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SEISMIC MACROZONATION OF THE PHILIPPINES BASED ON SEISMIC HAZARD ANALYSIS

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This paper proposes new seismic hazard maps and seismic macrozonation for the Philippines based on earthquake occurrence data. The completeness of two earthquake catalogues is examined and the time periods in which the data are complete are identified for each magnitude level. For the maximum use of the available data, the data of large earthquakes are taken from the long time period while the data of small earthquakes are taken from the shorter time period in which they are complete. The seismic design provisions of the Philippines are compared with those of Japan and are found to be substantially lower. To check the significance of this, the seismic hazard of Japan is also analyzed and compared with the Philippines. Based on the distribution of the 100-year return period peak ground acceleration, a new seismic zonation map of the Philippines is developed.

Key Words *: seismic hazard, seismic macrozonation, design code, Philippines*

1. INTRODUCTION

The 1990 Luzon earthquake disaster[1] exacted a heavy toll in the human, economic, and social resources of the Philippines. 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. Obviously, the ground motion exceeded the strength of the structures. However, no in-depth review of the collapsed structures was made to check if there were deficiencies in the design and/or construction. If the collapsed structures did not violate the design code, then there is a need to revise the code. But since no strong motion record of the main shock was taken, it is difficult to specify the provisions that need to be revised.

To mitigate earthquake disasters in the Philippines, the seismic hazard should be evaluated appropriately. Unfortunately, there is a lack of strong motion data in the Philippines. Even the seismic design provisions were adopted from the United States. Without actual data, it is very difficult, if not impossible, to assess the level of safety used for design.

To evaluate the seismic hazard of the Philippines under this condition, earthquake occurrence data (e.g., time, magnitude, location) compiled by several organizations must be used. There are two general types of seismic hazard methodologies based on earthquake occurrence data. The first method, pioneered by Kawasumi[2] and applied recently by Tomatsu and Katayama[3], uses historical earthquake occurrence. The second, pioneered by Cornell[4], is based on probabilistic principles. The latter method has been widely used in the United States[5)-7)] and Japan[8),9)], among other countries. The probabilistic approach assumes seismic sources as being points, lines, or dipping planes. Seismic parameters such as seismic activity and maximum probable magnitude are assigned to each source based on historical events and geological surveys.

Previous researchers computed the seismic hazard in the Philippines using the probabilistic approach. Acharya[10] assumed the earthquake generators as line sources with a depth of 25 kilometers, while Su[11] used more complicated source zones from earthquake catalogue data, geologic and geotectonic data. However, the relatively short span of the earthquake catalogue data used (1964-1976 for Acharya and 1964-1983 for Su) will give large uncertainties in assigning seismic parameters to the sources given the complex nature of the seismicity in the Philippines. Villaraza[12] proposed a new seismic zonation map based on the hazard maps of Su, simulation of strong ground motion, and assessment of isoseismal maps. In this study, the method based on historical earthquake data was chosen because of the high uncertainties in identifying seismic sources and assigning seismic parameters for each source. A technique is introduced to utilize a longer set of data for the analysis.

As more data and knowledge regarding the seismological and geological characteristics of the Philippines are acquired, a more accurate estimation of the seismic hazard may be made. For small localized regions, more detailed investigations are

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economically and technically feasible. Since this study is concerned with the entire Philippine region, it is necessary to use a simple model at this time. It is believed that the general characteristics of the regional seismic hazard developed in this study can help engineers make sound decisions regarding seismic design.

2. METHOD OF SEISMIC HAZARD ANALYSIS

(1) Brief summary of analysis method

The seismic hazard is based primarily on the assumed relationship of the mean annual occurrence rate, ν, of a peak ground motion equal to or greater than a given value as

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

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 an assumed 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 earthquakes whose peak values exceed a given value y is assumed to be a Poisson process, then the probability of k occurrences of the peak ground motion in t years is given by

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

The probability of no occurrence in t years (non-exceedance probability, Q) is then given by

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

From Equations (1) and (3), the value of the peak ground motion for a given Q and time period, t, is then obtained as

$$\log y = \frac{\log(-\ln Q/t) - a}{b} \quad\cdots\cdots(4)$$

From the assumption of the Poisson process, the relation between the exceedance probability and the return period of peak ground motion, T, is given by

$$T = \frac{1}{\nu} = \frac{-t}{\ln Q} \quad\cdots\cdots(5)$$

For example, the 10% probability of a peak ground motion, $Y \geq y$, in $t=50$ years is equivalent to a return period of $Y \geq y$ of 475 years.

(2) Attenuation laws

Results of seismic hazard analysis are sensitive to the attenuation law used. Hence, the selection of an appropriate attenuation law is very important. Unfortunately, however, no attenuation law of peak ground motion has been developed for the Philippines because of the absence of strong motion records. Although attenuation laws were developed from isoseismal maps of large earthquakes by Acharya[13] and Su[14] using the Philippine Rossi-Forel intensity, they give little information for this selection. In this situation, attenuation laws based on data of other countries must be used.

Since attenuation laws are dependent on the data used, it is desirable to select attenuation laws using data from a seismic environment similar to the Philippines. However, the seismicity of the Philippines is very unique. The Philippine Trench, one of the major earthquake generators in the Philippines, is formed by the subduction of the Philippine Sea Plate under the China Plate. Thus, the earthquakes in this region are rather deep and are in circumstances similar to the Pacific Ocean side of Japan. The Philippine Fault, another major earthquake generator extending about 1,200 kilometers in the middle of the archipelago, is a strike-slip fault. Therefore, roughly speaking, similarity exists between this region and the western United States. But the Philippine Fault generates deeper events than those in the San Andreas region, where focal depths are usually less than 20 km.

Therefore, one of the key issues in selecting attenuation laws is the depth of earthquakes. The data used for developing the recent attenuation laws in the United States (McGuire[15], Joyner and Boore[16], Campbell[17]) are mostly from shallow earthquakes. The attenuation laws in Japan, where most earthquakes are rather deep, also limit their data by the focal depth, up to 60 km (Kawashima et al.[18]) or 30 km (Fukushima and Tanaka[19] in their final proposed equation). Then, the epicentral distance is used as a parameter. This is partially due to the fact that major Japanese events mostly occur at sea and have long distances. Thus, the results of taking either the epicentral distance or the hypocentral distance do not vary so much and the epicentral distance often shows a better fit. The work by Crouse et al.[20] is one of a few studies which consider the depth effect seriously. However, they did not show the attenuation of peak acceleration. Research may be needed in this topic using the data from intermediate depth (60-300 km) earthquakes.

Another key issue when selecting attenuation laws for the Philippines is the near-field saturation effect of peak acceleration because there are a lot of inland events in the Philippines. This is also related to the definition of the distance from site to source. In this regard, the closest distance to the surface projection of the fault[16] is better than the epicentral distance. But to collect proper data and to perform seismic hazard analysis become more

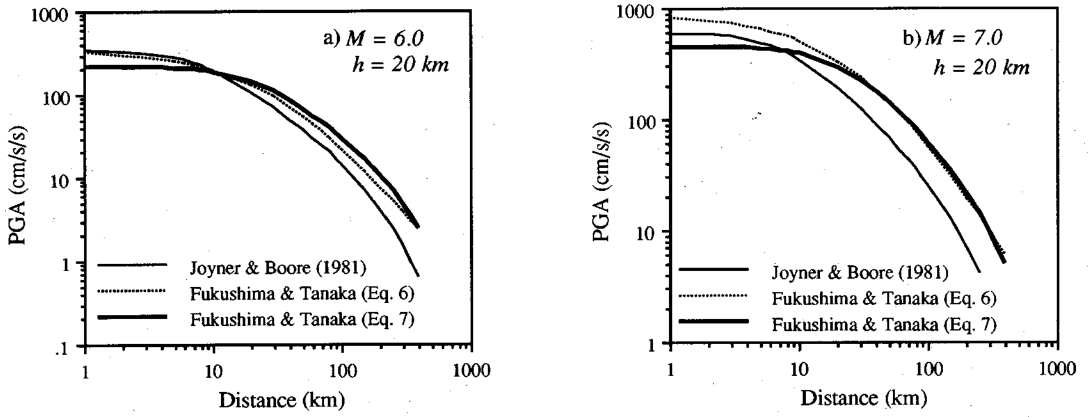


Fig.1 Peak ground accelerations estimated by three attenuation laws

difficult using this definition of distance.

There is no attenuation law which satisfy all these conditions. Hence, a compromise must be made. To use the Philippine data effectively, earthquakes with focal depths up to 100 km should be utilized. If this condition is set first, available formulas are limited to the ones by Fukushima and Tanaka[19]:

$$\log A = 2.09 + 0.52M_J - 1.87\log(\Delta + 30) \quad \cdots\cdots (6)$$

or

$$\log A = 1.18 + 0.40M_J - \log r - 0.00164r \cdots (7)$$

where A is the mean of the peak acceleration from two horizontal components at each site in cm/s^2, M_J is the Japan Meteorological Agency (JMA) magnitude, Δ is the epicentral distance, and r is the hypocentral distance. The original data used to calculate the parameters of these equations are 2,204 horizontal components from 43 earthquakes satisfying the following criteria : $M_J \geq 6.0$; focal depth ≤ 100 km ; and more than five records were observed for each earthquake.

Equation (6) has the same form as most of the attenuation laws commonly used in Japan (e.g., Kawashima et al.[18]). It considers the near-source saturation effect but not the depth effect. Equation (7) has basically the same form as Joyner and Boore[16] for North American data and Ambraseys and Bommer[21] for European data. It considers the depth effect but may produce large acceleration values in a near-source region when the depth is small. Together with the examination of the Philippine data, it was decided to use these two equations for the seismic hazard analysis of the Philippines.

The conversion of M_J in Equations 6 and 7 to the surface wave magnitude, M_S, is performed by an empirical formula proposed by Hayashi and Abe[22] and used also by Fukushima and Tanaka[19]:

$$M_S = 1.27M_J - 1.82 \cdots\cdots (8)$$

Fig.1 compares Equations (6) and (7) with the attenuation law by Joyner and Boore[16] for $M_S = 6.0$ and 7.0. For Equation (7), the peak ground acceleration (PGA) is plotted for a focal depth equal to 20 km. Joyner and Boore used the moment magnitude, M_W, but the difference is small for these magnitudes. The Joyner and Boore equation used the larger of the two horizontal components. Thus, their values were reduced by 1/1.13 (Joyner and Boore[16]) in **Fig.1**. It is observed that the Japanese attenuation laws show higher acceleration than the American one for distances larger than 10 km. Possible reasons are the differences in fault mechanism, transmission path (notably depth), and soil condition of their original data.

Note that Equations (6) and (7) as well as Joyner and Boore's do not consider soil effects. Thus, the peak ground acceleration estimated is one on the average soil condition of the observation sites. Also, since Equations (6) and (7) use the epicentral distance or hypocentral distance, they will be erratic for large magnitude events with long fault lengths. However, since the analysis method assumes the recurrence of the same events at the same location for the same time period, the amount of this error may be permissible compared with the amount of uncertainties involved in the other part of the analysis. The purpose of this study is to demonstrate the seismic hazard in the Philippines using the best knowledge available.

3. EARTHQUAKE OCCURRENCE DATA OF THE PHILIPPINES

Data catalogues from the Philippine Institute of Volcanology and Seismology (Phivolcs), the Inter-

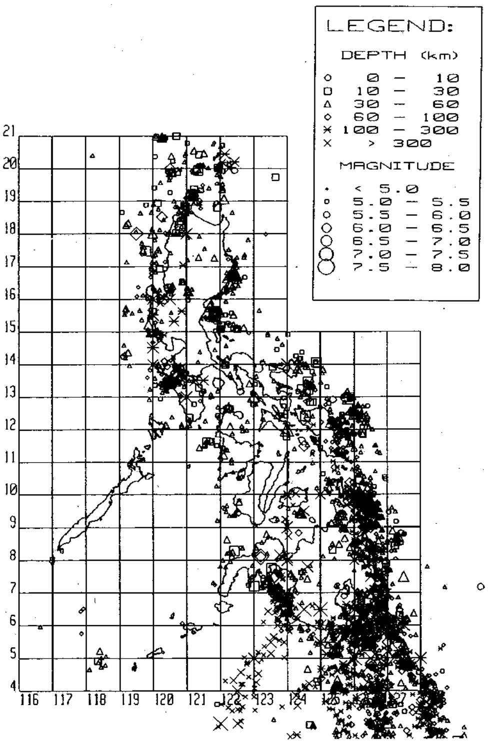


Fig.2 Epicenters of the earthquake catalogue used in this study (USGS data for 1986-1990, and ISC data for 1907-1985 ; $M_S \geq 5.0$)

national Seismological Center (ISC) and the United States Geological Survey (USGS) were collected.

The Phivolcs catalogue includes earthquakes from 1907 to 1990. The magnitude scales used are the body wave magnitude (m_b) from 1907 to 1970 and the Local magnitude (M_L) from 1971 to 1990. Due to the change in the magnitude scale, the Phivolcs catalogue was not used for the hazard analysis. The USGS data catalogue is from 1963 to 1990 and the ISC data catalogue is from 1907 to 1985. Both the USGS and ISC catalogues for the Philippines were extracted from a worldwide database compiled by the Earthquake Research Institute, The University of Tokyo. Both extracted data catalogues were limited to latitudes 4°N to 21°N and longitudes 115°E to 128°E and with surface wave magnitudes (M_S) greater than 4.5.

The two databases were analyzed for completeness using the method proposed by Stepp[23]. In general, this method determines the time period in which the estimate of the occurrence rate of a certain magnitude range is stable.

The USGS catalogue was found to be complete for $5.0 \leq M_S < 7.0$ from 1963 to 1990. Although the time period of the data set is too short to establish stable occurrence rates for M_S greater than 7.0, it can be assumed that these earthquakes were completely reported at the given time period. For the ISC catalogue, although the time period of compilation is longer, the reported earthquakes earlier than 1960 is complete only for magnitudes greater than 6.0.

To maximize the use of these data, the USGS data from 1986 to 1990 were appended to the ISC data from 1907 to 1985. The distribution of epicenters of the new catalogue is shown in **Fig.2.** For this new catalogue, examination of the data and the Stepp analysis showed that the catalogue is complete from 1964 to 1990 for $M_S < 6.0$; from 1921 to 1990 for $6.0 \leq M_S < 6.5$; and from 1911 to 1990 for $M_S \geq 6.5$. To establish the occurrence rates of the peak ground acceleration, only the earthquakes whose magnitudes are within the range of completeness for the given time of occurrence are used. This ensures the maximum use of data within the time period of complete reporting.

If y_i is the *i*th largest peak ground motion at the site, then the occurrence rate, ν_i, can be calculated as

$$\nu_i(Y \geq y_i) = \frac{N}{t} \cdots\cdots (9)$$

where N is the number of peak ground motion equal to or greater than y_i and t is the time period of the observation.

Let n_k be the number of occurrences for $Y = y_k$ for all y_k's$\geq y_i$. Then Equation 9 can be rewritten as

$$\nu_i(Y \geq y_i) = \frac{\sum_{k=1}^{i} n_k}{t} \cdots\cdots (10)$$

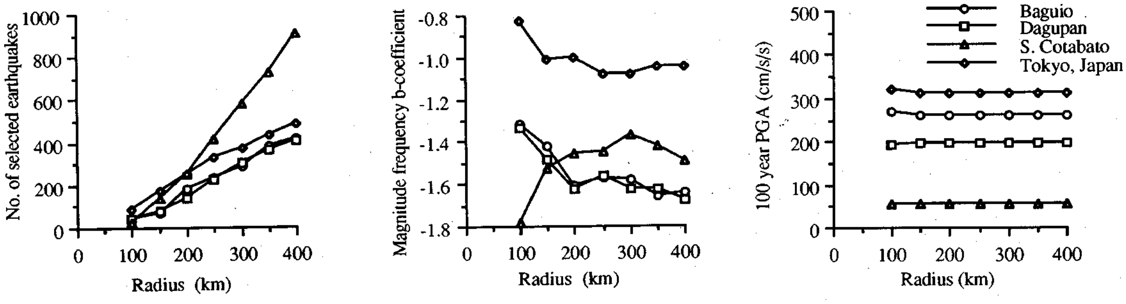
Let t_r be a reference time period, and t changes for each data. Then,

$$\nu_i(Y \geq y_i) = \frac{\sum_{k=1}^{i}\left(n_k \cdot \frac{t_r}{t_k}\right)}{t_r} \cdots\cdots (11)$$

where t_r/t_k is a correction factor applied to the number of occurrence of the peak ground motion for earthquakes not belonging to the reference time period.

In this study, the longest time period was used as the reference. For earthquakes with $M_S < 6.0$ from 1964 to 1990, a correction factor of 80/27 or 2.96 was used. For earthquakes with $6.0 \leq M_S < 6.5$ from 1921 to 1990, a correction factor of 80/70 or 1.14 was used. For earthquakes with $M_S \geq 6.5$ from 1911 to 1990, the correction factor is 1.0. By doing this, data taken from different time periods can be used together in the regression analysis.

In this study, a focal depth of 10 km is assumed for all earthquakes with unknown focal depths.



(a) Number of selected earthquakes (b) Magnitude frequency (b-coef.) (c) 100 year peak ground acceleration

Fig.3 Sensitivity analysis on the radius used in the hazard analysis for four sites (i.e., Baguio, Dagupan, South Cotobato, and Tokyo, Japan)

These earthquakes constitute about 1.5% of the data set but most of these are old data with small magnitudes. Earthquakes with focal depths greater than 100 km were excluded from the analysis.

4. EARTHQUAKE OCCURRENCE DATA OF JAPAN

To have a basis for comparison for the data and seismic hazard analysis, the earthquake occurrence data of Japan was also analyzed.

Japan has a long historical account of earthquakes and official earthquake observation was started by the JMA in 1885 (Utsu[24]). The earthquake data prior to 1885 were gathered from historical documents in which the magnitude and epicenter were estimated from observed effects (Usami[25]). The earthquakes in the database are from 679 to 1989.

The Stepp analysis was also done and it was concluded that $5.5 \leq M_J < 6.0$ is complete from 1895 to 1989 ; $6.0 \leq M_J < 7.5$, from 1885 to 1989 ; and $7.5 \leq M_J < 8.0$, from 1855 to 1989. For $M_J \geq 8.0$, the period of observation is too short to establish occurrence rates although it can be assumed that earthquakes were completely recorded for this magnitude range.

As with the Philippine data, correction factors are applied to the occurrence rates based on the magnitude's time period of complete reporting.

The focal depths of several earthquakes were reported in the Utsu catalog as very shallow, shallow, deep, etc. For these data, a focal depth of 5 km was assumed for very shallow earthquakes ; 25 km for shallow earthquakes; and 10 km for unknown depth earthquakes. Earthquakes with focal depth greater than 100 km and deep earthquakes were excluded from the analysis.

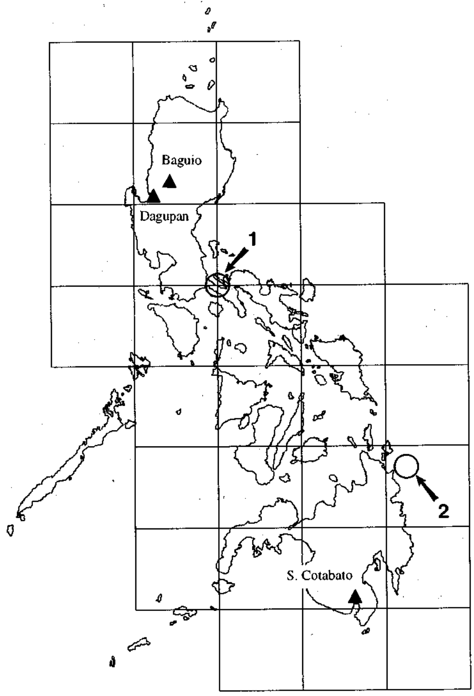
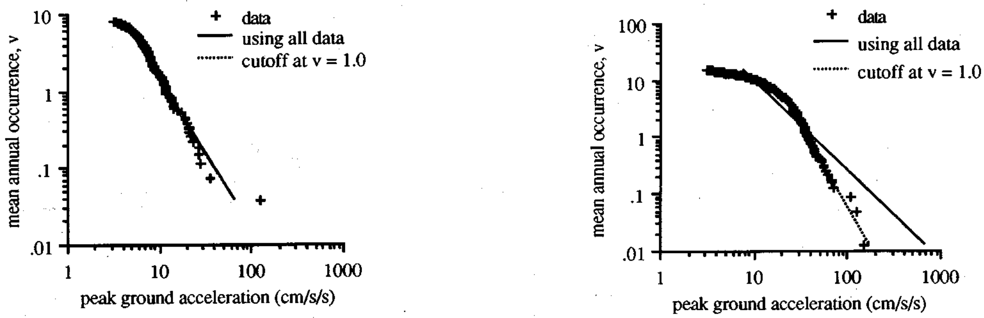


Fig.4 Subregions for the Philippines used in the analysis and sample sites for regression fitting

5. RESULTS OF SEISMIC HAZARD ANALYSIS

(1) Sensitivity to maximum epicentral distance

The methodology requires some parameters to select the earthquakes used in the analysis. From the completeness analysis, the time period and magnitude range of the earthquakes to be used can be surmised. However, there are no clear criteria for selecting the maximum epicentral distance to the site. Earthquakes which considerably affect the hazard parameter must be included. However, if a very large distance is taken, uniform earthquake



(a) Site 1 (122°E, 14°N) (b) Site 2 (126.5°E, 9.5°N)

Fig.5 Plot of the peak ground acceleration vs. the mean annual occurrence rate for the sample sites shown in Figure 4. Site 1 is far from an earthquake source while site 2 is near an earthquake source.

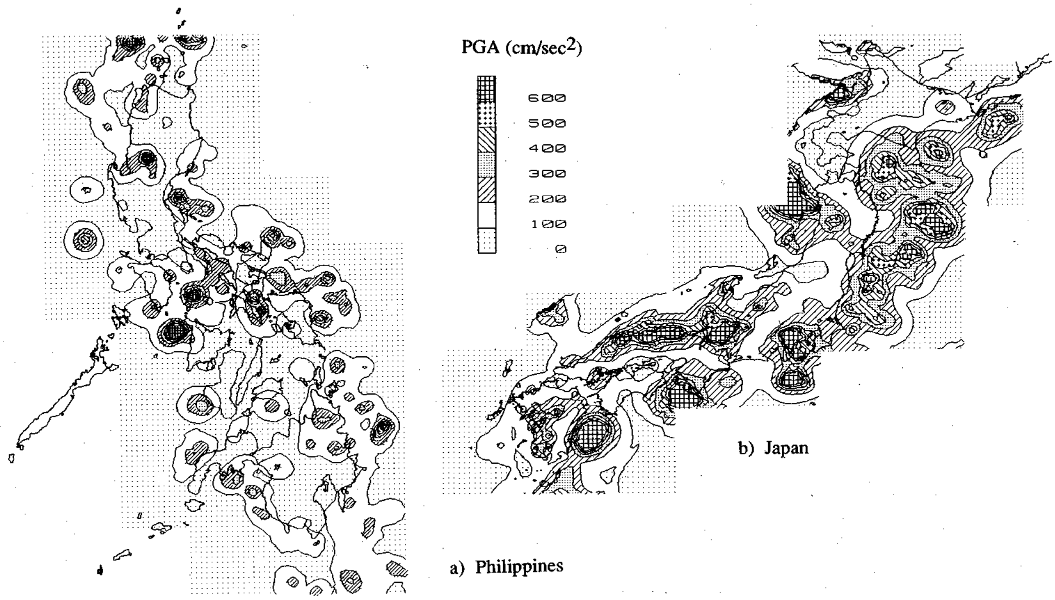


Fig.6 100-year peak ground acceleration using the attenuation law of Equation (7)

occurrence is assumed within the circle by the hazard analysis. Hence, the maximum distance must be determined by these two facts. To determine the effect of the maximum distance, sample calculations for several output parameters were done for different maximum distances for three sites in the Philippines and one site in Japan. The results of the sensitivity analysis are given in **Fig.3**. It can be seen that the 100-year PGA is relatively insensitive to a maximum epicentral distance greater than 150 km. This is due to the fact that as earthquakes of large epicentral distances are considered, the PGA estimated by the attenuation laws will be smaller. Due to the cutoff of data from the regression analysis based on the occurrence rates of the PGA, the effects of these earthquakes are effectively excluded from the regression. Details of the data cutoff for the regression are discussed later in this paper.

If a small radius is chosen, however, regions of low seismicity may not have enough data points to estimate the seismic hazard. For subsequent discussions, a maximum epicentral distance of 250 km is used. It is observed that with this distance, the b-coefficient of the magnitude frequency ($\log N = a - bM$) is relatively stable.

(2) Regional Seismic Hazard

To efficiently calculate the seismic hazard for a region, a new computer program was developed on an HP-9000 series workstation.

The entire Philippine region is first divided into thirty square sub-regions having sides of two degrees as shown in **Fig.4**. These sub-regions are further divided into 13,230 grid points. Such a high resolution of calculated points can show the regional hazard without the need for interpolation between points.

(3) Regression line

Preliminary results showed that unusually high peak ground accelerations are computed for regions with earthquake clusters. Investigations revealed that at these regions, the assumed linear relationship of the peak ground motion and its occurrence rate does not fit the curve very well. Several sites near earthquake clusters and far from earthquake clusters were studied. The location of two of these sites are given in **Fig.4**. For sites near an earthquake source, it was observed that the occurrence of many small accelerations tends to flatten the regression line. Since the earthquakes of interest for seismic hazard analysis are those of low annual occurrence rates, it was deemed suitable to use only that portion of the plot for the regression. For this study, the cutoff rate for the regression is taken as 1.0 per year for the Philippine data and 0.5 per year for the Japanese data. **Fig.5** shows the curve fitting for two sites in the Philippines using all data points and data points with a recurrence rate, ν, of less than 1.0 per year. The use of the regression cutoff gives a good fit at the low occurrence rate region.

(4) Seismic hazard maps

Fig.6 a) shows the distribution of the peak ground acceleration corresponding to a return period of one hundred years (100-year PGA) for the Philippines using Fukushima and Tanaka's attenuation law (Equation (7)). By comparing the hazard map with the plot of earthquake epicenters, it can be seen that higher seismic hazard areas follow a band corresponding to the earthquake generators in the country. In general, the highest seismic hazard were computed for regions which experienced several shallow earthquakes. High seismic hazard is observed for the northern tip of Luzon, Central Luzon, in the middle portion of the archipelago and the northeast and western parts of Mindanao island. Central Luzon experienced heavy damage during the 1990 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 all 1990 earthquakes. It was found that the region of high seismic hazard still exists.

Similarly, in Japan (**Fig.6**(b)), high seismic hazards were computed for regions near earthquake clusters. In this case, however, the highest seismic hazards were computed in the sea. It can also be observed that Japan has a generally higher seismic hazard than the Philippines.

Seismic hazard analysis were also conducted using the attenuation law with epicentral distance (Equation (6)). Hazard maps similar to **Fig.6** were obtained for the Philippines and Japan. However, for sites near earthquake clusters, higher PGAs were estimated by this attenuation law.

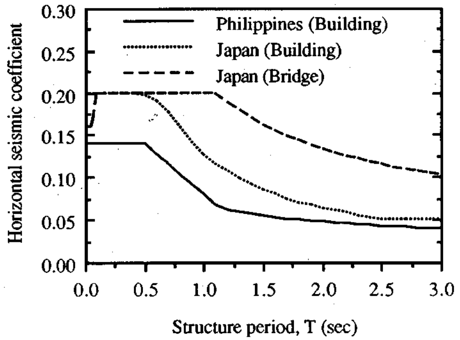


Fig.7 Comparison of seismic coefficients for structures on rock site for the Philippines and Japan

6. SEISMIC DESIGN CODES

The Philippine seismic design provisions[26] for buildings 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

$$\text{Base Shear}/W = Z \cdot C \cdot S \cdot I \cdot K \cdots\cdots\cdots\cdots\cdots (12)$$

where W is the weight of the structure ; Z, the zoning factor ; C, the response factor ; S, the soil factor ; I, the 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 $K=1.0$ and $I=1.0$ and the corresponding seismic coefficients in the Japanese building[27] and bridge codes[28] are plotted in **Fig.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 buildings with fundamental periods less than 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. For these structures, the maximum value of the required seismic coefficient is 0.14. Using Equations (4) and (5), the return periods for exceeding the design seismic coefficient of 0.14 can be calculated as shown in **Fig.8**(a). There are some regions in the country which have a high probability (i.e., low return period) of exceeding the design

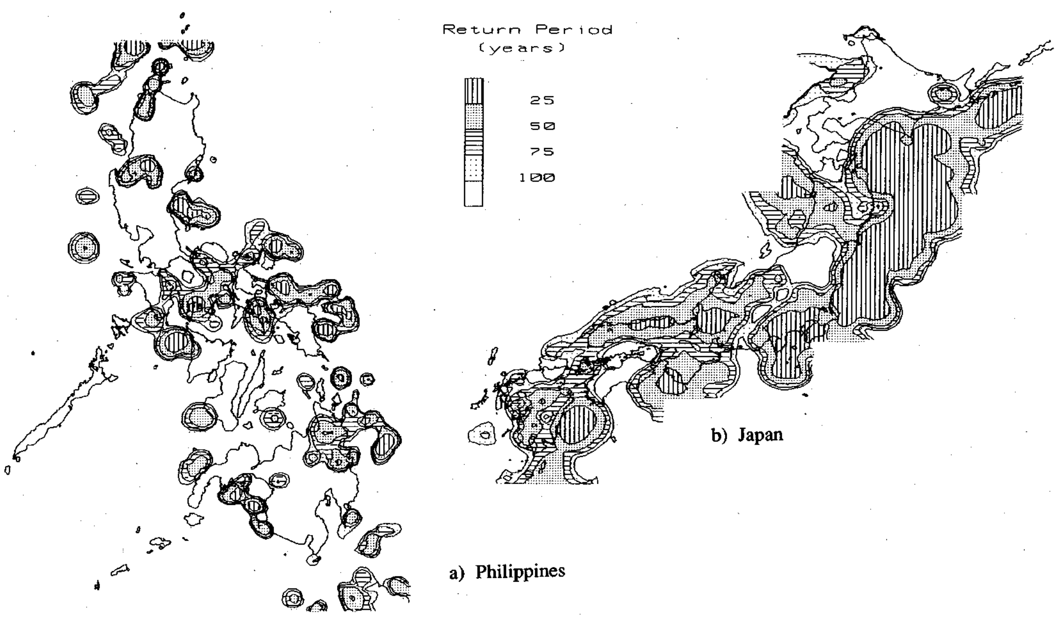


Fig.8 Return period in years for PGA$\geq$140 cm/s^2 using the attenuation law of Equation (7)

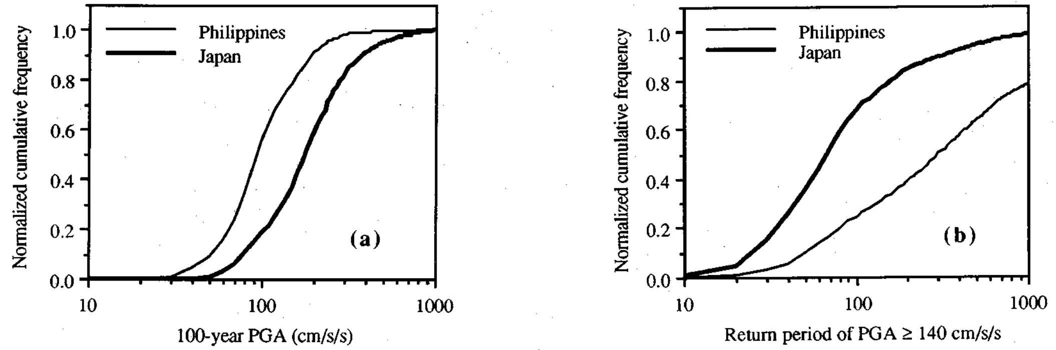


Fig.9 Cumulative frequencies of (a) the 100-year PGA and (b) the return period for PGA$\geq$140 cm/s^2 for grid points in land

seismic coefficient, most notable of which is Central Luzon. **Fig.**8(b) shows the return period for PGA$\geq$140 cm/s^2 for Japan. This figure shows that parts of the Philippines have hazard levels similar to Japan. For these regions, an increase in the value of the seismic coefficient is indicated.

It should be noted that damage to structures not only depends on the elastic strength as given by the design code but also on the deformation capacity of the structure. Therefore, provisions for ductility in the design codes are also very important to prevent structural collapse.

7. SEISMIC MACROZONATION

Since there are a lot of sea portions in the whole analysis area (**Fig.**4), the analysis points on land are selected for engineering use. **Fig.**9(a) shows the cumulative frequency of the value of the 100-year PGA for the grid points in land using Equation (7). From this figure, the numerical distribution of the 100-year PGA throughout the Philippines and Japan can be compared. In terms of percentages, the seismic hazard in Japan in terms of the 100-year PGA is much higher than in the Philippines. Similar observation can seen from **Fig.**9(b), which shows the cumulative frequency of the return periods for PGA$\geq$140 cm/s^2 for the grid points in land.

For a rational seismic zonation, the relative risk or reliability of structures built on the different regions of the country should be more or less uniform. Since strong ground motions in the Philippines have not yet been recorded and the present seismic coefficients were adopted from the UBC of the United States, there is no way to estimate the actual reliability of structures in the

Table 1 Mean and standard deviation of the 100-year PGA for land areas in the Philippines

ZONE	Mean (cm/s^2)	Std. dev. (cm/s^2)
2	55.45	9.41
3	96.73	18.26
4	185.20	34.55
All	108.11	50.31

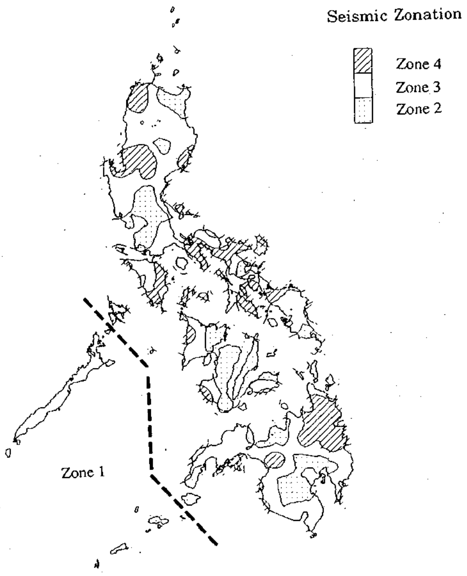
Philippines. The present code in the Philippines specifies that the entire country be assigned as seismic zone 4 (i.e., the highest design coefficient, $Z=1.0$). At present, the best way to reduce the seismic risk is to identify regions with high and low seismic hazards and to reassign the design seismic coefficients of the present provision based on it.

The authors propose a new seismic zonation based on the 100-year PGA : Zone 4 covers the upper 25% of the cumulative distribution ; Zone 3, the middle 50% ; and Zone 2, the lower 25%. From **Fig.9**(a), the 100-year PGA which divides Zones 3 and 4 was found to be 140 cm/s^2 and Zones 2 and 3, 70 cm/s^2. Zone 1 is historically considered aseismic and the PGAs were not calculated for this region.

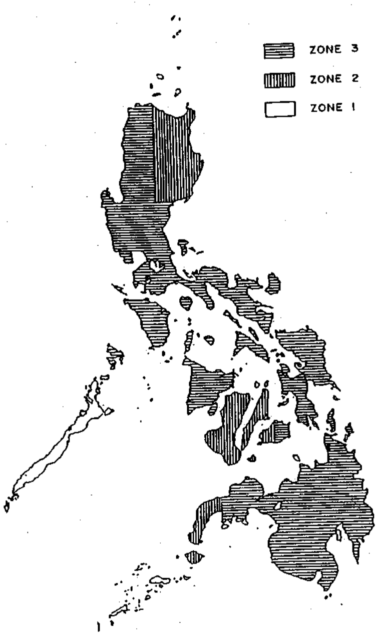
Table 1 gives the mean and standard deviation of the expected PGAs for the land areas for Zones 2, 3, 4, and for the entire land area. In calculating the mean and standard deviations for the zones, the lower and upper 2.5% of the expected PGAs were excluded to reduce the effect of extreme values which may not be reasonable. By taking the mean of Zone 3 as the reference, the zone factors can be computed by normalizing the mean of the expected PGA with respect to this reference. Using this criterion, the zone factor, Z, is taken as 1.91 and 0.57 for Zone 4 and Zone 2, respectively, while Zone 3 is assigned the reference valuc of 1.0. For Zone 1, an arbitrary value for the seismic coefficient should be given to provide minimum seismic resistance.

It should be noted that the proposed seismic zonation is purely based on the hazard analysis. In determining the actual seismic zones and the final value of the zoning factors, several factors must be considered. These include the various regional characteristics, importance of specific areas, provincial divisions, and compatibility with the previous codes, etc. These considerations, however, are beyond the scope of this study.

Fig.10 shows the proposed seismic zonation together with the one proposed by Villaraza[12] which has three zones. By comparing the two zone maps, several observations can be made. Both maps have the same Zone 1. A region near the central portion of the archipelago is assigned as Zone 2 in both maps. For the zone map of Villaraza, most of the remaining regions are assigned as Zone 3.



(a) Proposed Seismic Zonation



(b) by Villaraza (1991)

Fig.10 Comparison of seismic zoning maps for the Philippines proposed in this study and by Villaraza (1991)

It can also be noticed that the capital, Metro Manila, is assigned as Zone 2 in the proposed map. This map is based on the PGA ; therefore, is appropriate for short-period structures. However, since Manila has many medium- and high-rise structures, a further examination of the response spectra covering these period ranges is necessary.

CONCLUSIONS

The seismic hazard in the Philippines was calculated using historical earthquake occurrence data. Three earthquake occurrence data sets were collected and examined. The data set from the Philippine Institute of Volcanology and Seismology (Phivolcs) was not used because of the change in magnitude scale used. Using the method proposed by Stepp, it was concluded that the USGS data set is complete but the time period is short (1963 to 1990). For the ISC data set, the time period is longer (1907 to 1985) but is not complete for small magnitude earthquakes. For the maximum use of these data, the USGS data from 1986 to 1990 were appended to the ISC data. Since the time periods of complete reporting are different depending on the magnitude, a correction factor for the occurrence rate was introduced to use all the data from different complete reporting periods simultaneously in the hazard analysis.

The seismic hazard analysis was performed for 13,320 points of the Philippines using the attenuation laws developed from Japanese data with focal depth up to 100 km. The regions with high seismic hazard were identified in terms of the 100-year peak ground acceleration. 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 those in Japan. However, similar seismic hazard analysis for Japan showed that Japan has a higher seismic hazard compared to the Philippines. Based on the hazard maps and the seismic coefficients, a new seismic zoning with four zones was proposed for the Philippines. By identifying high seismic hazard regions, a higher seismic design coefficient can be assigned so as to increase the safety of structures in these regions.

There is a need to develop seismic provisions based on data from the Philippines. For this purpose, collecting strong ground motion records should be given high priority in the Philippines. Until better information regarding the ground motion characteristics in the Philippines is obtained, the authors believe that the results of this study can help engineers in deciding seismic design levels.

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地震危険度解析に基づくフィリピンのマクロゾーニング

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地震発生データに基づいて，フィリピンの地震危険度マップを構築し，マクロゾーニングを行った．2つの地震カタログのデータの欠落を調べに結果，マグニチュードの大きい地震に対しては長い期間を，小さい地震に対しては短い期間を用いる方法を考えた．適当な距離減衰式とポアソン過程を仮定し，再現期間100年の最大加速度をフィリピン全土について求め，これに基づくゾーニングを行い，地震危険度の高い地域と低い地域を明らかにした．