X. ECONOMIC CONSEQUENCES OF EARTHQUAKES

10.1 Introduction

For the purpose of physical development planning, it is now necessary to define the criteria by which the effects of seismicity can be translated into economic terms.For it is only in economic terms that a common denominator can be expressed for the different factors taken into consideration in physical planning, one of which is seismicity. Planners should know the economic incidence of earthquakes on all investment sectors: agriculture, stockbreeding, industry, housing, etc. Here, however, we shall deal only with the economic effects of earthquakes on building, not only because this is the type of investment most vulnerable to seismic activity, but also because this sector covers all the main aspects of the problem.

In the first place, it may be stated that the economic incidence on a building cannot be measured solely by the cost of the damage which might be caused by future earthquake. Estimation of the cost, as determined by the probability of seismic events, is like the technical problems an insurance company has to solve when trying to establish the earthquake risk it will have to cover, or, in the context of planning, like the problems that arise when estimating natural disaster risks solely with regard to the cost of relief and reconstruction.

In the context of the more general problems considered here, however, it is necessary to add the cost of all the preventive measures taken to increase the earthquake resistance of buildings, and the cost resulting from the effect of earthquake protection on building density. This latter cost takes the form of increased expenditure on land as a component of total building costs.

Lastly, the risk of loss of life must also be taken into account and translated into monetary terms. All these aspects will be discussed in the present chapter. First of all, however, we must draw attention to certain general problems connected with these evaluations and their uses.

The first problem is that the cost of both expected damage and preventive measures depends on the level of protection adopted as a function of the seismicity; in other words, the risk of collapse which is considered acceptable. Obviously, the stronger the building, the smaller the risk is for a given seismic intensity.

It should be noted that the level of risk implicitly accepted by the standards now in force in various countries is not based on a cost-benefit analysis of the different possible degrees of strictness of these standards, but rather results from a certain tradition deriving from empirical observation of the damage caused in past earthquakes.

Considerable efforts are now being made in civil engineering circles to rationalize these traditional choices. The studies take into account the difficulties resulting from the interruption of industrial or commercial activities caused by evacuation of a town, as well as many other costs and benefits which cannot be expressed directly in monetary terms. In short, they take into account the aspects described as "intangible", which are bound up with a society's actual quality of life.

Pending determination by these researches of the most rational levels of acceptable risk, the additional costs of earthquake-resistant building will be presented here adopting as a variable the seismic coefficient, i.e. the fraction of weight to be taken as a horizontal force when calculating the structure of a building. This coefficient is directly related to the accepted risk.

Moreover, in the context of physical development planning, it now seems reasonable to tie the additional cost to the values of the seismic coefficient already adopted by the legislators. Here it is advisable to examine the spirit in which standards for earthquake-resistant building have been drafted.

10.2 Spirit of building standards for earthquake zones

As shown by the information given in the annex on the "main destructive earthquakes" the most reliable data for the United States show 1,200 people killed by earthquakes along the Pacific coast, where seismic activity is most intense. The most interesting cases are the 20 most violent earthquakes of the last 40 years, since they affected buildings which were mostly of a recent type, built according to earthquake-resistant standards. During these last 40 years, the total number of victims was 320. Of these, 110 people were killed by the tsunami which followed the 1964 Alaska earthquake; 28 by landslides; 4 by falling objects; and 3 died as a result of heart attacks. It can be concluded that loss of life due to structural weakness of buildings occurred only in isolated cases. According to the same source, the total damage caused by these last 20 earthquakes was over $ 1.5 billion. The cost of damage is considerably lower for earthquakes of lesser intensity, although they occur more frequently.

The figures are very different for countries in which most buildings are designed without any regard for the effects of horizontal forces in seismic zones; and the same is true of the relatively recent past, when building codes did not exist.

For instance, according to various reports, earthquake disasters caused 25,000 deaths in Italy during the last century.

Much more accurate figures are available for the Kern County (California) earthquake of 1952, after which a comparison was made of the damage sustained by two different types of school buildings; recent buildings which had been designed according to earthquake standards and older buildings which had not. The highly significant results are shown in the following table:

Damage	Buildings designed according to earthquake standards	Buildings not designed according to earthquake standards
No damage	21	1
Slight damage	6	9
Moderate damage	1	9
Severe damage	0	13
Collapse	0	1

Enough information is available to be able to affirm that the adoption of technical standards for buildings in earthquake zones achieves the main purpose of the legislators: to save human lives. On the other hand, all old stone buildings, especially if they are in bad condition, should be treated with caution.

Another observation can be made regarding the damage caused by the 20 earthquakes listed as the most severe in the United States between 1933 and the present time. Part of the damage affected buildings of recent construction, correctly designed to earthquake standards. But earthquake protection regulations are intended to limit damage by low-intensity shocks: they do not ensure that buildings will remain intact in more violent earthquakes. Generally speaking, it can be expected that there will be an average of one small earthquake during the nominal life of a building, i.e. 100 to 150 years.

Buildings should be designed with a third object in view: hospitals, electric power stations, police stations, fire stations and other public buildings, whatever the event, must be able to serve as centres of relief, organization and shelter, even after a natural disaster. Moreover, if radio stations and telephone and telegraph systems are put out of action by a disaster, the disorganization and damage will be greatly aggravated. The use of transport facilities should also remain possible in the affected area, so special attention must be given to the protection of bridges, railway lines and roads. In many places, for example, it is important to check the stability of slopes verging on lines of communication and to take care that landslides will not cut off access to areas likely to be struck by a disaster.

There are other types of building which should be able to resist even the most violent earthquakes without damage: those housing people who cannot be quickly evacuated in case of danger, such as kindergartens, primary schools and hospitals. Buildings holding dangerous substances are in the same category: nuclear power stations, oil refineries, chemical plants, etc.

In short, structural design is now developing to meet various requirements. Private dwellings and industrial buildings must be able to withstand without damage an earthquake of an intensity which, in the area in question, will have a return period equal to the nominal life of the building, i.e. an average of 100 years. Their structures must also have a sufficient margin of strength beyond the elastic limit to withstand without collapsing the most violent earthquake foreseeable in the area, even if they sustain substantial damage.

Communication lines and the special buildings mentioned above, on the other hand, must be able to withstand without damage the most violent predictable natural event in the area in question.

These ideas need some clarification, however. The "most violent foreseeable earthquake" does not and cannot correspond to an absolute limit; in other words, it is not possible to fix a nominal intensity which can never be exceeded by any future earthquake. What can be done (when the seismicity of the area is well known) is to correlate the intensity of an earthquake with its return period, i.e. period of time in which, on the average, an earthquake of the same or greater intensity will occur once.

To be more precise, it can be said that the choice of nominal intensity is intended to ensure that an earthquake capable of destroying the building will have an extremely long return period; it follows that insofar as the destructive effects of earthquakes are concerned, the life of buildings will be statistically much longer than their nominal life. The same idea can be expressed in more concrete terms: the purpose of the standards is to ensure that the risk of collapse, i.e. the average number of collapses per unit of time due to earthquakes, is sufficiently small for private dwellings and practically nil for the special buildings mentioned above.

10.3 Cost-benefit analysis

As has already been mentioned, the present section deals only with the economic incidence of seismic activity on buildings. They represent the type of investment most vulnerable to earthquakes and their case covers the main aspects of the problem raised in the other sectors of activity. For the purposes of delimiting and analysing the research done on this problem, it will be convenient to divide the subject into three parts :

1/ the technical problem, i.e. evaluation of the risk of collapse of a building, which depends on the seismic characteristics of the site and the strictness of the design standards to be adopted;

2/ the economic problem, which comprises the evaluation of direct and indirect costs, either at the building stage or in the event of collapse;

3/ the problem of intangibles, which includes all the non-monetary costs and benefits, such as the expected number of victims and the quality of individual or community life.

The technical problem and the economic problem reflect different aspects and therefore require different methods, depending on the type of building considered. A proposed model calculation for a residential block will be discussed later. The problem to be solved would be the same for the special buildings mentioned above though the calculations would be more complicated : the collapse of these buildings would have disastrous results, but fortunately such an event may be considered extremely rare. It is necessary, however, to make probability calculations where extrapolation from the existing data becomes more uncertain.

10.4 The technical problem

This problem comprises all aspects of seismic activity at a given place, represented by the function P(I), which expresses the probability that an earthquake of intensity $\geqslant$ I will occur at the site considered in a given number of years. Particular attention should be paid to the value P_n (I_m) of this function, which is the probability that within a period of time equal to the nominal life of a building (100 to 150 years for a private dwelling) there will be an earthquake of intensity greater than or equal to the intensity I_m, which the standards implicity regard as the maximum foreseeable intensity for the site in question.

If it is assumed that an event of intensity greater than or equal to I_m can, in theory, cause the collapse of a building, then P_n (I_m) represents the probability that the building will collapse during its nominal life as a result of seismic events. We shall call this value the seismic risk, or risk of seismic collapse, which will be more briefly denoted by the letter P.

The essential elements of the calculation are given below.

10.4.1 Frequency-magnitude relation

The frequency-magnitude relation for a series of earthquakes is expressed by the classic equation of Gutenberg and Richter: log. N = a-bM, where N represents the number of earthquakes in a given region of magnitudes included in the interval M+dM. The cumulative frequency distribution for a magnitude equal to or greater than M is obtained by integration of the above relation, log. N = a' - bM. The coefficient a (or a') varies from one region to another and depends on the period of observation; it may be regarded as a comparative measure of seismic activity. The coefficient b should not depend on the period of observation; long considered as constant and having a universal value, this parameter in fact varies significantly from one region to another; in old tectonic regions it has low values (0.5 to 0.7); in young tectonic regions the values are higher (oceanic seismic zones: 0.9 to 1.5; circumpacific zone: 0.8 to 1.5; alpine zone: 0.7 to 1.1).

V. Karnick (1968, 1971)has confirmed the existence of different values of b for different European seismic zones and noted that there is an approximate relation between b and the average depth of the foci, and between b and the maximum magnitude.

10.4.2 Index of seismicity and specific seismicity

The frequency-magnitude relation can be used to calculate the annual number of earthquakes of magnitude $M \geqslant M_1$. This number is the index of seismicity N_1

$$N_1 = 10^{a'-bM_1}$$

Specific seismicity is defined as the average annual number of earthquakes of magnitude $M \geqslant M_1$ affecting the unit of area (for example 10^5 km2).

Some authors, extrapolating the magnitude-frequency relation towards large magnitudes, have concluded that in each region an earthquake of very great magnitude ($M > 8$) can be expected after a longer or shorter period of time.

In the case of France, for example, it is found that the average periods for the occurrence of earthquakes of magnitude 8.5, 8.0, 7.5 and 7.0 would be 1429, 556, 217 and 85 years, respectively; these figures are in direct contradiction with the observed data, which show that for the last 500 years the magnitude of earthquakes in France has not exceeded 6.5 (Radu, 1973).

In fact there must be a specific maximum magnitude for each region, depending on its seismotectonic activity. For example, the maximum magnitude will be smaller in old substrata in which there has been no orogenic activity since the Hercynian era; on the other hand, it will be greater in zones where stress is caused by contact between the various large plates mentioned above.

The formula given above was in fact obtained by Gutenberg and Richter on the basis of a large number of events of medium magnitude (of the order of 4).

Vit Karnick, who has calculated the formula for the European and Mediterranean seismic regions (see, for example, fig.: 10-1, 10-2, 10-3, 10-4), also used for each region several hundred data relating to events of magnitude 4 and a few events of $M = 6$. Consequently, extrapolation of such a formula to $M = 7$ or 8, the values which are important for the evaluation of seismic risk, is rather hazardous.

For the asymptotic values of the frequency-magnitude relation, a statistical formula using what are called "extreme values" is more appropriate. It is used for many natural phenomena (winds, river flooding) in cases where attention must be drawn to asymptotic values necessarily linked with a small number of statistical events. It must be noted, however, that this runs counter to historical results in practically all countries : for past centuries all trace has been lost of the many low intensity events, but not of the very few which were disastrous. The theory of extreme values, which establishes a relation mainly for large magnitude events, is particularly suitable for this kind of calculation.

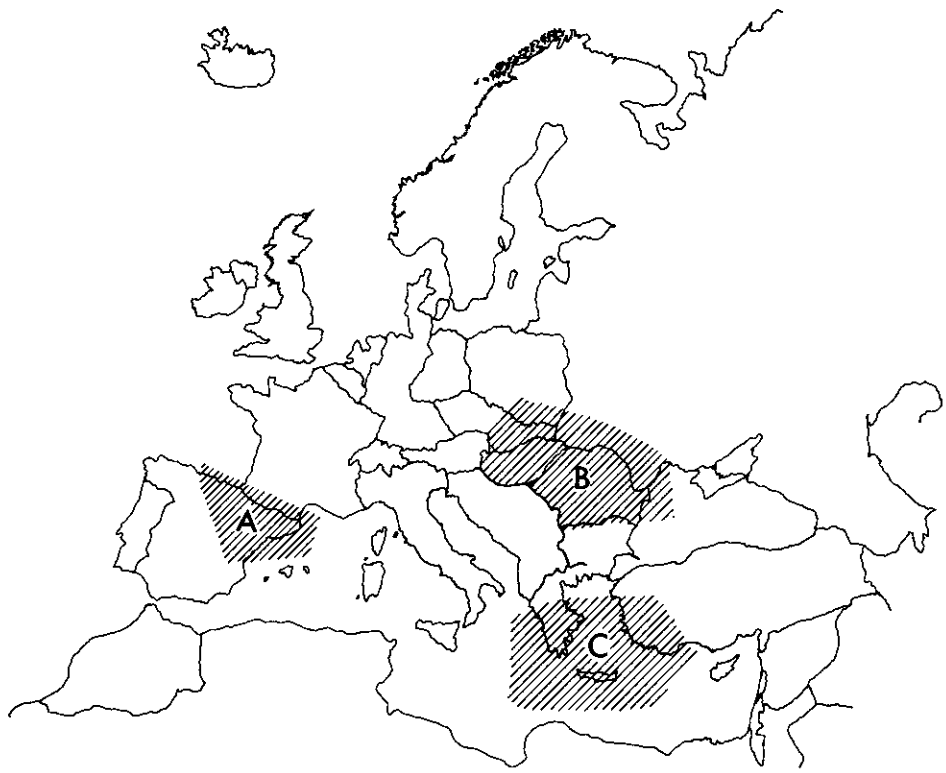

Fig. 10-1

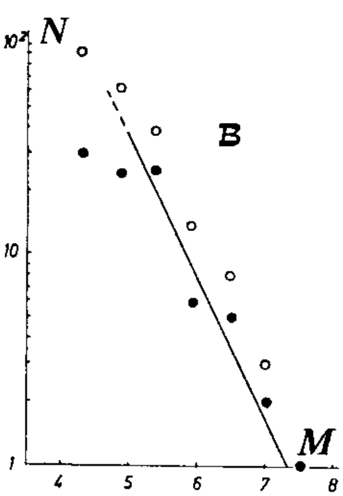

Fig.10-2

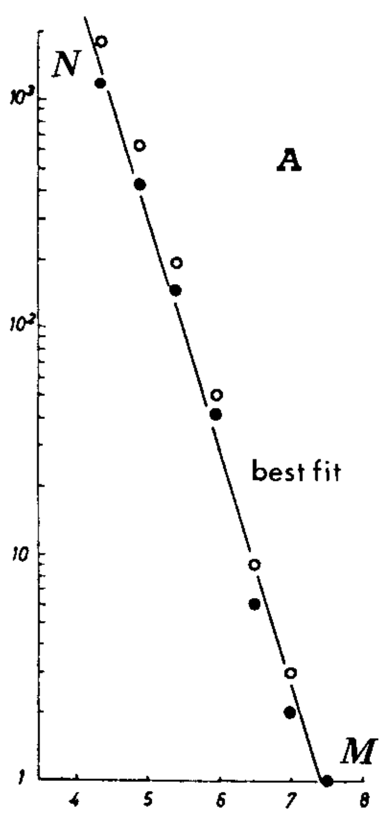

Fig.10-3

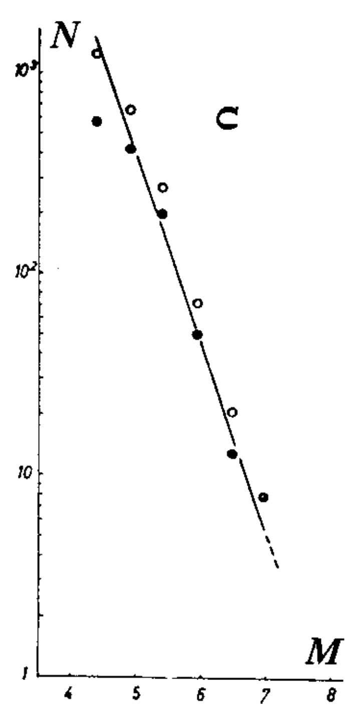

Fig.10-4

These theories cannot be discussed at length here; however, the reader is referred to the work of Lomnitz and to some recent publications by the Massachusetts Institute of Technology (USA), which has often been commissioned to make maps of seismic risk for planning urban areas in the process of development or areas expected to receive a considerable volume of public or private investment.

10.5 Estimation of costs

On the basis of what was said above in paragraph 4, we can define I_n, which is the intensity of an earthquake having a return period comparable to the nominal life of the building, and I_m, which is the maximum intensity for the site associated with a very long return period. Let us also assume that the earthquake-protection standards require buildings to withstand without damage earthquakes of intensity $I \leqslant I_n$, and to withstand without collapsing, even if they sustain a greater or lesser degree of damage, earthquakes of an intensity between I_n and I_m.

The two values $P_n(I_n)$ and $P = P_n\ (I_m)$ will then represent the probability of an earthquake occurring during the nominal life of the building which is theoretically capable of damaging it or causing it to collapse.

Assuming that these two values are known within the limits stated in paragraph 4, the three essential parameters of the cost-benefit analysis, according to Wiggins, are as follows:

- the cost of prevention, i.e. the cost accepted by society for protecting its buildings against earthquakes. This cost is clearly linked with the choice of the two values I_n and I_m;

- the cost of earthquake damage to the structures, infrastructure and social activities of a region. In theory such damage is only attributable to earthquakes of intensity greater than I_n and increases as the difference $I-I_n$ increases, the collapse of the building occurring when $I \geqslant I_m$;
- the number of victims of structural collapses which will occur in earthquakes of intensity $I \geqslant I_m$.

Even if only within the limits of these parameters, the problem which arises has been debated at length, because the third consideration - the number of victims - is not a parameter of the same order as the other two and has been found difficult to translate into monetary terms.

An interesting formula for overcoming the difficulty has been proposed by Grandori, the present President of the European Committee on Earthquake Construction, whose reasoning is as follows:

Let us assume that for a given activity (involving a known risk) the community has attained a satisfactory cost-benefit equilibrium, so that any subsequent change in the risk would entail a cost which the community would consider excessive. This does not necessarily lead to the establishment of a direct equivalence between a human life and a sum of money. The judgement of the community can be interpreted as follows: the additional cost of the preventive measures needed to save one more human life in the activity considered is higher than the additional cost of similar measures in another activity; it would therefore be more economical, insofar as a greater number of human lives would be saved, to use the resources of the community for reducing the risks incurred in other activities.

This leads to consideration of a new index of comparison between the different risks: the additional cost per life saved, $\frac{\Delta D}{\Delta L}$.

With this new interpretation of the Wiggins parameters, the cost-benefit analysis applied to earthquake engineering requires a quantitative evaluation of the following three elements:

- the additional cost of building,
- the direct and indirect costs of the damage which will result from future earthquakes,
- the additional cost per life saved.

The additional cost of building is generally considered to vary between 2 and 10 per cent of the total cost for a building with few storeys, without taking into account the requirements imposed by the seismic characteristics of the zone in question: limits on structural choices (especially for foundations), etc...

The information available on the cost of damage is inconsistent. According to an estimate of the United States Department of Commerce, the cost of damage in California during the period 1933-1967 was one dollar per person per year. Yet "Earthquake Engineering Research", in an estimate for the next thirty years for the same area, arrives at a figure of 10 dollars per person per year.

These are overall data covering zones of different seismicity and all existing buildings, including those built before earthquake standards came into force, so they are only useful as a guide. Grandori proposes generally higher values for the additional cost of building (see fig. 10-5) as a function of the seismic coefficient C imposed by the standards.

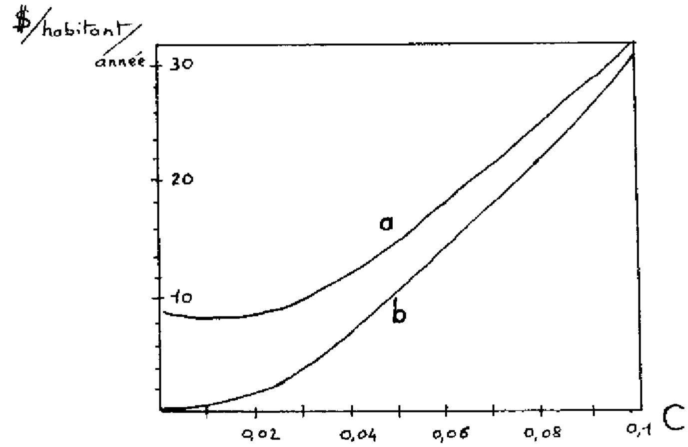

Fig. 10-5 : Cost per inhabitant per year, as a function of the seismic coefficient laid down by regulations.

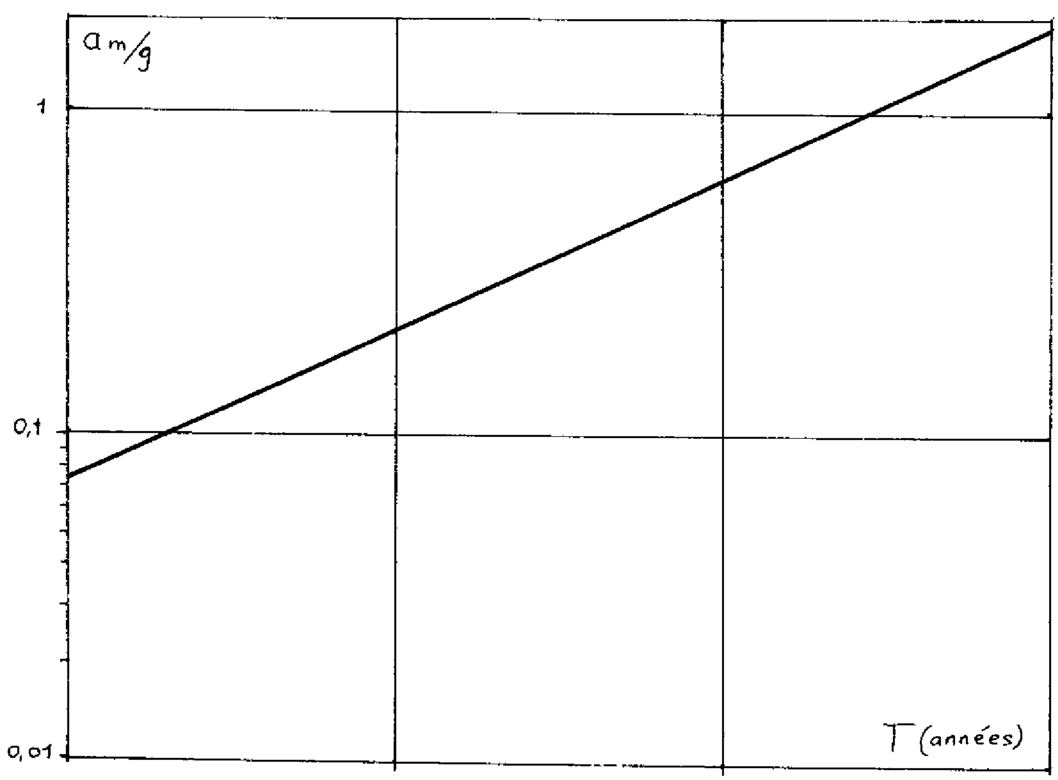

Fig. 10-6

The graph corresponds to the following hypothetical conditions:

- dwellings of 25 m2 per person,
- typical 10-storey buildings without structural walls,
- cost of masonry in Italy in 1972,
- interest on capital: 10 per cent per year,
- nominal life of building: 150 years,
- intensity of earthquakes expected at the site, defined by maximum earth acceleration a_m as a function of the return period T expressed in years (according to fig. 10-6).

The seismicity of the site comes into this type of calculation for the estimation of the cost of expected damage. In fig. 10-5 the additional cost incurred in a seismic zone (curve a) is the sum of the additional cost of building (curve b) and the cost of the expected damage.

For the additional cost per life saved, the statistics were first examined to ascertain the percentage of earthquakes in which the main shock was preceded by foreshocks of considerably lower intensity. In this connexion see "Foreshocks and aftershocks" in the chapter "General information on earthquakes".

This percentage varies with the intensity; for violent earthquakes it is on the order of 25 per cent. It was then assumed that in the case of earthquakes causing the collapse of buildings without warning, the number of victims would be equal to the number of residents of the building, whereas in the case of earthquakes preceded by weak foreshocks there would be no victims.

It was thus possible to deduce the annual number of victims from the annual number of building collapses, still as a function of the seismic coefficient. The curve $\Delta D / \Delta L$ fig. 10-7 was obtained from the cost components and the data on the number of victims. The ratio $\Delta D / \Delta L$ represents the additional cost of saving one more human life and clearly depends on the value adopted for C.

Diagrams such as that in fig. 10-7 are useful for comparing seismic standards in zones which differ in seismicity but are similar in other respects (for example, zones in the same country). In comparisons of this kind, the assumption made for purposes of simplification should not have much effect, since they play the same part in the different cases compared.

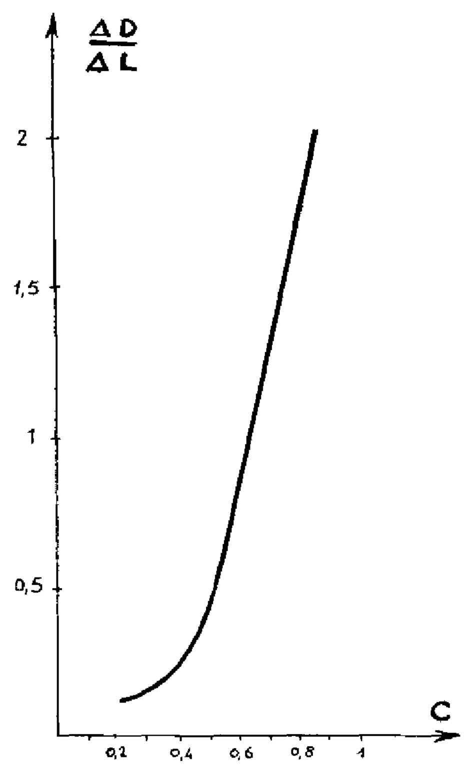

Fig. 10-7

Additional cost per additional life saved per inhabitant per year as a function of the seismic coefficient adopted, in a zone having the seismic activity defined by fig. 10-6.

It should not be expected that the same will apply to the choice of an acceptable level of seismic risk as compared with other kinds of risk.

On this point, all that can be said is that the index $\Delta D / \Delta L$ may be a help in making increasingly rational choices, that is to say choices tending towards balanced prevention efforts by the community.

Even assuming that a satisfactory balance can be attained between the different risks, there still remains the problem of choosing the total amount of resources to be allocated to prevention of all risks. Here, comparison of the benefits which could be obtained elsewhere with the same sums of money becomes the decisive factor. But this is a problem which should perhaps be allowed to mature for a few decades, always supposing that in the meantime the conditions of life on our planet have not changed so much that the problem of safety is posed in entirely different terms than is now possible to foresee.