Seismic Hazard Maps

Summary

The Steering Committee of the Seismic Hazard Project - Latin America and the Caribbean - directed IPGH to compile a "five level" probabilistic seismic hazard map for the project area using the historic parametric method to compute the gridded estimates. This map would serve as a common reference to the seismic hazard maps to be produced independently by each of the regions using a computational procedure of their choosing (all but the Caribbean chose the source zone method).

The five levels of seismic hazard defined by the Steering Committee are:

- 0 - 62.5 gal - minor hazard
- 62.5 - 125 gal - low hazard
- 125 - 250 gal - moderate hazard
- 250 - 500 gal - significant hazard
- > 500 gal - high hazard

The computer programme developed by IPGH especially for the project and this assignment has the following features:

- incorporates estimated uncertainties of the earthquake parameters into the calculations using pseudo-random numbers to scale standard deviations assigned to each parameter - a normal distribution has been assumed for all parameters except those (attenuation and depth) which may generate values less than zero in which case we assumed a log-normal distribution.

- aftershock sequences have been removed from the list of earthquakes used for the calculations by the method of Davis and Frolich (1991) with a cut-off interval of seventy-five (75) "space-time" days

- extrapolation to the required return period (474.56 yr for 10% probability of exceedance in 50 yr) has been carried out using the equation

$$\ln A = \ln A_{\max} - \alpha e^{-\beta R},$$

where α and β are constants to be estimated from the data, A_{max} is the maximum possible value of PGA at the field or target point and R is the return period. Note that when $R \to \infty$, $A \to A_{max}$

As directed by the Steering Committee, the computer programme has been applied under the following conditions.

- all events with moment magnitude M≥4.0 have been selected from the earthquake catalogue

- the catalogue has been assumed to be complete for M ≥ 4during the period 1964-1993

- we chose CLIM94 for the computations from among the following attenuation relations provided by the members of the Steering Committee:

    - ORDAZ94 (Mario Ordaz of UNAM, personal communication, 1994)

    - CLIM94 (Climent et al, 1994)

    - KAUSEL94 (Edgar Kausel, Universidad de Chile, personal communication, 1994

    - WC82 (Woodward-Clyde, 1982)

- used the JB93 (Boore et al, 1993) for events shallower than 15 km in all regions

- A_{max} has been assumed to be 2500 gal for all points of computation

- each solution at each field point was iterated 100 times with pseudo-random numbers

The CLIM94 attenuation relation is the best documented of all those suggested and appears to have a good balance of near and far field data available for the computation of its coefficents Its peak values are somewhat lower than those computed using other attenuation relations, but this will have to be accepted until improvements in our knowledge and understanding of attenuation can be made

As there is no analytical method available at this time for establishing the value of A_{max}, several values were tried and checked for such things as A_{max} being exceeded (forcing an arbitrary but unacceptable reset within the computer programme to a value 1 gal less than A_{max}). The results of these tests suggest that no great error is introduced into the calculations by using a single value for all field or target points which then led to the adoption of the value 2500 gal for A_{max}; a value that is nowhere exceeded by the result of any single interation.

Pseudo-random numbers provide an excellent low pass filter and when combined with the smoothing in both the gridding and contouring processes of SURFER, the result is a sesimic hazard map devoid of a a large number of "bullseyes" which we believe to be an undesirable feature.

Our technique of extrapolation to the desired return period, the use of the CLIM94 relation and the smoothing inherent in the use of pseudo-random numbers lead to peak seismic hazard values that are slightly lower in the high range of hazard values than those on maps for South America and México compiled by CERESIS and UNAM respectiveley. However, a comparison of the mean values of each of the "five levels" (see above) of seismic hazard computed for the IPGH maps with those computed by the regions gives good agreement generally for the four lower levels and fair agreement for the upper level. For the moment this is about the best we can expect, but there is no doubt that the IPGH maps a reasonable reference map for the project area as a whole.

As our catalogue covers a time interval of about 500 yr and several participants have expressed interest in seeing a map of maximum PGA due to a single event, we have computed and compiled a map of what we call "one-time maximum" hazard values using the CLIM94 attenuation relation. Comparison with the probabilistic map suggests that the values are for the most part everywhere less. However, we emphasize that this "one-time maximum" map has no meaning in a probabilistic sense and cannot be used in place of it.

Resumen

El Comité Directivo del Proyecto de Peligro Sísmico - América Latina y el Caribe - le indicó al IPGH la compilación de un mapa probabilístico de peligro sísmico en "cinco niveles" para el área de proyecto usando el método paramétrico histórico para calcular las estimaciones en la rejilla. Este mapa servirá de referencia común para los mapas de peligro sísmico que serán producidos en forma independiente por cada una de las regiones usando el procedimiento de cálculo de su elección (exceptuando el Caribe, todos los demás escogieron el método de zona fuente).

Los cinco niveles de peligro sísmico definidos por el Comité Directivo son:

0	- 62 5	gal	- peligro menor
62.5	- 125	gal	- peligro bajo
125	- 250	gal	- peligro moderado
250	- 500	gal	- peligro significativo
	> 500	gal	- peligro elevado

El programa de computadora desarrollado por el IPGH especialmente para el proyecto y esta asignación tiene las siguientes caracteristicas:

- incorpora en el cálculo las incertidumbres estimadas de los parámetros de los sismos utilizando números pseudo-aleatorios para escalar las desviaciones estándar asignadas a cada parámetro, se asumió que todos los parámetros tienen una distribución normal, exceptuando aquellos (profundidad y atenuación) que pueden generar valores menores a cero, en cuyo caso asumimos una distribución log-normal.

- se removieron las secuencias de réplicas de la lista de sismos usadas para el cálculo, usando el método de Davis y Frolich (1991), con un intervalo de corte de setenta y cinco (75) días "espacio-tiempo".

- se efectuó una extrapolación al periodo de retorno requerido (474.56 años para un 10% de probabilidad de excedencia en 50 años), utilizando la siguiente ecuación:

$$\ln A = \ln A_{máx} - \alpha e^{-\beta R}$$

donde α y β son constantes que deben ser estimadas de los datos, $A_{máx}$ es el valor máximo posible de PGA en el campo o punto de interés y R es el periodo de retorno. Cuando $R \rightarrow \infty$, $A \rightarrow A_{máx}$.

De nuevo, con la aprobación de Comité Directivo, el programa de computadora se aplicó bajo las siguiente condiciones:

- todos los eventos con magnitud de momento $M \geq 4$ fueron seleccionados del catálogo de sismos,
- se considera que el catálogo está completo para $M \geq 4$ durante el periodo 1964 - 1993,
- seleccionamos la relación de atenuación CLIM94 para los cálculos, de entre las siguientes relaciones de atenuación proporcionadas por el Comité Directivo
  - ORDAZ94 (Mario Ordaz de la UNAM, comunicación personal, 1994),
  - CLIM94 (Climent et al, 1994),
  - KAUSEL94 (Edgar Kausel, Universidad de Chile, comunicación personal, 1994),
  - WC82 (Woodward-Clyde, 1982)
- el Comité Directivo también requirió el uso de JB93 (Boore et al, 1993) para eventos mas superficiales que 15 km, en todas las regiones
- para $A_{máx}$ se asumió un valor de 2500 gal en todos los puntos de cálculo
- cada solución para cada uno de los puntos de campo fue iterada 100 veces usando números pseudo-aleatorios.

La relación de atenuación CLIM94 es la mejor documentada de todas las que fureron sugeridas y parece tener un buen equilibrio entre los datos de campo cercanos y lejanos disponible para el cálculo de sus coeficientes Sus valores máximos son algo menores que los calculados usando otras relaciones de atenuación, pero esto debe ser aceptado hasta que haya mejorado nuestro conocimiento y comprensión de la atenuación.

En vista de que hasta este momento no existe ningún método analítico disponible para establecer el valor de $A_{máx}$, se probaron y se revisaron diversos valores para situaciones tales como que $A_{máx}$ sea excedido (lo que obliga a que el programa de computadora lo redefina en forma arbitraria e inaceptable a un valor de 1 gal menor de $A_{máx}$) Los resultados de estas pruebas sugieren que no se introducen grandes errores en los cálculos por el hecho de usar un valor único para todos los puntas seleccionados o de campo, lo que condujo a adoptar el valor 2500 gal para $A_{máx}$; valor que no es excedido en ninguna parte por el resultado de cualquiera de las iteraciones individuales.

Los números pseudo-aleatorios proporcionan un excelente filtro pasa-bajas y al combinarlos con el suavizamiento tanto en la rejilla como en los procesos de contorno del SURFER, el resultado es un mapa de peligro sísmico sin la presencia de un gran número de "ojos-de-buey" los que consideramos una característica indeseable en estos mapas.

Nuestra técnica de extrapolación al periodo de retorno deseado, el uso de la relación CLIM94 y el suavizamiento inherente al uso de números pseudo-aleatorios, producen valores pico de peligro sísmico que son menores que los proporcionados para el rango de peligro elevado en los mapas para América del Sur y México compilados por CERESIS y UNAM respectivamente. Sin embargo, comparando los valores medios entre los mapas de peligro sísmico calculados para el IPGH con aquéllos calculados por cada región, para cada uno de los "cinco niveles" de peligro sísmico (ver arriba), encontramos que, para los cuatro niveles inferiores existe una buena concordancia general, mientras que para el nivel superior la concordancia es razonable Por el momento, esto es lo mejor que podemos esperar, pero no hay duda de que los mapas del IPGH son mapas de referencia razonables para el área total del proyecto.

Como nuestro catálogo cubre un periodo de tiempo de 500 años y varios participantes han expresado su interés en ver un mapa de PGA máximo debido a un evento aislado, calculamos y compilamos un mapa de valores de peligro sísmico de lo que llamamos "máximo - por - única - vez", usando la relación de atenuación CLIM94 La comparación con el mapa probabilístico de este mapa muestra que en le mayor parte, los valores producidos son menores. Sin embargo, deseamos enfatizar que este mapa "máximo - por - única - vez" no tiene sentido desde un punto de vista probabilístico y no puede ser usado en su lugar.

Part 1. Methodology

Introduction

The classic paper by Cornell (1968) represents the beginning of what might be called the modern era of seismic hazard estimation. In this paper Cornell laid the foundation for probabilistic seismic hazard estimation by means of the source zone method. Subsequently, many individuals, notably in the USA, have contributed enhancements to this method to the point where a rather sophisticated industry exists. Despite these advances in the art we should never forget that good results depend to the first order on the catalogue upon which the computations are based In the absence of a top quality catalogue with magnitude estimates on a uniform scale (preferably moment magnitude), seismic hazard estimates to modern standards are not possible

For this project the Steering Committee took the position that each region should compute its own seismic hazard estimates by a method of its choosing and that the project (IPGH) would compute, or otherwise compile, a map of global estimates of seismic hazard to provide a reference for comparing seismic hazard estimates from locale to locale within the project area. This decision was further refined at the meeting in Brazil where the committee decided that, the project office would compile a "five-level-seismic hazard map" because several members believed there might be serious problems in the event a contoured project map differed from that extant in any particular country The values of PGA upon which these five subdivisions would be based were also established and IPGH was asked to compile such a map for discussion at the next meeting of the Steering Committee.

As considerable research and development had already been done on a method of seismic hazard estimation that was fast on a computer and easily adapted to situations where extensive testing and evaluation were required, IPGH decided to apply this method to the assignment from the Steering Committee. Known as the *Historic Parametric Method*, our development of it proved equal to this task and one of us (JBS) presented a five level seismic hazard map to the next meeting of the Steering Committee in Melbourne, Florida The Steering Committee directed that IPGH compile such a map for the final report of the project based on a 10% probability of exceedance in 50 years.

The project office developed an operational version of the computer programme which included adaptations related to the use of random numbers, to the method of extrapolation to the required return period (in our case 474.56 yr) and to the removal of aftershock sequences. The final hazard map was compiled and presented for the approval of the Steering Committee at its final meeting (in Melbourne, Florida in 1995).

We proceed first to a brief description of our version of the historic parametric method, followed by a presentation and discussion of the seismic hazard maps. Our conclusions follow.

The historic parametric method

Diverse and often equivocal discussions between the authors regarding the computation of seismic hazard estimates eventually led to the programming and testing of an early version of our adaptation of this method by JBS and his graduate students at Lancaster University in the UK. This method at the time was believed to be original, but subsequently we found that others (e.g., Grases, 1990; Veneziano, Cornell and O'Hara, 1984) had considered the method before us. Nevertheless, we persisted with the development of this method because it was fast on a computer and therefore offered the opportunity of testing a wide variety of hypotheses for the hazard calculations before the final computations were necessary.

Some of the main points that emerged from our early discussions are:

- Most of the existing computer programmes were cumbersome and time consuming and not at all suited to testing various hypotheses quickly on a PC.

- The choice of source zones was (and is) subjective with the result that different individuals and groups would almost certainly derive different models

■ Patterns of seismicity often influence to a considerable extent the choice of source zones.

■ The only real evidence for a particular fault being active is an earthquake and in this sense it might be better to allow the earthquakes individually to define hazard rather than assume that any given event may occur anywhere within a given source zone.

■ Inclusion in the seismic hazard computations of uncertainties in the data contained in the catalogue is relatively easy to carry out with the Historic Parametric Method.

■ Extrapolation in one manner or another is a necessary evil in any technique of computing seismic hazard.

Comparisons of the results using this method with the source zone method by students at the University of Lancaster in the UK and presented at various technical workshops of the project showed clearly the methods gave comparable results. This, among others, led to the decision of the Steering Committee to retain the method for use in the compilation of the five level reference map by IPGH.

Shepherd, Tanner and Prockter (1994) presented the results using an early version of our computer programme. Since that time we have added the use of pseudo-random numbers, an improved, we think, method of extrapolation and removal of aftershock sequences. More will be said of these later.

We start with the usual assumptions that the distribution of earthquakes with time is Poissonian and that rate of activity of any given source follows the Gutenberg-Richter relationship:

$$LogN = a - bM \qquad (10)$$

We then proceed as follows:

1. Define the periods of completeness for different magnitude ranges (for a catalogue covering a period 1471 to mid-1994 we have chosen a completeness interval of 30 yr (1964-1993) for all events with magnitude $M \geq 4.0$).

2. Choose the attenuation relation(s) to be used for the region under consideration (in our case we are interested in the computing the ground motion at sites on solid rock or equivalent).

3. Select the earthquakes to be included in the computation (in our case those events of magnitude 4 or 4.5 and above, all depths and no area restrictions (i.e., select from the entire project area)) for the region under consideration.

4. For each earthquake selected, calculate the distance of its hypocentre from and then the Peak Ground Acceleration (gal) at the field or target point under consideration using pseudo-random numbers generated by standard methods (Press, Teukolsky, Vettering and Flannery, 1992) to scale estimated uncertainties of the parameters involved in the computation..

5 Set up a series of bins, each with an increasing threshold of acceleration, and compare the computed level of acceleration with each until a bin is encountered with a threshold that is larger than the computed acceleration - for each bin accepted augment the number of events by one.

6. Once all earthquakes selected have been processed, compute the return period for the events in each bin, rejecting any bin with less than three events - the longest possible return period is thus 10 yr in our case.

7. Extrapolate the bin information (acceleration level and return period) to the required return period (we have used 456.74 and 10000 yr) - use at most the five adjacent bins with the largest return periods and abandon the computation point should any iteration contain less than three bins meeting the specifications for extrapolation.

8 Iterate steps 4-7 100 times (or more if time of computation is not an important factor) placing the results in an array of estimated PGA values - in our programme we do not use random numbers for the first iteration so that we can compare randomized and non-randomized results

9. Calculate the median and upper and lower quartiles for the randomized acceleration values for each target point

10. Step to the next point in the area under consideration and repeat steps 4-9.

We now turn to a consideration in more detail of some aspects involved in the computation of seismic hazard.

Attenuation relations

Seismic waves are affected by physical conditions near the focus of the event, by physical conditions between the focus and the target point and by local conditions beneath the target point. Conditions of this complexity underscore the difficulties of deriving an expression for the attenuation of seismic waves in the estimation of probabilistic seismic hazard, especially for an area of the size involved here. They also help understand why attenuation of seismic waves is one of the largest sources of error (up to a factor of two for this area) in the calculation of probabilistic seismic hazard estimates .

The project grappled with the problem of attenuation at various meetings of the Steering Committee and Technical Workshops without reaching a conclusion. At a meeting of the Steering Committee in Melbourne in May, 1994, we were fortunate to have in attendance Dr. Mario Ordaz of UNAM who is among the most knowledgeable of individuals in Latin America on this subject. At this meeting each regional representative suggested what he thought to be the attenuation relation best suited to computations of seismic hazard for their respective regions Each was carefully reviewed with Dr. Ordaz by programming it on a notebook computer to study its behaviour with distance and to compare it with the others.

To avoid problems of too rapid attenuation in the vicinity of the epicentre, the Steering Committee decided, on the recommendation of Dr. Ordaz, to apply the Singh et al (1980) equation, an empirical relationship which relates the magnitude of an event to the area of the fault zone (here termed the "Singh rupture sone"). In the form used by Singh et al this equation is written

$$M = a \log A + b$$

where a and b are constants here assigned the values 1 and 4 respectively, A is the area of the fault zone and M is the magnitude of the event. If we assume that the rupture area is square, this equation can be inverted to define a half-width (RD) of the fault zone as follows:

$$RD = 1/2(10^{M-4})^{\frac{1}{2}} \qquad (11)$$

where RD is the distance from the epicentre to the edge of the "Singh rupture zone" and M is the moment magnitude of the event. For our purposes Dr. Ordaz recommended that RD be limited to a maximum distance of 37 km.

The four attenuation relations proposed for the consideration of IPGH are:

1. México

Provided by Ordaz (1994, personal communication) this law is:

$$A = 1.76 + 0.3M - \log D - 0.0031D \qquad (12)$$

Where A is the acceleration in gal, M is the moment magnitude and D is the depth to the focus if D is less than RD (equation 11) or else the distance from the target point to a focus transposed to the edge of the "Singh rupture zone". Dr. Ordaz also recommended that the maximum acceleration values generated by this equation be limited as follows:

- If $M \geq 8$ then $A_{max} = 526$ gal;

otherwise

- $A_{max} = 253 - 162M + 265m^2$ gal.

Central America

The coefficients of this attenuation relation have been computed from the results of about 220 strong motion recordings (Climent et al, 1994), of which about 60 are located in México and about 90 on hard rock locations. The coefficients have been computed for eight different frequencies, although we do not use it in this mode The relationship as used in this report is:

$$\ln A = -1.687 + 0.553M - 0.537\ln R - 0.00302I \qquad (13)$$

where M is the magnitude and R is the depth to the focus if R is less than RD of equation 11 or the distance to a focus transposed to the edge of the "Singh rupture zone".

South America

This relation has been derived by Edgar Kausel (personal communication) of the Universidad de Chile and recommended to the Steering Committee by Alberto Giesecke, the Director of CERESIS. No details are available as to the numbers and distribution of strong motion recordings nor the method of determining its coefficients. The equation as used in this report is:

$$\ln A = \ln 71.3 + 0.83M - 1.03\ln(R + 60 \qquad (14)$$

where M is the magnitude and R the distance computed in the context of the "Singh rupture zone". Dr. Kausel has also recommended additional constraints on the maximum acceleration values generated by this equation as follows:

- for $M \geq 9$ the maximum acceleration permitted is 525 gal
- for $M \geq 8.5$ the maximum acceleration permitted is 520 gal
- for $M \geq 8$ the maximum acceleration permitted is 512.5 gal
- for $M \geq 7.5$ the maximum acceleration permitted is 500 gal.

Constraints on the accelerations of very large earthquakes have been applied in both México and South America on the basis of strong motion recordings which show that these large events do not produce the peak accelerations that have been observed elsewhere for events of similar magnitude.

The Caribbean

Aspinall et al (1994) examined a number of attenuation relationships and concluded that the equation developed by Woodward-Clyde (1982) for subduction zone settings best fit the scene in the Trinidad-Tobago region. Although this is intended for subduction zones this has been suggested for consideration by the project office for all of the Caribbean, largely because it agrees as well or better than other relations with the limited data available.. This relation is:

$$\ln A = 5.347 + 0.5M - 0.85\ln(D + \exp(0.463M) \qquad (15)$$

where D is the distance within the contexr of the "Singh rupture zone" and M is the magnitude.

Shallow events

As indicated earlier the meeting of the Steering Committee undertook an extensive discussion of the effects of shallow earthquakes (say at depths of less than 15 km) and concluded, albeit reluctantly on the part of one or two individuals, that some allowance should be made in the compilation of the maps at the project level for the increased accelerations observed in the event of shallow earthquakes. Consequently, we decided to include the Joyner and Boore (1993) relationship in the computations and to apply it to those events with depths of 15 km or less.

This law as used here is:

$$\log A = -1.229 + 0.227M - \log(D^2 + 44.225)^{\frac{1}{2}} - 0.00231(D^2 + 44.225)^{\frac{1}{2}} \quad (16)$$

where D is the distance within the context of the "Singh rupture zone" and M is the magnitude.

The Steering Committee concluded its lengthy discussion on attenuation with the recommendation that IPGH choose any or all of these relations to compute its reference map for the project area

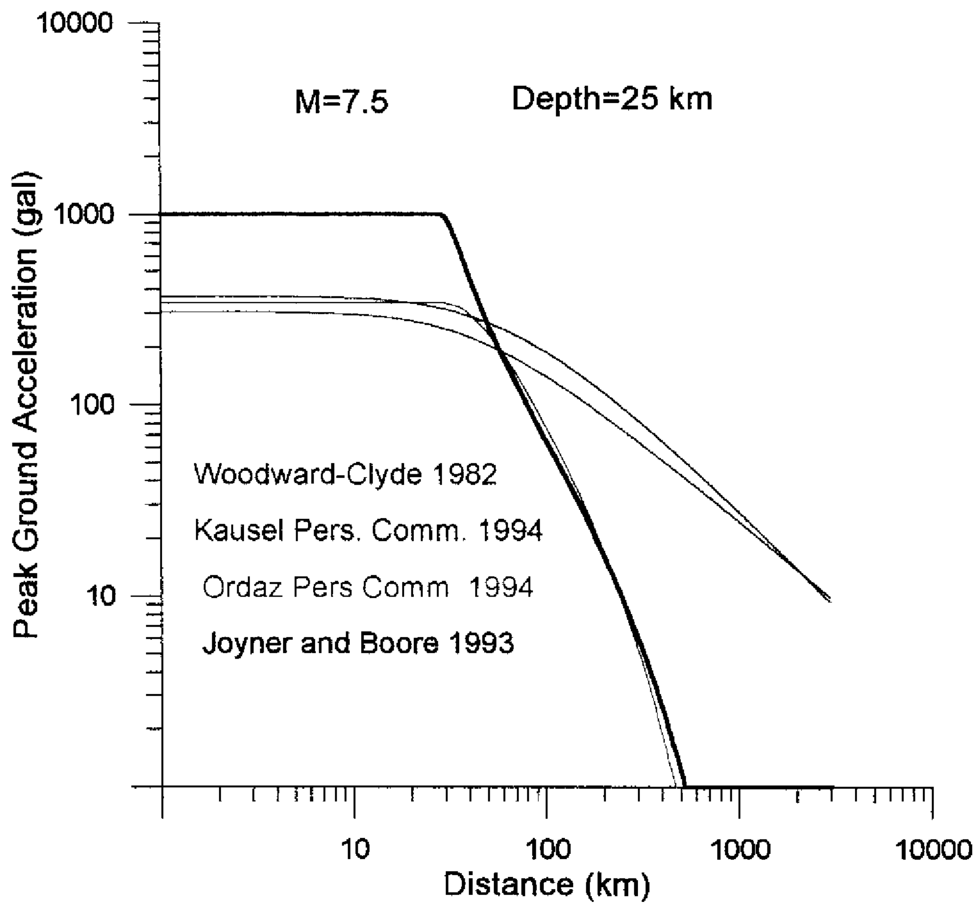

Figure 10. Behaviour with distance of the five attenuation relations considered in this report. Note that these relations are assumed to hold over the range for which they are non-zero, which may differ from the limitations imposed by the originators of the particular relation

A comparison of the four attenuation relations (the Joyner and Boore relation is included for completeness, but is intended only for use with shallow earthquakes) is given in Fig, 10 from which we draw the following conclusions:

- The Kausel and Woodward-Clyde relations attenuate very slowly and would produce probabilistic seismic hazard maps for which the pattern of the contours would be far broader than any we have seen to date. This behaviour probably stems from limited horizontal distances over which strong motion data are available or their distribution or a combination of both, with the result that the relation can only be applied over a restricted horizontal distance. Dr. Kausel (personal communication) has confirmed this in the case of the attenuation law he used in Chile. We therefore conclude we can not use these relations in the general case.

- The CLIM94 law attenuates more slowly than does ORD94, but its peak value is lower for an earthquake of the magnitude used to compile Fig. 10 As the CLIM94 law includes data for México, it would appear to have the good balance of near and far field strong motion records necessary for an attenuation law to be representative of the conditions found within the project area. The rapid attenuation of ORD94 seems to be too severe for general use.

Discussions with various individuals involved in the project indicated general agreement to use the CLIM94 to compute probabilistic seismic hazard estimates for the project map.

There is always a concern about the distance over which the particular attenuation law is valid. Boore et al (1993) for example tend to limit this distance in the interests of avoiding correlations that might otherwise bias the results. Others (Climent et al, 1994) use all of the data available. We also note that the events for which strong motion recordings exist are most likely greater than magnitude 6 or 6.5 which introduces another bias since we use these relations for all magnitudes. Problems of distance and magnitude range accepted, we have applied these relations universally assuming in the process solid rock or equivalent as the medium of response. This rather generous extrapolation on our part does not seem to have produced erratic results if comparisons with the results of other methods are any measure

Finally, we note that operating agencies in each of the regions are in the process of modernizing their equipment and we hope that in the not-too-distant future a comprehensive review can be made of the different attenuation relations determined from data collected in the regions

Selection of earthquakes

For events smaller than 4.5 the moment magnitude scale is probably not uniform. The contribution of events of magnitude 4 to the final hazard estimates is very small, but the presence of acceleration values due to these events may be useful in providing the minimum of three levels required for the extrapolation process. In some cases, however, the smallest levels of acceleration may not be considered because of the way in which exptrapolation is applied (see above).

We experimented with areas of various sizes and found that the penalties in terms of computation time were not that great if we chose all the events in the project area meeting the magnitude and depth criteria. Undoubtedly we are extending the attenuation relations well beyond their range of actual observation. As we are calculating the effects on solid rock or equivalent, we must assume a more uniform and predictable response of the medium at greater distances with the result that any errors due to this extrapolation are not large.

Each earthquake is considered as an isolated or point source and not part of some larger source zone of whatever definition. Earthquakes that have occurred within the period of completeness define the patterns to be used for the seismic hazard estimates. Although this approach has its problems when the rate of seismicity for a given area is very low (a problem for any method), the results generally compare well with those of other methods.

The use of pseudo-random numbers

One of the features of our seismic hazard estimation computer programme is the inclusion of procedures in the computation of the seismic hazard estimates that use pseudo-random numbers to scale uncertainties assigned to the earthquake parameters used in the calculation. Iterative procedures then lead to a solution based on some optimum arrangement of the number of iterations needed to give a reasonable statisical sample and the time to compute the particular result.

For each earthquake the predicted PGA at the target site depends on the location of the earthquake relative to the target site, its magnitude and the ground motion relationship. For our computations we have made the following assumptions with respect to these parameters:

- Uncertainties in the latitude and longitude of the earthquake are normally distributed with a mean of zero and a standard deviation of 0.25 deg.

- Uncertainty in the magnitude of each earthquake is normally distributed with a mean of zero and a standard deviation of 0.25 units of magnitude.

- Uncertainty in the focal depth is log-normally distributed, i.e.,

$$\ln Z = \ln Z_0 + \delta_z$$

  where Z_0 is the nominal depth and $\delta_z = 0.1Z_0$ is a normally distributed quantity with a mean of zero.

- Uncertainty in ground motion is also log-normally distributed, i.e.,

$$\ln A = \ln A_0 + \delta_A$$

  where δ_A is normally distributed with a mean of zero and a standard deviation as stated by the authors of the ground motion equation.

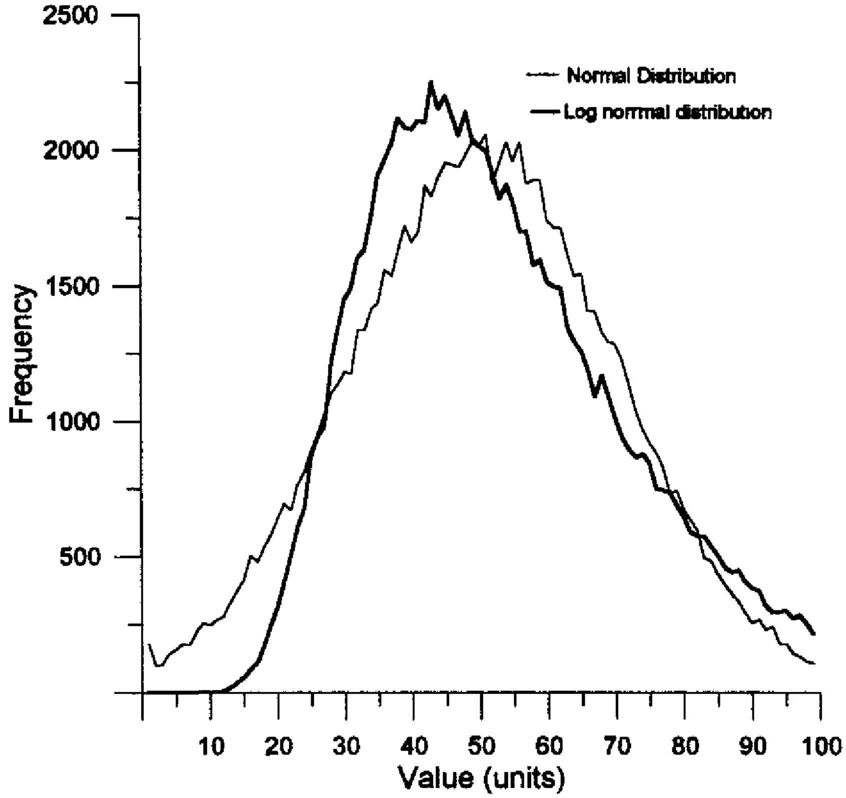

Figure 11. Comparison of the normal and log-normal distributions for a parameter with the same uncertainty. The ragged appearance of the two graphs is a consequence of the limited number of iterations and the number of divisions used to compile the histogram. Considerable smoothing could be achieved by expanding the cell width to 2 or 3 units.

Fig. 11 shows a comparison of the normal and log-normal distributions for a parameter with a value of fifty (50) with error estimates of ±20 units and ±0 4 X respectively, where X is any variable The skewed distribution of the log-normal distribution is readily apparent. This skewness does not affect the median computed for each curve (both have a median of 50), but the upper and lower quartiles differ for each curve, as might be expected. Note also that the normal distribution results in negative values for the variate, which would force some arbitrary choice such as setting the variable to zero which would bias the computed result.

For our computations we have specified that 100 iterations are sufficient to determine the computed result as this was found to be an optimum combination of time saving and accuracy . Fig. 12 gives a probability density function (PDF) for both 100 and 1000 iterations for a station located in the Caribbean. The PDF for 100 iterations is more ragged than that for 1000 iterations, but gives about the same result as expressed in terms of the median. However, the time required to compute the result is about ten times greater in the case of 1000 iterations. Even with the fastest (at the time) of PCs available to the project the time needed to complete the calculations using 1000 iterations per point of computations would be months and not days as was the case for

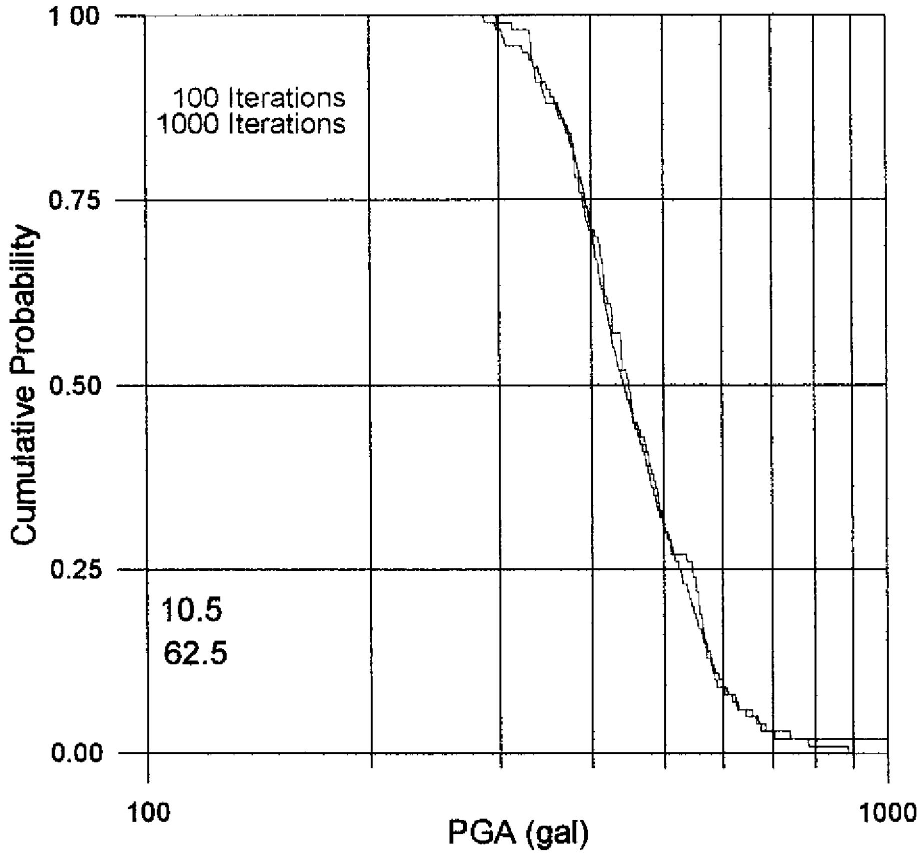

Figure 12. Probability Density Function (PDF) for solutions determined from 100 and 1000 iterations using the random number generator. Aside from a more ragged PDF for 100 iterations the two solutions give about the same result.

100 iterations in an area the size of South America. This time is unacceptably long and we therefore opted to use 100 iterations for each point of computation in all regions.

We have used the more portable and, we think, better random number generators available in Press, Teukolsky, Vettering and Flannery (1992). We have employed a combination of their functions GASDEV and RAN1. RAN1 produces a string of random numbers with values uniformly distributed between 0 and 1 and GASDEV converts these to a normal distribution with a mean of zero (0) and a standard deviation of one (1). We tested all the other random number generators given by Press et al with about the same results.

Extrapolation

To determine the seismic hazard estimate on the basis of a 10% probability of exceedance in 50 yr we must extrapolate to a 474.56 yr return period from a maximum possible calculated return period of 10 yr (for a catalogue with a period of completeness for $M \geq 4$ of 30 yr and a requirement that there must be at least three events in any given bin to calculate a return period for that particular level of acceleration). The return period for any given probability can be calculated from the expression $P(a) = -e^{\frac{t}{R}}$, where P(a) is the probabilitiy, t is the lifetime of the particular edifice (in this case 50 yr) and R is the return period for which the probability is valid. If we substitute the value 0.90 (90% probability of non-exceedance) and the value 50 for t into this equation we get the value 474.56 for R. Interested readers should look up Algermissen et al, 1982 for a good discussion of this topic.

We now set about a brief development of the method of extrapolation used for our calculations. We start with the following assumptions:

- The ground motion law is of the general form

$$\ln A = c_1 + c_2 M + c_3 \ln(R + c_4) \quad (17)$$

- Source zones are infinitesimal elements of volume

- Within the i'th source zone the rate of earthquake occurrence is governed by the Gutenberg-Richter law

$$\ln N_i = a_i - b_i M$$

- a_i varies from element to element and b_i is assumed constant for all elements (Scholz (1990) for example has argued that when M is the moment magnitude scale this quantity should be constant).

Let **A** be the ground motion generated at site **j** by an earthquake of magnitude M in element **i**. Then from equation 17

$$M = \frac{1}{c_2}(\ln A - (c_1 + c_3 \ln(R + c_4)))$$

where R is the return period. The quantity ($c_1 + c_3\ln(R + c_4)$) depends only on the combination of site and element and on the ground motion relationship We can therefore replace it with a constant α_{ij}. Therefore

$$\mathrm{M} = \frac{1}{c_2}(\ln A - \alpha_{ij})$$

Combining this equation with the Gutenberg-Richter relationship (see above), we have

$$\ln \mathrm{N}_i = a_i - \frac{b_i}{c_2}(\ln A - \alpha_{ij})$$

$$= \{a_i + \frac{b_i}{c_2}\alpha_{ij}\} - \{\frac{b_i}{c_2}\ln A\}$$

N_i is the total number of earthquakes in the i'th source zone which generate a ground motion of A or greater We also note that

- the term inside the first set of curly brackets depends on the activity rate in the i'th source zone and on the constants defining the ground motion relationship. It therefore depends on both i and j.

- subject to our assumption that b is constant over all source zones, the term $\frac{b_i}{c_2}$ is a constant over all source zones.

The total number of occurrences of ground motion of amplitude A or greater at the j'th site is

$$(N_A)_j = \sum_{i=1}^{n} N_i$$

where n is the total number of elemental sources. Therefore

$$(N_A)_j = \exp[(\tfrac{-b}{c_2}\ln A)\sum_{i=1}^{n}(a_i + \tfrac{b_i}{c_2}a_{ij})]$$

which can be written

$$\ln\{(N_A)\} = \{\sum_{i=1}^{n}(a_i + \tfrac{b_i}{c_2}a_{ij})\} - \tfrac{b}{c_2}\ln A$$

or for simplicity

$$\ln\{(N_A)_j\} = \mu_j - \tfrac{b}{c_2}\ln A$$

The reciprocal of the number of events per unit time is the return period, R, so that we have finally

$$\ln R = \ln(\tfrac{1}{(N_A)_j}) = \tfrac{b}{c_2}\ln A - \mu_j$$

or

$$\ln A = \tfrac{c_2}{b}\ln R + \tfrac{c_2}{b}\mu_j$$

as the equation relating the level of ground motion to the corresponding return period. An alternative form of the relationship is the power-law representation suggested by Grases (1990)

$$A = \alpha R^{\beta} \qquad (18)$$

The unmodified power-law relationship is unbounded at the upper end. That is, it predicts that as

$$A \to \infty \; R \to \infty.$$

We consider that this result is physically unreasonable - it follows from the fact that the simple Gutenberg-Richter relationship allows all magnitudes up to $M = \infty$. In order to remove this feature we have used an extrapolation relationship of the form

$$\ln A = \ln(A_{max}) - \alpha \exp(-\beta R) \qquad (19)$$

where α and β are new empirical constants determined from the data and A_{max} is the maximum possible PGA at the site This relationship is exactly equivalent to the power-law relationship when A is small compared with A_{max}, but has the property

$$A \rightarrow A_{max} \text{ as } R \rightarrow \infty.$$

Fig 13 illustrates the extrapolation procedure used in this study for a field or target point in an area in which the rate of seismicity is low (eastern central Brasil). The plus marks in this diagram represent the return periods and acceleration levels upon which the extrapolation has been based - the programme considers only the top five points if more than five exist. (Recall that a minimum of three valid bins, each of which contains the results of processing three events or more that meet or exceed the acceleration level for the particular bin, are required for the point of calculation to

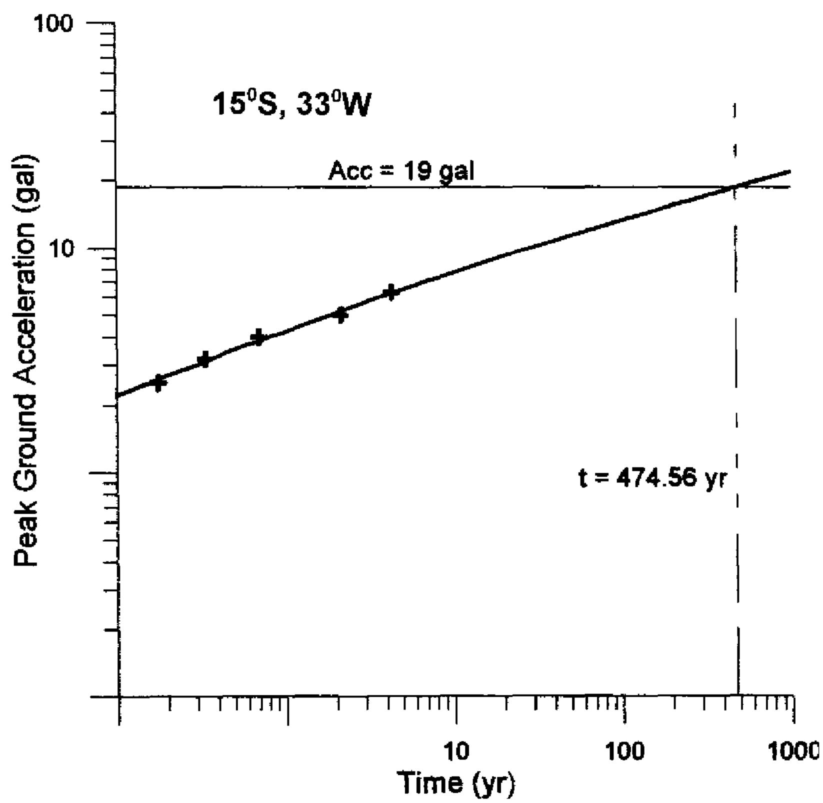

Figure 13. Extrapolation of PGA versus return period by means of the method outlined in the text for A_{max} = 2500 gal. This target point is located in an area of low seismicity in east central Brasil

be accepted). All points that we have checked, admittedly limited, in the above manner have five values available for the extrapolation to 474.56 yr

We have been unable in the time available to arrive at some quantitative method of determining A_{max}. There is also the problem with random numbers of any iteration producing a value in excess of A_{max}, forcing some arbitrary decision to reduce it to less than A_{max}. Any such arbitrary action is unacceptable. Experimentation has shown the results do not differ in a major way due to choice of A_{max} with the consequence that we have tended to adopt the rather large value of 2500 gal This value has been approached at some target points within the project area, but to our knowledge has not been exceeded.

Fig. 14 shows the results for three different values of A_{max} for one of our favourite test points in the Caribbean. As can be seen from the diagram there is relatively little to choose between the three values In this case A_{max}= 2500 gal produces a somewhat larger result than the others with A_{max} = 2000 gal producing the smallest value; the differences are probably a result of the use of random numbers. We checked a sample of 10 values calculated with A_{max} = 2500 gal and found a

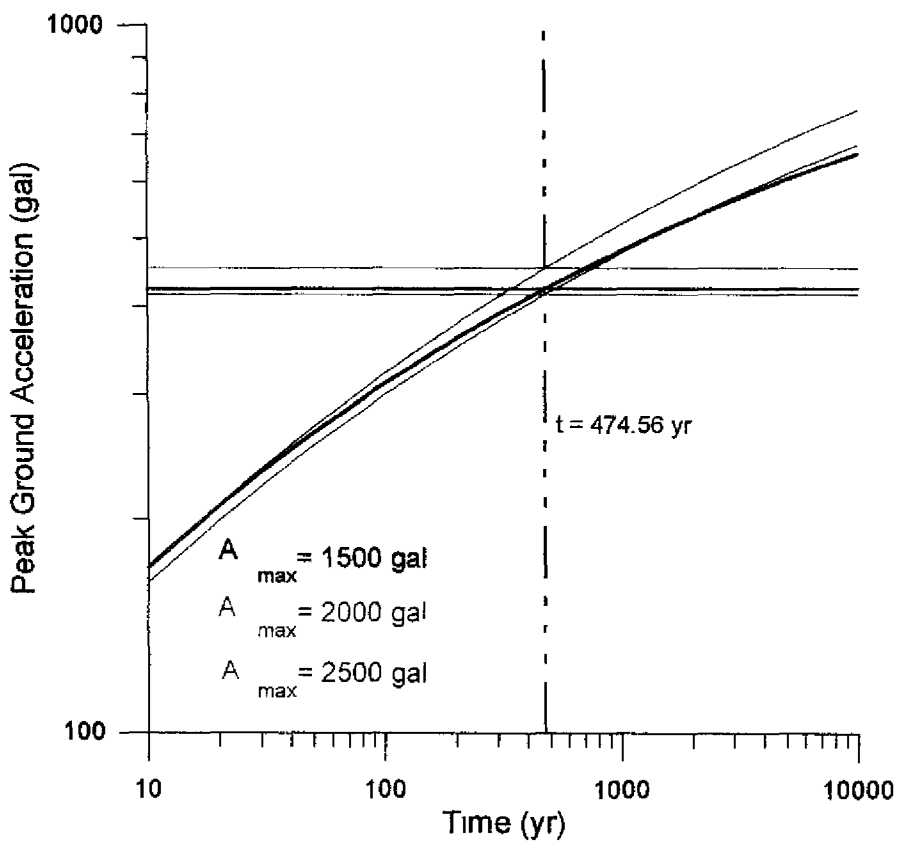

Figure 14 Comparison of extrapolations using three different A_{max} values for a computation point located in the Caribbean. The estimated hazard values vary from 424 gal for A_{max} = 1500 gal (black) to 454 gal for A_{max} = 2500 gal (green) with A_{max} = 2000 gal (red) producing the smallest value. The differences are probably due to the use of pseudo-random numbers..

mean of about 450 gal with the spread between the maximum and minimum values being 40 gal or just less than 10%. Perhaps more indicative of the behaviour of the results with different values of A_{max} are those obtained without the use of random numbers. These can be seen in Table 4 which shows the computed PGAs with and without the use of random numbers for three different A_{max} values. This table shows that the computed PGA without the use of random numbers decreases by about 6% as A_{max} decreases from 2500 to 1500 gal which suggests that in this case 1500 gal might have been a better choice for A_{max} as the computer gave no indication that A_{max} had been exceeded.

Unfortunately we have not been able in the time available to establish an optimum value for A_{max} on a target point by point basis. Giving the computer special instructions on how to assign the A_{max} value for each field point would be a monumental and time consuming (never ending might be more appropriate) task. Our conclusion is that the use of A_{max} = 2500 gal does not seem to produce results that are too much different from those for lower values and as we know it is not

Table 4
Variation of PGA with A_{max}

A_{max}	Random Numbers	Normal
2500	454	335
2000	416	327
1500	424	316

exceeded anywhere in the project area during any iteration using random numbers, its use seems to be as reasonable as any other value of A_{max}

Table 4 also shows that the seismic hazard values computed using random numbers are larger than those computed without random numbers - comparisons in the Caribbean show an average increase of about 30% in the computed seismic hazard with the use of random numbers. This increase probably occurs because the behaviour of PGA is logarithmic and therefore the contribution of an augmented parameter is greater than that for a diminished parameter. The use of random numbers also smoothes the computed seismic hazard values, and we would expect that any contoured seismic hazard map compiled with their use would contain fewer isolated high and low values than that compiled from unmodified parameters.

Aftershock sequences

To remove aftershocks from the computations of seismic hazard, we have adopted the method suggested by Davis and Frolich (1991) who describe a procedure using what they call single-link cluster analysis. They have suggested the empirical relationship

$$d_{ST} = \text{space-time "distance"} = (d^2 + C^2 T^2)^{\frac{1}{2}}$$

where d is the geographic separation, in three dimensional Euclidean space, between earthquakes, T is the time difference (days) and C is a parameter that relates time to distance. They also suggest the value one (1) for C which is a sort of tectonic constant for any given area In their Table 1, their results suggest a cut-off distance (i.e., a maximum value for d_{ST}) for any possible linkage of 70 to 80 ST-km for our project area - we have taken the mid-point of this range of values and have used 75 ST-km as the limit for tagging aftershocks.

When this aftershock sequence relationship is applied to our catalogue we get the following results when selecting the earthquakes for the computations:

- for $M \geq 4$ there are 31,447 events of which 10,947 are tagged as aftershocks,
- for $M \geq 4.5$ there are 11,737 events of which 2,672 are tagged as aftershocks.

Part 2: Seismic hazard maps

Introduction

The seismic mapping hazard procedure as employed here is summarized as follows.

- Select the target site(s)
- Select the earthquakes meeting the retrieval criteria and tag those that are determined to be aftershocks
- For every earthquake selected, calculate the PGA at the target site
- Repeat the calculation 100 times perturbing the earthquake parameters during each iteration by pseudo-random numbers which scale the estimated standard deviation of each earthquake parameter.
- Find the median and upper and lower quartiles of the resulting distribution.
- Place the acceleration for this site in the file to be used for extrapolating to the required return period.
- Repeat for all earthquakes
- Extrapolate to R = 474.56 yr.
- Step to the next site and continue until all sites are completed.
- Grid, contour and plot the data.

All maps presented in this section have been compiled from the data computed with our seismic hazard programmes with the latest WINDOWS version of SURFER (trademark registered to Golden Software in Colorado, USA), an easy-to-use system that can produce outputs that are professional in their appearance. Like all such contouring systems, SURFER can get into difficulty due to aliasing in regions of high horizontal gradient. We have attempted to overcome this by using this system's matrix smoothing method which acts as a low-pass filter. This approach removes genuine as well as spurious highs and lows.

Results

Maps produced entirely by IPGH for presentation in this report have been compiled from results obtained with the historic parametric method as described earlier and with the use of the CLIM94 (Climent et al, 1994) attenuation relation. Maps from regional agencies contained in this volume, with the exception of the Caribbean, have been compiled from results obtained with their respective versions of the source zone method as described by them in subsequent volumes of this final report All maps presented in this volume have been compiled using the SURFER (Copyright Golden Software in Golden, CO, USA) mapping system following the specifications laid down by the Steering Committee for IPGH-produced maps.

In using the CLIM94 attenuation relation, we accept that the peak values may be lower than those obtained with laws suggested by other regional representatives, but results obtained with other attenuation laws would likely be subject to other criticism. In adopting the CLIM94 relation we reiterate that several individuals from within the project area agree with this decision.

In this portion of the report we first present regional results and comparisons, demonstrate the necessity to use local presentations and finally present a probabilistic seismic hazard map for the entire project area along with what is here termed a "one-time maximum" map of PGA compiled from a grid of the largest accelerations experienced at points throughout the project area due to a single event throughout the life of the catalogue (about 500 yr).

All maps in this volume have been compiled assuming solid rock or equivalent as the medium for which the computed PGA applies. In addition to the smoothing realized from the use of random numbers, the maps compiled independently by IPGH have also been smoothed within SURFER during the gridding and contouring processes. The grids provided by the regions have been smoothed during the contouring process only.

As is the case elsewhere in this volume the phrase "seismic hazard" is used in the sense of "probabilistic seismic hazard".

Regional representations and comparisons

Table 5 gives the results of a comparison of mean values for each seismic hazard level of the grids for Mexico as computed by UNAM using the source zone method and by IPGH using the historic parametric method The agreement of the mean values for the four lower levels of seismic hazard is very good, but that for the fifth or highest level agrees well in terms of the mean value, but not in terms of the number of grid points with values within this range of PGA.. In this latter case there are only 32 values within the IPGH grid above the value of 500 gal whereas the UNAM grid contains 84, i.e , is greater by a factor of about two and one-half. The likely explanation would seem to be the use of different attenuation relations for the computations and the two methods of computing seismic hazard (the source zone method assumes a maximum earthquake that is "smeared" over the whole of the particular zone and thus could tend to emphasize the "high" hazard values more) Despite this, we can conclude that for México the IPGH grid appears to give a good representation of the general level of seismic hazard

Table 5
México
Comparison of UNAM and IPGH Gridded Seismic Hazard Values
Return period = 500 yr

Value	UNAM Grid			IPGH Grid		
gal	Number of Grid Values	Average gal	RMS Dispersion gal	Number of Grid Values	Average gal	RMS Disersion gal
>500	84	632	84	32	627	103
250-500	172	334	70	219	327	62
125-250	248	185	37	362	177	35
62.5-125	294	88	17	369	90	19
<62.5	1,892	14	17	1708	19	15

Figs. 15 and 16 show versions of seismic hazard maps for México respectively based on the grid provided by UNAM and that computed by IPGH using its version of the historic parametric method. The UNAM map in Fig. 15 shows the PGA values to be confined to a relatively narrow belt along the west side of the country. When compared to the results shown in Fig. 16, several similarities and differences emerge:

- the IPGH map shows a slightly broader belt of linear seismic hazard values along the western part of the country with a much sharper "elbow" in the latitude range of 20-24^{0}N - this elbow is a manifestation of the Rivera Plate, a small plate that has all but disappeared, referred to by Zúñiga et al (1997) in Volume 2 of this series. See also Singh et al, 1985 for more discussion on the tectonics of this plate,

- the IPGH map shows variously shaped patterns to the west and east of the continous belt of seismic hazard values (one of which is located in the USA and not of interest here) not found on the map compiled from data provided by UNAM,