Computational models of seismic effects taking into account the extent of the seismological information completeness

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Abstract. Approaches to the models formation of seismic effects are proposed, taking into account the uncertainty and incompleteness extent of the initial seismological information. Earthquake-prone territories are divided into three types. The 1st degree uncertainty areas include territories where seismic effect parameters can be specified in the form of probabilistic distributions, the 2nd degree uncertainty areas include territories where effects parameters can be predicted at certain intervals. The 3rd uncertainty degree includes territories where all seismological information is expressed in terms of the intensities and repetitions given in the maps of the general seismic zoning of the Russian Federation territories (GSZ-93). The computational effects with varying extent of the seismological information uncertainty and the corresponding risk functions are determined.

Introduction

Every strong earthquake is a unique natural phenomenon that requires extensive scientific research in order to understand the physical laws of its origin and distribution. As science develops in the seismology field, it becomes more and more obvious that neither historical data nor instrumentation recordings cover a sufficiently long period of time to predict strong earthquakes parameters in the future with high accuracy. Therefore, it is necessary to develop predictive models of seismic effects. For the majority of territories, intensities and probabilities of earthquake frequency are the main parameters characterizing seismicity. But the analysis of instrumentation recordings of earthquakes shows that, even with the same intensities, the seismic effect for different territories can differ quite significantly in spectral composition (the prevailing periods of earthquake grounds motion, displacement, duration of intense motions, etc.) and a number of other properties [1, 2,3,4]. The values of seismic earth movement parameters depend on many factors, the main of them are the energy and the source depth, hypocentral distance, geological structure, geomorphology, ground conditions, etc. Therefore, it is obvious that the assessment of the predicted earthquake only in intensities and repeatability is insufficient. Recently, in some regions work was under way on quantitative seismic territory microzonation, indicating not only accelerations and repeatability, but also possible intervals of the prevailing periods of earthquake ground motions on the map. This allows a more realistic assessment of the territory seismic risk.

For many Russian regions, the seismological situation is still poorly explored. According to the degree of uncertainty and incompleteness of the initial seismological information on the effect and earthquake frequency parameters, earthquake-prone territories can be divided into three types. Seismic
areas with the 1st uncertainty degree include areas with more complete statistical information about the parameters and frequency of seismic effects. As a rule, these are areas with high seismic activity. Seismological information here should be considered sufficiently complete, if the effect parameters can be predicted in the form of probability distributions. This requires a large amount of data on regional seismicity and sufficient statistics of instrumentation recordings of strong earthquakes.

The 2nd uncertainty degree can include relatively little explored areas with limited historical data on past earthquakes and an insufficient set or complete absence of instrumentation recordings of strong earthquakes. Here the known data are the location of focal zones, magnitudes of expected earthquakes, epicentral distances, geology, events repetition and weak earthquakes recordings.

The 3rd uncertainty degree should include areas where information is given only in the intensities form corresponding to certain periods of earthquake frequency. Other effect parameters are unknown. These may be sparsely populated and consequently little explored territories or territories that are related to those with low seismic activity.

**Building of a seismic impact model for territories with the 1st uncertainty degree**

Building of a seismic impact model for territories with the 1st uncertainty degree seems to be a task more than clear. Here, characteristics with certain probability that determine the seismic territory hazard are known.

Different exploration degree of earthquake-prone territories requires a different approach to the impact models formation, i.e. the smaller the exploration degree, the greater must be the caution proportion in these models.

If we exclude the earthquakes duration time the main ones are the earthquakes frequency and the parameters of earthquake ground motions that depend primarily on the characteristics of earthquake sources, epicentral distances and ground conditions. In the end this all leads to a wide variation of these parameters. At best, they can be given in the form of probability distributions. The probabilistic nature of seismic effect has two sources. First, every earthquake is a random event. Secondly, the earthquake movement at each surface point is the result of a complex phenomenon of wave propagation from an accidental discontinuity in the inhomogeneous medium and is a non-stationary random process.

Estimated impact level for territories with the 1st uncertainty degree can be set from the standpoint of the reliability theory. Imagine predicted parameters distributions of earthquake ground motions in the form of S vector with a joint probability density f(S), then the risk function (probability of structure failure) over the time interval [0, T] will look like [5]:

\[
Q(T) = \sum_{i=1}^{n} Q(Z_i) \cdot P(Z_i; T),
\]

where \( P(Z_i; T) \) is the recurrence probability of the earthquake of \( Z_i \) class for a period of time T, \( Q(Z_i) \) is the failure structure probability when exposed to the earthquake of \( Z_i \) class, is defined as:

\[
Q(Z_i) = \int_{S|Z_i} Q(Z_i; S) \cdot f(S) \, dS
\]

Here \( Q(Z_i; S) \) is the conditional probability of the structure failure when the earthquake of \( Z_i \) class is affected at a fixed value of S vector.

If the seismic effect parameters are independent, then f(S) can be divided into the distribution density of each parameter separately.

Quantitative intensity indicator can determine the seismic effect belonging to one or another class, i.e. by intensity. If within each class earthquakes are possible from different sources, then the expression (1) takes the form:
where \( k \) is the an earthquake source number.

Data on average periods of the earthquakes frequency of one or another intensity is given in the maps of seismic perturbation. They are determined both on the basis of a statistical analysis of the seismological regime (1st uncertainty degree) and on the basis of seismological studies in conditions of insufficient statistics (2nd uncertainty degree). To set the level of repetition period sufficiency determined on the basis of statistical analysis, let us present the earthquakes sequence of each class as independent Poisson processes. It is assumed that all earthquakes are independent events.

Average value of the repeatability period of an earthquake with an acceleration equal to or greater than \( a \), based on the statistics of past years, is defined as [6]:

\[
Q(T) = \sum_{i=1}^{n} \sum_{k=1}^{m} Q(Z_{ik}) P(Z_{ik}; T),
\]

(3)

where \( t_i^* \) is the time period between the occurrence of the \( i \)-th earthquake. To determine the distribution density \( \Psi(T_a) \), we represent (4) in the form

\[
T_a = \left( \frac{1}{n} \right) \sum t_i^*,
\]

(4)

where \( V = \sum t_i^* \).

The distribution \( \Psi(V) \) of \( V \) random variable can be calculated as a composition of \( n \) exponential distribution laws. This representation is known to correspond to the Gamma distribution:

\[
\Psi(V) = B_a \cdot V^{n-1} \cdot e^{-B_a V},
\]

where \( B_a \) is the intensity of the earthquake frequency

Since \( T_a \) is a linear function of \( V \) random argument, using the well-known rules, the distribution density \( \Phi(T_a) \) can be represented as:

\[
\Phi(T_a) = \left[ \frac{(n \cdot B_a)}{(n-1)!} \right] \cdot T_a^{n-1} \cdot e^{-n \cdot B_a \cdot T_a}
\]

Denote \( Z = 2 \cdot n \cdot V \) we get

\[
\Phi(Z) = \left( \frac{Z^{n-1}}{Z^n} \right) \cdot e^{Z/2}.
\]

Then the upper and lower confidence limits in \( B_a^u \) and \( B_a^l \) for the intensity of \( B_a \) repetition can be determined from the following equations:

\[
\int_0^{2 \cdot n \cdot B_a^u \cdot Z^{n-1}} e^{-Z} dZ = 1 - \zeta
\]

(5)
It follows from (5) \( B'_a = \frac{1}{2 \cdot n \cdot T_a} \cdot \chi^2_a \); \( B''_a = \frac{1}{2 \cdot n \cdot T_a} \cdot \chi^2_{1-a} \).

Here: \( \chi^2_a \), \( \chi^2_{1-a} \) are the quantile \( \chi^2 \)-distributions, which tabular values are chosen when the freedom degrees number is 2n.

It should be noted that the information availability on the 1st uncertainty degree allows developing the calculated synthesized accelerogram for the construction site, specifying spectral and other parameters corresponding to the given security level. The security levels of random exposure parameters can be assigned by different depending on the calculation of SLE or DLE.

Among strong earthquakes recordings one of the most dangerous accelerograms for the structure in question can be chosen as a calculation one for the calculation on the DLE occasion. For calculations on the SLE occasion, the calculated accelerogram should be taken in view of the occurrence frequency based on the probability response spectra.

**Building of a seismic impact model for territories with the 2nd uncertainty degree**

The 2nd uncertainty degree should include areas of medium seismic activity, relatively little explored, with limited statistical data and also not having an instrumentation recording of a strong earthquake. Such data as the location of focal zones, magnitudes of expected earthquakes, geology, epicentral and hypocentral distances and occurrence frequency shown in percussibility maps are known here. Based on these seismological data using empirical dependencies obtained for various regions of the world [7, 8], it is possible to estimate some quantitative parameters of ground motions (maximum accelerations, range of prevailing oscillations periods, effects duration) and develop a regional model of the seismic effect. The applicability of a particular dependence should be determined by comparative analysis of existing recordings of weak earthquakes. Since here for the computational model being compiled, only certain changes intervals in the parameters of seismic grounds vibrations are known, it is necessary to take some caution when choosing their design values. In this case, the decision will be more cautious when the calculated acceleration is taken to be equal to the maximum of the predicted interval determined during the considered period of time, and from the interval of prevailing periods of grounds motions, the effect with the prevailing period that represents the greatest danger to the structure being considered is taken, i.e. corresponding to the maximum response spectrum. The impact duration can be taken as equal to the average duration for a given class of earthquakes when simulating earthquake ground motions in the form of a non-stationary random process and equal to the average effective duration when presenting it as a stationary random process.

In this uncertainty case, when the repeatability period \( T_a \) is determined under the absence of insufficient or statistics, the best solution would be if the repeatability period specified in ground shaking maps is taken to be equal not to the mean value but to the maximum \( T_a = T_a^m \). Then the repetition period of the earthquake corresponding to the availability level \( \zeta \) can be determined by the condition:

\[
\int_{T_a^m}^{\infty} B_a \cdot e^{-B_a \cdot T} dT = 1 - \zeta, \quad \text{where} \quad T_a^m = -\frac{1}{B_a} \cdot \ln(1 - \zeta).
\]

Since \( B_a = 1/T_a \) we get
Using expression (6), it is possible to determine the earthquake recurrence probability corresponding to the given availability level \( \zeta \).

Thus, for territories with the 2nd uncertainty degree, seismic effects can be represented as a class of nonstationary random processes with parameters and repeatabilities calculated in accordance with the above proposed approach.

Risk function for the model under consideration has the form (3), where the probability of the structure failure when exposed to the \( k \)-th earthquake of \( Z \) –th class \( Q \left( Z_{ik} \right) \) is determined with fixed impact parameters selected as suggested above.

### Building of a seismic effect model for territories with the 3rd uncertainty degree

In poorly explored areas or in areas with low seismic activity, it is impossible to obtain more or less objective information about the repeatability probabilities and parameters of the expected seismic impacts. Here the active sources of information are the maps GSZ-97 and construction code and regulations “Construction in seismic areas”. However, to carry out calculations of reliability and risk, a spectral-temporal calculation model of seismic effect should be developed. Y.M. Aizenberg model is more suitable for this situation. [9]is presented in the form of numerous nonstationary random processes occupying a certain area of prevailing frequencies of ground motions overlapping the natural oscillation frequencies of buildings and structures. At the same time, spectral parameters of earthquake ground motions of each effect are presented as functions of the prevailing exposure frequency and the maximum oscillation acceleration is corresponding to the calculated intensity. Here the probability of repetitive effects is taken equal to one.

Practical application field of this model is limited to highly demanding constructions since it is proposed here to take the most dangerous impact for a structure as a design one. This approach is extremely cautious, but it guarantees the structures reliability.

For buildings and structures of normal responsibility, the design base spectra of seismic impact, among a certain range of prevailing frequencies specified in the above model, can be determined not on the extreme pessimism (always designed on the worst outcome) and not on the extreme optimism (always designed on the best outcome) and on some average pessimism, i.e. to a certain caution level. At the same time, it will be possible to take as a basis the criterion of pessimism-optimism of Hurwitz [10], which looks like:

\[
H = \min \left(\alpha \max r + (1-\alpha) \min r \right),
\]

where \( r \) is the risk symbol, \( \alpha \) is some coefficient chosen between 0 and 1. If we take \( \alpha = 0 \), this will be a case of extreme optimism, and for \( \alpha = 1 \), extreme pessimism, corresponding to the acceptance as designed, the most dangerous impact.

The value of \( \alpha \) coefficient can be determined based on the risk analysis of the decision-making or the probabilistic-economic criterion for the design optimization of structures for seismic effect [11].

### Summary

Different seismic activity and the exploration depth of territories leads to different certainty degrees of the initial information, on which the reliability degree of calculations for seismic effects depends. Therefore, it is required to systematize the available seismological and statistical information and to make territorial computational models of seismic effects, taking into account the completeness degree of the initial information and making a certain amount of caution in the calculations. In this work, the territories are divided into three types according to the completeness degree of seismological information about the parameters of possible seismic effects and for each of them a method is given.
for selecting the calculated accelerogram and drawing up a probabilistic calculation effect model that introduces a certain amount of caution to the seismic risk assessment.

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