

Seismic hazard analysis in the Philippines using earthquake occurrence data

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ABSTRACT: The seismic hazard in the Philippines is evaluated from historical earthquake data using a new computer program called the Seismic Hazard Mapping Program (H-MaP). The seismic hazard is given in terms of the expected peak ground acceleration and the expected acceleration response spectrum. Regions of high seismic hazard are identified. These include Central Luzon which suffered heavy damage during the 16 July 1990 earthquake. The design levels of the seismic force of the Philippines are compared with those of Japan and are found to be considerably lower. Long period structures are found to be more vulnerable to damage. The collection of strong ground motion records from Philippine earthquakes is necessary for more realistic design levels for the Philippines. From the seismic hazard maps, a seismic zoning map based on the expected maximum accelerations is proposed.

1 INTRODUCTION

The 1990 Luzon earthquake disaster exacted a heavy toll in the human, economic, and social resources of the Philippines at a time when she was struggling for development. The first two authors joined the investigation teams of the Architectural Institute of Japan (AIJ) and of the Japan Society of Civil Engineers (JSCE) which surveyed the damage of the earthquake a month after it occurred.

The earthquake affected a wide area and many seismic hazards like building and bridge collapse, landslides, and liquefaction were observed. Building collapse was the main cause of human casualties. Although there were two isolated cases of building collapse near the epicenter, heavy damage was observed in some areas which are more than 100 kilometers from the epicenter. Since no strong motion records of the main shock were taken, it is difficult to quantify the main causes of the structural collapse.

To address the need to mitigate earthquake disasters in the Philippines, a seismic hazard study using earthquake occurrence data was made. It is hoped that this work can help engineers to better understand the magnitude of hazard or risk faced by natural and man-made structures in the Philippines.

For engineering purposes, earthquake monitoring data in the Philippines is severely lacking. Even the seismic design provisions were adapted from the United States. But without actual data, it is very difficult, if not impossible, to assess the level of safety that is being used for design.

This study aims to assess the seismic hazard in the Philippines and its implications to the seismic design

code. By using earthquake occurrence data, the task of identifying seismic sources and their parameters is avoided. Due to the lack of data, this task has inherent uncertainties. It is acknowledged that the simple model used in this study has limitations, but the general trend in the regional seismic hazard can be immediately seen. It is believed that this work can help engineers make more sound decisions regarding seismic design.

2 EVALUATION OF SEISMIC HAZARD FOR ONE SITE

There are two general types of seismic hazard methodologies. The first method uses the historical earthquake occurrence as pioneered by Kawasumi (1951) and applied recently by Tomatsu and Katayama (1988). The second is based on probabilistic principles pioneered by Cornell (1968). The probabilistic approach assumes seismic sources as being points, lines, or dipping planes. Seismic parameters such as seismic activity and the maximum probable magnitude are assigned to each source.

Due to the complex nature of the seismicity in the Philippines and the uncertainties in identifying the locations of seismic sources and in assigning seismic parameters, the method based on historical earthquake data was chosen for this study. The seismic hazard is based primarily on the assumed relationship of the mean annual occurrence rate, v , of a peak ground motion equal to or greater than a given value as:

$$\log v = a + b \log y \quad (1)$$

where y is the peak ground motion, and a and b are regression constants.

To evaluate the seismic hazard at a given site, earthquakes within a given epicentral distance from the site are chosen. For each earthquake, the value of the peak ground motion is estimated using attenuation laws. A regression analysis is then performed to determine the values of a and b .

If the occurrence of peak ground motion values is assumed to be a Poisson process, then the probability of k occurrences of the peak ground motion in t years is given by:

$$P(k, t) = \frac{\nu t^k e^{-\nu t}}{k!} \quad (2)$$

The probability of no occurrence in t years is then:

$$P(0, t) = e^{-\nu t} \quad (3)$$

The value of the peak ground motion for a given non-exceedance probability, Q , and time period, t , is then given by:

$$\log y = [\log(-\ln Q / t) - a] / b \quad (4)$$

For this type of analysis, the relation between the exceedance probability and the return period of peak ground motion is given by:

$$T = -t / \ln Q \quad (5)$$

Thus the 10% probability of exceedance in 50 years is equivalent to a return period of about 475 years.

Data catalogues from the Philippine Institute of Volcanology and Seismology (Phivolcs), the International Seismological Center (ISC) and the U.S. Geological Survey (USGS) were collected and analyzed for completeness using the method proposed by Stepp (1972). The catalogue is deemed to be complete for a given magnitude category if the slope of the standard deviation of the mean annual occurrence rate for the period is close to the slope of the model line. The catalogue taken from the USGS data set was found to be complete for magnitudes 5.0 to 7.0 from 1963 to 1990 (Figure 1). Thus, this data set was used for the analysis. The plot of epicenters of the data used is given in Figure 2.

The attenuation law for peak ground acceleration (PGA) used in the analysis was developed by McGuire (1977) as:

$$a = 0.482 e^{0.64 M} (r + 25)^{-1.3} \quad (6)$$

where a is the peak ground acceleration in g , M is the magnitude, and r is the hypocentral distance in kilometers.

For the acceleration response spectrum of a 5% damped system, the attenuation law used was developed by Katayama (1982) as:

$$S_A(T, h=0.05) = f_M \cdot f_\Delta \cdot f_{GC} \quad (7)$$

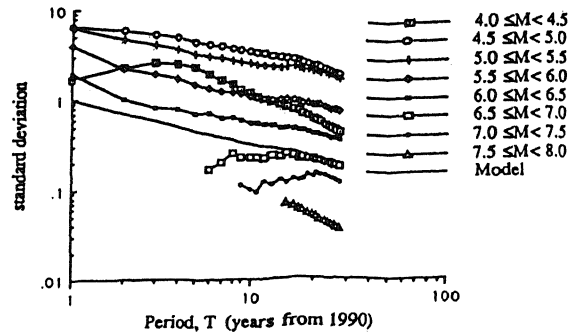


Figure 1. Standard deviation of the mean annual occurrence rate with respect to the sample period.

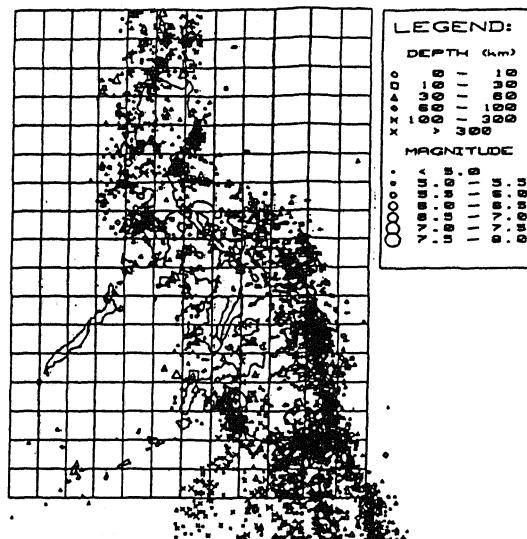


Figure 2. Plot of epicenters of the data used in the analysis (USGS, 1963-1990).

where f_M , f_Δ , and f_{GC} are the weighting factors for the magnitude, epicentral distance, and ground condition, respectively. The weighting factors are dependent on the period, T .

In the absence of strong ground motion records, a survey of fallen objects in the affected area can give rough estimates of the maximum accelerations experienced at different sites. The upper and lower bounds of the maximum accelerations can be estimated by calculating the aspect ratio of simple objects like tombstones. During the damage survey of the JSCE, fallen objects with simple shapes were used to estimate the maximum accelerations. These included gateposts, highway markers, furnitures, and religious statues. A summary of the results is given in Figure 3.

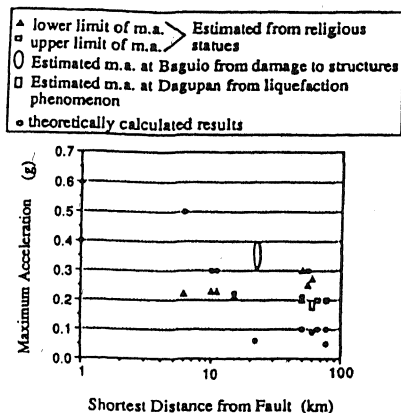


Figure 3. Estimated maximum accelerations from field survey and theoretically calculated results.

3 REGIONAL SEISMIC HAZARD

A new computer program called the Seismic Hazard Mapping Program (H-MaP) was developed and used to compute the seismic hazard parameter. The seismic hazard value was calculated for 13,230 points in the Philippines and this can be displayed as color maps or as contour maps. The parameters that can be computed are the return period of the peak ground motion and the probability of exceedance for a given time period. By using color codes, the regional differences in the seismic hazard can be immediately seen.

Preliminary analysis showed that as the site being evaluated goes nearer a seismic source (represented by a dense cluster of earthquakes), the value of the expected PGA becomes very large. This was caused by the non-linear tendency of the relationship between the PGA and the occurrence rate in the log-log scale (Figure 4). Since the concern of seismic hazard analysis are the regions of high PGAs, a cut-off scheme for the regression at a mean annual occurrence rate of 2.0 was used.

Figure 5 is a contour map of the 100-year peak ground acceleration (PGA) in cm/s^2 for the country. By comparing the hazard map with the plot of earthquake epicenters of the data used, it can be seen that higher seismic hazard areas follow a band corresponding to the earthquake generators in the country. The highest seismic hazard can be found in regions where several shallow earthquakes have occurred. These regions, with 100-year PGAs greater than 200 cm/s^2 , are in Central Luzon, Southern Luzon, and the peninsular portion of Western Mindanao. Central Luzon experienced heavy damage during the Luzon earthquake. To check if its high seismic hazard is caused by seismic activity related to that earthquake, the analysis was repeated for the data excluding the 1990 earthquakes. It was found that the region of high seismic hazard still exists.

Figure 6 shows the hazard in terms of the 100-year acceleration response spectrum for the period $T=0.7\text{s}$.

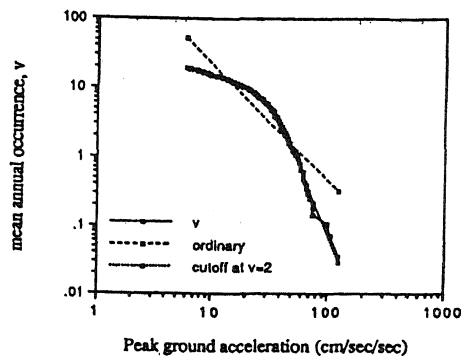


Figure 4. Regression of the mean annual occurrence rate and the PGA for a site near a seismic source.

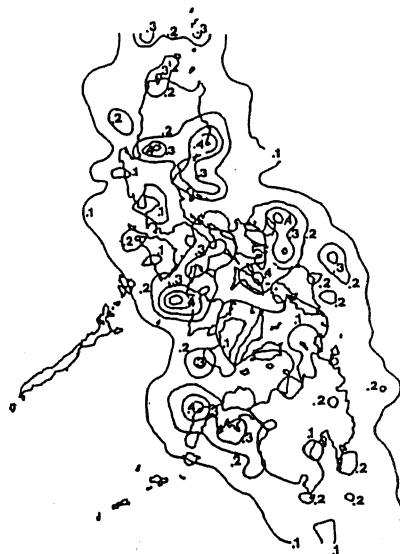


Figure 5. Contour map of 100-year peak ground acceleration (PGA) in g.

4 CONSIDERATION OF EARTHQUAKE FORCE IN DESIGN

The Philippine seismic design provisions are patterned after the Uniform Building Code (UBC) of the United States. Unless dynamic analysis is performed, the lateral seismic force applied to the structure is evaluated by calculating the base shear using the modified seismic coefficient method as:

$$\text{Base Shear} / W = Z \cdot C \cdot S \cdot I \cdot K \quad (8)$$

where W is the weight of the structure; Z , the zoning factor; C , the response factor; S , the soil factor; I , the

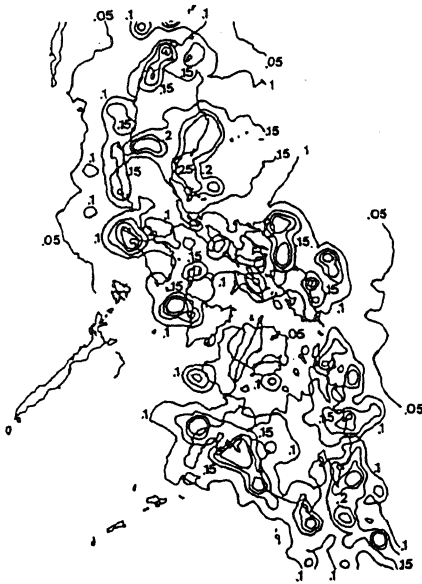


Figure 6. Contour map of 100-year acceleration response spectrum for period, $T=0.7s$, and 5% damping.

importance factor; and K , the structural type factor.

The seismic coefficient is dependent on the fundamental period of the structure and the fundamental period of the ground. The seismic coefficient for ordinary structures on rock sites for different fundamental periods of the structure and the seismic coefficients for the Japanese building and bridge codes are plotted in Figure 7.

When the coefficients are compared, it can be seen that the seismic coefficient for the Philippines is considerably lower than that for Japan. This is especially true for structures with fundamental periods from 0.2s to about 1.2s where the difference is from 0.05 to about 0.06.

For short period structures, the response of the structure is close to the PGA of the ground motion. In this case, the maximum value of the seismic coefficient is 0.14.

In longer period structures, the seismic coefficient for the Philippine code decreases drastically. By taking the hazard maps in terms of the acceleration response spectrum for several periods, the values of the seismic coefficients and the expected response can be compared.

A survey of buildings in an area in Baguio City revealed that most of the buildings which were severely damaged or collapsed are those with seven to nine stories. A summary of the percentage of damaged buildings with respect to the number of stories is shown in Figure 8.

Figure 9 shows the distribution of the return periods for exceeding the design seismic coefficients. It can be seen that there are some regions in the country which have a high probability (i.e., low return period) of exceeding the design seismic coefficient. For these

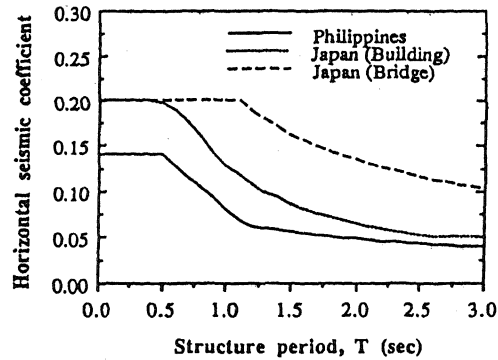


Figure 7. Design horizontal seismic coefficients for the Philippine building code and the Japanese building and bridge codes (rock sites).

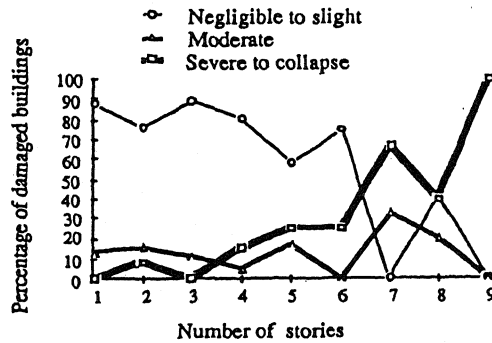


Figure 8. Percentage of damaged buildings in Baguio City with respect to the number of stories.

regions, an increase in the value of the seismic coefficients is indicated.

5 SEISMIC ZONATION

Results of the previous section showed that by using the current design codes, structures built in some regions of the country may be under-designed based on the expected seismic forces. One of these regions is Central Luzon where heavy damage was experienced during the Luzon earthquake. For these regions, a higher seismic coefficient should be used.

From these results, a new seismic zoning map based on the 100-year PGA is proposed (Figure 10). Table 1 gives the mean and standard deviation of the expected PGA for Zones 2 to 4. Zone 1 is historically considered aseismic and the PGAs were not calculated for this region. Table 2 gives the mean and standard deviation for the return period for exceeding the current design seismic coefficients. Zone 4 corresponds to a return period of about 40 years; Zone 3, from 40 to 200 years; and Zone 2, more than 200 years.

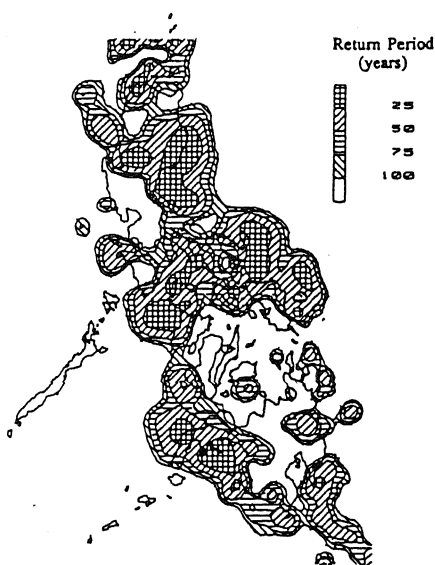


Figure 9. Return periods for exceeding seismic coefficient of the Philippine code ($I = 1.0, K = 1.0$, rock sites).

By taking the mean of Zone 3 as a reference, the zone factors can be computed by normalizing the mean of the expected PGA with respect to Zone 3. The resulting zone factors are given in Table 3. It should be noted, however, that the values in Tables 1 and 2 were computed from the entire analysis area which also includes the sea. Currently, a scheme for calculating only for the land portion is being studied.

Figure 11 is the current seismic zoning map. While the current zoning map has three zones, the proposed zonation has four. Zone 4, which represents the highest expected PGAs, is assigned the highest value of the zonation factor, Z .

By comparing the two zone maps, several observations can be made. For both maps, Zone 1, which represents aseismic regions in the country, are identical. A region in Central Visayas is assigned as Zone 2 in both maps. For the current map, most of the remaining regions are assigned as Zone 3.

One main contradiction is the peninsular portion of Western Mindanao which is assigned as Zone 4 in the new map. It is assigned as Zone 2 in the current map. Some portions of Northern Luzon also have the same situation.

It can also be noticed that the capital, Metro Manila, is assigned as Zone 2. Manila has many medium- and high-rise structures; therefore, it must be cautioned that the proposed seismic zone map is for short period structures on rock sites. As shown in Figure 6, the distribution of the seismic hazard is different for long period structures. A study of the response spectrum for Philippine earthquakes is needed for a possible change in the shape of the design spectrum.

Table 1. Mean and standard deviation of the 100-year PGA for zones 2 to 4.

ZONE	Mean (cm/s ²)	Standard deviation (cm/s ²)
2	66.7	19.8
3	142.2	26.8
4	269.9	61.4

Table 2. Mean and standard deviation of the return period of exceeding the design seismic coefficients.

ZONE	Mean (years)	Standard deviation (years)
2	2446.1	4379.5
3	97.9	43.6
4	26.4	7.9

Table 3. Zone factors for seismic coefficient computation.

ZONE	Zone factor, Z
1	0.5
2	0.7
3	1.0
4	1.5

6 CONCLUDING REMARKS

A new computer program was developed to calculate the seismic hazard in the Philippines using historical earthquake occurrence. The seismic hazard was calculated in terms of the expected peak ground acceleration and the expected acceleration response spectrum. Regions with high seismic hazard were identified. These included Central Luzon which was heavily damaged by the 1990 Luzon earthquake.

A comparison of seismic coefficients used for design showed that the design levels in the Philippines are considerably lower than that in Japan. Based on the hazard maps and the seismic coefficients, a new seismic zoning map is proposed. The new hazard map has four zones and the value of the highest zone factor, Z , is given as 1.5. The new zoning map is based on the expected PGA on rock sites; therefore, it is applicable for short-period structures.

Several buildings with seven to nine stories in Baguio City experienced severe damage or collapse. This phenomenon is similar to damage in Manila during the 1968 and 1970 earthquakes. The seismic design provisions of the Philippines are patterned after the UBC code in the United States. This stresses the need to develop seismic provisions based on data from the Philippines.

The attenuation laws used in this study are based on data from the United States and Japan. This was necessary because of the lack of data in the Philippines.

Because of these observations, a review of the design values specified by the design code and the shape of the design spectrum is needed. For a better estimate of the seismic hazard and the seismic forces applied to structures during earthquakes, strong ground motion records in the Philippines should be collected and



Figure 10. Proposed seismic zoning map for the Philippines based on the expected peak ground acceleration.

analyzed. Thus, the collection of strong ground motion records should be given a high priority to improve earthquake disaster mitigation in the Philippines.

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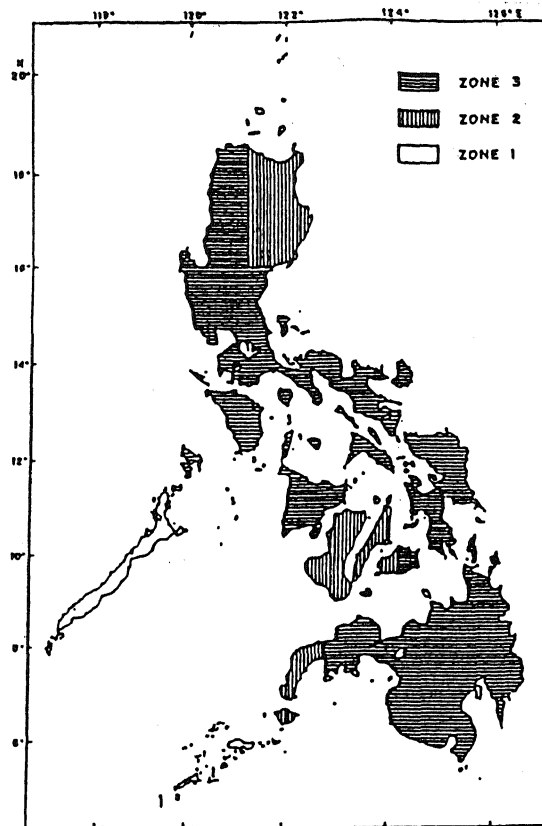


Figure 11. Current seismic zoning map in the Philippines (Villaraza, 1991).

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