THE STATISTICAL ESTIMATION OF EARTHQUAKE RISK*

D. Vere-Jones**

ABSTRACT

The concept of Earthquake Risk is considered from three points of view: the geophysical risk, referring to the probability of occurence of a damaging earthquake in a specified region; the engineering risk, referring to the probability of structural failure; and the insurance risk, referring to the probability of claims being lodged to a specified amount. In each case a general discussion is given of some practical and technical difficulties involved in estimating the risk.

The difficulty in dealing with earthquakes from a statistical point of view is that, fortunately as it may be, damaging earthquakes are rare events. Not many insurance companies, for example, have had the experience of handling claims for two major damaging earthquakes; by the same token, not many insurance companies are in a position to make an adequate assessment of the risks involved in earthquake insurance.

Barren ground though this may appear to the statistician, the practicalities of the situation are that important decisions concerning building codes, design criteria, town planning, civil defence arrangemenrs, insurance and compensation schemes, to name only the most obvious, are constantly being made with some reference to the question of "earthquake risk". If the professional statistician has nothing to say on these matters, others, with fewer scruples, may usurp his role. To cite a rather extreme and hypothetical example, a large corporation, wishing to satisfy its shareholders that all necessary precautions have been taken, hires a "risk consultant" to prepare, at a cost of 0.1% of a multimillion dollar structure, a glossy brochure containing much jargon and few facts to the effect, in the final analysis, that someone's subjective estimate of the probability that the building will be severely damaged in the next 50 years is .007543. Such a possibility illustrates that although, statistically speaking, not a great deal of value can be said, there is still some point in saying it clearly, in trying to distinguish valid procedures from invalid ones, and in dispelling false expectations.

In the present paper, I have set myself the more limited aim of trying to explain what is meant by "earthquake risk", and how its statistical estimation has been or might be accomplished. As is usually the case, the problem becomes more complex the more closely it is examined, and I have found it helpful to distinguish three types of earthquake risk, the <u>geophysical risk,</u> the <u>engineering risk</u>, and the <u>insurance risk</u>, each of which entails its own set of problems and philosophy of approach.

The word "risk" itself is a difficult one to pin down, as it involves elements of at least two kinds: the <u>probability</u> (a number between 0 and 1) that some kind of loss will be incurred, and the <u>value</u> (in dollars or some other unit, not necessarily monetary) of what is "at risk". It also has more specific technical meanings, for example in the theory of brittle fracture and in insurance theory. Not professing to be an expert in any of these fields, I shall use it generally to mean a <u>probability of loss</u>, the nature and circumstances of the loss to be specified by the context. Then by <u>geophysical risk</u> I shall mean just the probability of occurrence of a specified type of earthquake within a specified region in a specified interval of time, the loss remaining implicit and unspecified. By the <u>engineering risk</u> I shall mean the probability of failure (due to earthquakes), in part or in whole, of the structure of interest during a specified time interval. Finally, by the <u>insurance risk</u> I shall mean the probability that claims for a specified amount will be lodged (on account of earthquake damage) against the insurer during a specified time interval. There is a kind of logical progression in the three types of risk considered; each requires for its determination a specification of the ones which precede it.

2. The Geophysical Risk - Basic Data

A crude basis for the determination of the geophysical risk is presented by the catalogues of earthquakes published annually by the Seismological Observatory of the D.S.I.R. (for New Zealand data) and by similar institutions overseas. Among other information, the catalogues list the estimated origin times, epicentres (latitude and longitude readings), depths, and magnitudes of earthquakes which occurred during the year and were large enough to be felt locally or registered instrumentally with a sufficient degree of precision. The concepts of a point focus, or hypocentre, and instantaneous origin time, are of course mathematical idealizations; the approximations may be reasonable for small or moderate earthquakes, but during a really major earthquake, shaking may last for several minutes, and the surface of the earth may be ruptured along a fault extending for tens or even hundreds of kilometers. Similarly, the Richter magnitude of an earthquake, defined in terms of the

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* Based on an address given to the Annual Meeting of the New Zealand Statistical Association, July 1973.

** Mathematics Department, Victoria University of Wellington.

Bulletin of the N.Z. Society for Earthquake Engineering, Vol. 6, No. 3, September 1973

of the response of a standard instrument at a standard distance from the source, gives at best a crude estimate of the size and consequent damaging propensity of an earthquake. Difficult and uncertain computations and measurements suggest that the magnitude is approximately linearly related to the logarithm of the energy released in seismic radiation, an increase of 1 in the Richter scale corresponding to a multiplication of the energy by a factor of about 30.

Such data provide some indication of the relative rates of occurrence of shocks of different magnitudes. The 30-odd years for which adequate instrumental data is available for New Zealand allow some kind of estimate to be made for the frequency of occurrence of earthquakes up to about magnitude 6½, beyond which the numbers become so few that direct determinations of the frequency are unreliable. (By comparison, the Napier earthquake, which is probably one of the two largest to have occurred in New Zealand this century, is estimated to have had magnitude 7¾). A very characteristic feature of the frequency/magnitude relations so obtained is the approximately linear relationship between magnitude and log frequency. (For the New Zealand data, an increase of 1 in the magnitude corresponds to a decrease in the frequency by a factor of about 10). In probabilistic terms, this implies that the marginal distribution of magnitudes is approximately exponential, with density function say

$$(1) \quad f(M) = be^{-b(M-M_o)} \qquad (b \doteqdot 2.5)$$

where M_o is a threshold to the recorded magnitudes imposed by limitations on the recording network ($M_o = 4$ for recent data on a New Zealand-wide basis).

Since direct data on large earthquakes are inadequate, estimates of the rates of occurrence for larger magnitude shocks must be made indirectly, for example by an extrapolation of the above relationship, which has been well verified over an enormous range of energies and in many different seismic regions. However, geophysicists are divided in their opinion of the validity of such an extrapolation. In part this related to the possibility of an upper bound on the magnitudes of the earthquakes in a given region, imposed by considerations of a maximum possible fault length. The largest known shocks approach magnitude 9, but the limitations suggested here lie more in the region 6.5 - 8.5. The statistical evidence for such a cut-off is, so far as I know, entirely inconclusive, which suggests in turn that the practical consequences, in terms of risk estimates, may not be great. This view is reinforced by the further suggestion that the intensity of ground motion experienced in the Napier earthquake might not be greatly exceeded in an earthquake of larger magnitude; it would be a question rather of a longer duration of shaking and a wider region of damage.

A more difficult suggestion to counter is that the pattern of seismic activity may vary significantly from one region to another, not only in the overall rate of occurrence, but also in the relative frequencies for shocks of different magnitudes. Some authorities go so far as to suggest that a high general level of background seismicity argues against the likelihood of large shocks occurring, while its absence is a suspicious feature indicating a large accumulation of unreleased stress. The direct statistical evidence for such an effect is again inconclusive, at least for New Zealand data, and only time will tell whether some of our presently quiescent regions should really be placed in this dangerous category. That variations exist in the overall rates of occurrence from region to region is not to be doubted; the overall numbers, though fluctuating in detail from year to year, suggest a fairly stable pattern for the thirty odd years for which data is available. There is some evidence for minor variation (~ 10%) in the value of b from region to region, and possibly also in time. One way which has been suggested of taking such variations into account is to use the overall data to suggest a prior distribution for the value of b and to use recent local data to obtain posterior estimates in a Bayesian analysis. This technique is also useful where little reliable instrumental data is available but some analogy with other seismic regions can be expected.

How stable the pattern of seismic activity is likely to remain over periods longer than a few decades is a most important point. Historical evidence from the Middle East and China, where written records of major earthquakes go back for several millenia, does indicate appreciable fluctuations in the rate of energy release over periods of one or two centuries. Nevertheless, the major seismic regions of the world seem to have been much the same in biblical times as they are today.

Yet another controversial point is the relation between epicentres and active faults. While there is no doubting the general relation between faulting and earthquake activity, the New Zealand data show no striking lineations of the kind exhibited by Californian data, where epicentres cluster round the San Andreas fault like ants round a line of poisoned honey. On the whole the geological evidence seems more difficult to interpret or to incorporate into quantitative risk estimates than the direct seismic evidence.

To try and summarize the discussion in this section, it is my personal impression that the frequency/magnitude relation (1), with some allowance for minor local variations of b, offers an adequate basis for the magnitude extrapolations required to compute short-term estimates of earthquake risks. On the other hand, there are much stronger grounds for circumspection in assuming that the present geographical distribution of seismic activity will remain stable for periods of more than a decade or so, or that present data runs give an adequate indication of the seismicity in all regions of New Zealand. Here it is not a question of instrumental coverage, but simply of the lapse of a longer time period before we can be confident that all aspects have revealed themselves.

3. The Geophysical Risk - More Sophisticated Methods

The most urgent question the layman is likely to address to the statistician-seismologist is "Where and when will the next big earthquake occur?" Whether or not we shall ever have the technical knowledge to make adequate predictions of this kind - and at the present time it is no more than a possibility on the horizon - I am probably not alone in believing that very great caution would have to attend the public release of such information.

It is also my belief that the most constructive formulation of the prediction problem, at least for the time being and possibly also in the long run, is precisely in terms of improved estimates of the earthquake risk.

Implicit in the discussion of the preceding section is the assumption that the only parameters of interest in the estimation of earthquake risk are the rates of occurrence of earthquakes of different magnitudes in different regions, and this in turn rests on the assumption that no information about the probabilities of occurrence are carried by more complicated statistics based either on the past data or on the values of auxiliary geophysical variables.

The mathematical model corresponding to this "no-memory" situation is of course the Poisson process, and to a very crude approximation it is indeed the case that the numbers of earthquakes in specified time intervals do follow a Poisson distribution. Any attempt at a more refined investigation of this aspect soon indicates quite marked divergences from the Poisson model. In particular, correlation analyses, while showing no evidence whatsoever for periodic effects, show a small but persistent positive correlation between the numbers of shocks in successive time intervals of equal length. In part, these correlations are due to the existence of large aftershock sequences and earthquake swarms, but they persist even after attempts have been made to screen out such features, and seem to indicate a generally cohesive response of the whole region to slow fluctuations in the applied stress or rate of energy input. The slow fluctuations of seismicity mentioned in connection with historical evidence may be a more extreme manifestation of the same effect.

Even such relatively unexciting features suggest that the risk should not be regarded as a constant, rather as a variable whose instantaneous value fluctuates in time in accordance with the overall state of the physical system. From the statistical point of view we should consider the risk not on an absolute basis but conditionally on whatever additional information we have to hand concerning the state of the physical system.

In the most restricted case, this information would be limited to the past records of the occurrence times of the earthquakes in different spatial and energy categories. If $N_i(t)$ denotes the cumulative number of earthquakes up to time t in the i-th category, the simplest conditional estimates of the risk would take the form

$$r(t) = a + \sum_i \int_{-\infty}^{t} g_i(t-u)\,dN(u)$$

where the constant a and the transfer functions $g_i(.)$ could be estimated, in what are basically standard techniques, from the second order (cross-correlation) analysis of the sequences $N_i(t)$. One might expect this use of linear estimates in a highly non-Gaussian situation to be rather inefficient, but A. N. Hawkes has introduced a class of processes, which he has in fact fitted to earthquake data, for which such estimates are fully efficient in the sense of having minimum variance from the class of all possible estimates with finite variance. The fit to earthquake data is not perfect, but good enough to suggest that estimates of the above form could provide reasonable approximations for practical purposes.

From the conceptual point of view an advantage of the above formulation is that in principle it can be extended to include similar terms in other geophysical variables, and even if the linear, additive form proves too restrictive, the same general approach could be applied. In fact, recent experiments have indicated that physical parameters such as the magnetic and electric field intensities, the strain, the velocities of seismic waves, electrical or thermal conductivity, may show a pattern of minute but systematic changes before an earthquake. The measurement of these changes lies on the boundary of what is technically feasible at the present time, and extraordinarily complex instrumentation would be needed to cover all the directions or locations where such minute changes might be taking place. Despite these great technical difficulties, such developments, taken in conjunction with cruder features such as the correlation with past activity, do hint at the possibility of raising the effectiveness of risk estimates by several orders of magnitude. At least I think it has reached the time when it would be worth giving consideration to the possibility of preparing regular "risk forecasts". This suggestion may seem facetious, but the research that would be required to put such a programme into operation would, I am sure, help greatly in understanding the nature of "risk". Moreover, the publication of official estimates would deprive charlatans and crackpots of the opportunity, if not of making predictions, at least of using their predictions to fill an official vacuum. Finally, I believe that publication of such risk estimates could play a useful educative function in developing a greater public awareness of the dangers and responsibilities of living in an earthquake-prone region.

4. The Engineering Risk

Calculations of the performance of a given structure with respect to earthquakes may be crudely broken down into the following steps. Firstly, the probability of a given type of loading or ground motion is estimated. Then the response of the structure to the given ground motion is calculated. Finally, the probability of failure of any element of the structure can be estimated from its calculated response and known properties of materials. If desired these components can then be recombined to give a probability of failure of the structure as a whole.

Such calculations have two main applications. Firstly, they may be applied to any particular structure being designed for an earthquake-prone region. Secondly, generalized calculations of this kind enter into the specification of building codes designed to secure a reasonable level of public safety.

It is my impression that the second and third stages of the calculations outlined above, relating to the response of the building and the probability of failure under a given loading, are relatively well understood (although I suspect that a probabilistic approach to the problem is not adopted as often as it might be). On the other hand, considerable uncertainty exists with regard to the first stage, of specifying the ground motion itself. Let us examine some of the sources of this uncertainty.

One major difficulty is the lack of adequate records of strong motion during earthquakes. For many years, building codes in many countries were based on the records of the single occasion where a strong motion recorder happened to be working in a town (in Southern California) which happened to be hit by a moderately severe earthquake. More recently an international effort has been made to obtain further strong motion records, but information about the character and in particular the frequency resolution of the ground motion in the vicinity of the epicentre of a moderate or strong earthquake is still scanty. One idealization which has gained favour recently is to view the ground motion as a segment of white noise of limited duration. Such assumptions allow the probability distributions of the maximum values of acceleration or ground velocity to be calculated as functions of some integrated parameter such as mean spectral density. For brevity, I shall refer to such a parameter as the intensity of the ground motion.

The problem then remains of relating the probability distribution of the intensity at the site with factors such as the soil type at the site, the site geometry, geological and topographical features near the site, the probability distribution of epicentres and magnitudes, and the geological structures intervening between the given site and any chosen epicentre. Any one of these factors may well exert a critical influence on the final motion in appropriate conditions. In particular, it is commonly estimated that a change in soil type (say from bedrock to alluvium) may have an effect equivalent to that of an increase of several units in the magnitude of the shock. From this stems the importance of microzoning within any given region, so that soil type and related features can be taken into account. As for the uncertainties in the transmission of earthquake waves from the focus to the site, so far as I know the best that has been attempted is to relate the ground intensity I at the site to the magnitude of the earthquake by summary formulae of the type

$$I(M,\underset{\sim}{x}) = a(M)\, b(\underset{\sim}{x})$$

where x is the coordinate vector of the focus referred to the site as origin, and a(.), b(.) are functions determined empirically by pooling qualitative estimates of the ground motion at various points round the epicentres of past earthquakes. Typical estimates take the form $a(M) = Ae^{\alpha(M-M_o)}$, $b(\underset{\sim}{x}) = (b^2 + |x|^2)^{-1}$ where $|\underset{\sim}{x}|$ is the distance from source to focus. In passing, this assumption of isotropy is almost certainly inappropriate most cases. The only reassuring aspect to offset the crudity of these assumptions is that the aim of the exercise is not so much to predict the ground motion from a specified earthquake source as to obtain the probability distribution of ground motion intensities over relatively long periods such as the 50 years commonly used as the natural life-span of many structures. The resultant distribution is itself an integral average and hence relatively insensitive to the actual form of $b(\underset{\sim}{x})$.

The critical feature is the exponential form of the dependence on the magnitude. If this is satisfied the intensities will follow a Pareto (inverse power law) type distribution under very general conditions. Indeed, let the rate of occurrence of earthquakes of magnitude M or greater in a small volume ($|d\underset{\sim}{x}|$ at location x be $\rho(\underset{\sim}{x})\ Me^{-b(M-M_o)}\ |d\underset{\sim}{x}|$, where b is assumed independent of x. Since an earthquake at x gives rise to ground motion I or greater at the site if and only if $a(M)\, b(\underset{\sim}{x}) \geqslant I$, or in the case $a(M) = e^{-\alpha(M-M_o)}$ if and only if $M - M_o \geqslant \frac{1}{\alpha}$ $\{\log I - \log b(x)\}$ we have after integrating that the overall rate of occurrence of intensities I or greater at the site is given by

$$(I)^{-b/\alpha} \int \sigma(\underset{\sim}{x})\ \{b(\underset{\sim}{x})\}^{b/\alpha}\, |d\underset{\sim}{x}| = C.I^{-b/\alpha}$$

where the local variations in the transmission function $b(\underset{\sim}{x})$, as well as local variations in the density of occurrence $\sigma(\underset{\sim}{x})$, have been lumped into the overall rate constant C.

At this point the approach favoured by the engineering profession is to make use of extreme-value distributions, which enter very naturally in this context. For example, if λ represents the overall rate of occurrence of earthquakes of magnitude M_o or greater, the probability distribution of the maximum magnitude in an interval of length T is given by

$$F_{\max}(M) = \text{Prob}(\max \leqslant M)$$

$$= E_N\{F(M)^N\} = e^{-\lambda T\{1 - F(M)\}}$$

where F(M) is the distribution function for the magnitude of a single earthquake and the expectation is taken over the number N of earthquakes which we assume to have a Poisson distribution with parameter λT. Giving F(M) the usual form $1 - e^{-bM}$ we at once obtain an extreme value distribution of type I, viz $e^{-\lambda T e^{-bM}}$. Similarly, if the power law distribution is substituted in place of F(M) we find the maximum ground intensities follow an extreme value distribution of type II.

The rationale behind the use of extreme value distributions is that failure will occur if the ground motion exceeds a threshold value I_o but not otherwise. The probability of failure then reduces to the probability that the maximum intensity over the stated period exceeds I_o. If this assumption is not accepted, and we suppose instead that there is a probability q(I) of failure whenever the intensity takes the value I_x, we obtain the more general formula for the probability of failure in the interval T

$$1 - P_F(T) = e^{-\lambda T} \int q(I)\,dF(I).$$

The extreme value distribution is recovered if $q(I) = 0$ for $I < I_o$, $q(I) = 1$ for $I > I_o$.

The relative convenience of such formulae should not be allowed to obscure the fact that they gloss over many moot points such as the variability of response due to soil type and topography, the possibility of non-stationarity, deductions based on data runs of too short a length, etc.

5. The Insurance Risk

Insurance against natural hazards is an aspect of insurance theory not easily brought within the framework of conventional acturial procedures. Some of the reasons for this situation, at least as far as earthquakes are concerned, are as follows :-

(i) Although large damaging earthquakes occur extremely rarely, they are associated with an extremely high loss potential.
(ii) Individual risks are not independent.
(iii) All forms of insurance are affected simultaneously.
(iv) Statistical information about the occurrence of large damaging earthquakes is inadequate to use as a basis for premium calculations.
(v) Assessing the amount at risk as well as the degree of risk presents considerable technical and practical difficulties.

Let us examine some of these points in more detail.

Traditional insurance practice is based on achieving a balance between the annual income received from premiums and the annual loss paid out in claims. In order to strike such a balance it is necessary to determine with some accuracy the expectation of the annual amount of claims, which will usually be estimated from the experience of companies which have dealt with the same type of insurance over some length of time. As we have already observed, there is very little data on which to base such a calculation in the case of natural hazards. Moreover, features such as economic development, inflation, increasing urbanization, mean that the basic process under observation is highly non-stationary, to such an extent that it is doubtful whether any past experience of claims paid out has any direct relevance as a basis for estimating the likely amounts of future claims.

A further assumption of traditional insurance theory is that the number of independent claims is large, so that the total claim can be represented as the sum of a large number of small independent components. The standard deviation of the total annual claims is then not an excessive proportion of the total annual turnover of the company, so that it is not difficult to build up a sufficient reserve to cover most contingencies arising from random fluctuations of the annual claims about their mean. The bane of an insurer's life, I imagine, are the occassional "outliers"; the once in a lifetime claims that can bring the company to ruin. Earthquakes and natural hazards are precisely these outliers. Or put more technically, we have already seen the occurrence of power law distributions in connection with earthquakes, and such distributions may have a very large standard deviation (effectively infinite perhaps) compared with the mean. Hence a colossal contingency fund would be required to secure a company which took on a large amount of earthquake insurance.

It is customary to attempt to meet difficulties of this kind by spreading the risk over several companies, or selling the residual risk to internationally based reinsurance companies. The situation which has currently arisen with regard to earthquake reinsurance is that the risk market is already saturated. It is virtually impossible, for example, to sell Japanese earthquake reinsurance on the world market. The two principal limitations which operate appear to be, firstly, that it is difficult to sell earthquake risk to countries not subject to earthquakes, and, secondly, that a large proportion of the potential market is either too poor to afford earthquake insurance or adopts a political system which is not compatible with private insurance schemes.

As far as possible it would be desirable, from the point of view of spreading the risk, to persuade all types of insurance companies to take on a small amount of earthquake insurance. Even here, however, the situation is complicated by the simultaneous involvement of all forms of insurance in a major catastrophe. Moreover, it is at least arguable whether the combined resources of all insurance companies operating in a country would be adequate to cover the total claims on a major earthquake occurring in a major city, particularly if the claims on secondary effects (subsequent fires, landslides, tidal waves, losses due to failure of power and water supplies, etc.) were included.

In addition, there are great practical and technical difficulties in the way of a company assessing adequately the extent of its liability for earthquake damage. What kind of damage is likely to occur in the buildings which the company has insured or where property or personnel assured by the company is lodged? Do the buildings meet the legal minimum requirements? What is the fire hazard in case of an earthquake? What proportion of the company's portfolio is likely to be affected by an earthquake in any given region? To answer such questions adequately would require a team of expert assessors. In the absence of such expertise, there will be a tendency to avoid earthquake insurance by setting exorbitant premiums. A private insurance company cannot be forced to take on earthquake insurance it if finds it unprofitable or unduly troublesome.

All of these difficulties persuade me that the problems of insurance against natural hazards are unlikely to find an effective solution in terms of private insurance, and that we can be grateful to the foresight of our forebears in setting up New Zealand earthquake insurance on a national, non-profit-making basis. In the final analysis it will always be the country itself, not any collection of insurance companies, which bears the bulk of the real cost of a major natural disaster, particularly when, as in New Zealand, some of the most vulnerable assets (communications, electric power) are already state-owned. Setting up a national fund spreads the risk over all members of the population. Moreover, looking at the problem on a national basis focusses attention not on the artificial and, in the present instance, almost meaningless question of balancing premiums against claims, but on the critical question of what can be done to minimize the losses that an earthquake may cause. Here, totally different questions come into the picture, foremost among them the requirement to take all reasonable precautions. Here, if anywhere, is the most effective role for a state insurance scheme. Premiums should not be viewed primarily as a means of raising funds, but as a means of putting pressure on all concerned to comply with minimal safety requirements. It is in the interest of all members of the population that such requirements be met, and it is the State which could most appropriately employ the expert assessors needed to carry out the checking. Earthquake insurance on property and equipment should be compulsory, with high differential premiums on substandard buildings, particularly where many persons or valuable property is at risk.

6. Conclusions and Acknowledgements

My interest in this topic arose chiefly out of an invitation to take part in a U.N.E.S.C.O. meeting on the statistical investigation of natural hazards. I am most grateful to U.N.E.S.C.O. for this opportunity, and to many colleagues and acquaintances, particularly in the Geophysics Division of D.S.I.R., for illuminating conversations both prior and subsequent to this meeting. It will be seen that the statistical questions cannot readily be divorced from the broader context in which they arise, and as a consequence I have dealt with a range of topics well outside my own sphere of competence. I have found the questions of interest and importance, however, and this paper will have more than succeeded in its aim if I have persuaded any of you that statisticians might take a greater part in the attempt to clarify the complex of technical, scientific and social issues involved in the discussion of earthquake risk.

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