Proposed Method and Framework for Evaluating and Calculating a Seismic Vulnerability Index of Malaysia

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Abstract. There are various constraints and challenges faced in conducting seismic vulnerability assessment studies in Malaysia due to key factors related to appropriate data availability, methods and frameworks. This paper would highlight on the proposed method and framework for assessing and calculating the seismic vulnerability index at district level for Malaysia condition. A set of vulnerability index indicators that incorporate exposure, resilience and capacity elements had been constructed to identify and evaluate local features that would contribute to the vulnerability of populations and properties to the occurrence of earthquakes. Specifically, a multivariate data analysis method would be performed to identify and assess the relative contribution (weightage value) of respective indicators and following with the use of Geographical Information System (GIS) technology to map and generate the spatial heterogeneity of total vulnerability index map and potential seismic vulnerability index map. Finally, the derived maps could provide preliminary information on the seismically vulnerable area classifications in order to improve the disaster mitigation and preparedness strategies by response disaster agencies.

1. Introduction
Seismic vulnerability assessment is an important process as an alternative to comprehensive risk reduction and earthquake disaster planning, particularly in high density areas and complex construction environments. Diverse methodologies of risk assessment including vulnerability assessment have been established from various viewpoints since the last decade [1]. However, nowadays, the seismic vulnerability assessment is not commonly focussed on the physical assessment of the structure, but it is developed on a holistic assessment of factors that have the potential to contribute to the socio-economic fragility conditions and the lack of resilience conditions in an area [2].

In previous study, various methods and frameworks on seismic risk and vulnerability index evaluation had been established and applied to all over the countries, such as the HAZUS (HAZards United States), the well-known methodology produced by Federal Emergency Management Agency (FEMA) in estimating seismic risk and potential loss based on extensive urban data of buildings,
population, and economic activities [3]; the Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters (RADIUS) method that evaluates the potential losses attributed to building and population vulnerabilities aspects; the Earthquake Disaster Risk Index (EDRI) model to measure the seismic risk by considering the seismic hazards and vulnerability [4]; both the Integrated Earthquake Safety Index (IESI) [5] and Relative Seismic Risk Index (RSRI) [6] that had been developed to assess seismic risk in Tehran using the holistic technique. Methods for assessing seismic risk from multiple perspectives, including hazard factors, vulnerabilities (exposure, resilience and coping capacity) that could potentially contribute to seismic risk had also been introduced by other researchers [7–10]. However, those methods and frameworks were found to be inappropriate to be implemented in Malaysia due to several complications, especially on the absence of comprehensive data required for the assessment.

Earthquake disaster management in Malaysia is still at the beginning stage with multiple challenges where few researches and research papers related to earthquake mitigation have been published [11]. Most of the researches were focussed on seismic hazard assessment, and thus only a handful of researches were done on the evaluation of seismic vulnerability and seismic risk in Malaysia [12]. This could be due to the lack of comprehensive data available on building stock inventories (building age, number of storey, building type, height, building condition and others) and also due to several restrictive issues related to the access of the demographic data for different types of scale (national, regional, residential and micro) including integrity, reliability, accuracy and lack of transparency [13]. Therefore, as an alternative, the assessment of seismic vulnerability should be carried out from a different perspective, depending on the suitability of the disaster management requirements and the criteria of the study area.

Vulnerability in this study would be defined from a multi-perspective approach that incorporates population exposure and risk building; resilience conditions; and the capacity of public facilities in coping with the consequences of earthquakes [2]. Based on the available data, the seismic vulnerability assessment index would be performed to compare and classify the vulnerable region at a district scale. The calculated seismic vulnerability index would allow for a direct comparison of the relative cumulative seismic vulnerability and would also describe the contribution of a number of indicators for the total vulnerability.

2. Proposed Methodology

The proposed methodology in this study is to perform the seismic vulnerability index at the district level based on previous approach, data availability and expert opinion. The integration of the multivariate data analysis and GIS technology approaches would be applied in this research. The procedure to estimate the seismic vulnerability index consists of three main phases is shown in Figure 1.

2.1. Phase 1
The first phase emphasises on the systematic literature review and support data required for this study. The main primary goal is to identify the study area and the appropriate variables to assess seismic vulnerability. The systematic review of literature is accompanied by a process for collecting data from the relevant agencies. The data that were obtained from the Malaysian Centre for Geospatial Data Infrastructure (MacGDI), the Malaysian Meteorological Department (MET Malaysia), the Mineral and Geoscience Department Malaysia (JMG) and the Department of Statistics Malaysia (DOSM) would be gathered and organised according to the module application in the GIS database. The output would be the proposed framework for seismic vulnerability index assessment.
2.2. Phase 2

This phase describes on the method of calculating the vulnerability index together with the weightage value for respective indicators. Mathematical approaches for the implementation of vulnerability assessment in Malaysia would be used in developing and calculating the total vulnerability index. The process is started with the normalisation process applied in equation (1).

\[ X_{ij} = \frac{(x_{ij} - \text{Min}(x_{ij}))}{(\text{Max}(x_{ij}) - \text{Min}(x_{ij}))}, (0 \leq x_{ij} \leq 1) \]  

(1)

Where \(X_{ij}\) represent the normalised value [14] of \(x_{ij}\) that represent the size and value of the \(i\)-th development indicator in the \(j\)-th component \((i = 1, 2, ..., j = 1, 2, ..., M)\). \(\text{Max}(x_{ij})\) and \(\text{Min}(x_{ij})\) are the maximum and minimum values of the \(x_{i1}, x_{i2}, ..., x_{iM}\) indicators \(i\) respectively. Next is to calculate the linear sum of \(x_{ij}\) using equation (2), where \(K\) is indicators of vulnerability with \(x_{ij}\) is the normalised scores \((i = 1, 2, ..., M; j = 1, 2, ..., K)\). \(w_j\) is the weight reflecting the relative importance of indicator variable \((0 < w < 1)\) and \(\sum_{i=1}^{K} w_i = 1\). The weight is assumed equal.

\[ \bar{y}_i = \sum_{j=1}^{K} w_j x_{ij} \]  

(2)

Figure 1. Flowchart of seismic vulnerability index construction.

However, rationally the weights are assumed to vary inversely, as variation between respective indicators of \(K\) value. Equation (3) and (4) would determine the weight \((w_j)\) of different indicator variable with \(c\) is the normalising constant.
\[ w_j = \frac{c}{\sqrt{\text{var}(x_j)}} \]  
\[ c = \left[ \sum_{i=1}^{n} \frac{1}{\sqrt{\text{var}(x_i)}} \right]^{-1} \]

The selection of the measured weights should ensure that the broad variance of each indicator would not unduly influence the contribution of the overall indicators. The seismic vulnerability index (SVI) lies between 0 and 1 where 1 indicating the maximum value of vulnerability and 0 for no vulnerability at all. The Beta distribution, which is generally skewed has been applied using equation (5). The beta function \( \beta(a, b) \) is represented in equation (6).

\[ f(z) = \frac{z^{a-1}(1-z)^{b-1}}{\beta(a,b)}, \quad 0 < z < 1 \text{ and } a,b > 0 \]

\[ \beta(a,b) = \int_0^1 x^{a-1}(1-x)^{b-1} \, dx \]

Both parameters \( a \) and \( b \) would estimate based on Iyengar and Sudarshan [15] or using software tools. Five significance intervals \((0, z_1), (z_1, z_2), (z_2, z_3), (z_3, z_4), (z_4, z_5)\) could be used to classify the vulnerability with the same probability weight of 20% as follow: Less vulnerable if \( 0 < y_i < z_1 \), Moderately vulnerable if \( z_1 < y_i < z_2 \), Vulnerable if \( z_2 < y_i < z_3 \), Highly vulnerable if \( z_3 < y_i < z_4 \) and Very highly vulnerable if \( z_4 < y_i < z_5 \)

2.3. Phase 3
The final phase is to apply the GIS tools to generate the total vulnerability index map. In order to produce the final potential seismic vulnerability index (SVI) map, the total vulnerability map would be overlaid with seismic hazard map for Malaysia by JMG.

3. The proposed framework for seismic vulnerability index assessment
In previous studies, various frameworks and models have been developed and applied to assess seismic vulnerability. Therefore, a proposal framework (Figure 2) that is relevant to the study area has been identified and developed based on local factors, data availability and expert opinion. Based on the literature review on historical earthquake activities and catalogue, the identified study areas are Sabah that is located at the northern part of Borneo and Pahang in Peninsula Malaysia. The strongest earthquake with a magnitude of 6.0 (Richter Scale) that hit Ranau in 2015, which caused damage and death, had urged the authorities to act and raised local awareness of disaster preparedness for the foreseeable future.

3.1. Total Vulnerability Index
A cumulative result of vulnerability indicators with the considerations for exposure, resilience and capacity module would determine the spatial relationship between the variables in reaction to natural disaster. The total vulnerability index map would highlight the distribution of geographic location of vulnerable area and population groups at regional scale.

3.1.1. Exposure Index. Exposures always refer to populations and properties, especially structures located in hazard areas of natural disaster. Thus, demographic statistics data are highly suitable for the construction of exposure indices that would reflect the population criteria such as age, gender, disabilities status, population density, household density and others. Most of the criteria or variables deal with social elements of the population [16,17]. The exposure to the properties is represented by
the density of residential building in the study area. Vulnerable buildings are a significant factor that could cause damage to properties in the event of an earthquake [18,19].

![Figure 2. Framework of seismic vulnerability index assessment.](image)

3.1.2. Resilience Index. Resilience is always measured by the ability of a population to recover from disasters. The community with high resilience level is able to cope, absorb, resist or adapt to hazards in a timely and efficient manner [20]. The construction and selection of resilience indicators combined with the economic resilience, important communication facilities, and community capital [21][22]. The proposed resilience variables would focus on the percentage of community that owned the telecommunication equipment and services, gross income, gross domestic product (GDP) from agriculture activities and the population growth in the study area. The resilience functional relationship is non-linear with vulnerability level, indicating the high resilience community is low in vulnerability and vice versa [6,10,23–25].

3.1.3. Capacity Index. Capacity refers to the integration of strengths, capacities and resources that are available to the organisation or people to face or manage the consequences of disaster and to improve resilience [20][26]. In this study, the researchers suggest the physical coping capacity consists of public infrastructure such as police station, fire station, healthcare services, school and road network to determine the vulnerability level. The coping capacity in an area would depend on these public safety
and health infrastructures that are the elements-at risk that could be affected by an earthquake [5,27,28].

3.2. Seismic Hazard
Seismic hazard is defined as the ground motions associated to an earthquake occurrence and is quantified by the peak ground acceleration (PGA). The seismic hazard map would be combined with the total vulnerability map to produce the final seismic vulnerability index map. The process would involve the use of raster calculator function in GIS software.

3.3. Seismic Vulnerability Index
The combination of total vulnerability map and seismic hazard map through geostatistical technique in GIS software would produce a seismic vulnerability index map of study area. The derived map would enable users to identify the spatial classification of vulnerable areas and community groups that deserved the most assistance from disaster response agencies in the aftermath of a devastating earthquake.

4. Conclusions
In this paper, a method and a multi-perspective framework for seismic vulnerability index assessment have been proposed based on the fact that each of the vulnerability components; exposure, resilience and capacity have different contribution to the earthquake consequences. Firstly, the significant indicators of the assessment would be identified together with the relative contribution through the weightage calculation. Then, the GIS tools would be applied to implement the spatial analysis in order to generate and map the total vulnerability map and the final seismic vulnerability map. In addition, mapping of the vulnerability components separately also enables the comparison of the vulnerability levels to seismic hazards with the following combinations of maps; exposure map with hazard map or resilience map with hazard map or capacity map with hazard map. The application and the effectiveness of the method and framework would be performed and presented in future papers. Finally, the proposed method and framework are the first attempt in evaluating the seismic vulnerability index of Malaysia, which undoubtedly could be used as a basis for further improvement in future assessment.

Acknowledgements
This work was financially supported by TIER1 Grant from Research Management Centre (RMC), Universiti Tun Hussein Onn Malaysia (UTHM).

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