A MULTI-SPATIAL ASSESSMENT FRAMEWORK TO GEOLOGICAL HAZARD FOR HIGH-RISE BUILDING PROJECT IN METRO MANILA, PHILIPPINES

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Abstract. On Metro Manila Earthquake Impact Reduction Study (MMEIRS) conducted from 2002 to 2004 by Japan International Cooperation Agency (JICA) together with the Philippine Institute for Volcanology and Seismology (PHIVOLCS) and the Metro Manila Development Authority (MMDA), a worst-case scenario with a 7.2 earthquake magnitude in Makati, would have structural impacts on 50% of infrastructures from partial to heavy damage, 18.3% would be heavily damaged, 32.8% would be partially damaged, and major lifelines and utilities that provide electricity, telephones, and water could be cut off. There will be 2,300 casualties, 7,700 injuries, and 156,000 displacements. Geological hazard threatens the City residents and its attractiveness as the preferred residential and business location in the country. In this study, we model the earthquake risk of high-rise building projects in Global City, located at the eastern portion of Makati City near Marikina Valley Fault System. To accomplish this, we identified important geological hazard-related factors and distributed survey question to experts to gather estimation of the importance of each factor, and Monte Carlo Analytic Hierarchy Process (MCAHP) was used to determine the consistency of the expert’s judgment. These factor weights from the MCAHP are applied to the gathered data, and a Quantum GIS software tool was utilized for visualization, producing a geo-hazard map that is color-coded representing weighted-simulation levels of estimated earthquake hazard risks.

1. Introduction

In a recent survey conducted by Skyscraper center, within the last decade an average of about seven new high-rise buildings every year is completed making the Philippines top ten among countries around the world with the greatest number of high-rise buildings 150 meters and taller. Metro Manila provides a salient example almost all new buildings, office towers and particularly residential buildings have more than thirty floors as shown in figure 1 Progression of High-Rise Buildings in the Philippines [1].

Moreover, the rapid progression of high-rise building in high seismic areas in Metro Manila has led the greatest risk associated in its development. Geological hazard threatens safety and health of the City residents and its attractiveness of as the preferred residential and business location in the country. Disaster risks must be carefully assessed so that measures may be introduced to avert potential danger to life and damage to property. In this study, we model the earthquake risk of high-rise building projects located at Makati City.
Makati City is occasionally beset by natural and man-made disasters brought about by geological, meteorological, and technological hazards. The proximity to West Valley Fault System contributes to geologic hazards, notwithstanding the density of high-rise building, infrastructure and technological development in the City. Makati lies within a tectonically active region in the Philippines known as the Philippine Mobile Belt and has experienced numerous destructive earthquakes in its recorded history. There are six (6) known tectonic earthquake generators affecting the area, namely (MGB, 2003 and Daligdig and Besana, 1993): (1) the Valley Fault System, (2) the Philippine Fault Zone, (3) the Lubang Fault, (4) the Casiguran Fault, (5) the Philippine Trench, and the (6) Manila Trench. The nearest active fault within the City is the West Valley Fault.

Based on Metro Manila Earthquake Impact Reduction Study (MMEIRS), a worst-case scenario with a 7.2 earthquake magnitude would have the following impacts in Makati based on 2004 data [2]:

- **Structural Impacts:** 50% of infrastructures would suffer partial to heavy damage
  - 18.3% (9,200) would be heavily damaged
  - 32.8% (16,500) would be partially damaged
  - Major lifelines and utilities that provide electricity, telephones, and water could be cut off due to seismic activity
- **Human Impacts:** There will be 0.5% (2,300) casualties, 1.6% (7,700) injuries, and 156,000 displacements.

As shown in figure 2, the official trace of the Marikina Valley Fault System can be seen on the eastern portion of Makati City. This fault system cuts across Barangays East Rembo, West Rembo, Comembo, Pembo and Rizal in District II. Earthquakes are part of a natural process and the damage it causes to urbanized areas affects decisions made on where and how to build. Whether these are houses, roads, skyscrapers, malls or any other structure needed for habitation or commerce, the structural system must fit the type of underlying material on which it rests [3].

The objective of this study is to determine the importance of the identified geological risk factors on a highly urban Central Business District in Metro Manila. Furthermore, this study explores how the Analytic Hierarchy Process (AHP) can be combined with Monte Carlo method and spatial modeling using GIS for vulnerability assessment due to earthquake hazard. AHP is popular as a practical decision-making tool applied in different fields. It converges traditional judgments of decision makers to a single numeric preference in order to estimate the pairwise comparisons of all pairs of objectives and decision alternatives while Monte Carlo method is known in testing statistical significance and
variation due to uncertainty [4]. This paper proposes the use of both methods to test the statistical significance and variation due to uncertainty of the resultant rankings of earthquake risk factors.

The Analytical Hierarchy Process (AHP) is a decision-aiding method developed by Saaty [5]. It aims at quantifying relative priorities for a given set of alternatives on a ratio scale, based on the judgment of the decision-maker, and stresses the importance of the intuitive judgments of a decision-maker as well as the consistency of the comparison of alternatives in the decision-making process [5]. Since a decision-maker bases judgment on knowledge and experience, then makes decisions accordingly, the AHP approach agrees well with the behavior of a decision-maker. The strength of this approach is that it organizes tangible and intangible factors in a systematic way and provides a structured yet relatively simple solution to the decision-making problems [6]. In addition, by breaking a problem down in a logical fashion from the large, descending in gradual steps, to the smaller and smaller, one is able to connect, through simple paired comparison judgments, the small to the large [7]. AHP is MCDM method where the process factors are hierarchically organized. Vertically, objective is on the highest level, with criteria, sub-criteria and alternatives on lower levels, respectively, as it is showed on the hierarchical structure on figure 3 [8].
For each level—the criteria, sub-criteria and alternatives, elements are compared in pairs. It means that one unfamiliar with the methodology of AHP can compare two elements from the same level according to verbal description scale. Fundamental scale used to compare the elements consists of verbal judgments ranging from equal to extreme (equal, moderately more, strongly more, very strongly more, extremely more) [8]. Corresponding to the verbal judgments are the numerical values (1, 3, 5, 7, 9) and intermediate values (2, 6, 8).

Comparison results of \( n \) elements belonging to Saaty’s scale and AHP hierarchical structure levels are comparison matrices. These matrices ensue vectors priority or \( \omega = (\omega_1, \omega_2, \ldots, \omega_n)^T \), \( \omega \) is the eigenvector of corresponding matrix. Vector priority involves normalized values which determine importance of the elements—weights of the elements which are compared. This is the method for determination of the priority vector of criteria, the priority vector of alternatives, and the final result of the priority vector of the objective. The priority vector of objective ranks alternatives respect to the importance of the criteria. Judgment consistency ratio (CR) of \( CI = (\lambda_{\text{max}} - n) / (n - 1) \), \( n \) is the matrix size with the appropriate value in table 1. If CR is more than 0.10, the judgment matrix is inconsistent [5].

| n  | 1   | 2   | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|----|-----|-----|-------|-------|-------|-------|-------|-------|-------|-------|
| RI | 0   | 0   | 0.58  | 0.90  | 1.12  | 1.24  | 1.32  | 1.41  | 1.45  | 1.49  |

GIS-multi-criteria evaluation have been used intensively in environmental planning and ecology management. Most analyses within this application area concern land suitability, resources allocation, plan/scenario evaluation, impact assessment and site search/selection problems [9]. The application of MCDM in general and especially spatial MCDM in the context of geological risk management is still rare. However, several methods are previously been employed and developed for vulnerability assessment. Among them, the analytic hierarchy process (AHP) is one of the most commonly used method of assessment [10], which works on a premise that decision making of complex problems can be handled by structuring the complex problem into a simple and comprehensible hierarchical structure. GIS model approach was utilized to research the current condition of eco environment quality for typical area of red soil hilly region [11]. GIS was also used to establish an environmental information system database. Based on the database, an eco environmental vulnerability assessment method using integrated fuzzy AHP (FAHP) and GIS was developed for the Danjiangkou Reservoir Area. According to eco environmental conditions and entropic effects, vulnerability was classified into five levels: potential, light, medium, heavy and very heavy [12].

2. Methodology

In order to accomplish the objectives of the study, factors associated to geological hazard that affects high-rise building projects are first identified using literature review and expert’s opinion. Based from these reviews, a classification method will be adopted to arrange risk factors into groups and sub-groups for the purpose of risk identification and modelling as illustrated in figure 3.

In the second stage of data collection, selection of group subject matter experts. The group of experts are defined according to skills, knowledge and unique qualities and the sample subject matter expert are selected using a probability sampling process. The subject matter should have undertaken and completed high-rise construction projects for the past 10 years and held managerial position. The data acquired from this group will play a vital role in the successful identification of geological risk factors and application of the proposed technique. In this study, subject matter experts from contractors and consultants from the high-rise construction industry in the country are involved. Finally, once the group of subject matter experts are selected, a survey questionnaire was administered. The pair-wise comparison matrices were formulated based from Saaty’s 9-point priority scale measurement as shown in table 2.
Table 2. Types of questions used for data collection

| No. | Question                                                                 | Answer          |
|-----|---------------------------------------------------------------------------|-----------------|
| 1   | In assessing geological hazard which do you think is most influencing factor between (Q1) Distance from valley fault and (Q2) Alluvial & rock material deposits? | Rating (1 to 9) |
| 2   | Which category do you think (Q1) Distance from valley fault best falls?   | (High, Medium, Low) |

Table 3. Saaty’s pair-wise comparison scale

| Numerical rating | Verbal judgments of preferences          |
|------------------|------------------------------------------|
| 9                | Extremely preferred                       |
| 8                | Very strongly to extremely               |
| 7                | Very strongly preferred                  |
| 6                | Strongly to very strongly                |
| 5                | Strongly preferred                       |
| 4                | Moderately to strongly                   |
| 3                | Moderately preferred                     |
| 2                | Equally to moderately                    |
| 1                | Equally preferred                        |

This study performed pair-wise comparisons at every level using the numeric preference of the subject matter expert’s judgement as input data from the survey questionnaire. Using Analytic Hierarchy Process (AHP) will utilize the derivation of potential importance and the level of riskiness of between potential risks factors as illustrated in figure 4 is the proposed geological risk breakdown for high-rise building.

![Figure 4. Proposed geological risk breakdown.](image)

Assuming the factors are independent and there is no feedback loop from elements in level of risk (High, Medium and Low) to factor elements. Judgment consistency ratio (CR) of $\text{CI} = (\lambda_{max} - n) / (n - 1)$. 

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1), n is the matrix size with the appropriate value in table 1. If CR is more than 0.10, the judgment matrix is inconsistent [5].

To address the ambiguity gap that occurs during the judgement of the selected group of subject matter experts in answering the survey questionnaires, this different judgement will be collected to define the probability distributions in order to create the probabilistic pairwise comparison matrix. Figure 5 illustrates an example of the proposed probabilistic distribution matrix. Since probabilistic judgements uses random variables the computation of eigenvectors and eigenvalues cannot be done in a traditional way, the Monte Carlo simulation technique will be used.

\[
\begin{array}{cccc}
Q_{11} & = Q_{12} (X \leq x) & \cdots & = Q_{1n} (X \leq x) \\
Q_{21} & = Q_{22} & \cdots & = Q_{2n} (X \leq x) \\
\vdots & \vdots & \ddots & \vdots \\
Q_{n1} & Q_{2n} & \cdots & Q_{nn}
\end{array}
\]

Figure 5. Proposed probabilistic distribution matrix.

Weighted simulation analysis using MCAHP was applied and integrated with the spatial data in order to describe the causative factors of a phenomenon under concern. The selection of criteria was based on the expert’s opinion and availability of data. This overlay was carried out as a Boolean overlay. In the second phase, Ranking Method was used, where every criterion under consideration was ranked in the order of the decision maker’s preference. Each factor was weighted according to the estimated significance. The inverse ranking was applied to these factors. Factor of rank 1 is the least important and 9 is the most important factor. In the third phase, the formula \(P (X \leq x)\) will be used to draw a random number equal to or greater than 1/9 and not greater than 9 in the Pair-wise Comparison Matrices to test the statistical significance, and variation due to uncertainty of the resultant rankings of each risk factors using Monte Carlo simulation. Figure 6 below illustrates the proposed procedure used to create geological hazard maps for the study area. The simulation of iterations \(n\) will provide estimates of the probabilities associated with the vector of priorities of the following criteria below:

- Six contributing factors for Earthquake are:
  - **(Q1) Distance from Valley Fault** – Areas within 5-meter buffer zone are exposed to ground rupture
  - **(Q2) Alluvial and Rock Material Deposits** – Areas with this type of material underneath produces deterministic Possible Ground Acceleration or shaking.
  - **(Q3) Loose sand and Shallow Ground Water Table** – Areas with this type of subsurface soil are prone to liquefaction.
  - **(Q4) Very Steep and Unprotected Slopes** – Areas of rock slides from towering walls of adobe are susceptible to landslide.
  - **(Q5) Infrastructure Density** - Above and underground utilities particularly electrical line and gas pipes may cause fire outbreak.
  - **(Q6) Distance from Sea Coast** – Proximity to source of tsunami.

For the Mapping and Table inputs, the CBD barangay maps are subdivided into equidistant square grids for distance reference using a customized Python Application Programming Interface (API) on Google Maps. Vertical elevation intersections and horizontal boundaries identified and marked for
analytical measurement. For the AHP Expert Judgment portion, a survey Questionnaire was distributed. The data for AHP was gathered, analyzed and tabulated to calculate the weight of each disaster criteria as shown in table 4.

![Diagram](image)

**Figure 6.** Methodology integrating GIS with Analytic Hierarchy Process and Monte Carlo simulation.

### 3. Results and Discussion

Pair-wise comparison matrix is created by assigning weights by experts. The weights are further evaluated in finding alternatives and estimating associated absolute numbers from 1 to 9 in fundamental scales of the AHP. These weights can be computed automatically in Microsoft Excel. Hence, the results of the relative weights of Q1 = Distance from Valley Fault, Q2 = Alluvial and Rock Material Deposits, Q3 = Loose sand and Shallow Ground Water Table, Q4 = Very Steep and Unprotected Slopes, Q5 = Infrastructure Density and Q6 = Distance from Sea Coast.
The result of MCAHP computation reveals that the Very Steep and Unprotected Slopes (Q4) at 31.00% is assessed by experts to be the largest contributing factor for earthquake hazard, followed by (Q2) Alluvial and Rock Material Deposits at 19.00%, (Q3) Loose sand and Shallow Ground Water Table at 16.00%, (Q6) Distance from Sea Coast at 15.00%, (Q1) Distance from Valley Fault at 11.00% and (Q5) Infrastructure Density at 9.00%. The consistency as measured in the in pair-wise comparisons of $C.R = \frac{1}{0.014}$ (value < 0.10) indicates that the basis expert judgment is reasonably consistent. For the simulated weights, (Q4) Very Steep and Unprotected Slopes at 31.00% to be the largest contributing factor for earthquake hazard as shown in table 4.

Table 4. Simulated priority weights for earthquake related factors

|     | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 | Wt | C.R |
|-----|----|----|----|----|----|----|-----|-----|
| Q1  | 1  | 0.6| 0.6| 0.3| 1.1| 0.9| .11 |     |
| Q2  | 1.7| 1  | 1.8| 0.6| 1.6| 1.0| .19 |     |
| Q3  | 1.7| 0.6| 1  | 0.5| 2.3| 1.1| .16 |     |
| Q4  | 2.9| 1.7| 2.2| 1  | 3.4| 1.8| .31 | 1.4%|
| Q5  | 0.9| 0.6| 0.4| 0.3| 1  | 0.7| .09 |     |
| Q6  | 1.1| 1.0| 0.9| 0.6| 1.4| 1  | .15 |     |

Finally, a Geo-hazard map was generated from the integration of criteria weights from MCAHP with the criteria maps into the GIS software. The map presents a rank of highest and lowest suitability areas. The geo-hazard classification is divided into three classes: Low Risk, Moderate Risk and High Risk (see figure 7, figure 8 and figure 9).
4. Conclusions

In this study, MCAHP is combined with GIS to come up with a tool for evaluating geological hazards in the CBD areas in Makati City. Such tool was developed after gathering topological information about the city and reliable (C.R.< 0.10) expert criteria assessment for each earthquake related risk factors, and then applying multi-criteria analysis techniques based on AHP to an open source Quantum GIS software.

The proposed method will aid the private sector specially the project owners in weighing and valuation of high-rise project risks and sources in terms of impact and consequences during planning stage and before construction. The most significant contribution of this study in the field of high-rise building construction in the Philippines, is its pioneering endeavor to evaluate, prioritize and quantify potential impact and probability of occurrence of the identified geological risk factors which will provide an effective and reliable basis in the allocation of resources and identifying ways in minimizing its consequential losses.
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