UNIVERSITY OF TECHNOLOGY SYDNEY

Development of semi-quantitative earthquake risk assessment models using machine learning, multi-criteria decision-making, and GIS

by Ratiranjan Jena

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Distinguished Professor Biswajeet Pradhan and Professor Ghassan Beydoun

University of Technology Sydney
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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I, Ratiranjan Jena declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctoral of Philosophy, in the FEIT at the University of Technology Sydney.
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Ratiranjan Jena

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DEDICATION

This thesis is dedicated to my Parents.

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Praise belongs to God, the Lord of the world who inspires me everywhere.

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LIST OF PAPERS/PUBLICATIONS

Published journal articles

1. Jena, R., Pradhan, B., Beydoun, G., Sofyan, H. & Affan, M. 2020, 'Integrated model for earthquake risk assessment using neural network and analytic hierarchy process: Aceh province, Indonesia', *Geoscience Frontiers*, vol. 11, no. 2, pp. 613-34. https://doi.org/10.1016/j.gsf.2019.07.006 (IF. 4.202)

2. Jena, R., Pradhan, B., Beydoun, G., Alamri, A.M. & Sofyan, H. 2020, 'Earthquake hazard and risk assessment using machine learning approaches at Palu, Indonesia', *Science of The Total Environment*, p. 141582. https://doi.org/10.1016/j.scitotenv.2020.141582 (IF. 6.551)
3. Jena, R., Pradhan, B. & Beydoun, G. 2020, 'Earthquake vulnerability assessment in Northern Sumatra province by using a multi-criteria decision-making model', *International Journal of Disaster Risk Reduction*, vol. 46, p. 101518. https://doi.org/10.1016/j.ijdrr.2020.101518 (IF. 2.896)

4. Jena, R. & Pradhan, B. 2020, 'Integrated ANN-cross-validation and AHP-TOPSIS model to improve earthquake risk assessment', *International Journal of Disaster Risk Reduction*, vol. 50, p. 101723. https://doi.org/10.1016/j.ijdrr.2020.101723 (IF. 2.896)

5. Jena, R., Pradhan, B., Beydoun, G., Al-Amri, A. & Sofyan, H. 2020, 'Seismic hazard and risk assessment: a review of state-of-the-art traditional and GIS models', *Arabian Journal of Geosciences*, vol. 13, no. 2, p. 50. https://doi.org/10.1007/s12517-019-5012-x (IF. 1.327)

Published conference papers

1. Jena, R. & Pradhan, B. 2019, 'Earthquake Vulnerability Assessment using Expert-based Approach in GIS', 2019 6th International Conference on Space Science and Communication (IconSpace), IEEE, pp. 53-6. IEEE. 10.1109/IconSpace.2019.8905929.

2. Jena, R. Pradhan, B., & Beydoun, G. 2019, Structural vulnerability assessment using an artificial neural network for earthquake hazard in Banda Aceh city, Aceh Province, Indonesia, IAG Conference 2019, Hobart, Tasmania. *(Published abstract only)*

3. Jena, R. & Pradhan, B. 2020, 'Earthquake Risk Assessment Using Integrated Influence Diagram–AHP Approach', IOP Conference Series: Earth and Environmental Science, vol. 540, IOP Publishing, p. 012078. https://doi.org/10.1088/1755-1315/540/1/012078.

4. Jena, R. & Pradhan, B. 2020, 'Earthquake Social Vulnerability Assessment Using Entropy Method', IOP Conference Series: Earth and Environmental Science, vol. 540, IOP Publishing, p. 012079. https://doi.org/10.1088/1755-1315/540/1/012079.

All the aforementioned papers have been published during my Ph.D. candidature.

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Contributor	Statement of contribution	Thesis chapters
Ratiranjan Jena	Literature review and analysis (100%) Research direction and manuscript writing (75%)	Chapter 3, 4 and 5
Biswajeet Pradhan	Research direction and manuscript review (15%)	
Ghassan Beydoun	Research direction and manuscript review (5%)	
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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANN	Artificial Neural Network
ANN-CV	Artificial Neural Network-Cross Validation
AUC	Area Under the Curve
CR	Consistency Ratio
DEM	Digital Elevation Model
ERA	Earthquake Risk Assessment
EVA	Earthquake Vulnerability Assessment
EHA	Earthquake Hazard Assessment
GIS	Geospatial Information System
HCA	Hierachical clustering Analysis
LiDAR	Light Detection and Ranging
LULC	Land Use / Land Cover
MCDM	Multi-criteria Decision Making
MLP	Multi-Layer Perceptron
MMI	Modified Mercalli Intensity
MSL	Mean Sea Level
PGA	Peak Ground Acceleration
PLC	Pure Locational Clustering
RI	Random Index
ROC	Receiver Operating Curves
SVM	Support Vector Machine
TOPSIS	Technique of Order Preference Similarity to the Ideal Solution
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje (Multi-criteria Optimization and Compromise Solution)
WGS	World Geodetic System

DEVELOPMENT OF SEMI-QUANTITATIVE EARTHQUAKE RISK ASSESSMENT MODELS USING MACHINE LEARNING, MULTI-CRITERIA DECISION-MAKING, AND GIS

By

RATIRANJAN JENA

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Supervisor: Professor Biswajeet Pradhan,

Abstract

Catastrophic natural hazards, such as earthquakes, pose serious threats to properties and human lives in urban areas. Earthquake risk assessment (ERA) is specifically required for areas with complicated tectonics because of the catastrophic nature of mega-events that result in a massive death toll. Therefore, ERA is indispensable in disaster management. The prerequisite for earthquake risk estimation is probability, hazard and vulnerability assessment. Several research gaps such as failure to establish comprehensive GIS-based models, not much work on ERA has been done in city scale using integrated geospatial information system (GIS) techniques, use of limited conditioning factors, and little research on optimization of factors are specified in literature. Therefore, this study aims to develop models and estimate risk in city scale that is necessary to reduce future fatalities. The study evaluates the earthquake vulnerability by using the multi-criteria decision-making approach through a novel integrated analytical hierarchy process and VIseKriterijumska Optimizacija I Kompromisno Resenje method using a geographical information system in the first objective. This research develops an integrated model by using the artificial neural network–analytic hierarchy process for constructing the ERA map in the second objective. The third objective presents a novel combination of artificial neural network cross-validation (fourfold ANN-CV) with a hybrid analytic hierarchy process-Technique for Order of Preference by Similarity to Ideal Solution (AHP-TOPSIS) method to improve the ERA and applied to Aceh, Indonesia to test.

Firstly, in the objective 1, several factors were used to produce social vulnerability, structural vulnerability, and geotechnical vulnerability indices. Subsequently, the adopted approaches were integrated and applied to estimate the criteria weight, priority ranking,

and alternatives of criterion by applying the pair-wise comparison at all levels. Finally, vulnerability layers were superimposed to estimate the earthquake vulnerability index and produce the vulnerability map. The proposed method for earthquake vulnerability assessment (EVA) provides useful information that could assist in earthquake disaster mitigation.

Secondly, in the objective 2, the aim of the ERA was to quantify urban population risk that may be caused by impending earthquakes. The ANN is used for probability mapping, whereas AHP is used to assess urban vulnerability after the hazard map is created with the aid of earthquake intensity variation thematic layering. The risk map is subsequently created by combining the probability, hazard, and vulnerability maps. Then, the risk levels of various zones are obtained. The validation process reveals that the proposed model can map the earthquake probability based on historical events with an accuracy of 84%. The model is applied to the city of Banda Aceh in Indonesia, a seismically active zone of Aceh province frequently affected by devastating earthquakes. The findings of this research are useful for government agencies and decision-makers, particularly in estimating risk dimensions in urban areas and for future studies to project the preparedness strategies for Banda Aceh.

Thirdly, in the objective 3, this study explored and specified the major indicators needed to improve the predictive accuracy in probability mapping. Previous studies have suggested that neural networks improve the probability mapping on a city scale. The network architecture design with the probability index remains unexplored in case of an earthquake-based probability study. First, probability mapping was conducted and used for hazard assessment in the next step. Second, a vulnerability map was created based on social and structural factors. Finally, hazard and vulnerability indices were multiplied to produce the ERA, and the population and areas under risk were calculated. The proposed model achieved an improve accuracy of 85.4%. The model’s performance changes based on the input parameters, indicating the selection and importance of input layers on network architecture selection. The proposed model was found to generalize better results than traditional and some existing probabilistic models.

The proposed models are transferable to other regions by localizing the input parameters

that contribute to earthquake risk mitigation and prevention planning. Therefore, as a case study, the third model was implemented to estimate the earthquake risk based on probability and hazard in Palu region along with cross-correlation among the derived parameters, Silhouette clustering (SC), pure locational clustering (PLC) based on hierarchical clustering analysis (HCA). There is no specific or simple way of identifying risks as the definition of risk varies with time and space. The main aim of this study was to conduct the clustering analysis to identify the earthquake prone areas, to estimate probability based on ANN-CV technique, and to assess earthquake risk. Using ANN-CV model the probability assessment was conducted while SC and PLC were implemented to understand the spatial clustering, Euclidean distance among clusters, spatial relationship and cross-correlation among the estimated Mw, PGA and intensity including events depth. Finally, AHP was implemented for the vulnerability assessment. To this end, earthquake probability assessment (EPA) and earthquake vulnerability assessment (EVA) results were employed to generate risk. These results obtained from this research have important implications for future large-scale risk assessment, land use planning and hazard mitigation.

The current research designs novel combination of multi-criteria decision making (MCDM), machine learning and GIS to develop models such as AHP-VIKOR, neural network-AHP and k-fold neural network cross-validation (Fourfold ANN-CV) with a hybrid AHP-TOPSIS method for probability, hazard, vulnerability, risk estimation and the ERA improvement in a city scale.

Keywords: Earthquake, probability, hazard, vulnerability, risk, machine learning, multi-criteria decision making, integrated models development