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SEISMIC RISK ANALYSIS—A REVIEW

V. N. SINGH*, L. S. SRIVASTAVA*, AND A. S. ARYA*

INTRODUCTION

To have an idea of the earthquake risk to a structure at a given site, one must anticipate the parameters of future earthquakes in a region surrounding the site. By some means, the ground motions expected at the site due to a damaging earthquake at a known distance from it should also be predicted alongwith the extent of damage which may result from such moions. However, due to the uncertainty in the number, sizes and location of future earthquakes, it is not possible to express the corresponding earthquake risk to a structure in deterministic terms. The earthquake risk is thus defined in terms of probability of equalizing or exceeding a prescribed limit which may be the size of a future earthquake or intensity of ground motion at a given site.

Data on past seismic history of a region, tectonic processes leading to earthquakes, structural features of the region, character of near surface unconsolidated sediments, performance of structures during earthquakes, acceptable economic loss and other factors are utilised to evaluate the earthquake risk. The significance of each of these factors and their contributions is difficult to evaluate in quantitative terms. For practical applications this risk may be considered from three points of view: the geophysical risk, the engineering risk and the insurance risk (Vere Jones, 1973). The geophysical risk is defined as the probability of occurence of a specified type of earthquake within a specified region in a specified type of earthquake within a specified region in a specified interval of time. The engineering risk is the probability of failure of the structure in part or in whole, due to earthquakes during a specified time interval. The insurance risk, is the probability that claims for a specified amount will be lodged on account of earthquake damage against the insurer during a specified time interval. In the following only the first kind of risk, the geophysical risk, will be discussed and this will be termed "the seismic risk". This seismic risk is defined in terms of probability of occurrence of certain earthquake and therefore, the evaluation of the characteristics of such an earthquake should be on the basis of laws of probability, and statistical techniques should be employed for its determination. The only available information for such a determination is data on past earthquake occurrences in a region. The difficulty in dealing with earthquake occurrence from a statistical point of view is that, fortunately though it may be, damaging earthquakes are noted to be few in number and separated by long intervals of time. Also historical data on past earthquakes is usually not complete. Owing to this difficulty other methods have been employed to extract information from the catalogue of earthquakes, which could be used in determining seismic status of a region.

Considering the above, in order to suitably portray the seismicity of a region and evaluation of earthquake risk it is suggested that (a) seismicity maps providing information about earthquake occurrence and related parameters be prepared and (b) choice of design earthquake parameters be evaluated from probabilistic approach.

SEISMICITY MAPS

Seismicity maps provide information about earthquake occurrence in one form or the other. The simplest seismicity map is a plot of magnitude rated epicentres of past

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* School of Research and Training in Earthquake Engineering, University of Roorkee, Roorkee. (U.P.).

earthquakes. They provide an idea of seismicity of the region in qualitative manner. Such maps are, however, not adequate for any quantitative deductions since epicentral locations alone can be quite misleading for they do not give enough information on the areal extent of strong shaking for large earthquakes (Housner and Jennings, 1973). On such maps one may find a region with a few large events and another with a number of small events. Judgement as to which of these regions is more seismic is not easy to make. Nonhomogeneity in the distribution of epicentres in a region is often a direct result of nonuniformity in location of seismological observatories.

Seismicity maps drawn on the basis of earthquake intensity on the Modified Mercalli intensity scale, or other similar scale give a better indication of the areal extent of strong shaking. However, since assignment of intensities is subjective in nature and their relationship with ground motion parameters are not well established, such maps alone cannot be used for determining intensity of strong ground shaking. However, in regions with network of seismoscopes or structural response recorder data obtained can be correlated in an approximate way with intensity scales to provide on improved quantitative significance in such maps (Srivastava, 1967).

Various measures of quantitative seismicity have been proposed and discussed and maps based on such measures prepared. Some of these are:

1. energy release maps
2. tectonic flux maps
3. *a*, *b*, value maps where *a*, *b*, are parameters of frequency magnitude relationship.

The general procedure in evaluation of energy release and tectonic flux is to compute strain energy density in each of the large number of elements of the area in which a given region is divided (Lomnitz, 1974). The square root of strain energy gives tectonic flux. High energy release or high tectonic flux thus signify higher seismicity and the contours of tectonic flux on a map indicate the seismotectonic lineaments in the region. Such maps when drawn on shorter time spans can be used to determine correlations with changing patterns of regional seismicity and probable inter-relations with known tectonic features. However, since large earthquakes contribute much more to the total annual energy release during earthquakes, such maps are highly biased towards larger events. The energy release picture of a given region may change rather suddenly with the occurrence of a large event and thus seismicity pattern portrayed by energy release or tectonic flux maps is not likely to be consistent in time.

Frequency magnitude analysis of past earthquake data is a popular way of determining quantitative estimates of seismicity of a region (Gaur and Chauhan, 1968, Karnik 1964). The parameters *a*, *b*, of the frequency magnitude relationship $\log N = a - bM$ (Gutenberg and Richter, 1954) are avaluated by graphical methods and seismicity is defined in terms of a (Riznichenko 1958) *b*, and *a*/*b* (Chauhan, 1968). Kaila et al. (1971, 1972) carried out frequency-magnitude analysis of earthquake data published by Mizou (1967) for the whole world divided into 65 regions, and derived a relation between *a* and *b* values so determined. They introcuced the idea of detectability level which is an indirect measure of lack in number and uniformity in the distribution of seismological stations. They presented *a*, *b*, value maps for India, South East Asia and South West Asia (Iran, Afghanistan etc.) and obtained correlation with tectonic features. Frequency magnitude relation is utilised to evaluate return periods of earthquakes of various magnitudes, and in this particular aspect, such data are often useful to an engineer. But an engineer is tempted to attach too much significance to the return period concept which though is the best of all the non-probabilistic methods, possess certain amount of uncertainties which are generally not indicated and go against the random nature of the phenomenon. Also it has been shown (Lomnitz, 1974) that the frequency-magnitude relationship is based on purely probability considerations and all quantities derived from such an analysis should be understood in a probability sense. It has been recognised by various workers that the frequency-magnitude relationship is only valid in the intermediate range and that deviations can be appreciable at higher magnitudes as revealed from the downturn in the plot of log N versus M curve for high magnitude values. The results based on frequency magnitude analysis should therefore be used with caution for magnitudes in the region of downturn. Moreover lack of adequate data makes the results of frequency-magnitude analysis far less accurate than what they would have been if enough data were available.

SEISMIC RISK ANALYSIS

As emphasized earlier the characteristics of earthquake occurrence should be described on the basis of laws of probability. The analysis of earthquake data from a purely statistical point of view has been carried out by a number of workers (Cornell, 1968, 1971; Merz and Cornell, 1973; Esteva, 1969; DcCapua and Liu, 1974; Lomnitz 1966, 1974).

Lomnitz (1974) has described the characteristics of earthquake considered as stochastic process. Various kinds of models based on different stochastic processes have been applied in the analysis of data on earthquakes to obtain information of different kinds.

Some aspects of earthquake occurrence considered as a stochastic process for evaluation of the probability of occurrence of a large magnitude earthquakes are given below:

(a) The magnitude distribution of earthquakes in a region follows an exponential low:

$$F(M)=1-e^{-\beta M} \qquad \ldots(1)$$

where $F(M)$ is the probability that an earthquake with magnitude upto and including M will not occur at a site, and β is a destribution parameter governing the mean magnitude considered as a regional invariant, exhibiting long term stability.

(b) The number of earthquakes in a year follows a Poissonian distribution law. The probability that there will be exactly n events in a time interval t when the mean rate of events of magnitude M per unit time is λ is given by

$$P(n, \lambda)=\frac{(\lambda t)^n \, e^{-\lambda t}}{n!} \qquad \ldots(2)$$

(c) The probability that an earthquake of magnitude M will be a maximum in a year is given as follows (Gumbel, 1958)

$$G(M)=1-\exp\,(-\alpha e^{-\beta M}) \qquad \ldots(3)$$

where α is the mean number of earthquakes per year above magnitude zero and β the distribution parameter as given in equation (1).

It may be pointed out that reliable estimates of α, β cannot be obtained from data on past earthquake occurrences. However, relation (3) can be written as follows:

$$\log_e[-\log_e G(M)]=\log_e \alpha-\beta M \qquad \ldots(4)$$

For evaluation of α, β data on large magnitude earthquake can be plotted on special logarithmic paper and an estimate of annual numbers of large magnitude earthquakes can be determined. This method does not provide an upper bound for magnitudes and the probability of occurrence of such an earthquake during the life of a structure will have to be determined as indicated below:

(d) The probability of occurrence of an earthquake of magnitude M or more in a D year period defined as seismic risk is given by

$$R_D(M)=1-\exp\,(-\alpha D\, e^{-\beta M}) \qquad \ldots(5)$$

The above formulation enables computation of the probablity of occurrence of an earthquake of magnitude M in space and time, the probability that such an earthquakes would occur once in a year (or n events in a time interval t), and the probablity that such an earthquake will be a maximum in a year peroiod and the prbability of its occurrence in a D year period (or life of the structure) defined as seismic risk. These probabilities thus enable a more judicious assessment of seismic risk with confidence limits portrayed by the probability functions. The above analysis also help in evaluating the magnitude of the earthquake relevant to the design of the structure having largest seismic risk during the relevant period of time.

The parameters α, β in equation (3) are related to parameters a and b of the frequency magnitude relationship $\log N=a-bM$ as follows:

$$\alpha=10^{a},\ \beta=b\log_{10}e \qquad \ldots(6)$$

The frequency magnitude relationship bounded at the minimum magnitude (lower bound) observed in a given region can be expresed as follows:

$$\log N=a-b\,(M-M_l) \qquad \ldots(7)$$

where M_l is the lower bound on magnitudes.

It is argued (Cornell, 1971) that equation (7) implies no upper bound on earthquake magnitudes and thus a truncated magnitude frequency law would be the natural law as magnitudes higher than 8.7 are not observed. If a linear frequency magnitude relationship is adopted, as stated earlier plots of log N *vs* M curve do not follow straight line and show a downturn at higher magnitudes. Merz and Cornell (1973) thus favour the adoption of a quadratic magnitude frequency law as follows:

$$\log N=\begin{cases}0 & M<M_l\\ a_1+b_1\,(M-M_1)+b_2\,(M-M_1)^2 & M_l\leqslant M\leqslant M_u\\ 0 & M>M_u\end{cases}$$

where M_u is upper bound on the magnitudes in such a truncated distribution. The above law predicts less number of events of high magnitudes than the linear one. So the risk curve falls off faster with increasing ground acceleration. The assumption of a quadratic magnitude frequency law yields slightly higher risks for small ground acceleration due to the fact that this law predicts more events in the range of magnitudes 4.0 to 5.5. To counteract this the above authors recommend that linear law may be assumed for smaller events and quadratic law for larger events. The fact that quadratic magnitude frequency law predicts less events of higher magnitudes is an indication of a larger volume of rock participating in the earthquake and a high stress level required for the occurrence of a large earthquake.

For actual design applications, the engineer needs a record of ground accelerations at a site. In favourable casec one may have a record of maximum ground accelerations over a suitable period which could be used as input in some prediction scheme derived from any method. More often instrumental data on ground accelerations is totally lacking. In such a case, maximum ground acceleration at the given site during past earthquake on the basis of the magnitudes and epicentral distances may be calculated by using some general formula e.g., that proposed by Orphal and Lahoud, (1974). Such indirect methods of estimation are referred to as composition methods. The accuracy of such methods depends on the assumptions involved and the formulas used. Local factors (geology, soils) cannot be taken into account in a satisfactory way. Nevertheless, composition methods represent the only partical way in problems of seismic risk at locations where sufficient intrumental data is not available. The following technique has been used to obtain consistent results.

The probability of occurrence of an earthquake of magnitude less than M_C at its epicentre is given by

$$p_i = 1 - \exp(-\beta_i M_c) \qquad \ldots(9)$$

Where M_C is defined as the magnitude which produces a critical acceleration a_C at a distance Δ_i and p_i represents the probability that an earthquake at ith epicentre will not produce an acceleration in excess of a_c at the given locality. A suitable magnitude-distance-acceleration formula may then be used to compute the critical magnitudes M_C at all known epicentres. The probablity p_i for each of these computed critical magnitudes can be determined, and the composition of probabilities for all such known epicentres is

$$P = \prod_i p_i \qquad \ldots(10)$$

The probability that the given acceleration will be exceeded would be $(1-P)$. This technique assumed that the period of record is sufficiently long and at each epicentre a value of β_i is available. In practice this will not be possible and one has to adopt characteristic values of β for different tectonic provinces.

This approach offers distinct advantages as the probability of exceedence of an acceleration level can be evaluated and portrayed as a risk map. The usefulness of composition methods can be further enhanced if local factors such as soil response could be effectively incorporated into the estimation of critical acceleration a_c. Using these methods seismic risk maps of California and Chile have been prepared (Lomnitz, 1969). It would be evident that such a risk map is weighed toward areas of frequent earthquakes rather than areas of few shocks. Also it has been argued that the region of low apparent risk along major faults may be precisely the most likely spots for great earthquakes since they show little evidence of strain release and serves to bring into light areas where potentially damaging earthquakes may occur in future. The 1966 Parkfield Earthquake and the 1971 San Fernando Valley earthquake which occurred in saddles between two high areas on the San Andreas fault system are mentioned as examples. Therefore, in order to obtain the true values of the probablity of exceedence a threshold critical magnitude $M_{c\ min}$ could be evaluated for the nearest epicentre and the quantity $M_c - M_{c\ min}$ can be used in place of Mc in equation (9) in order to normalize the probability p_i. Such a procedure for preparation of risk maps delineating probability of exceedence of ground acceleration is likely to smooth out the low apparent risk areas for evaluating the design acceleration with the desired probability of exceedence.

OTHER STUDIES

The earthquake engineering research group headed by E. Rosenblueth and L. Esteva have advanced the use of Bayesian methods for the estimation of seismic risk. Such methods utilize partial knowledge of the mechanism and limited data runs in a region in such a way so as to improve the prediction of the process. An initial distribution having some predictive relevance to the process (earthquake occurrence) is assumed and the available body of data is used to determine whether the distribution is true or not. The initial distribution is modified until the present body of data satisfies it at the highest significant level. As more data accumulate, further modification to the already modified distribution can be attempted. The initial probability has to be assigned on the basis of our theoretical and practical knowledge of the mechanism of earthquake occurrence. (Newmark and Rosenblueth, 1971). The Bayesian methods allow us to make use of geophysical models (e.g. plate tectonics) for arriving at the initial hypothesis. However, the assignment of prior probability distribution involves an arbitrary decision on the part of the user. This varies greatly among different seismologists. The amount of personal judgement which goes into a Bayesian procedure is not always easy to pin down (Lomnitz, 1974).

Howell (1974) presented a technique to subdivide a region into zones of roughly equal expected hazard from future earthquake and introduced the concept of a Cumulative Seismic Hazard Index and Average Regional Seismic Hazard Index the former represents the logarithm of the sum of the seismic energies experienced at any location and the latter the regional average of former normalized to 100 years. Both the hazards could be expressed in units of Modified Mercalli intensity. The results have been compared with regional tectonics.

Liu and Fagel (1974), proposed to divide whole of United States into a total of 10 seismic areas based on the historical earthquake data in 1°×1° quadrilaterals. The earthquake occurrence was assumed to follow a Poisson distribution law. They presented regionalization maps showing the maximum earthquake magnitudes for various return periods.

DeCapua and Liu (1974) presented a method of seismic microzonation based on statistical analysis of past earthquake data. The results of their analysis were in the form of frequency-intensity recurrence relations and maps showing intensity and acceleration contours for 50 year and 100 year return periods. The earthquake occurrence was assumed to follow a Poisson point process.

EARTHQUAKE PARAMETERS FOR DESIGN

A time history record of ground motions at an engineering project site is required for earthquake resistant design of structures. Such information is best collected from accelerograph records during past earthquakes. However, due to lack of instrumentation for strong ground motion measurements such records are generally not available. Recourse thus could be taken to evaluate the probable maximum magnitude that could occur along a seismotectonic lineament (active fault zone) and evaluate the response of the local soil subjected to sesimic waves arriving at the site from such an event to get the probable strong ground motion. The earthquake parameters for such an evaluation could be listed as follows:

a. magnitude of the earthquake

b. distance of the earthquake

c. local soil conditions

These parameters are usually determined from a knowledge of past earthquake history of the region in which the site lies, and geological and tectonic set up of that region. Generally due to lack of detailed knowledge about seismc history of the region and its poor correlation with regional geological structure the problem of determination of the above earthquake parameters does not lend itself to a straight forward solution.

As discussed earlier frequency magnitude relation provide a technique of evaluating the probable maximum magnitude of earthquake for the desired return period (expected or design life of the structure). However, as frequency magnitude relation is valid in the intermediate magnitude range, a probabilistic approach is considered more suitable for determining the probable maximum magnitudes. This approach also takes care of the inhomogeneity in data on earthquakes specially in low magnitude range. The location of such a probable maximum magnitude earthquake in relation to the project site is the most important parameter because any seismic risk estimation without considering the potential source region and attenuation characteristics of the intervening medium upto the site would otherwise lead to appreciable deviatious from the statistical derivations. The compositional approach as discussed earlier which gives a technique of evaluating peak ground accelerations with known probabilities of their exceedance, which could directly be used for evaluating design seismic coefficient assumes location of causative seismotectonic lineament at the distance of nearest epicentre. Identification of the causative fault near a given site therefore should be considered a necessary exercise so that the probability of exceedance of any characteristics of strong ground motion could be evaluated accordingly. Cornell (1968) hes incorporated the size of the fault in such computations in terms of the rate of earthquake occurrences per km of fault length per year on an active fault zone. In the absence of data on the active status of a fault near the site, energy release or tectonic flux maps (Lomnitz, 1974) and maps indicating Cumulative Seismic Hazard Index or Averege Regional Seismic Hazard Index (Howell, 1974) could be utilized to demarcate the probable locations of seismogenic lineaments around the site. Alignment of epicentres and/or fault plane solutions indicating the attitude of nodal planes can also be utilized in such demarcation.

Correlations of magnitude, and distance with ground motion characteristics have been established by various workers based on data from actual records in various geologic environment. Peak ground acceleration velocity and displacement are computed from such relationship as an index of ground motion characteristics. These correlations are valid for the regions for which data were available. Attempts have also been made to have statistical correlations among these parameters for their general application. However no unique relationship has been found so far. Local soil conditions are noted to have significant influence on the intensity of strong ground motion. The choice of utilizing the particular relationship for evaluation of intensity of ground motion depends upon the acceptable level considered to provide adequate safety in the structures on engineering judgement. The probability that this acceptable level of intensity of ground motion is exceeded once or more number of times during the design period of the structure could be evaluated. The risk involved in choosing a particular value is then known.

Peak ground acceleration, velocity and displacement, though useful indices of strong ground motion characteritsics do not provide sufficient information for time history record of ground motion. Peak ground acceleration is often utilized for evaluating design seismic coefficients for pseudo-static analysis. Peak ground velocity has been noted to show better correlation with resultant damage. In the absence of actual records of strong ground motion the knowledge of time history of strong ground motion expected at the site has therefore to be determined from indirected methods, utilizing the peak values of intensity of ground motion taking into account the influence of source paramaters and the dynamic characteristics of soil and rock formations at the site. One of the approaches is to utilize an accelerogram recorded elsewhere in some past earthquake after suitable modification in the light of intensity of ground motion expected in a future earthquake and the soil properties expected at the site. In this approach, as sufficient data on ground response at large number of sites covering a wide range of soil conditions, as well as of earthquake magnitude of epicentral distances is available, a group of strong motion secords obtained under conditions as comparable as possible are selected and assembled. Extrapolation from these records by simple scaling are considered as adequate and best suited to the present state of knowledge. Peak ground velocity expected at the site and the predominant natural frequency are utilized in such scaling. It is often emphasized that such extrapolation is derived from reliable data as compared to the results based on analytical approaches which introduce approximations without providing any more basic data. The above approach for evaluation of the strong ground motion is considered as the most appropriate way in the absence of a unique approach to calculate surface motion.

Several analytical methods have been proposed recently for the calculation of surface ground motion during an earthquake of specified magnitude on a selected fault taking into account the nature of source mechanism, the effect of the geological formations upon attenuation of seismic waves, and the site conditions. Some techniques begin at the source while others begin at the base of local site with bedrock motion adjusted for distance from the fault. Such analytical approaches have been used to estimate strong ground motion for the design of important structures. Such estimates when combined with probablistic estimates of occurrences of an earthquake at a given fault gives the intensity of strong ground motion as a more realistic indication of seismic risk for design of earthquake resistant structures.

DISCUSSIONS

The methods of seismic risk analysis based on laws of probabillity assume. that sufficient data on past earthquake occurrence are available. Such analysis is thus easily carried out for active seismic belts with seismological stations operating in the region. The probabilities of occurrence of earthquakes on any part of our dynamic earth can not be ruled out completely. However, there are many regions where data on earthquake occurrence is not available. This is sometimes due to lack of seismological observatories and/or undeveloped nature of the terrain with no scientific or historical records of earthquake occurrence in the past. Sometimes such regions occur along extensions of active seismic belts or possess tectonic framework which show seismic activity in other regions. For evaluation of seismic risk in such regions, indirect methods based on similarities in tectonic framework with another region where data on earthquake occurrence is available can be used. Earthquake occurrence as stated earlier is a random phenomenon and estimates on such comparison can however sometimes lead to erroneous results as the operating geological process in the crust and upper mantle leading to the accumulation of strain energy may be different. It is therefore desirable to have a network of seismological observatories established and record microearthquake and other seismic activity which is the only convincing and positive evidence of strain accumulation and its release. In the absence of seismological instrumentation such regions are often considered as seismically stable and no concern is shown to evaluate the seismic risk which is not a desirable practice.

CONCLUSIONS

A number of methods have been describedto evaluate earthquake risk at a site. Of all these methods the one which gives exceedence probability of a given value of peak ground acceleration during a future earthquake, offers distinct advantages. This will have direct use in actual design applications. If the lack of data on past earthquakes does not permit the use of probabilistic techniques, other indirect means based on geologic and tectonic history of the region should be utilized. Simultaneously efforts must be made to obtain more data on earthquake occurrences by establishing a network of seismological observatories and recording microearthquake activity which is the only convincing and positive evidence of strain accumulation and its release.

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