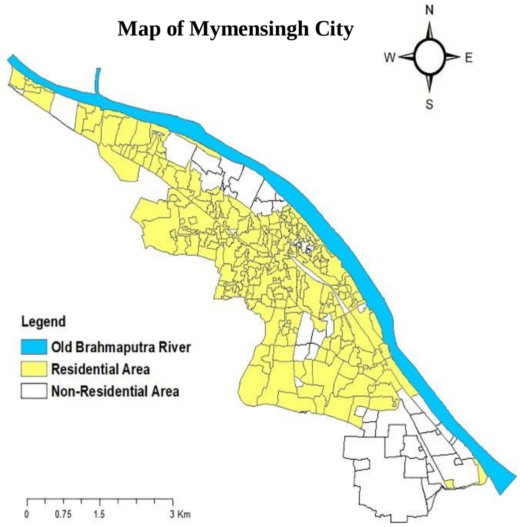

Fig. 1: Residential neighborhoods of Mymensingh city

3.2. Selection of Parameters of Earthquake Vulnerability Assessment

In this study, 23 influential earthquake vulnerability parameters have been selected based on diligent literature review, expert opinion and by analysing available data, under four vulnerability dimensions, viz., geological, structural, socio-economic and systematic vulnerability.

3.2.1. Geological earthquake vulnerability parameters

Geological parameter refers to the factors related to the earth that affects the earthquake vulnerability of an area. The geological parameters considered in this study are shown in **Table *1***.

Table 1 Geological Earthquake Vulnerability Parameters

Parameter	Vulnerability Level			Supporting Literature
	Low	Medium	High	
Soil Type	Hard Soil	Stiff Soil	Soft Soil	Isihita and Khandakar2010; Sarvar, Amini, and Laleh-Poor2011; Vicente et al.2010; Maddox,2015;
Peak Ground Acceleration	0.346485 - 0.369287	0.369288 - 0.392051	0.392052 - 0.410747	Rezaie and Panahi2015; Habibi et al.2014; Peek-Asa et al.2003; Moradi, Delavar and Moshiri,2014
Shear Wave Velocity	More than 360 m/s	180m/s to 360 m/s	less than 180m/s	Capilleri, Maugeri and Raciti, 2010; Martin and Diehl,2004

This study excludes some other most critical geological parameters including earth slope, depth of water table, etc. due to data unavailability or rare existence in Mymensingh city.

3.2.2. Systematic Earthquake Vulnerability Parameters

One of the influential earthquake response issues in cities is the accessibility of residential neighbourhoods to different infrastructure and service facilities such as medical care facilities, open spaces, road networks, fire service, emergency shelter, etc. (Raizee and Panahi,2015). These physical accesses to critical facilities are referred as systematic vulnerability, focusing on rapid post seismic building usability assessment, number, and quality of temporary shelters, accessibility to work sites and services from temporary shelters and vulnerability of strategic public facilities (Atun and Menoni, 2014). Parameters considered for assessing systematic earthquake vulnerability are shown in **Table 2**.

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Table 2 Systematic Earthquake Vulnerability Parameters

Parameter	Vulnerability Level			Supporting Literature
	Low	Medium	High	
Distance to hospital	<500m	500m to 1km	>1km	Daneshvar, Rezayi, and Khosravi2013; Bac–Bronowicz and Maita, 2001
Distance to Fire Service	<1km	1km to 1km	>2km	Armas,2012; Scawthorn, Eidinger& Schiff, 2005
Distance to Emergency center	<500m	500m to 1km	>1km	Rezaie and Panahi,2015;Atun and Menoni, 2014; Alam and Haque 2018
Distance to Evacuation Route	<500m	500m to 1km	>1km	Bac–Bronowicz and Maita, 2001, Meshkini, Habibi and Alizadeh, 2013

3.2.3. Structural Earthquake Vulnerability parameters

Structural earthquake vulnerability parameter refers to the factors that relate to the built up environment such as buildings, bridge, road, etc. Structural parameters have a great influence on earthquake vulnerability and damage potential of a neighbourhood. In this study, eight most influential structural parameters are considered to assess the earthquake vulnerability of Mymensingh city which is shown in **Table 3**.

Table 3 Structural Earthquake Vulnerability Parameters

Parameter	Vulnerability Level			Supporting Literature
	Low	Medium	High	
% of poor building	< 25%	25 to 50%	> 50%	Moradi, Delavar and Moshiri(2014), Ghajari et al.(2017), Güzey et al.(2013), Ebrahimian-Ghajari et al.(2015)
% of BFL Building (masonry building with flexible roof) building	< 25%	25 to 50%	> 50%	Isihita and Khandakar(2010), Rahman, Ansary and Islam (2015)
Average Building Storey	1 Stroey	2 Storey	≥3 story	Sarris et al.,(2009), Vicente et al., (2010), Nath et al., (2015), Isihita and Khandakar(2010)
Average Road Width(ft.)	>16ft	8ft to 16ft	<8ft	Isihita and Khandakar(2010) ,Ghajari et al., (2017)
Building Density/acre	<10 building	10 to 15 building	>15 building	Zebardast (2012), Armaş (2012) , Martins, e Silva and Cabral,(2012)
Irregular Shape Building (%)	<10 %	10 to 15 %	>15 %	Güzey et al., (2013), Ferreira et al.,(2013), Maio et al.,(2015)
Pounding Possibility (%)	<10 %	10 to 15 %	>15 %	Jeng and Tzeng, (2000), Ahmed, Jahan and Alam,(2014)
Heavy Overhanging (%)	<10 %	10 to 15 %	>15 %	Ahmed, Jahan and Alam, (2014), Güzey et al.(2013)

Some other most crucial structural vulnerability parameters such as- soft storey, short column, the age of a building, lateral stiffness, existence of the shear wall, etc. are excluded from this study due to data unavailability or rare existence in residential neighbourhoods of Mymensingh city.

3.2.4. Socio-economic Earthquake Vulnerability Parameters

Unfortunately, during recent years, earthquake experts have not paid enough attention to socio-economic dimensions of earthquake vulnerability, and therefore only a handful of studies have been conducted in this regard. The socio-economic vulnerability parameters that are considered in this study are mentioned in **Table 4**.

Table 4 Socio-Economic Earthquake Vulnerability Parameters

Parameter	Vulnerability Level			Supporting Literature
	Low	Medium	High	
Percentage of child Population(<5 yr)	<5%	5 % to 10%	>10%	Zebardast,(2012), Rahman, Ansary and Islam,(2015)
Percentage of Elderly population(65+yr)	<2.4%	2.4% to 4.8%	>4.8%	Zebardast, (2012), Armaş and Gavriş,(2013)
Women population (%)	<25%	25% to 50%	>50%	Armaş et al.,(2017), Schmidtlein et al.,(2011)

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Literacy Rate	>70%	35% to 70%	<35%	Güzey et al., (2013), Islam, Swapan and Haque, (2013); Fatemi et al. 2017
Average Household income	>16475BDT	8238 BDT to 16475 BDT	<8238BDT	Armaş and Gavriş,(2013), Duzgun et al.,(2011); Rahman, Ansary and Islam,(2015)
Population Density/acre	<100 person/acre	100 to 150 person/acre	>150 person/acre	Barbat et al.,(2010), Nath et al.,(2015), Armaş and Gavriş,(2013)
Average Household size	<2.21	2.21 to 4.41	>4.41	Schmidtlein et al.,(2011), Armaş,(2012),Güzey et al.,(2013)
Religion	Islam	Sanatan	Others	Atun and Menoni,(2014), de Ruiter et al.,(2017)
Economically dependent population (%)	<25%	25% to 50%	>50%	Kalaycioglu, 2006; Armaş et al.,(2017), Moradi, Delavar and Moshiri,(2014), Martins, e Silva and Cabral,(2012), Walker et al., (2014)

3.3. Method

3.3.1. Analytical Hierarchy Process

In this study, the Analytical Hierarchical Process (AHP) is used to develop indices to measure spatial variations of earthquake vulnerabilities of the residential neighbourhoods of Mymensingh city. AHP is a widely used multi-criteria decision-making method (MCDM) of vulnerability assessment due to its simplicity and rationality (Alam and Mondal,2018) which considers both qualitative and quantitative parameters to develop a hierarchical solution in decision making among various alternatives and its sub-category. Analytical Hierarchical Process (AHP) uses the opinions of experts to weight vulnerability parameters and sub-parameters, and as a result, transparency and consideration of local socio-economic condition, special conditions of the study area are ensured that global indices cannot consider (Füssel, 2010). Three major steps are followed by the AHP model in assessing earthquake vulnerability which are;

First step- The first step is the generation of binary comparison matrices on a scale of 1–9 developed by Saaty, (1980) in which 1 indicating that the two parameters are equally important, and, 9 implying that one parameter is more important than another. The scale of importance is shown in **Table 5**.

Table 5: Magnitude of importance for pairwise comparison (Saaty, 1980)

Decreasing Relative Intensity of Importance ←								Equally Important	Increasing Relative Intensity of Importance →							
1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9

Second step- In the second step, weights of different parameters are calculated from the row-multiplied value (RMV), in unnormalized and normalised values using the following eq-1 and 2.

$$\text{Unnormalized value, } m_i = \sqrt[n]{RMV} \qquad (1)$$

$$\text{Normalized value} = \frac{\text{mi}}{\sum_{i=1}^{n} mi} \qquad (2)$$

Here m_i refers to the unnormalized value of the i^{th} parameter and n represents the total influential parameters.

Third step- The most important issue in weighting the factors is the consistency between judgments and weights which is done in the 3rd step. The consistency is measured using consistency index and consistency ratio using eq-3 &4. If the consistency ratio is greater than 0.1, the matrix has inconsistency, and pairwise comparison must be reperformed between indicators and sub-indicators.

$$\text{Consistency index, CI} = \frac{L-n}{n-1} \qquad (3)$$

$$\text{Consistency ratio, CR} = \frac{CI}{RI} \qquad (4)$$

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L represents the Eigenvalue of the pairwise comparison matrix, and RI is the random inconsistency index, which has some developed value and depends on the number of vulnerability assessment parameters (N). The variations of RI value for different parametersare shown in **Table 6**.

Table 6: Random inconsistency indices (RI) for n = 1, 2, . . ., 12. (Saaty, 1980)

N	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54

3.3.2. Weighted Linear Combination

WLC technique is an additive weighting method in which a weight is assigned to each factor at the initial stage. The weight of vulnerability parameters determined by using AHP method based on expert opinions is used with their corresponding individual standardised criteria as input for the WLC aggregation method. In the final step in developing the earthquake vulnerability map, all the weighted layers are combined using a weighted overlay technique in the ArcGIS platform. The final vulnerability score is determined according to the linear addition of given weight to all parameters and their sub-categories (according to Eq. 5).

$$W=\sum_{j=1}^{n} Wjwij \qquad (5)$$

Here W shows the index value of each neighbourhood in vulnerability map, W_j shows the normalised weight of each parameter, w_{ij} is the weight of i_{th} sub-category related to the j_{th} parameter and n denotes the total number of influential parameters.

In this study, comparison matrices of 23 earthquake vulnerability parameters (3 Geological, 8 Structural, 8 Socio-economic and 4 Systematic vulnerability parameters) are developed based on judgments of 3 experts. Then, to aggregate opinions into one matrix, geometric means of the expert's opinion are calculated (Shown in **Table 7**,**Table 8**,**Table 9** and **Table 10**). The aggregated comparison matrix of earthquake vulnerability assessment used in this study is shown in **Table 11**.

Table 7: Pairwise comparison matrix, weight and consistency ratio of Geological earthquake vulnerability parameters based on the expert’s opinion

Geological Parameters	PGA	Soil Type	SWV	Weight
Peak Ground Acceleration (PGA)	1	0.63	1.59	.318
Soil type	1.59	1	2	.466
Shear Wave Velocity (SWV)	0.63	.5	1	.216
(Consistency Ratio=0.003, Random inconsistency=0.58)				

Table 8: Pairwise comparison matrix, weight and consistency ratio of Systematic earthquake vulnerability parameters based on the expert’s opinion

Systematic Parameters	Hospital	Fire service	Shelter	Route	Weight
Distance to hospital	1	0.55	1.82	1.26	0.253
Distance to fire service	1.82	1	1.82	1.82	0.374
Distance to emergency shelter	0.55	0.55	1	0.69	0.162
Distance to Evacuation route	0.79	0.55	1.44	1	0.211
(Consistency Ratio=0.014, random inconsistency=0.9)					

Table 9: Pairwise comparison matrix, weight and consistency ratio of structural earthquake vulnerability parameters based on the expert’s opinion

Structural Parameters	1	2	3	4	5	6	7	8	Weight
1. Building Storey	1	0.29	0.55	0.29	0.69	0.69	0.63	1.82	0.074
2. Poor conditioned building	3.44	1	1.44	0.69	1.14	1.25	0.87	1.25	0.143
3. BFL building	1.81	0.69	1	0.31	0.48	0.63	0.5	1.82	0.088
4. Pounding	3.44	1.44	3.22	1	1.59	2.62	1	2.28	0.213

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5. Irregular shaped building	1.45	0.88	2.08	0.63	1	1	0.55	1.26	0.116
6. Overhanging	1.45	0.8	1.59	0.38	1	1	0.55	3.12	0.118
7. Road width	1.59	1.15	2	1	1.82	1.82	1	2.88	0.178
8. Building Density	0.55	0.8	0.55	0.44	0.79	0.32	0.35	1	0.068
(Consistency Ratio=0.034, Radom Inconsistency=1.41)									

Table 10: Pairwise comparison matrix, weight and consistency ratio of Socio-economic earthquake vulnerability parameters based on the expert's opinion

Socio-economic parameters	1	2	3	4	5	6	7	8	9	Weight
1. Household income	1	2.62	1.26	0.19	0.19	1.26	0.32	1.26	3.56	0.072
2. Household size	0.38	1	0.33	0.18	0.18	0.44	0.26	0.38	1.26	0.034
3. Population density	0.79	3.00	1	0.28	0.28	1.26	0.40	1.26	3.56	0.077
4. Elderly population	5.19	5.59	3.56	1	1.00	3.00	2.00	3.56	5.59	0.258
5. Child Population	5.19	5.59	3.56	1.00	1	3.00	2.00	3.30	5.19	0.255
6. Dependent population	0.79	2.29	0.79	0.33	0.33	1	0.32	1.44	3.56	0.073
7. Women (%)	3.11	3.91	2.52	0.50	0.50	3.11	1	2.08	4.64	0.162
8. Literacy rate (%)	0.79	2.62	0.79	0.28	0.30	0.69	0.48	1	3.00	0.068
(Consistency Ratio=0.024, Radom Inconsistency=1.41)										

Table 11: Aggregated Pairwise comparison matrix, weight and consistency ratio of composite earthquake vulnerability parameters based on the expert's opinion

Composite index	Geo-logical	Structural	Systematic	Socio-economic	Weight
Geo-logical	1	2.29	2.29	3.92	0.459
Structural	0.45	1	1	2.62	0.223
Systematic	0.45	1	1	2.62	0.223
Socio-economic	0.26	0.38	0.38	1	0.095
(Consistency Ratio=0.01, Random inconsistency =0.9)					

In this study 24 vulnerability parameters are weighted on a scale of 0 to 1. It is essential to assign a weight to every sub-category of the abovementioned 24 parameters. Providing different weight to every sub-factor is a complex task and time consuming also. This study classifies each of the vulnerability parameters into three categories viz., low, medium and highly vulnerable. Based on the recommendation of the experts and literature review (Islam, Swapan, and Haque, 2013), the subcategories are weighted in a scale of 0 to 1 where the weight of highly vulnerable category is 0.500, the medium vulnerable category is 0.333, and the low vulnerable category is 0. 167. The framework used for earthquake vulnerability assessment of Mymensingh city is shown in **Fig.2**.

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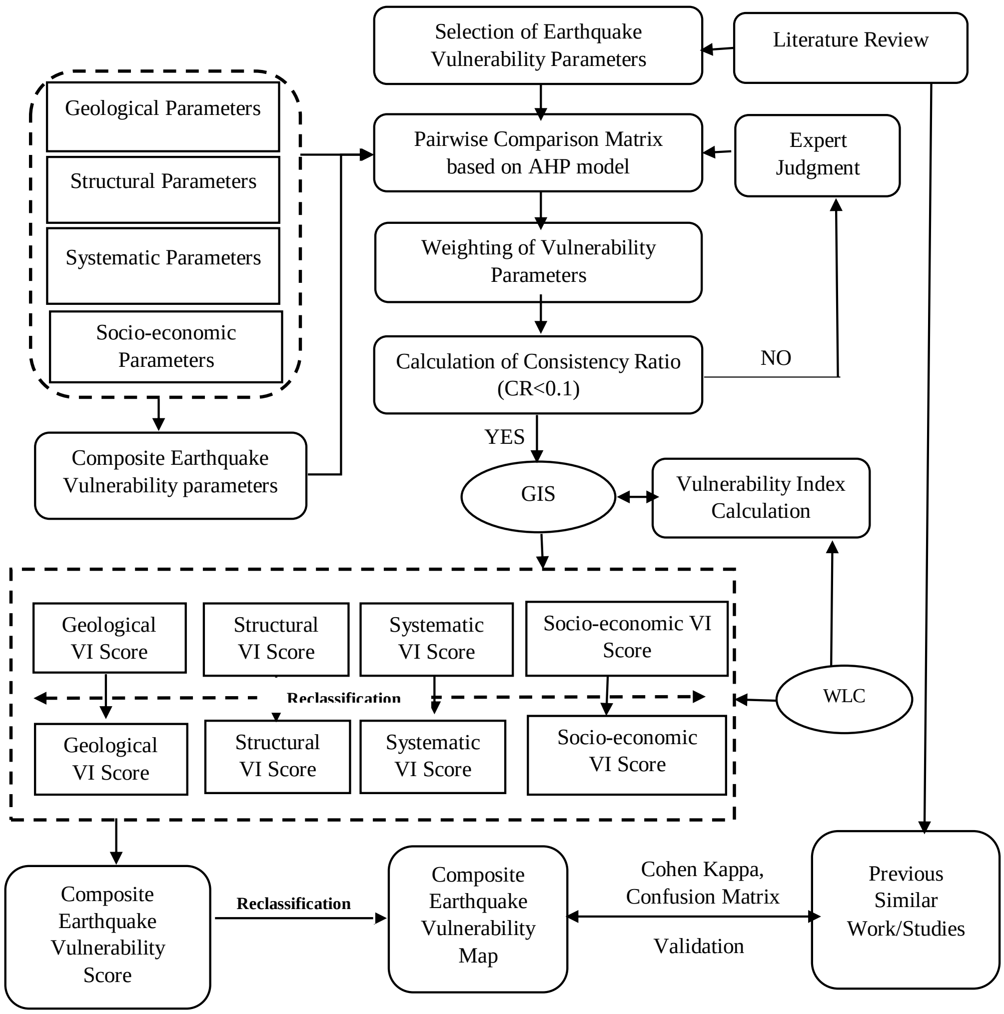

Fig. 2: Framework of composite earthquake vulnerability assessment

3.4. Data Source

In this study, Databases of Mymensingh Strategic Development Plan (MSDP), 2011-2031 prepared under Comprehensive Disaster Management Programme (CDMP)-II of the Ministry of Disaster Management and Relief and Urban Development Directorate (UDD), Ministry of Housing and Public Works, Bangladesh (UDD,2016) has been used. Data of structural parameters are collected from the physical feature database, land use database, and road network database of MSDP. Data of geological and socio-economic parameters are collected from the geological and socio-economic survey database of MSDP respectively. To calculate systematic vulnerability index, distances of each of the neighbourhoods from important facilities are calculated through employing a Network Analyst tool of proprietary ArcGIS, using point feature database of MSDP.

3.5. Data Analysis and Vulnerability Maps Preparation

In this study, the Analytical Hierarchical Process has determined weights of different factors and sub-factors of seismic vulnerability. All gathered data has been processed in the following sequential order: Firstly, the socio-economic data and vulnerability scores of earthquake vulnerability of Mymensingh city has been stored in SPSS environment and converted into Microsoft Access database to make them usable for analysis in GIS software

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(ESRI product ArcGIS has been used). Secondly, neighbourhood wise data of structural and geological earthquake vulnerability of Mymensingh city have been extracted using geo-processing in the ArcGIS environment. Then, the databases are joined with the residential neighbourhood map of Mymensingh city map in vector-based GIS. The centre points of each residential neighbourhoods are delineated using the conversion tool in ArcGIS. In the next step, the maps have been reproduced for determining systematic vulnerability parameters using closest facility function under Network Analyst tool in proprietary GIS software to identify neighbourhoods which are inaccessible or possess less accessibility to the hospital, fire service, emergency shelter, and evacuation route. The score of systematic earthquake vulnerability is reclassified and joined with the residential neighbourhood map of Mymensingh city in vector-based GIS. Finally, the composite earthquake vulnerability map of the residential neighbourhoods of Mymensingh city is produced using WLC method based on reclassified composite vulnerability score in the ArcGIS environment (**Fig.3**).

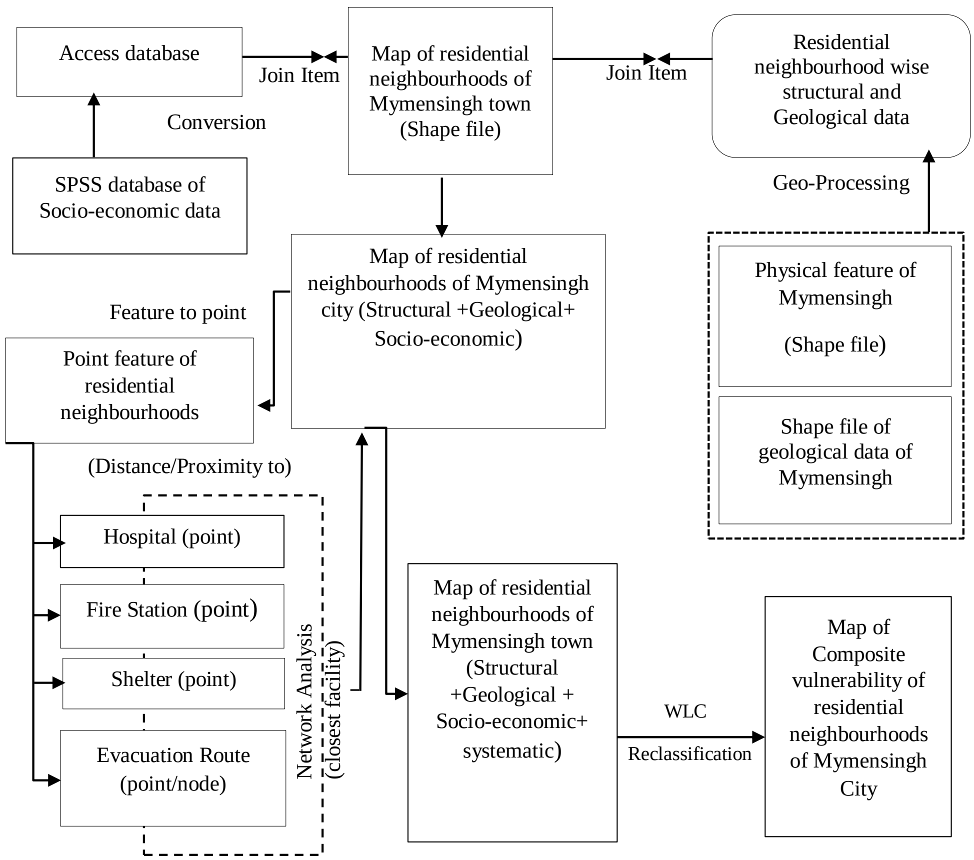

Fig. 3: Steps in GIS analysis

3.6. Validation Methods Adopted

Cohen kappa statistics and confusion matrix methods are used in this study to compare the result of this current study with other similar studies.

The Cohen kappa statistic, well-recognised accuracy assessment algorithm mostly used to assess the performance of the classifier, is a metric that compares an Observed Accuracy with an Expected Accuracy and illustrates the agreement between two accuracy results on a scale of 0 to 1. Cohen kappa score 1 indicates complete agreement and values 0 indicate no agreement between the two results. In this study, a comparison

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between the result of other similar studies (observed accuracy) and the result of this study (expected accuracy) are done using the Cohen kappa statistic. The vulnerability map of other similar studies and the composite vulnerability map of the current research need to be converted into 1m× 1m raster grid to measure the agreement using Cohen kappa. Cohen kappa statistics follow several steps. In the first step, a 2×2 metric is developed based on the results, and observed accuracy (P_o) is determined by summing the total number of agreement and dividing it by the number of total cells. In the second step, expected accuracy (P_e) is calculated by multiplying the probability of agreement between high vulnerability cells of two similar studies with the probability of agreement between low vulnerability cells. In the final step, the Cohen kappa score is calculated using the following equation (6).

$$\text{Cohen Kappa} = \frac{Po-Pe}{1-Pe} \quad (6)$$

Here, P_0 and P_e represents observed accuracy and expected accuracy respectively. Pontius (2002) and Sousa et al. (2002) suggested that kappa score less than 0.4 indicates poor performing models, 0.4 to 0.6 are fair,0.6 to 0.8 are good, and kappa score greater than 0.8 represent excellent agreements between expected model and observed dataset.

Confusion matrix, also known as error matrix, is a spatial contingency table used to describe the performance of a classification or prediction model on a test sample which true values are known and predicted or classified sample. This table provides four different combinations of predicted and actual values. True Positive (TP) indicates the prediction is positive and it's true whereas true negative (TN) means prediction is negative and its true. On the contrary, false positive (FP) signifies the prediction is positive and its false whereas false negative (FN) denotes prediction is negative and its false. Confusion matrix can be easily interpreted using **Fig. 4**.

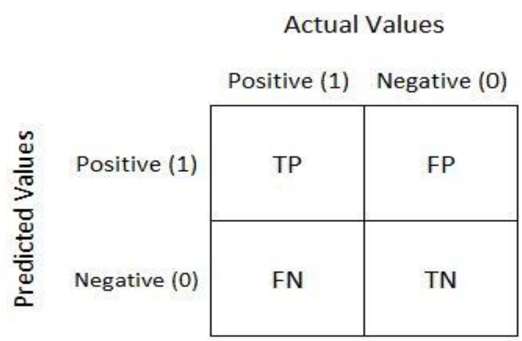

Fig. 4: Confusion Matrix classification system

4. Result and Discussion

The spatial variations of vulnerabilities are analyzed and shown in maps in 3 vulnerability zones, viz., high, medium and low. From the city planning context for better understanding of the priorities of risk mitigation activities, it is also essential to identify the relative importance of vulnerability parameters influencing earthquake vulnerability of the neighbourhoods and therefore, have also been discussed in the following section as well.

4.1. Geological Vulnerability

According to the geological dimensions, vulnerability analysis shows that 44 residential neighbourhoods are in highly earthquake-vulnerable, 175 residential neighbourhoods are in medium earthquake-vulnerable; and only 22 neighbourhoods fall in low vulnerable zones in Mymensingh City. The spatial variation of geological earthquake vulnerability of residential neighbourhoods of Mymensingh City is shown in **Fig.5**.

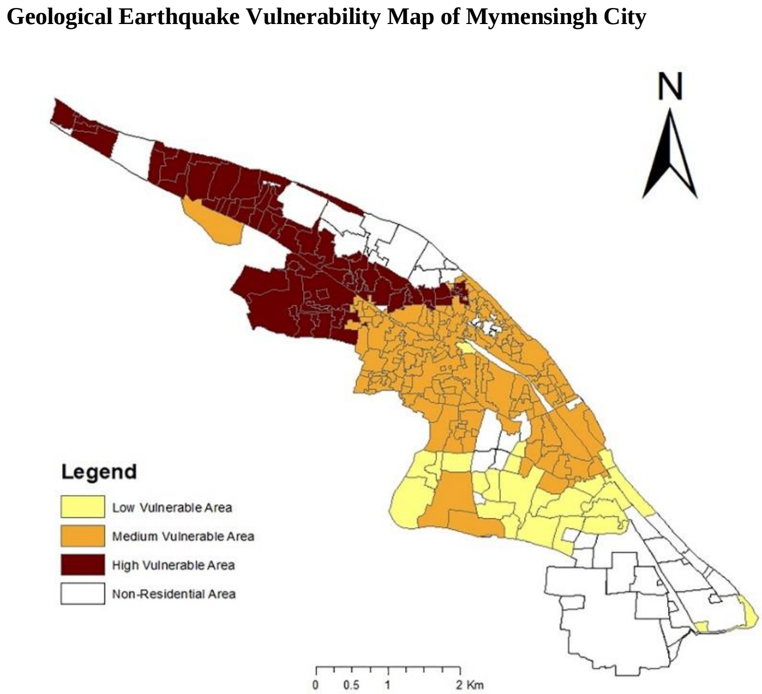

Fig. 5: Geological Vulnerability Map of Residential Neighbourhoods of Mymensingh City

Fig. 6 shows the influences of different geological parameters on earthquake vulnerability (on a scale of 0-1). It is observed that Soil type has the highest (0.5) influence among the parameters followed by PGA (0.32). Shear Wave Velocity (0.18) has the least influence among the three parameters used in this analysis.

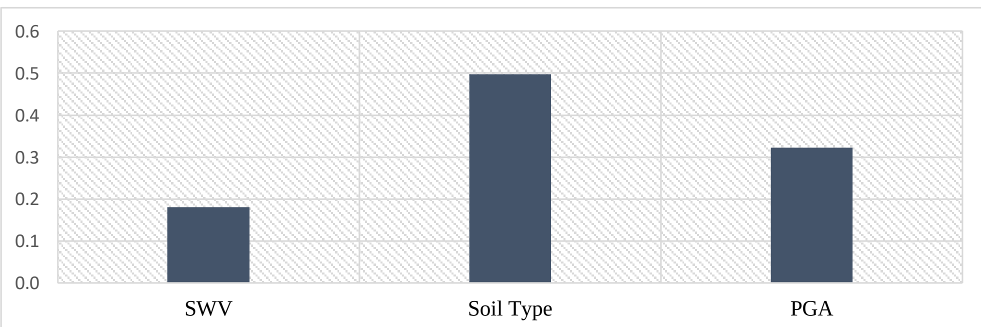

Fig. 6: Influence of Geological-Parameters on Earthquake vulnerability in Mymensingh city

4.2. Systematic Vulnerability

The distances of the hospital, fire station, emergency shelter and emergency evacuation route from the geometric centre of each neighbourhood are considered and analysed in ArcGIS environment to assess the spatial variation of systematic vulnerability. The result shows that 88 residential neighbourhoods of Mymensingh city are stuated in the high earthquake-vulnerable zone as far as a systematic dimension of earthquake vulnerability is concerned with feeble connections with these four emergency facilities. About 90 residential neighbourhoods of Mymensingh city fall in the medium systematic vulnerablezone. Only 63

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residential neighbourhoods, which have close spatial links with the above mentioned facilities, are in the low systematically earthquake-vulnerable zone (**Fig. 7).**

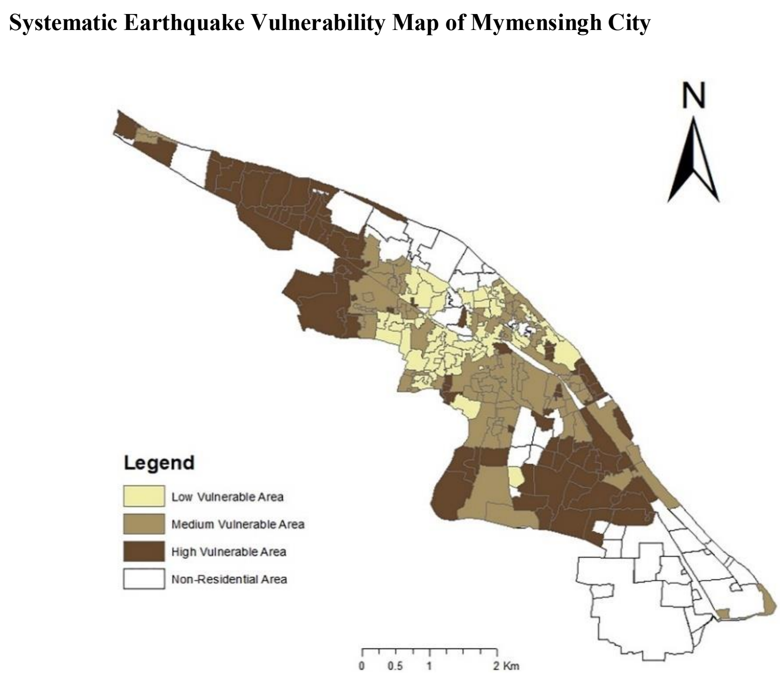

Fig.7: Systematic Vulnerability Map of Residential Neighbourhoods of Mymensingh City

The parameter wise assessment of systematic earthquake vulnerability of Mymensingh City on a scale of 0-1 is shown in **Fig.8**. According to **Fig.8**, most of the residential neighbourhoods in Mymensingh City are highly vulnerable due to their long distances from fire service stations (0.43), hospitals (0.24) and emergency shelter (0.2) respectively.

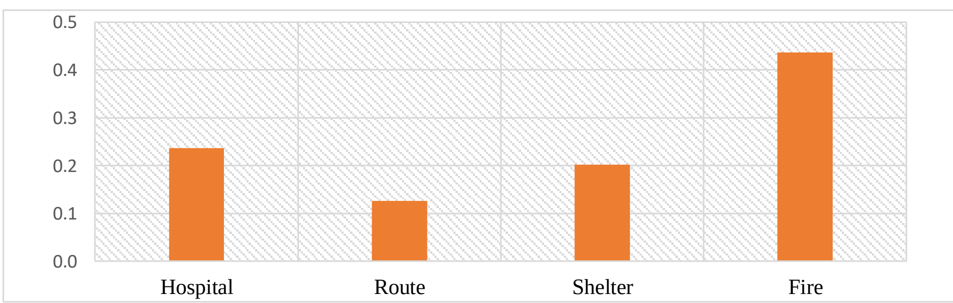

Fig. 8: Influence of Systematic Parameters on Earthquake vulnerability in Mymensingh city

4.3. Structural Vulnerability

From the analysis, it is found that eight residential neighbourhoods of Mymensingh city are highly structural vulnerable, 54 residential neighbourhoods are medium structural vulnerable and 179 residential neighbourhoods are low structural vulnerable. It is interesting to observe that in Mymensingh city neighbourhoods, which are structurally vulnerable, are not geologically vulnerable. The reason behind this difference is the location of the

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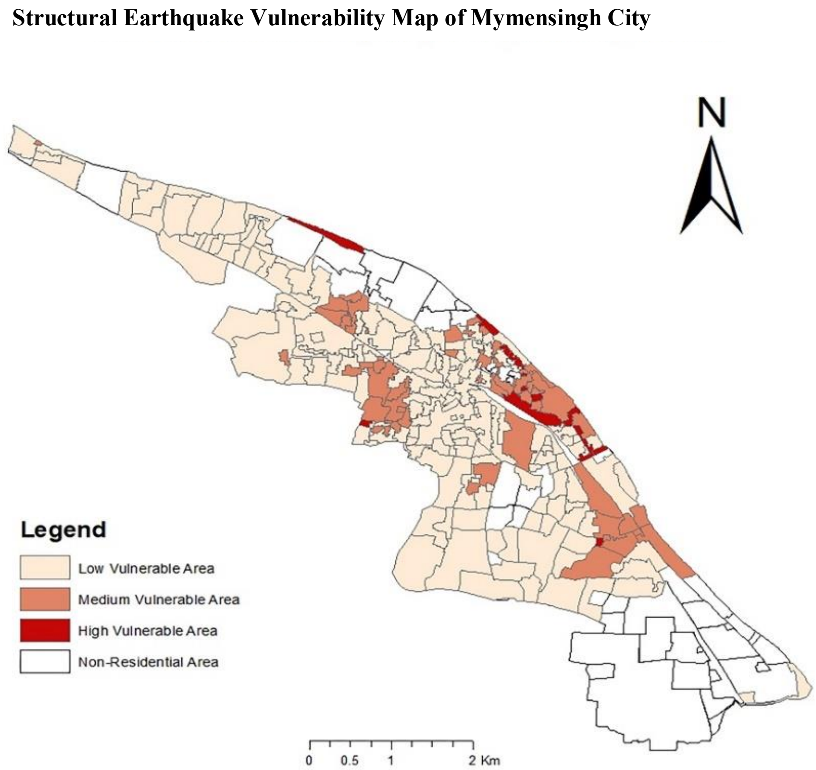

Fig. 9: Structural Earthquake Vulnerability Map of Mymensingh City

CBD area in the middle part of the city which is medium geologically vulnerable. In Mymensingh city, the vulnerability parameters that make a city structurally vulnerable are comparatively high in the residential neighbourhoods within or close to the CBD area than the neighbourhoods of other parts of the city. The spatial variation of earthquake vulnerability of the residential neighbourhoods of Mymensingh city according to structural dimension is shown in **Fig.9.**

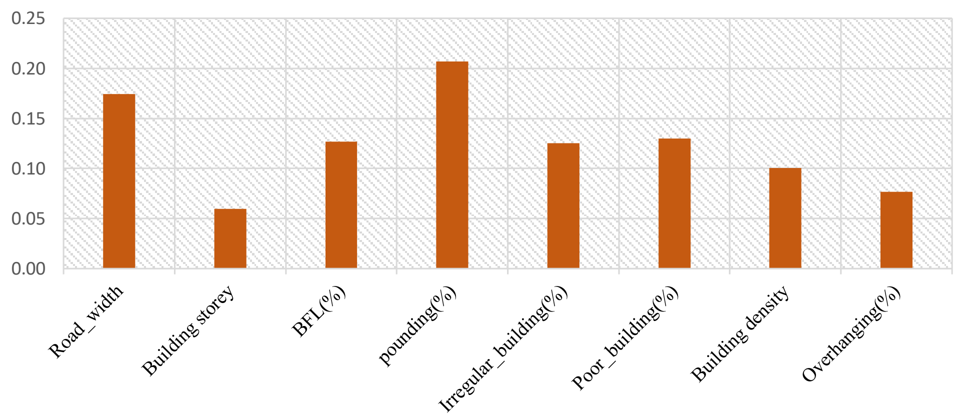

Fig. 10: Influence of Structural Parameters on Earthquake vulnerability in Mymensingh city

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It is critical to know which parameter has the most influence onthe structural vulnerability to prioritise city planning implications. **Fig.10** illustrates that the influence of 8 structural vulnerability parameters on overall structural vulnerability (measured on a scale 0-1) and it is found that high pounding possibility (0.21), low road width (0.17), a high percentage of poor building (0.13), irregular (0.13) and BFL buildings (0.13) respectively are the primary reasons behind structural vulnerability in Mymensingh city.

4.4. Socio-economic Vulnerability

To get a complete picture of vulnerability situation of Mymensingh city, it is also essential to understand the socio-economic characteristics of people living in different neighborhoods of the city. The result shows that 75 residential neighbourhoods of Mymensingh City are highly earthquake vulnerable from the socio-economic context whereas 158 residential neighbourhoods are medium earthquake-vulnerable. Only eight residential neighbourhoods are in a low vulnerable category in Mymensingh City. The spatial distributions of socio-economic earthquake vulnerability in Mymensingh City are visually represented in **Fig. 11.**

Socio-Economic Earthquake Vulnerability Map of Mymensingh City

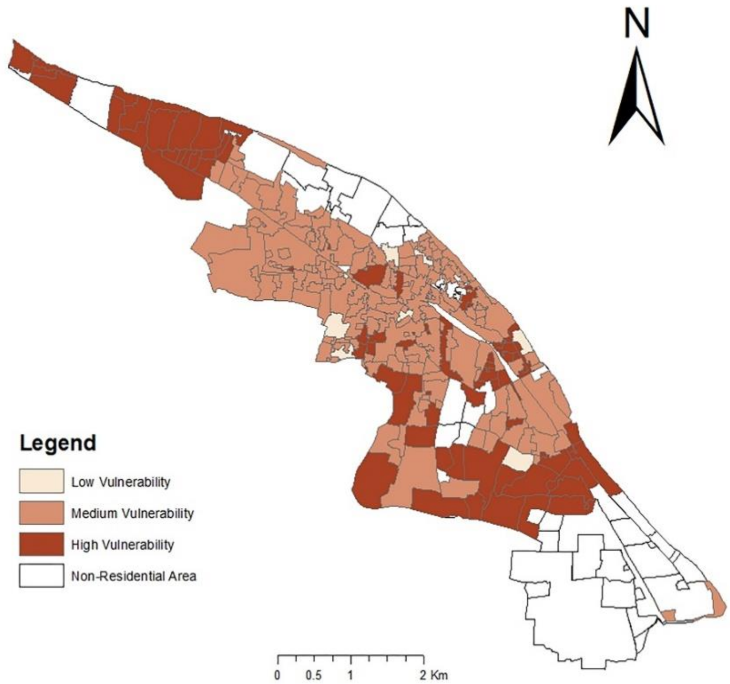

Fig.11: Socio-Economic Earthquake Vulnerability Map of Mymensingh city

The parameter wise socio-economic vulnerability analysis (**Fig.12**) of the residential neighbourhoods of Mymensingh City shows that mainly the city is socio-economically earthquake-vulnerable due to the high percentage of the elderly population (0.32), a high percentage of the child (0.24) and women population (0.16) and population density (0.07). Other parameters' contribution to socio-economic vulnerability is less than 0.05. As Mymensingh city is one of the oldest city and remarkable economic hub of the country since British colonial period, the percentage of the elderly population, child and women are higher in the neighbourhoods of the city than the national urban area average of Bangladesh (BBS,2010) which make its residential neighbourhoods more socio-economically vulnerable.

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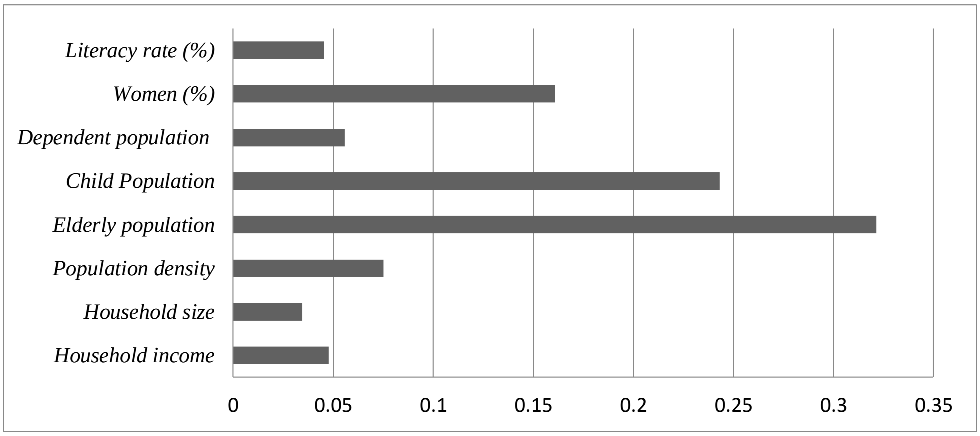

Fig.12: Influence of Socio-Economic parameters on Earthquake Vulnerability of Mymensingh City

405 **4.5. Composite Earthquake Vulnerability**

406 The result of composite earthquake vulnerability index shows that 51 residential neighbourhoods of
407 Mymensingh are highly earthquake-vulnerable from all four dimensions of vulnerability. About 123 residential
408 neighbourhoods are medium earthquake-vulnerable, and 67 residential neighbourhoods are in the low
409 earthquake-vulnerable category. Spatial distribution of composite vulnerability in residential neighbourhoods of
410 Mymensingh City is shown in **Fig.13**.

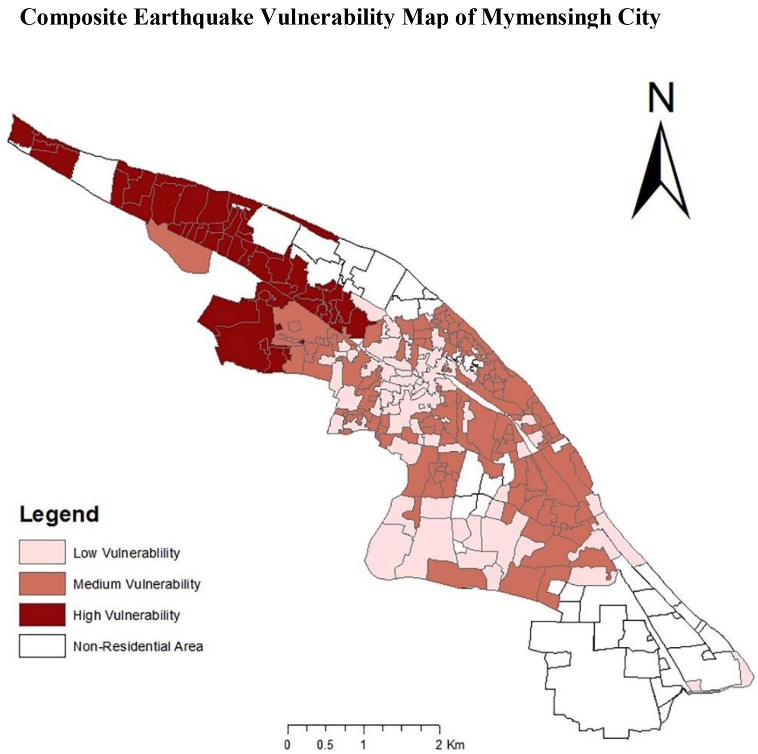

Fig.13: Composite earthquake vulnerability map of residential neighborhoods of Mymensingh city

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In this study, 24 most important earthquake vulnerability parameters are considered to assess earthquake vulnerability, and influence of each of the parameters on the composite earthquake vulnerability of Mymensingh City are analysed and shown on a scale of 0-1. The concerned city planning and development agencies may prioritise their earthquake risk reduction activities in Mymensingh City based on the influence of each of the parameters on earthquake vulnerability as shown in **Fig.14**.

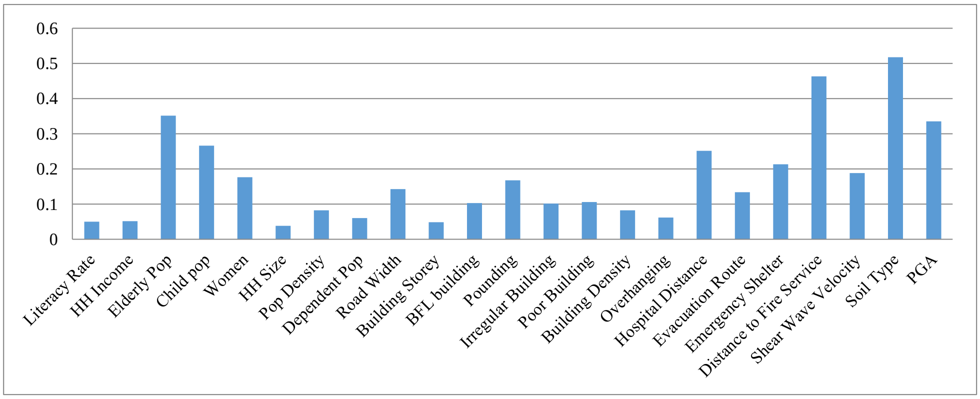

Fig.14: Influence of vulnerability parameters on composite earthquake vulnerability

According to the analysis, it is found that soil type (0.52), distance to the fire station (0.46), elderly population (0.35), Peak Ground Acceleration (0.34), child population (0.27) and distance to hospital (0.25) respectively are the topmost factors that make Mymensingh City highly earthquake-vulnerable. To be more specific, the existense of 90% soft soil, only one fire station, high PGA value, a high percentage of elderly and child population than national urban area average, spatial concentration of hospitals in the middle part of the city are the main reasion behind the earthquake vulnerability of Mymensingh city.

On the Contrary, household size (0.04), building storey (0.05), literacy rate(0.05), income per household (0.06) and overhanging (0.06) has less influence on high earthquake vulnerability of Mymensingh city. Explicitly, high percentage of muslim dominated neighbourhoods, small household size, high percentage of low rise buildings, high literacy rate and income, etc. parameters are responsible for the low and medium earthquake vulnerability of some residential neighbourhoods in Mymensingh.

5. Validation

The composite vulnerability map, produced as an output of this research, has been compared with the output simillar other assements to observe the accuracy of the adopted methodology and to validate the applied method. Comprehensive Disaster Management Program, phase-II (CDMP-II,2014) developed earthquake sensitivity map for Mymensingh city using HAZUS methodology during the preparation of Mymensingh Strategic Development Plan (MSDP), considering among other parameters PGA, spectral acceleration, foundation condition, soil type, amplification factor, high and low-rise structure sensitivity (Haque,2015). The earthquake sensitivity map developed by CDMP-II for Mymensingh city is shown in **Fig.15** in which the earthquake sensitivity of Mymensingh city is classified into two categories viz. 1st degree and 2nd-degree earthquake sensitivity. According to CDMP-II, 1st-degree earthquake sensitivity explicates the areas with high earthquake hazard risk, and 2nd-degree earthquake sensitivity indicates the areas with low earthquake hazard risk.

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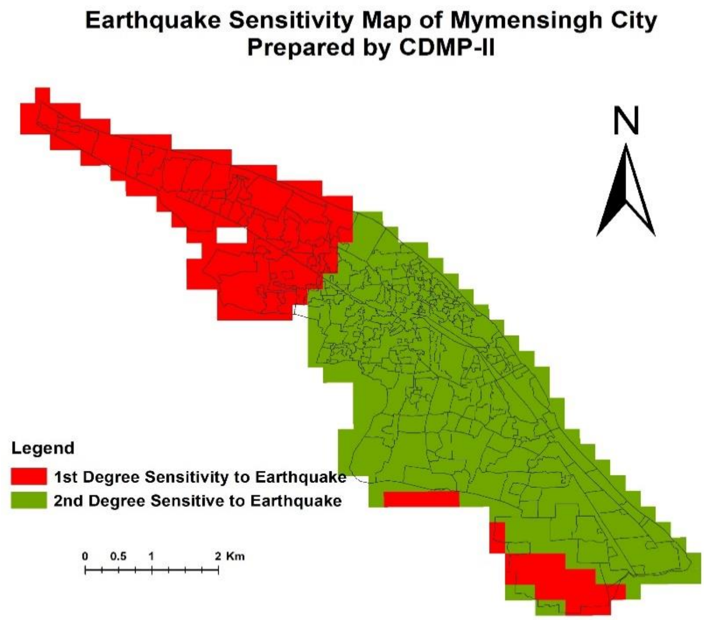

Fig.15: Earthquake sensitivity map developed by CDMP-II

Sarker, et al. (2009) did another work of earthquake risk assessment of Mymensingh city-based on SPT data of boreholes, peak ground acceleration, site amplification, liquefaction and took the earthquake of 1897 as a scenario event. In the seismic micro-zonation map of Mymensingh city, shown in **Fig.16,** high intensity indicates high vulnerability. To compare the result of this study with results of CDMP-II, the result of this study is classified into two categories viz. high earthquake vulnerability and low earthquake vulnerability where high earthquake vulnerability represents the same highly vulnerable neighbourhoods and medium with low vulnerable neighbourhoods jointly represent the low vulnerability. The result from CDMP-II (**Fig.15**) and Sarker et al. (2009) (**Fig.16**) has been compared with the result of this study **(Fig.13**) using Cohen kappa statistics and confusion matrix.

Applying equation (6), Cohen kappa score of this study, in comparison with CDMP-II is calculated, and the score is found to be 0.6 which explicates that there is 60% agreement between the two results. According to the kappa scale category, Cohen kappa score of this study falls in the good category which means there exist a good agreement between the result from CDMP-II and the result of this study. Cohen kappa score of this study, in comparison with Sarker et al. (2009) is found to be 0.53 indicating 53% agreement between two results and which could be considered fair according to the scale of Pontius (2002).

The earthquake sensitivity map developed by CDMP-II mainly considered geology and infrastructure related parameters and whereas in Sarker et al. (2009) only geological properties for seismic zonation was considered. In both the studies very little attention has been given to the socio-economic context of the study area. On the contrary, in the current study, vivid considerations have been given to the socio-economic dimensions of vulnerability along with other dimensions which could be the main reason for disagreement of vulnerability assessment among the mentioned results. The agreement and disagreement between high and low vulnerability residential neighbourhoods of the two abovementioned results can be easily illustrated through the use of confusion matrices.

Confusion matrix for CDMP-II map and vulnerability map of the current study is shown in **Fig.17**. Confusion matrix without normalisation shows 2970 (60%) highly vulnerable cells of vulnerability map of the current study are correctly classified and 1993 (40%) cells are falsely classified to low vulnerable zones which mean the highly vulnerable area of this study has 60 percent similarity with CDMP-II produced vulnerability map.

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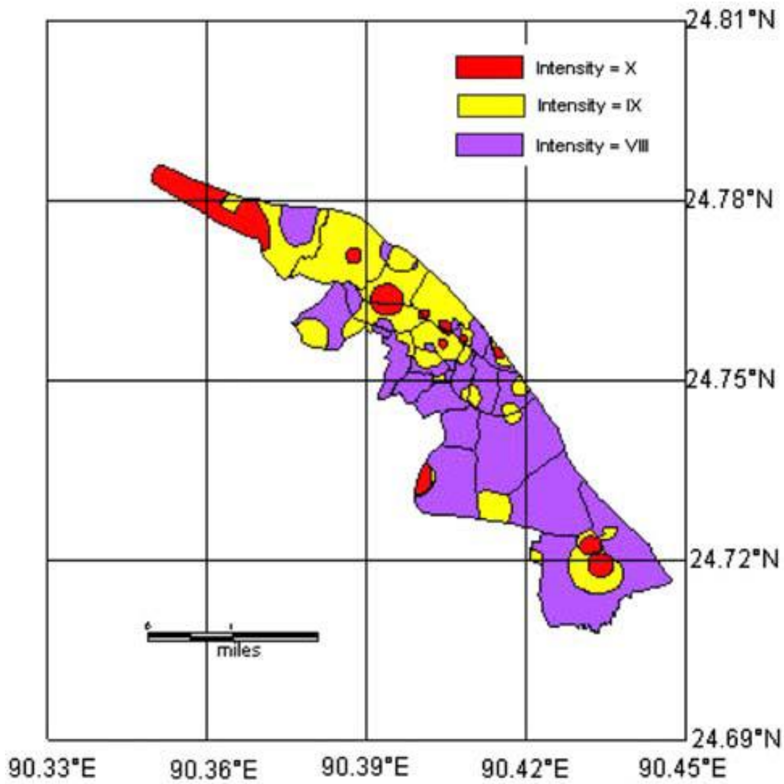

Fig.16: Seismic hazard intensity mapping of Mymensingh city (Source: Sarker et al., 2009)

Similarly, 10417 (94%) cells of low vulnerable zones of the current study are correctly classified in the low vulnerability zone of CDMP-II map and 621 (6%) low vulnerability cells are falsely classified to the highly vulnerable class of CDMP-II map which reveals that 94 percent of medium and low vulnerable area of this study is similar to the 2nd-degree earthquake sensitive area marked by CDMP-II. The agreement or disagreement between the result of this study and the result of Sarker et al. (2009) is also analysed using a confusion matrix. The comparison of these two results is done only for residential cells. The confusion matrix score shows that there exist 71% agreement in defining the highly vulnerable zones and 90% agreement in determining low

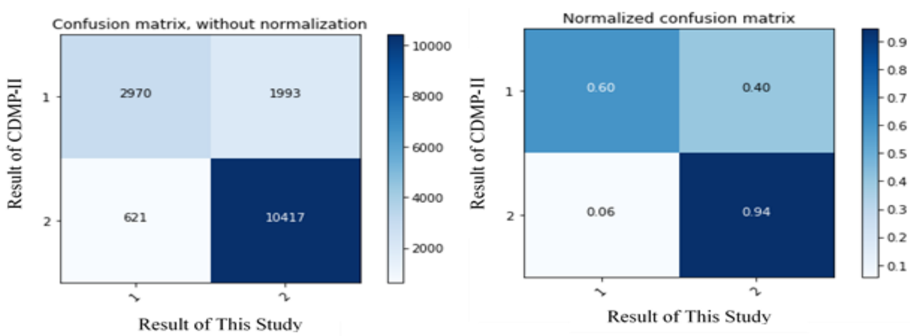

Fig.17: (a) Confusion matrix without normalization and (b) Normalized confusion matrix.
1=High Vulnerability and 2= Low Vulnerability

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vulnerable zones (**Fig. 18**). The normalised confusion matrix shows that there exists 57% disagreement in defining a medium vulnerable area which slightly misclassified as low vulnerable in the result.

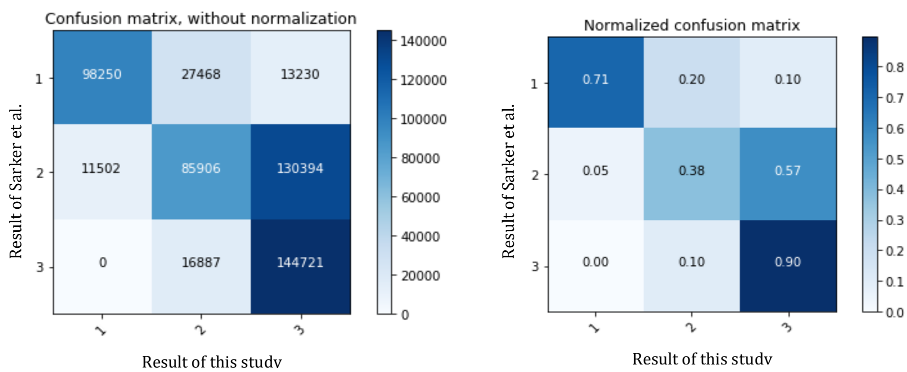

Fig.18: Confusion matrix (a) without normalization and (b) Normalized confusion matrix. 1=High Vulnerability,2= Medium Vulnerability and 3= low Vulnerability

6. Conclusion

Understanding spatial variability of earthquake vulnerability of a city in the earthquake susceptible zone is of paramount importance for deciding on appropriate planning and development control interventions. Incorporating earthquake risk in the city planning process for developing countries like Bangladesh is even more challenging due to resource constraint, technological backwardness, deficiency of trained workforce, etc. Though the HAZUS methodology is widely used for earthquake risk assessment, the methodology is found to be of limited use in developing countries particularly in Bangladesh due to its enormous expertise, resource and data support requirements. A more efficient, less resource and expertise consuming method needs to be introduced for cities of developing nations which can assess earthquake risk with reasonable accuracy. This paper introduced micro level land use specific earthquake vulnerability assessment methodology for Mymensingh city with the application of GIS technology and employing an index-based approach which follows several simple steps. The major strength of this method is its capability to provide a reasonably accurate result of earthquake vulnerability and its spatial variation with minimum resource and expertise requirements. The results by adopting the current AHP-GIS integrated approach is found to be reasonably accurate in comparison with the results found by adopting the HAZUS methodology and the methodology suggested by Sarker et al. (2009). Major advantages of using this suggested methodology for earthquake vulnerability assessment are, it is cheaper, less time, resource and effort consuming and reasonably accurate for a city planning application in the developing countries. This methodology can be applied in any earthquake-vulnerable geographic location and expected to be helpful for policy makers in low-income countries to prioritise special consideration area or hotspot for disaster management. The results of this paper are expected to be useful in designing appropriate seismic risk reduction strategies for the local planning and development authorities.

List of Abbreviations

AHP= Analytical Hierarchy Process, GIS= Geographical Information System,WLC= Weighted Linear Combination, FEMA= Federal Emergency Management Authority, CDMP= Comprehensive Disaster Management Program, MSDP= Mymensingh Strategic Development Plan

Declaration

- **Availability of data and material:** The data used in this research is uploaded in a public domain(http://www.msdp.gov.bd/) of government of peoples republic of Bangladesh
- **Competing Interest:** The authors declare that they have no competing interests
- **Funding:** This research got no funding from any sources.
- **Authors' contributions:** Md. Shaharier Alam analyzed and interprets the whole article with supervision of Prof. Shamim Mahabubul Haque. All authors read and approved the final manuscript.

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