THE ECONOMICS OF EARTHQUAKE ENGINEERING RESEARCH*

by

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SYNOPSIS

The paper discusses an outline of possible reasons for carrying out research in the area of earthquake engineering. Since such research requires a decision by government, industry or some private individual to allocate some part of their scarce resources to this activity, the paper examines some of the benefits to be anticipated by such "clients" as a result of research and suggests a basic methodology of analysis in those areas where economic benefits are available.

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* The views expressed in this paper are those of the authors. They should not be interpreted as reflecting the views of any governmental agency.

INTRODUCTION

Unlike the majority of the papers presented at this meeting, this paper is not the report of a well thought out experiment or a rigorous piece of analysis. It is a concept paper whose main objective is to stimulate discussion, and controversy if necessary, about the role of research, in particular earthquake engineering research. Thus the basic approach, the methodology of analysis and certainly the numbers used are not meant to be defended if subjected to the usual scholarly criticism of a technical paper. We accept "ab initio" that better, more rational analysis of needs will be developed. The only point of the paper which we would defend with any amount of energy is the basic assumption that research expenditures must be justified in a rational manner, rational in this context meaning that it must provide the decision maker who has to allocate resources, the means to do this between conflicting demands on a better basis than "I believe this is important".

Man is one of the most successful biological species to inhabit the earth, and he has achieved his eminence through his ability to adapt to the natural hostilities which confront all life and, apparently, to manage the available resources better than his competitors. Since the beginning of time changing circumstances have inflicted a variety of disasters on species struggling for existence, and there are no indications that nature has ceased her assault on residents of the biosphere.

As the human population increases, and concentrates more and more in large cities which are more closely allied with volumes than with areas, earthquakes are becoming an ever-increasing factor in managing human society. This is not to imply that earthquakes will determine the ultimate success of humans to survive on this planet, but they are a major factor to be reckoned with in many parts of the world.

In order to contend with these natural phenomena, we probe where we must. We look for a basic understanding of the reasons for earthquakes, in the hope that we can predict their occurence and we need an understanding of man-made systems, so that we can take some preventative measures through urban design to minimize the social costs when earthquakes do take place.

We are unlikely, in the foreseeable future, to be in a position where we will be able to control or inhibit earthquakes, although there are indications that we may inadvertently be able to facilitate some forms of crustal energy release through deep-well disposal of liquid wastes. Since control is not the immediate goal, the search for understanding is motivated by the desire to minimize the effects of earthquakes, rather than to prevent them. In this respect it is similar to flood forecasting and, in some ways, to anti-pollution research. Results of an increased understanding of the earthquake phenomenon will not lead directly to an improved socio-economic environment, but the translation of its results into positive actions will minimize the costs resulting from an occurence.

Research and the Allocation of Resources

Crustal movement and earthquake phenomena are studied on a significant scale by scientists throughout the world. Since activities of this nature, like most others, consume both human and financial resources, it is natural that those responsible for the allocation of resources question the need for Canada to contribute to activities in this field. Although the search for knowledge, *per se*, has so far eluded the attempts of economists and others to contain it within the framework of a benefit-cost analysis model, nevertheless, financial support must be justified on other than purely philosophical or emotional grounds.

At the present time Canada can probably not be considered a major candidate for potential disasters. Furthermore, our population and resources do not qualify us to be a leading producer of knowledge in all fields. Since most of the knowledge gained from earthquake studies is basic, rather than proprietary, it is a free good, equally available in published journals to all who may wish to acquire it. Under these circumstances, the rationale for undertaking earthquake research in Canada must be very carefully examined and understood if funds and people are to be found for its pursuit despite the competition for scarce resources.

Broadly speaking, there are three reasons for undertaking research - prestige, cultural and technological - and, as in all activities, the aim is to secure the highest returns with the least expenditure. As an activity generally considered creative, Research attracts many of the best minds in our society. Since creativity is a highly individualistic characteristic, the choice of fields tends to be made on the basis of personal interest rather than on prescribed or perceived needs. Development of significant theories concerning all facets of the universe and our role within it is generally rewarded by international recognition. Apart from the personal satisfaction of the researcher, and along with other activities, this serves to increase the national stature and thereby, adds some credence to international undertakings. Since we are becoming more involved in world activities as modes of communication continue to improve, prestige is important, and we must devote part of our national effort towards its enhancement.

The cultural aspects of research are commonly associated with the university community, where basic research is undertaken in association with the education process. Although knowledge is often advanced through basic break-throughs in technology, in general, new knowledge is based upon existing knowledge, and it is through the universities that the latest advances pass on to the coming generations. Without the modifications made possible by research, knowledge itself becomes sterile and it is therefore incumbent on those who transmit knowledge to ensure that its boundaries do not remain static.

Research performed in support of technological activities begins to approach the realm of benefit-cost models, and it is here that care must be taken to ensure that resources are spent in pursuit of well understood goals and that these resources are applied efficiently. As mentioned previously, published research is a free good and may be obtained for the reading. In terms of the annual growth of knowledge, it is estimated that Canada contributes less than 5% to the world aggregate. If this is disaggregated among fields and performers, it may be concluded, statistically at least, that any one contributor adds little to world knowledge. The primary purpose of undertaking research under these circumstances is therefore, not so much to generate the needed knowledge but, to consume it from the world bank, digest it, and pass it to technology in a form that will allow innovations to take place.

Because of the highly specialised nature of research, access to world knowledge, at least at the frontiers, can only be had by those working in the field who are themselves at the frontier. At this level, information does not flow freely - there is a quid pro quo - and any country that wishes to remain in the forefront scientifically must support at least sufficient research to be able to acquire the world knowledge. Although it is a free good as far as dissemination is concerned, this world knowledge can only be acquired in a useful manner if resources are expended in developing the receiving mechanisms.

The arguments for support of research, and this includes earthquake research, are clear. The questions that remain pertain to the sectors of performance, the level of support and the translation of research results into activities that will enhance social conditions.

Sectors of Performance

Conceptually, we might expect that earthquake research would be pursued in two segments of society; in universities, as part of the education process referred to above, and in the construction industry, where research results can be rapidly converted into practical applications. Certainly, the university community will be involved to some extent for the reasons already presented. The situation with respect to the private sector is not so clear.

Although there are firms where earthquake studies could be logically undertaken, in a large measure the members of the private sector who could make use of research results are smaller companies where an R & D laboratory is out of the question. A further complication arises in the matter of construction standards which tend to be under municipal jurisdiction and, in effect, determine the extent to which potential earthquake effects enter into design criteria. Because, at the present time there appear to be no economic rewards for construction that exceeds standards, as opposed to meeting the minimum requirements, there is no incentive to the private owner or builder to incorporate the results of the latest earthquake engineering research into new construction, much less to invest in the research itself. (This does not seem to be the case in Japan, at least if we can judge by the listings of the International Association for Earthquake Engineering which lists many private agencies engaged in earthquake research.)

An earthquake disaster, however, can have a social cost in terms of lost jobs, reduced incomes, etc., well beyond the limits of the immediate area affected, and for these reasons the federal government has an interest in promoting the application of methods that will minimize these costs. Where there are many customers requiring a common service, as is the case with information about earthquake effects, economic considerations suggest that such services can be concentrated, with easy access provided to the clients. In some cases, if the industry or different levels of government are organized in a fashion that can respond to the perceived needs, an institute may be formed funded for the most part by the goups themselves. Where the clientele is more fragmented, the federal government has attempted in the past, and may attempt in the future to fill the need by establishing research competence within its own institutional structures.

The major portion of applied research should take place in close proximity to the market place, and this activity might logically be devided between the larger construction and consulting firms and the federal government. It then remains to decide how the research should be managed.

Management Principles

The prime responsibility of a manager is to achieve the maximum results with the minimum expenditure of resources. In principle this should be easily achieved. In practice however, we have great difficulty in defining what we mean by results and hence measuring effectiveness. As a result we also experience some difficulty in assigning research priorities and in the allocation of resources.

In the case of university research it seems likely that the current forms of support will continue and that funds will be provided by federal agencies, either on the basis of excellence as determined by the peer assessment process, or by research contract. Some funds will also flow into the universities from the private sector. In any event, these funds, apart from contracts, are allocated in a belief that earthquake research will enlarge the education of some Canadians and no other form of payoff or management is conceived.

Applied research on the other hand, must be dealt with in a different manner. Since this work is applied, funds must be provided by a client (or clients) in the expectation that there will be some significant payoff, at least over a period of time. Research carried on in isolation from application can quickly lose direction and, although creative minds and serendipity will combine to produce results, these are unlikely to be of a specific interest to those who pay the bills. This becomes especially true in a government laboratory, where the client is not the direct provider of funds and rarely has a determining voice in the assignment of priorities.

This is not to suggest that government laboratories should be abolished. We have ample evidence that when the private sector is in financial difficulties the R & D laboratories are very likely to disappear. With no government R & D and little industrial activity we would be in a poor position to even import technology, let alone develop our own.

The answer lies in a partnership arrangement between government and industry, where each provides a portion of the funds and each has a commensurate say in the priorities. There will always be situations where a company deems it advisable for proprietary reasons to conduct its own R & D. In these cases governments, naturally, have no cause to intervene. However, where pooled risks in R & D are concerned, government has a legitimate role to play. The private sector, the main ultimate client, must also be involved if the results of research are to be translated into benefits for society. The challenge is to develop the working relationships between government and industry to ensure the optimum use of resources, when these are allocated for specific purposes such as earthquake research.

This part of the paper has essentially discussed general principles of justification for research. The next part of the paper will attempt to get to closer grips with the hard economics of the problem.

THE CLIENTELE

Before suggesting a methodology for analysis it is necessary to examine the specific clients for the results of research and what each of them expects to gain. It is an axiom of benefit-cost analysis that a benefit is only classified as such when it contributes to the achievement of the objectives of projects or activities. In this case this means that the individual client for research must derive some kind of economic benefit from the knowledge to be made available.

We propose to list and discuss some of the possible groups of clients for earthquake engineering research. Each of these clients has a separate and distinct interest and therefore must be approached and sold in a distinct way of the merits of research, since we are asking him to commit a part of his scarce resources to fund research.

It is appreciated that the list of clients and benefits is far from complete and more work is justified in this area. However a start must be made somewhere and we shall begin with the limited list presented here.

Individual Citizens

The individual citizen has a responsibility and desire to protect his family, home and business. In modern society he delegates some of this responsibility, since he expects the State to preserve his family from physical harm and he probably protects himself against the possibility of loss of his home by insurance. In actual practice of course, some homes are not insured for earthquake risks and,in the event of a major disaster, the citizen would expect the State to make good some major part of his losses. Thus in these two areas the individual citizen is probably not a client for economically justified research (although he may still be approached for a donation to a good cause, like a university). The citizen as the owner of a business is in a different position since he is likely to suffer losses, not just by the physical damage to his building or facilities but also secondary damage to the contents of the building which may be caused by the failure of his building. There is also the loss of business when the building or facilities are inoperative while awaiting repairs or replacement. These factors can be insured against, but most policies include some form of deduction or co-insurance which means that the property owner is still exposed to substantial risk in case of disaster. This risk can be quantified in dollar terms and the reduction due to research can be estimated.

Engineers and Architects

It is interesting to quote from a rating manual issued by a major insurance company that:

> *"The design of buildings over three to five stories high in seismic areas require a competency which is not common in the ordinary architect or engineer and the design may be beyond the capacity of the enforcing officials to check".*

Thus one can see a number of possible economic benefits for the designing professions in the achievement of knowledge. First of all there is the direct economic benefit of improved methods of analysis, preferably computerized to cut down the design costs. Then there is the requirement by the competent professional for more and better knowledge so that he can provide a better service to his clients.

Insurance Companies

It is a popular misconception that insurance companies are gigantic gambling syndicates with the dice reasonably loaded in their favour. In reality, of course, this is not so. Insurance companies endeavour to assess a risk as accurately as possible by a variety of actuarial techniques and base their rate structure on these statistics with a reasonable mark-up for over-head and profit. This rather rational approach tends not to hold up in the case of earthquake insurance because the time scale of the incidence of earthquakes is so very much different in most cases than the life span of the objects insured. Rate setting based on historical statistical data therefore becomes a very risky proposition.

Thus, through no fault of their own, and almost certainly against their wishes, insurance companies become involved in what is almost a blind gamble when selling earthquake insurance and many companies are understandably reluctant to play in this rather risky game. The risks in this area are compounded by the fact that the risk spreading which normally occurs with fire, industrial hazards, etc., may not be applicable for earthquakes since an entire area may be seriously damaged and cause losses of the billion dollar order of magnitude. Better information in this area will have undoubted dollar value for insurance companies.

Local Governments

One of the most obvious needs for information by local governments would appear to be in the Planning Department who are hopefully trying to correct mistakes which occured in the past by the poor location of population and services, and to insure these mistakes will not be repeated in the future. One ever present example of Murphy's Law in urban areas is that the worst and most vulnerable buildings seem to be inevitably placed on the most sensitive soils in the most earthquake vulnerable areas. As indicated previously, building inspectors need better information regarding modes of failure, both from research in the laboratory and observations in the field at the scenes of disaster.

In this connection it is interesting to cite the National Board of Fire Underwriters report on the Alaska earthquake, Reference 6, which stated that among the major causes of property damage were:

a) Lack of professional plan checking.

b) Inadequate field inspection.

c) Faulty construction.

d) Inadequate soils analysis.

It is interesting to note that failures or errors in design and analysis were not considered to be major contributory factors to structural damage.

While it is understood that the function of a building code is primarily the protection of life and health, i.e. public safety, not enough is known about causes and modes of failure to enable a building official to really check that the public welfare is being protected.

In this connection it is also worth noting that insurance companies and building inspectors have entirely different objectives in the area of earthquake resistant design. Most building codes effectively permit extensive property damage and the building might not be assumed to have failed if all the occupants can leave safely, even if the building must be demolished the following day. Insurance companies and building owners are not usually so philosophical.

There is a further need for improved data in local governments to ensure the provision of essential public services under a variety of circumstances. Among the needs that immediately come to mind are fire services, health services, electrical power, water, sewage, police, transportation, etc. The reduction of vulnerability in any of these services is a rational objective for local government.

Federal Government

In actual practice a major earthquake affecting one of the larger urban areas in Canada would automatically be a matter of serious concern to the Federal Government. Thus improved knowledge of the exposure to risk would be extremely useful. There is also the possible effect on the total national economy by virtue of the risk attached both to specific federal government projects and the systemic interaction between the major urban areas. This makes it very important for rational emergency planning that information be available on the probable effects of earthquakes in Canada.

A further concern of the federal government may be in the area of shared cost programmes, particularly where capital investments are concerned, since this makes the federal government a co-risk taker with some other level of government.

There is also the responsibility for providing the best possible National Building Code as a model to be used by other levels of government who may not have the full capability of acquiring the necessary technical expertise to draft such a sophisticated document. It may also be argued that constitutionally it could be a federal government responsibility to legislate the earthquake provisions of the National Building Code, or similar code, since it is a matter of general public welfare and earthquakes are no respecters of constitutional divisions of power.

Methodology

To this stage we have dealt with some of the potential clients for knowledge derived from research and we not propose to look at a possible methodology of analysis which may be utilized in this area.

The first problem is to establish a relationship between the magnitude of damage and its probability. Using extreme value prediction methods (similar to work done by Milne & Davenport, References 2 and 3) it is possible to make probabilistic statements defining the incidence of earthquakes of varying intensities. These intensities can then be related, in most cases by estimating, to a probability of physical damage to a specific structure or facility. This in turn can be analysed to define a loss in dollar terms.

It is appreciated that the entire analysis would be seriously affected by a major earthquake which might have occurred immediately before data became available. Nonetheless as an example we shall ignore this and other shortcomings in the analysis in order to make our major point and leave further researchers to improve and refine the methodology.

By this type of procedure we can calculate a number of points on a graph and the area under this line is the actuarial risk of damage per year for the specific facility. In actual practice it is probably not necessary (even if it were possible) to define the damage-probability function since the integration can be carried out within the accuracy of the entire process by summing the area of the rectangles defined by the one point at the outer corner which has been derived from the probability calculation. (See figure 1)

It must be borne in mind that the economic loss related to any specific intensity of earthquake consists of a number of inter-related factors of which the direct physical damage to a facility is only one. From the individual building owner's point of view, he is concerned with the damage to his building, physical damage to the contents and, last but not least, loss of business and profits caused by the physical damage.

In addition there is the added problem of system damage, since no single building or facility exists in isolation from the community around it and thus the individual building owner may have an enormous interest in an understanding of the vulnerability of these parts of the economic system with which his business interacts.

To this stage we have only considered the loss in any one year while obviously the benefits of successful research will be reaped by the client over many years. In order to make a rational decision it is therefore necessary to treat expenditures for research as a long-term investment and discount the benefits with respect to time. Now in any one year the benefit of research is some reduction of risk which, as previously suggested, can be defined in dollar terms. However, a dollar in the future does not have the same present value as a dollar today and we can therefore define the present value of a future benefit in year i as:

$$\frac{B_i}{(1 + R)^i}$$

Where

R is the discount rate used by the particular client.

For a business this may be the corporate target rate of return, the cost of money at the margin or the average cost of capital.

B_i is the benefit in year i directly attributable to the research proposal.

But B_i = benefit due to reduction in risk to the structure (S_i)

+ benefit due to the reduction in risk to the contents (C_i)

+ benefit due to the reduction in risk to the profitability of business (P_i)

And

S_i is a function of the depreciation rate and time and may look like:

$$S_i = A(1 - R_1)^i$$

Where

A is a constant

R_i is the annual depreciation rate.

C_i is a function of inflation and may look like:

$$C_i = B(1 + R_2)^i$$

Where

B is a constant

R_2 is the anticipated inflation rate.

P_i is a function of anticipated growth of business and profitability and may look like:

$$P_i = C(1 + R_3)^i$$

Where

C is a constant

R_3 is the growth rate.

Combining these functions we get the benefit of the research program to be worth:

$$\sum_{i=0}^{n-1} \frac{A(1 - R_1)^i + B(1 + R_2)^i + C(1 + R_3)^i}{(1 + R)^i}$$

$$= A \left[\frac{1 + R}{R + R_1}\right] \left[\frac{(1 + R)^n - (1 - R_1)^n}{(1 + R)^n}\right]$$

$$+ B \left[\frac{1 + R}{R - R_2}\right] \left[\frac{(1 + R)^n - (1 + R_2)^n}{(1 + R)^n}\right]$$

$$+ C \left[\frac{1 + R}{R - R_3}\right] \left[\frac{(1 + R)^n - (1 + R_3)^n}{(1 + R)^n}\right]$$

with B and C being dependent functions of A.

To try and anticipate the obvious critical comment that this seems to be a lot of analysis for little return, let us examine some of the numbers involved

In "Private and Public Investments in Canada" reference 5, it is estimated that the volume of construction in Canada 1970 was expected to be $11.4 billion, with a further $6.4 billion to be spent on machinery and equipment. Let us make the following simplifying assumptions:

a) 50% of this investment is made in areas subject to earthquake risk.

b) The average actuarial risk in these zones is ¼% per annum (some rough calculations by one of the authors (M.Z.) indicate that this is a reasonable figure).

c) The value of loss of business due to physical damage is practically the same as the damage to the initial value of the structure, and business volume is expected to expand.

d) The value of other contents in a building is about the same as the value of machinery (this is borne out, at least to the accuracy of the order of magnitude, by data from rate manuals of a number of insurance companies).

e) The life expectancy of individual projects is an average of 20 years.

Then -

for a building depreciation rate of declining balance,	5% p.a. on the
an inflation rate of	3% p.a.
an anticipated business growth rate of	3% p.a.
and a discount rate of	10% p.a.

The vulnerability of the economy to damage to one years construction is:

$$\frac{.0025}{2}\left[11.4\ (6.95) + 6.4 \times 2\ (11.45) + 11.4\ (11.45)\right]$$

= \$99 million + \$184 million + \$164 million

= \$447 million

Thus research leading to a possible reduction of only 1% of the actuarial risk to one years increment of the economy is worth \$4.47 million.

However this benefit will continue to accrue, since the same knowledge will continue to be utilized in future years and hence we can accumulate the value of risk reduction to future construction and bring that back to the present value also. For simplicities sake, and realizing that no amount of research is likely to reduce the risk to zero, let us assume that the benefit of current research will only accrue for 20 years. However, from a quick and nasty regression analysis of capital expenditure patterns in Canada, we find that both construction and machinery investments are increasing at an average rate of about 8% p.a.

Using the same assumptions as previously, the present value to the community of current research would therefore be:

$$\left[\frac{1 - \left[\frac{1.08}{1.10}\right]^{20}}{1 - \frac{1.08}{1.10}}\right] \times 4.47$$

= $76.4 million for every 1% reduction in vulnerability.

It is not suggested that the individual business man, corporation or trade association is likely to be prepared to finance future users of new knowledge generated and it may be necessary for government to finance such research as a public good. It will be up to the researchers to justify their particular bite of the total pie in terms of the benefits to be created and the particular beneficiary of the results of the research.

What we are really suggesting is a multi-disciplinary approach to research by groups, possibly organized as institutes, to examine the total impact of earthquakes on society. However this should really be the topic of a separate paper.

To summarize, we have identified a number of justifying arguments for research in earthquake engineering. First of all there is the cultural benefit of the research in itself. Then there is the education aspect, and finally the economic value of the information generated. However, since any country generates only a small proportion of the total information in any one field and it is desirable to tap into the total reservoir of such knowledge, it becomes necessary to make an investment in "club membership", which means essentially that people tell you things if you tell them something in return.

Secondly, there is what one might call the "encyclopaedia syndrome" i.e. it is necessary to be able to read to obtain information from an encyclopaedia and similarly it is necessary to be doing some research (and to make mistakes) to be able to evaluate research carried out and published by others.

Finally there is the straight-forward economic justification of research done within Canada for the benefit of the national economy or specific clients.

The real purpose of this paper is not to define the methodology of economic or other justification for research but more to outline the patterns of thought which may be necessary for such justification in the near future. If that has been achieved this paper is successful.

BIBLIOGRAPHY

1. MacDonald, J.B. "The Role of the Federal Government in Support of Research in Canadian Universities", Special Study No.7, The Science Council of Canada, Published by - The Queen's Printer, Ottawa 1969

2. Milne, W.G., "Earthquake Epicenties and Strain Release in Canada", Canadian Journal of Earth Sciences 4, p.p. 797 - 814 (1967)

3. Milne, W.G. and Davenport, A.G., "Distribution of Earthquake Risk in Canada", bulletin of the Seismological Society of America, Vol.59, No. p.p 729 - 754, April 1969

4. Pecora, William, T., "Proposal for a Ten Year National Earthquake Hazards Program - A Partnership of Science and the Community", Federal Council for Science and Technology, December 1968, Dist. by Clearinghouse for Federal Scientific & Technical Information

5. "Private and Public Investments in Canada Outlook 1970 and Regional Estimates ", Dominion Bureau of Statistics, Publication No. 61 - 205

6. "The Alaska Earthquake March 27, 1964", report by the National Board of Fire Underwriters and Pacific Fire Rating Bureau, 465 California Street, San Francisco, California 94104

7. Prest, A.R., and Turvey, R., Cost Benefit Analysis: A Survey. The Economic Journal, December 1965

8. Marglin, S.A., Public Investment Criteria, Allen & Unwin, London

9. Samuelson, P., and Scott, A., Economics, An Introductory Analysis.Canadian edition, McGraw Hill Co.

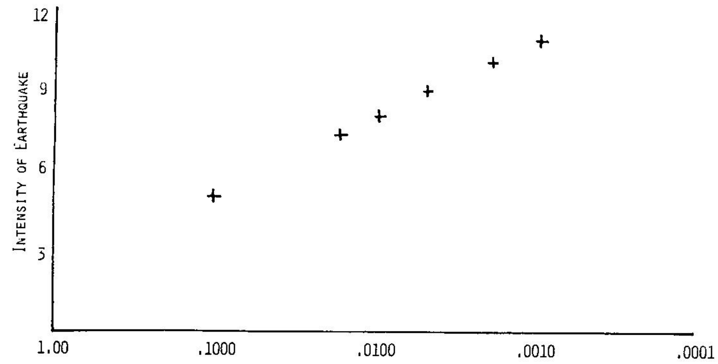
12
9
6
3
Intensity of Earthquake
1.00
.1000
.0100
.0010
.0001
PROBABILITY PER YEAR

Fig. 1 (a)

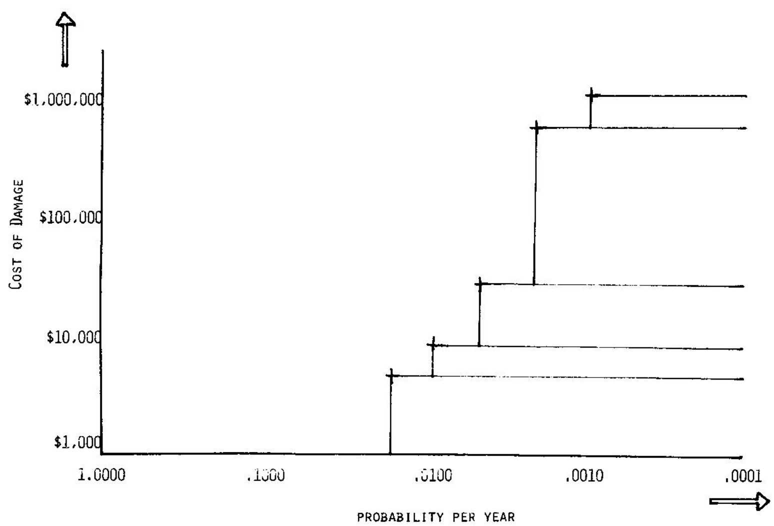
$1,000,000
$100,000
$10,000
$1,000
Cost of Damage
1.0000
.1000
.0100
.0010
.0001
PROBABILITY PER YEAR

Fig. 1 (b)

DISCUSSION OF PAPER NO. 24

THE ECONOMICS OF EARTHQUAKE ENGINEERING RESEARCH

by

J.D. Keys and M. Zelman

The following detailed written discussion to Paper No. 24 was summarized at the Conference and is presented here in its entirety. It is entitled

AN ALTERNATIVE VIEW OF EARTHQUAKE ENGINEERING BENEFITS

by

K. Whitham*†

ABSTRACT

A wide spectrum of activities in earthquake research, engineering seismology and earthquake engineering is necessary to protect Canadian society and environment against the worst effects of earthquakes. Government agencies, universities and industry all have roles to play in this complex interacting problem: coordination, wherever useful, through the Canadian National Committee on Earthquake Engineering is an essential part of a well-planned approach.

Because prediction is not yet possible and measures of research effectiveness generally impossible to define, purely economic studies of the earthquake engineering problem can produce misleading results, which may reflect the premises of the calculations more than scientific truth. Some examples of generally inadequate and sometimes misleading economic arguments are presented as illustrations.

Continuing Canadian activities in this field are essential for national welfare: some of the qualitative and semi-quantitative arguments for this belief are outlined.

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† The views expressed in this paper are those of the author and should not be interpreted as reflecting the views of any governmental agency.

DISCUSSION OF PAPER NO. 24

INTRODUCTION

In a recent paper, Keys and Zelman (1971) have presented an outline of possible reasons for justifying earthquake engineering research. Cultural and educational arguments are summarized, together with a simplified mathematical model which is used to illustrate the patterns of thought which may be necessary for economic justification of earthquake engineering research in the near future.

Science managers, at least in government and industry, are today fully aware of the increasing need to justify their use of finite resources, to consider alternative courses of action and to manage science activities to meet the aims and objectives of approved programmes. For governments, with the universality of science, the programmes to which science contributes may be economic, educational, cultural and political. Fashionable terms, such as cost-benefit studies, cost-effectiveness studies and output budgeting, are now a part of the scientific management lexicon.

Concrete examples of such studies in science are, however, comparatively infrequent because of the well-known difficulties of quantitatively defining benefits, quantitatively predicting the results which would be achieved by an allocation of x man-years of effort and y million dollars over z years, and because a particular activity is extremely rarely an island unto itself. When such studies appear, it is therefore extremely important that they be submitted to the same process of critical appraisal as that accepted in the scientific domain for scholarly papers.

Keys and Zelman have very generously supplied the writer with a preprint of their work, and have invited criticism. This author believes that there are errors in the argument presented by them and that their arguments are incomplete and may be open to misinterpretation by others. The only adequate way to criticize the study is to present the arguments for an alternative view of earthquake engineering benefits.

It will be up to the reader of the two papers to judge the relative value of the two different approaches used. If clarification of the issues for interested geophysicists and engineers results from this written dialogue, the purpose of this note will have been well served. Certainly this paper, like that of Keys and Zelman, makes no attempt at completeness. It should be evident that, although the writer finds the quantitative basis of the approach of Keys and Zelman incorrect and believes the whole subject is much more complex than their approach suggests, he believes strongly in the utility of earthquake engineering research in Canada for humanitarian, social, economic and scientific reasons. Keys and Zelman neglect the contribution that basic seismological research makes to urgent technical needs, and their discussion of sectors of performance appears to bear no relation to current practices, western methods and the real needs, despite repeated re-examination of such matters in the past in investigations sponsored by the Science Secretariat and the Science Council (Rose, 1967, and Smith, 1970).

Part of the confusion which an interested reader may detect in the paper by Keys and Zelman is caused by a lack of precision in their apparently interchangeable use of the terms "earthquake research" and "earthquake engineering research". To avoid this problem in our discussion, a terminology will be defined which, it is hoped, will clarify the problem.

DISCUSSION OF PAPER NO. 24

TERMINOLOGY

To protect any society against the effects of earthquakes requires an estimate of seismic risk, an engineering seismology effort to measure adequately the strong motions at sites of interest from earthquakes of the size expected during the lifetime of the structure of interest, and an earthquake engineering effort to design structures to resist earthquake loads with a minimum human, economic and social penalty.

A continuing effort in all three areas is required, and the key questions are whether the national effort today safeguards national welfare, whether it is effective socially and economically, whether any elements of the programme have outlived their usefulness in a time of scarcity of scientific resources (at least of money), and whether the components of the effort are being performed in the right place and sector in an effective and well coordinated manner.

The study of Keys and Zelman implies that earthquake engineering can be studied usefully in isolation. This produces a consequent distortion of the role of government, university and industry. It must be emphasized that to protect the national welfare, a synergetic approach is necessary. Thus, briefly, the writer believes that it is the role of governmental agencies to provide the data-gathering infrastructure and technical expertize to estimate seismic risk and to gather strong-motion data. Both aspects proceed in cooperation with active university groups, and the Canadian situation is parallel to that in all Western countries. Earthquake engineering research is a function of university, industry and government: industrial participation is likely to be limited to ad-hoc studies necessary for a particular problem-solving aspect of industrial development.

None of the three aspects can proceed in isolation from each other, and any realistic economic model would have to recognize this. Furthermore, the effort in any one of the three areas produces benefits which extend beyond the particular problem, as will be outlined in later sections.

SEISMIC RISK ESTIMATION

For example, a seismic network, seismic equipment and trained seismologists contribute to far more than an estimate of seismic risk. In Canada, the same infrastructure is used for seismic verification research in arms control studies, which is a political priority of the government. In addition, the existence of the network with small extra resources allows an international contribution for humanitarian purposes to the assessment of seismic risk throughout the world and to the study of earthquakes. Finally, the network provides basic data for seismic studies of the evolution of the planet earth by university and government geophysicists, both national and international. As technology, an increasing population and a rising standard of living lead to the exhaustion of non-renewable energy and mineral resources, the study of the planet earth using seismological techniques becomes more and more essential to survival. The seismic exploration industry in Canada alone is a hundred million dollars per annum business (Smith, 1970). Reasons of this kind, which could be greatly expanded, leave the writer with an abiding sense of scepticism about the worth of current mathematical models for the determination of research priorities.

The arguments of Keys and Zelman proceed from the implicit assumption that the seismic risk is now adequately defined in Canada. This is scientifically incorrect, as any geophysicist with a feel for a geological time scale knows. In Canada, a quantitative assessment of the seismic risk has been made for the 1970 Edition of the National Building Code (Whitham, Milne and Smith, 1970). This assessment is regarded as the best possible one in our present state of imperfect knowledge, and with a data sample which represents a mere moment of time in the geological time scale. The lessons to be drawn from it are the need for government agencies to extend the data base in time and space, to improve its quality and precision including the accuracy of focal depth determinations, and the vital necessity to understand better the causes and mechanism of earthquakes by suitable earthquake research in universities and government. This latter problem is particularly acute in Canada because Eastern Canadian, Yukon, Arctic and some British Columbia earthquakes are not generally understood within the framework of the new global tectonics, which can rationalize much of the extensive worldwide seismicity.

To be of use for planning, for the siteing of nuclear reactors and other critical structures, for discussing major pipelines or other critical multimillion and sometimes billion dollar economic activities, information on earthquakes is required prior to and not following the decision or national necessity to build or develop, often for energy reasons. Furthermore, geological time cannot be scaled in this context no matter what the economic urgency or available funds, and a continuing coordinated effort by government throughout Canada is therefore vital. In the interests of brevity, the cogent reasons of efficiency and economy for assigning this role to government are not repeated here. They are described in the Rose Report (1967).

It is of interest to adopt some of the figures used by Keys and Zelman in the context of the earthquake risk problem. It is clear that more precision and certainty in seismic risk estimation would produce a net saving in the penalty for earthquake-resistant construction. A naive viewpoint (in analogy with theirs) would be to claim that the present annual penalty is

$$(1 \text{ to } 6\%) \times 11.4 \times 10^9 \times 50\% \doteq 60 \text{ to } 340 \text{ million dollars per annum}$$

following their figures of 11.4×10^9 dollars of construction in Canada in 1970, of which they claim one-half to be made in areas subject to earthquake risk, and using the accepted American figures that the added cost of earthquake resistant design increases building costs from 1 to 6 percent. It could then be claimed that any research in earthquake risk estimation leading to a possible reduction of 1% in this penalty by improved seismic risk estimation is worth 0.6 to 3 million dollars per annum. Using their accrual rates and applying the appropriate geometrical progression, we obtain 10 to 50 million dollars as present value. For all the reasons quoted earlier, it is not possible to assign costs realistically to this aspect of the government's seismological activities since, for scientific effectiveness and economy, they are integrated, but it is reasonable to cost that portion of the current programme applied to seismicity studies at perhaps between 0.2 and 0.3 million dollars per annum.

Has a 1% per annum reduction been achieved with such a high cost-benefit ratio as that theoretically and naively defined above? Certainly research in the last decade will produce considerable economic savings in Eastern Canada from the change in seismic zoning for the Montreal-Ottawa region in the 1970 National Building Code. The geophysicists, however, are under no illusion about such a claim. Having made the best possible estimate of the situation from the data available, the geophysicist accepts that he might be wrong, in which case the cost-benefit analysis may show negative benefits.

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More fundamental, however, than such a hypothetical mathematical model which reflects the viewpoint of the originator is whether a civilized country can afford not to maintain a service of seismic risk estimation. Certainly public interest and concern in this age of instant communications and world-wide awareness suggest such activities meet a social and psychological as well as a purely economic need. And how do we measure these - by the volume of letters received?

Since the future is unpredictable, and no amount of resources in money and manpower assigned to short term, priority research can overcome the geological time limitation, as development spreads throughout Canada, the case for a continuing national seismicity programme becomes stronger. For example, any mathematical model would have rejected the necessity on purely economic grounds to study Canadian seismicity in the Mackenzie Valley until very recently. Population density was low, and capital-intensive development negligible. However, the geophysicists with their sense of completeness and curiosity persisted in such studies, admittedly with a priority lower than elsewhere in Canada. Today, national decisions on multi-billion dollar pipeline routes with economic penalties of up to several tens or hundreds of millions of dollars, depending upon a route choice, must consider the data which heretofore was regarded as of no economic significance. No matter how large any immediate feasible investment to gather data, the facts of the geological time scale would prevent a crash programme solution. Fortunately, far-sighted scientific planning and operations have provided some data which can now be turned to meet a national need.

Tsunami prediction by international cooperation in earthquake research is an extreme but very relevant example for Canada of the utility of earthquake research: lives are saved by international cooperation in earthquake research, although no amount of conceivable engineering research can avoid the flood damage.

The principle reason for dismissing the possibility of earthquake control in Canada at the present time is that surface expressions of active faults with shallow focus earthquakes have not been unequivocally identified by the limited seismic research to date. It is a mistake to equate in principle earthquake risk estimation to flood forecasting - in the latter case locations are determined by topography and water courses. For earthquakes in Canada, no similar obvious restriction exists. For floods, there is usually a time warning and height of water versus time are the variables. The earthquake motion problem is infinitely more complex.

This writer would also question the assumption that Canada can probably not be considered as a major candidate for potential disaster - obviously the words "probable" and "major" need precision of definition before such a viewpoint should have any meaning for decision-making purposes.

Finally, the excellent geography and terrain of Canada suggest excellent and cogent reasons why Canada should contribute to studies of earthquake research as a contribution to a study of international problems quite apart from all the important national seismicity, arms control and natural resource considerations. It is noted that, for example, the United Kingdom with almost no seismic risk finds it advantageous to operate a Global Seismology Unit.

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ENGINEERING SEISMOLOGY

This author has used this term to define the problem of obtaining representative strong-motion records for the range of earthquakes likely to be experienced at the site of interest. The spectrum of accelerations and its variation with the duration of shaking depends, of course, on the magnitude of the earthquake, its focal depth, its fault parameters, the epicentral distance, the regional or local geology, and the character and topography of the foundation materials, or soils at the site of interest.

Theoretical simulations are, of course, important, but experience in California and Japan has demonstrated that there is no generally accepted method for the analytical determination of the signal character of the expected motions at a building site other than practical estimates from an ensemble of representative records (and their response spectra). Thus, the input spectra most effective for a dynamic engineering design of a structure must be measured. To obtain such records for a variety of representative earthquakes, distances and soils, suitably emplaced networks of accelerographs and seismoscopes must be operated in earthquake-prone areas for long periods of time. At one extreme of academic thought, the data obtained can be regarded as useful for the close-in study of earthquakes as geophysical phenomena: at the practical extreme, the soil or foundation problem is one of interest for a variety of reasons in engineering construction. American experience is the best guide to the problems, and the time scale constraints. California has the great advantage that its earthquake locations are comparatively well defined, and a strong-motion programme started in 1931, so that several hundred sites are now instrumented. The San Fernando earthquake of February 1971 thus generated about 200 usable records, but surprised everyone with a record from Pacoima Dam, situated on rock near the earthquake epicenter with a peak amplitude of motion which exceeded 1 g , several times larger than the expected value extrapolated from previous measurements at longer distances. This one record alone will change the thinking of many engineers involved in earthquake-resistant design and construction. It must also be remembered that strong-motion records for great earthquakes are non-existent, even in California.

The very modest Canadian programme of the Earth Physics Branch on the West Coast is described by Milne and Rogers (1971): a small number of instruments have also been installed in the St. Lawrence Valley by the N.R.C., and the Dept. of Energy, Mines and Resources have one instrument being installed in the Mackenzie Valley. Three strong-motion records exist for western Canada and none elsewhere in Canada.

Annual expenditure on this decade-old programme by government agencies has averaged perhaps ten thousand dollars in the last decade: it requires no imagination using the figures of Keys and Zelman or other more reasonable ones to argue a high cost-benefit ratio for this programme in a statistical sense. Patience and a long period of time will be required to collect systematically a representative collection of records. More investment can sample more sites and foundation conditions, but cannot affect the frequency of usable earthquakes.

Economic studies of the optimum investment in strong-motion studies cannot be usefully made unless some clear case histories become available of the design and construction economies achieved in Canadian critical structures using Canadian records. The circle is a vicious one, and, meanwhile, as Keys and Zelman suggest, we import the technology and Californian information, maintaining enough competence to exceed the norms of their encyclopaedia reader. We do this, despite the clear geophysical evidence that California records cannot represent the situation in eastern Canada, and the evidence from the Parkfield and San Fernando earthquakes that our "imports" are somewhat imperfect, as the "manufacturer" has just found out with the recent San Fernando earthquake.

A final point under this heading is that much earthquake damage is not produced by the shaking of structures, but by the instability of soils under strong vibration. Thus, decisions about the allocation of resources in earthquake engineering must involve judgements about the relative importance of the soils problem: for a country with vast hydroelectric schemes, and the notorious clays of eastern Canada, this is a further real complication in an already complex and interacting study.

EARTHQUAKE ENGINEERING

The writer is not a professional engineer. However, under this heading he includes the ensemble of activities involved in designing and constructing high-rise buildings, critical structures, pipelines, transportation facilities and, indeed, construction generally, with a minimum economic penalty to meet a given requirement. This may be a National Building Code requirement, a requirement by a regulating agency such as the National Energy Board for environment protection and public safety with, for example, nuclear reactors and pipelines, a requirement to avoid collapse under certain predicted earthquake loads, a stiffer requirement to avoid all structural damage under another earthquake load, and so on. To meet any defined requirement in the most effective way, the engineer needs to know the "design earthquakes" for the lifetime of the structure - the information summarized earlier under the headings of Seismic Risk Estimation and Engineering Seismology. He, or the profession, needs to undertake research on structural dynamics. A non-exhaustive list would include such topics as experimental studies of scaled models, studies of the dynamic response of full-scale structures, studies of the dynamic properties of construction materials, structural connections and so on, studies of the non-linear response of materials and models, and so on. If he is a soils specialist, he needs information on the mechanical and dynamic properties of soils and foundation materials in the linear and non-linear regions. The earthquake engineer needs to observe the effects of earthquakes on structures and foundations of different kinds by earthquake damage inspection.

What is the purpose of the earthquake load provisions of the N.B.C.? The N.B.C. provisions can most simply be described as an attempt to find a reasonable compromise in enforcing earthquake-resistant construction with its attendant economic penalty in areas of high earthquake risk. The reasonable compromise is that loss of life should be minimized, and the code should guard against structure collapse under the probable loads. The basis of estimating seismic risk in the 1970 N.B.C. accepts a one percent annual probability that the design load may be exceeded. The precautions will also reduce the dollar loss to property, and drastically reduce the adverse psychological effect of earthquakes on modern society.

For certain critical structures such as nuclear power stations and pipelines, considerable over-design is essential, either by regulation or otherwise, for large scale safety of the public or the environment. Even in California, the efficiency of earthquake-resistant structures has not yet been tested under loads from magnitude 8 earthquakes. Thus, all earthquake codes today are in one sense substantially untested, although Californian experience with schools suggests that, to intensity VIII, the damage/dollar value ratio of earthquake-resistant buildings built to good code specifications can be reduced to 1%.

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The analysis of Keys and Zelman errs in ignoring the important human element. Furthermore, the writer believes that their estimates are grossly in error. In the U.S.A., the average annual destruction to property caused by earthquakes between 1933 and 1971 is between 27 and 40 million dollars annually. The uncertainty in the annual average is due to the uncertainty of the value of property damage caused by the recent San Fernando earthquake of February 1971. The average for nearly forty years includes the Anchorage earthquake of 1964 and an unofficial estimate of the San Fernando event. Canadian building practices are very grossly similar to those in the U.S.A., our density of development is very much less, and the earthquake risk averaged throughout the developed area of the country is no higher than that in the U.S.A. Our rate of capital investment, and total capital investment is at least an order of magnitude less than the U.S.A. On all grounds, therefore, we should expect, with statistical fluctuations, a loss rate between one and two order of magnitudes lower than the U.S.A. Adopting a factor of thirty, a realistic assessment of the annual vulnerability to property damage is less than about one million dollars. Indeed, although precise figures have never been collected and ignoring tsunami damage, the evidence since the 1935 earthquake is that Canadian annual losses are much less than one hundred thousand dollars per annum. This compares, in Keys and Zelman's attempt to assess the overall vulnerability of the economy to one year's construction, to an equivalent figure of $.0025 \times (11.4 + 6.4)/2 \times 10^9$ dollars, or 24 million dollars, which is at least one, and most probably two, orders of magnitude too high. The geometric progressions used by Keys and Zelman to assess the gross vulnerability are also arguable: if the population is protected against loss of life, at least in a gross sense, and if the population is well educated, informed about earthquakes and resilient, production is maintained, though, of course, it is different and may be heavily involved in reconstruction with consequent modernization.

The fallacy of the third term in the Keys and Zelman model is clear if one considers the post-war development of the German economy following wartime devastation of property and contents.

Another reason for the discrepancy in the two approaches is that much of the capital investment figure quoted is in structures which, for the most probable earthquakes during their lifetime, are extremely earthquake resistant - frame housing, for example.

The author thus disputes the conceptual base of the economic model of Keys and Zelman, and the numbers employed. However, the entire problem is an extreme value one, and the day after this is written, an earthquake may cause more than 100 million dollars of property damage in a major Canadian centre. One causing several billion dollars of property damage may similarly occur in San Francisco or elsewhere in California.

It is the job of the earthquake engineer to minimize this property damage, and certainly to avoid collapse and heavy loss of life. As explained earlier in this paper, following the figures of Keys and Zelman, the annual economic penalty to avoid this loss of life and to minimize property damage could be naively estimated between 60 and 340 million dollars. However, allowing for housing and other forms of capital investment, it seems safe to divide this estimate by at least three. The net effect is to suggest that the present economic penalty is between 20 and 100 million dollars annually, a non-negligible sum. A reduction in this amount by 1%, modified in the accrual manner suggested by Keys and Zelman, suggests that research leading to a reduction of 1% in the economic penalty for earthquake-resistant construction would have a present value of about

$$1\% \times (20 \text{ to } 100) \times 10^6 \sum_{i=0}^{20} \left(\frac{1 + .08}{1 + .10}\right)^i$$

or about 3 to 17 million dollars.

It is interesting to note that this estimate is only about an order of magnitude lower than the figure of Keys and Zelman. They overestimate the annual vulnerability of the economy to damage, but their model does not recognize that the economy is paying a substantial penalty to avoid loss of life and certain gross catastrophes. Earthquake engineering research can certainly minimize that penalty but, as with all research, it is not possible to estimate, particularly beyond a certain point, that a further investment in effort will produce a specific economic consequence or financial saving.

Adopting 20 million dollars per annum as the economic penalty for safeguarding human life from earthquakes, the enthusiast for calculations can go further. This sum is about equal to the contribution to the Gross National Product during their lifetime of 60 people: therefore, if 120 deaths per annum were saved, the expenditure could also be justified on economic grounds. The author makes these estimates, not because he thinks they are seriously relevant, but to illustrate how dangerous it is to make decisions or to suggest that decisions might be taken based on artificial mathematical models. As an extreme example, if one believes in the necessity to control population growth, the support of earthquake engineering could be regarded as producing only negative benefits - medical research would be, of course, in the same position (always provided the lack of it hurts others).

The reality is that a rich, well-informed technologically advanced Canadian society increasingly preoccupied with the quality of life can afford a modest premium to be informed about earthquake risk, and can afford engineering seismology and earthquake engineering research for exactly the same reasons it maintains a great many humanitarian and protection services - to protect the individual, to maintain public order and safety and to minimize the disruptive effects of natural catastrophes. The mathematical models used in purely economic justification of such activities must be regarded with considerable scepticism. Equally valid assumptions based on other viewpoints can lead to different conclusions.

Finally, it must be re-emphasized that earthquake engineering advances cannot be viewed in isolation: the results achieved are, of course, useful for the solution of wind-loading and other dynamical problems and produce better construction practices generally of benefit to the economy.

THE EARTHQUAKE ENGINEERING ECONOMIC PENALTY AND BENEFITS

The reader will now understand the dangers in too simplified studies of a complex problem, and hopefully will now understand how different answers are obtained with different assumptions.

In order to make any economic cost-benefit analysis, gross over-simplification is necessary and it must be possible to have a measure of the protection of earthquake-resistant construction to property damage in earthquakes. There is no Canadian analysis (in itself significant), but an excellent and realistic article by Crumlish and Wirth (1967) provides a basis from American surveys to make some extremely crude estimates.

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Crumlish and Wirth illustrate that the universal adoption of earthquake-resistant construction could produce about a forty percent saving in property damage for an earthquake of intensity VIII in a North American urban area (magnitude 6 to 7). The price paid for this is between a one and six percent economic penalty. Using a discount rate, R, of 10%, and a depreciation rate, R_1, of 5%, if the annual probability of such an earthquake is x percent (the "design" earthquake for this argument is a geophysically reasonable one), then a balance is struck with a cost-benefit ratio of unity and life saved when

$$1 \text{ to } 6 = .4x \left(\frac{1 + R}{R + R_1}\right) .$$

Therefore, $x \doteq 0.3$ to 2%, for buildings with a lifetime of several decades. Notice the difference in this calculation made by somewhat arbitrary decisions about the discount and depreciation rates. A more exact calculation is possible for finite lifetimes, but the precision of the calculation does not warrant the minor extra algebra. Thus, we see that for cities in Zone 3 in Canada ($x = 1\%$ approximately), using present technology the formal cost-benefit ratio is close to unity. Hardly, per se, a striking result, but quite possibly a useful one when economic arguments are to be discussed.

This calculation illustrates another problem - if a lower probability of a higher magnitude earthquake is accepted (a reduction in probability by a factor of 10 per unit increase of earthquake magnitude is a good geophysically-supported estimate), a complication is introduced for which no calculation is possible since the basic damage data do not exist. Keys and Zelman err in this respect. Their Figure 1 suggests a decreasing probability of a larger earthquake which is geophysically real, but at lower probabilities the damage per earthquake is rising more rapidly than the decreasing probability. In this sense their vulnerability is without a finite bound, which is logically absurd. The error which has been made is to extrapolate formal calculations to return periods which are absurdly long with respect to the time base generating the probability function. If a formal calculation were to be attempted assuming magnitude 8 earthquakes (intensity X to XII) at near the 1 percent probability level, it seems clear that all economic calculation would be invalid in that all a code can really do is safeguard life and minimize disruption of essential services.

Again the answers obtained depend heavily upon the premises written into the appropriate model: one of the problems is that the casual reader of such studies may lose track of these assumptions and be all too ready to accept uncritically the result of the calculation.

EARTHQUAKE ENGINEERING BENEFITS AND INSURANCE PREMIUMS

It appears to this writer that Keys and Zelman obscure the difficulty with insurance premiums: because of the difficulty in estimating seismic risk with precision in time (and often in space), and because major losses are comparatively infrequent, occurring with a time interval comparable to the lifetime of a company, it is very difficult for an insurance company to build up reserves to cover losses in a statistical actuarial sense without charging premiums which in a shorter interval of time may appear to be excessive. Earthquake insurance is often not bought by property owners because the owner judges the premium to be excessive: it is doubtful if he does a calculation, but rather uses historical personal prejudices about the risk.

The writer does not know any Canadian studies in the field, but Californian experience may be relevant to a Canadian economic overview. Thus, one can ask whether it is possible that the costs of improved earthquake-resistant design and construction could be recovered by the possible decrease in earthquake insurance premiums. In California, and it is suspected in Canada, only a limited saving is possible because most commercial and residential property owners do not purchase earthquake insurance. A number of calculations have been published by Crumlish and Wirth (1967) which show that for a 20-year depreciation, with California earthquake insurance premiums, expenditures up to 3.5 percent in earthquake-resistant construction can be realized at no additional cost if the maximum premium differential of $0.60/$100 is granted by insurance companies. In this calculation, maintenance and tax rates were assumed to be 1% each of the original cost of a building, and an interest rate of 6% was assumed. Of course, if the arguments of Keys and Zelman for consideration of the value of the business conducted in the property are used, this aspect of the case for earthquake-resistant construction is strengthened.

It must be remembered that in the event of a major short-term loss, the insurance companies have no option but to increase premiums. In the U.S.A., there have been suggestions, because of the actuarial difficulties, that the Federal government play a role in providing earthquake insurance.

SUMMARY

Studies of the benefits of earthquake engineering should avoid the appearance of an economic precision which is really non-existent. Expenditures in earthquake-resistant construction are for most cases primarily to save life with a minimum economic penalty: however, there are cases of certain unusual projects, usually of a massive capital nature, where the earthquake-resistant construction is essential to protect the environment.

Economic benefits do accrue from such activities, and in certain cases the additional costs could be recovered by a reduction in earthquake premiums - in an actuarial paradise, this would obviously be true.

There is no general way in which the economic effects can be predicted from additional investment in research programmes and an effective cost-benefit analysis made. However, it is clear that seismic risk estimation, engineering seismology and earthquake engineering activities must be pursued together in Canada for social, humanitarian, economic, cultural and technical reasons. Improvements must be made in the development, implementation and enforcement of earthquake-resistant building codes.

In a judgement about research priorities, it must be remembered that if seismic risk estimation for an area can prove there is no risk, then, in principle, no money need be spent on earthquake-resistant construction in that area.

None of the problems is solved in Canada and a continuing effort on the part of government, universities and industry is necessary to safeguard the quality of Canadian life. The Canadian National Committee on Earthquake Engineering with representation from all levels of government, industry and university has a key role to play in coordination of the many different activities which contribute.

If a major earthquake causes appreciable property damage in Canada, inspection, survey and analysis of the damage to construction with and without earthquake-resistant qualities is necessary in order to obtain a figure for the net saving in property damage which might be expected in Canada. Some very rough estimates based on Californian experience suggest that in the event of a major earthquake about forty percent of the property damage which can be expected might be avoided by the use of earthquake-resistant construction techniques. Since the penalty for this protection may lie between 1 and 6 percent, purely economic arguments with infrequent major earthquakes in developed areas will not be too convincing in Canada. This is because the value of life, psychological factors and public morale are neglected in mathematical models.

Any economic models of benefits really require prediction of earthquakes with a precision which is not possible. Intrinsic in such models is the necessity to know the relation between expected damage and some measure of earthquake activity and strength, and information on the economic penalty of different forms of earthquake-resistant construction and the corresponding levels of damage to them. To date the problem in Canada is intractable and this author hopes that decision-making on such a matter will appreciate the clear difficulties and lack of an adequate data base. No Canadian information is known to the writer on the performance of research in earthquake engineering: it is known semi-quantitatively with respect to seismic risk estimation.

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The analysis and initiative of Dr. J.D. Keys and Mr. M. Zelman provided the necessary stimulus to the author to organize and present his views on the topic: he would like to thank these writers for giving him the opportunity to express his differing views.

REFERENCES

1. Crumlish, J.D. and Wirth, G.F., "A Preliminary Study of Engineering Seismology Benefits", U.S. Dept. of Commerce, Environmental Science Services Administration, 1967.

2. Keys, J.D. and Zelman, M., "The Economics of Earthquake Engineering Research", Paper No. 24, First Canadian Conference on Earthquake Engineering Research, Vancouver, May 1971.

3. Milne, W.G. and Rogers, G.C., "Earthquake Engineering Research at Victoria Geophysical Observatory", Paper No. 2, First Canadian Conference on Earthquake Engineering Research, Vancouver, May 1971.

4. Rose, D.C. (editor), "Physics in Canada - Survey and Outlook", Special Study No. 2, commissioned by Science Secretariat, 1967.

5. Smith, C.H. (editor), "Background Paper on the Earth Sciences in Canada", Geological Survey of Canada, GSC Paper 69-56, pp. 187-199, 1970.

6. Whitham, K., Milne, W.G. and Smith, W.E.T., "The New Seismic Zoning Map for Canada, 1970 Edition", Can. Underwriter, June 15, 1970.

Authors' Reply to the Discussion Paper Entitled: "AN ALTERNATIVE VIEW OF EARTHQUAKE ENGINEERING BENEFITS" by K. Whitham

It is difficult to rebut Dr. Whitham's criticism of our original paper since he largely addresses himself to methodological details which we stated to be only a general introduction and basis for discussion. In fact we specifically pointed out that much more research was required in the methodology of justification and also that we had no intention of defending what was, at best, a first shot into the general area.

Thus the statement by Dr. Whitham that "the argument of Keys and Zelman proceeds from the assumption that the seismic risk is now adequately defined in Canada", is simply not so. The assumption made in our paper is that it is possible to make an intelligent estimate of the seismic risk, at the very least to the extent of making a probabilistic statement about the lower bounds of this risk.

It is not proposed to advance a rebuttal of Dr. Whitham's numerical analysis since the mere fact that he has suggested an alternative methodology in itself is already justification for our paper. What is disturbing, however, in Dr. Whitham's paper is the general assumption that because we cannot foresee future benefits, such as the apparent present economic value of knowledge of the seismicity of the MacKenzie Valley, we must do research on a very broad basis because of possible eventual need for the information.

In our paper we suggested three possible justifications for research, i.e. cultural, educational, and economic. If the economic value cannot possibly be predicted on even a very long shot probabilistic basis, then we would suggest that the research must be justified on cultural or educational grounds in competition with all other cultural and educational type research which must be funded from the public purse, and the justification in these areas is entirely different.

Dr. Whitham seems to have missed one of the basic theses of our paper which states that the policy decisions to invest public resources in research should be specific and explicit depending on some type of national objectives. Dr. Whitham's argument that our view completely fails to explain why the United Kingdom finds it advantageous to operate a global seismology unit, completely ignores what we have referred to as cultural values of research. By cultural in this context, we mean at least partially what he has referred to as "social and psychological" needs.

For obvious reasons within the objectives of our paper we deliberately did not differentiate in our terminology between seismic risk estimation, engineering seismology and earthquake engineering, since in the economic area all three have a part to play in the minimization of risk. Thus, once the general case has been made for economic type research, the actual allocation of resources between the different areas will have to be based on a further breakdown among the various disciplines.

At the same time research by itself does comparatively little to reduce the risk and is generally required to be accompanied by a sizeable investment of extra construction costs, location costs, etc. Partially for this reason we only assumed a reduction of 1% in the actuarial risk as being attributable to research whereas looking at the reports of a number of major earthquakes which have occurred in practice considerably greater reduction in risk can be achieved by intelligent construction practices. That, however, was not the topic of our paper.

It is difficult to resist the temptation to be very critical of Dr. Whitham's economic model as described in pages 7 - 8 of his paper and perhaps it is sufficient to state that average annual damage in the United States between 1933 and 1971 is irrelevant both from his own arguments about the time scales of earthquake risk, and also the fact that the results of research are generally only incorporated in future construction. Thus trend forecasting based on econometrics seems to be a more reliable guide.

A further argument in Dr. Whitham's paper would almost suggest that, taking the analogy of the post war development of the German economy following its wartime devastation, one could assume that periodic destruction of the economy is a good thing. However, we feel that to succumb to the temptation to engage in a critical review of the economics of Dr. Whitham's paper would be wrong. It is very interesting that he argues "that a rich, well-informed, technologically advanced Canadian society, increasingly preoccupied with the quality of life, can afford a modest premium to be informed about earthquake risk". This is perfectly true on cultural grounds and would entitle Dr. Whitham to take his place in line with the National Gallery, national parks, historic sites, etc. We completely rebut the suggestion that the approach recommended in our paper requires a purely economic justification of such activities. What is required is a differentiation between the varying objectives of government.

In summary, one can perhaps briefly look at Dr. Whitham's summary of his paper. He states that "engineering seismology and earthquake engineering activities must be pursued together in Canada for social, humanitarian, economic, cultural and technical reasons". We have no argument with this except that the various reasons must be sorted out and the case made for research in each area specifically in competition with all the other activities in the country which contribute towards this particular objective. The kind of statement that "a continuing effort ----- is necessary to safeguard the quality of Canadian life", is the type of irrelevancy which in actual fact means precisely nothing since, in the applied science research area, we are not entitled to expect society to financially support our work towards the achievement of what we define as "the good life", unless we are prepared to specify in detail what this means.

Further when Dr. Whitham suggests that "the value of life, psychological factors and public morale are neglected in mathematical models" this is simply not so. If one studies two of the texts cited in our bibliography, i.e. Prest & Turvey and Marglin, and a number of the publications of the Brookings Institution and other publishers in this area, various methodologies for including what one might call psychic values have been developed in a number of areas in the world.

The final point is that Dr. Whitham's assumption that the problem in Canada is intractable is a kind of negative approach which we find completely untenable. We agree entirely that the problem has not been solved but we feel that on our part it would be arrogant to assume that because we do not have the solution, none exists.