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 research 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 neighbourhoods 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

1.1. Background

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, analysing, quantifying and visualizing the complexity of the vulnerabilities caused by numerous natural calamities is the most difficult task of disaster risk reduction which enable authorities, decision makers and other stakeholders managing and reducing existing and emerging risks (Papathoma-Köhle Schlögl & Fuchs, 2019; Alam, Chakraborty and Islam, 2019). 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. 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.

1.2. 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 et al., 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.

1.3. 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 (Walker et al., 2014). 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. Barbat et al. (2008) 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 & Khandaker,2010, Jena and Pradhan (2020), Barbat et al. (2008), 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) in their researches highly focused on the social dimension of vulnerability of natural hazard and undervalued the other dimensions. Though remarkable development is observed in physical and social aspects vulnerability research, no significant endeavor has been taken to assess systematic dimension of earthquake vulnerability and incorporate it into a comprehensive index by the researchers so far (Walker et al.,2014). 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 endeavors to assess the land use specific earthquake vulnerability of Mymensingh City combining all dimensions of vulnerability including structural, geological, socio-economic and systematic dimensions.

1.4. Methods of Earthquake Vulnerability Assessment

While assessing overall vulnerability, it is always difficult to find an appropriate methodology that can incorporate multidisciplinary dimensions of vulnerability since most of the contemporarily developed methods cannot integrate revealed and stated preference data at a time (Rezaie and Panahi, 2015, Alam and Haque, 2020). 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. 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. 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 Capacity Spectrum Method (Barbat et al., 2008), Non-linear Dynamic Analysis
(Fajfar, 2000), Vulnerability Index Method (Lantada, 2010), Failure Mechanism Identification and Vulnerability
Evaluation (FaMIVE) method (D’Ayala and Speranza, 2003), 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
in place 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. The
application of using AHP technique in spatial analysis is escalating as weights can be used to combine objectives
into a composite objective and results can be a reasonable decision support framework (Armas, 2012). 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.

2. Methodology

2.1. 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.

2.2. 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.

2.2.1. 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                                      |
|-----------------|---------------------|----------------------------------------------------------|
| Soil Type       | Low                 | Medium                                                  | High                                |
|                 | Hard Soil           | Stiff Soil                                               | Soft Soil                           |
| Peak Ground     | 0.346485 - 0.369287 | 0.369288 - 0.392051 - 0.410747                          |
| Acceleration    | Rezaie and Panahi,2015; Jena and Pradhan,2020; Moradi, Delavar and Moshiri,2014 |
| Shear Wave      | More than 360 m/s  | 180 m/s to 360 m/s - less than 180 m/s                  |
| Velocity        | Jena and Pradhan,2020; Chandler et al.,2005 |

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.

2.2.2. 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 risk assessment, number, and quality of temporary shelters, accessibility to work sites and services from temporary shelters (Walker et al., 2014). Parameters considered for assessing systematic earthquake vulnerability are shown in Table 2.

Table 2 Systematic Earthquake Vulnerability Parameters

| Parameter                     | Vulnerability Level | Supporting Literature                                      |
|-------------------------------|---------------------|----------------------------------------------------------|
| Distance to hospital          | <500m               | 500m to 1km                                               | >1km                                  |
| Distance to Fire Service      | <1km                | 1km to 1km                                               | >2km                                  |
| Distance to Emergency center  | <500m               | 500m to 1km                                               | >1km                                  |
| Distance to Evacuation Route  | <500m               | 500m to 1km                                               | >1km                                  |

2.2.3. 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
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 excepted from this research because of data unavailability or rare existence in residential neighbourhoods of Mymensingh city.

2.2.4. 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 (Zebardast, 2012, Armaş, 2012). Poor social settings can often lead to inappropriate land use planning and poor building construction, which can result in an increase in the built environment vulnerabilities, human casualties, and economic losses (Zhang et al., 2018). 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%                 | 5% to 10%                             | >10%                                 | Zebardast,(2012), Rahman, Ansay and Islam,(2015)                            |
| (<5 yr)                            |                     |                                       |                                      |                                                                             |
| Percentage of Elderly population   | <2.4%               | 2.4% to 4.8%                          | >4.8%                                | Zebardast, (2012), Armaş and Gavrış,(2013)                                 |
| (65+yr)                            |                     |                                       |                                      |                                                                             |
| Women population (%)               | <25%                | 25% to 50%                            | >50%                                 | Armaş et al.,(2017), Schmidtlein et al.,(2011)                              |
| Average Household income           | >16475BDT           | 8238 BDT to 16475 BDT                 | <8238BDT                             | Armaş and Gavrış,(2013), Duzgun et al.,(2011); Rahman, Ansay and Islam,(2015) |
| Population Density/acre            | <100 person/acre    | 100 to 150 person/acre                | >150 person/acre                     | Barbat et al.,(2008), Nath et al.,(2015), Armaş and Gavrış,(2013)          |
Average Household size

| Average Household size | <2.21 | 2.21 to 4.41 | >4.41 |
|------------------------|-------|--------------|-------|

Schmidtlein et al.,(2011), Armaş,(2012),

Economically dependent population (%)

| Economically dependent population (%) | <25% | 25% to 50% | >50% |
|----------------------------------------|------|------------|------|

Armaş et al.,(2017), Moradi, Delavar and Moshiri,(2014), Martins, e Silva and Cabral,(2012), Walker et al., (2014)

2.3. Method

2.3.1. 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 (Rezaie and Panahi, 2015, Alam and Mandal, 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.

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

Normalized value = \( \frac{m_i}{\sum_{i=1}^{n} m_i} \) (2)

Here \( m_i \) denotes 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 eqs. 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.

Consistency index, $CI = \frac{L-n}{n-1}$  

Consistency ratio, $CR = \frac{CI}{RI}$  

$L$ 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 parameters are shown in Table 6.

| 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|

2.3.2. 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).

\[ W = \sum_{i=1}^{n} w_i \times x_i \]  

Here $W$ shows the index value of each neighbourhood in vulnerability map, $w_i$ is the weight of each criterion, $x_i$, 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 1: 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 2: 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 3: 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 |
|-----------------------|---|---|---|---|---|---|---|---|--------|
| Building Storey       | 1 | 0.29 | 0.55 | 0.29 | 0.69 | 0.69 | 0.63 | 1.82 | 0.074  |
| Poor conditioned building | 3.44 | 1 | 1.44 | 0.69 | 1.14 | 1.25 | 0.87 | 1.25 | 0.143  |
| Masonry building      | 1.81 | 0.69 | 1 | 0.31 | 0.48 | 0.63 | 0.5 | 1.82 | 0.088  |
| Pounding              | 3.44 | 1.44 | 3.22 | 1 | 1.59 | 2.62 | 1 | 2.28 | 0.213  |
| Irregular shaped building | 1.45 | 0.88 | 2.08 | 0.63 | 1 | 1 | 0.55 | 1.26 | 0.116  |
| Overhanging           | 1.45 | 0.8 | 1.59 | 0.38 | 1 | 1 | 0.55 | 3.12 | 0.118  |
| Road width            | 1.59 | 1.15 | 2 | 1 | 1.82 | 1.82 | 1 | 2.88 | 0.178  |
| Building Density      | 0.55 | 0.8 | 0.55 | 0.44 | 0.79 | 0.32 | 0.35 | 1 | 0.068  |

(Consistency Ratio=0.034, Random Inconsistency=1.41)

Table 4: 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 |
|---------------------------|---|---|---|---|---|---|---|---|---|--------|
| Household income          | 1 | 2.62 | 1.26 | 0.19 | 0.19 | 1.26 | 0.32 | 1.26 | 3.56 | 0.072  |
| Household size            | 0.38 | 1 | 0.33 | 0.18 | 0.18 | 0.44 | 0.26 | 0.38 | 1.26 | 0.034  |
| Population density        | 0.79 | 3.00 | 1 | 0.28 | 0.28 | 1.26 | 0.40 | 1.26 | 3.56 | 0.077  |
| Elderly population        | 5.19 | 5.59 | 3.56 | 1 | 1.00 | 3.00 | 2.00 | 3.56 | 5.59 | 0.258  |
| Child Population          | 5.19 | 5.59 | 3.56 | 1.00 | 1 | 3.00 | 2.00 | 3.56 | 5.19 | 0.255  |
| Dependent population      | 0.79 | 2.29 | 0.79 | 0.33 | 0.33 | 1 | 0.32 | 1.44 | 3.56 | 0.073  |
| Women (%)                 | 3.11 | 3.91 | 2.52 | 0.50 | 0.50 | 3.11 | 1 | 2.08 | 4.64 | 0.162  |
| 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, Random Inconsistency=1.41)

Table 5: 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  |
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.

### 2.3.3. Development of Composite Earthquake Vulnerability Index

Each of the earthquake vulnerability dimensions has its own significance in disaster research, but developing a composite index integrating all the dimensions is highly important for the policy makers for resource targeting, devising proper prediction and mitigation strategies and enhance the resilience of cities (Walker et al, 2014; Armas, 2012). In this study, separate index has been developed for geological, structural, social, and systemic dimensions of vulnerability using the weights from AHP method and equation of WLC method. Finally, using the following equation 6 which is a generalized version of the WLC equation, this study develops a composite earthquake vulnerability index combining geological, structural, social, and systemic dimensions, moving towards a more comprehensive assessment of vulnerability.

\[
\text{Composite Earthquake Vulnerability Index} = W_{\text{geo}} \times X_{\text{geo}} + W_{\text{str}} \times X_{\text{str}} + W_{\text{sys}} \times X_{\text{sys}} + W_{\text{soc}} \times X_{\text{soc}}
\]  

(6)

Here, \(W_{\text{geo}}, W_{\text{str}}, W_{\text{sys}}\) and \(W_{\text{soc}}\) detones the weight of geological, structural, systematic and socio-economic vulnerability dimensions respectively (Table 11). \(X_{\text{geo}}, X_{\text{str}}, X_{\text{sys}}\) and \(X_{\text{soc}}\) represents the index value of geological, structural, systematic and socio-economic vulnerability respectively.
In this study, Databases of Mymensingh Strategic Development Plan (MSDP), 2011-2031 prepared under Comprehensive Disaster Management Programme (CDMP)-2nd Phase 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.
2.5. 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 (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 neighbourhood 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).
2.6. 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 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 x 1m raster grid to measure the agreement using Cohen kappa. Cohen kappa statistics follow several steps. In the first step, a 2x2 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).

\[
\text{Cohen Kappa} = \frac{P_o - P_e}{1 - P_e}
\]

Here, \(P_o\) and \(P_e\) represents observed accuracy and expected accuracy respectively. Pontius (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.

3. 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 neighborhoods and therefore, have also been discussed in the following section as well.
3.1. 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.

**Geological Earthquake Vulnerability Map of Mymensingh City**

![Geological Earthquake Vulnerability Map of Mymensingh City](image)

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

![Influence of Geological-Parameters on Earthquake vulnerability in Mymensingh city](image)

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

3.2. 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 situated 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 vulnerable zone. Only 63 residential neighbourhoods, which have close spatial links with the above mentioned facilities, are in the low systematically earthquake-vulnerable zone (Fig. 7).

Systematic Earthquake Vulnerability Map of Mymensingh City

![Systematic Earthquake Vulnerability Map](image_url)

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.

3.3. 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

Structural Earthquake Vulnerability Map of Mymensingh City
structurally vulnerable, are not geologically vulnerable. The reason behind this difference is the location of the 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. 9: Influence of Structural Parameters on Earthquake vulnerability in Mymensingh city](image)

It is critical to know which parameter has the most influence on the 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 masonry buildings (0.13) respectively are the primary reasons behind structural vulnerability in Mymensingh city.

### 3.4. 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.
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).

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

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

3.5. Composite Earthquake Vulnerability

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

![Influence of vulnerability parameters on composite earthquake vulnerability](image)

**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 existence 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 reason 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.

### 4. Validation

The composite vulnerability map, produced as an output of this research, has been compared with the output similar other assessments 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. 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.

**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.

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

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

**Fig.18:** Confusion matrix (a) without normalization and (b) Normalized confusion matrix. 1=High Vulnerability, 2= Medium Vulnerability and 3= low Vulnerability
5. 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 and can also be found from corresponding author by request.

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Reference

Alam MS, Haque SM (2017) Assessing Spatial Variability of Earthquake Vulnerability of the Residential Neighborhoods of Mymensingh Town and Their Implications in City Planning and Management In: International Conference on Disaster Risk Mitigation-2017, Dhaka.

Alam MS, Haque SM (2018) Assessment of urban physical seismic vulnerability using the combination of AHP and TOPSIS models: A case study of residential neighborhoods of Mymensingh city, Bangladesh. Journal of Geoscience and Environment Protection, 6(02), 165.

Alam MS, Mondal M (2019) Assessment of sanitation service quality in urban slums of Khulna city based on SERVQUAL and AHP model: A case study of railway slum, Khulna, Bangladesh. Journal of Urban Management, 8(1), 20-27.

Alam MS, Haque SM (2020) Seismic vulnerability evaluation of educational buildings of Mymensingh city, Bangladesh using rapid visual screening and index based approach. International Journal of Disaster Resilience in the Built Environment. Vol. 11 No. 3, pp. 379-402.

Alam MS, Chakraborty T, Islam MD (2019) Assessment of Social Vulnerability to Flood Hazard Using NFVI Framework in Satkhira District, Bangladesh. In: International Conference on Disaster Risk Mitigation, Dhaka

Armas I (2012) Multi-criteria vulnerability analysis to earthquake hazard of Bucharest, Romania. Natural Hazards, 63(2), pp1129-1156

Armaș I , Gavriș A (2013) Social vulnerability assessment using spatial multi-criteria analysis (SEVI model) and the Social Vulnerability Index (SoVI model) – a case study for Bucharest, Romania. Natural Hazards and Earth System Science, 13(6), pp1481-1499.

Armaș I, Toma-Danila D, Ionescu R and Gavris A (2017) Vulnerability to Earthquake Hazard: Bucharest Case Study, Romania. International Journal of Disaster Risk Science, 8(2), pp182-195, 2017
Arouq MK, Esmaeilpour M, Sarvar H (2020) Vulnerability assessment of cities to earthquake based on the catastrophe theory: a case study of Tabriz city, Iran. Environmental Earth Sciences. 2020 Jul; 79(14):1-21.

Barbat AH, Pujades LG, Lantada N (2008) Seismic damage evaluation in urban areas using the capacity spectrum method: application to Barcelona. Soil Dynamics and Earthquake Engineering. 28(10-11), 851-865

BBS(2010) Bangladesh Bureau of Statistics, Bangladesh Population Census: Mymensingh Zila Series, Planning Commission, Ministry of Planning, Dhaka.

BBS (2010) Bangladesh Bureau of Statistics, Household Income and Expenditure Survey(HIES), Planning Commission, Ministry of Planning, Dhaka

Bessason B, Bjarnason JÖ (2016) Seismic vulnerability of low-rise residential buildings based on damage data from three earthquakes (Mw6.5, 65 and 63). Engineering Structures, 111, 64-79

BNBC (2015) Bangladesh National Building Code, HBRI-BSTI Draft Version Retrieved from https://www.scribd.com/document/339174596/Bangladesh-National-Building-Code-2015-Vol-2-3-Draft-pdf 2015

CDMP (2014) Scenario-based Earthquake Contingency Plan for Mymensingh Municipality, Ministry of Disaster Management and Relief, Government of the People’s Republic of Bangladesh, Dhaka.

Duzgun H, Yucemen M, Kalaycioglu H, Celik K, Kemeec S, Erteugay K, Deniz A (2011) An integrated earthquake vulnerability assessment framework for urban areas. Natural Hazards, 59(2), pp917-947

Economic and Social Commission for Asia and the Pacific (ESCAP) (2017) Leave No One Behind: Disaster Resilience for Sustainable Development: Asia-Pacific Disaster Report 2017 Bangkok: United Nations publication

Fajfar P (2000) A nonlinear analysis method for performance-based seismic design. Earthquake Spectra, 16(3), 573-592 446.

Fatemi F, Ardalan A, Aguirre B, Mansouri N, Mohammadfam I (2017) Social vulnerability indicators in disasters: Findings from a systematic review. International Journal of Disaster Risk Reduction, 22, 219-227.

Ferreira T, Vicente R, Mendes da Silva J, Varum H, Costa A (2013) Seismic vulnerability assessment of historical urban centres: case study of the old city centre in Seixal, Portugal. Bulletin of Earthquake Engineering, 11(5), pp1753-1773

D’Ayala D, Speranza E (2003) Definition of Collapse Mechanisms and Seismic Vulnerability of Historic Masonry Buildings

Earthquake Spectra 19 (3) pp 479-509

Füssel HM (2010) Review and Quantitative Analysis of Indices of Climate Change Exposure, Adaptive Capacity, Sensitivity, and Impacts Washington, DC: World Bank Available at https://openknowledge.worldbank.org/handle/10986/919

Ghajari Y, Alesheikh A, Modiri M, Hosnavi R, Abbasi, M (2017) Spatial Modelling of Urban Physical Vulnerability to Explosion Hazards Using GIS and Fuzzy MCDA. Sustainability, 9(7), p1274

Ishita RP, Khandaker S (2010) Application of analytical hierarchical process and GIS in earthquake vulnerability assessment: case study of Ward 37 and 69 in Dhaka City. Journal of Bangladesh Institute of Planners, ISSN, 2075, 9363

Islam M, Swapan M, Haque SM (2013) Disaster risk index: How far should it take account of local attributes?. International Journal of Disaster Risk Reduction, 3, pp76-87
Inel M, Ozmen HB, Bilgin H (2008) Re-evaluation of building damage during recent earthquakes in Turkey. Engineering Structures, 30(2), 412-427

Jena R, Pradhan B (2020) Integrated ANN-cross-validation and AHP-TOPSIS model to improve earthquake risk assessment. International Journal of Disaster Risk Reduction, 101723

Jeng V, Tzeng W (2000) Assessment of seismic pounding hazard for Taipei City. Engineering Structures, 22(5), pp459-471,2000

Lantada N, Iziraj J, Barbat AH, Goula X, Roca A, Susagna T, Pujades LG (2010) Seismic hazard and risk scenarios for Barcelona, Spain, using the Risk-UE vulnerability index method. Bulletin of Earthquake Engineering, 8(2), 201-229

Maio R, Ferreira T, Vicente R and Estêvão J (2015) Seismic vulnerability assessment of historical urban centres: case study of the old city centre of Faro, Portugal. Journal of Risk Research, 19(5), pp551-580

Martins V, e Silva D, and Cabral P (2012) Social vulnerability assessment to seismic risk using multicriteria analysis: the case study of Vila Franca does Campo (São Miguel Island, Azores, Portugal). Natural Hazards, 62(2), pp385-404

Chandler AM, Lam NTK, Tsang HH (2005) Shear wave velocity modelling in crustal rock for seismic hazard analysis. Soil Dynamics and Earthquake Engineering, 25(2), 167-185.

Moradi, M, Delavar, M and Moshiri, B (2014) A GIS-based multi-criteria decision-making approach for seismic vulnerability assessment using quantifier-guided OWA operator: a case study of Tehran, Iran. Annals of GIS, 21(3), pp209-222.

Nath S, Adhikari M, Devaraj N and Maiti S(2015) Seismic vulnerability and risk assessment of Kolkata City, India. Natural Hazards and Earth System Science, 15(6), pp1103-1121

Nwe Z, Tun K (2016) Identification of Seismic Vulnerability Zones based on Land Use Condition. American Scientific Research Journal For Engineering, Technology, And Sciences (ASRJETS), 23(1), 90-102

Papathoma-Köhle M, Schlögl M, Fuchs S (2019) Vulnerability indicators for natural hazards: an innovative selection and weighting approach. Scientific Reports, 9(1), 1-14

Pontius RG(2002) Statistical methods to partition effects of quantity and location during comparison of categorical maps at multiple resolutions. Photogrammetric Engineering and Remote Sensing 68, 1041-1049.

Rahman N, Ansary M and Islam I (2015) GIS based mapping of vulnerability to earthquake and fire hazard in Dhaka city, Bangladesh. International Journal of Disaster Risk Reduction, 13, pp291-300

Rezaie F, Panahi M (2015) GIS modeling of seismic vulnerability of residential fabrics considering geotechnical, structural, social and physical distance indicators in Tehran using multi-criteria decision-making techniques. Natural Hazards and Earth System Science, 15(3), pp461-474

Sarris A, Loupasakis C, Soupios P, Trigkas V and Vallianatos F (2010) Earthquake vulnerability and seismic risk assessment of urban areas in high seismic regions: application to Chania City, Crete Island, Greece. Natural Hazards, 54(2), pp395-412

Sarvar H, Amini J, Laleh-Poor M (2011) Assessment of Risk Caused By Earthquake in Region 1 of Tehran Using the Combination of RADIUS, TOPSIS and AHP Models. Journal of Civil Engineering and Urbanism, 1(1)je, pp39-48

Scawthorn C, Eidinger JM, Schiff A (Eds) (2011) Fire following earthquake (Vol 26). ASCE Publications, 2005
Schmidtlein M, Shafer J, Berry M, Cutter SL (2011) Modeled earthquake losses and social vulnerability in Charleston, South Carolina. Applied Geography, 31(1), pp269-281, 2011.

Shirley WL, Boruff BJ, Cutter SL (2012) Social vulnerability to environmental hazards. In: Hazards Vulnerability and Environmental Justice (pp 143-160) Routledge.

Steckler M, Mondal D, Akhter S, Seeber L, Feng L, Gale J (2016) Locked and loading megathrust linked to active subduction beneath the Indo-Burman Ranges. Nature Geoscience, 9(8), 615-618

UDD (2016) Mymensingh Strategic Development Plan (MSDP) 2011-2031, Urban Development Directorate, Ministry of Housing and Public Works, Government of the People’s Republic of Bangladesh

VahidiFard H, Zafarani H, Sabbagh-Yazdi SR, Hadian MA (2017) Seismic hazard analysis using simulated ground-motion time histories: The case of the Sefidrud dam, Iran. Soil Dynamics and Earthquake Engineering, 99, 20-34.

Vicente, R, Parodi, S, Lagomarsino, S, Varum, H and Silva, J (2010) Seismic vulnerability and risk assessment: case study of the historic city centre of Coimbra, Portugal. Bulletin of Earthquake Engineering, 9(4), pp1067-1096.

Walker B, Taylor-Noonan C, Tabbernor A, McKinnon T, Bal, H, Bradley, D, Schuurman, N and Clague, J (2014) A multi-criteria evaluation model of earthquake vulnerability in Victoria, British Columbia. Natural Hazards, 74(2), pp1209-1222.

Zhang X, Tang W, Huang Y, Zhang Q, Duffield CF, Li J, Wang E (2018) Understanding the causes of vulnerabilities for enhancing social-physical resilience: lessons from the Wenchuan earthquake. Environmental Hazards, 17(4), 292-309.

Zebardast E (2012) Constructing a social vulnerability index to earthquake hazards using a hybrid factor analysis and analytic network process (F’ANP) model. Natural Hazards, 65(3), pp 1331-1359.