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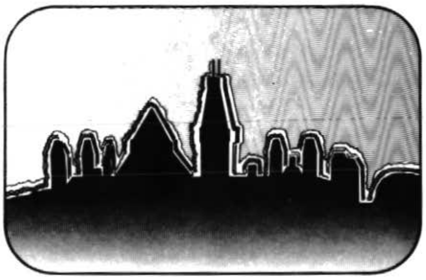

The Estimation of Seismic Risk in Canada

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Introduction

In recent months several of us at the Earth Physics Branch have been spending a good deal of time re-analysing the problem of how best one can estimate seismic risk in Canada. This rethinking has arisen from some rather difficult demands placed on us by the Atomic Energy Control Board (AECB) and from some developments in the National Building Code (NBC) earthquake load provisions. This has led me to attempt to assess the progress and problems in the estimation of seismic risk in Canada and to try to analyse the uncertainties in the different approaches which have been tried in the past. There is of course a fundamental problem in Canada because in general there is no adequate neotectonic framework for understanding Canadian seismicity generally. Not surprisingly it is this lack of an understanding of the tectonic framework which is the key factor inhibiting a better expression of seismic risk in Canada both in the NBC, and more so in the more low risk expressions which are required nowadays, for example, for AECB licensing of nuclear reactors.

Definition of the Problem

The estimation of seismic risk is fundamentally the problem of the prediction of future ground motions or their causative earthquakes and seismic risk estimation therefore requires considerable scientific judgment. Because our knowledge is somewhat variable, it is probably true that there is no unique best solution on a national scale. There is also a responsibility of those involved in risk estimation to attempt to estimate the reliability and probability associated with projecting past data in the future.

The first Canadian problem and opportunity arises from the variety of tectonic environments in Canada. Thus, as you all know, we have off western Canada the Juan de Fuca plate and possibly additional further small plates so that spreading centres are found close to the western Canadian coast. In the eastern Arctic, we have activity associated with a possibly dying spreading system. This is only a beginning because we also have an enormous scatter of earthquakes (Fig. 1) which are apparently appearing inside plates and whose mechanisms can only be poorly understood in terms of present concepts of plate tectonics. Eastern Canadian earthquakes, Yukon and Mackenzie valley earthquakes, earthquakes in the Sverdrup basin, earthquakes associated with the Boothia uplift, and many other examples are common. Indeed, very simply, most Canadian earthquakes appear to be intraplate earthquakes rather than the more easily understood earthquakes which occur along the margins of separating or interacting plates.

The National Building Code of Canada provides minimum standards which if legally adopted are supposed to assure an acceptable level of public safety by designing buildings to prevent major failure and loss of life. Structures designed in accordance with the earthquake load provisions of the NBC should resist moderate earthquakes without significant damage and major earthquakes without collapse, although with some structural damage.

Seismic risk inputs in such a code are usually expressed on a national scale by the use of one or more imperfect seismological expressions. These expressions may be such things as strain release maps, which have been produced for areas of Canada, they may be epicentral location maps which are being produced on a current basis by workers at the Earth Physics Branch, and which have been produced for historical earthquakes in eastern Canada back to 1534 by studies of the records of early settlers. Such geophysical expressions are then mathematically manipulated with or without tectonic controls to derive seismic zoning maps, which are translated directly by the engineers into the static load provisions of the National Building Code. Such manipulated information is more easily used by engineers than the basic factual information such as epicentre maps.

Increasingly there is another requirement in Canada. This arises from public perceptions that in the case of critical structures such as nuclear power plants, the consequences of environmental misjudgment can be perhaps catastrophic in terms of, for example, radioactivity release. In other cases there is the question of the

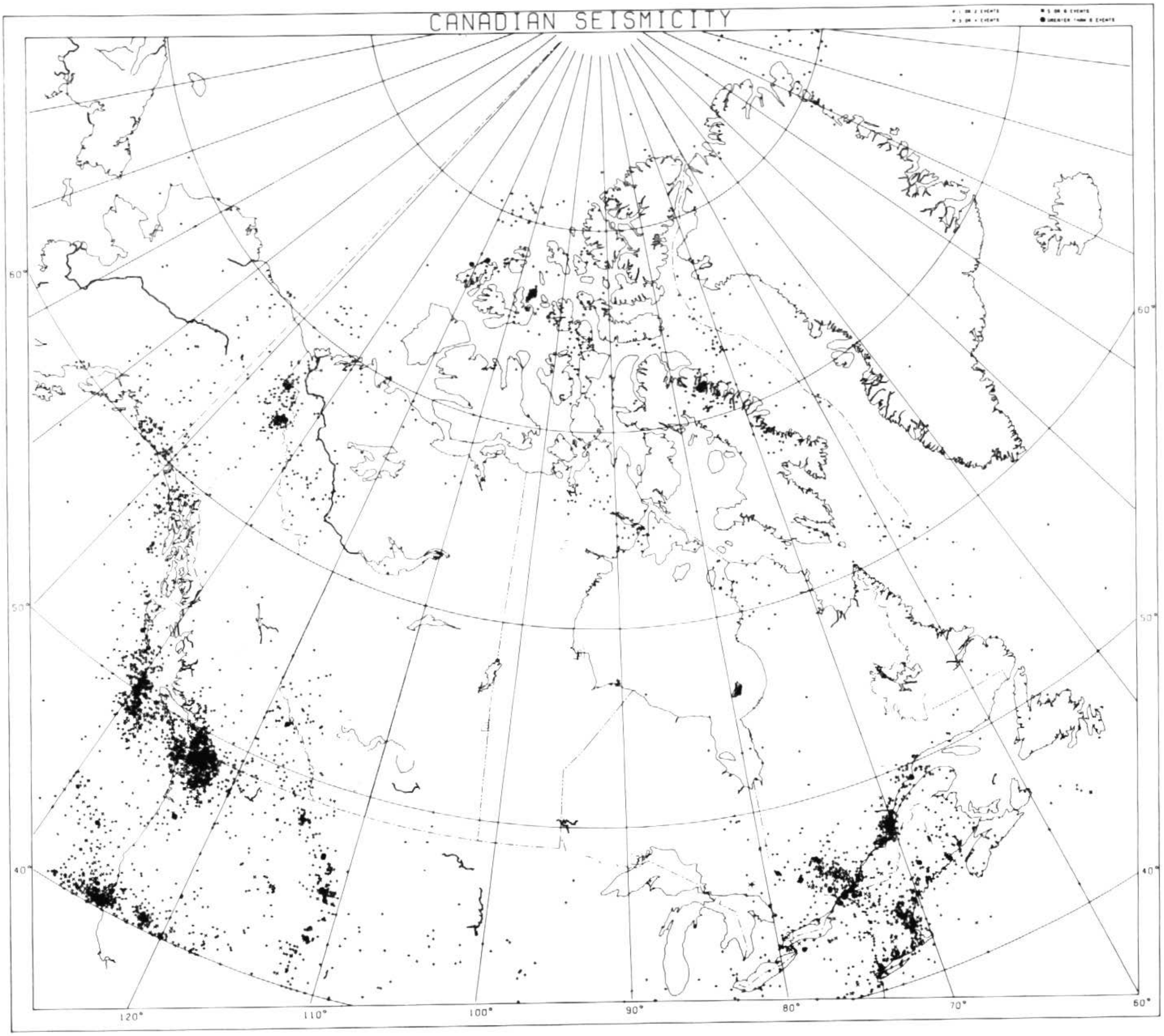

Figure 1

Computer plotted map of all epicentres in the Canadian earthquake files. Coverage has been arbitrarily extended to Latitude 40°N in the USA and to other regions surrounding Canada. Some 6000 earthquakes are plotted (after Anglin and Basham).

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reliability of energy supply and there is considerable concern in the next few decades regarding the reliability of supply from projected major pipelines in northern Canada. The result of these concerns is increasing pressures on geophysicists to conduct more site-specific or route-dependent studies, and make predictions at much lower risk levels than those normally used in the NBC. Apparently society seems to be willing to pay more for such protection than in the more general NBC case. This makes sense to me, since there is now a body of empirical experience from Caracas, from Anchorage, from San Fernando and elsewhere in the general performance of, for example, high rise buildings. Accordingly we have field experience on how the theoretical design of high rise and other orthodox structures works out during economically important earthquakes. However, in contrast, we lack working experience of nuclear power plants during earthquakes and over many decades, and this is another reason for prudence as expressed in the licensing policies of the AECB. It is reassuring that appropriate regulatory groups in Canada are consulting with earth scientists, with the engineering community, the Canadian Nuclear Power Association, and with others to develop an overall safety philisophy as expressed in a series of codes which, I believe, will adopt *inter alia* a much more conservative approach for the critical structures which come under their licensing authority.

In making predictions at low risk levels, we must be careful to avoid any ill-judged opinions which could contribute to irrational local hysteria. Even in California where earthquakes are much more visible a balanced viewpoint is essential. I think this is clear if you stop to consider the fact that in the United States fewer than 2000 lives have been lost due to earthquakes in the past 200 years. This compares with a worldwide average death toll of perhaps 20,000 lives per year from earthquakes. Furthermore, as far as the public is concerned the loss of lives from other hazards must be considered when discussing earthquake risks and the cost of protection. The loss of life in one year resulting from murders in Los Angeles county is over 1600, and in California alone 4500 lives are lost each year as a result of motor vehicle accidents. When one realizes public acceptance of mortality statistics of this kind, it is very easy to understand why even in California there are many people who find it difficult to accept that earthquakes are a serious concern. On the other hand there are others for whom the danger is perpetually personally exaggerated. Some of you may remember the days of 1968 and 1969 when there was on the hit parade a song which predicted that California would slip into the Pacific Ocean. You may remember at that time Howard Hughes was rumored to have purchased land in Nevada because this was going to become the shoreline or the beach area of the new Pacific Ocean. Strangley enough this sort of hysteria actually spread quite extensively in the same period into areas of British Columbia, and was, of course, fed by complete misunderstanding of plate tectonics and transform faults. In all our work we in the government have to be particularly careful to avoid publicising estimates or statements susceptible of inducing irrational, local mass hysteria.

Canadian Earthquakes

Earthquakes do occur in Canada with sufficient frequency and intensity to be of concern. Each year at the Earth Physics Branch, we determine the epicentre and magnitude of some 200 to 300 earthquakes in Canada. In general instrumental coverage is complete to magnitudes less than or equal to magnitude 4 in all parts of Canada and appreciably better this in certain urban areas where special purpose seismograph networks have been installed. On the average 14 percent of these 200 to 300 earthquakes per annum are located in eastern Canada, about 27 percent in western Canada, and 59 percent in the north with occasional other central region earthquakes. Of these 200 to 300 earthquakes, currently an average of some 10 to 20 excite some sort of public and media interest and this is usually by being widely felt. The number is rather variable. We have a file in the Division of Seismology and Geothermal Studies at Ottawa which is called the Current Seismicity file. This is a file which deals with urgent near real-time action, because there has been external media, public, governmental, ministerial or some other sort of public inquiry to us. In the last six-month period this file indicates activity on some 24 Canadian earthquakes.

Most of the 200 to 300 earthquakes each year are too small to cause damage but we should remember that some major earthquakes have occurred in Canada. In the last 75 years some six major earthquakes with magnitude greater than seven have occurred, two in eastern Canada, one in the Arctic and three in western Canada. Great earthquakes with magnitude eight or larger have occurred this century in the Queen Charlotte Islands and near Quebec City in historical times. We have been very fortunate in general in avoiding major damage because of our sparse settlement. The last major damage in eastern Canada was from the Cornwall earthquake of 1944 which had a magnitude of only 5.9, but minor damage in eastern Canada is somewhat more frequent, the last example being at Woburn, Quebec in 1972 with chimney damage. In western Canada damage was last substantiated in July 1972: major widespread earthquake damage was last reported for the Gulf of Georgia earthquake of 1946 which had a magnitude slightly greater than seven. By all predictive standards we are overdue for a significant near-urban earthquake.

In a very general way the problem can be put into perspective by noting that on the average one earthquake each decade with magnitude greater than six has occurred in eastern Canada in the last 50 years and two each decade with magnitude greater than 6.5 in western Canada. A magnitude 6.5 earthquake or greater occurs somewhere in the Arctic, usually either in the Yukon or the Mackenzie Valley or on or offshore Baffin Island on the average each five years. To put magnitude 6 to 6.5 into perspective, you should recall that the last significant damaging urban earthquake in North America was the San Fernando earthquake of 1971, which killed 58 people and did more than half a billion dollars damage in Los Angeles, and had a magnitude of about 6.4.

A few summary observations might be useful to illustrate the difference from California. For example, in California a clear relationship is usually evident between earthquakes and the surface expression of their causative forces; this is not the case in Canada. Our relative ignorance of Canadian intraplate earthquakes is really quite remarkable. For example, in the southern part of eastern Canada the Woburn earthquake of 1972 has provided the first really satisfactory focal mechanism solution. Even in western Canada such information is comparatively rare and there is still room for considerable technical disagreement on the interpretation of key earthquakes. Similarly, we are very limited in our knowledge of focal depths in Canada and it is the exception rather than the rule when reliable focal depths are determined with close seismograph networks. There has been considerable controversy on possible tectonic patterns in eastern Canada with some authors wishing to connect the St. Lawrence Valley zone, through the Great Lakes, down into the United States, through Ohio, Indiana, Illinois, Kentucky, to the great New Madrid earthquake zone of 1811 in Missouri. Others dispute this strongly and prefer instead to adopt a northwest-southeast trend along the Ottawa Valley to Boston together with a centre of crustal activity northeast of Quebec City. The data are scattered, interpretations involve arguments about the best location of a 1630 earthquake and the evidence for a seismicity gap between the two trends mentioned above. Other alternative alignments can be suggested. I think that I prefer the interpretation involving a real gap in seismicity between Montreal and Quebec.

In western Canada the offshore earthquakes follow a system of ridges and faults which link the Gorda ridge and the Fairweather-Denalli faults. This plate-tectonic picture provides an intellectual framework for many of the significant off-shore earthquakes but even here many unresolved problems arise. An example is the recent examination by Rogers of a magnitude 5.7 earthquake near the west coast of Vancouver Island in 1972. For this earthquake he has conducted rather intensive studies which suggest that well-defined pressure and tension axes do not follow the predictions from Cenozoic geology: indeed, it and earthquakes in the Strait of Georgia may define a northern plate boundary of the Juan de Fuca plate. In any case the generalized geological picture drawn by most plate tectonicists seems to be inadequate to explain the particular observations. There is no obvious geological correlation or an adequate tectonic understanding of the significant numbers of earthquakes that occur in southern Vancouver Island, in Georgia Strait and in Puget Sound. The earthquake risk to the major cities of British Columbia is quite similar to the earthquake risk of Seattle. In 1965, an earthquake killed several people and caused considerable damage at Seattle and Tacoma.

First Seismic Zoning Map of Canada

The first seismic probability map for Canada was produced by Hodgson in the early 1950s and it was based on the scale established originally in the United States, which divided the country into four zones 0, 1, 2 and 3 corresponding to zones of anticipated zero, minor, moderate or major damage. The map was based on a knowledge of the larger earthquakes in Canada in historical times and in recent instrumental times, and on general tectonic considerations of the possible regional extent of earthquake zones. Its limitations were described by its author. Engineers were not very happy with this map because the method of preparation resulted in gross discontinuities across zone boundaries. Furthermore the map placed both Montreal and Ottawa as well as Quebec City in the zone of the highest risk which was not very well accepted by many of the potential map users in terms of commercial arguments. The heart of the problem was that it really made no numerical attempt to introduce even a semi-quantitative estimate of the probability of damage associated with a particular zone definition. Clearly better maps were required.

In the mid 1960s, Milne published several strain energy release maps for Canada but these can be criticized in the following way. The presentation is in a form that cannot be used directly by design and earthquake engineers, and any national interpretation of the maps is affected by the lack of uniformity in Canadian coverage and the different earthquake history limitations in different parts of the country.

Earthquake epicentre maps are more easily understood by geophysicists but once again one finds that the presentation of information on earthquake epicentres is not in a form which can be directly used by design engineers or the National Code. Indeed, such maps can be quite misleading to non-seismologists unless there is a clear understanding of the time interval, the range of magnitudes plotted, the different symbols if any for them, the accuracy of epicentral and magnitude determination, and other problems. For example, if the strain in some areas is fully relieved by a recent high stress drop earthquake, then such maps may run the risk of giving a partial anti-correlation on a very local basis with the immediate future risk.

A lot of time can be spent thinking about different ways of presenting seismic risk and concluding that the time element must enter uniformly into the expression of seismic risk for national codes. At our present stage of knowledge, I believe you can quite easily demonstrate in Canada that there is no practical or acceptable way of introducing time in a deterministic manner and only a probabilistic approach is possible in Canada for the National Code at this time.

The Seismic Zoning Map of 1970

Such a probabilistic approach is implicit in the method which Milne and Davenport developed and published in the late 1960s. Their procedure was to use the available earthquake history of Canada, the available intensity, magnitude, distance information in eastern Canada derived from macroseismic investigations, peak acceleration and maximum intensity information synthesized from Californian experience and peak acceleration, magnitude, distance information in California, which was assumed from very limited experimental data to be applicable to western Canada, in order to produce a peak acceleration amplitude map throughout Canada based on an average annual probability of one percent of being exceeded. One can think of this as a map of the maximum or peak acceleration which can be expected at any location with a return period of 100 years. On such a map appropriate smoothing can be introduced, and seismic zones and factors for the static loading characteristics of the NBC can be selected depending upon certain interval considerations. This work formed the basis of the new NBC 1970 seismic zoning map (Fig. 2): it essentially predicted probabilities of peak accelerations, and thus very skilfully avoided the seimological problem of defining earthquake zones on tectonic grounds. The process thereby avoids the possibility of having large discontinuities in risk which, of course, upsets the engineers. I can summarize the weaknesses by noting that when risk levels substantially below the one percent level are involved, the data base cannot be adequately stretched. Secondly, there is in this decade an increasing realization from strong motion seismology and the theoretical modelling of earthquakes that peak acceleration is not a sufficiently stable parameter on which to define zoning.

Recent Developments

Unfortunately from my viewpoint the 1970 approach was so welcomed by engineers that by 1975 engineering pressure succeeded in replacing the static factors R in the Code by a fixed acceleration for each of the four zones. A muted warning was added to the Code that much greater peak accelerations can be expected than the equivalent assumed accelerations but there is a serious hidden danger in the step taken. The higher predicted acceleration values in some key urban areas of Canada may be successively undervalued in design until an urban tragedy occurs. This engineering decision neglects the weaknesses of the method, and indeed there are now strong pressures to use the formal map contours directly in design, a procedure which appears to me to be scientifically

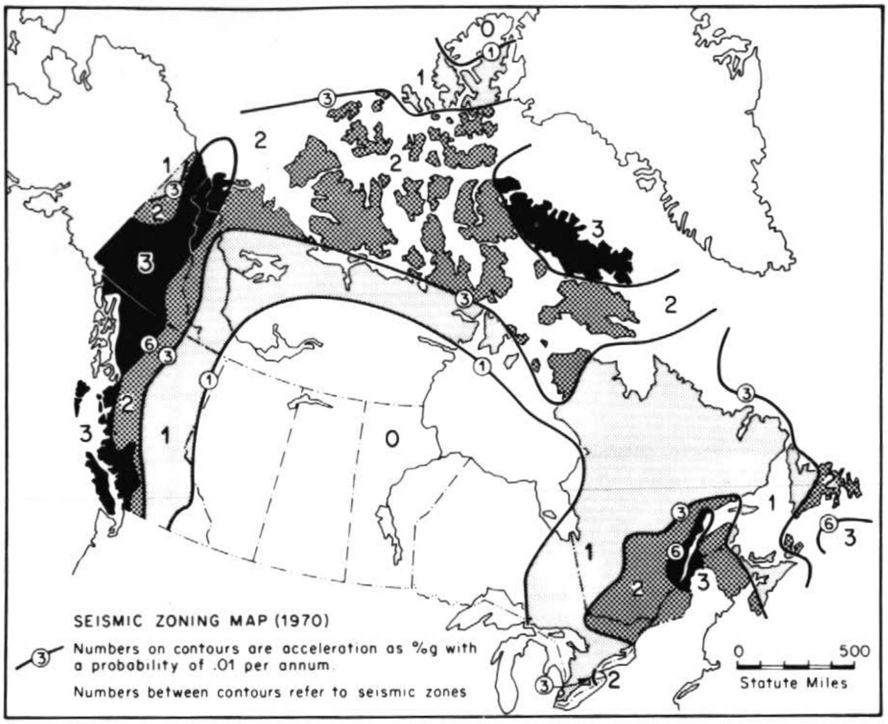

Figure 2
The seismic zoning map for Canada 1970 (after Whitham et al., *1970).*

most unwise. What this would signify is that in a young large country without a unifying tectonic framework more precise estimates of seismic risk can be made than anywhere in the world including Southern California with its well mapped Quaternary fault systems. My colleagues and I hope that a more realistic approach will be taken by the user engineering community.

In our view further progress for NBC purposes depends upon revising the strong motion relationships in the construction of the seismic zones and upon adding information on peak velocity probability estimates. Such a major re-examination of the problem is underway by Milne and other seismologists.

Seismic Risk Estimation for Critical Structures

An alternative procedure which we are recommending to the Atomic Energy Control Board for critical structures such as nuclear power plants is to produce for the designer the best possible time history of the strongest ground motion which can be expected during the life time of the critical structure. This involves a series of approximations, the first step of which is the specification of design earthquakes. We believe that design earthquakes can be specified for different risk levels or for different degrees or types of structural response. For example for nuclear power plants, an operating design earthquake will be specified together with a safe shutdown design earthquake. The latter is of course larger than the former and corresponds to a more conservative risk approach. The zones of earthquake occurrence will need to be defined using a variety of tectonic hypotheses, and then, using all the available data, estimates will be required of the occurrence rates of the significant earthquakes of the zone. The most severe earthquake or earthquakes that can be expected to produce the most severe ground motion at the site will need to be specified, and such earthquake or earthquakes may need to be assumed to occur at the location in the zone that is nearest to the site or at the minimum geophysically-reasonable focal depth, if the zone contains a site. We have been studying the relationship of this approach to that in the NBC if a lower risk level or a lower probability of exceedence were to be adopted in the NBC approach. It is interesting but rather disconcerting to realize that at very low risk levels the formal available mathematical models become increasingly inconsistent and we can demonstrate this by some comparatively simple approximations. In other words our conclusion at the present stage of this study is that if we are faced with a nuclear power plant design to accept the cumulative risk of five percent or less, say, over the life time of the plant of, say, 50 years, then the design earthquake method appears to be far more stable than peak acceleration calculations. The reason for this is that the peak accelerations are being extrapolated beyond their range of scientific validity.

Strong Motion Seismology

Once the design earthquake is specified it is then necessary to define the peak ground motions and here some statistical observations from strong motion seismology guided by earthquake modelling can be used. Our information nowadays is much more reliable than even a decade ago prior to the San Fernando earthquake. We now have strong motion records available from California from earthquakes with a magnitude slightly greater than three to a magnitude slightly less than eight, but the data base is heavily weighted to earthquakes between magnitudes five and seven. This has a consequence in deriving the best empirical relationships, and unfortunately there are no strong motion records available for earthquakes with magnitude greater than seven at epicentral distances less than 50 km. In Canada there have been only three earthquakes from which strong motion records have been obtained and these are all in western Canada. Even today we do not have an actual strong motion record from an eastern Canadian earthquake and this is a severe limitation to the optimum economic structural design of critical structures.

We have been examining the very many expressions which relate peak ground motion to hypocentral distance and magnitude, and we now believe that we have better expressions of the relationships than heretofore. In particular in the far field, that is at distances from the fault greater than several fault lengths, we are fairly confident of new empirical relationships connecting peak ground acceleration with magnitude and distance that agree reasonably well with actual data. The extrapolation of theoretical predicted results to the near field i.e., to distances within a fault length, does however still result in widely diverging theoretical values. We believe that there is fairly good evidence for an upper limit to peak ground motions at magnitude of about 7.5. The existence of such a peak value is a very important consideration in the very low risk design of critical structures. We also believe that there is very good evidence that the maximum ground velocity that can be obtained in the near field of large earthquakes is in the range of 150 to 200 cm per second.

Response Spectra

Some recent theoretical work by Hasegawa is proving extremely useful in providing guidance to engineers on the response spectra required by them in structural design. A seismologist cannot interpret a response spectrum directly in terms of seismic parameters because the response spectrum essentially tells how a damped oscillator responds to the time history of ground motion. Theoretically it can be shown, however, that the undamped velocity response of a single degree of freedom oscillator can be related to ground motion. In other words there is a relationship between the Fourier amplitude of the ground acceleration and the undamped oscillator response. For this reason Hasegawa has constructed a large number of theoretical Fourier spectrum curves for a variety of earthquake sources, using as a basic expression the far field displacement function in Savage's model of earthquakes. These theoretical curves have been compared with actual curves from strong motion records derived in California and in many cases a close fit between the theoretical and actual curves can be obtained. A well known record often used in design is the El Centro record of the Imperial Valley earthquake of 1940, a magnitude 7 earthquake. Hasegawa can obtain a marvelously good fit to this record (Fig. 3). However if there are important surface wave contributions because of low velocity surficial sediments and for a particularly shallow focal depth for an earthquake, there is a deterioration in the goodness of fit between the actual and Fourier spectrum curves particularly at longer periods. At the present stage of these investigations we believe that the theoretical curves are likely to be a lower limit to the actual curves, because of these contributions from surface waves and because of contributions from complex crustal reverberations and from scattering. We can, however, explain theoretically why the main features of the actual Fourier spectrum curves show three general straight line trends when plotted on a log-log basis.

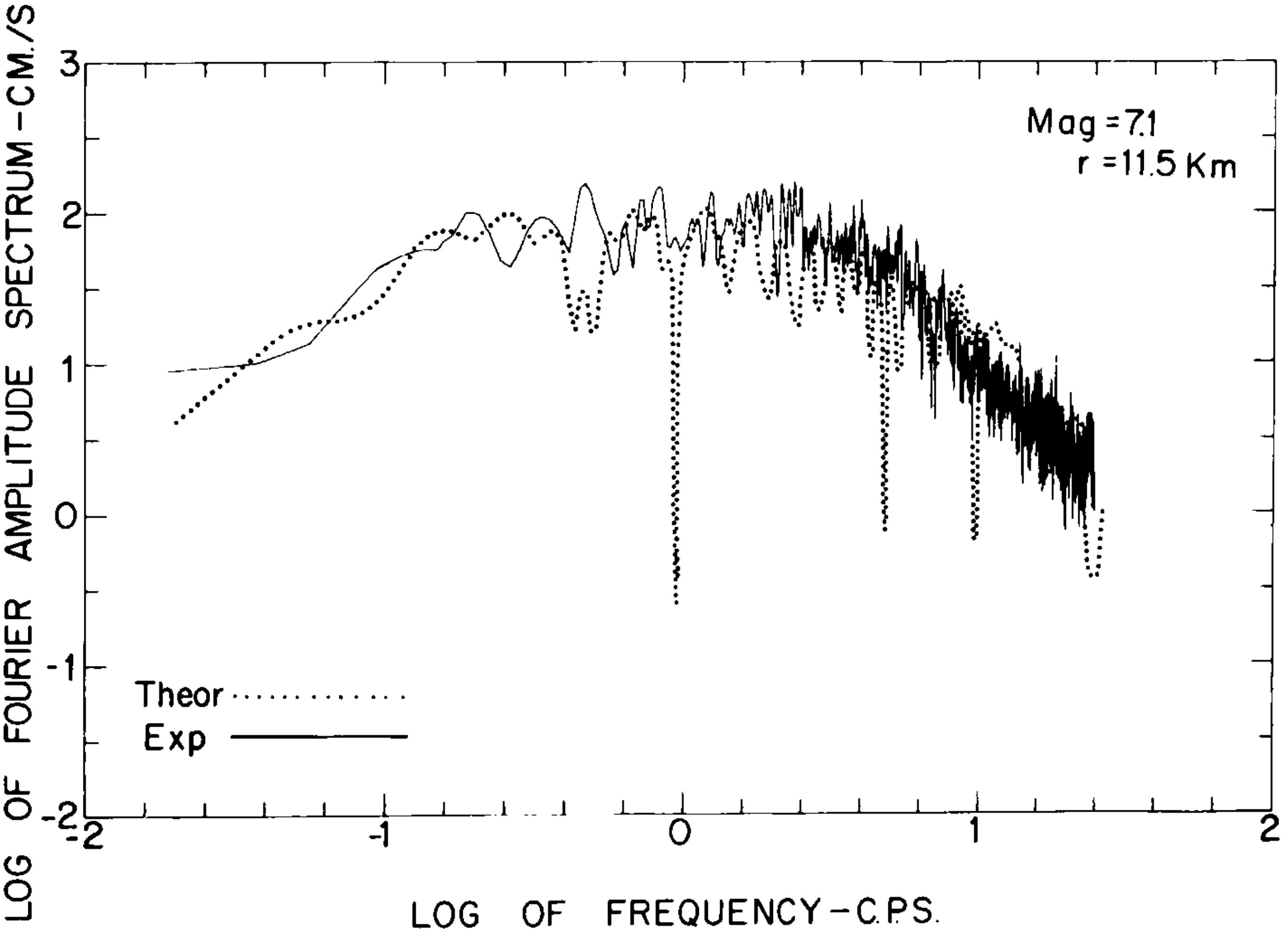

Figure 3
Illustration of a close fit between a theoretical Fourier amplitude spectrum and an experimental spectrum obtained at El Centro for the Imperial Valley earthquake of May 18, 1940. The epicentral distance was 11.5 km from a magnitude 7.1 earthquake (after Hasegawa, 1974)

In this way it now appears possible to consider how best to modify California strong motion data to suit Canadian conditions, and in particular to suit eastern Canadian conditions. This is very important if one looks into the way that structural design actually occurs in practice. In practice engineers adopt an average response spectrum, sometimes without adequate consideration as to whether the average they are using is representative of local conditions and sometimes without any idea as to what geophysical factors have contributed to that particular average. The average is represented by several straight line bounds and is obtained from multiplying the peak ground motion bounds.

An important elementary point which has only recently become clear is that the averages used by engineers are essentially arbitrary averages which mix data that depend upon magnitude, distance and site conditions in a manner that is often chosen more or less arbitrarily by the engineer suggesting the particular average.

As geophysicists we should perhaps recall that the techniques used of linking the average design spectrum uniquely to a peak ground acceleration are strictly speaking invalid (Fig. 4). Despite the common engineering assumption, there can be no unique smoothed response spectrum for a specified peak acceleration level.

It is now becoming clearer how the influence of soils enters the problem: in a very general way the influence of soft soil can be represented by a shift of the corner frequencies of the peak ground motion bounds to lower frequencies by a factor of up to about two. This corresponds physically to soft soils amplifying low frequencies and to soft soil attenuation reducing the high frequencies. With this picture it is possible to look at the recommendations made in the National Codes, and there may be some inconsistencies developing in the commentaries regarding dynamic recommendations in connection with the NBC.

In addition to the influence of the site conditions on the predominant periods of the ground motion and thus the amplitude of the seismic forces, ground failure can occur in earthquakes due to local liquefaction of sands, remoulding of sensitive clays, landslides or fault displacements.

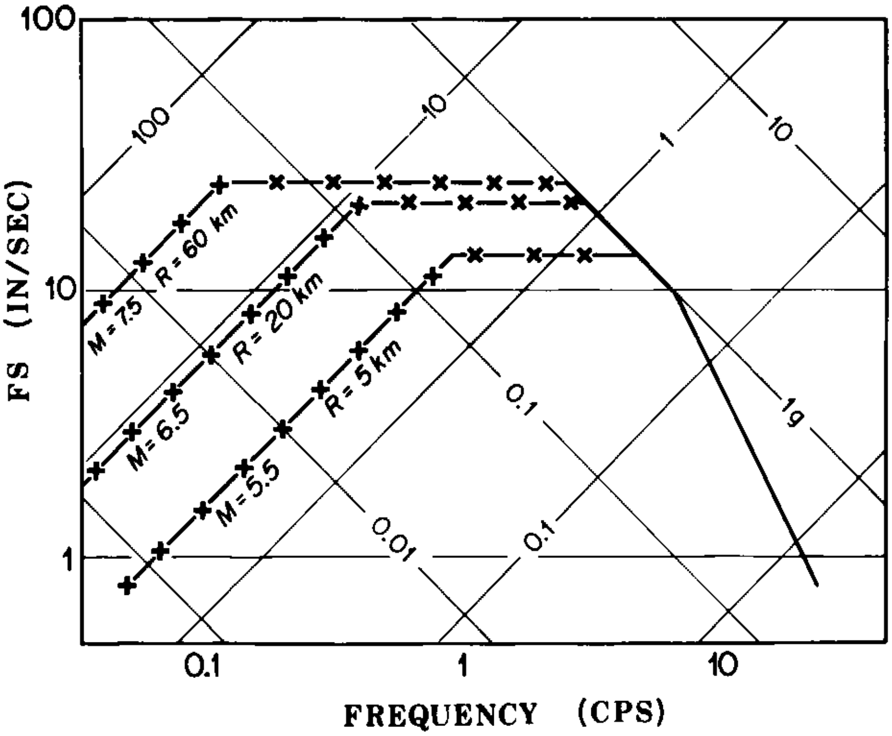

Figure 4
Three Fourier spectrum curves are illustrated for three earthquakes with magnitude 5.5 to 7.5 at epicentral distances from 5 to 60 km. In this schematic diagram, each spectrum has the same acceleration-flat portion, but elsewhere the spectra differ greatly.

Conclusions

Our first conclusion is that seismic risk estimates for almost any purpose in Canada are predictions of one kind or another whose reliability in both space and time are severely hampered by the lack of an adequate tectonic framework.

Secondly, we are concerned whether our historical data on earthquakes are adequate for the expression of seismic risk in the present national codes. We believe that if the present national code formulation is up-dated with completely revised strong motion expressions and all available seismic data, it represents a good way to proceed for practical code purposes, but we do wish that the users would understand better the relative instability of peak acceleration as an expression of risk, and the approximations and limitations involved in the method.

Thirdly we believe that for critical structures considerable geophysical judgment is required in the estimation of design earthquakes. We prefer an approach of this kind introducing tectonics into the problem to one that is purely a mathematical extrapolation of the national code technique to return periods of many hundreds or thousands of years. We think we can demonstrate that the design earthquake approach is not only much more realistic but also scientifically much more valid.

Fourthly, we believe there has been considerable progress in understanding the nature of average response spectra and it is possible to first order to understand why the different response spectra recommended by different engineers have significantly different corner frequencies, which depend upon the selection criteria used by the originator of the average. This means that scientifically valid geophysical guidance in the selection of an appropriate average response spectrum is becoming increasingly possible.

Finally we realize that public acceptance is necessary to support the incremental costs involved in protection against earthquakes in Canada. The support of the public requires an education process without resort to exaggeration or over reaction.

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