Earthquake Social Vulnerability Assessment Using Entropy Method

Ratiranjan Jena & Biswajeet Pradhan*
Centre for Advanced Modelling and Geospatial Information Systems (CAMGIS), Faculty of Engineering and IT, University of Technology Sydney, NSW 2007, Australia

*Email: Biswajeet.Pradhan@uts.edu.au

Abstract. Earthquake is the most devastating event in the current time. Given the probability of highly dangerous future events, risk estimation should be given focus by using the limited and freely available data to predict future vulnerable scenarios of an area that observe the involved uncertainty in the analysis. However, vulnerability assessments should be prospective and based on expected scientifically acceptable events. Therefore, we applied a valuable weight calculation approach called entropy to produce a social vulnerability map for a particular city. We used the population data, including educated and non-educated people and household information, to develop the earthquake social vulnerability map. We used entropy to evaluate the actual weight and produce a good quality map because of some difficulty in the fuzzy synthetic evaluation method for factor weight calculation and relationship ignorance among layers. Results showed that approximately 6% of the population is under very high vulnerability and around 14% are under high vulnerability areas in Banda Aceh City. The developed model is accurate by considering the inventory earthquake vulnerability map. The applied method was favorable, and the process provided good evaluation results, which was reasonable for earthquake hazard, vulnerability, and risk assessment.

Keywords: Earthquake; social vulnerability; entropy; GIS; mapping

1. Introduction

Natural hazards, such as earthquakes, often result in serious damage or loss of lives and properties. Mitigating the disaster risks and intensifying society's resilience, emergency capability and response is the present which is never ignored major problems. Therefore, several researchers keeping attentions on vulnerability mapping in the current period. The rapid societal growth accelerates geological changes; inevitably, natural disasters cause the potential range of the damage. Earthquake social vulnerability is defined as society's susceptibility to the destructive effects of an earthquake [1]. Several researchers have highlighted the importance of social vulnerability analysis in human vulnerability and natural hazards. Numerous countries worldwide have actively integrated disaster research in the last decade on the “International Decade for Natural Disaster Reduction” (1990), thereby resulting in a new era of hazard analysis. In general, scientists and researchers have mainly focused on examining the attributes of natural hazards, such as earthquakes [2, 3]. Disaster studies have been barely undertaken from the view of other prospects, specifically earthquake social vulnerability to risk. The authors in [4] conducted the most exciting research on social vulnerability. They discussed the basics of natural hazards, vulnerability and then projected the methodology for the application on social vulnerability. The authors also described the impact of social vulnerability.
assessment in natural disaster reduction and concluded that evaluation of social vulnerability should be performed in future analysis. According to the socio-economic and population data of the USA, the authors in [8] applied 42 factors and conducted a factor analysis approach in calculating the social vulnerability index to generate a map in their research. The authors in [4] and [5] selected 10 indicators from the extended literature review, applied principal component analysis, performed the social vulnerability analysis to natural hazards of 11 cities in Shaanxi Province. Ref [10, 11] conducted objective reality research to estimate the vulnerability to natural hazards. Their research was on the concept of natural hazards and vulnerability estimation. Finally, they proposed the methodological assessment of how social vulnerability could contribute to natural hazards. They pinpointed the utmost impact of social vulnerability estimation for natural hazards monitoring and mitigation planning. They also mentioned in their research that the evaluation of social vulnerability should be conducted in future research. [12] developed an index of social vulnerability up to four levels such as; economy, structure, population, disaster. The whole study was conducted using ArcMap software and other GIS-based spatial analysis software.

After the 2004 earthquake and tsunami, multiple hazards appeared often in the tsunami-affected areas of Aceh Province, thereby growing major involvement in the social effects of natural hazards. In this study, we combined previous works on risk estimation and conducted a study on earthquake social vulnerability index estimation of earthquake hazard areas in Aceh Province after the 2004 event, which is vital and may lead to disaster prevention planning and human life and property protection.

2. Materials and methods

2.1. Study area

Indonesia is an archipelagic country situated between 6° 8′ north and 11° 15′ south latitude and between 94° 45′ west and 141° 05′ east longitude (BPS, 2010b). Indonesia is the country having a dividing line in the southern part by the South China Sea, the Indian Ocean presents at the south and west part of the country while the Pacific Ocean is in the north and east. Banda Aceh is the economic capital of Aceh Province, is specifically located on a fault population, including the Seulimeum and Aceh Faults [9]. Urban growth, nonstandard and poor building construction and rapid growth of population density make the city extremely vulnerable to earthquakes. The recurrence of earthquakes in Banda Aceh is 150 years, which was also the period when the last large earthquake was experienced in the city [9]. Thus, a large earthquake is imminent in Aceh Province. Site effects in Banda Aceh City vary significantly because of its unique geological setting. However, Banda Aceh lies in a basin, which is structure-controlled in Krueng Valley. The city is surrounded by two major tectonic faults on either side, which are seismically active. The Aceh Fault can be found in the southwest, whereas the Seulimum Fault is located in the northeast and covered by vegetation. Therefore, Banda Aceh plains tremble strongly when any seismic activity occurs around the city.
2.2 Materials
In the set of the first indicator, several variables were selected for the analysis on the basis of the recent literature review on earthquake vulnerability assessment [4, 8, 9]. Some specific and potential indicators, such as hospitals, distance from hospitals and emergency services were not considered in this study because of the limited availability of data at the city scale. A multicollinearity test was performed, and four variables were employed to calculate the index and produce a map. These variables are listed in Table 1. Data were collected from Statistics Indonesia (https://www.bps.go.id/) based on 2010 Sensus Penduduk (SP). SSN is the data source that provides annual economic information and education infrastructure and system, housing state, welfare, annual income, and cultural characteristics. SP provides the data of population census; they collect population characteristics, such as gender, age, migration, religion, etc. However, the population census data are obtained in every 10 years, the most recent of which is from 2010, which was used in this study.

Table 1. Data used in this study.

| Indicators                      | Scale   | Type          |
|--------------------------------|---------|---------------|
| Population density             | 1:30000 | Raster type   |
| Educated people characteristics |         |               |
| Village chiefs                 |         |               |
| Household density              |         |               |
2.3. Methodology

The entropy method is a probability distribution technique that is comprehensive in nature. Theoretically, entropy is the uncertainty measure for any specific problem. However, an information entropy index is evaluated as small, where the coefficient difference is large, which results in a large index weight. Therefore, a lot of information was provided by the indicators. Therefore, a comprehensive entropy method required for an application that involves several aspects. Ref. [13] applied the entropy method to estimate the vulnerability for towns in association with combined fuzzy logic theory to estimate the total vulnerability. However, the social structure could be considered as entropy. However, a complex variance leads to differences associated with their entropy, respectively. Further, this principle of entropy method was used to evaluate social vulnerability is highly practical. In the current research, GIS was integrated with the entropy value method to analyze the social vulnerability objectively and intuitively for earthquakes in Banda Aceh city in Indonesia.

Zhan [14] described the steps required in the entropy processes for comprehensive evaluation are described below.

Step 1: Data standardization

Different characteristics among the magnitudes, dimensions, and the changes in factors are obtained. They are perceived to influence the results. The data should be unified to remove the effect of dimensional processing, which is called a standardized deviation. Standard deviation should be selected as needed [1].

Step 2: normalization of data

In this step, to make the data standardization, normalization is necessary to remove the differences among indices.

Step 3: Information entropy processing

In this step, with the degree of vulnerability, each index is defined. The weight $p_{ij}$ of scheme $i$ under index $j$ is calculated as follows [2]:

$$\frac{x_{ij}}{\sum_{i=1}^{n}x_{ij}}, \quad (1)$$

Step 4: Estimation of difference coefficient

$$g_j = 1 - e_j, \quad (2)$$

where $g_j$ is the difference coefficient, and $e_j$ is the entropy.

Step 5: weight estimation

The weight of index $j$ can be calculated as

$$\frac{g_j}{\sum_{j=1}^{n}g_j} \quad (3)$$

where, $a_j$ denotes the weight, and $e_j$ represents the entropy.

Step 6: Calculation of sample score
The sample score for the comprehensive study is quite complicated and must be calculated as follows [1, 2]:

\[
Z_i = a_1x_{i1} + a_2x_{i2} + a_3x_{i3} + \ldots, a_kx_{ijk} + \ldots, ap_{xpp},
\]  

(4)

Step 7: Data processing and classification using GIS

The social vulnerability map can be created using the weights of layers calculated from the entropy method via the ArcGIS platform. We used the approach of weighted overlay and a technique of natural break default system for mapping and classifying the vulnerability map. We comprehensively analyzed the social vulnerability of the city using the score of the entropy method (Figure 2).

3. Results and Discussion

The spatial distribution of social vulnerability is shown in Figure 3. The distribution of social vulnerability in the city center of Banda Aceh projects the strong influence of vulnerability for urban development. In case, the most vulnerable locations can be found in the city center, whereas the surrounding areas show less vulnerability. Observations on the city structure indicate that the city center is highly developed along with some old buildings with the maximum population. The number of housing is also relatively higher in the city center compared with the surrounding areas. Meanwhile, with a higher educational level, the younger generations are commonly found in the city center. The social vulnerability was calculated considering several factors of people’s characteristics. Urban
expansion in the city increases the number of buildings with a growing population. Therefore, the city needs a well-planned infrastructure that considers other areas of the state. Specific interesting situations were not considered in determining social vulnerability. The constructed social vulnerability map shows that vulnerability is classified into five, namely, very high, high, moderate, low, and very low.

Figure 3 shows the percentages of social vulnerability through a map of Banda Aceh City. An interesting study can be performed with regard to socioeconomic characteristics for vulnerability assessment [6, 7]. Old buildings in the city increase the percentage of vulnerability if managed by less educated people. Therefore, the recent replacement of old masonry buildings by highly educated people is needed in the city to reduce social vulnerability. However, as the RC buildings are seismically strong therefore, the social vulnerability score will be low for RC buildings, whereas the score rises with masonry buildings. Moreover, this is a standardized trend that needs further investigation.

As the Banda Aceh city is the home to 223,446 population however, earthquakes and tsunami could cause massive losses. The possible reasons could be building coverage, huge population, distance from the road, road density, educated people for which highly vulnerable areas were observed in the map. However, the vulnerability could be lower if high-quality medical services, personnel support, and social welfare were provided. Support of social forces could help in quick response time that could reduce expected losses that might result from earthquakes. Therefore, the social vulnerability index could help in mapping the future risk to a certain level. Emergency response in Banda Aceh could reach a higher level of earthquakes occurs. Relatively, the self-recovery ability becomes weaker with
respect to the high social vulnerability area. Proper emergency support needed in Banda Aceh with a corresponding area.

The achievements of the estimation of social vulnerability to earthquake hazards in Banda Aceh City have a base of successful researches associated with the current knowledge framework. The data collection involved is at different difficulty levels. The collected data are complete and highly accurate, thereby making the vulnerability evaluation perfect and acceptable. Nevertheless, some improvements are necessary to execute analysis with improved accuracy for the prevention of earthquake hazard in future research.

4. Conclusion

This study can be considered as an initial effort of natural hazards mitigation and reduction at a city scale in Indonesia. The approach applied in this study is to quantify the earthquake social vulnerability in Banda Aceh City to analyze its conditioning factors. The three main conditioning factors that affect social vulnerability are infrastructure, population growth and economy. According to the obtained results, the earthquake social vulnerability varies potentially among different city sections in Banda Aceh City. This analysis applies only five specific variables to assess the earthquake's social vulnerability due to constraints in data availability. The major indicators of social vulnerability can be analyzed and chosen by considering the importance of the variables and modifications. Finally, the method used in this study, namely, entropy approach at the city level, should be given focus. By applying several machine learning and high-quality data Indonesian districts and sub-districts can also be analyzed in the future.

Acknowledgments

This research was funded by the Centre for Advanced Modelling and Geospatial Information Systems, University of Technology Sydney, under Grant Nos. 323930, 321740.223235 and 321740.2232357.

References

[1] HR. Pourghasemi, M. Mohammady, B. Pradhan. “Landslide susceptibility mapping using index of entropy and conditional probability models in GIS: Safarood Basin, Iran,” Catena, Vol.1, pp. 71-84, Oct 2012.
[2] KC. Devkota, AD. Regmi, HR. Pourghasemi, K. Yoshida, B. Pradhan, IC. Ryu, MR. Dhital, OF. Althuwaynee. “Landslide susceptibility mapping using certainty factor, index of entropy and logistic regression models in GIS and their comparison at Mugling–Narayanghat road section in Nepal Himalaya,” Natural hazards, Vol.1, pp.135-65, Jan 2013.
[3] AM. Youssef, B. Pradhan, AF. Gaber, MF. Buchroithner. “Geomorphological hazard analysis along the Egyptian Red Sea coast between Safaga and Quseir,” Natural Hazards & Earth System Sciences, Vol.1 pp. 9, May 2009
[4] B. Pradhan, AA. Monceir, R. Jena. “Sand dune risk assessment in Sabha region, Libya using Landsat 8, MODIS, and Google Earth Engine images,” Geomatics, Natural Hazards and Risk, Vol. 1, pp. 1280-305, 2018 Jan
[5] B. Pradhan, R. Jena. “Spatial relationship between earthquakes, hot-springs and faults in Odisha, India”. In IOP Conference Series: Earth and Environmental Science 2016 Jun (Vol. 37, No. 1, p. 012070). IOP Publishing.
[6] AM. Youssef, B. Pradhan, AF. Gaber, MF. Buchroithner. “Geomorphological hazard analysis along the Egyptian Red Sea coast between Safaga and Quseir,” Natural Hazards & Earth System Sciences, Vol.9, 9(3), May 2009.
[7] R. Jena, B. Pradhan. “A novel model for comparing Peak Ground Acceleration derived from three attenuation laws using an integrated GIS technique in Sabah area, Malaysia,” IJSRP, Vol. 11,
pp. 1-10, Sep 2018.

[8] SL. Cutter, BJ. Boruff, WL. Shirley. “Social vulnerability to environmental hazards,” Social science quarterly, Vol. 84, pp.242-61, Jun 2003.

[9] M. Delescluse, N. Chamot-Rooke, R. Cattin, L. Fleitout, O. Trubienko, C. Vigny. “April 2012 intra-oceanic seismicity off Sumatra boosted by the Banda-Aceh megathrust,” Nature, Vol. 490, pp. 7419, Oct. 2012.

[10] J.S. Yang, P.T. Robinson, C.F. Jiang, Z.Q. Xu. “Ophiolites of the Kunlun Mountains, China and their tectonic implications”. Tectonophysics, Vol. 258, pp.215-231, 1996.

[11] C.L. Jiang, L.H., Xu. Diversity of aquatic actinomycetes in lakes of the middle plateau, yunnan, china. Appl. Environ. Microbiology, Vol. 62, pp.249-253, 1996.

[12] L. Tang, Y.J. Liu. Index evaluation system and spatial pattern of social vulnerability to natural disasters. J UESTC (Soc Sci Ed), Vol. 14, pp. 49–53, 59 (In Chinese), 2012.

[13] Y. Jiang. An integrated entropy weight variable fuzzy sets evaluation approach for small town disaster Vulnerability Problem. Geogr Geo-Inf Sci, Vol. 25, pp. 88–91 (In Chinese), 2012.

[14] W.Q. Zhao. The evaluation systematic index of social vulnerability to natural hazards—a case study of Chongqing City. Chongqing Normal University, Chongqing (In Chinese), 2008.