研 究 速 報

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# Seismic Hazard Analysis and Macrozonation of the Philippines

## フィリピンの地震危険度とマクロゾーニング

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### 1. Introduction

The Philippines has experienced several destructive earthquakes. To mitigate earthquake disasters in the Philippines, the seismic hazard should be evaluated appropriately. However, basic data for seismic hazard analysis are lacking, especially strong ground motion records, which are needed to develop attenuation laws and design response spectra. In this situation, it is important to extract as much information as possible from the limited data.

The probability–based seismic hazard methodology pioneered by Cornell[1] has been widely used in the United States, Japan, and other countries. However, due to the complex nature of the seismicity in the Philippines, there are many uncertainties in identifying the locations of seismic sources and in assigning seismic parameters. Thus, this study directly uses the earthquake occurrence data as pioneered by Kawasumi[2] and applied recently by Tomatsu and Katayama[3].

Based on the results of the seismic hazard analysis, a new seismic zonation for the Philippines is proposed.

### 2. SEISMIC HAZARD ANALYSIS

A computer program called the Seismic Hazard Mapping Program (H–MaP) was developed and used to calculate the seismic hazard in the Philippines. To evaluate the seismic hazard parameter for one site, all earthquakes within 250 km from the site are selected from the earthquake catalogue. The peak ground acceleration (PGA) at the site due to each earthquake is then estimated using an appropriate attenuation law. Regression analysis is then performed to correlate the PGA with the occurrence rate. By assuming a Poisson process, the seismic hazard can then be calculated.

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#### (1) Attenuation of PGA

The selection of an appropriate attenuation law is important to the seismic hazard analysis. Unfortunately, however, there are no attenuation laws of the PGA developed for the Philippines. Therefore, the use of attenuation law from different countries is necessary at this time. However, since the attenuation equation is affected by the data used, it is important to choose an attenuation equation derived from data from a seismic environment similar to the Philippines.

A key issue in the choice of attenuation law is the depth of earthquakes. Most attenuation laws for the United States and Japan consider shallow events only and may not be appropriate to use for the Philippines. From this consideration, the attenuation law developed by Fukushima and Tanaka[4] that uses data with depths up to 100 km was used.

$$\log A = 1.18 + 0.40\, M_J - \log r - 0.00164 r \qquad (1)$$

where $M_J$ is the JMA magnitude and $r$ is the hypocentral distance in km. To convert $M_J$ to $M_S$, the empirical formula proposed by Hayashi and Abe[5] is used.

#### (2) Earthquake occurrence data

A data catalogue from the International Seismological Center (ISC), which includes earthquakes from 1907–1985, and from the United States Geological Survey (USGS), which includes earthquakes from 1963–1990, were collected. To maximize the use of the data, the USGS data from 1986 to 1990 was appended to the ISC data from 1907 to 1985 (Figure 1).

The resulting catalogue was then analyzed for com-

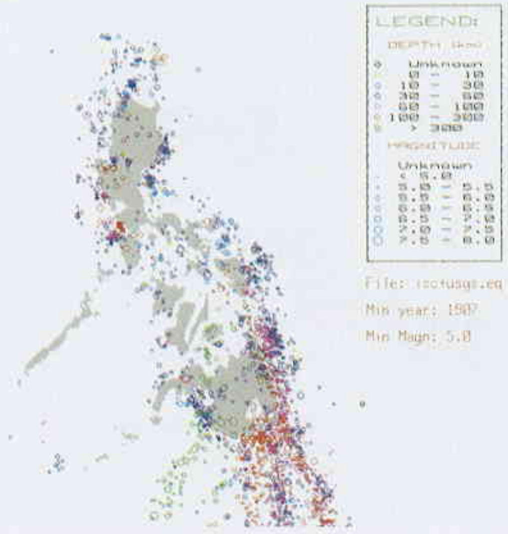


Fig. 1 Epicenters of the earthquake catalogue used in this study (USGS data for 1986–1990, and ISC data for 1907–1985; $M_S \geq 5.0$)

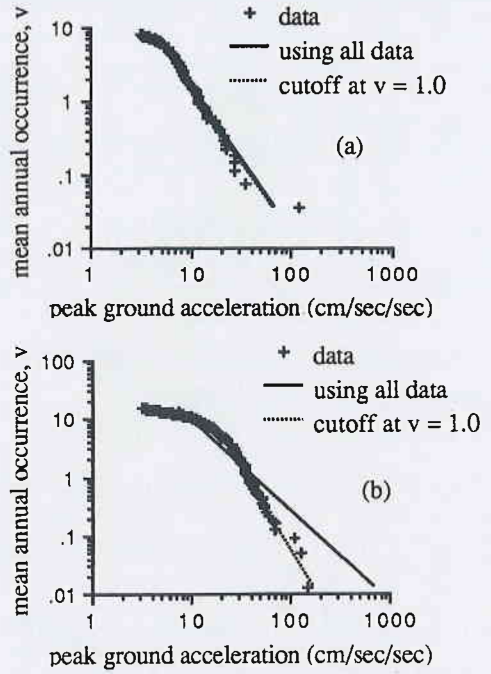


Fig. 2 Plot of the peak ground acceleration vs. the mean annual occurrence rate for (a) site far from an earthquake source; and (b) a site near an earthquake source

pleteness using the method proposed by Stepp[6]. It was found 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 PGA, only the earthquakes whose magnitudes are within the range of completeness are used. This ensures the maximum use of data within the period of complete reporting.

If $y_i$ is the $i$th largest peak ground motion at the site and $n_k$ is the number of occurrences for $Y=y_k$ for all $y_k$'s $\geq y_i$, then the occurrence rate, $v_i$, can be calculated as

$$v_i\,(Y \geq y_i) = \frac{1}{t_r} \sum_{k=1}^{i} (n_k \cdot t_r \,/\, t_k) \qquad (2)$$

where $t_r$ is the reference time period and $t_k$ is the time

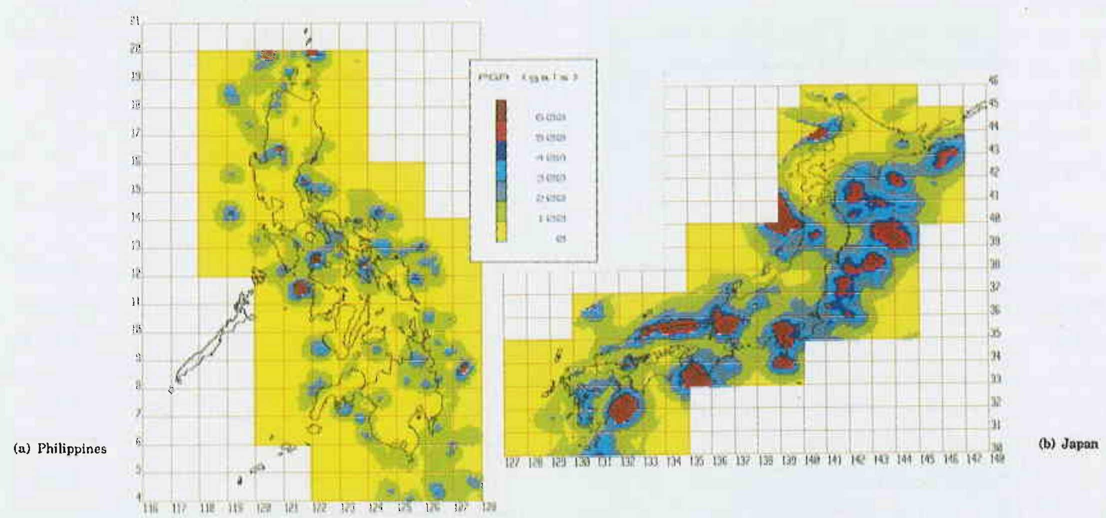


Fig. 3 Distribution of the 100-year peak ground acceleration

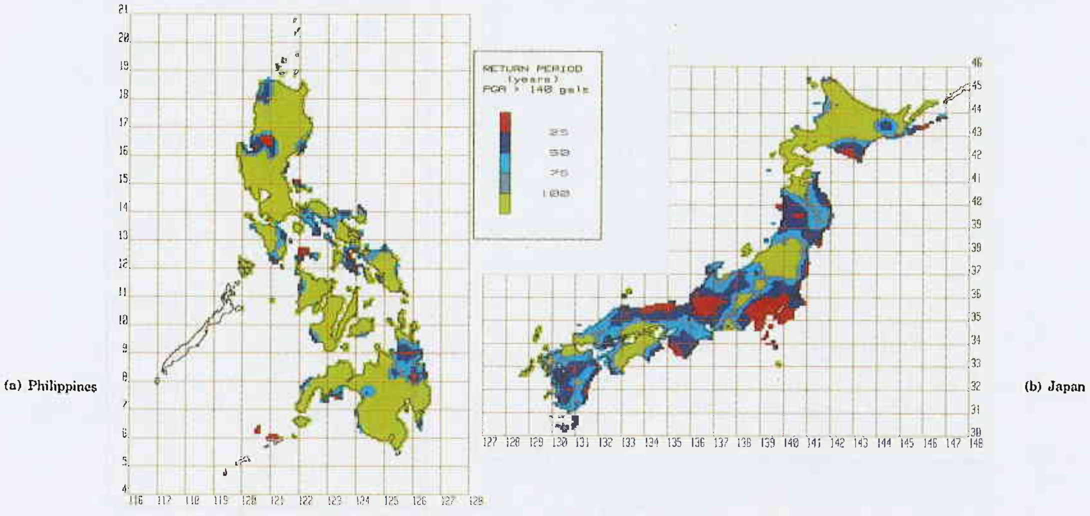


Fig. 4 Distribution of the return period in years for PGA≥140 cm/sec²

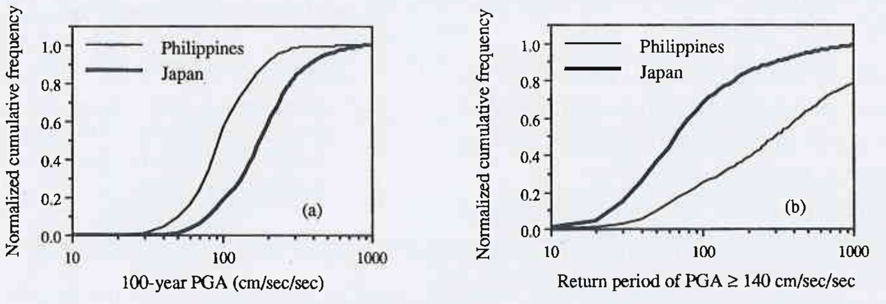


Fig. 5 Cumulative frequencies of (a) the 100-year PGA and (b) the return period for PGA≥140 cm/sec² for grid points in land for the Philippines and Japan

period in which the *k*th magnitude is completely reported. By applying this correction factor, data taken from different time periods can be used together in the regression.

To have a basis for comparison, the earthquake occurrence data of Japan were similarly analyzed.

### (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. It was observed that the occurrence of many small PGAs tends to flatten the regression line. Since the interest of the hazard analysis is in the region of low occurrence rates, it was deemed suitable to use only that portion of the plot for the regression. In this study, the cutoff rate for the regression is taken as 1.0 per year for the Philippine data (Figure 2) and 0.5 per year for the Japanese data.

## 3. SEISMIC HAZARD MAPS

Figure 3a shows the distribution of the peak ground acceleration corresponding to a return period of one hundred years (100-year PGA) for the Philippines. 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. High seismic hazard is observed for the northern tip of Luzon, Central Luzon, the middle portion of the archipelago and the northeast and western parts of Mindanao. Central Luzon sustained heavy damage during the Luzon earthquake. To check if its high seismic hazard

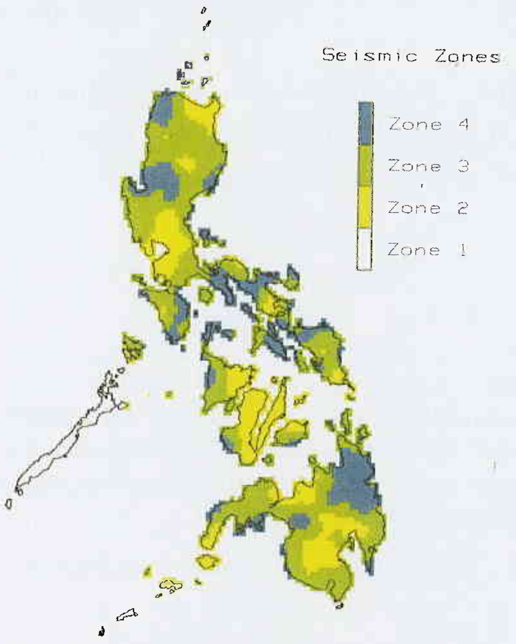


Fig. 6 Proposed seismic macrozonation for the Philippines

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.

For Japan (Figure 3b), high seismic hazards were also computed for regions near earthquake clusters. However, most of these are in the sea. It can also be observed that Japan has a generally higher seismic hazard than the Philippines.

The seismic design provisions of the Philippines are basically adopted from the Uniform Building Code of the United States. To design for the lateral seismic load the modified seismic coefficient method is used. For short period structures, the response of the structure is close to the PGA. For this case, the return period for exceeding the seismic coefficient is approximated by the return period of exceeding the PGA. The result is given in figure 4. It can be seen that there are several regions which have high probabilities (low return periods) of exceeding the design seismic coefficient.

## 4. SEISMIC MACROZONATION

Figure 5a and 5b show the cumulative frequency of the 100–year PGA and the return period for PGA ≥140 cm/sec$^2$, respectively. The authors propose a new seismic zonation based on the 100–year PGA (Figure 6): Zone 4 covers the upper 25% of the cumulative distribution; Zone 3, the middle 50%; and Zone 2, the lower 25%. From Figure 5a, the 100–year PGA which divides Zones 3 and 4 is found to be 140 cm/sec$^2$ and Zones 2 and 3, 70 cm/sec$^2$. Zone 1 is historically considered aseismic and the PGAs were not calculated for this region.

## 5. CONCLUSIONS

A seismic hazard analysis was conducted for the Philippines using earthquake occurrence data. A similar analysis was done for Japan to obtain a basis for comparison. It was found that Central Luzon, which was heavily damaged by the Luzon Earthquake, and the northeast portion of Mindanao have high seismic hazards. The seismic hazard in the Philippines is relatively lower than in Japan. The results of the seismic hazard analysis were used as the basis for the seismic macrozonation to identify regions of high and low seismic hazards. Such seismic macrozonation will be useful for Filipino engineers in deciding seismic design levels.

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