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THE ESTIMATION OF SEISMIC RISK IN CANADA – A REVIEW

K. WHITHAM and H.S. HASEGAWA

Abstract. Progress and problems in the estimation of seismic risk in Canada are reviewed, with some emphasis on the uncertainties in the different approaches which have been tried. There is no adequate neotectonic framework for Canadian seismicity generally, and this is the key factor which is inhibiting more accurate delineation and expression of seismic risk in national codes. However, some progress in understanding the tectonic framework is being made, particularly in western Canada.

The present national building code formulation of seismic risk needs to be updated with better seismic strong motion information: the range of validity of any expressions used should not be exceeded, and users should beware over-simplification and understatement of error. In particular users should understand that the expression of seismic risk by exceedance estimates of one (or even two) simple peak motion parameters is physically a gross approximation.

Risk formulation for specific sites for critical structures can be made more conservatively than for the national building code within a very approximate tectonic framework: an approach using design earthquakes is necessary. In general it can be shown that the results cannot be compared at very low risk levels with calculations based on extrapolation of the national building code method. This is because the statistical extreme value model is being extended beyond its range of validity. Geophysical judgments cannot be avoided in the design earthquake approach and some, at least, of these are essentially non-quantifiable.

Some progress is being made in understanding the seismological factors that enter into the time history of ground motion as seen in strong motion records. Better strong motion empirical deterministic and statistical relationships are known now than in the past, and the Fourier spectrum approach is suggesting ways in which the average response spectrum approach can best be modified to suit local conditions. Much remains to be accomplished including the comparison of theoretical predictions of eastern Canadian strong motion data with actual data, once it is acquired. Once again, the users of an average response spectrum approach to design need to understand how the average adopted depends upon the selection criteria adopted by the spectrum proponent.

Résumé. L'auteur passe en revue les progrès réalisés et les problèmes rencontrés dans l'évaluation du risque sismique au Canada, en insistant sur les incertitudes qui subsistent dans les diverses approches tentées jusqu'à maintenant. On peut dire, d'une façon générale, qu'aucun modèle néotectonique ne rend compte de la sismicité du Canada, et c'est la raison principale qui nous empêche de délimiter et de formuler plus précisément le risque sismique dans nos codes nationaux. Cependant, l'étude du bâti tectonique progresse de plus en plus, notamment dans l'Ouest canadien.

Il est nécessaire de mettre à jour la formulation actuelle du risque sismique dans le code national du bâtiment en y incluant des renseignements plus précis sur les secousses fortes: il ne faut pas sortir du domaine de validité des formules utilisées, et ceux qui les utilisent doivent se garder de trop simplifier leurs calculs et de sous-estimer les erreurs probables. En particulier, ils doivent comprendre qu'exprimer le risque sismique en évaluant les dépassements d'un paramètre (voire de deux) d'un mouvement correspondant à un seul pic, constitue, en pratique, une aproximation grossière.

La formulation du risque sismique propre aux emplacements de structures toutes spéciales, peut se faire de façon plus prudente que par le code national du bâtiment, si l'on a une bonne approximation des conditions tectoniques: mais il faut faire appel aux méthodes du génie des tremblements de terre. En général, on peut démontrer que, pour un risque sismique faible, les résultats ne peuvent être comparés à ceux des calculs basés sur une extrapolation de la méthode utilisée dans le code national du bâtiment. En effet, le modèle de l'extrémum statistique est alors utilisé au-delà de ses limites de validité. Dans l'approche par les méthodes du génie des tremblements de terre, on ne peut éviter de porter des jugements de valeur en matière de géophysique et il est presqu'impossible de formuler quantitativement certains de ces jugements.

Certains progrès ont été accomplis dans l'étude des facteurs sismologiques compris dans la séquence chronologique des mouvements de la croûte terrestre, facteurs notés lors de secousses fortes. En ce qui concerne les secousses fortes, nous avons une meilleure connaissance empirique qu'autrefois des relations de cause à effet et des relations statistiques qui les régissent; quand on a adopté l'approche par les spectres de Fourier, on s'est aperçu que l'on pouvait, de plusieurs façons, modifier la méthode des spectres de réponse moyenne pour l'adapter le mieux possible aux conditions locales. Mais il reste beaucoup à faire; entre autres, il faut comparer les révisions théoriques relatives aux données sur les secousses fortes dans l'Est du Canada avec les données réelles, après qu'on les aura obtenues. Encore une fois, ceux qui utilisent la méthode des spectres de réponse moyenne, appliquée à l'architecture, doivent comprendre de quelle façon la moyenne adoptée dépend des critères de sélection choisis par celui qui propose un spectre.

I. Introduction

The estimation of seismic risk is fundamentally the problem of the prediction of future ground motions, or their causative earthquakes. Thus seismic risk estimation requires considerable scientific judgment, there is no unique best solution on a national scale and seismologists should attempt to estimate the reliability and probability associated with projecting past data into the future.

Major difficulties arise in Canada from the variety of tectonic environments, most of which are only poorly understood, from the comparatively short period and sparseness of human settlement in Canada which severely limit historical contributions, from a shortage of strong-motion instrumental data and from a growing realization and understanding, which parallels that developing elsewhere, of the difficulties and challenges in formulating seismic risk in a manner which engineers can usefully use. Yet this must be done in a manner which is scientifically valid and which allows expression of the possible margin of error.

The purpose of this review is to examine critically some past formulations of seismic risk in Canada, to suggest ways of improvement, to point out weaknesses in present practices and recommendations and to illustrate the complex problem facing the seismologist trying to formulate his advice in a manner which can directly assist the engineer and yet remain scientifically accurate. It is hoped that the review will assist in improved understanding by engineers of the seismic risk estimation problem and its uncertainties.

2. The Canadian scene

It is convenient to outline and discuss seismic risk requirements in Canada in two general classes.

2.1 General construction

The earthquake-resistant design requirements of the National Building Code (NBC) of Canada provide *minimum* standards which, if legally adopted, assure an acceptable level of public safety by designing to prevent major failure and loss of life. Structures designed in accordance with its earthquake load provisions should resist moderate earthquakes without significant damage and major earthquakes without collapse, although with some structural damage.

Seismic risk inputs into such a code are usually expressed on a national scale by the use of one or more imperfect seismological expressions, such as

... strain release maps

... epicentral location maps

... seismic zoning maps derived from some hypothesis or other.

In Canada, the earthquake loading provisions of NBC 1970 depend upon a seismic zoning map constructed on the basis of exceedance calculations of peak horizontal ground acceleration. Its strengths and weaknesses will be outlined later. From a purely engineering viewpoint, this approach to a revised seismic zoning map has apparently been so successful that in NBC 1975, seismologically inexact approximations have been introduced for future engineering convenience. The authors regret this.

2.2 Critical structures

The view of the authors is that such critical structures as nuclear power plants (where the perception exists that the consequences of a misjudgment can be catastrophic in terms of, for example, the release of radioactivity), future hot-oil pipelines or other major energy facilities (which society cannot replace if supply is interrupted without widespread economic disruption and suffering) require a different approach in seismic risk estimation. More site-specific or route-dependent studies are required to estimate earthquake hazard better, and/or a more conservative risk calculation should be made. We believe that society is willing to pay more for such protection than in the more general NBC case. From social indicators, it appears that society in general is willing to pay more to guard against the very small risk of a greater catastrophe than the somewhat larger everyday risk of a lesser catastrophe (as expressed, e.g., in the earthquake risk for and construction practices in Victoria).

Another reason for additional prudence with such structures as nuclear power plants is our lack of working experience of many plants over many decades, whereas in general construction, there is now a body of empirical experience from Caracas, Anchorage, San Fernando and elsewhere which gives some field experience on how the theoretical design of high-rise and other structures works out during economically important earthquakes.

2.3 Involvement of the general public

For both general and specific cases, imperfect seismological and tectonic information must be converted to a code whose application to the design of specific structures carries with it a subsequent economic penalty, the magnitude of which, for a given seismic risk level, depends upon the state-of-art of earthquake engineering.

In the authors' view, such judgments regarding risk, which are now more usually engineering and commercial judgments, need to involve further not only the seismologists and geologists but also interested and informed members of the general public. This seems self-evident to us if a local electorate is to urge and support the municipal or provincial adoption of the NBC, or if local groups are to accept such developments as nuclear power plants, without protest.

From a series of ad-hoc steps, progress has now been made in examining the seismic risk problem systematically in Canada for those critical structures which fall under the licensing authority of the Atomic Energy Control Board. Although final decisions remain to be taken, it is encouraging that AECB has consulted with earth scientists and inter-alia is developing a safety philosophy that a much more conservative approach is needed for such critical structures than can be justified in Canadian experience for NBC.

Such considerations relate to the degree of concern and awareness expressed by the general public. In California where public awareness fluctuates but is generally much higher than in Canada, the legal Seismic Safety Element provides the opportunity for public determination of levels of acceptable risk to be used as a framework for modification of building codes to meet local conditions (in particular, modification involving the banding of zones parallel to the strike of local faults and gross effects of site conditions).

However, even in California a balanced view is essential. Fewer than 2000 lives have been lost due to earthquakes in the United States in the past 200 years. This loss is very small compared to the great death tolls from many single earthquakes in such countries as Peru, Morocco, Turkey, Iran, China and Japan. Furthermore, loss of life from other hazards must be considered when discussing earthquake risks. As an example, the one-year loss of life resulting from murders in Los Angeles county in 1974 was over 1600, and in California alone 4500 lives are lost each year as a result of motor accidents. Deaths from hurricane, tornado, flood and fire exceed deaths caused by earthquakes in the western developed world.

In summary therefore, the problems of earthquakes and seismic safety must be kept in perspective: society needs to equate hazards and problems and order them in a rational context. Even with the short-comings in building codes, the U.S., and even more Canada, still has a very good record related to damage and loss of life in earthquakes.

The dangers of exaggeration are real. Again California leads the way. In 1968-69, many people in California prepared for a doomsday when California would slip into the Pacific Ocean. The news media contributed to the excesses and rumour had it Howard Hughes purchased land in Nevada which was going to become the shoreline or the beach area of the new Pacific Ocean. Even the west coast of Canada was not free from some elements of hysteria over a possibility which is so completely unsupported scientifically. As earth scientists we must avoid any ill-judged opinions which could contribute to irrational mass or local hysteria.

3. Earthquake risk in Canada and tectonics

Earthquakes do occur in Canada with sufficient frequency and intensity to be of concern.

The Division of Seismology and Geothermal Studies of the Earth Physics Branch determines the epicentre and magnitude of some 200 to 300 earthquakes annually which occur in Canada. In general instrumental coverage today in Canada is complete to magnitudes less than or equal to M4 in all parts of Canada. In certain developed areas where denser seismograph networks have been installed, there is a greater than 90 per cent probability of locating earthquakes down to M3 or less. Detection without accurate location is possible to even lower magnitude levels with currently deployed networks.

On the average 14 per cent of the earthquakes located are in eastern Canada, 27 per cent in western Canada and 59 per cent in the north with only very occasional central region earthquakes. Currently an average of some 10-20 Canadian earthquakes annually excite public and media interest, usually by being widely felt, but the number is quite variable. The current seismicity file in the Division indicates external, media, public or governmental enquiries on some 24 Canadian earthquakes in the period November 1974 to April 1975.

In the last 75 years, some six major earthquakes with magnitude > 7 have occurred, two in eastern Canada, one in the Arctic and three in western Canada: in addition, a great earthquake with magnitude 8 occurred in the Queen Charlotte Islands. Although major damage in eastern Canada was last reported from the Cornwall earthquake of 1944 (M5.9), minor damage from earthquakes is more frequent, the last example being at Woburn, Quebec in 1973 with some 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 (M7.3).

Bearing in mind the San Fernando earthquake of 1971 (M_L6.4, 58 deaths and more than half a billion dollars of damage), it should be noted that in the last 50 years, there has been on the average one earthquake each decade with magnitude greater than 6 in eastern Canada and two each decade with magnitude greater than 6.5 in western Canada. Whitham and Milne (1972) have summarized recently the available information of this kind. The north including transportation routes for pipelines cannot be forgotten in this era of major energy developments. Widespread seismicity is found throughout the Arctic, with concentrations in the Yukon-lower Mackenzie Valley and on- and off-shore Baffin Island. A magnitude 6.5 earthquake or greater occurs on the average each five years. Recently much smaller earthquakes in the Sverdrup Basin have interfered with deep drilling exploration activity on King Christian Island.

Figure 1 shows a computer plotted map of all epicentres in the Canadian earthquake files. Coverage has been arbitrarily extended to latitude 40°N in the U.S. and in other regions surrounding Canada. Some 6000 earthquakes are plotted: in eastern Canada historical coverage back to 1534 exists from the work of the late W.E.T. Smith (1962, 1966), in western Canada to 1841 from the work of Milne (1955) and in northern Canada to 1899 from the work of Meidler (1962).

The purpose of this paper is not to discuss the tectonic implications of Canadian seismicity, but a few brief summary observations are required to illustrate

(a) the difference from southern California, for example, where a clear relationship between earthquakes and the surface expression of their causative faults is clear

(b) the potential geophysical richness of Canadian seismicity with its intrinsic capability of providing a means to make quantitative studies of neotectonics – both within plates and at the interaction of plate boundaries. Indeed in the eastern Arctic we may be experiencing the situation at the dying stage of previously active plate interactions

(c) our relative ignorance. Thus in eastern Canada, the Woburn earthquake of 1973 has provided the first satisfactory focal mechanism solution (Wetmiller, 1975), and even in western Canada, such information, unequivocally determined, is comparatively rare (Chandra, 1974; Rogers, 1975) and there can be disagreement on key earthquakes and the selection of preferred focal planes. Similar uncertainties exist over focal depths in Canada, and it is the exception rather than the rule that reliable focal depths can be determined without close-in temporary observing seismograph networks.

There has been considerable controversy concerning tectonic patterns in eastern Canada with some authors connecting the St. Lawrence Valley zone through the Great Lakes down into the United States through Ohio, Indiana, Illinois and 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 cluster of activity northeast of Quebec City. The data are scattered, and interpretation involves arguments about the best location of a 1638 earthquake and the evidence for a seismicity gap between the two trends mentioned above. Other alternative alignments can be suggested, but there is not enough evidence to choose between these possibilities.

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 framework provides an intellectual framework for many of the significant earthquakes, but even here unresolved problems arise. Earth-

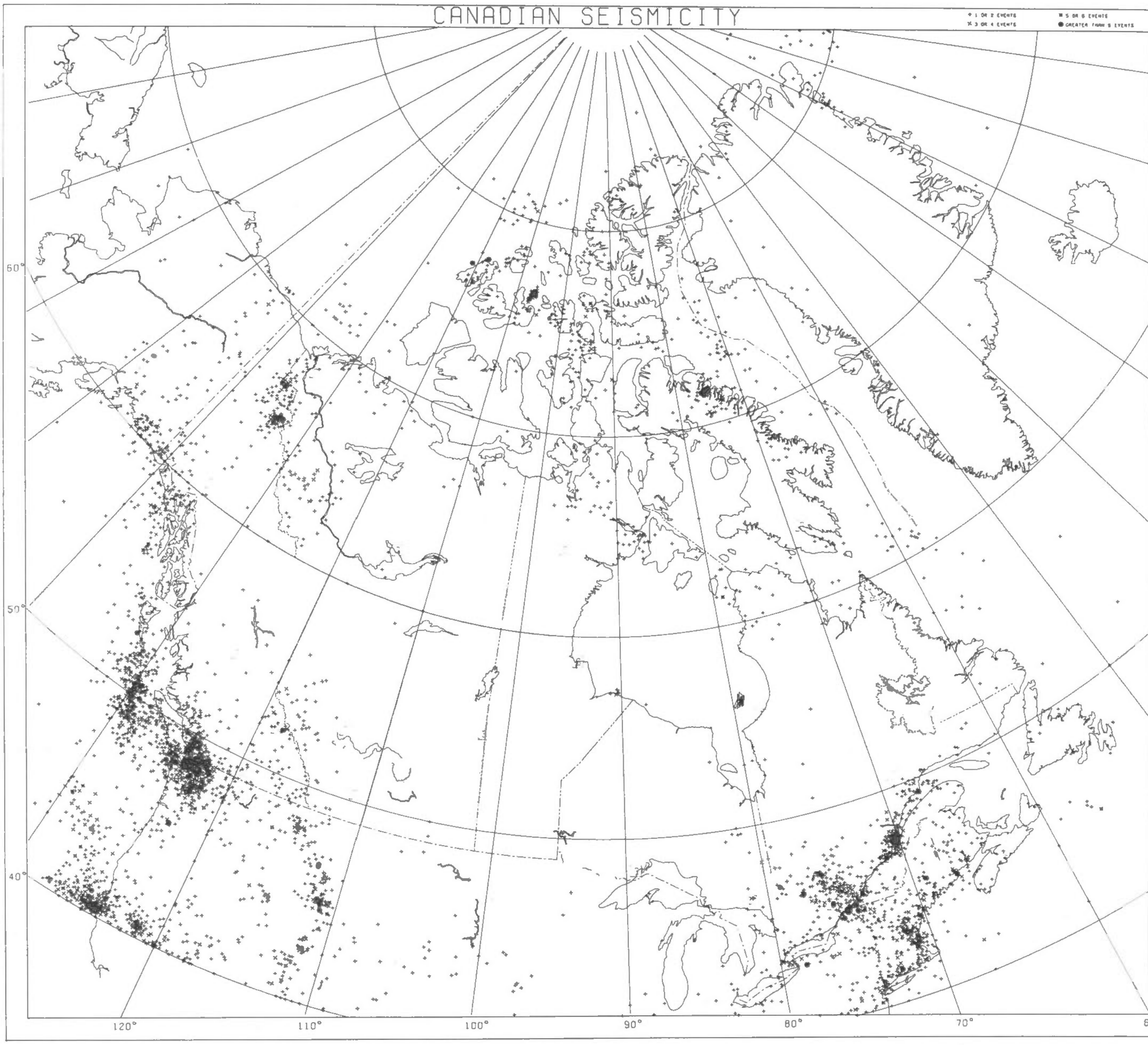


Figure 1. Computer plotted map of all epicentres in the Canadian earthquake files (extended to latitude 40°N in the U.S.A. and other regions surrounding Canada).

quakes occur in large numbers on southern Vancouver Island and on the adjacent continental margin and no geological features can be related to these. Rogers (1975) has examined the question based on an m_b 5.8 earthquake near the west coast of Vancouver Island in 1972. For this earthquake intensive studies have suggested that well defined pressure and tension axes do not follow the deductions from Cenozoic geology. This earthquake might better be considered as an intraplate event rather than one that represents interaction at a plate boundary: alternatively it may help define the northern plate boundary of the Juan de Fuca plate (with left lateral strike-slip motion). In any case complications in the generally accepted plate tectonic framework are necessary to explain the significant numbers of earthquakes on southern Vancouver Island, in Georgia Strait and in Puget Sound, where major damaging earthquakes occur producing substantial earthquake risk to the major cities of British Columbia, not dissimilar from that at Seattle.

In 1946, a damaging earthquake at the north end of Georgia Strait had magnitude M7.3; in 1965 an M6.7 earthquake at deeper than normal focal depth caused moderate damage in Seattle and Tacoma, killed two people and injured many more. Moderate earthquakes occur inland in western Canada: the M7.5 earthquake of 1872 is one of the largest with an inland epicentre and whose tectonic explanation is unknown.

In the Arctic, our information is even more limited but again a harvest of hypotheses arise on examining an epicentre map. Leblanc and Hasegawa (1974) have discussed the tectonic framework and earthquake risk in the northern Yukon and Mackenzie Valley, Wetmiller (personal communication) has discussed the situation in Baffin Bay and onshore Baffin Island. Basham and Forsyth (private communication) are studying other seismicity trends such as that along Wager Bay to Queen Maud Gulf, that along the Boothia peninsula, trends across strike of the Sverdrup Basin and others.

As for the prairies, occasional earthquakes in southern Saskatchewan continue to excite intense but passing interest. For a review of the tectonic framework see the discussion on the Bengough earthquake by Horner, Stevens and Hasegawa (1973).

4. The expression of seismic risk

4.1 The seismic probability map for Canada, 1952

When the first edition of the National Building Code was being prepared in 1953, it was decided to include provisions for earthquake risk. The map was based on a 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 and major damage. The map (Figure 2) was based on a knowledge of the larger earthquakes in and near Canada and general tectonic considerations on the possible regional extent of earthquake zones. Its limitations were well described by its author Hodgson (1956).

Engineers were not very happy with this map. The method of preparation resulted in gross discontinuities (e.g. zone 3 to zone 0) across zone boundaries: furthermore the map placed both Montreal and Ottawa, as well as Quebec City, in the zone of highest risk which was not accepted by many of the potential map users.

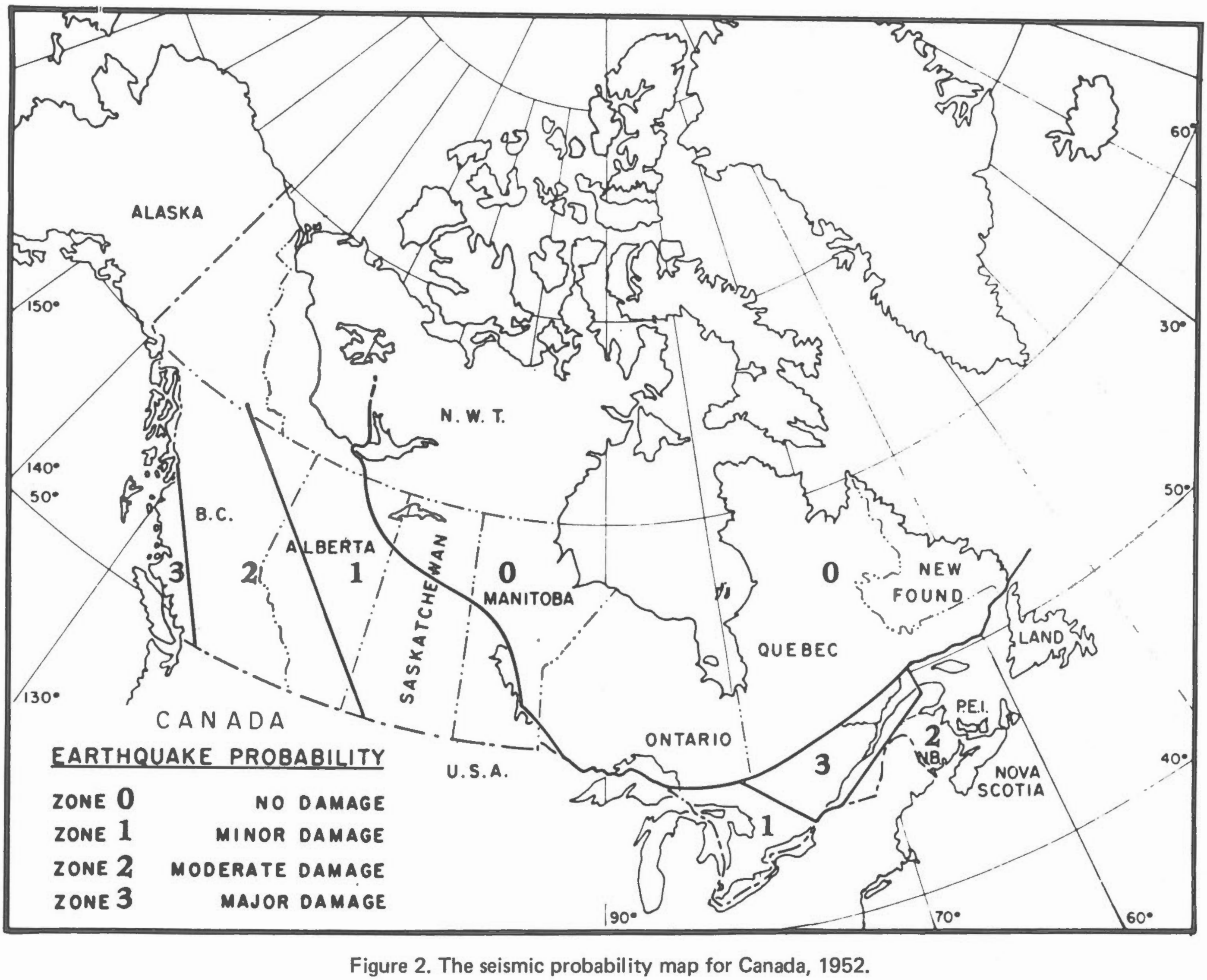


Figure 2. The seismic probability map for Canada, 1952.

The heart of the problem was that such a map made no numerical and convincing attempt to introduce even a semi-quantitative estimate of the probability of occurrence of the damage associated with a particular zone.

Clearly better methods were required and for these more seismic data were necessary.

4.2 Strain energy release maps

Milne (1967) has published strain energy release maps for Canada. They require an adequate knowledge of earthquake history including reliable estimates of earthquake energy release. Problems with such maps are

(a) the presentation is in a form which cannot be used directly by design engineers in earthquake engineering: further assumptions are then necessary to produce a code document

(b) the presentation can only reflect an imperfect knowledge of earthquake history. Fortunately the maps are insensitive to the lack of historical information on lower magnitude earthquakes. However the lack of uniformity in Canadian earthquake history limits regional inter-comparisons

(c) the limited data must be contoured. Without doubt subjective judgments on tectonic trends can be introduced in the process of contour closing. This is not necessarily a disadvantage

(d) depending upon the time history and the nature of the stress release, there is always the possibility that such maps can give a partially reversed picture of future seismic energy release

(e) there is considerable uncertainty in energy-magnitude relationships, which can approach an order of magnitude.

Among different merits of such maps are

(a) the ability to introduce tectonic guides into the contouring where these are available and understood

(b) the automatic smoothing nature of the process. Such smoothing on a suitable scale helps to define areas of historical seismic risk which can provide a prediction for the future, without risking the more local anti-correlation outlined in (d) above.

Nevertheless a better representation of seismic risk was sought; one more attuned to specific engineering needs.

4.3 Earthquake epicentre maps

Such maps are published annually in the Seismological Series of the Earth Physics Branch, and cumulative maps for different intervals and for different magnitude ranges have been widely used for many geophysical and tectonic purposes.

Problems with such presentations for representing seismic risk are

(a) the presentation is in a form which cannot be used directly by design engineers or in a national code: further assumptions are necessary for a code document

(b) the maps can be misleading to non-seismologists unless there is a very clear understanding of the time interval, the range of magnitudes plotted, the different symbols, if any, for them, and the accuracy of epicentral and magnitude determination. Indeed if stress in some areas is fully relieved, such maps may run the risk of giving a partial anticorrelation on a very local basis with immediate future risk. It seems clear that the time element in the available epicentral and magnitude data, and the time interval of importance in the prediction for the future are tangible factors which enter into the expression of seismic risk and the application of earthquake epicentre maps to the problem.

Advantages of epicentral maps such as that in Figure 1 are

(a) such presentations, at least of current instrumental data, are presentations of fact: the accuracy of the parameters involved can usually be determined sufficiently well, although some argument still remains about the best way of expressing the magnitudes of eastern Canadian earthquakes, and focal depth is often comparatively poorly defined

(b) the maps, of course, have a tremendous use in developing and testing tectonic models, and in many geophysical areas of activity. Although as outlined above general tectonic correlations are possible, at least offshore in western Canada, in eastern Canada the not surprising result emerges that there is no obvious unique correlation between the position of faults in eastern Canada and earthquake epicentres

(c) the maps for different time intervals contain spatially distributed data which allow for research in the distribution in space and time of seismicity. For example, Kelleher and Savino (1975) have investigated the distribution of seismicity before large strike-slip and thrust-type earthquakes. The Queen Charlotte Islands-Fairweather fault zone is a dextral transform fault connecting the Juan de Fuca ridge with the northeast end of the Aleutian system: since 1927 seven large earthquakes with magnitude >7 have ruptured almost the entire fault zone. These authors believe that the seismic evidence demonstrates that as the time approached of the main Queen Charlotte Island shock of August 1949, the future zone of rupture was quiet except for a number of shocks near the future location of the epicentre.

Although it is still difficult in the authors' view to obtain convincing hypotheses of spatial and time dependence, such maps illustrate clearly that even in the one region of Canada where tectonic control is best understood, the nature of the seismicity along the transform fault is distinctly non-uniform. Indeed there is evidence for a general relationship between the spatially varying nature of seismicity and the distance from a spreading centre. Geophysical models would suggest that this is not surprising.

The result of Smith (1967) on space and time relationships of eastern Canadian earthquakes should be noted. After concluding that surface faults were of no use in predicting the location of significant future earthquakes, he examined the history of the region and ten earthquakes which he considered would, with today's development, be the most damaging if repeated today. He concluded that

(i) earthquakes must be expected in areas where they are known to have occurred both in the last decades and in the last few hundred years ... thus six out of the ten earthquakes occurred in the general area 100 miles below Quebec City and in a time frame extending from 1663 to 1925

(ii) the remaining four occurred at widely separated points from the Grand Banks to approximately 200 miles north of Toronto at Temiskaming in 1935. There appears to be no clear tectonic link or single hypothesis which covers all the events

(iii) the smallest earthquake of the ten actually did the most physical damage – this was the earthquake with M5.9 at Cornwall in 1944.

We conclude that no uniformly acceptable deterministic as distinct from probabilistic manner of introducing space and time inter-relationships is yet possible in Canada in a national code.

4.4 The estimate of peak acceleration probabilities

The problems outlined above suggest that for NBC purposes, the time element must be built into the expression of seismic risk. Furthermore the extensive engineering criticism of major discontinuities in the earlier seismic zoning map were valid, although these arose from an attempt to introduce tectonic control on imperfect data. Furthermore it is desirable to avoid local anticorrelation of risk for a limited time period with immediate past history. With considerations such as this in mind Milne and Davenport (1969) developed a seismic zoning map based upon calculating and contouring the peak acceleration amplitude throughout Canada with an average annual probability of 1 per cent that it would be exceeded (a_{100} values). This map is shown in Figure 3. The method thus calculates peak acceleration estimates on firm ground probabilistically at sites, using as input

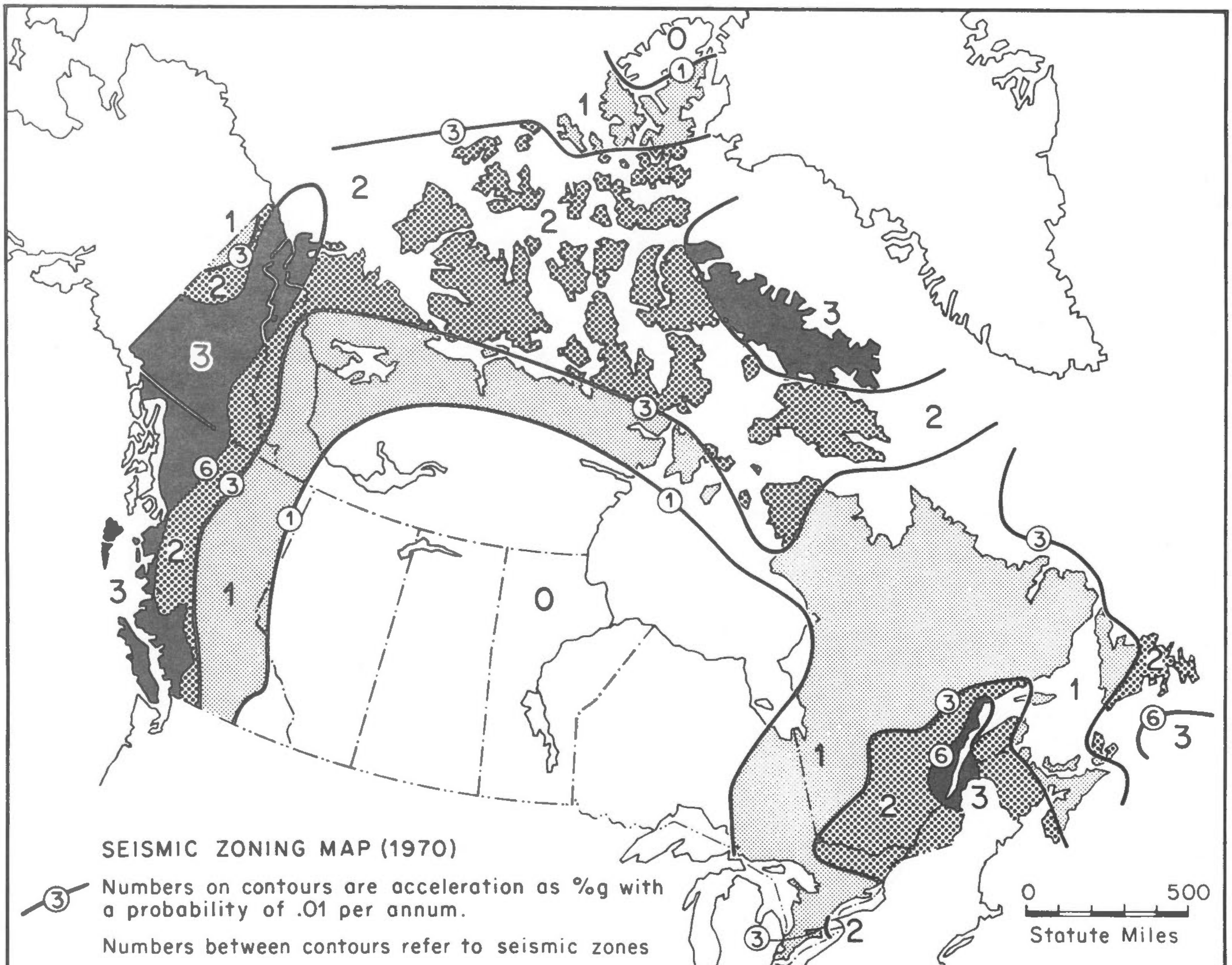


Figure 3. The seismic zoning map for Canada, 1970.

(1) the available quantitative earthquake history of Canada i.e. all instrumental data from 1899 onwards

(2) intensity – magnitude – distance information in eastern Canada derived from macroseismic investigations of five earthquakes with magnitudes between 5.8 and 7.2, plus peak acceleration – maximum intensity information synthesized from Californian experience

(3) peak acceleration – magnitude – distance information in California assumed from very limited experimental data to be applicable to western Canada.

The seismic zoning map NBC 1970 was obtained by contouring a_{100} values. Seismic zones and R factors for loading were selected as follows:

Limits	*Zone*	*Classical Zone Descriptor (without reference to time)*	*R-factor*
$0 \leqslant a_{100} < 1\%g$	0	Zero damage	0
$1\%g \leqslant a_{100} < 3\%g$	1	Minor damage	1
$3\%g \leqslant a_{100} < 6\%g$	2	Moderate damage	2
$6\%g \leqslant a_{100}$	3	Major damage	4

Actually Milne and Davenport describe two methods. In the first method the peak amplitudes for any site for each year are selected from the computed data set, and are ranked and plotted

$$\log_e a_m \text{ against } -\log_e\left[-\log_e\left(\frac{m}{N+1}\right)\right]$$

where N is number of years of data and a_m is the value of the m^{th} largest amplitude (starting at m = 1 weakest).

This is equivalent to

$$\log_e a = \log_e C - \frac{1}{\alpha}\log_e[-\log_e p] \text{ where}$$

a is the amplitude with an annual probability (1−p) that it will be equalled or exceeded. A least squares estimate can be made of $\log_e C$ and $\frac{1}{\alpha}$, from which a_{100} values can be calculated.

The alternate method is as follows. If N (a) is the average number of shocks p.a. in which the shock amplitude exceeds a at the site of interest

$$\log_e a = \log_e C - \frac{1}{\alpha}\log_e[N(a)]$$

and once again $\log_e C$ and $\frac{1}{\alpha}$ can be calculated from a data set.

The first or extreme value method was adopted in the construction of the seismic zoning map of Figure 3. It is not immediately clear why NBC 1970 adopted the annual extreme alternative: hindsight suggests that arguments at the time on the effects of data incompleteness due to the historical distribution in number and sensitivity of seismograph stations in or near Canada were probably not so cogent as once thought. Fortunately the two methods give much the same answer.

Several advantages of this approach are to be noted

(1) essentially it predicts probabilities of peak accelerations from historical data, thereby providing directly a design parameter which engineers can use in calculating static base shears

(2) the process inherently smooths and integrates the effect of different earthquakes in earthquake zones. In this way it should avoid serious possibility of anticorrelation between historical seismicity and predicted risk

(3) the process skilfully avoids the seismological problem of defining on tectonic grounds an earthquake zone and then wrestling with the problem of whether the largest conceivable earthquake should be allowed to have its epicentre anywhere in the zone for seismic risk estimates, i.e. it avoids the process which produces large discontinuities in risk

(4) using the work of Smith (1962, 1966) it is possible to check results obtained in eastern Canada from instrument records (post 1899) against the entire historical record from 1638. Remarkably similar acceleration prediction results are obtained for post-1638 and post-1899 by both techniques described by Milne and Davenport.

Comment is required on the adoption of a return period of 100 years in NBC 1970. This appears to be initially rationalized from a comparison by Ferahian (1970) of wind and earthquake loads in NBC 1970: the a_{100} zoning adopted is regarded as giving approximately the same likelihood of structural collapse for cities in zone 3 as the 30-year return wind speed employed elsewhere in the NBC. Later Whitham (1972) suggested very approximate cost benefit arguments which indicated that the zone assignments outlined above in terms of ranges for a_{100} provided a reasonable compromise between excessive conservatism and cost, and too weak precautions in NBC.

Criticisms and weaknesses of these methods are as follows:

(1) The assumptions made in the development of the calculations tend to be glossed over: when risk calculations at the level of 1 per cent, 0.1 per cent or lower are involved, the data base generally in Canada is being considerably stretched and we have to worry whether the limited time history available justifies the use of the statistical model. In particular the method does not allow a tectonic assumption to be made that significant earthquakes will occur in locations not sampled by the available historical record. Fortunately, to date, the limited tests which can be made suggest that a few tens of years of data fit the statistical model and calculations for return periods of 100 years or so have statistical justification and a precision at any site which can be statistically defined.

(2) There is a problem that an arbitrary cut-off is required at the small end of the acceleration range: otherwise predicted peak accelerations can be exaggerated.

(3) The influence of focal depth is ignored.

(4) Although the process adopted implies that a sense of time duration of strong ground motion is inherent in the eastern Canadian calculations through the use of intensity, this is not true for western Canada.

(5) Perhaps most important is the increasing realization in this decade from strong motion seismology and theoretical modelling of earthquakes that peak acceleration is not a stable parameter on which to define zoning and that peak acceleration may not be the optimum single parameter which best correlates with intensity. This will be considered further in Section 7.

(6) As distinct from formal precision in calculation and goodness of fit, geophysical arguments on uncertainties in magnitudes and the other real uncertainties in the process suggest that the 1 per cent per annum peak accelerations are in general uncertain by a factor of about two.

4.5 Seismic risk estimation for future NBC editions

It should be clear from Section 4.4 above that the 1970 NBC earthquake load provision introduced for the first time (albeit imperfectly) an explicit numerical concept of risk, and at the same time, to the engineers' joy, reduced the zone discontinuities.

By NBC 1975, engineering pressures succeeded in replacing the static factors R by a fixed acceleration for each of the four zones: 0, 2, 4 and 8 per cent g equivalent is used, with a muted warning that much greater peak accelerations can be expected at the 1 per cent annual exceedance level in zone 3.

The authors regret this step on several grounds

(1) there is a serious danger that the higher predicted acceleration values in some key urban areas of Canada in zone 3 will be successively undervalued, until an urban tragedy occurs

(2) these frequent changes suggest to the engineering community an accuracy in the prediction of such numbers which is quite unreal. As explained earlier many factors involving the completeness of the data base, its representativeness for future projections on different scales, and other strong motion seismology relationships affect the accuracy

(3) engineering over-simplification is leading to pressures to create more zones, or indeed use formal map contours. This appears to be scientifically most unwise: indeed such a decision would infer that a young, large country without a unifying tectonic framework could make more precise estimates of seismic risk than anywhere else in the world (including southern California with its well mapped active Quaternary fault system). The authors hope that a more realistic approach will be taken by the engineering community.

(4) it appears to sustain the false impression that strong ground motion is well characterized by peak acceleration, which reinforces the reluctance, noted by the authors, of many engineers and others to accept the seismological fact that strong ground motion is characterized by various parameters, of which peak acceleration is only one. Some of these parameters are not too stable in a statistical sense, and have a large dispersion which makes them less than ideal for predicting and specifying future ground motion. It is now clear with information obtained very largely since NBC 1970 was prepared that peak acceleration is such a relatively unstable parameter.

It therefore appears to the authors that further progress depends upon adding information on peak velocity probability estimates, re-examining macroseismic data in different areas of Canada, reconsidering the functional dependence of acceleration on hypocentral distance and magnitude in different areas of Canada taking into account geophysical differences, and again re-examining the possibility of introducing tectonic controls. Such a re-examination of the problem is underway in the Division of Seismology and Geothermal Studies, Earth Physics Branch, EMR: until the results of such a re-examination are available and have been subjected to responsible scientific review and criticism, the authors believe that suggestions to further subdivide an essentially unstable parameter should be shelved.

4.6 Design earthquake specification

For critical structures such as nuclear power plants, the designer requires for purposes of adequate and predictable dynamic analysis, a time history of the strongest ground motion with a low probability of exceedance at the site during the lifetime of the critical structure. This can usually only be provided in a series of approximations which involve as a first step specifying design earthquakes. Design earthquakes can be specified for different risk levels or for different types or degrees of structural response. For example, for a nuclear power plant in the United States, an "operating" design earthquake is often specified, together with a "safe shut-down" design earthquake. The latter is of course larger than the former, and corresponds to a more conservative risk approach. In Canada, consideration is being given to defining the "design seismic ground motion" as the maximum effects from an ensemble of "design earthquakes" appropriately placed within their "zones of earthquake occurrence" and which would produce safe shut-down, and the "operational seismic ground motion" as the ground motion that the plant must withstand in a fully operational state.

In Canada, EMR geophysicists are working with the Canadian Nuclear Association, AECL and AECB to study how best to formulate a code of seismic design requirements for Canadian nuclear power plants. It seems clear that zones of earthquake occurrence will need to be defined using a variety of tectonic hypotheses. Unfortunately the seismic risk in eastern Canada can easily be seen to vary formally with the size of the zone of occurrence, and there can be no alternative to bringing some unquantifiable tectonic judgment into the estimate. Then using all the available data, estimates will be required of the recurrence rate of the significant earthquakes of each zone. The severe earthquake or earthquakes for each zone of earthquake occurrence, with associated estimates of probability of exceedance will need to be specified. 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 or hypocentral distance, if the zone contains the site.

Ideally the design seismic ground motion should be specified in as many different forms as is possible, e.g. by maximum acceleration, velocity and displacement with their appropriate frequency ranges, the duration of strong seismic motion over the appropriate frequency range, by actual or representative ground motion spectra or actual or representative accelerograms. Further discussion of this problem of specifying spectral information for different areas of Canada will follow in Section 6. Needless to say it is a difficult problem where all concerned, particularly the regulatory body, feel a need to adopt some defensible but realistic criteria which can be quantitatively expressed as a risk.

It is interesting but disconcerting to realize that at very low risk levels, the formal available mathematical models may well become increasingly inconsistent. Some elementary approximations can illustrate this.

In the extreme value method, at a site let a_{T1} and a_{T2} be the predicted peak maxima for a probability of exceedance in any one year of $\frac{1}{T1}$ and $\frac{1}{T2}$ respectively (i.e. T1 and T2 are the respective return periods). Then it is easy to show that for $\frac{1}{T} \ll 1$, to a good approximation

$$\frac{a_{T2}}{a_{T1}} = \left(\frac{T2}{T1}\right)^{+\frac{1}{\alpha}}$$

In general in Canada $+\frac{1}{\alpha}$ appears to be equal to 1 ±0.3 and therefore $\frac{a_{T2}}{a_{T1}} \simeq \frac{T2}{T1}$

It is immediately clear, ignoring the real problem of the stability of a_T, that if a cumulative risk of 5 per cent (say) over the 50-year life time (say) of a plant is accepted for the design seismic ground motion, then T2 = 1000 years and predicted accelerations could equal up to ten times the NBC values of a_{100}. This is absurd for the higher risk areas of Canada, and indicates that the model under these circumstances is being extrapolated beyond its range of scientific validity – not perhaps a surprising result in view of the instability problem to be described in Section 6 and with only 70 years of incomplete historical data. Obviously tectonic judgment will have to overrule a formal model. It should be noted in passing that the zone of earthquake occurrence approach indicates more reasonable extrapolation to lower risk levels: thus extrapolation of the maximum earthquake from (say) 100 years to (say) 1000 years, generally is thought to correspond to a design earthquake of about 1 magnitude unit larger: at short epicentral distances this corresponds to factors of about 2 to 3 times higher peak accelerations, which appears geophysically more reasonable and makes more engineering sense.

In summary much remains to be done to define the appropriate zones of earthquake occurrence and to examine critically the available data. Then the design earthquakes must be used to scale complete spectral information from reasonable earthquake models if strong motion data for the region are not available.

The problem is of course minimized by a choice of sites in quiet earthquake areas: in the future this may become increasingly difficult to ensure in both Canada and the U.S. Furthermore spectral information expressed differently requires consideration of both the body wave magnitude m_b and the surface wave magnitude M_s of the design earthquakes. Nuttli (1973) has suggested that for the difficult New Madrid faulted zone of the central U.S. a design earthquake with m_b 7.2, M_s 7.5 appears reasonable in terms of about a 500-year return period. As will be seen later, this effectively requires design against virtually the maximum possible peak ground motions.

5. Strong motion seismology and peak ground motions

5.1 Available strong motion records

Earthquake engineers and seismologists interested in strong motion seismology in Canada use as their data base the extensive collection of strong seismic ground motion records and associated Fourier amplitude and response spectra compiled by the Earthquake Engineering Research Laboratory (EERL), California Institute of Technology. This recourse to predominantly Californian strong-motion seismograph data is required because of insufficient Canadian strong-motion data. Only a few strong ground motions have been recorded for several earthquakes originating along or adjacent to the Pacific Coast belt of British Columbia. But, so far, no strong motion records have been obtained for other active seismic regions in Canada where strong motion seismograph instruments have been deployed, such as the St. Lawrence valley. This is a most important limitation since macroseismic investigations have clearly demonstrated for many years the much greater felt areas of eastern Canadian earthquakes of any given magnitude than for corresponding magnitude California and western Canadian earthquakes.

Prior to the San Fernando earthquake of February 9, 1971, most of the strong motion records in the EERL volumes could be associated with shallow (<20 km), vertical strike-slip earthquakes. The San Fernando event was a low-angle thrust fault. For vertical strike-slip faults, most of the energy in the near field is in the form of SH waves, for which the particle motion is in the transverse horizontal direction. There is also energy in the P and SV waves, which contribute to the vertical component. For a low-angle thrust fault, most of the near field energy would also be in the form of SH waves, supplemented by P and SV waves. At greater distances from the causative fault, surface waves (Love and Rayleigh) waves tend to predominate over body (SH, P and SV) waves. For shallow focal depths and travel paths for which there are low velocity unconsolidated layers near the surface, higher mode surface waves can be an important contributor to the strong motion signal. Thus the fundamental records or accelerograms, that form the North American data base are generally for shallow focus earthquakes of the vertical strike-slip fault type and the near-surface geology consists of an appreciable thickness of alluvium. In some Canadian areas, the focal depths are greater, the fault plane orientations are often different and not yet understood in a systematic way and therefore may appear to be random, and there is a different geologic environment. Then differences can be expected in the corresponding accelerograms.

The range of earthquake magnitudes (M) over which strong ground motion records have been obtained vary from a magnitude slightly greater than three to a magnitude slightly less than eight. However, most of the records are for magnitudes between five and seven, and this has a consequence in deriving empirical relationships. For magnitudes greater than seven, there are only three events for which there are strong motion records and, moreover, for these earthquakes there are no records at epicentral distances less than 50 km. Information on peak ground accelerations for magnitudes less than five are tabulated in the annual United States Earthquakes publication by NOAA/Environmental Date Service/Dept. of Commerce.

5.2 Peak ground motions

Using strong ground motions from earthquakes (and in one instance from underground nuclear explosions) as a data base, seismologists and design engineers have evaluated empirical relations and/or graphs expressing peak ground motion (acceleration, velocity and displacement) as a function of earthquake magnitude and hypocentral (from fault to accelerograph) distance. For magnitudes between five and seven, for which the data base is most complete, the minimum epicentral distance for which the empirical relations can be considered to be reliable can be taken to be of the order of 10 km. However, there are exceptional cases, (e.g., the Parkfield earthquake of June 27, 1966) for which records have been obtained within 1 km of the surface expression of the fault. Figures 4 and 5 illustrate the variability or scatter in theoretically predicted maximum ground acceleration close to the fault for two extremes of earthquake magnitude, Figure 4 for a magnitude 7.7 earthquake with focal depth 16 km and Figure 5 for a magnitude 4.7 earthquake at 2 km focal depth. Actual data are superimposed upon the theoretical curves. The wide scatter in the theoretical curves for distances within a fault length of the source indicate the necessity of using extreme caution where applying these theoretical formulae at short epicentral distances. As epicentral distance from the fault increases, the long period end of the body wave amplitude spectrum tends to correlate with seismic moment, which in turn is related to the surface wave magnitude, M_s. At intermediate frequencies (near 1Hz) the body wave amplitude spectrum tends to correlate with body wave magnitude m_b. At high frequencies on the other hand, the relation between body wave amplitude spectrum and source parameters (magnitude; seismic moment) is uncertain because of the intrinsic difficulty in separating the contribution of the source from that of travel path complexities (geometric spreading, attenuation and scattering). In spite of the uncertainty, in the "far-field" (distances from the fault greater than several fault lengths) empirical relations connecting ground acceleration with magnitude and distance predict values that agree reasonably well with the actual data. However, the extrapolation of theoretically predicted results to the "near-field" (within a fault length) results in widely divergent values. This large scatter in theoretical values is due, primarily, to two factors: the data base used in deriving the empirical relations and to a preconceived notion as to what trend the sparse data in the near field is indicating.

For epicentral distances within about one fault length of a large magnitude (>7) earthquake, there is an increasing tendency among strong motion seismologists to put an upper limit to peak ground motions at a magnitude of about 7.5. Theoretical curves of peak accelerations versus epicentral distance flatten at short epicentral distances because focal depth tends to predominate over epicentral distance; the "hypocentral" (focus to detector) distance governs peak ground motion amplitude and near the source, hypocentral distance changes very slowly for focal depths of the order of 20 km or more, whereas epicentral distance goes to zero.

The physical basis for postulating an upper limit to peak ground motion near the source is that the dislocation time function is the governing parameter close to the source, whereas at greater distances it is, effectively, magnitude and distance. Since peak ground motion near the source seems to be related to peak dislocation or relative offset of the fault faces, there is increasing speculation as to the maximum ground motion parameters possible near very large magnitude earthquakes. Trifunac (personal communication, 1975) suggests that the maximum ground acceleration is about 1.75 g, which can be attained for a magnitude 7.5 earthquake. For larger magnitude earthquakes, if this hypothesis is correct, the maximum ground acceleration cannot exceed this value, and this is crucial in very low risk estimates (see Section 4.6). At the present time, it would appear reasonable to assume that the maximum ground acceleration from earthquakes is in the range 1.5-2.0 g and that the maximum ground velocity is in the range 150-200 cm/sec. Recently, higher values (400 ±150 cm/s) for maximum ground velocity have been proposed by

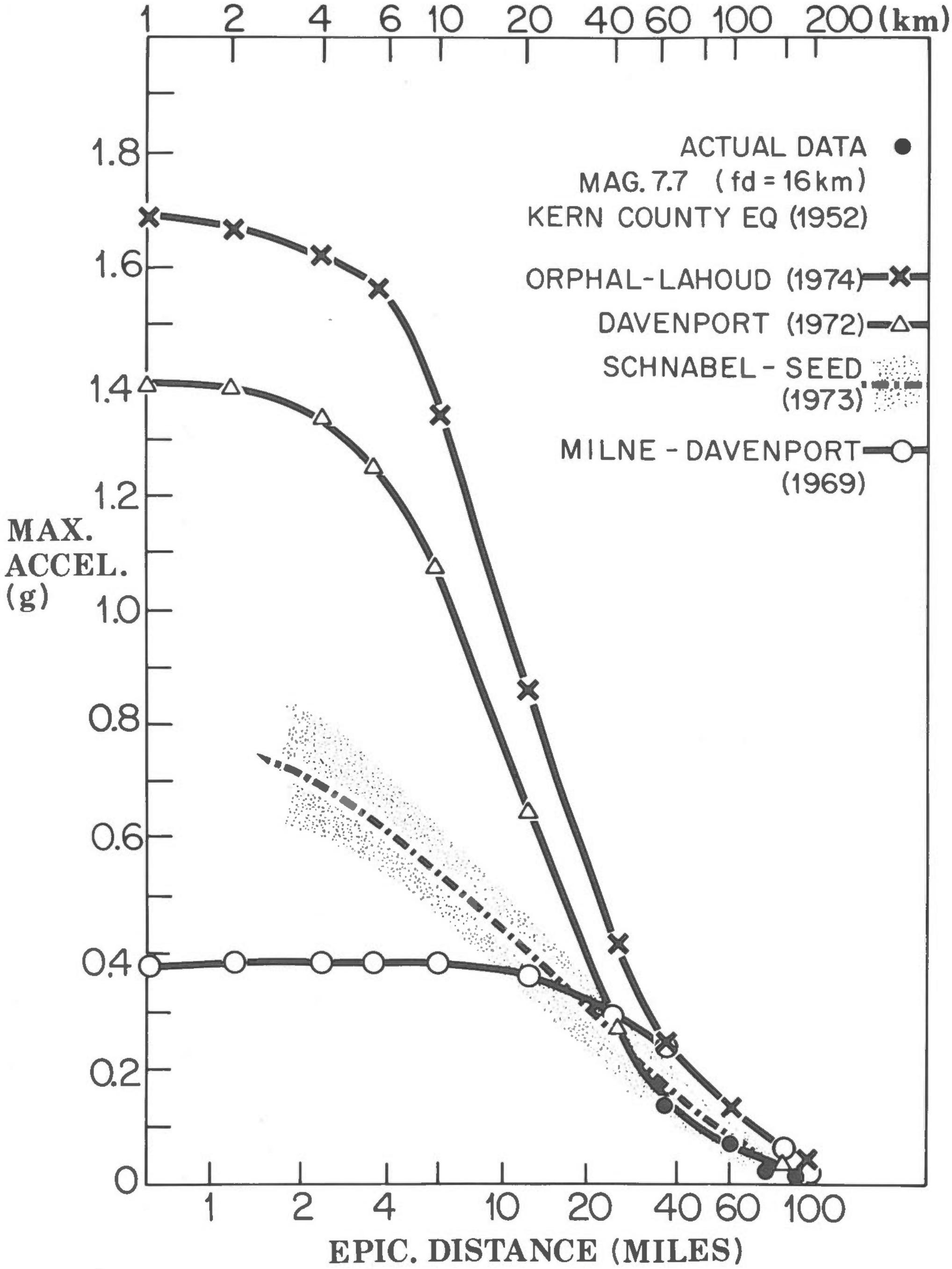


Figure 4. Actual data for the Kern County, California, earthquake of July 21, 1952, superimposed upon theoretically predicted maximum ground accelerations.

Nuttli (1973) for the New Madrid zone in the central United States: Nuttli believes this to be controlled by the stress drop. It should be pointed out that Nuttli's estimates are based on an indirect technique, necessitated because of a lack of strong motion accelerograms. However dynamic ground displacement is difficult to estimate because surface waves can be an important contributor at low frequencies. The maximum recorded transient ground displacement near the source is 43 cm (1971 San Fernando earthquake), but there is currently some doubt about this value because of the filter used. Nuttli (1973) has proposed values as high as 200 ±50 cm for the Design Earthquake for the central U.S. Other earthquake parameters of interest are (i) maximum shear stress drop 100 – – – – 1000 bars (Nuttli, 1973), (ii) maximum (com-

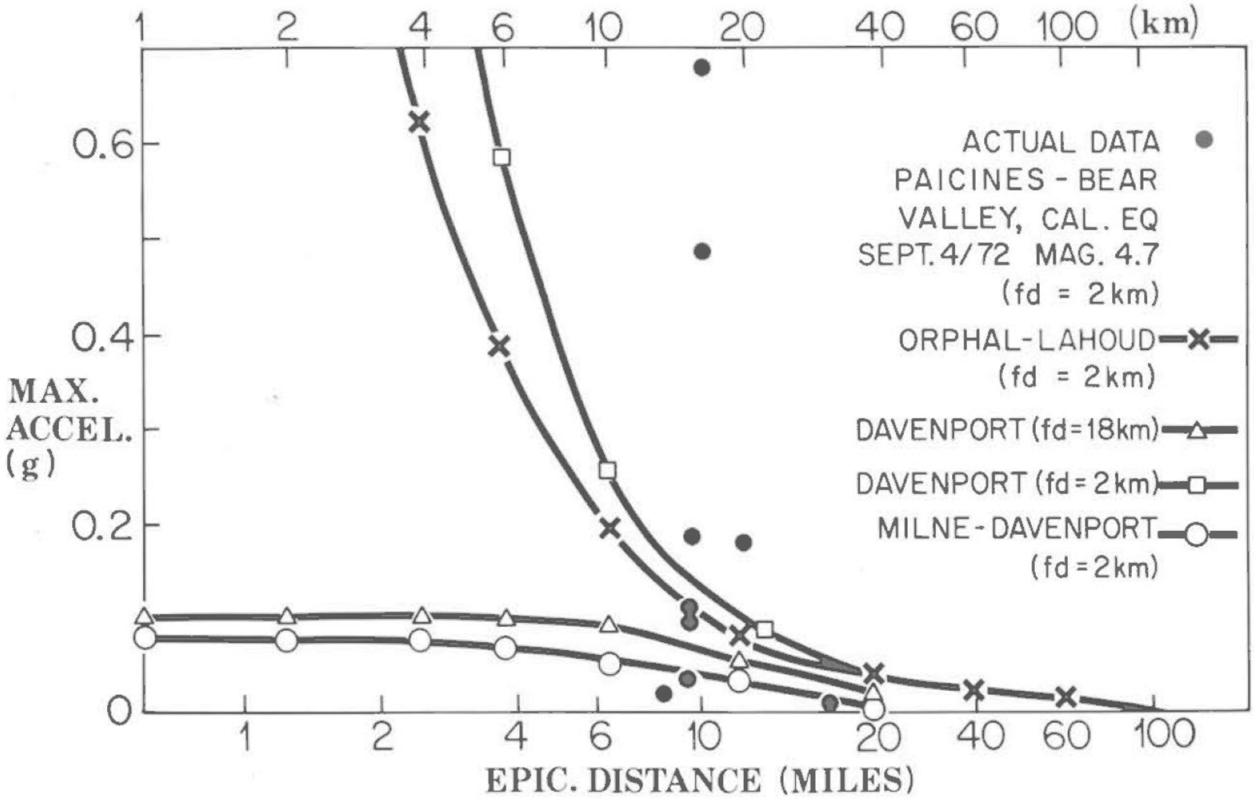


Figure 5. Actual data of the Paicines-Bear Valley, California, earthquake of Sept. 4, 1972, superimposed upon theoretically predicted maximum ground accelerations.

puted) residual dislocation at fault interface 13.3 metres (Alaska 1964; Montana, 1959).

5.3 The significance of peak ground motions

A few comments on maximum ground motion parameters are required since they can very easily be misapplied to a problem. Even today it is not clear which part of the spectrum best correlates with intensity since this depends upon the periods of the structures affected and the time history or duration of strong shaking. It is pertinent to note the following

(1) Peak acceleration values are generally 20-40 per cent larger than neighbouring values (smoothed envelope). This indicates that constructive interference, primarily from travel path effects (scattering, dispersion) can influence the maximum.

(2) The largest value ever recorded for ground acceleration (1.25 g) near an earthquake occurred near the apex of a shallow-angle thrust fault that intersected the surface (Pacoima Dam, San Fernando). Surface waves generated at the apex seem to be the primary contributor to this hitherto surprisingly large value for a magnitude 6.6 event.

(3) Design engineers use as one of their criteria of the destructive effects of an earthquake the "incremental velocity response". This is related to the maximum value of an integral, over a half cycle, of a time history of the velocity response of a damped oscillator.

(4) Sustained levels of smaller acceleration levels are more important than peak accelerations. The duration of these smaller levels can have a more significant effect upon time history response curves than peak levels (Perez, 1973).

(5) The correlation between the frequency content of the dominant portion of the strong ground motion signal and the natural period (or frequency) of the structure is important. In particular, it is the energy in (suitably chosen) pass-bands centred about the natural periods of the structure that are more important contributors to structural response rather than peak energies well removed from these periods.

(6) From (3), (4) and (5) it would appear that the portion of an accelerogram that corresponds to the largest "incremental velocity response" and sustained oscillations in the appropriate frequency range is a more important parameter for

earthquake-resistant design than the peak value. However, it is the difficulty in quantifying by simple parameters these more important, but less obvious measures of ground motion, that so often leads to the utilization of peak values in the earthquake-resistant design of structures. Engineers and strong motion seismologists need to be critically aware of this over-simplification.

5.4 The expression of intensity in terms of simple design parameters

It should be clear that the authors regard intensity as the convolution of the time history of strong motion with the delta function time response of the structures affected. Therefore empirical relations between intensity and peak acceleration will also be relatively unstable: perhaps a somewhat less unstable relationship would be obtained from the substitution of peak velocity which occurs at lower frequencies in such approximate expressions. An engineering intensity scale for earthquakes and other ground motion (e.g. from underground nuclear explosions) has recently been proposed by Blume (1970). A major advantage of this scale is that period identification is incorporated, thereby resulting in a more useful damage estimate. However, instrumental records are required for this technique.

5.5 Empirical relations and strong motion data recommended for use in Canada

In western Canada, Milne (personal communication, 1975) reports that the Orphal-Lahoud relation ($a = 6.6 \times 10^{-2} 10^{0.40M} R^{-1.39}$ in units of g) when slightly modified should be a reasonable approximation at moderate distances. The question arises as to the validity of this expression near the source (within 50 km) of large magnitude (say, 7.7) earthquakes (see Figure 4). In this region the Orphal-Lahoud curve agrees with Trifunac's current estimate of 1.75 g. However, this estimate is likely based on the Pacoima Dam value, which occurred near the apex of a thrust fault that intersected the surface of the ground. In Canada it is believed that causative earthquake faults rarely rupture the surface. Consequently, if we wish to be conservative, then we should perhaps use the Orphal-Lahoud relations near large magnitude events, but reduce any calculated acceleration values greater than 1.75 g to that level. However, if we wish to be less conservative and are interested not in isolated peak values but smaller levels of sustained oscillations, then values closer to those predicted by Schnabel and Seed (1973) (see Figure 4) may be more appropriate. The choice depends upon the type of structure and the "safety margin" required.

Empirical relations connecting intensity with a ground motion parameter for California should be appropriate for western Canada. Some of the common ones are quoted below.

$\log v = -1.14 + 0.30\,I$ — v in cm/sec, I, M.M. scale

$\log a = I/3 - 3.5$ (Richter, 1958) a in units of g

Some suggested recent revisions of these are:

$\log v_v = -1.10 + 0.28\,I$	Trifunac and Brady (1975)
$\log v_H = -0.63 + 0.25\,I$	for $IV \leqslant I \leqslant X$
$\log a = I/4.5 - 2.25$	Davenport (1972)
$\log a_v = -3.09 + 0.3\,I$	Trifunac and Brady (1975)
$\log a_H = -2.90 + 0.3\,I$	for $IV \leqslant I \leqslant X$
$a\,(g) = 6.6 \times 10^{-2} 10^{0.40M} R^{-1.39}$	Orphal and Lahoud (1974)
$v\,(cm/sec) = 7.26 \times 10^{-1} 10^{0.52M} R^{-1.34}$	
$d\,(cm) = 4.71 \times 10^{-2} 10^{0.57M} R^{-1.18}$	

In eastern Canada the sparse and sometimes non-existent data base increases the difficulties. Problems are thought to be analogous to those in the central U.S. where Nuttli has proposed a design earthquake for the New Madrid faulted zone that is based on an extrapolation of surface wave data at distance of 100 km back to source for three discrete frequencies. Peak acceleration values are of the order of San Fernando (Pacoima Dam) values. Peak particle velocities are about 3-4 times maximum San Fernando results and peak particle displacement about 4 times maximum San Fernando values. The authors consider these peak values to be rather extreme, and their suggested derivation open to some argument.

The main area of uncertainty is the character of strong ground motion within 50 km of the epicentre. Within this region the important parameters are magnitude, focal depth, source mechanism (especially dislocation and rupture process) and the attenuation and scattering properties of the near-surface layering. At the present time, it is an unresolved question as to whether it is preferable to extrapolate from available standard seismogram data in eastern Canada to determine strong ground motion parameters near the source than use empirical strong motion accelerogram results derived from (primarily) California earthquakes. Or can we use California results suitably modified for eastern Canada? Housner and Jennings (1973) suggest that it is more appropriate to determine ground motion by direct extrapolation from comparable recorded accelerograms, but this only avoids the problem if future eastern Canadian strong motion records are not comparable with those from California.

The current (1975) set of empirical relations that relate ground motion parameters to magnitude and distance from a causative fault for eastern Canada are shown below (from W.G.

Milne, written communication, 1975). These relations are a combination of actual seismogram data for eastern Canada with actual accelerogram data for western North America (primarily California) and actual seismogram data for western North America incorporated in such a way as to reflect the well-known phenomenon that earthquakes of a specified magnitude are felt to greater distances from the source in eastern than in western Canada. The formulae suggested for eastern Canada are as follows:

(1) $\log_{10} a = \frac{I}{3} - 3.5.$

(2) $I = I_7 - 9.66 - 0.00370\,\Delta + 1.38\,M + 0.000528\,\Delta\,M.$

For $\Delta \leqslant 1210$ km, I_7 is the intensity of a magnitude 7 at the same location (see Figure 8, Milne and Davenport, 1969).

For $\Delta > 1210$ km, $I_7 = (\Delta - 1200) \times (-.00446) + 3.04.$

There are two sets of acceleration versus magnitude and distance empirical relations for eastern Canada but, for a specified magnitude and distance, it is the expression that gives the larger acceleration that is to be used. In the epicentral region the following expression which is similar to that of Orphal and Lahoud (1974), namely

(3) $a = 0.066\,(\exp|0.92M|)\,R^{-1.38}$

gives the larger value. However at greater distances, depending upon magnitude (e.g. for $M = 5$, $\Delta > 300$ km; for $M = 8$, $\Delta > 70$ km), the combination of equations (1) and (2) (Milne and Davenport, 1969) gives the larger value. In the above expression, a is the acceleration in units of g's, I is the Modified Mercalli Intensity, Δ is the epicentral distance in kilometres, R is the hypocentral distance (km), where $R = (h^2 + \Delta^2)^{1/2}$ and h is the focal depth (assumed to have a mean value of 18 km), and M, the magnitude of the earthquake.

6. Response spectra

6.1 The Fourier amplitude spectrum of ground motion

Earthquake engineers are primarily interested in response spectra whereas strong motion seismologists are interested in strong seismic ground vibrations. Seismologists are not able to interpret response spectra directly in terms of seismic parameters because of the damped oscillator response. However, the undamped velocity response of a linear single-degree-of-freedom oscillator can be related to ground motion (e.g. see Trifunac, 1972). Figure 6 shows (in the top part) a schematic diagram of the types of seismic waves radiated from the causative fault and (in the bottom part) the relation between the Fourier amplitude of ground acceleration (FS) and the 0% damped (λ) oscillator response (SV 0%λ).

The published curves of the Fourier amplitude spectra of ground acceleration of earthquakes in EERL (volume IV) are mainly for California earthquakes, for which the faults are generally of the vertical strike-slip type. For this reason theoretical FS curves have been generated for a vertical strike-slip type of earthquake source. The direct horizontal shear (SH) wave is assumed to carry most of the energy up to about 100 km from the fault. The basic expression is the far-field displacement density $|U^s|$ of Savage (1972). FS is related to $|U^s|$ by

$$FS = |U^s|\omega^2 e^{-\alpha R}\, 2$$

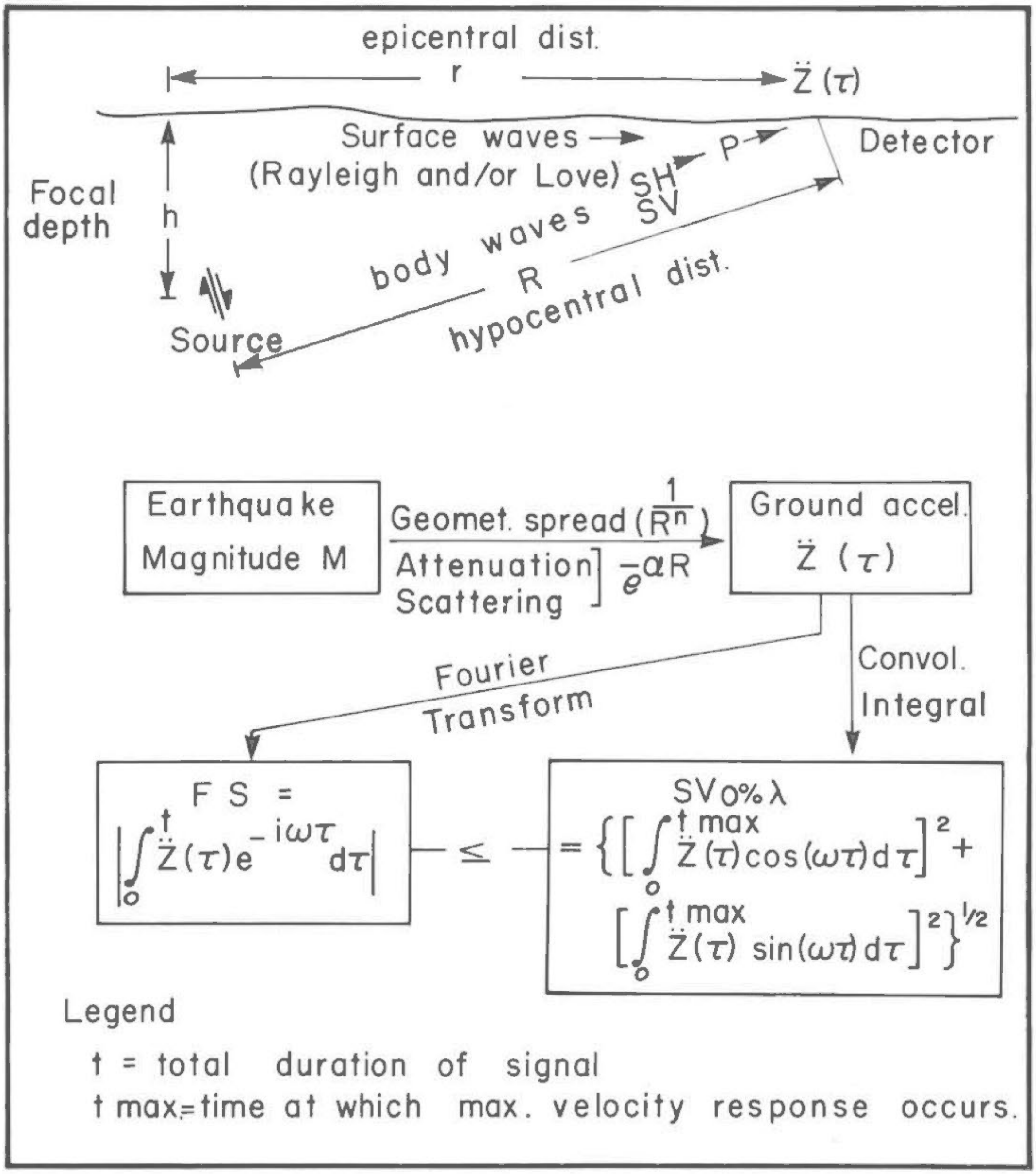
where ω is angular velocity of the wave, α the attenuation coefficient for shear waves and R the total travel path. The ω^2 term converts ground displacement density to ground acceleration density and the factor 2 takes into account the free-surface reflection.

Figure 7, taken from Hasegawa (1974), shows a step-by-step generation of FS from $|U^s|$ for various Q_s values ($\alpha = \frac{\pi f}{Q\beta}$) for the shear wave with velocity β: Q values as low as 20 have been measured in the upper 6 km of the crust in California by Kurita (1975).

Theoretical FS curves have been compared with actual FS curves from the western U.S. by Hasegawa (1974). An example of a close fit between theoretical and actual FS curves is shown in Figure 8, which is for an El Centro record of the Imperial Valley earthquake of May 18, 1940. (M_s 7.1, M_L 6.7, h = 16 km).

An example of a poor fit between theoretical and actual FS curves is shown in Figure 9, which is for the Borrego Mountain earthquake of April 8, 1968 (Mag. 6.5, h = 11 km). Much of the discrepancy between theoretical and actual curves is almost certainly due to the important surface wave contribution because of the low-velocity surficial sediments, and shallow focal depth, both of which increase the neglected surface wave contribution. The surface wave contribution shown is for a granite crust (see Hasegawa, 1974) and consequently, if low-velocity surficial sediments were included in the crustal model, then the theoretically predicted surface wave contribution would be enhanced, thereby resulting in a closer fit between the theoretical and experimental FS curves. A more complex source mechanism than the one assumed is also possible.

A smoothed envelope representing the main features of actual FS curves has three general trends. A more-or-less flat trend at intermediate frequencies (centred around 1 Hz) flanked by asymptotic trends that fall off towards low and high frequencies, i.e. a concave downwards shape. At low frequencies surface waves tend to predominate, especially for shallow focus events. At intermediate frequencies complex crustal reverberations tend to augment the contribution from the direct shear wave; in addition the building response of high-rise structures is quite often manifest in this frequency range (e.g. see FS records of San Fernando earthquake, EERL, Volume IV). At high frequencies the travel path effects, namely attenuation and scattering, tend to predominate over



$$FS = \left| \int_0^t \ddot{Z}(\tau) e^{-i\omega\tau} d\tau \right| \leq SV_{0\%\lambda} = \left\{ \left[\int_0^{t\,max} \ddot{Z}(\tau) \cos(\omega\tau) d\tau \right]^2 + \left[\int_0^{t\,max} \ddot{Z}(\tau) \sin(\omega\tau) d\tau \right]^2 \right\}^{1/2}$$

Figure 6. Top part: schematic diagram of seismic waves radiated from a causative fault. Bottom part: relation between Fourier amplitude spectrum (FS) of ground acceleration and velocity response spectrum (SV) for a damping of 0% critical damping (λ).

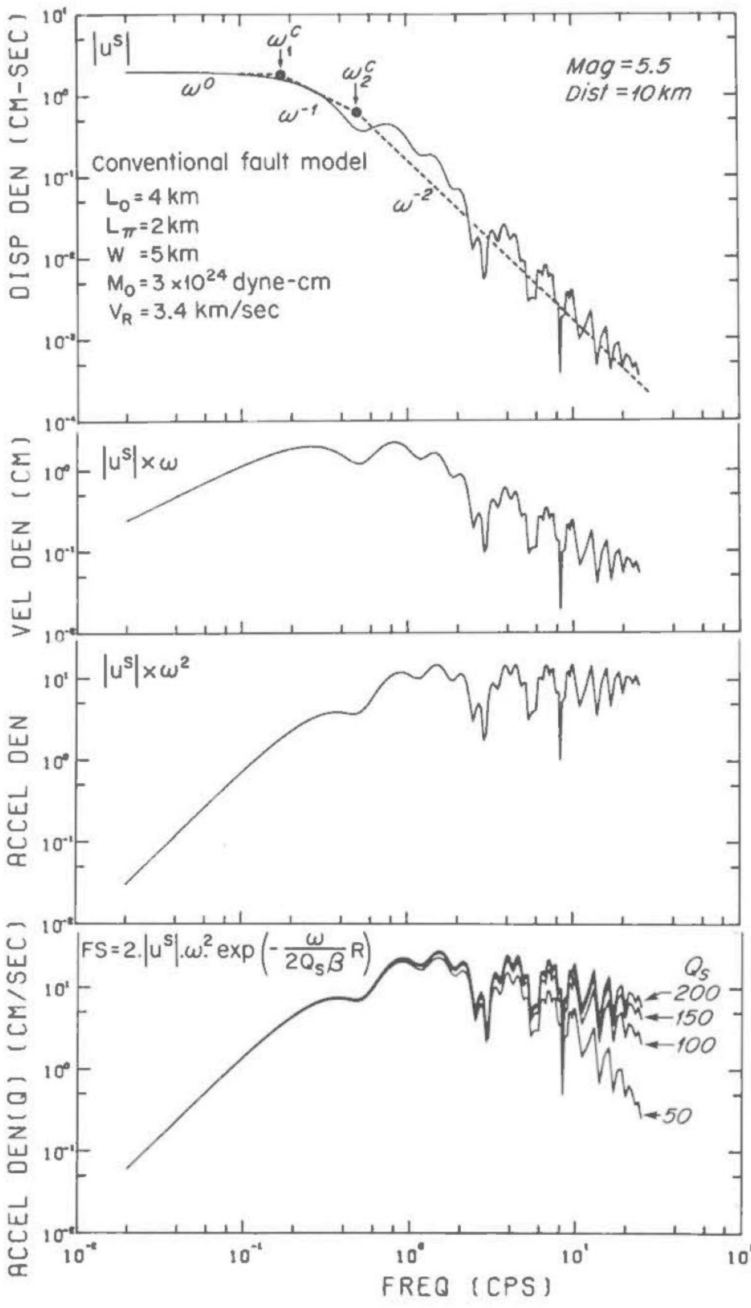


Figure 7. Step-by-step generation of FS curves of various levels of intrinsic absorption (1/Q) from the displacement density $|U^S|$ curve for shear waves radiated from a deterministic model of faulting (from Hasegawa, 1974).

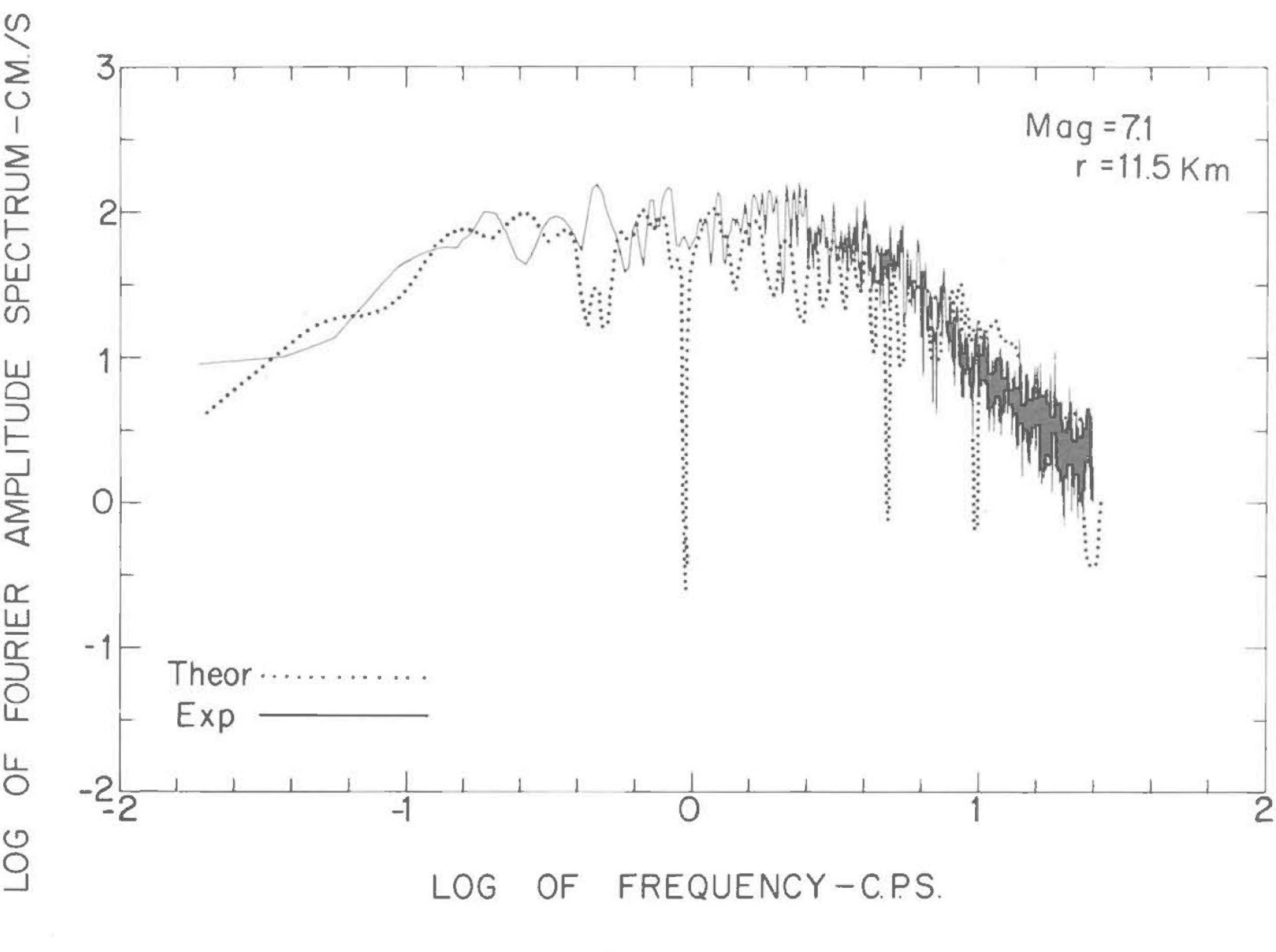


Figure 8. Illustration of a close fit between theoretical FS (shear wave) curve and an El Centro FS curve of Imperial Valley earthquake of May 18, 1940; the epicentral distance is r and shear wave is designated by s (actual curve from EERL, Volume IV – see Hudson (Editor), 1972b).

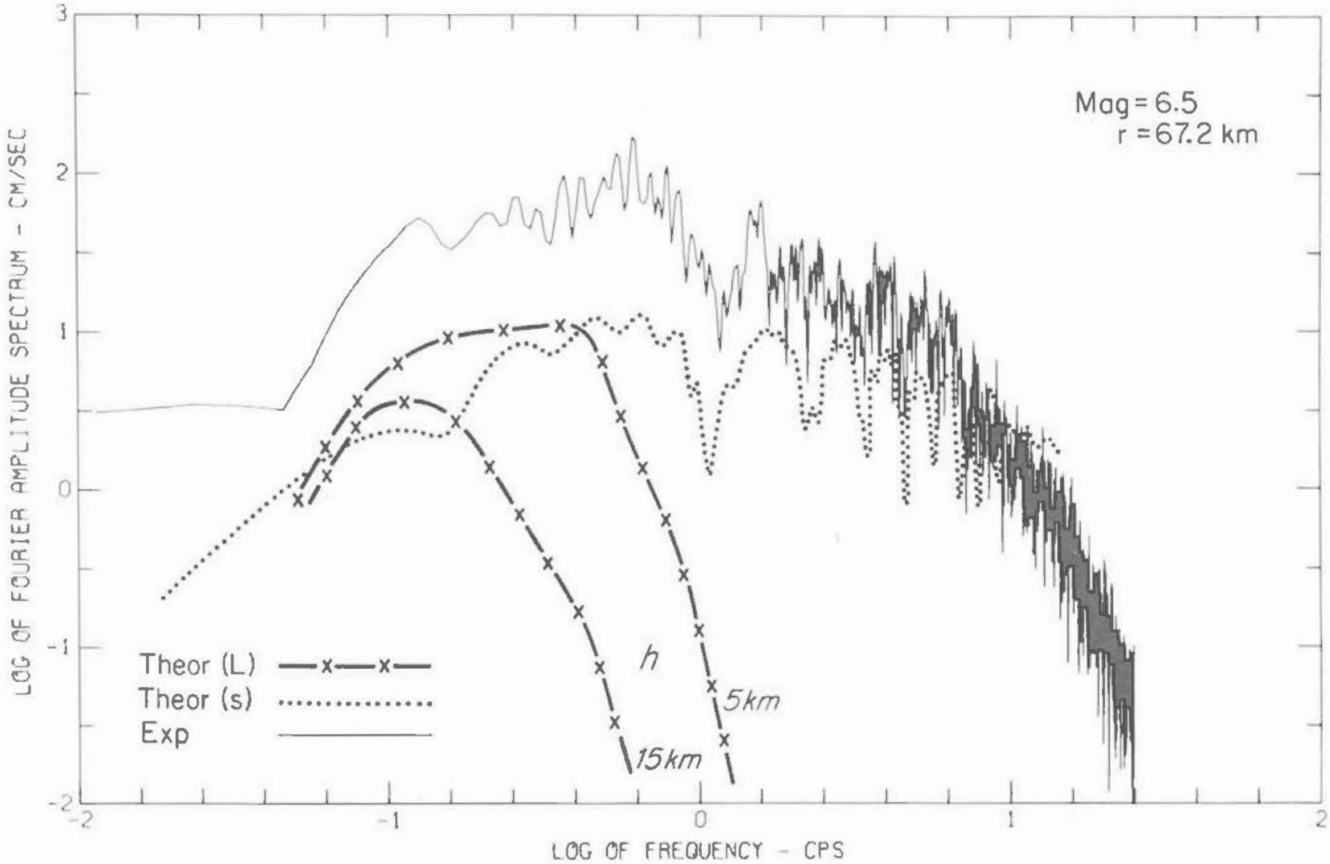


Figure 9. Example of a poor fit between theoretical FS (shear (s)) and actual FS curve for the Borrego Mountain earthquake of April 8, 1968. Theoretically predicted surface wave contribution is represented in the form of Love (L) wave. The actual curve is from EERL, Volume IV – see Hudson (Editor), 1972b.

source mechanism effects. This is one of the main reasons why theoretical accelerograms are generally constructed using stochastic techniques rather than deterministic methods.

6.2 The relationship between FS and velocity response spectra

Because of the relation between FS and $SV_{0\%\lambda}$ (FS $\leqslant SV_{0\%\lambda}$), insight into the geophysical processes that govern the shape of FS curves can be utilized by design engineers to provide them with similar information about $SV_{0\%\lambda}$ curves.

In Figure 10, which shows an actual FS curve superimposed upon actual SV curves (from EERL – Volume III), it is easy to visualize that an envelope drawn through the peaks of the FS curve is a reasonably good facsimile (albeit a lower limit) to an envelope drawn through the peaks of the $SV_{0\%\lambda}$ curve. Consequently smoothed envelopes, which in practice can be represented by three linear asymptotic trends similar to smoothed response curves, can be drawn through theoretical FS curves such as are shown in Figure 11 from Hasegawa (1974). In this suite of curves the lower corner frequency shifts to lower frequencies with increasing magnitude whereas the upper corner frequency does not appear to vary to any significant amount with either a change in magnitude or distance.

It is in this way that it appears possible to consider how best to modify California data to suit eastern Canadian conditions. But the site effects at the accelerographs must also be considered in such a synthesis (see Section 7).

6.3 Average design spectrum approach and peak ground motion bounds

In many cases, an average response spectrum is used, sometimes without adequate consideration as to whether the average is representative of local conditions or indeed what geophysical factors have contributed to that particular average. The average is usually represented by four or five straight line bounds. The average is calculated from three intersecting straight line peak ground motion bounds, which are derived by normalizing peak ground displacement and peak ground velocity to peak ground acceleration and then taking an average. Here it is important to note that such arbitrary averages can mix data which depend upon magnitude, distance, site conditions, etc. in a manner chosen more or less arbitrarily by the proponent of the average.

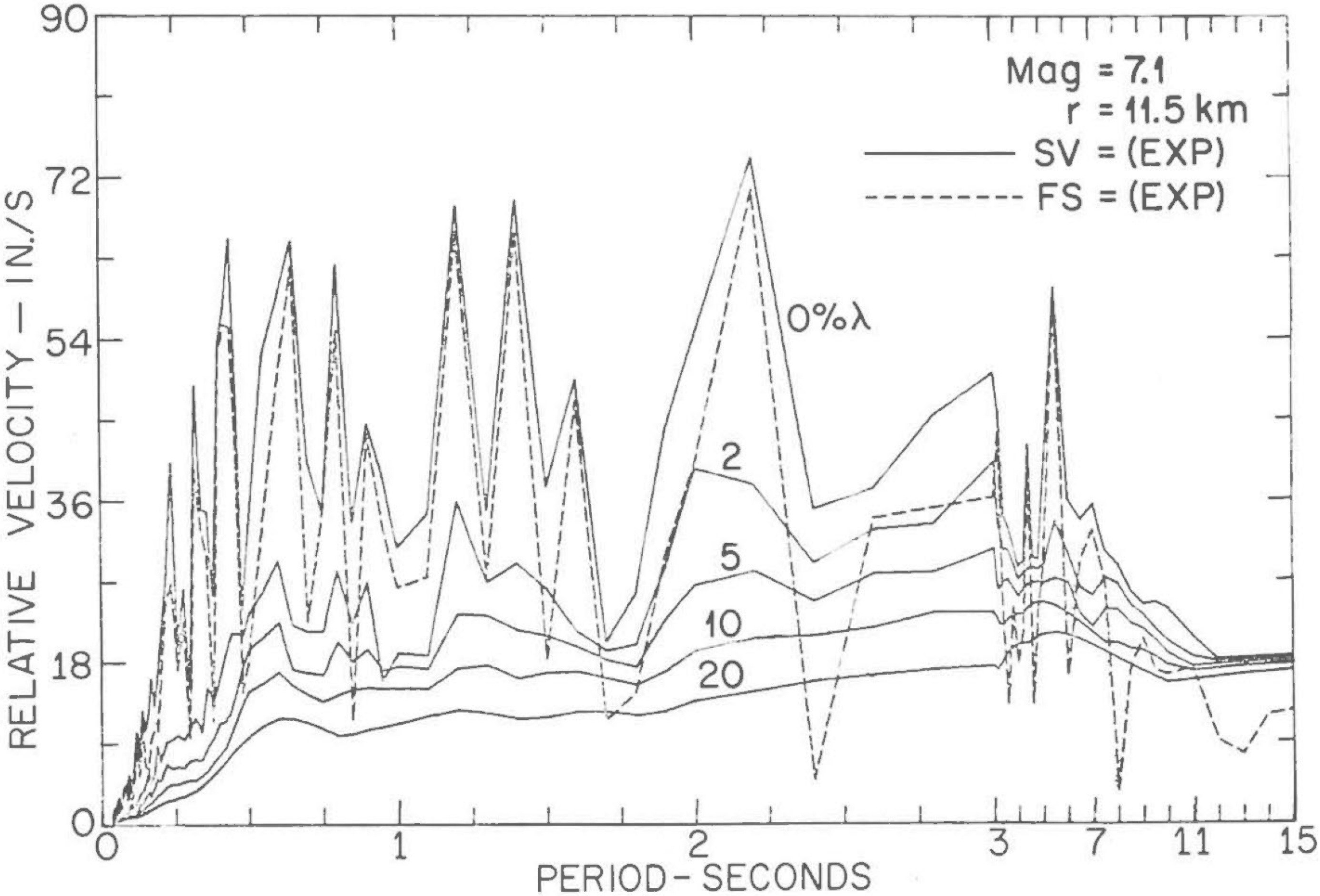


Figure 10. Actual FS curve superimposed upon actual SV curves for various levels of damping (λ) for the Imperial Valley earthquake of May 18, 1940 (from EERL, Volume III – see Hudson (Editor), 1972a).

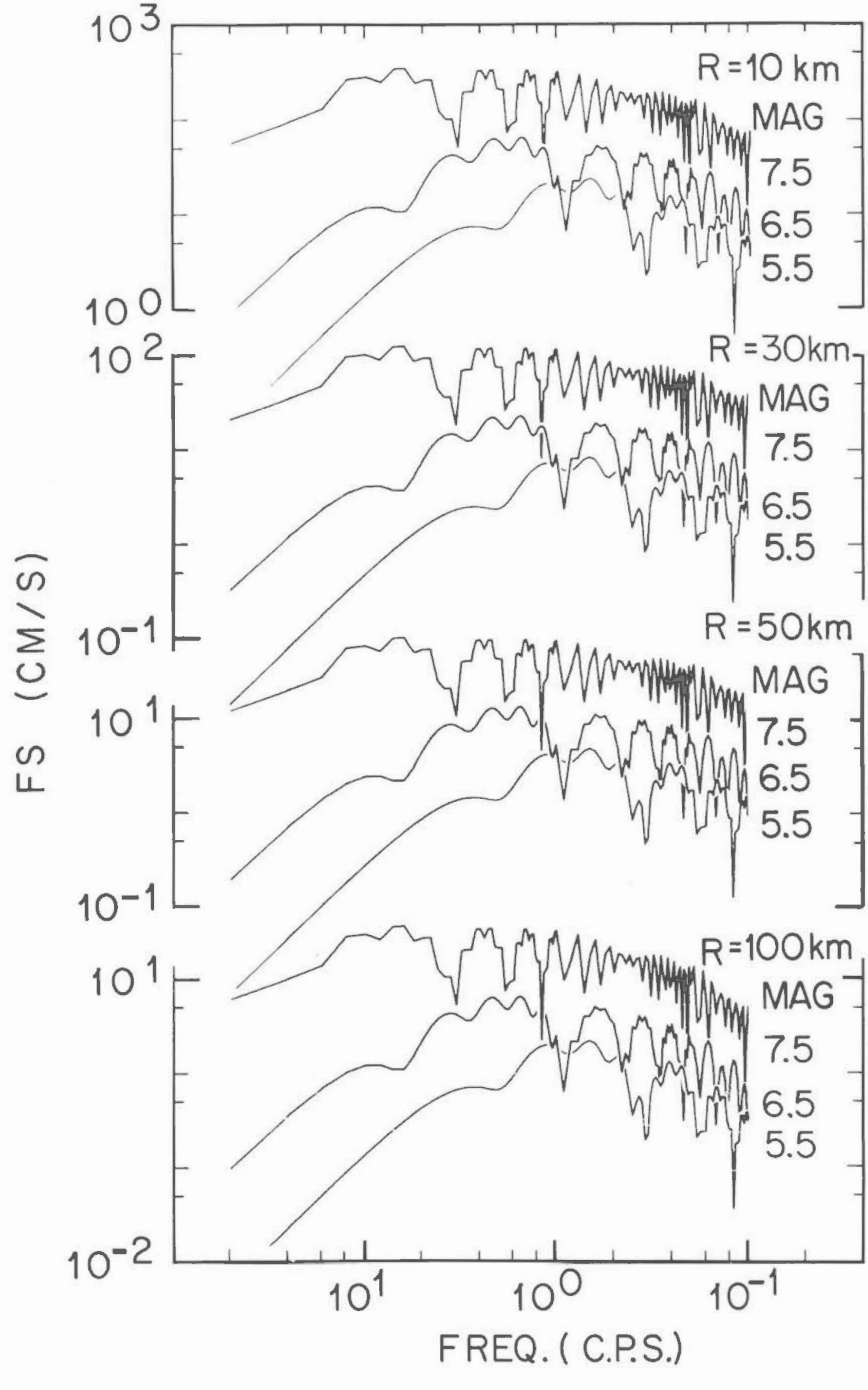


Figure 11. Theoretical FS curves (for shear waves) for three magnitudes (M_s) and the specified (hypocentral) distances (from Hasegawa, 1974).

In many cases, the peak ground motions are linked to the seismic risk level by means of the peak horizontal ground acceleration that can be expected. This is the practice recommended in Commentary K of supplement No. 4 to NBC 1975. Provided a good average, relevant to the region has been adopted, and provided acceleration scaling is not pressed to extreme limits, this approach can be justified as one reasonable approximation.

From a rigorous view point, it must be recalled that these techniques are predicting a *unique* smoothed response spectrum for a specified peak acceleration level. However as Figure 12 (bottom diagram) illustrates, for any specific acceleration response, there are an infinite number of corresponding levels of velocity and displacement for the FS, because FS is a function of both magnitude and distance and not just one parameter. Figure 12 (top diagram) illustrates variability primarily in velocity and displacement response in design spectra for 2%λ for design ground motions with the same acceleration level.

The conclusion is that an average design spectrum approach should be used with care: the nature of the average and the influence of site dependence should be better specified than is often the case. Typical averages urged by various proponents have corner frequencies from 0.2 to 0.3 Hz at the lower frequency and 1.5 to 2.5 Hz at the higher frequency: these differences are considerable. Geophysical considerations may provide a guide in certain circumstances to suitable modifications of the average.

Attenuation measurements of body and of surface waves east of the Rocky Mountains indicate much lower values than for similar measurements along the west coast. These effects should appear in FS calculations as a relative enhancement of the high-frequency end of the amplitude spectrum. Figure 13 shows the difference expected between FS curves (for S waves) for eastern and western North America for the same epicentral distance from an identical source mechanism.

For the FS curves related to the shear wave, the higher acceleration level, the marginally higher velocity levels and identical displacement levels for the east as compared to the west should be noted. In addition, scattering of high-frequency waves, which seems to be an important phenomenon for the western geologic environment, is, *à priori*, not expected to be so prominent for the comparatively more homogeneous eastern environment. If the surface wave contribution were to be included, then the low-to-intermediate frequency portion of the FS curve might also be enhanced to a greater extent for the east as compared to the west. Consequently, if all potential contributors to the FS spectrum are taken into account, then the above discussion would indicate that the FS curve for the east would tend to be above that for the west over all three frequency ranges, namely low, intermediate and high ranges. At the origin there is no difference, but these higher FS curves probably explain why eastern Canadian earthquakes of a given magnitude are felt out to larger distances than are western Canadian or California earthquakes for statistically the same epicentral peak intensity.

6.4 Time history of strong motion

For a specified location, the ideal input to design would be the appropriate suite of accelerograms. Perez (1973) has published a Pacoima Dam accelerogram (San Fernando earthquake) together with the response spectrum and a time history of a damped (5%λ) oscillator for undamped natural periods up to 3.5 sec. It is clear that this is a powerful way of examining response and it clearly confirms that maximum response does not occur when peak acceleration occurs. Another useful technique is to depict the time duration of the velocity response envelope (Perez, 1973).

At the present time there appears to be no consensus as to whether actual accelerograms (suitably modified, if necessary) or theoretical accelerograms generated using stochastic techniques are more appropriate for a specified site. Housner and Jennings (1973) believe the former are more appropriate whereas some design engineers (e.g. see Saragoni and Hart, 1974) believe that stochastic techniques may be more readily adapted to a specific site.

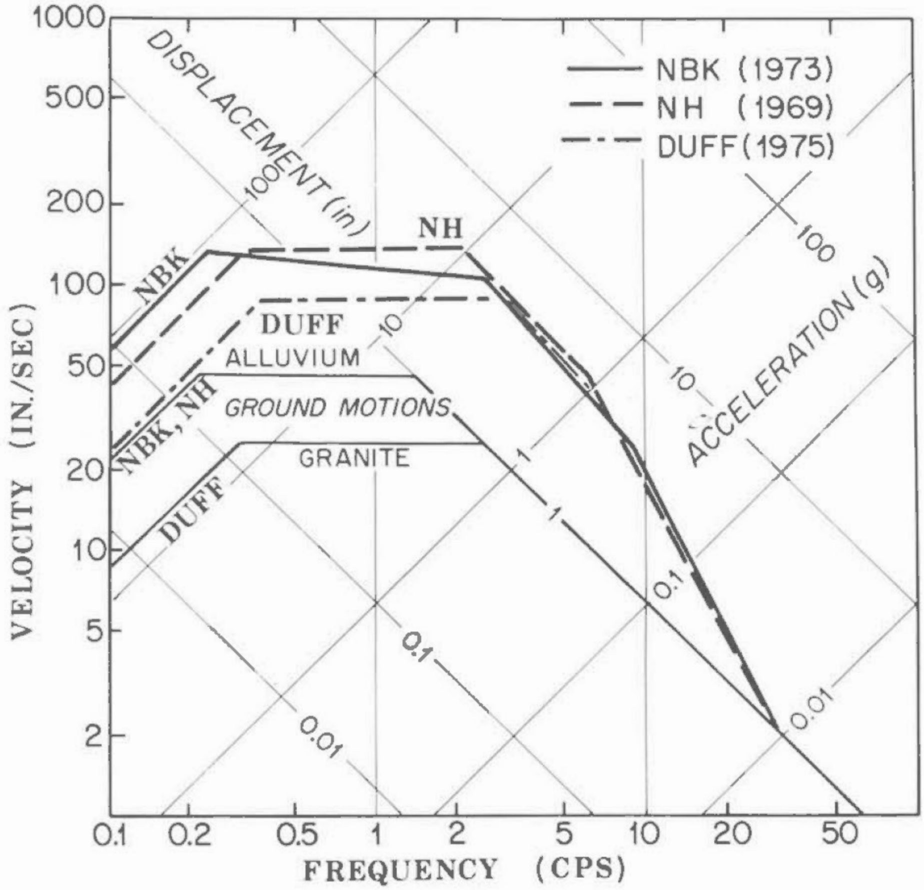
7. Influence of soils

Trifunac (1975) has recently studied 187 accelerograms from 57 earthquakes between 1933 and 1971. He concluded that the influence of geological conditions at the recording station is of minor importance for scaling peak accelerations but of more significance for peak velocity, and even more for peak displacement. Furthermore the duration of strong ground motion on a soft site is about two times longer than duration at a hard rock site.

If data are grouped by intensity, e.g. modified Mercalli intensity, at a common intensity the influence of a soft site can be represented by a movement of the peak ground motion bounds (displacement and acceleration) with the velocity-flat bound relatively unchanged. This change of the corner frequencies to lower frequencies (longer periods) by a factor of up to about two corresponds physically to soft soils amplifying low frequencies and to attenuation in soft soils reducing the high frequencies. It explains very simply why the average design spectrum approach is site dependent.

In Canada, NBC 1975 specifies soft soil multipliers: although peak acceleration may not be very dependent upon the softness, modified Mercalli intensities are greater on alluvium or earth fill sites compared with those on hard rock sites for the same earthquake at the same epicentral distance. Thus a soft soil multiplier to allow for this is necessary: it is an artifact of the Code that it is formally applied to an assumed ground acceleration which may be a physically incorrect way of doing it.

In Commentary K, there is some inconsistency. The authors agree with the statement that for medium and soft soil deposits, the maximum velocities and displacements corresponding to a given peak ground acceleration are generally larger, but this does not seem entirely consistent with later advice in the Commentary that the F-factor be applied as a multiplier to the average response spectrum.



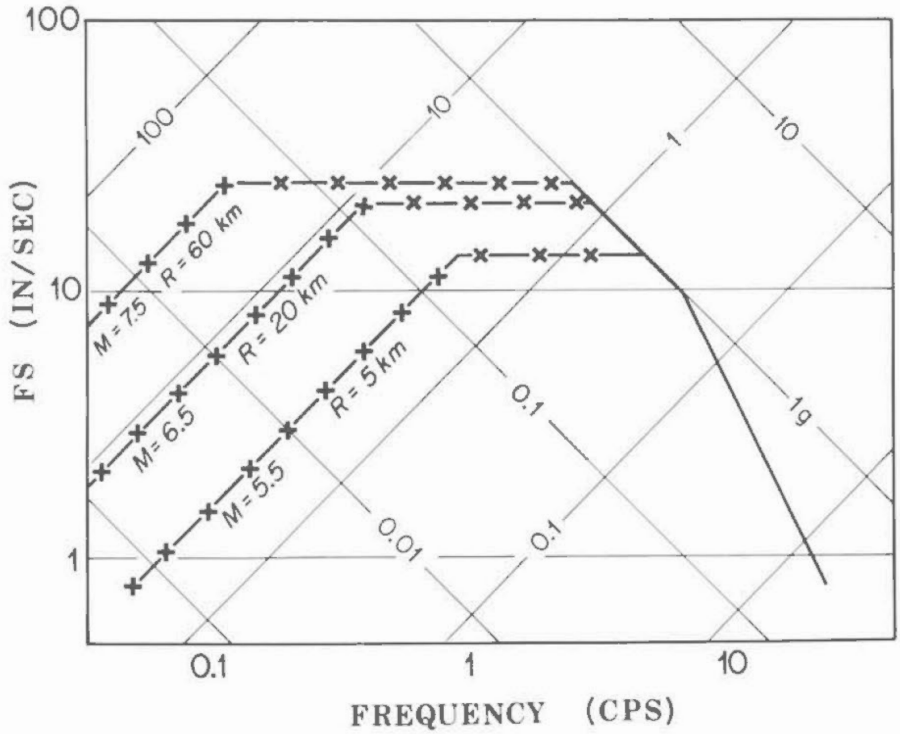


Figure 12. Top diagram illustrates variability in design spectra for 2%λ for specified ground motion levels. Bottom diagram illustrates non-uniqueness of smoothed FS curves for a specified acceleration level (of 1g in this example). NBK stands for Newmark, Blume and Kapur (1973) and NH stands for Newmark and Hall (1969).

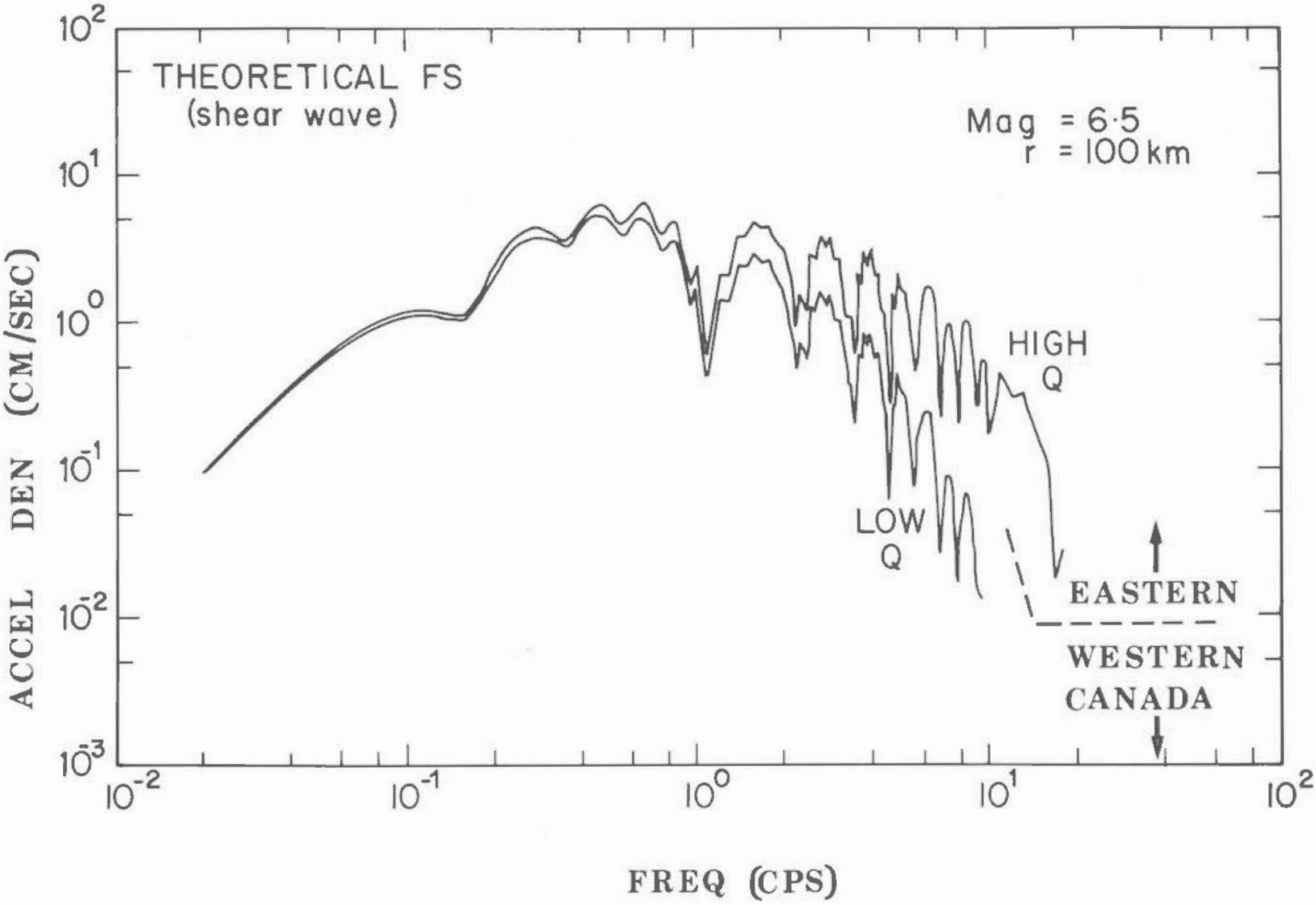


Figure 13. General trend of expected difference between FS curve (for shear waves) for eastern and western North America assuming the same epicentral distance from an identical source mechanism.

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.

8. Conclusions

(1) 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 a neotectonic framework for many Canadian earthquakes.

(2) This situation has led to the present national code situation where, in the estimation of seismic risk, tectonics is introduced only through historical earthquake data. This immediately leads to the scientific concern that our historical data are inadequate, particularly in western and northern Canada, to properly represent seismic risk. This may well be true in terms of a future time span of many decades and centuries, and only a better tectonic understanding or the development of a scientific capability to predict earthquakes better in space and time will overcome this.

(3) With these limitations in mind, the present national building code formulation needs to be updated with completely revised strong motion expressions using all available seismic data. The relative instability of peak acceleration as an expression of risk needs to be recognized. Unfortunately current user tendencies appear to be the contrary. Fortunately for many special critical structures for which the resonant frequency of key components is 2Hz or more, ground acceleration is the significant ground motion parameter. The utility of other, perhaps more stable, simple ground motion parameters should be carefully investigated for similar extreme value calculations. In particular ground velocity may be a more appropriate parameter for urban areas because ground velocity correlates more closely with both intensity and structural damage than does ground acceleration. There is good reason to believe progress can be made provided the uncertainties, approximations and limitations are clearly articulated and understood.

(4) The estimation of design earthquakes for critical structures is possible, but considerable geophysical judgment is required. When only a cumulative very low risk can be accepted for societal protection of key structures, the applicability of the models needs very careful assessment. In general the authors do not favour mathematical extrapolation of the national building code technique to return periods of many hundreds or thousands of years because of the relative instability of peak acceleration values, because recent strong motion and theoretical evidence suggests limiting values for peak ground motions, and because the more conservative approach required for such structures should allow for the introduction of some tectonic considerations, even if these are necessarily judgmental and not absolutely quantifiable.

(5) There has been considerable progress in understanding the nature of average response spectra. It is possible, to first order, to understand why the different average response spectra recommended by different proponents have significantly different corner frequencies depending upon the selection criteria used by the originator of the average.

(6) In turn this means that scientifically valid geophysical guidance in the selection of an appropriate average response spectrum is becoming increasingly possible. This should assist in the economic and effective protection of the public.

(7) Ultimately public acceptance is necessary of the incremental costs involved in protection against earthquakes. In Canada, as elsewhere, progress in achieving this is spotty and much remains to be done in the education process without resort to exaggeration and over-reaction.

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