Characterization of Cebu Province Municipalities using Probabilistic Seismic Hazard Assessment (PSHA) And Geographic Information System (GIS)

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Abstract. Cebu province is considered to be one of the most developed provinces in the Philippines with 2.94 Million population. Last October 2013, a Magnitude of 7.2 earthquake affected the province and left a death toll of 222. Many of the cultural heritage structures were affected, and with this it is important that seismic assessment is performed for the province of Cebu. Information regarding its vulnerability to earthquake damages is needed to lessen the casualties. In this study the structures were assessed though Probabilistic Seismic Hazard Assessment and thoroughly characterized qualitatively according to Low, Medium and High Priority by Geographic Information System (GIS). These characterizations may be used as basis for seismic provisions in building codes, budget allocations for risk reduction and for risk models.

1. Introduction

It is necessary to evaluate the earthquake hazards to mitigate these losses. One of the forms in assessing the hazards of earthquakes is by utilizing the Probabilistic Seismic Hazard Assessment [1], a tool which aims to quantify the uncertainties involved in seismic activities, and combine these to generate a distribution of earthquakes that may occur at a particular location and earthquakes can cause losses in billions of dollars and thousands of lives yearly. It has also attracted human curiosity since ancient times, but the scientific study of earth tremors is a fairly recent attempt [2].

Many studies on seismic hazards have been conducted such as the faults, sources of earthquakes, and ground shaking, the data garnered were transformed and updated into a medium that will serve as a guide to reduce the risk from the said hazards. Most of these guides are in a form of maps using obtained hazard results in terms of exceedance rate curves [3].

These assessments may be used as basis for seismic provisions in building codes and for risk models for structures especially for perilous cities with high population density, inappropriate constructions, inadequate infrastructure systems, and high levels of seismic activity [4].

Cebu province is a part of Central Visayas Region (Region VII) and is considered to be one of the most developed provinces in the Philippines. It is located 584 km south of Manila and is surrounded by the Camotes Sea on its eastern side, Tanon Strait on its western side, Visayan Sea on its northern side and Bohol Strait on its...
southeast side as shown in Figure 1. The province is approximately 220 km long and 41 km with respect to its widest area. Cebu City, its capital, is also known as the Queen City of the South due to its promising potential in economic growth and infrastructure development. The province’s coastlines are narrow and are mostly inhabited by the locals. The central part of the province is composed of limestone plateaus and predominantly hilly and mountainous. The rugged mountain ranges traverse from Daan Bantayan, northern area, to the town of Santander, southern part. The highest peak of Cebu province is approximately 1,000 m above sea level and it is located at the northern end of Cebu Island.

Last October 15, 2013 an earthquake with tectonic origin with a Magnitude of 7.2 occurred at Bohol Island. Its epicenter is located at coordinates of 9.86˚ latitude and 124.07˚ longitude with respect to Bohol Island and 6 km southwest of Sagbayan, Bohol. The earthquake affected the provinces of Region 7 namely, Bohol, Cebu and Siquijor. It also affected some provinces from the Negros Island region, Negros Oriental, and Region 6, Iloilo. The most devastated area is Bohol were 208 out of the 222 total death toll was from the province only. The second most affected province is Cebu. 13 people died in but several infrastructures were also damaged by the earthquake. Basilica Minore del Sto Niño is one of those structures. Natural disasters, like an earthquake, can happen again and this can be quantified by determining the return period. This parameter predicts when this magnitude will happen once again. Usually it may take 100 years or more but accurate prediction is difficult to achieve. With this, it is important that seismic assessment is performed for the province of Cebu. Information regarding its vulnerability to earthquake damages is needed to lessen the casualties.

Figure 1. Location of Cebu Island

2. Methodology
The study will commence with the Probabilistic Seismic Hazard Analysis (PSHA) followed by the Geographic Information System (GIS) then the Prioritization based on the Probability of Exceedance (PoE), shown on Figure 2.
2.1. Probabilistic Seismic Hazard Assessment (PSHA)

Probabilistic Seismic Hazard Assessment will consider all possible earthquake events and resulting ground motions, along with their associated probabilities of occurrence, in order to find the level of ground motion intensity exceeded with some tolerably low rate. A proposed five (5) basic steps in Probabilistic Seismic Hazard Assessment [5]:

1. Identify all earthquake sources capable of producing damaging ground motions.
2. Characterize the distribution of earthquake magnitudes.
3. Characterize the distribution of source-to-site distances associated with potential earthquakes.
4. Predict the resulting distribution of ground motion intensity as a function of earthquake magnitude, distance, etc.
5. Combine uncertainties in earthquake size, location and ground motion intensity, using a calculation known as the total probability theorem.

The end result of these calculations will be a full distribution of levels of ground shaking intensity, and their associated rates of exceedance. The results can then be used to identify a ground motion intensity having an acceptably small probability of being exceeded.

In detail, to identify all earthquake sources capable of producing damaging ground motions, seismic records by the Philippine Institute of Volcanology and Seismology (PHIVOLCS) were used and magnitudes are presented as surface magnitude, thus surface magnitudes were converted to moment magnitudes, using in Equation 1:

\[
M_w = e^{-0.222+0.233M_s} + 2.863 \\
M_w = e^{-4.664+0.859M_b} + 4.555 \\
M_w = 1.280M_L - 1.585 \quad M_L < 6.08 \\
M_w = 0.898M_L + 0.742 \quad M_L > 6.08
\]

Equation 1

Where: \(M_w\) is the earthquake moment magnitude, \(M_L\) is the earthquake live wave magnitude and \(M_s\) is the earthquake surface wave magnitude.

A total of 1209 seismic data were collected from PHIVOLCS. The converted magnitudes greater than 5.0 were considered in the analysis. Since, it is at this magnitude that damages to structures can start to occur. North Bohol Fault was included in the analysis since there are only few seismic data available in Cebu. A total of two sources were deduced from the filtered data. The sources were grouped in such a way that the seismic activity chosen per source must be close to the original location of the fault line. Line source 1 (LS1) is the South Cebu Segment (in red) and Line source 2 (LS2) is the North Bohol Fault (in blue), shown on Figure 3.

To characterize the distribution of earthquake magnitudes, the Gutenberg – Richter recurrence law [6] was used to determine the Probability Distribution of Seismic Magnitude \(M\), \(P(M)\), shown on Equations 2 to 4:

\[
\lambda_m = 10^{a-bm} = \exp(\alpha - \beta m)
\]

Equation 2
\[
\alpha = 2.303A
\]

Equation 3
\[
\beta = 2.303b
\]

Equation 4
Where: \( \lambda_m \) is the annual rate of exceedance of magnitude M earthquake; \( a \) and \( b \) are the constants derived from regression analysis;

Equation 5 was used to determine the probability density function, the equation developed was used [7]:

\[
f_m(m) = \frac{\beta \exp[-\beta(m - m_0)]}{1 - \exp[-\beta(m_u - m_0)]}
\]

Equation 5

Where: \( m_l \) and \( m_u \) are the upper limit of magnitude range and lower limit of magnitude range, respectively.

![Figure 3. Seismic Sources of Cebu Province](image)

The earthquake sources was considered as linear, the rupture length (L) must be determined [10], and Equation 6 was used:

\[
\log L = 0.74 M_w - 3.55
\]

Equation 6

Where: \( L \) is the rupture length and \( M_w \) is the earthquake moment magnitude.

The classification of the distribution of source-to-site distances associated with potential earthquakes was also done, thereafter. The coordinates of the South Cebu Segment and North Bohol Fault was garnered using the Google earth application, shown on Table 1:
Table 1. Coordinates of South Cebu Segment and North Bohol Fault

| Fault Name     | North Bohol Fault | South Cebu Segment |
|----------------|-------------------|--------------------|
| LoM longitude  | 123.858379        | 123.337223         |
| LoM latitude   | 9.834842          | 9.623139           |
| RoM longitude  | 124.147889        | 123.605135         |
| RoM latitude   | 10.023667         | 10.139637          |
| Earth's Radius, km | 6,371             | 6,371              |
| Length, km     | 38.0717           | 64.5652            |

It is also necessary to model the distribution of distances from earthquakes to the site of interest to predict ground shaking at a site, shown on Table 2 and 3. It is generally assumed that earthquakes will occur with equal probability at any location on the fault for a given earthquake source. It is generally simple to identify the distribution of source-to-site distances using only the geometry of the source given that locations are uniformly distributed. The probability density function (PDF) of $R$ is determined by Equation 7 and a sample probability density function (PDF) of $R$ is shown on Figure 4.

$$P(R = r) = \frac{\text{length of fault within distance } r}{\text{total length of fault}}$$

Equation 7

Figure 4. Probability Density Function

Given the different parameters for the resulting distribution of ground motion intensity as a function of earthquake magnitude and distance can now be determined. An attenuation model developed was used in the study [8], shown on Equation 8.

$$\log A = 0.41 M - \log (R + 0.03 \times 10^{0.61 M}) - 0.0034 R + 130$$

Equation 8

Where: $A$ is the mean PHA value, $R$ is the shortest distance between the site and the rupture and $M$ is the surface wave magnitude.

With the above information in place, we can now combine uncertainties in earthquake size, location and ground motion intensity, using a calculation known as the total probability theorem [8].

$$[X \geq x] = \sum_{i} v_i \int_{M_{\text{max}}}^{M_{\text{max}}} \int_{X \geq M, R} f_{M[R|M]} dM dR M_{0} R | M$$

Equation 9

Where: $[X \geq x]$ is the overall annual frequency that ground motion at a site exceeds the chosen level $X = x$; $v_i$ is the annual rate of occurrence of earthquakes on seismic source $i$ having magnitudes between $M_0$ and $M_{\text{max}}$; $M_0$ is the minimum magnitude of engineering significance; $M_{\text{max}}$ is the maximum magnitude assumed to occur on the source; $[X \geq x|M, R]$ is the conditional probability that the chosen ground motion level is exceeded for a given magnitude $M$ and distance $R$; $f_{M}[M|R|m]$ is the probability density function of earthquake magnitude; $f_{R}[M|r|m]$ is the probability density function of distance from the earthquake source to the site.
The end result of the PSHA calculations will be a full distribution of levels of ground shaking intensity, and their associated rates of exceedance. The results can then be used to identify a ground motion intensity having an acceptably small probability of being exceeded, a sample is shown in Figure 5.

2.2. Geographic Information Systems (GIS)
To capture, store, manipulate, analyze, manage, and present all types of spatial or geographical data is what Geographical Information System (GIS) is designed. It is a system that integrates, stores, edits, analyzes, shares, and displays geographic information which can be used in the different technologies, processes, and methods in the field of engineering, planning, management, transport/logistics, insurance, telecommunications, and business.

Many applications of GIS has been used for Disaster Mitigation study, in particular to disseminate such critical information to wide audience as possible. GIS was used to serve as a warning to vulnerable communities against disaster [9]. The provinces and municipalities of Cebu is shown on Figure 6. The workflow involved the use of GIS software [10] in the visualization of the Probability of Exceedance (PoE) for each Cebu Municipality is shown in Figure 7.

![Figure 5. Peak Ground Acceleration vs. Probability of Exceedance](image1)

![Figure 6. Provinces and Municipalities of Cebu](image2)
2.3. Prioritization of Cebu Municipalities
The end result of the PSHA calculations will be a full distribution of levels of ground shaking intensity, and their associated rates of exceedance. The results can then be used to identify a ground motion intensity having an acceptably small probability of being exceeded.

Once the Probability of Exceedance (PoE) values were obtained for each structure or bridge, such would then be classified according to their PoE values using Table 2 [11]. The basis would be in terms of the occurrence/probability for a disaster to happen.

![Figure 7. Cebu Municipality Priorities](image)

| Level | Qualitative Rating | Description | Likelihood (POE) | Expressed in Percentage |
|-------|--------------------|-------------|------------------|-------------------------|
| 1     | Low                | Low likelihood of occurrence | 1/1,000-1/10,000 | 0.1% or less            |
| 2     | Moderate           | Moderate likelihood of occurrence | 1/100-1/1,000 | 1% or less > 1%         |
| 3     | High               | High likelihood of occurrence | >1/100         | >1%                     |

3. Results and Discussions
Cebu has a total population, as of 2010, of 4,632,359 with 53 municipalities. The province is approximately 220 km long and 41 km with respect to its widest area. Cebu City, its capital, is also known as the Queen City of the South due to its promising potential in economic growth and infrastructure development. The province’s coastlines are narrow and are mostly inhabited by the locals. The central part of the province is composed of limestone plateaus and predominantly hilly and mountainous. The rugged mountain ranges traverse from Daan Bantayan, northern area, to the town of Santander, southern part. The highest peak of Cebu province is approximately 1,000 m above sea level and it is located at the northern end of Cebu Island.

With the given instances, Probabilistic Seismic Hazard Assessment may be used as basis for seismic provisions in building codes and for risk models used in insurance rate structures for each municipality. PSHA quantify the uncertainties involved in seismic activities of each municipality. The end result of this study are PSHA calculations will be a full distribution of levels of ground shaking intensity, and their
associated rates of exceedance. The individual results can then be used to identify a ground motion intensity having an acceptably small probability of being exceeded.

When all the possible earthquakes and magnitudes have been considered in the Cebu, shown on Table 3, the prioritization with respect to the Probability of Exceedance for Cebu. Each municipality is grouped into: High, Medium and Low Priority based on their Probability of Exceedance and considering their total population.

With the location of southern municipalities of Cebu, such as Alegria and Alongsian, the Probability of Exceedance for this municipality is highest, since their location is very near the South Cebu Segment and North Bohol Fault. Shown on Table 3, joining them in the High Priority category are the following municipalities: Argao, Badian, Barili, Boljoon, Carcar, Dalaguete, Dumanjug, Ginatilan, Malabuyoc, Moalboal, Oslob, Pinamungajan, Ronda, Samboan, San Fernando, Santander and Sibonga. The budget allotment for these municipalities in Disaster Response should be looked into since the probability of exceedance for these municipalities are high, and frequent ground motions are usually felt in these areas.

To validate, a Magnitude 7.2 earthquake struck the Province of Cebu on October 5, 2013. The epicenter 6 kilometers S 24° W of Sagbayan, and its depth of focus was 12 kilometers. One of the notable damage is the Basilica Minore del Sto Niño, located at the Cebu City, shown on Figure 8. It can be noted that Cebu City was classified as moderate in the assessment, thus the prioritization is valid.

| Table 3. Cebu Municipality Priorities |
|--------------------------------------|
| **HIGH**                             | **MEDIUM** | **LOW**                      |
| Alcantara                            | Asturias   | Bantayan                     |
| Alcoy                                | Balamban   | Bogo                         |
| Alegria                              | Borbon     | Daanbantayan                 |
| Aloguinsan                           | Carmen     | Madridejos                   |
| Argao                                | Catmon     | San Remigio                  |
| Badian                               | Cebu City  | Santa Fe                     |
| Barili                               | Compostela |                             |
| Boljoon                              | Consolacion|                             |
| Carcar                               | Cordova    |                             |
| Dalaguete                            | Danao      |                             |
| Dumanjug                             | Lapu-Lapu  |                             |
| Ginatilan                            | Liloan     |                             |
| Malabuyoc                            | Mandaue    |                             |
| Moalboal                             | Minglanilla|                             |
| Oslob                                | Naga       |                             |
| Pinamungajan                         | Pilar      |                             |
| Ronda                                | Poror      |                             |
| Samboan                              | San Francisco|                            |
| San Fernando                         | Sogod      |                             |
| Santander                            | Tabogon    |                             |
| Sibonga                              | Tabuelan   |                             |
|                                       | Talisay    |                             |
| Total Population: **860,231**        | **419,555**| **3,352,573**               |

Total Population: **860,231**

Total Population: **3,352,573**
4. Conclusions and Recommendations
The study provided an assessment though Probabilistic Seismic Hazard Analysis and thoroughly classified qualitatively according to Low, Medium and High Priority by Geographic Information System (GIS). With enough knowledge on the seismicity of Cebu Segment and North Bohol Fault, designers can ensure that their structures can withstand a given level of ground shaking, while maintaining a desired level of performance. There is uncertainty on the location, size, and resulting shaking intensity of future seismic motions in the said provinces but with the use of Probabilistic Seismic Hazard Analysis (PSHA), it will quantify the uncertainties, and combine them to produce an explicit description, such as the Probability of Exceedance.

Once the Probability of Exceedance is available, GIS may be used to disseminate such critical information to as wide an audience as possible. These information may be used as basis for seismic provisions in building codes, budget allocations for risk reduction and for risk models used for municipalities.

It is recommended to apply the acceleration for the structure in consideration, spectral acceleration, which is the amount of earthquake force the structure experience, for corresponding values of period is determined. A response hazard curve must be generated for the reliability analysis of the various structures for the following periods: 0.1, 0.2, 0.3, 0.5, 1, 2, 3 and 4 seconds.

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