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SEISMIC RISK AND PRINCIPLES OF SEISMIC ZONING

by

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16. Abstract (Limit: 200 words)

A short, nonmathematical account of basic methods of estimating seismic risk is given. Some preliminary considerations about the use of seismic risk estimates for the most rational seismic zoning and for optimization of a complex of antiseismic measures are presented. To measure seismic risk, it is first necessary to establish models for the following factors: probable number of earthquakes in a given period of time as a function of their energy and coordinates of their centers; intensity of shaking at various points on the earth's surface for each earthquake as a function of their energy and coordinates of their centers; and, the damage caused by shaking of one or another intensity at each point of the object. The effectiveness of antiseismic measures is discussed and a plan for regulating a whole complex of antiseismic measures is outlined. It is felt that the realization of this plan would lead to an essential increase in the population's safety and, also would reduce economic losses from earthquakes.

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PREFACE

The article translated in this report appeared originally in Computational Seismology, Volume 6, 1974 (in Russian). The publication was given to Professors Whitman and Cornell during their visit to Moscow in January 1974 and discussed extensively with the authors at that time. Following initial translation in Cambridge, the translation was edited first by Dr. Keilis-Borak and then by Prof. Whitman.

A translation of the entire table of contents of Volume 6 appears on the pages following this preface. A translation has also been made of the second paper in the volume, and will subsequently be available as a separate Internal Study Report.

Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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INTRODUCTION

Earthquakes constantly cause great damage. In the U. S. from earthquakes between 1905 and 1965 about 1400 people died, and material losses exceeded 1200 million dollars [19]. A number of catastrophes are known, such as the 1972 earthquake in Central America, in which over 10 thousand people were killed, the city of Managua was completely destroyed, and a billion dollars was lost.

Damage from earthquakes increases with the growth of population and industry. If, for example, from the San Francisco earthquake of 1906 losses were 480 million dollars, then from the same earthquake in the same place at the present time the losses would be many billions [19], not to mention the effect of the chain reaction on the U. S. economy.

To prevent and to compensate for the damage of earthquakes, a broad complex of actions are taken: legislative (for example, compulsory strengthening of buildings), and economic (for example, insurance); also related is the work of restoration, and help for afflicted regions. We will call these, for simplicity, "antiseismic measures" (of which earthquake resistant construction is only one). In the U.S.S.R., 13% of the territory of which (2.9 million km^2 with a population greater than 3.2 million) is located in zones where destructive earthquakes are assumed to be possible [11], earthquake-resistant construction alone costs each year over 100 million rubles [11].

Together with growth of the damage from earthquakes, the scale of antiseismic measures and their significance are rapidly growing. The problem arises---to optimize the development of a whole complex of antiseismic measures[1]. This problem arises because of the possibility of different types of antiseismic measures. The differences can be in engineering methods of improving earthquake-resistance, location of buildings, financing and others (see below Section 2.2). If non-optimal

1. Of course, optimization does not mean "economy at the cost of safety" but, on the contrary, maximum increase in safety by the most effective mobilization and use of resources.

types are chosen, antiseismic expenses can be unjustifiably high and/or anti-seismic measures can turn out to be insufficiently effective and not in balance with actual risks.

To solve this problem on a modern scientific level, it is necessary to establish estimates of seismic risk. This is defined as a summary of possible damage from earthquakes in the territory studied during the time interval under study. By estimating how this damage would be changed under various types of anti-seismic measures, an optimal type can be arrived at.

This series of articles[2] deals with methods for evaluating seismic risk.

This article is introductory. In Part 1, a short, nonmathematical account of basic methods is given. In Parts 2 - 4, some preliminary considerations follow about the use of seismic risk estimates for the most rational seismic zoning and for optimization of a complex of antiseismic measures.

Discussion of the practical side of questions touched upon in Parts 2 - 4 is published in [2]. Theoretical foundations of methods and an example of their application are published in [4, 5, 18]. In article [12] of this collection, further elaboration of methods and corresponding algorithms for calculations are given. In the following articles, concrete examples of methods for estimating various types of initial models are given: frequency of earthquakes [13], models of isoseismals [7, section 2]; maximum magnitude [1, 7]. In [7] an example is given of estimating the seismic risk for Central Italy.

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2. Four articles in Computational Seismology, Vol. 6, Moscow, 1974 (in Russian).

SECTION 1. SEISMIC RISK

1.1 MEASURES OF SEISMIC RISK.

Seismic risk is evaluated for concrete objects. There are various types of damage to these objects caused by earthquakes (various effects of earthquakes). The total damage from earthquakes in a given period of time is regarded as a random variable. The probability distribution functions of this variable actually defines seismic risk. The distribution function $F(x)$ is the probability such that the effect will be less than x. This function can deal with the distribution of a single effect, or with the combined distribution of several effects.

We will consider the following objects:

a) combinations of points--for example, buildings or small towns;

b) combinations of lines--for example, roads;

c) combinations of two-dimensional areas--for example, economic regions, large cities, and so on;

d) any combinations of objects of types a, b, c.

The following two effects are of main importance, since they directly characterize the losses inflected by earthquakes:

1. Number of casualties: (a) total number (b) the reduction achieved by antiseismic measures.

2. Economic losses from earthquakes: (a) total losses; (b) losses prevented by antiseismic measures. Let us clarify the meaning of this effect. In the course of a period of time studied, earthquakes occur. During each earthquake there is a possibility of loss. The sum of these losses is effect 2a. Part of the loss will be prevented; the sum of the prevented loss is effect 2b.

The following types of effects indirectly characterize the losses:

3. Total number of people present in the zone of a given intensity of shaking.

4. Total value of property present in the zone of given intensity.

5. Shaking of the object--sum size of those parts of the object which were present in the zone of a certain intensity. Each part is counted as many times as it experiences shaking (that is,

during several earthquakes). For point objects this effect is the number of points experiencing a tremor; for lines and two-dimensional objects--the respective sum of length or area experiencing parts of the tremors.

The suggested methods allow an estimation of any other effects of consecutive earthquakes, if their statistical model is known for a single earthquake.

If we take a shoreline as an object and look at only tsunami-generating earthquakes, and replace the intensity of earthquakes by the intensity of the tsunami, then the above mentioned effects will characterize the probable loss from tsunami.

The probability of total loss 1a, 2a is the direct measure of seismic risk. It is necessary to know also the probability of prevented loss 1b, 2b in order to optimize antiseismic measures. Characteristics 3 - 5 give only an indirect idea of seismic risk (for example, the total value of property in zones of tremors only indirectly characterizes the possible losses). However, these indirect characteristics can be useful for preliminary analysis, especially since their calculation requires fewer data.

1.2 INITIAL MODELS.

In order to calculate the numerous measures of seismic risk, it is first necessary to establish models for the following factors:

--probable number of earthquakes in a given period of time as a function of their energy and coordinates of their centers;

--intensity of shaking at various points on the earth's surface for each earthquake as a function of their energy and coordinates of their centers;

--damage caused by shaking of one or another intensity at each point of the object.

These factors apply for earthquakes sufficiently strong to cause damage to the object under study.[3] However, strong earthquakes are rare

3. The necessity of these factors is not peculiar to the suggested method. It results from the very meaning of seismic risk.

events, and factual data about them are very limited. Therefore, at the present time, one can construct only roughly approximate models of these aforementioned factors. This should not raise feelings of hopelessness. Rough estimates of seismic risk are sufficient for making many practical decisions. And, in any case, the suggested method allows one to estimate the accuracy of the estimate obtained, and thus to avoid unfounded decisions. Keeping this in mind, we will specify the form of the above mentioned factors:

A. A model of earthquakes sequence is represented by functions of random values $N(G_k, M_k, T)$. N is the number of earthquakes that can take place in T years in M_k range of magnitude in regions G_k, $k = 1,2,\ldots$

In practice one uses a logarithmic measure of energy--magnitude. Regions G_k should be roughly homogeneous: inside each the probability of an earthquake is distributed evenly. Consequently, the distribution of values of N defines the probability of this or that number of earthquakes in the neighborhood of any point.

Distribution functions for values $N(G_k, M_k, T)$ can be estimated by the method outlined in [13]. Catalogues of earthquakes and tectonic maps are the necessary factual material.

B. Model of distribution over the earth's surface of shaking occurring during one earthquake. This model establishes the random values $c(g, \tilde{g}, M)$. Here c is the intensity of shaking at point $\tilde{g}$ during an earthquake with hypocenter at point g and with magnitude M.

The suggested method applies to any measures of intensity. However, in practice we have yet only been successful in collecting enough material to describe shaking on a point macroseismic scale. Hence the model comes down to a simple model of isoseismals. Its parameters are random values, whose distribution depends on g, $\tilde{g}$, M. The initial factual material includes isoseismal maps for separate earthquakes, geological and tectonic maps, and, as much as possible, maps of soil recovery (microseismic zoning). An example of construction of models of isoseismals can be found in [7, section 2].

C. Characteristics of possible effects from shaking of a given intensity. Here we mean the shaking from one earthquake (together with aftershocks if model A does not consider them). Let us enumerate those characteristics which correspond with the various effects (see section 1.1):

Shaking (effect 5): territorial (geometric) location of objects.

Value in the zone of shaking (effect 4): maps of territorial location of property values under consideration, and data about their evolution with time (for example, a plan of construction and plans for development of new enterprises).

Population in the tremor zone (effect 3): maps plotting population density and data about its evolution.

Economic losses (effect 2a): the same data as for (effect 4) and, besides that, an estimate of probable damage with different types of antiseismic measure. This should include both direct losses (from damage to buildings) and indirect losses from halted production and so on.

Damage to population (effect 1a): the same facts as for (effect 3) and, besides these, percentage estimates of the number of casualties with various types of antiseismic measures.

Damage averted by antiseismic measures (effects 1b and 2b): the same facts as for effects (1a) and (2a) respectively also the economic consequences of antiseismic measures not connected with earthquakes (for example, the effect of raising the earthquake-resistance of buildings on their longevity and cost of operation).

Losses at different times are reduced to one common moment in time: losses x at moment t are equivalent to losses $x.\exp(-\beta(t - t_o))$ at moment t_o; β is the average rate of interest (by present norms $\beta = 0.12$).

The loss, complete or prevented, from a single shaking in essence also should be studied as a random value. However, for constructing probability models of this damage there is not yet enough factual material. Therefore, in practice one must limit oneself to deterministic models: averaged or extremal with an eye toward the aim of estimating seismic risk (see section 4).

A priori hypotheses. For constructing the listed models, besides sufficient factual material, some hypotheses are necessary; partly they are necessary to compensate for insufficient data. We will list the most essential hypotheses.

Model A [13]. Earthquakes in non intersecting volumes (space - time - energy) are statistically independent ; therefore the total number of earthquakes obeys the Poisson distribution.

Model B [7]. With homogeneous soil conditions, isoseismals are concentric elipses. Their parameters (area, elongation, azimuth of long axis) are random values, the distribution of which depends on the magnitude and coordinate of the epicenter.

The average azimuth of the long axis coincides with the strike of the major faulting.

Models C. The probable damage at each point of the object is defined by the intensity of the shaking; the total damage from one earthquake is the sum of the damage values at all points; effects of various earthquakes are statistically independent.

These hypotheses, as well as the lack of factual material, make models A, B, C approximate and limit their applications.

None of these hypotheses appears absolutely necessary. However, to discard or to elaborate a single hypothesis is not always simple: this can be done only with more complete data. Some considerations about the need for exactness in constructing model approximations are brought up in section 4.

1.3 A SCHEME FOR ESTIMATION OF SEISMIC RISK.

Seismic risk is estimated on the basis of all the listed factors. Descriptions of algorithms are given in [12], examples of calculations are presented in [4, 5, 7, 18]. We will describe a general system of calculation.

The algorithm consists of three parts.

I. In the memory of a computer the image of the studied territory is constructed. This includes the object and the epicentral zones (that is, the source zones in which an earthquake can produce the studied effect at least in one point of the object). This image contains the initial information: models of type A, B for each point of the epicentral zones, models of type C for each point of the object.

This information is presented in maps and tables. Maps show contours given inside which the parameters of one of the models are considered constant. In tables the corresponding values of these parameters are shown.

II. Distribution functions F(x) are constructed for the effects of one arbitrary earthquake. Let us clarify the idea of these functions. An earthquake with fixed characteristics (coordinates of the hypocenter, magnitude and isoseismals) produces certain effects. The effects are determined as a sum of effects at each point of the object (these effects are approximated by a model of type C). All the listed characteristics of earthquakes are random (their probability is approximated by models A, B). Thus the total effect of one earthquake is also a random value. The distribution of this effect will be evaluated in this part of the calculations. The general scheme of calculation follows (for more detail see [12]).

In a discrete grid, all the points in an epicentral zone are considered; each point is regarded as a possible hypocenter. For each combination (hypocenter, magnitude) all the parameters of isoseismals--area, azimuth and extension--are considered in succession using model B (the magnitudes are taken inside the given interval). For each combination (hypocenter, magnitude, parameters of isoseismals) the intensity of shaking at each point of the object is determined. Corrections are introduced for soil conditions (in microseismic zoning) if they are known. With the help of models of type C the studied effect is defined for each point of the object, and then the total effect for all points of the object.

As a result, for each possible combination (hypocenter; magnitude; area, azimuth and elongation of isoseismals) we get a pair of figures: x - the total effect, p - its probability. The value p is the product of the probabilities of each parameter in the given combination. The set of pairs (x, p) actually defines the distribution

F(x) for which we are looking. It refers to one arbitrary earthquake. From model A we know also the distribution of the general number of earthquakes in the whole epicentral zone. From these two distributions the end result is obtained:

III. An estimate of seismic risk F (x,T) is constructed --distribution functions of the total effect of all earthquakes in the time interval T of interest.

The basic idea as to the degree of seismic risk can be obtained from the main parameters of the function: average m_{Σ}, dispersion σ_{Σ} and a set of quantities x_p--the solution of the equation $F_{\Sigma}(x, T) = p$ for p close to 1. Roughly speaking, the total effect x exceeds the level x_p in (1-p) 100 cases out of 100; on the average it is equal to m_{Σ}.

SECTION 2. THE REGULATION OF ANTISEISMIC MEASURES

2.1 HISTORY OF THE QUESTION.

Of all the possible antiseismic measures (see page 14) regulation by building code alone is used at present. Code requirements are based only on a maximum likely intensity of shaking. As this form, the principle of this type of regulation can be formulated thus: structures should be sufficiently stable for shaking of an intensity up to $c_{max} + \delta_m + \delta_k$. Here c_{max} is the maximum likely intensity, shown on maps of seismo-zoning; δ_m is a correction for local soil conditions; δ_k is a correction for the category of the structure.

The weaknesses of this principle are well known. In [8] it was shown that within a zone with the same c_{max} the average annual number of tremors for a given point can be hundreds or thousands times different. For example, by the estimates of [8], within the zone of c_{max} = VII in Central Asia the average interval of time between shakings of intensity VII in different places is from 100 to 20,000 years. It is clear that in places where tremors occur more often, more serious antiseismic measures are necessary. Modern regulations ignore the frequency of occurrence of the tremor and therefore do not insure correct regulation of antiseismic measures. These codes lead to direct inconsistencies: for example, one and the same bridge can be insured both for floods, which occur on the average of every 100 years, and for earthquakes, which occur on an average of every thousand years.

With respect to all other basic catastrophes a more natural and effective approach--probability--is used: measures of safety are calculated from the probability of disasters of one or another intensity. For this, of course, the very maximum possible intensity is considered. Such an approach allows the working out of an optimal system of safety measures and actually raises their effectiveness.

Frequency-of-occurrence of tremors. From the considerations in [8] it was suggested that antiseismic measures be regulated on the basis of the parameter L_c. This parameter was introduced in [8] and [10]; L_c is the average annual number of tremors of intensity at a given point.

To define L_c, the following formula was introduced [8], with the help of which, with a few simplifications, the values quoted above were obtained for Central Asia:

$$L_c(g_o) = \sum_{b=c}^{c_{max}} \int_{g_c} A_b(g)\, d_g.$$

Here b is a measure of an earthquake's energy (magnitude, energy class and so on); A_b is the average annual number of earthquakes of energy b in a unit volume of hypocentric region; g_{bc} is the volume of the hypocentral region, defined by the following conditions: an earthquake of energy b in this volume causes at point g_o a shaking of intensity c.

A series of works beginning with [14] is also dedicated to the calculation of L_c; a review of this work can be found in [11]. In these works the symbol B is used in place of L_c, and the term "tremorosity" is used.

If we know L_c at the "averagepoint" of a certain region, we can approximate the average economic effect from the occurrence of an earthquake during an interval of T years on the structures located at this point.

For this in [8] the following relation was used

$$X_{RT} = \sum_{t=o}^{T} \sum_{c=c_{min}}^{c_{max}} L_c D_{cR}(t),\ D_{cR}(t)=\exp\{-(\beta-\beta')t\}\, D_{cR}(0).$$

The symbols given here are as in this present collection: t is time in years; R is intensity for which structures are reinforced, D_{cR} is the average economic effect from tremors of intensity c during an individual earthquake; c_{min} is the minimum intensity of tremor that would cause damage; β is the normative rate of interest, β' is the relative change of D_{cR} in time; X_{RT} is the total economic effect from all earthquakes during T years. D_{cR} and X_{RT} can signify complete economic loss, or that part of the damage that was averted by antiseismic measures (an integral can be substituted for the summation over t).

The role of the frequency of occurence of tremors L_c was formulated in [8] in the following manner:

"The parameter L_c unites in the practical way the influence on the degree of seismic danger of all the seismological factors: maximum intensity B, shown on present maps of seismic zoning; seismic activity; attenuation of the intensity of the tremor with epicentral distance; configuration of the border between zones of different intensity, and others.

The results of seismic zoning should be presented in the form of a map of average values of L_c; it is desirable to know also the scatter of L_c. The role of seismology in regulating earthquake resistant construction should end with the presentation of facts about L_c (together with a quantitative description of the shaking-such as a spectrum of accelerations). They form then a part of the initial data for econo-engineering estimates of the effect of earthquake-resistant constructions."

The frequency of occurence tremors has a large dispersion: large variations from the average are possible. For example, in [4, 5] for a linear object of length 1000 km in the Baikal area the effect (5) was estimated as the total length of the parts experiencing shaking of intensity $\geq$ IX in 10 years. The average value of this effect was estimated to be 80 km; the dispersion however was 170 km, with a probability of 20% that the effect will exceed 250 km. Thus, as was shown also in [8], for decisions connected with antiseismic measures, it is necessary to estimate not only the average value, but also the possible scatter of the total effects.

As shown in [4,5] the number of tremors at a point is distributed according to Poisson's law, with parameters equal to the average value of L_c. In this manner, the values L_c define not only the average values of the number of tremors at an average point, but also the whole distribution of this number. This L_c also defines the distribution of the maximum intensity of shaking in a fixed interval of time.

Insufficiency of use of L_c. Maps of L_c are useful for preliminary analysis of seismic danger. However, in practice the usefulness of L_c is limited much more severely than is represented in [8]. The above quotation gives the impression that the value of L_c at a point can be used for the further calculation of other effects: shaking of non-point objects and damage from earthquakes. In reality this is not so.

Maps of L_c permit the estimation of seismic risk only for a single point object, and only allow a rough quantitative estimate of the average risk for distributed objects. The exactness of the estimate depends in the first case on the adequacy of the models of isoseismals in the vicinity of the point object. For obtaining probability estimates of risk for non-point objects, the information given by L_c is insufficient, inasmuch as the field of shaking is defined not only by the distribution of tremors at each individual point, but also by overall distributions which take into consideration complex correlations among shaking at different points. Thus, in order to calculate the effects (1-5) for real objects (not single points) it is necessary to return to the original (and simpler) models A, B, C. We notice also that no effect can be obtained from another; each effect should be calculated separately.

Estimating seismic risk. Formulae for calculating seismic risk and examples of the calculations for line objects are given in [4, 5, 18]. Estimates of a broader variety of effects for point, line and area objects in Central Italy are presented in [19]. Estimates of the average value of effects (5-shaking) and (2a-economic damage) for area objects in California are presented in [19]; this work is interesting for its detailed discussion of insurance.

The set of questions discussed here are similar to those that are discussed in monograph [15]; which deals with point objects (in our terminology) studied as complicated engineering structures. The method of estimating risk in [15] is based on a not completely adequate theory of extreme values, but is interesting in that it considers the joint risk of earthquakes and other natural disasters.

2.2 ON THE ESTIMATION OF EFFECTIVENESS OF ANTISEISMIC MEASURES.

As was said earlier, many different types of antiseismic measures are possible: various engineering means for raising the earthquake-resistance of structures; moving structures to zones of lesser seismic risk; laying in reserves of raw materials; organizing relief help, and many others.

Various measures are connected with various expenses: capital investment and operating expenditure. For example, increase in earthquake-resistance is connected with additional investment; along with this, it results in a reduction of operating expenditure: loss compensation, often better building utilization [9], and others. If the combination of these factors appears too unfavorable, then the question can be raised of moving construction to a region with less seismic risk; this lessens the cost of increasing earthquake-resistance, loss compensation and others, but it might significantly raise other cost aspects--for example, transport.

The problem arises--to estimate the economic effectiveness of various types of antiseismic measures. It is of decisive importance in the larger part of the zone with a maximum likely shaking $\leq$ VII, where earthquakes might cause only economic damage. It is important, though not decisive, for a zone of greater maximum likely intensity.

Economic effectiveness. Let us look at a case when earthquakes can produce only economic loss. Let some types of antiseismic measures cause spending S (investment and current expenditure). Thanks to them, in the course of T years, losses os size x are avoided.

The economic effect ("return") from antiseismic measures for T years is $D = x - S$ (we relate all expenditure and loss to one moment of time). Expenditures S are fixed and should be known. For the value x, by the scheme described in 1.3, we estimate the distribution function $F_\Sigma(x, T)$. This defines the effectiveness of the given type of antiseismic measure. It is more convenient to look directly at only a few parameters of this function. For economic decisions the principal role is usually played by $m_\Sigma(T)$--the average value of economic effect. Perhaps also a value $P(T) = 1 - F_\Sigma(S,T)$

is important--the probability that the economic effect will not be negative: the prevented losses will not be smaller than expenditure. The larger m_Σ or P(T), the more effective the antiseismic measures. The dependence of these measures on the period T (for example on the building's length of service) is natural: the shorter the time the less the chances of an earthquake occurring, and, therefore, the expenditure will be justified.

Another measure of the effectiveness of antiseismic measures might be the rate of return of expenditure. Let us find the interval T_p for which expenditures are repaid with the probability P, P being sufficiently large. For this we calculate $F_\Sigma(S, T)$ for various T. The unknown time T_p is defined by the condition: $F_\Sigma(S, T_p) = 1 - p$. The smaller T_p, the more effective the measures will be.

Practically, it is worthwhile also to look at the return not of all expenditures, but of a large part of them. This is due to the fact [8] that the last small part of the expenditure has an especially small chance of being repaid, or might be repaid especially late. For example, in [8] a case is shown in which the average time of return was about 20 years for 80% of the cost and infinity for the entire cost.

Criteria of the optimum. We will consider, as above, the case when earthquakes can cause only economic damage. In this case, we will naturally consider optimum that type of antiseismic measure for which the values of m_Σ or P (characterizing that part of the expenditure which is repaid in the given period), are maximim or the time T_p (in which a large part of the expenditure is paid with sufficiently large probability p), is a minimum.

Calculating these values for various types of antiseismic measures, one can choose the optimum type. Still, this involves the calculation of a large number of factors, which are listed above. Each is rather complicated by itself, and not always sufficiently studied (for example, the cost and effectiveness of various engineering methods for strengthening buildings). Therefore, practically, the question is not of absolute optimization, but of some approximation of the optimum type that is possible with present levels of knowledge.

Effectiveness of measures to provide safety for population centers. All types of measures should provide a normative level of safety (see paragraph 3.3 below). Therefore they differ only by their cost and the degree to which they prevent purely economic damage. To apply to them the same reasoning as in the last section would be incorrect. These measures are a part of a broad complex of measures to protect against natural disasters and for public health. The problem of optimization[4] for this whole complex consists of the following: it is necessary to insure maximum overall safety, and not simply lessen different specific dangers separately. These questions are outside the scope of this collection. We simply note that among the data necessary for solving this problem, there are also included the aforementioned estimates of seismic risk, as well as the distribution functions not only of casualties but also of economic loss. In particular, in analyzing the costs of antiseismic measures one must take into consideration that part of the expenditure aimed at securing safety for the population will be returned as prevented economic loss. This lowers the actual cost of antiseismic measures.

2.3 A POSSIBLE APPROACH TO REGULATING ANTISEISMIC MEASURES.

We will outline a possible plan for regulating a whole complex of antiseismic measures. It appears to us that the realization of this plan would lead to an essential increase in the population's safety, and at the same time would give a large economic benefit.[5]

Antiseismic measures are either compulsory or optional. The first insure the safety of the population and defend against particularly large economic large economic losses; the second simply lessen

4. See footnote on page 2.

5. This plan is presented for discussion in [2, 4]. It is obvious that its realization would require complicated preparations, along with additional research. A similar approach, especially with respect to insurance, is being developed in the U.S.A. (17,19].

economic losses and, accordingly, are economically controlled. The principal economic lever could be a special system of earthquake insurance, in which the rates would depend on the possible loss (and, accordingly, which on antiseismic measures are used). For example, these rates would be higher for a building with less earthquake-resistance and for regions with greater seismic risk (for detail see [4, section 8]).

The suggested plan consists of the following.

Compulsory measures. They are put into effect if either one of the following relationships is violated:

$$F^{(I)}_{\Sigma}\ (0,\ T) > 1 - \varepsilon \qquad \text{(I)}$$

$$F^{(II)}_{\Sigma}\ (\bar{X},\ T) > 1 - \delta \qquad \text{(II)}$$

Here $F^{(I)}_{\Sigma}$ is the distribution function of damage for the population (effect 1a); $F^{(II)}_{\Sigma}$ is the distribution function of economic losses (effect 2a); ε, δ and $\bar{X}$ are normative thresholds. Condition I means that with a probability greater than $1 - \varepsilon$ the population will not experience casualties; if several kinds of casualties are considered, then the threshold ε will be a vector. Condition II means that with a probability more than 1-S, damage will not exceed the normative threshold $\bar{X}$.

The compulsory measures must insure the fulfilling of these conditions: increasing the safety of the population to normative levels, and preventing especially large damage.

To these measures it is worthwhile adding a compulsory minimum of insurance. This should cover expenses for antiseismic measures common to the whole seismic area (for example, for raising the earthquake resistance of public buildings) and should insure the interest of personnel at institutions and factories.

Optional measures. After fulfilling conditions I, II, there are still left some possible economic losses. In particular, earthquakes can cause only economic damage in large parts of where the maximum likely intensity is $\leq$ VII. Measures to ward off purely economic damage should be made optional.

Authorities responsible for the operation of the given object, should receive the right to independently choose the optimum type of antiseismic measure (subject to conditions I, II) with consideration of the insurance rates they will pay. Insurance would thus be one of the possible antiseismic measures connected with a rise in the cost of operation. From the size of the probable losses it is decided what department will get priority over this decision.

These measures, as well as a system of insurance rates, might be optimized on the basis of the distribution function of possible loss.

CONCLUSION

In regulating antiseismic measures, the following questions must be answered:

a) are the compulsory measures necessary, and, if necessary, then to what degree.

b) in the responsibility of which level does the choice of optional measures lie;

c) what is the effectiveness (approach to the optimum) of the projected type of measure.

The answer to the first question completely depends on estimates of the values $F_{\Sigma}^{(I)}(0, T)$, $F_{\Sigma}^{(II)}(\bar{X}, T)$. Those, and only those measures, are necessary, without which these values would not satisfy conditions I and II.[6]

Indirect characteristics of seismic risk--maximum intensity, repetition of tremors and even the overall distribution of effects (3, 4, 5)--are useful, but not sufficient for a well-founded decision.

In answer to the second question, the responsibility for decisions about optional measures depends on the size of the possible losses.

The effectiveness of projected measures is defined by the distribution of possible loss.

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6. Conditions I and II are dictated by the very aim of antiseismic measures, and hardly can be changed essentially, no matter how we evaluate the distribution of $F_{\Sigma}^{(I)}$ and $F_{\Sigma}^{(II)}$. These formulae are more flexible and natural than the present rules, which make it necessary, for example, to artificially raise the maximum likely intensity of zones to force an increase of antiseismic measures for large cities.

SECTION 3. PROBABILISTIC SEISMIC ZONING

3.1 THE GOAL OF SEISMIC ZONING.

Seismic zoning carried out today should give information sufficient for reaching decisions about antiseismic measures. We saw that these decisions should be based on estimates of seismic risk. In the same way, the purposes of seismic zoning is formulated thus: to give information allowing the estimation of seismic risk sufficiently quickly and in a standardized form. For typical objects, for which the locations and plans of structures are known, seismic zoning can (and in our opinion, should) include substantive estimates of seismic risk. From this purpose follows the very form of seismic zoning.

3.2 FORM OF SEISMIC ZONING.

Seismic zoning can be represented by the following basic information (referring to specific objects and intervals of time).

I. Distribution functions of various types of damage (effects 1a, 2a and 1b, 2b) for typical objects and standard types of antiseismic measures.

II. Distribution functions of effects (3-5) for various intensities: shaking; economic value present in the shaken zones; number of people present in the shaken zone.

III. Maximum intensity of shaking, which may be exceeded with probability less than the given threshold. This is a precisely defined analogue of maximum intensity c_{max}.

Besides the listed functions it might be worthwhile to include estimates of the mean value and dispersion of each effect for a more detailed treatment of objects.

It seems worthwhile to estimate these data beforehand, and to include them in seismic zoning for the following objects: a group of cities or other population centers; a network of roads, railroads and other lifelines; a group of agricultural objects (for example, areas under seed); a group of uniform structures. These can be existing objects or those still under construction. The objects should have approximately similar behavior during a shaking of fixed intensity. In this respect, sharply different objects (for example, cities with very different population densities, different types of buildings, etc., or even different types of structures in the same city) should be looked at separately.

It is difficult to foresee in advance which objects may be of the greatest interest, all the more since new construction plans are appearing. Therefore, seismic zoning should include the following information that allows estimates of seismic risk for new objects.

IV. Models of basic factors (see paragraph 1.2):

A. frequency of the occurence of earthquakes;

B. models os isoseismals (or intensity of shaking) with maps of soil corrections;

C. characteristics of possible damage from tremors of different intensities from one earthquake.

V. Standardized summaries of factual data, with which models A, B, C were constructed, inasmuch as different problems may require reestimation of these models.

3.3 THE ROLE OF SEISMOLOGY IN SEISMIC ZONING

Only that part of the data listed in paragraph 3.2 have to do strictly with seismology. We see that for the sound regulation of antiseismic measures, "purely seismological" data are insufficient: engineering, economic and demographic facts are also necessary (paragraph 1.2). This is natural: do not the very antiseismic measures lie in the domain of economy, and to regulate them by purely seismological data would be unwarranted.

During the stage of collection and analysis of each separate group of facts the "division of labor" between related specialities--seismologists, engineers, economists and others--is self determining. This stage concludes with the construction of models A, B, C. It is further necessary to analyze these models together. To this method of analysis a series of works in the first part of this collection is dedicated.

Which of this applies to seismic zoning is a question of terminology. It merits clarification. There are alternatives:

one can include in seismic zoning a summary of all necessary models and then it exceeds the boundaries of seismology, or it can be limited to only seismological facts and then seismic zoning will be insufficient for regulating antiseismic measures. A complete summary (paragraph 3.2) remains necessary, even if under a different title.

Present practice is intermediate: seismic zoning includes only seismological data, but economic decisions are based on it. This is unwarranted, and does not allow the correct selection of antiseismic measures.

SECTION 4. CAN SEISMIC RISK BE ESTIMATED FROM AVAILABLE (ROUGH AND INCOMPLETE) DATA?

We return to the question: is it realistic at the present time to make a summary of all the necessary data? Their acquisition and further elaboration are the content of a broad spectrum of research in the fields of seismology, economics, construction and many others. Some necessary fields of research (especially in economics) are only just developing.

It is difficult today to imagine a specialist who thinks that some group of data is completely explored. Therefore the list of initial factors in paragraph 1.2 might seem unrealistic. This is not far from the truth.

The suggested method, based on ideas of mathematical statistics and modern economy [3, 6, 16] takes into consideration the necessity of making a decision when the initial data are known to be inexact and in error.

Can the calculations be accomplished? The suggested method requires that possible limits be indicated for all initial models. These limits can always be found: either from statistical analysis of available data, or from a priori considerations. In this manner, for calculating seismic risk a complete set of very accurate data is not necessary. Something else is necessary: to indicate exactly what we do and do not know about all data.

By varying the initial data within permissable limits, we calculate for each measure of the seismic risk the maximum and minimum limits (high and low estimates). By analogy, by varying the mean value of the initial data, we calculate the limits for the mean value of this measure. Of course, the wider the possible limits of the initial data, the wider the calculated limits for seismic risk.

What results of the calculations should be used for practical decisions? If the question is: should compulsory antiseismic measures be taken, it is necessary to use the maximum estimate of danger of earthquakes--that is, in condition I the lowest estimate of $F_{\Sigma}^{(I)}(0, T)$ should be used.

For purely economic decisions, for example in problems of insurance, average values might be preferable.

Is it worthwhile to analyze the data that we already have? At the present time it is possible to establish only strongly averaged (or rough) initial models. The farther they are from reality, the more we overestimate (but do not inderestimate) the seismic risk, and the farther from optimum will be our decisions.

If our models are too imprecise, estimates of risk will be so indefinite that considerable intuition is required for the decisions. It is clear that making the initial data more precise can be of great and often conclusive importance. However, one must warn against the present tendancy to suspend analysis of available data until the accumulation of more data.

In the first place, without the construction and simultaneous analysis of initial models, it is impossible to establish to what degree is it really necessary to improve each of them since the required accuracy of one model depends on the accuracy of the other models. Secondly, by failing to make calculations we are not postponing the necessity of making practical decisions, and we are only denied beforehand, without proper reason, the possibility of even partially improving these decisions. This would be unjustified for many important problems.

For what problems is it possible to construct sufficiently accurate initial models? Inasmuch as these models will be crude, they can be used only for many sufficiently uniform objects distributed in a large territory. This is the case in the problem of setting insurance premiums for standard buildings within large areas, and so on.

For just this reason, the aforementioned principles of regulation of antiseismic measures will be that much more effective, the broader their application. We also note that the greater the cost of the measures under consideration, the rougher the initial modes can be. An excellent consideration of this can be found in [4], where calculations of shaking and prevented damage for routes of a length of 1,000 km are given. Owing to the lack of data the initial models were extemely crude: it is assumed that earthquakes appear only close to the routes, and that isoseismals will always be stretched along the line of the routes. Nevertheless, the obtained results are of practical interest.

Thus, the question presented at the beginning of this section deserves special attention in each specific instance. The answer can be given by a direct estimate of seismic risk from available data.

On the other hand, for unique individual objects, it is necessary to have not average, but specialized inital models; their construction could require detailed research on the process of earthquake occurrence in the region of the object.

In conclusion we note that the practical list of suggestions in sections 2, 3 would require serious preparations. Therefore there remains the problem--to work out, starting from these same principles, an intermediate, simpler, although perhaps still time-consuming system of regulation of antiseismic measures.

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