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GLOBAL EARTHQUAKE HAZARD AND RISK ASSESSMENT

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ABSTRACT

We summarize studies designed to test metholologies for the global assessment of earthquake hazard and risk, to determine the value of these methods as a contribution to the International Decade for Natural Disaster Reduction. Studies in Chile, El Salvador, Indonesia and the Philippines are presented and discussed. The results presented suggest that a considerable quantitization of earthquake hazard and risk is possible on a global basis using data available at the present time. It is particularly important to make use of all of the seismological, geological, and engineering data available in any given area, although considerable technical effort is required to integrate these data effectively. The improvement of assessments of earthquake hazard and risk, particularly in areas of the world that are expanding rapidly, both economically and in population, is of critical importance for the development of effective mitigation strategies in these areas.

INTRODUCTION

The global assessment of natural hazard and risk is one of the principal goals of the International Decade of Natural Disaster Reduction (IDNDR). The purpose of this paper is to review these regional assessments of earthquake hazard and risk pilot studies, and to discuss the results in terms of the techniques of earthquake hazard and risk assessment, the problems encountered, and the general application of regional earthquake hazard and risk studies to the IDNDR. Results of the program that have already appeared in published reports are only summarized here (Chile and Indonesia). Other results (in El Salvador and the Philippines) are reported here in as much detail as possible. Both probabilistic and deterministic approaches to hazard and risk assessment were used. A standard Poisson model probabilistic ground motion hazard assessment modeling program was used (Bender and Perkins, 1987), augmented to model large earthquakes as rupture surfaces.

CHILE

Nature of the Studies

A number of different types of earthquake ground motion were developed for Chile, including maps of peak accelerations with a 10 percent chance of exceedance in 50 years, calculated with and without consideration of variability in attenuation, and maps of peak Modified Mercalli intensity with a 10 percent chance of being exceeded in 50 years, for average ground and also taking into account the response of individual sites. Equal hazard (probabilistic) response spectra are estimated for Valparaíso and Santiago. The principal results of these earthquake hazard studies in Chile have already been published (Algermissen and others, 1992). Some results not emphasized in the original study are discussed here.

Results

The earthquake hazard studies in Chile produced very useful results because of the availability of an adequate strong ground motion data base, and an extensive intensity data base. No attempt was made to separate acceleration data in Chile on the basis of the geotechnical properties of the near surface materials at each site because of the relatively small sample size of 61 recordings. Thus, the probabilistic acceleration maps produced reflect an "average" site condition. It was also possible to produce a probabilistic intensity map of central Chile (50 year exposure time, 10 percent chance of exceedence) that could be compared with the acceleration map. A technique was developed and applied for the incorporation of site response into the intensity probabilistic map. The intensity map could then be compared with the acceleration map, and this comparison provided a means of qualitatively assessing the site response component of ground motion.

The 50 year acceleration values along the coast of Chile are about 1.25 g with variability in attenuation and fault rupture length included in the calculation, and about half that value when the variability is not included. The higher acceleration values reflect the large variance associated with acceleration attenuation developed using the Chilean data. The probabilistic acceleration map produced without including variability in attenuation and fault rupture length are nevertheless important because they can be used to approximate spectral response for building design purposes, using the approach proposed by Newark and Hall (1982). The Newmark-Hall approach is commonly used with probabilistic ground motion maps developed without the inclusion of parameter variability because there has been smoothing and a consideration of uncertainty included in the Newark-Hall approach. A comparison of the 50 year Modified Mercalli Intensity (MMI) map developed for central Chile without variability in attenuation and fault rupture length included, with the corresponding acceleration map shows that the peak values of about 0.6 g along the coast of Chile correspond, approximately, to MMI VIII. The correspondence of intensity VIII, and an acceleration of 0.6g reflects the fact that, on the average, lower intensity values are assigned for the same level of acceleration than in, for example, the United States, and represents local practice in interpreting the intensity scale.

Additionally, it was found that 5 percent damped, acceleration response spectra computed for a magnitude 7.8 earthquake using the attenuation relationships developed by Youngs and Coppersmith (1989) compared very favorably with the corresponding spectra computed from strong motion accelerograms recorded at Quintay and Santiago during the 1985 Chile earthquake. Accordingly, probabilistic uniform hazard spectra were computed for Valparaiso (near Quintay) and Santiago using this attenuation relationship.

EL SALVADOR

Introduction

Since 1710, at least eleven upper crustal earthquakes have damaged San Salvador (the latest in 1986), and a number of other shocks have damaged other parts of El Salvador. Damaging earthquakes in El Salvador originate from two principal sources: (1) earthquakes associated with the subduction of the Cocos plate beneath Central America, which can occur over a wide range of depths; although in Central America, the depths, particularly for earthquakes prior to about 1965, are not well known because of poor seismograph station coverage; and (2) shallow earthquakes that occur in a volcano-tectonic depression of late Pliocene and early Pleistocene age called the Median Trough.

Seismic Source Zones

The seismic source zones used in the development of the probabilistic ground motion model are shown in Figure 1. Seismic source zone 1 models the dipping megathrust boundary across which the Cocos oceanic plate and the Central American continental portion of the Caribbean plate is converging at a rate of about 7 cm/yr in the vicinity of offshore El Salvador (Spence and Person, 1976). Zone 2 encompasses seismicity occurring in the Median Trough. This volcano-tectonic depression is the most seismically active tectonic province in El Salvador as well as in neighboring countries and has been the source area for earthquakes in 1917, 1919 and 1965 that seriously damaged San Salvador. Zone 3 is a mixed-source zone that models the continental fault extensions of the oceanic Swan Fracture Zone. Main continental faults in this zone through Guatemala are the Polochic, San Agustin, and Motagua faults, and the Jocotan fault through Guatemala and Honduras. These faults have been modeled as linear rupture sources contained in a surrounding background zone in which smaller magnitude earthquakes are modeled as point sources throughout the source zone. Zone 4 is a mixed-source zone that encompasses the primary northeast-trending boundary fault of the Cordillera Entre Rios in Honduras. Zone 5 is a regional background zone that is used to collect somewhat random historical earthquakes that cannot be associated with major structural features or zones.

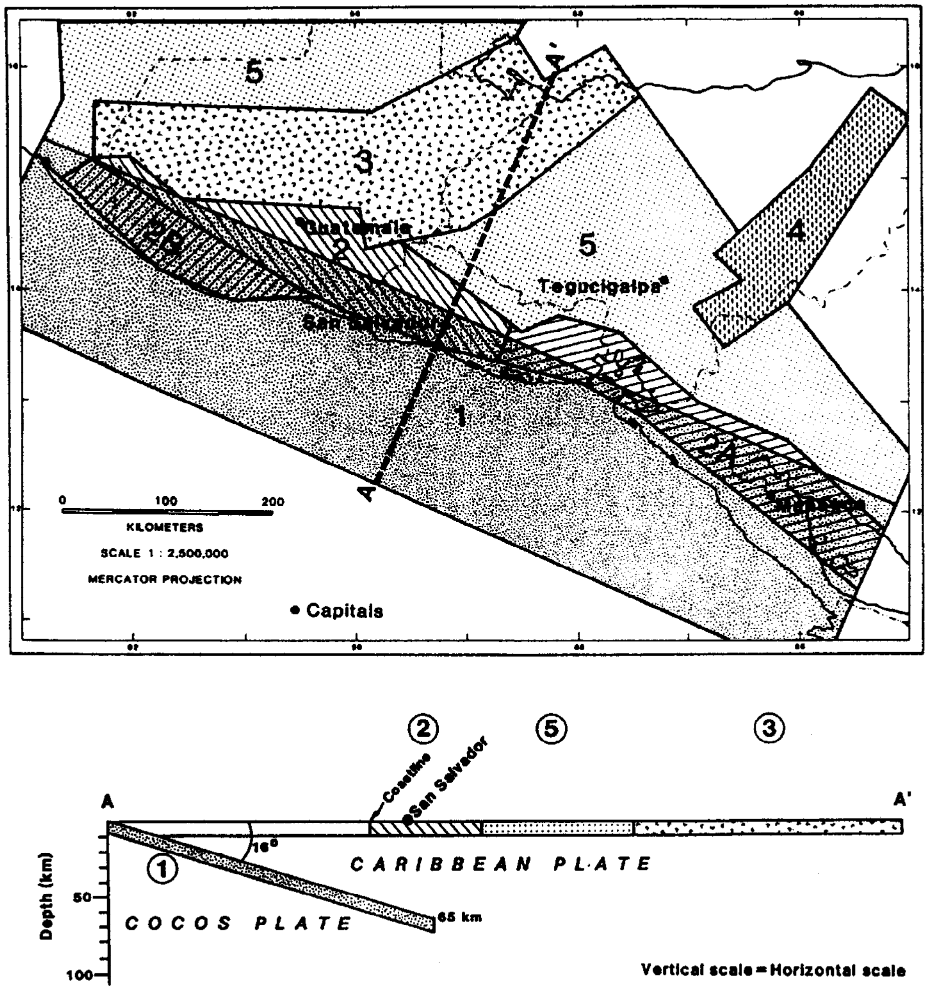

Fig. 1. Regional seismic source zones used in the probabilistic modeling of ground motion, and section showing the depth of the zones.

<u>Attenuation</u>

Strong ground motion data from three sources were used in the development of attenuation relationships for the probabilistic hazard model. The were: (1) peak accelerations from 82 accelerograms recorded in San Salvador during the period 1966-1986 (Linares, 1987); (2) peak accelerations, velocities, displacements and response spectra obtained from the accelerogram recorded at the Seismological Observatory in San Salvador (OBS) during the June 19, 1982, M_s=7.3 offshore earthquake located about 45 km south and slightly west of San Salvador (Campbell and Algermissen, 1988); and (3) from accelerograms recorded at seven stations in San Salvador during the October 10, 1986, M_s=5.4 earthquake (Shakal and others, 1987). The strong motion data from sources (2) and (3) above are particularly important because they provide response spectra from a close , moderate magnitude earthquake (the 1986 event) and spectra from a more distant, large shock (the 1982 event). Least square regression analysis of the acceleration data yielded the relationship:

$$\ln (a) = 1.987 + 0.604 M_s - 0.9082 \ln R - 0.00385 R \qquad (1)$$

where a is the peak horizontal acceleration (in percent g) and R is the hypocentral distance from the earthquake in kilometers. The standard deviation (σ) is 0.68 and this variability is taken into account in the calculation of probabilistic ground motion values. The mean peak acceleration attenuation (equation 2) is for an average thickness of volcanic tuff in San Salvador. Since most of the strong motion data recorded in El Salvador have not been processed to obtain velocity, displacement and response spectra, it was not possible to obtain a velocity attenuation relationship directly from the data set used to obtain the acceleration attenuation (equation 1). A value of v/a = 0.120 /cm. was selected as a reasonable weighted average representative of the strong motion data for average site response conditions in San Salvador. This value of v/a was then used to construct a velocity attenuation relationship scaled from the acceleration attenuation developed. The resulting velocity attenuation relationship is:

$$\ln(v) = 2.618 + 0.604\, M_s - 0.9082 \ln R - 0.00385\, R \qquad (2)$$

where R is the hypocentral distance as in equation (1). Because the relations were developed from accelerograms recorded in San Salvador, they inherently incorporate the propagation paths to San Salvador. We used a constant v/a ratio even though we would expect the v/a ratio to change with magnitude, distance, and site condition. The data are not available to establish these changes. The v/a ratio is a appropriate value for San Salvador, where the strong motion data was recorded. For other sites in El Salvador, where other site conditions may exist, or where earthquakes from other zones dominate, results may be somewhat different than those developed here for San Salvador.

Regional Ground Motion Hazard Maps

A probabilistic acceleration map (Figures 2) was computed for the entire country for an exposure times of 50 years, at the 90 percent extreme probability level (10 percent chance that the accelerations will be exceeded). Actual ground motion values were calculated over a 0.1° grid of longitude and latitude. The Median Trough source zone (Zone 2 and its subdivisions) dominates the ground motion hazard for San Salvador and much of El Salvador. This is consistent with the historical experience of damaging earthquakes affecting San Salvador.

Elastic Response Spectra for San Salvador

Comparison of the 5 percent damped response spectra among those response spectra for the 1986 San Salvador earthquake (M_s = 5.4, M_w = 5.6) and those for the 1982 offshore earthquake (M_w = 7.3) located about 45 km southwest of the city indicates higher response at San Salvador from the close, 1986 event of relatively small magnitude. Preliminary elastic response spectra for 5 percent damping for two levels of probability, the median and one standard deviation, were prepared using the Newmark and Hall procedure (Newmark and Hall, 1982) and the probabilistic 50 year peak acceleration and velocity values for San Salvador. Since a map for displacement is not available, the relationship ad/v^2 = 2.0 was used to estimate this parameter. The spectra are compared with the envelopes of the maximum and minimum spectral response actually recorded in San Salvador during the 1982 and 1986 earthquakes (Figure 3). The greatest response recorded in the 1986 earthquake is approximately equal to the median, plus one standard deviation response for the 50 year elastic response spectrum derived using the Newmark-

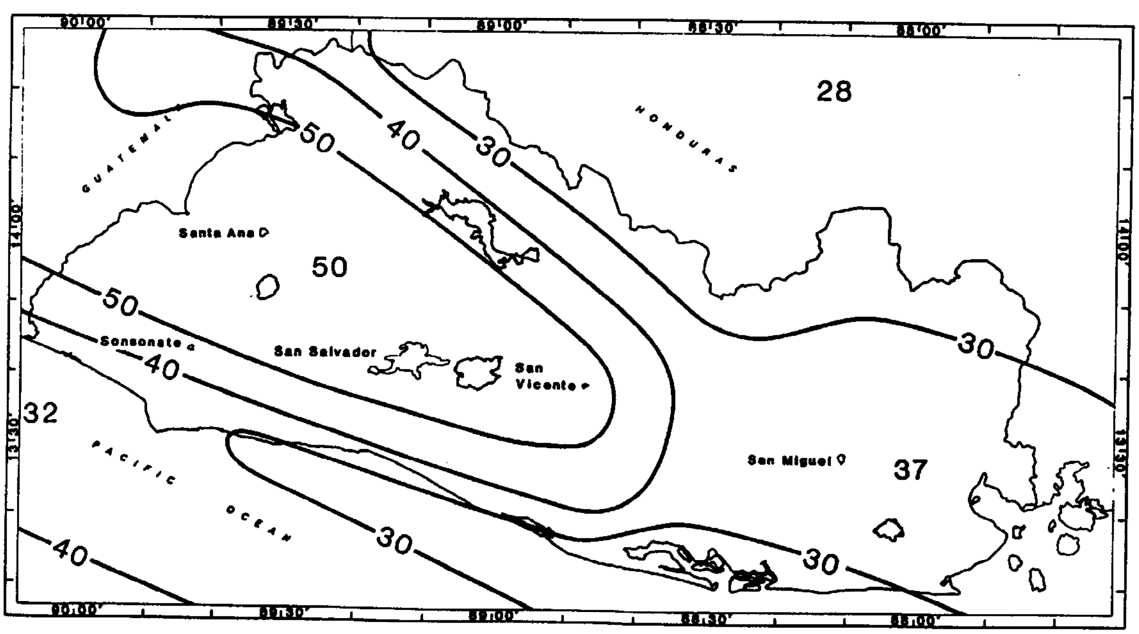

Fig. 2. Mean maximum peak acceleration in El Salvador in a 50 year period, with a 10 percent chance of being exceeded.

potential to a depth of 100 km beneath northern and central Sulawesi and include the Palu fault zone of western Sulawesi, the North Sulawesi subduction zone, and the southern most segment of the Sangihe subduction zone beneath the Molucca Sea.

The probabilistic, 50 year accelerations in North Sulawesi on soft soil are estimated to be 0.63 g at Palu, 0.31 g at Gorontalo, and 0.27 g at Mandado. Ground motions for rock conditions for the same probability level (90 percent) and exposure time (50 years) are 56 percent of those for soft soil. Based upon our investigation of actual damage resulting from the April 18, 1990 earthquake, the two soil characterizations (rock and soft soil) appear to give a reasonable estimate of the effects of site response in the area.

Very good inventory data were available from the Indonesian government on the distribution and nature of the housing stock in Gorontalo. Based on the post earthquake investigation of damage resulting from the April 18, 1990 earthquake, and comparisons to masonry construction in the United States, it was possible to construct a vulnerability relationships for the housing in Gorontalo. The average annual loss to masonry dwellings was estimated at 2.8 percent of the replacement cost of the dwellings, based on the simulation of losses from damaging historical earthquakes that affected the area in the period 1960-1991. The catastrophe potential, or single large loss to housing in Gorontalo was estimated by using the 250 year exposure time, 90 percent probability level probabilistic map values. It was estimated that a catastrophic loss to masonry dwellings in Gorontalo that has a 90 percent probability of not being exceeded in 250 years represents the equivalent of the replacement value of 25 percent of the present dwelling stock in Gorontalo.

The conclusion is that very useful results can be obtained for planning and mitigation in areas such as North Sulawesi (and Gorontalo) where some data are available on the seismicity, regional seismotectonics, and characteristics of the building stock. The damage data from the April 18, 1990 earthquake proved invaluable, as did the remarkable inventory of buildings available. The paper by Thenhaus and others,(1993),provides a comprehensive account of the results of the study summarized here.

THE PHILIPPINES

Introduction

The objectives of the project were to map the earthquake ground motion hazard throughout the Philippines and to conduct a pilot investigation of earthquake risk (loss). Probabilistic ground acceleration maps for three types of surficial material were developed for a 50 year exposure time, and a 90 percent probability of non-exceedance. The project was funded by the U. S. Agency for International Development (USAID) office in Manila.

Seismic Source Zones

Convergence of the Philippine Archipelago and the Philippine Sea Plate to the east is accommodated across the Philippine Trench and the East Luzon Trough. Large subduction zone earthquakes occur at relatively shallow depths where thrust movements occur along the plate interface. Seismic coupling for most subduction zones of the Circum-Pacific extends to a depth of about 40 ± 5 km. This depth was taken as the lower depth limit for the dipping plane seismic sources on which plate interface seismicity was modeled. Large earthquakes associated with subduction zones are all modeled as area ruptures that are scaled by magnitude and located on the plane of the subduction zone. Figure 4 shows the seismic source zones used to model earthquakes in the probabilistic model and the normalized rates of earthquake activity in each zone.

Attenuation

The acceleration attenuation developed by Fukushima and Tanaka (1990) for Japan was used in the probabilistic model since no significant strong ground motion data are available in the Philippines. This situation is not unique to the Philippines. As in our study in Indonesia, we assumed that the Fukushima and Tanaka relationship provides a reasonable approximation for the western Pacific island arc areas.

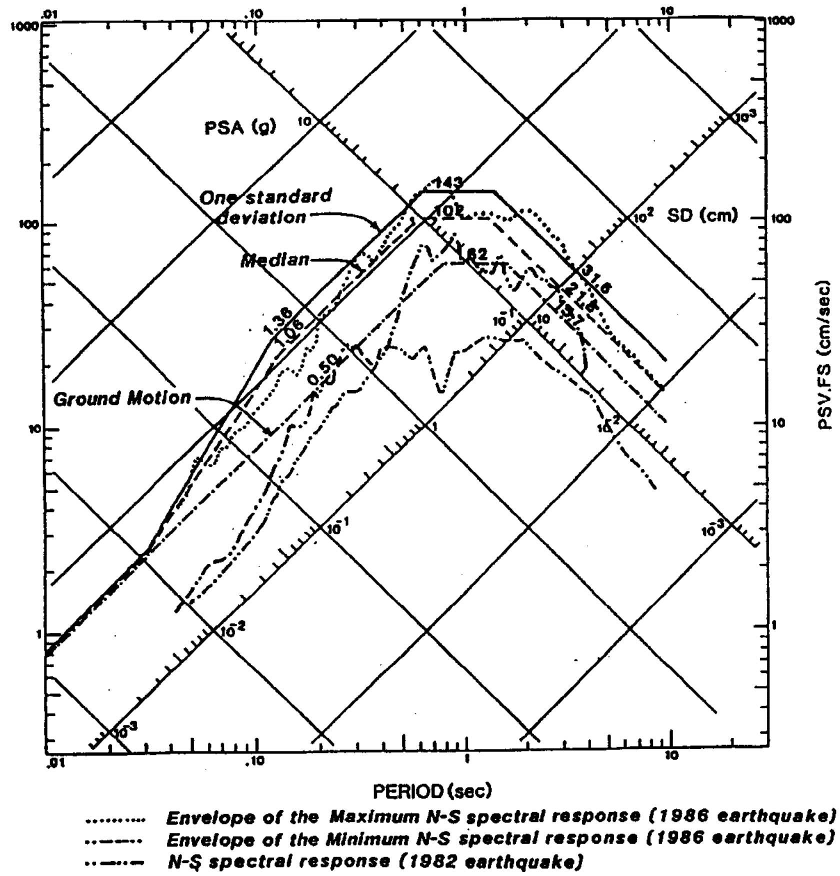

Fig. 3. Elastic response spectra (50 year exposure time), 5 percent damping, compared with a composite, North-South, 5 percent damped spectra of accelerograms from the 1986 San Salvador earthquake, and the North-South, 5 percent damped spectra from the 1982 offshore shock.

Hall technique. The spectral response from the 1982 earthquake falls consistently below the median of the 50 year elastic response spectrum.

INDONESIA

Nature of the Studies

An investigation of the earthquake hazard of North Sulawesi Province was undertaken with the support of the USAID office in Jakarta, Indonesia. Pilot studies of losses to dwellings were also undertaken. The damaging North Sulawesi earthquake of April 18, 1990 ($M_s = 7.3$) occurred just prior to the onset of the hazard and risk assessment project. The damage pattern of this earthquake was carefully studied and it provided valuable information on the vulnerability of dwellings, and proved invaluable in the pilot loss study. It is estimated that the economic loss to dwellings in Gorontalo in the 1990 earthquake was about 10 percent of their value.

Results

Probabilistic ground motion hazard maps for rock and for soft soil (acceleration in 50 years with a 10 percent chance of being exceeded) were prepared for North Sulawesi. The definitions of rock and soft soil are those given by Fukushima and Tanaka (1990) in their paper on attenuation. The acceleration attenuation relations developed by Fukushima and Tanaka for Japan were used in the North Sulawesi study, since no acceleration data are available for this area in Indonesia. In using this attenuation relationship, similar regional attenuation characteristics between the western Pacific island arc settings were assumed, and the attenuation curves were considered appropriate for use in subduction environments. The hazard estimates were obtained using seismic sources that model the earthquake potential to a depth of 100 km beneath northern and central Sulawesi and include the Palu fault zone of western Sulawesi, the North Sulawesi subduction zone, and the southern most segment of the Sangihe subduction zone beneath the Molucca Sea.

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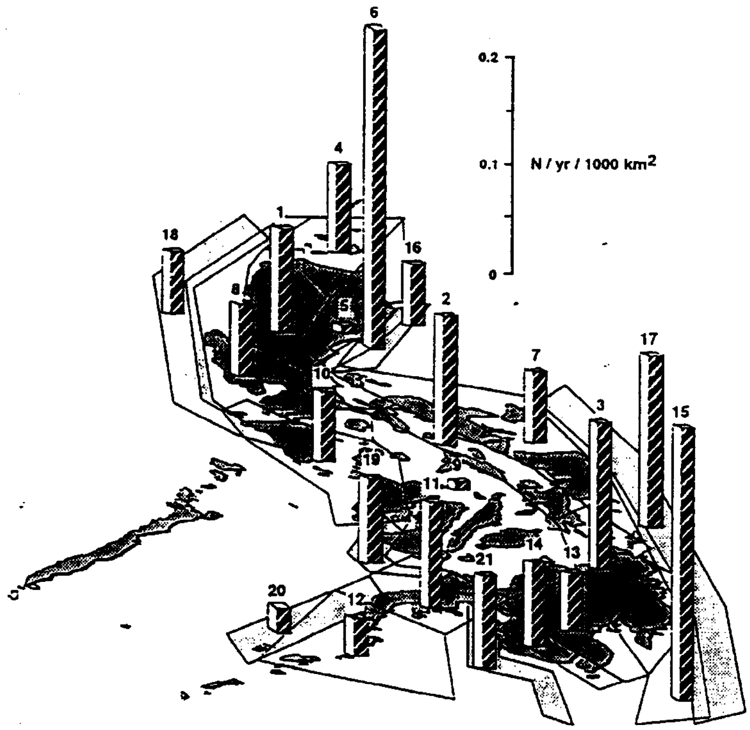

Fig. 4. Normalized rates of earthquake activity (M_s >5.1) in each source zone used in the probabilistic model of earthquake occurrence. The bar graphs are scaled by the cumulative number of earthquakes occurring annually in each zone per 1,000 km^2. Corresponding seismic source zone numbers are shown above the graphs.

<u>Regional Ground Motion Hazard Maps</u>

Probabilistic acceleration hazard maps were computed for the entire country for an exposure time of 50 years at the 90 percent extreme probability level (10 percent chance that the accelerations will be exceeded). Figure 5 shows the 50 year exposure time, 90 percent probability level acceleration maps for rock, and soft soil. The soils are as defined by Fukushima and Tanaka (1990). Qualitative comparison with intensity maps from earthquakes in the Philippines indicate that the acceleration maps produced for the three surficial materials rock, medium soil, and soft soil bracket the range of intensities experienced in earthquakes in the Philippines.

SUMMARY

The seismic hazard and risk studies discussed in this paper indicate that a considerable quantitization of earthquake hazard and risk is possible on a global basis using data available at the present time. It is important to make use of <u>all</u> of the data available in any given area. Integration of intensity data with whatever quantitative ground motion data are used greatly improves the ground motion estimates, and serves to validate the ground motion assessment. The importation of acceleration attenuation relationships, and other quantitative measures of ground motion developed in areas with strong motion data bases, and in areas with seismotectonics similar to the study area under consideration is a practical necessity, and, if carefully applied, yield reasonable results. The study of earthquake losses in North Sulawesi illustrates that good building inventory data and earthquake damage data may be more available than is generally realized. The evaluation of the risk to areas of the world that may be rapidly expanding, both economically and in population, cannot be overemphasized.

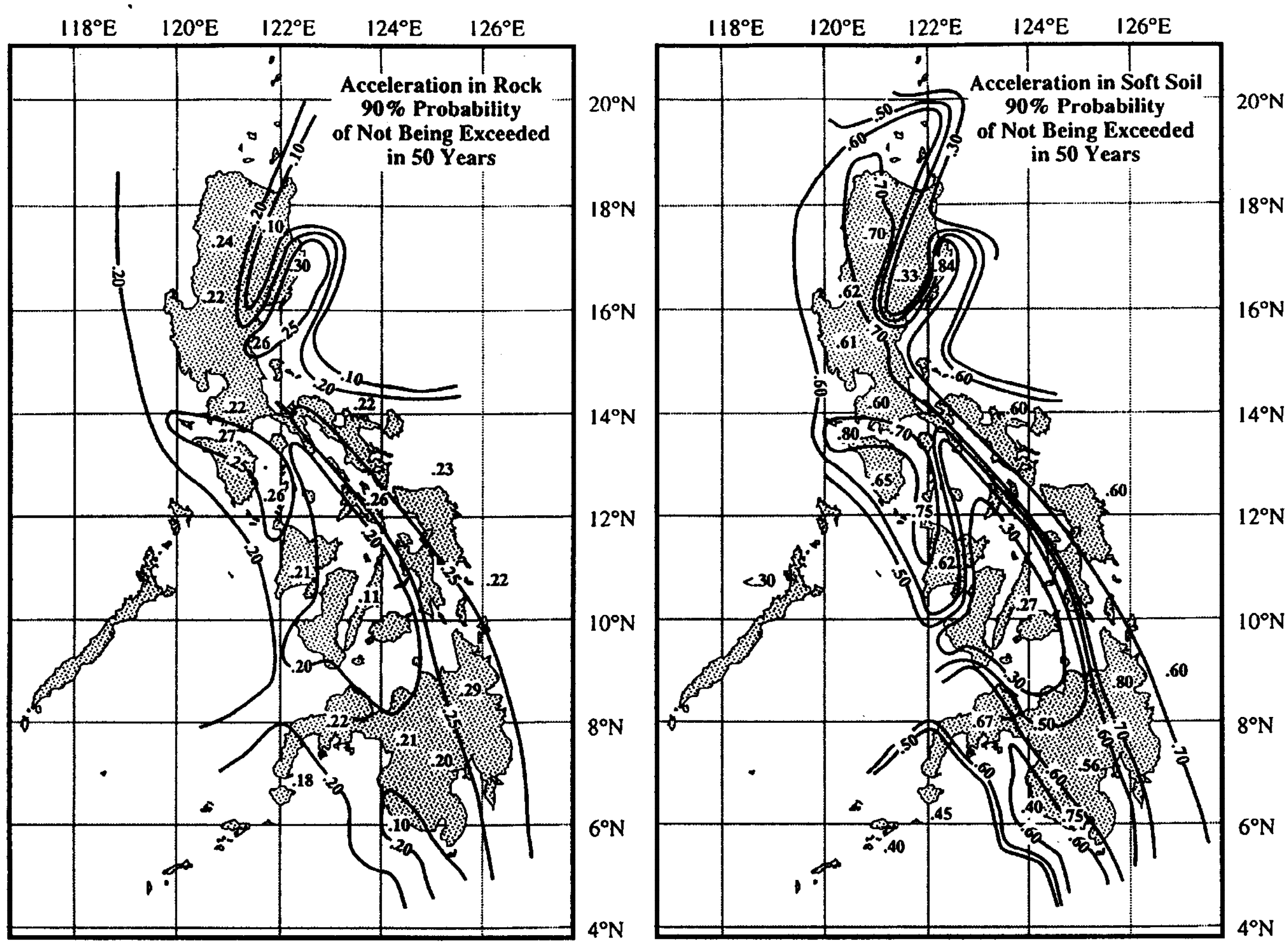

Fig. 5. Acceleration in rock and in soft soil, 90 percent of not being exceeded in 50 years.

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