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Seismic Risk in Intraplate Areas

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SEISMIC RISK IN INTRAPLATE AREAS

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Introduction

Seismic risk is the product of seismic hazard, expressing expected ground motions from earthquakes, and the vulnerability of a particular structure, or complex of structures, that are exposed to loading effects from earthquakes.

The seismic hazard is in general much lower in intraplate (stable continental) regions than in plate margin (interplate) areas, but it is important to note also that the intraplate return times for the largest earthquakes are much greater, and that these largest magnitudes can be expected to exceed 7 in many regions. Passive continental margins and abandoned rifts are particularly exposed in this way, with expected earthquake ground motions at low probabilities which are of potential importance to any sensitive installation. It is important therefore to take into consideration the seismic risk aspects also in such areas, preferably with a safety format as defined by authorities (regulatory agencies) in response to a clearly defined policy regarding acceptable risk.

While a deterministic methodology still can be a viable approach for some site specific earthquake hazard analyses in plate margin areas, it is more difficult to use such methods in intraplate areas, where probabilistic methods are more applicable. Such methods can now include and take advantage of a variety of geological, geophysical and seismological information in a balanced way, based on both multi- and inter-disciplinary approaches, with due consideration to the uncertainties involved. Available state-of-the-art probabilistic methods moreover provide a framework which and a platform for more flexible policy decisions concerning earthquake hazard and risk.

In all seismic hazard work it is important to distinguish clearly between a regional hazard zonation, often performed more as academic exercises, and site specific studies for particular industrial installations, often done by consultant companies. It is the latter type of studies which, in spite of this, are scientifically most interesting, since these require a more detailed assessment, understanding and modeling of the seismogenic processes.

In the present contaxt the main attention will be given to the seismic hazard problems, with emphasis on methodologies, methods, models and uncertainties, while risk problems will be treated only more generally.

Seismotectonics

Seismotectonics is the study of the tectonic component represented by seismic activity. Consequently, any seismic hazard analysis should be based on a seismotectonic model for the region which in a best possible way should incorporate all relevant information pertaining to the seismogenic processes in the region studied. This process is clearly both multi- and inter-disciplinary, including both geological and geophysical sciences, and is particularly challenging in that the model essentially is a prediction model, albeit in statistical terms, for the expected seismic activity.

Intraplate vs. Plate Margin Areas

The theory of plate tectonics states, to the first order, that the Earth's lithosphere consists primarily of a few rigid plates that move independently relative to one another, without internal deformation, on top of a viscous and warmer astenosphere. Within this model, deformation because of plate interactions occurs only at the edges of the rigid blocks, creating narrow zones of seismicity, since the plates themselves are considered incapable of sustaining earthquakes. The global distribution of seismic belts coincides almost perfectly with postulated plate boundaries and provides strong support for plate tectonics. Fig. 1 illustrates in this respect the great difference between the seismic activity along plate margins as compared to intraplate regions.

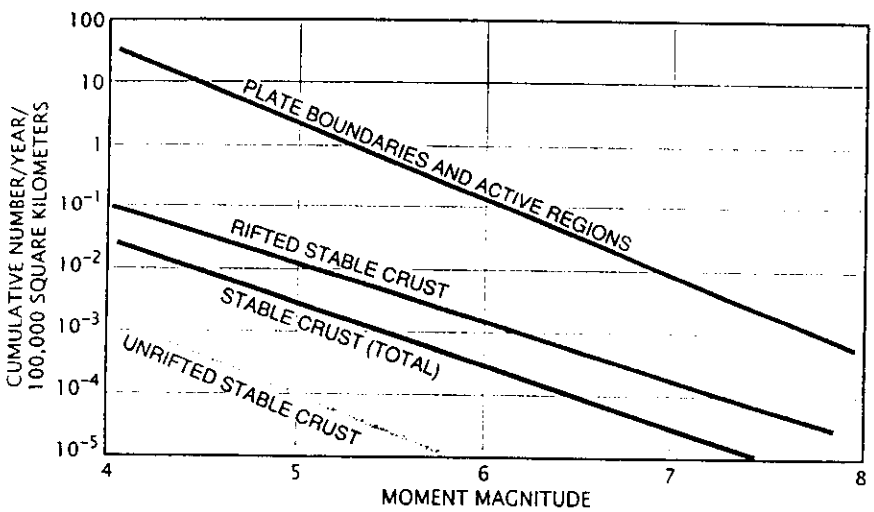

Fig. 1. Seismic activity at plate boundaries and associated active regions as compared with activity in several kinds of stable crust. From Johnston and Kanter (1990).

Earthquakes are experienced also in plate interiors, however, even though such events release less than five percent of the total seismic moment (Scholz, 1990; see also Tables 1-2 and Figs. 1-2). The assumption of rigid plates is, therefore, a good first-order approximation, even though seismic activity is not a complete measure of tectonic activity. Faults may also slip aseismically through creep, and basins may subside, all in a manner which is not observed seismically. It is believed, however, that aseismic slip is a rare phenomenon in continental crustal faulting, except in areas dominated by detachment and decollement structures.

	Type of crust	Max. mag.
Stable Continental Regions	Extended crust, intracontinental rift	8.3 ± 0.5
	Extended crust, passive margin	7.7 ± 0.2
	Non-extended crust, craton	6.8 ± 0.3
	Non-extended crust, fold belts	6.4 ± 0.2
Global	Plate boundaries	~9.5
	Active continental crust	~8.5
	Young (<35 m.y) oceanic lithosphere	~7.5
	Old (35-180 m.y.) oceanic lithosphere	~6.4

Table 1. Maximum observed earthquakes in different types of crust, in stable continental regions and globally. From Johnston et al. (1994).

Year	Event	Magnitude	Structure
1812	New Madrid	8.3	Rift
1811	New Madrid	8.2	Rift
1812	New Madrid	8.1	Rift
1819	Kutch	7.8	Rift
1933	Baffin Bay	7.7	Margin
1604	Taiwan Straits	7.7	Margin
1886	South Carolina	7.6	Margin
1918	Nanai	7.4	Margin
1929	Grand Banks	7.4	Margin
1356	Basel	7.4	Rift
1605	Hainan Island	7.3	Rift
1906	Exmouth Plateau	7.2	Margin
1935	Libya	7.1	Margin
1858	Portugal	7.1	Margin
1951	So. Tasman Rise	7.0	Margin

Table 2. The largest historical earthquakes from stable continental regions The locations of these events are shown in Fig. 2. From Johnston and Canter (1990).

Johnston et al. (1994) defined stable continental regions (SCR) as continental crust including continental shelves, slopes and attenuated continental crust. Active plate boundaries, zones of active tectonics, deformation zones caused by the major Mesozoic-Cenozoic orogenies, and the largest areas of Neogene rifting are excluded from the SCR. The main characteristics of SCR are low heat flow, low attenuation, and low elastic strain accumulation. Rates of deformation, or strain rates, in the crust, are generally in the range between 10^{-6} yr^{-1} for the most active plate margin areas and 10^{-13} yr^{-1} for stable continental regions. For example, across the Norwegian continental margin the upper tectonic strain rate is probably in the order of 10^{-9} to 10^{-10} yr^{-1}, while rates within the Baltic Shield are expected to be lower by at least two orders of magnitude (Muir Wood, 1993).

Using the SRC definition of Johnston et al. (1994), two-thirds of all continental crust is included and one-fourth of the total crust. Stress measurements inside plates generally show large areas with fairly similar stress orientations, thus suggesting a more or less random earthquake distribution inside iso-stress regimes (Zoback, 1992). Observations of intraplate seismicity show, to the contrary, that earthquakes cluster in some areas and are absent from others. This implies that the presence of older weakness zones is necessary, in addition to stress accumulation, to achieve seismic dislocations. Even though regional stresses inside continents often are too weak to create new faults, they may be large enough to reactivate older fault zones. Areas with old, buried zones of weakness are therefore more likely to experience earthquakes (e.g., Bungum et al., 1991).

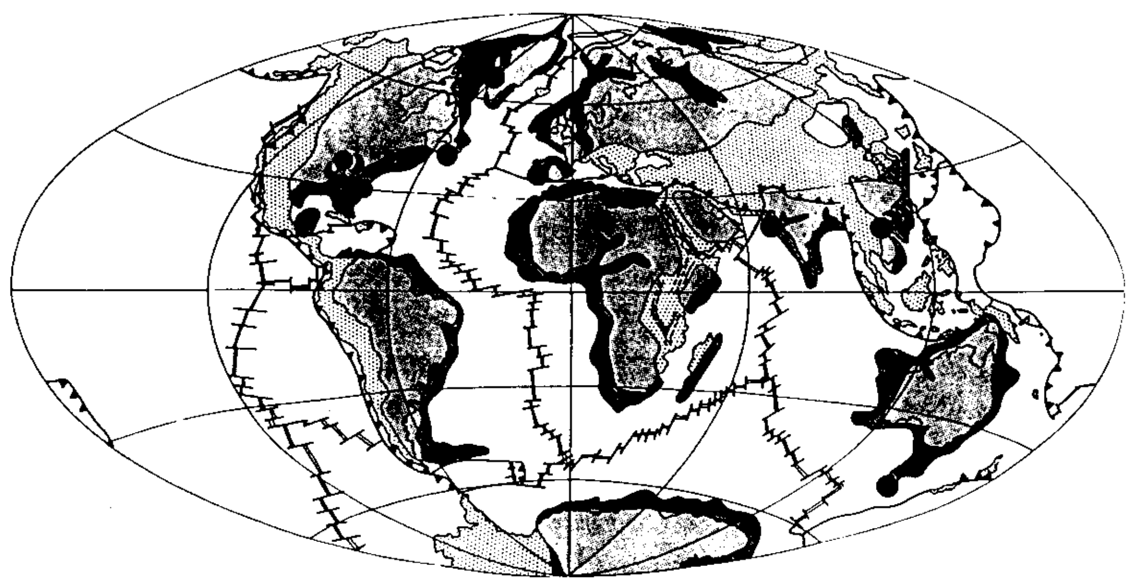

Fig. 2. The stable continental regions of the Earth (light grey for non-extended, hatched for extended) in relation to plate boundaries and other portions of plate interiors (active intraplate, stippled; oceanic intraplate, white). The stable continental region (SCR) earthquakes of $M \geq 7$ are included (filled circles). From Johnston et al. (1994).

The global pattern of SCR earthquakes (see Table 2 and Fig. 2) shows that around 75% of the seismic moment release occur on continental passive margins or in areas with old continental rifts. Extended SCR crust including passive margins and failed intracontinental rifts cover an area of approximately one-third of the non-extended SCR crust, but account on average for 94% of the total annual seismic moment release within SCR (Johnston et al., 1994). Created by crustal extension, old rift zones are commonly found today under compressional stress regimes (Zoback, 1992). The dominating nature of movements associated with older rifts is therefore strike-slip or thrust faulting along original normal faults (Johnston, 1989; Coppersmith et al., 1987). The seismic activity of old rift zones seems to depend on their age, with the younger (Mesozoic) rift systems being far more active than older rifts (Johnston and Kanter, 1990; Johnston and Schweig, 1996).

While the largest known intraplate earthquakes are the 1811-12 magnitude 8.1-8.3 New Madrid earthquakes, the 1933 magnitude 7.7 Baffin Bay earthquake showed that passive continental rifted margins are also quite earthquake prone (see Table 2 and Fig. 2). Along the Norwegian continental margin, which geologically is quite similar, the largest known earthquake is, in comparison, less than 6 in magnitude. A recent detailed study for the mid-Norwegian margin (Byrkjeland, 1996), reviewing a varity of geological and geophysical data of potential importance (main structural elements, depth to basement, sediment distribution, neotectonics, post-glacial rebound, bathymetry, free air gravity, crustal thickness, crustal stress), concluded with a particularly clear spatial correlation between post-Miocene (Plio-Pleistocene) sediment deposision centers, characterized by high (1-2 mm/year) sedimentation rates, and present seismic activity (see Fig. 3).

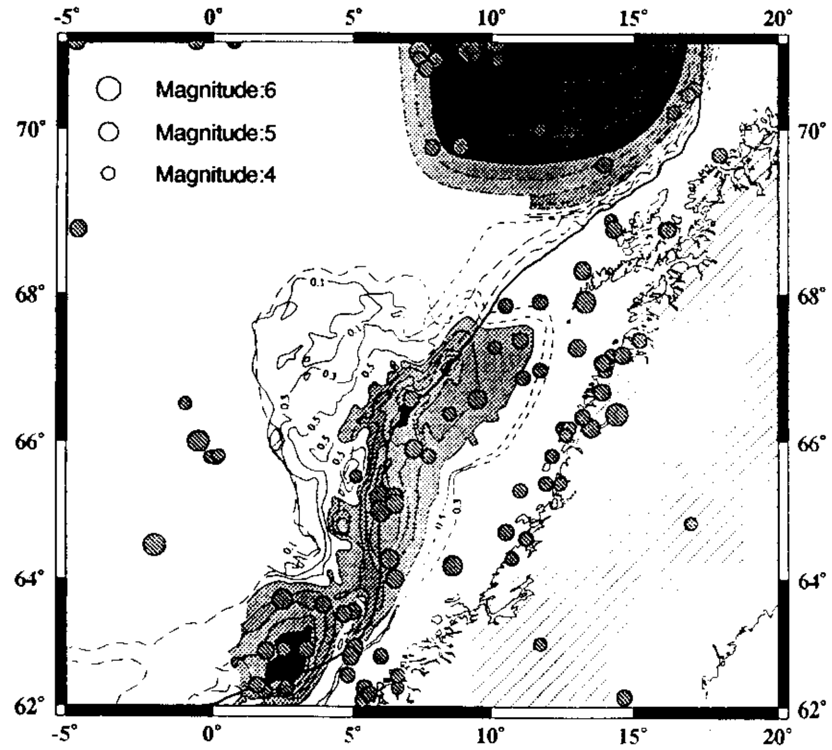

Fig. 3. Seismic activity on the mid-Norwegian margin superimposed on the post Miocene (Plio-Pleistocene) sediment distribution. From Byrkjeland (1996).

Use of Geological Data

The development of seismic design criteria, which normally is the purpose with a seismic hazard study, should preferably involve an evaluation of available geological information in order to identify faults and/or segments of faults which may represent a potential seismic source that could influence the seismic hazard for the site in question.

The relative importance of geological structures for this purpose depends on whether or not a given fault extends to seismogenic depths or is confined to shallower strata. In the context of many studies in intraplate areas it is found often that only those faults that penetrate crystalline igneous and metamorphic basement are considered relevant, since it is unlikely that earthquakes of engineering interest will be restricted to the cover sediments. The review and analysis of geological data is often primarily focussed on establishing the youngest age of tectonic deformation within the main structural regions for the purpose of evaluating the current activity of local faults and folds.

Use of Seismological Data

Seismological data represent 'snap shots' of earth (crustal) deformations, and when compared to geological information, such data cover very short time periods even if one by paleo-seismological means can bridge parts of that gap. Another important observation is that seismology only reflects a certain part of the total deformations, as there are invariably some aseismic movements. The associated seismic coupling coefficient (ratio between seismic and geologic moment release) is close to unity in some areas and much lower in others, dependent on deformation rate and rock characteristics.

A direct comparison between geological and seismological information could be misleading since the two 'see' different parts of the deformation picture and therefore are complementary to each other. The availability and quality of seismological data, early historical as well as contemporary, is intimately coupled to demographic and cultural factors and to the stage of development of the society at large.

For most seismic hazard studies, it is reasonable to discuss and to treat the seismological information within different time periods which contribute with information on earthquakes, but with different means and with different reliabilities. For example, historical data are normally based on a variety of older written sources, describing larger earthquakes in the past. From the time when a more systematic collection of information on felt earthquakes begins, a more detailed scientific analysis is allowed for.

Instrumental recording of earthquakes started in general around the turn of the century. The implementation of the World Wide Seismograph Station Network (WWSSN) in the early 1960s was a major advance in earthquake monitoring, but for many regions it was not until the 1970's that the density and quality of the recording systems reached a level where instrumentally recorded earthquakes were generally more reliable than the felt reports. More recent instrumental data are often much more reliable, but within the context of a hazard analysis it is important not to interpret this reliability directly as significance, on the expense of the long term but less reliable data.

Seismic Hazard Analyses

Seismic hazard analysis methodologies can be classified broadly into deterministic, semi-probabilistic, probabilistic with simple of multiple input, and hybrid procedures (Reiter, 1991). While deterministic methods were used extensively earlier, probabilistic methods are now used much more, in particular since these methods now have been developed to a stage where they essentially can take advantage of and use all of the information used in a deterministic analysis, and moreover provide additional advantages as discussed in the following.

Probabilistic methods are useful in that they are simple and tracable but have disadvantages in their insufficiency to handle uncertainties and probabilities, while deterministic methods can handle that and moreover use more information, but with the disadvantage that they are more complicated to use and to trace, and often more unstable. Simple analyses, with few details, are sufficient when only moderate probabilities are sufficient, while more sophisticated analyses, with detailed source and uncertainly models, are needed for installations requiring lower probabilities (10^{-3} to 10^{-6} per year). Also, probabilistic analysis are particularly well suited in cases when new knowledge has become available (Reiter, 1991).

Probabilistic Analyses

The foundations of probabilistic engineering seismic hazard analyses were established by Cornell (1968), who recognized the need for seismic design to be based on a method which properly accounted for the intrinsic uncertainties associated with earthquake phenomena. Since then, both seismological and geological knowledge and understanding applied to seismic hazard analysis have improved steadily together with advances in modeling techniques, so that current state-of-the-art practice is now able to utilize information from a variety of both seismological and geological data sources, with due considerations of uncertainties.

While the standard practice for a long time was to present the results of seismic hazard analyses in terms of a single best estimate hazard curve, the growing awareness of the importance of parametric variability and the trend to consult expert opinion in matters of scientific doubt, led to the formulation of Bayesian models of hazard analysis (Mortgat and Shah, 1979) which seek to quantify uncertainty in parameter assignment in probabilistic terms. This approach has been formalized into a logic tree methodology (Kulkarni et al., 1984; Coppersmith and Youngs, 1986), which represents the range of possible parameter values as branches of a computational tree which are individually weighted and whose contributions to seismic hazard are separately evaluated and statistically combined.

Definitions of motions commonly used in seismic hazard studies (bedrock outcrop and free-field) are provided schematically in Fig. 4, and a flow chart describing the various steps involved in probabilistic computation of seismic hazard at bedrock outcrop level is given in Fig. 5.

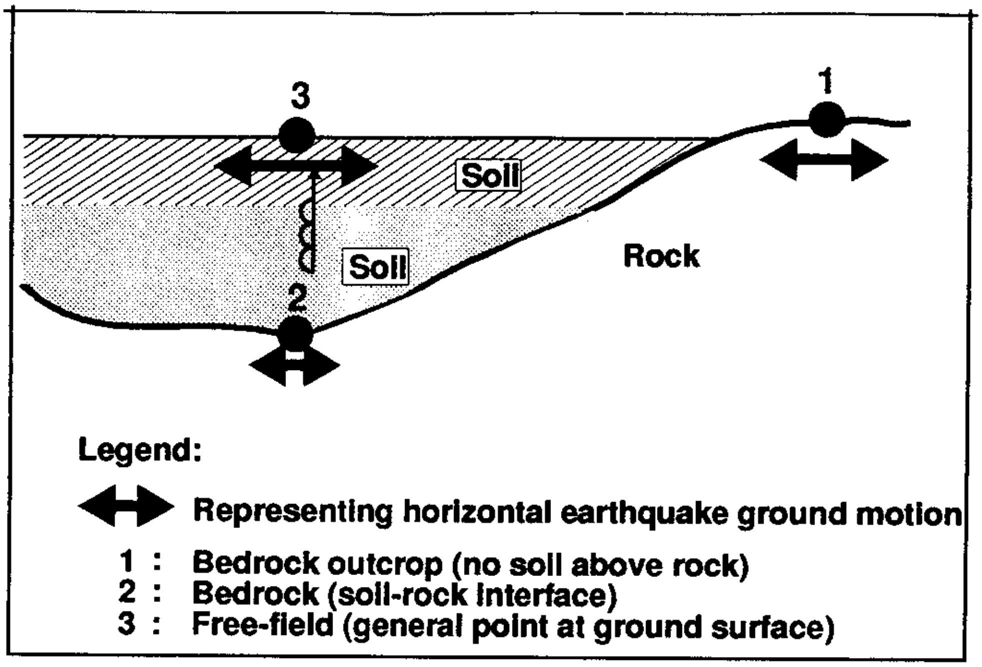

Fig. 4. Commonly used definitions of earthquake motions used in seismic hazard analyses. The motions at the top of the soil (point 3) are normally larger than at the bottom of the soil (bedrock, point 2). The effect of the soil layer above the rock is normally treated in a separate soil response analysis.

Probabilistic Methodology

The model for the occurrence of ground motions at a specific site in excess of a specified level is assumed to be that of a Poisson process. This follows if the occurrence of earthquakes is a Poisson process, and if the probability that any one event will produce site ground motions in excess of a specified level is independent of the occurrence of other events. The probability that a ground motion level z is exceeded at a site in unit time is thus expressed as:

$$P(Z > z) = 1 - e^{-\nu(z)} \tag{1}$$

where $\nu(z)$ is the mean number of events per unit time in which Z exceeds z.

Given that the mean number of events per unit time for which Z exceeds z is expressed for example as $1/T_R$, where T_R is the return period (inverse of annual exceedance probability), then the number of events in a time period T (e.g. the life time of a certain construction) for which Z exceeds z is given by T/T_R and the probability for Z exceeding z during that life time T is given by:

$$P(Z > z) = 1 - e^{-T/T_R} \tag{2}$$

For a life time T of 50 years and a return period T_R of 10.000 years (annual probability of exceedance 10^{-4}) the probability for Z exceeding z becomes 0.005, corresponding to 99.5% probability that this size ground motion is not exceeded in 50 years.

With several seismic sources, described through particular model parameters, the mean number of events per unit time in which the ground motion level z is exceeded can be expressed specifically, involving functions that model the inherent stochastic uncertainty in the frequency and location of earthquakes, and in the attenuation of the seismic waves.

Besides this natural uncertainty, there is also an element of uncertainty associated with the variability of model parameters. This source of uncertainty is accounted for by regarding these parameters as random variables, whose discrete values are assigned weights reflecting their likelihood.

These discrete values represent branches in a logic tree for the seismic hazard model (see Fig. 5). At each node, probabilities are attached to the diverse branches, which are disjointed and exhaustive of possible choices. Consideration of the complete set of tree branches allows the probability distribution of $v(z)$ to be calculated.

Earthquake recurrence model

The recurrence rate of earthquakes is in most seismic hazard analyses assumed to follow the cumulative Gutenberg-Richter relation:

$$\log N(M) = a - bM \tag{3}$$

where $N(M)$ is the number of events per year with magnitude greater than or equal to M. This relation appears with few exceptions to hold quite well, indicating a self-similarity of the earthquake process.

In seismic hazard analyses a modified and truncated version of this relation is used, involving an engineering threshold magnitude M_{low}, a limiting upper bound magnitude M_{max} for the source, a slope parameter $\beta = b \cdot ln(10)$ that describes the relation between the number of small and larger earthquakes, and an activity rate parameter $A = a(M_{low})$ which describes the number of events in the source area with magnitude equal to or greater than M_{low}.

The activity rate parameter a is liable to vary substantially from one seismic source to another while the b-value often is found to be more regionally stable, with variations less than the uncertainty limits. Faults which are separately included as seismic sources in addition to area sources may be attributed their own b-values, which need to bear no immediate relation to the values obtained from the regional recurrence statistics.

For both fault and area sources, the maximum magnitude parameter M_{max} is usually quite important, especially for sources with low b-values.

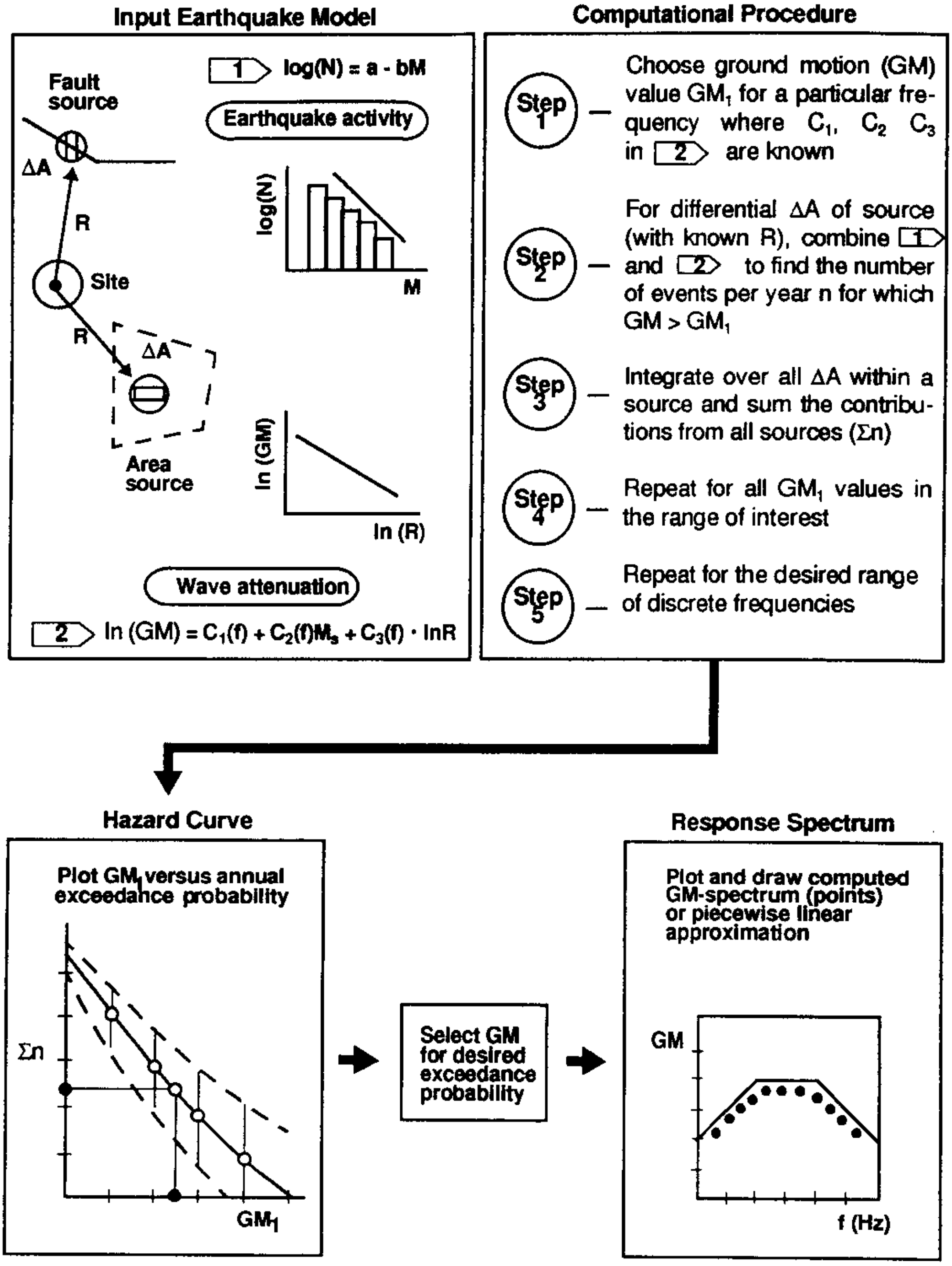

Fig. 5. Simple layout of a commonly used methodology for probabilistic earthquake ground motion (GM) hazard computation, resulting in an associated equal probability hazard spectrum which preferably should cover the whole range of frequencies which are of engineering interest.

Strong-motion attenuation

The computation of earthquake hazard is essentially a process in which one integrates the contribution at a particular site from earthquakes at different distances from the site (see Fig. 5). This requires, in addition to the source model, which delineates the characteristics of the expected occurrence in time and space of future earthquakes, detailed models for how the seismic waves that are generated at the source will attenuate with distance, for different types of ground motion (such as peak ground acceleration, PGA, or pseudo-relative velocity, PSV), and for the range of frequencies of engineering interest.

A common way to express such a relationship is the following simple form:

$$lnA = c_1 + c_2M + c_3lnR + c_4R + ln(\varepsilon) \quad (4)$$

where A is ground motion, c_1, , c_2 (magnitude scaling), c_3 (geometrical spreading) and c_4 (anelastic attenuation) are coefficients, M is magnitude, R is distance and ε is a normally distributed error term with expectance zero and standard deviation sigma (σ). The sigma, describing the variability in terms of scatter around the mean, is included because earthquake strong ground motion is an intrinsically stochastic phenomenon which can only be modeled realistically in a probabilistic way (Cornell, 1968).

Logic tree formalism

In most seismic hazard models using the logic tree formalism, weighted, discrete distributions are input for a number of principal seismological and geological variables such as wave attenuation, source geometry, maximum magnitude, focal depth, b-value and activity rate (see Fig. 6).

The attenuation parameters are usually assigned simultaneously for all area sources, while they should be separately assigned for individual faults, depending on directivity effects and nature of faulting. For fault sources, variations in geometry (both strike and dip) should be accommodated by inputting the different geometries with appropriate weights. For area sources, uncertainty in zonation can either be accommodated by varying the zone activity rate distributions, or by the application of alternative zone geometries.

For the individual seismic sources, both areas and faults, parameter variability in maximum magnitude, focal depth, b-value and activity rate can be introduced as shown in the logic trees (Fig. 6). For fault sources, the assignment of activity rates results from further tiers of branching, reflecting the significant uncertainty in associating recorded events with individual faults, the uncertainty in correlating slip-rate data with the occurrence of past earthquakes, and the primary uncertainty over whether a fault is active or not.

For each terminal node of the logic tree branches that stems from source n, having model parameters $S_n(m)$, one should compute the probability weight function $P(S_n(m))$. These weight functions are then used to construct the probability distributions of the random variables $v_n(z)$, the mean number of events per unit time in which the level z of ground motion is exceeded, and hence the sum:

$$v(z) = \sum_n v_n(z) \tag{5}$$

The probability distribution of $v(z)$ is close to lognormal for real seismic hazard problems of any complexity (Kulkarni et al., 1984), and estimates of its mean and variance allow confidence levels for the exceedance to be computed efficiently.

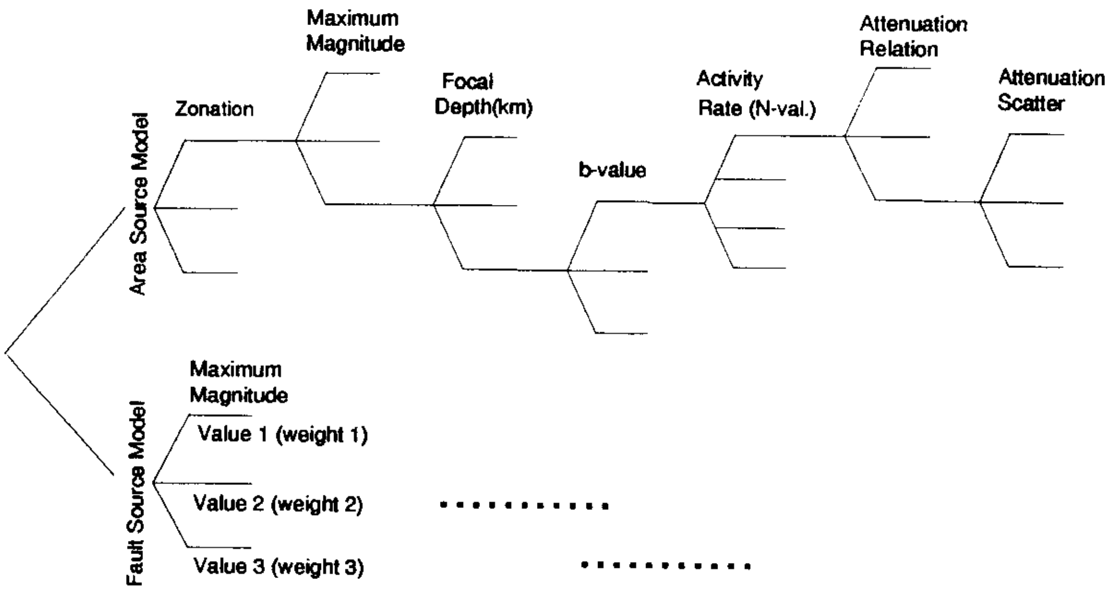

Fig. 6. Principle of logic tree branches used in probabilistic seismic hazard analysis.

Sources of Uncertainties and Variability

Sources of uncertainties in seismic hazard analyses are in principle tied to three separate but interconnected areas:

- Source effects, involving a variety of problems tied to spatio-temporal characteristics of seismicity distributions as well as earthquake source models and their scaling relations and rupture characteristics.
- Path effects, involving first of all strong motion attenuation models, which normally includes a source excitation term in addition to the dependence of observed ground motions on magnitude and distance, both defined in different ways in different studies.
- Site effects, involving various aspects of soil response and often covered through special geotechnical analysis based on detailed site information and on an estimate of the expected ground motion at 'bedrock outcrop' level (see Fig. 4).

There are essentially two types of contributions to the variabilities occurring in seismic hazard analyses (McGuire, 1987):

1. Randomness (aleatory uncertainty), covering random occurrences in nature that we cannot expect to predict (reduce) with additional data and better models. Examples here are the expected magnitude and location of the next earthquake on a fault, and ground motion characteristics resulting from details of the fault rupture process.
2. Uncertainty (epistemic), describing our lack of knowledge about appropriate models or parameters used in characterizing natural phenomena (random occurrences). Examples here are magnitude distributions and their parameters, mean strong ground motion relations, and maximum magnitude.

It is important to note here that the seismic hazard curve is produced by integrating over the random occurrences, while the second type of uncertainties in principle can be reduced, and may handled by producing multiple hazard curves, expressed through confidence intervals if the logic tree approach is used.

Modeling and Parameterization

A seismic hazard analysis involves the definition of different models as outlined above in the discussion of the logic tree approach, essentially covering the source (seismicity) and the attenuation characteristics, possibly also site effects if these are not already included in the attenuation relations (see the definition of motions in Fig. 4). Two quite connected problems encountered in such analyses will be touched upon in the following:

Earthquake occurrence models

As is well known, the conventional approach in a seismic hazard analysis, in particular in intraplate areas where specific seismogenic faults are difficult to delineate, is to describe the activity through area zones within which the activity is assumed to be uniform and Poisson distributed. This zonation should be based on a simultaneous analysis and assessment of geology and seismicity, and in this process one should use the following guiding principles:

- Each zone should be large enough to allow for a reasonably stable assessment of recurrence parameters.
- The zones should cover all areas where the seismicity can have some influence on the seismic hazard, which normally means 200-400 kilometers around the site, depending on activity level.
- The zonation should, if required, allow for possible regional differences in focal depths, maximum magnitudes and faulting mechanisms.
- The zonation should be consistent with the regional geology and tectonics.

The quantification of seismicity within each zone is based upon a fundamental scaling relationship for earthquakes which tells us that, for a given region and over a given period of time, the number of events $N(M_0)$ with seismic moment equal to or greater than M_0 is given by

$$N(M_0) = AM_0^{-B} \tag{6}$$

where A and B are empirical constants. This is the Gutenberg-Richter (or Ishimoto-Aida) relation, which combined with the loglinear relation between magnitude and seismic moment

$$\log M_0 = c + dM_S \tag{7}$$

gives a relation of the form shown in Equation (3).

This relation is essentially a power law typical for fractal sets that implies scale invariance and self-similarity, and where the exponent B (which is related to the fractal self-similar dimension) often takes a value near to or slightly less than one (e.g., Scholz, 1990). There are in fact two contrasting generic models that both lead to such a recurrence relationship. Firstly, if each fault or fault system has a power law seismicity distribution, then the sum of all the fault systems will have the same distribution. Secondly, if each fault generates only the same size ('characteristic') earthquakes, governed by the fault size, then the total activity over larger areas will also have a power law distribution, simply because fault sizes also are distributed in that way (fracture is also a self-similar process).

The estimation of b-values is often usually connected with significant sources of errors and bias, and this problem is even more pronounced in areas of lower seismic activity. Because of this, it may some times be advisable to determine only one common b-value for a larger region, and to impose that value on each of the area zones when determining the associated a-values in Equation (3).

In spite of this, it is often found in practice that the uniform seismicity assumption within each area zone, and the zone geometries, are both in conflict with the fractal spatial distribution of seismicity. Moreover, the zonation ignores that different-sized earthquakes often have different spatial distributions and correlations. The latter problem is well illustrated through the data shown in and behind Fig. 2, where several of the largest earthquakes have occurred in regions where the distribution of smaller earthquakes, often both before and after the event, should not directly indicate such large events. What result from this situation is often a seismic zonation which more or less encircles these larger earthquakes, in which case one may not sufficiently be accounting for the probabilities for similarly sized events in geologically similar areas. The point here is that the return times for the largest earthquakes in intraplate areas are probably often many thousand years, as compared to values in the range 30-200 years in plate margin areas.

One possibility for accounting for such variations between smaller and larger events (expressing deficiencies in the magnitude-frequency distributions) would be to use independent distributions and source zonations for small and intermediate as compared to larger earthquakes, reflecting the different distributions and the larger uncertainties for the larger events both in terms of locations and return times.

A more satisfactory solution, however, is to use the kernel estimation method published recently by Woo (1996), where an activity rate density is inferred from a regional seismicity catalog, and where the form of the kernel is governed by the concepts of fractal geometry and self-organized criticality, with the bandwidth scaling according to magnitude. This kernel estimation methodology makes provisions for moderate earthquakes to cluster spatially, while larger earthquakes may migrate over sizeable distances.

Maximum magnitude

Even though the influence of maximum magnitude on a seismic hazard estimate is dependent on both activity level and *b*-value, it is invariably quite important and tied closely the problems discussed above. The conclusions drawn from the global study of Johnston et al. (1994), where time was traded for space, is that the common assumption of building the assessment of maximum magnitude on the largest known earthquakes in the region often may lead to unconservative estimates, simply because of the very long return times for the very largest earthquakes. Table 1 shows that intracontinental rifts and passive (rifted) margins are particularly exposed in this sense. It is worth noticing that the latter type of areas coincide with some quite important areas for exploitation of petroleum reserves, with large industrial investments and large potentials for losses, including environmental pollution.

Seismic Risk

While seismic hazard is expressing characteristics of deformation processes in the Earth, seismic risk estimates are aimed at evaluating the potentials for damage and loss for people and for both the natural and the built environment.

Earthquakes are controlled by geological processes related to movements of the Earth's crust, and are therefore fairly stable over time. However, as a result of population increase, urbanization and industrial development, our vulnerability to earthquakes is steadily increasing. Despite recognition of this vulnerability we have only just started to mitigate and reduce the risk factors.

These problems are connected to developmental and socio-economic issues, but not only so, since some of the heaviest losses recently have occurred in industrialized countries. Even though the seismic risk is clearly highest in plate margin areas, the high level of infrastructural complexity in many intraplate areas, combined with the above-mentioned rare but large earthquakes, are making such areas too exposed to these threats to an extent which calls for concerted actions. These actions are in principle the same all over the world.

Present Situation

In parallel with this recent increasing risk, there have, paradoxically, been significant advances in earthquake mitigation capabilities. Among these are:

- Improved monitoring of seismicity worldwide and locally, which has facilitated better understanding of processes associated with Earth deformation.

- Improved integration of geological and seismological data has extended the chronology of earthquakes in seismically active regions where the historical record is short (i.e. less than the repeat time for large earthquakes). This approach has provided a stronger basis for statistical predictions of earthquake occurrence.
- Increased awareness and understanding of secondary seismic effects, such as fires, landslides, tsunamis (earthquake generated ocean waves), soil liquefaction and amplification of strong ground motion.
- Improved building codes and land use regulations arising from the factors listed above, and improved public preparedness in earthquake prone areas in many regions.

The risk of loss is composed of two factors, hazard and vulnerability (Fig. 7). The hazard may be defined as the probability that an earthquake will occur in a given region and period of time, while vulnerability reflects the degree of exposure to seismic hazard, due to population increase, urbanization and industrial development. In many regions, vulnerability increases for reasons such as:

- a general increase in building density and infrastructure complexity, and a continued use of traditional but inappropriate construction techniques, and
- lack of political will to implement and enforce precautionary measures, and insufficient public education and awareness.

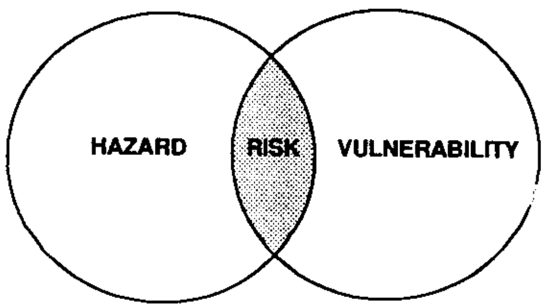

Fig. 7. Seismic risk is based on a combination of hazard and vulnerability.

Future Directions

The motivation for different earthquake hazard mitigation programs established in recent years (including IDNDR, the United Nation's International Decade for Natural Disaster Reduction), reflects mounting concern about the steadily increasing toll in lives and damages caused by earthquakes. It seems fundamental that we should not accept the increasing economic and human costs associated with earthquakes witnessed over the last decades, given that the average number of large earthquakes is not increasing.

There are many efficient measures that can be implemented to mitigate earthquake risk within the limits of available resources. First among these, is more effective integration and utilization of existing knowledge, combined with a willingness to acknowledge that some traditional design and construction practices are inappropriate.

It was the recognition of such factors that prompted the IDNDR initiative, which is designed to (i) increase worldwide awareness of natural disasters, (ii) foster the prevention of natural disasters, and (iii) reduce the risks of natural disasters. One of the important initiatives under IDNDR, is the "Global Seismic Hazard Assessment Program" (GSHAP) supported by several international scientific agencies and by UNESCO. The primary goals of GSHAP are to promote the establishment of regional centers to: (i) assist national efforts to compile homogeneous regional data bases, (ii) ensure coordination in across-boundaries hazard assessment, (iii) provide a framework for data exchange, and (iv) help to implement unified hazard assessment procedures.

Such measures represent a vital step forward, but will not suffice. Each country and city should mitigate the risks associated with natural hazards, yet in many parts of the world such problems are accorded a low priority by planning authorities. The reasons for this are rarely simple and always involve economic factors. Put simply, if money is to be spent on hazard mitigation it must be saved from other areas in society. Because large earthquakes in a given region may be relatively infrequent the 'politically urgent' needs receive the higher priority. As shown in Fig. 8 there is a trade off between community 'well-being' and the allocation of finite resources. The definition of 'acceptable risk' is one that must be considered by each community in turn. However, there is arguably no place in the world where spending on risk mitigation has reached dubiously high levels.

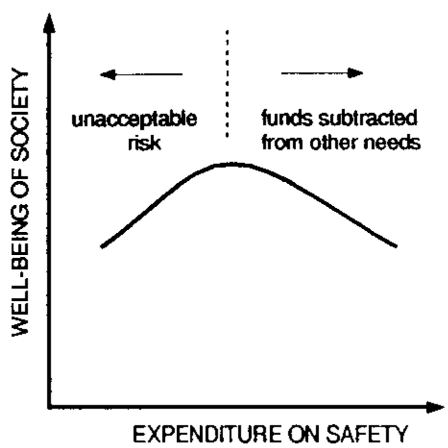

Fig. 8. Relationship between investment in risk mitigation and community 'well-being'.

Realizing the huge economic costs of for example the recent Los Angeles and Kobe earthquakes, one of the important tasks for the scientific, engineering and planning communities now is to convince authorities that risk mitigation represents a sensible long term investment. Future directions should include:

- Improved earthquake resistant design and construction, including strengthening (retro-fitting) of vulnerable facilities.

- Closer interaction between seismologists, geologists, engineers and planners, to integrate scientific information in a format that is most relevant to urban and industrial design.
- The specialists mentioned above should be trained to convey and assimilate the relevant technical information, which is often presented and used in different ways by different groups involved in natural hazard and risk assessment.

Clearly a large array of measures should be implemented at different levels. However, while all measures are dependent to some extent on political commitment, not all require significant increases in financial support. Much has been learned about earthquake hazard and risk mitigation during the last three decades, so we should not be deterred by the fact that several destructive earthquakes have occurred recently, before the new knowledge has been fully implemented.

It is already fair to claim that while the occurrence of earthquakes is inevitable, earthquake disasters are not.

Comments on Building Codes

The purpose in general of building codes is to secure a certain safety profile, and behind that one finds (usually only indirectly) some policy as to what the acceptable risk from earthquakes should be. Quite often, this is done in terms of an Progressive Limit State or an Ultimate Limit State analysis (equivalent to a Design Basis Earthquake in deterministic analysis), where the construction should resist (progressive) collapse, and a Serviceability Limit State analysis (equivalent to a Operational Basis Earthquake in deterministic analysis), where the construction should maintain in operation, essentially undamaged.

In the new Eurocode 8, importance factors are (proposed to be) defined following the classification of buildings into different importance categories which depend on the size of the building, on its value and importance for the public safety and on the probability of human losses in case of a collapse. The actual factors vary from 1.4 for to 0.8, where a factor of 1.0 is tied to a return period of 475 years, or 10% exceedance probability in 50 years (cf. Equation 2).

This use of importance factors is equivalent to specifying different exceedance probabilities, or return times, or acceptable risk levels, for different parts of our built environment. Given a hazard curve, expressing ground motion (such as PGA) vs. exceedance probability, an importance factor of 1.4 for a particular structure would then be equivalent to specifying for that structure an exceedance probability, or return period, which would result in a ground motion 1.4 times higher than the one for the reference return period of 475 years, or 2.1×10^{-3} per year.

A point of some importance here is that different regions (in particular plate margin vs. intraplate) should be expected to have different hazard curve slopes, and any such difference would mean that a given importance factor would not have similar implications in terms of change in acceptable risk level. The main reason why the hazard curves would have different slopes are tied to differences in attenuation relations, possibly also somewhat influenced by seismicity (source model) differences.

These effect are illustrated in Fig. 9, based on results from a study of the effects of differences in attenuation between plate margin and intraplate areas (Dahle and Bungum, 1993). What this figure shows is that different importance factors have to be used in different tectonic regimes, to maintain equivalent safety levels.

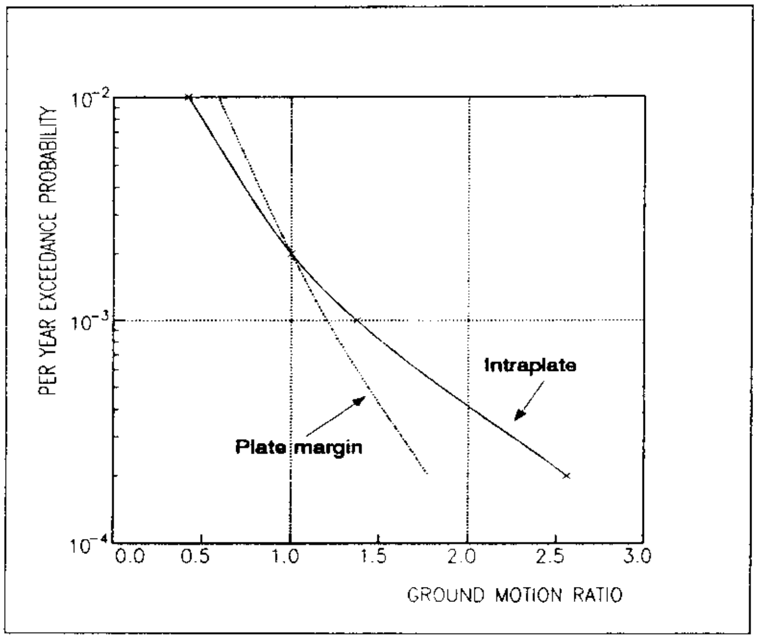

Figure 9. Average ground motion ratios plotted against annual exceedance probability (inverse of return period) for intraplate and plate margin areas, respectively.

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