REVIEW ARTICLE

The Assessment of Seismic Hazard and GSHAP Aspects

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Seismic hazard assessment is an important element in today's engineering practice. The input data are usually prepared by earth scientists and the output is mainly used by engineers and planners. Both sides have to subscribe to common principles and rules. This paper summarises some of these principles and describes currently used methods. Their choice and applicability depends not only on professional preferences but also on the basic data set available in a particular area. Probabilistic methods are at the forefront in the current practice, because of their relative ease of manipulation and the availability of user-oriented software. It is stressed that the knowledge of the limits of earthquake hazard assessment and the proper consideration of the inherent uncertainties are the main keys in producing trustworthy results. Among the probabilistic approaches, the deductive and historic methods are equally successful. Deterministic methods are still not equitably used. In many countries also the macroseismically determined intensity is the preferred hazard parameter, recognising that most historical events in catalogues are classified in terms of damage. The technical rules for the Global Seismic Hazard Assessment Program (GSHAP) foster the deductive approach (the "seismic source method") and ground motion acceleration as mapping parameter versus probability of occurrence.

INTRODUCTION

The objective of an earthquake hazard analysis is to evaluate the probability of exceeding a particular level of ground motion (e.g. a certain value of peak acceleration) at a site during a specified time interval (e.g. 100 years).

Seismic hazard assessment in low seismicity areas is much more subject to large errors than in areas with high earthquake activity. This is especially the case if the time span of the available data catalogue is considerably smaller than the mean return period of large events, for which the hazard is to be calculated.

Uncertainties are introduced by lack of data or lack of knowledge. In seismic hazard computations the uncertainties of the basic input data must be taken into account in a proper form. This task is accomplished by making alternative interpretations where significant uncertainties exist; it applies especially to the size, location and time of occurrence of future earthquakes, and the attenuation of seismic waves as they propagate from all possible seismic sources in the region to all possible sites.

A comprehensive Global Seismic Hazard Assessment Program (GSHAP) was launched in 1991/2 within the U.N.'s International Decade of Natural Disaster Reduction (IDNDR). It supports mainly the application of standard-

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ised methods and their engagement in multinational test areas and later in the production of homogeneous maps. Ten coordinating centres all over the world are responsible for the execution of the resolved technical rules [1] during the project period.

The following chapters try to summarise the current trends and requirements in the field of hazard calculation.

STANDARD PROBABILISTIC TECHNIQUES

In the standard probabilistic hazard assessment the following input models may be introduced.

Earthquake Source Model

The designation of seismogenic sources in the region is an important step in preparing input parameters for hazard calculation. According to the basic geoscience data available for this task, these sources may have different shapes and characteristics, specially faults and area sources.

Faults should be specified by geometry (in three dimensions), sense of slip, segmentation and possible rupture length. A "logic tree" can be developed to quantify uncertainties in these parameters [2].

If faults cannot be identified or associated to epicenters, the location of possible earthquakes must be represented by area sources. These are areas within which the same earthquake characteristics are assigned to all earthquakes. Experience from special projects has shown that several independent sets of such source models should be provided by different task groups, to estimate the scientific range of possible models [3,4].

Other types of source models are collection of line sources, and an area source encompassing a collection of line sources.

The following general rules for designing sources may be applied:

- A line source model is used when earthquake locations are constrained along an identified fault or fault zone.
- A spatial source is chosen if the seismicity occurs uniformly throughout an area.
- A set of line sources is used to model a large zone of deformation where earthquake rupture has a preferred orientation but a random occurrence.
- An area source encompassing a collection of line sources is used when large events are assumed to occur only on identified active faults, and smaller events are assumed to occur randomly within the region.

Occurrence Model

For each seismic source (fault or area), the earthquake occurrence model must be specified. It is usually a simple cumulative magnitude (or intensity) versus frequency distribution, characterized by a source-specific b-value and activity rate. It must be recognized that the largest earthquakes in such distributions often occur at a rate per unit time which is larger than predicted by the model. A "characteristic" earthquake distribution is added to the exponential model to account for these large events.

Different time of occurrence models such as Poissonian, time-predictable, slip-predictable and renewal have been used in the calculation process. Poissonian models are easy to handle but do not always represent correctly the behaviour of earthquake occurrence in a region.

For the general application, especially where area sources are used, the exponential magnitude model and average rate of occurrence are adequate to specify seismicity [2].

Ground Motion Model

The ground motion model relates the desired ground motion parameter to the distance from the source(s) and to the size of the earthquake. The choice of a ground motion parameter depends on the desired seismic hazard output. Usual parameters of interest are peak ground acceleration (PGA), peak ground velocity (PGV) and spectral velocity for a specified damping and structural frequency. Effective peak acceleration is used as a parameter when the large scatter of peak values is a problem.

In cases where the primary collection of earthquakes consists of pre-instrumental events for which intensity levels have been assigned, the site intensity is probably the best choice for the representation of the ground motion level also in the output. However, it must be kept in mind that this method bears high uncertainties and bias due to the subjectiveness of intensity estimation in general. Furthermore, information on ground motion frequency is not included.

The preferred procedure in many countries is to estimate magnitudes from the original intensity information and to use deterministic attenuation relationships for magnitude and distance to predict physical ground motion parameters.

Seismic Hazard Calculation

Two categories of hazard calculation may be distinguished, depending on the way the original data on the earthquakes in the area is handled.

1. The deductive method uses interpretations (or extrapolations) of the original data to explain the occurrence of earthquakes in time, space and their general characteristics. Applications are described in many publications [1,2,5-8]. The method is illustrated schematically in Figure 1.
2. The historic methods are merely based on the historical record of earthquakes which do not imply seismic source definitions or generalized seismicity parameters [9]. The method is illustrated schematically in Figure 2.

In each case, the probability of exceedence of different levels of ground motion in a given exposure time is calculated by considering the occurrence of earthquakes of all possible magnitudes and all possible distances from a site.

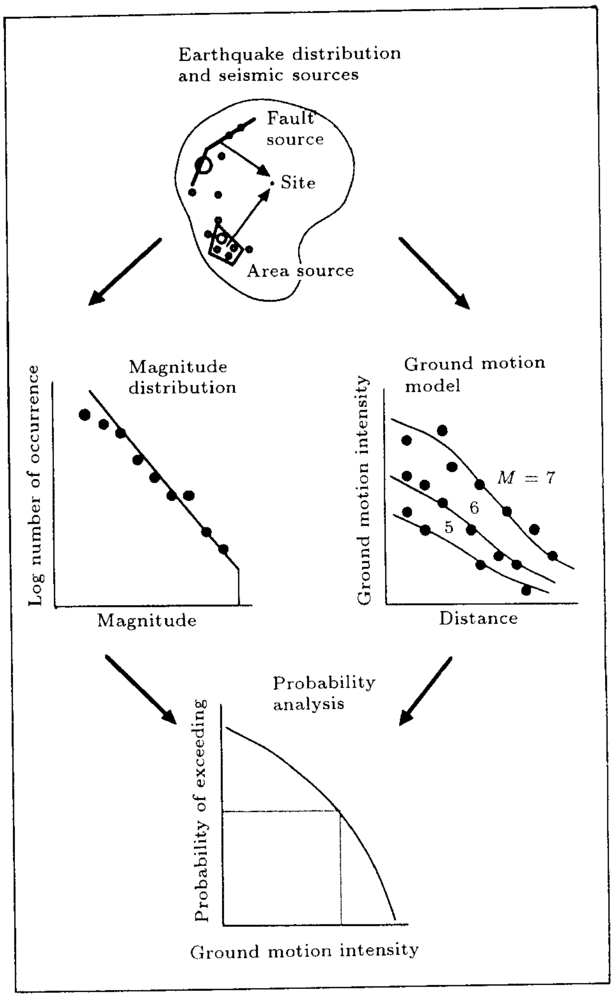

Figure 1. The deductive method [4] is currently the most used approach to earthquake hazard assessment.

Application of the Deductive Method

Step 1

Definition of seismogenic sources: Faults and area sources have to be delineated, which describe the geometric (3-dimensional) distribution of earthquake occurrence in the investigated area. Then distance and magnitude distributions:

$$f_R(r) \text{ and } f_M(m) \ , \tag{1}$$

are calculated, with hypocentral distance r and magnitude m.

Step 2

Definition of seismicity parameters: It is assumed that the rate of recurrence of earthquakes in general follows the Gutenberg-Richter relation:

$$\log_{10} n(m) = a - bm \ , \tag{2}$$

where $n(m)$ is the mean number of events per year having magnitudes m and greater, while a

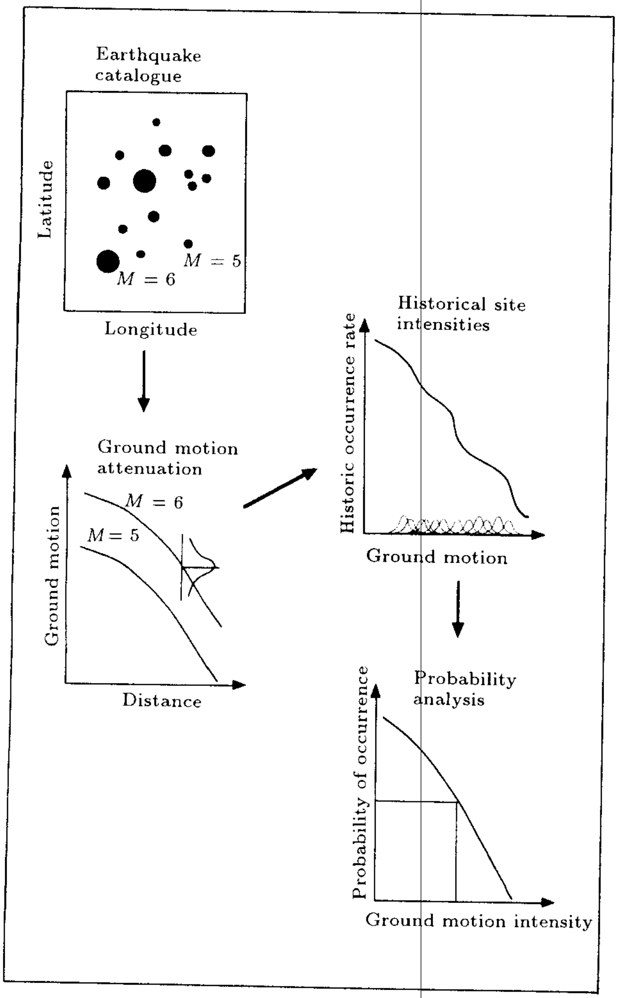

Figure 2. The historic method [9] is often used in areas with lesser known faults.

and b are constants defined by regression analysis. Then, for a single source the modified G-R relation for the annual mean rate of occurrence is:

$$n_o = a_N[1-\{1-e^{-b(m-m_1)}/1-e^{-b(m_u-m_1)}\}] \ , \tag{3}$$

where m_u and m_1 are the upper and lower bound magnitudes, and a_N is the number of events per year in the source, having magnitudes m equal to, or greater than, m_1.

Step 3

Establishing the ground motion model: The ground motion equation is calculated for the conditional probability of A exceeding $a^\star$, given an earthquake of magnitude m occurring at a distance r from a site:

$$G(A > a^\star \ |m, r) \ . \tag{4}$$

Step 4

Probability analysis: The contribution of each source to the seismic hazard at the site is calculated from the distributions of magnitude, distance and ground motion amplitude. The probability that the value A of ground motion at the site exceeds a specified level $a^\star$ is then:

$$P(A > a^\star) = \Sigma_i n_0 \iint G(A > a^\star|m, r) f_M(m) f_R(r) \ dm \ dr \ , \tag{5}$$

in which the summation is performed over all sources i, where n_0 is the mean annual rate of occurrence in a source.

ALTERNATIVE TECHNIQUES

Although the deductive methods in seismic hazard assessment are well established [1], other methods may also give useful results under special conditions.

Historic Methods

In contrast to deductive seismic source methods, non-parametric methods are often employed when the process of earthquake generation is not well known, or the distribution of historical earthquakes do not show any correlation with mapped geological features.

The historic method [9] is based only on historical earthquake occurrence and does not make any use of interpretations of seismogenic sources, seismicity parameters, and tectonics. It is less reliable at higher mean return periods, i.e., larger than the time span of the catalogue. It consists of the following steps:

1. Establishment of a complete catalogue of all historic events including rate, location, magnitude and/or intensity [10].
2. Adoption of an attenuation model which predicts ground motion intensity as a function of epicentral intensity or magnitude. Uncertainties may be introduced here in form of dispersion distributions.

3. Estimation of the distribution of ground motion for each historic earthquake using its value of epicentral intensity or magnitude and distance. This gives the historical rate at which different levels of ground motion are exceeded.
4. Estimation of an annual rate of exceedence by dividing this function by the number of years of the catalogue, which for small values is a good approximation to the annual probability of exceedence.

Deterministic Approach

The deterministic approach is often used to evaluate the ground-shaking hazard for a single site. The seismic design parameters are estimated for earthquakes of specific magnitudes occurring at a specified distance from a site. An often applied (simplified) procedure includes the following steps:

1. The design earthquake is chosen having normally the maximum magnitude that is judged being possible to occur in a seismogenic zone.
2. This earthquake is placed inside an area source at the nearest possible point, or on a fault at the shortest distance to the site.
3. A deterministic attenuation function for the desired ground motion parameter is adopted, usually the one which is evaluated for the respective area, or from another seismo-tectonically similar region.
4. A credible ground motion level is calculated using the above set-up.

Seismic hazard estimations using this method usually give rather conservative results. The most critical problem in the relatively simple procedure is the demarcation of the boundary of a source which is closest to the site.

In general, deterministic methods deliver physically meaningful results if all parameters necessary to describe the source-path-site-system are well known.

DATA REQUIREMENTS AND SOURCES

The ideal data base, which is not yet available for all geographic regions in the world, should contain the following information for the area under investigation [8].

Seismicity Data

- The most fundamental input required is a complete earthquake catalogue for the region under study. This catalogue must contain all locations, times of occurrence and size measures of earthquakes with for- and after-shocks identified.
- Uncertainties should be indicated with each of these parameters.
- It is required that uniform magnitude and intensity definitions are used throughout the catalogue [11].

Seismotectonic Data

- Maps showing the seismotectonic provinces and capable faults.
- Information about the earthquake potential of each seismotectonic province, including information about the geometry, amount, sense of movement and temporal history of each fault and the correlation with historical and instrumental earthquake epicentres.
- Correlation of historic earthquakes with tectonic models to estimate the upper-bound magnitude that should be associated with specific tectonic features.

Seismic Attenuation Data

- Isoseismal maps of significant historic earthquakes that occurred in the region or have influence on the site, see [12].
- Strong ground motion records of past earthquakes.
- Scaling relations and their statistical distribution for ground motion parameters as a function of distance.

Macroseismic Data

- Isoseismal maps of all significant historic earthquakes that have affected the site.
- Ensembles of strong ground motion records of earthquakes that occurred in the region of interest or in other regions that have similar source-site path characteristics.

Spectral Data

- Ensembles of spectra adequate for "calibrating" the near field, the transmission path and the local ground response.

Local Amplification Data

- Seismic wave transmission characteristics (amplification or damping) of the unconsolidated materials overlying bedrock and their correlation with physical properties including seismic shear wave velocities, densities, shear moduli and water content.
- Strong ground motion records at surface and other locations for a wide range of magnitudes and distances.

PRACTICAL ASPECTS

The earthquake data base which has to be used in seismic hazard assessment as a basic input usually consists of an instrumentally determined part and a normally much larger historical time span with macroseismically deduced earthquake source data.

It is essential to evaluate the historical (macroseismic) part of the data thoroughly by using uniform scales and methods. At least for the strongest events established standard methods must be applied [10,13]. Special care must be taken whenever catalogues of historical earthquakes and different origins are merged, e.g., for investigations across national borders. The total time span of earthquake catalogues can vary from some tens to some thousands of years. In general, the earthquake data base is never homogeneous with respect to completeness, uniform magnitude values or location accuracy. The completeness of catalogues have to be assessed in each case.

It is routine to extrapolate hazard from limited data, but the reliability of hazard calculations is questionable if the mean return period of the calculated parameter exceeds the entire time window of the catalogue. Those parts of extrapolated data distributions which are not confirmed by observed data should be investigated by parameter sensitivity studies. The possible user of the output of the seismic hazard assessment needs clear information about the possible error range to make optimum use of this information.

Different physical parameters for ground shaking may be used to describe seismic hazard: peak acceleration, effective (average) acceleration, the same for ground velocity and spectral values of these parameters. However, for practical and traditional reasons in most cases peak acceleration is chosen as the preferred parameter for presentation [8].

PRESENTATION OF HAZARD ASSESSMENTS

Hazard Terms

With respect to hazard parameters two equivalent results are typically calculated:

1. The peak acceleration corresponding to a specified interval of time (exposure time).
2. The peak acceleration having a specified average return period.

Consideration of recurrence times longer than 1,000 years may be required in the case of large dams, nuclear power plants and waste repositories (and certain lifeline systems). A very low probability of exceedance (i.e., 1% in 100 years) of a given level of ground motion is required, even though the life span may be as short as 30 to 50 years (e.g., in the case of a nuclear power plant) or as long as several thousand years such as in the case of high-level radioactive waste repositories.

Hazard maps

For the spatial distribution of the hazard parameter maps with contour lines are the usual

Table 1. Level of importance and scales in seismic hazard mapping (after [7]).

Level	Scale
National	1: 1000000
Regional	1: 250000
Local	1: 25000
Project	1: 5000

form of presentation of the results of seismic hazard investigations. These maps may be classified into different levels, according to the required detail of information displayed (see Table 1).

These scales are only approximative and may vary in other fields of natural hazards. Hazard assessment on the local and project level usually incorporates the influence of local or site geological conditions. The results are presented in the form of micro-zoning maps showing different susceptibility to ground shaking in the range of meters to kilometers.

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