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Long-term prediction for seismic hazard for radioactive waste disposal

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Abstract

We consider possible approaches to the long-term prediction for seismic hazard in relation to the practical need for the safety of geological disposal of long-lived radioactive waste. The required period of prediction significantly exceeds the one reflected in the set of maps of General Seismic Zoning of the territory of the Russian Federation (GSZ-97). The first geological repository in Russia is planned to be set up in the Nizhnii Kan granite massif in the Krasnoyarsk Krai. This region is an intraplate territory with a relatively high seismic activity. We summarize the analysis of the known empirical generalizations and theoretical principles underlying the seismic hazard prediction. Real seismic events constantly violate forward-looking statements even for relatively short periods of time. These and other arguments suggest that the hypothesis of stationarity of the seismic regime, which is the basis of long-term prediction today, has limited and uncertain applicability in time. Intraplate earthquake prediction is especially uncertain because of the uncertainty in the factor responsible for generating tectonic stresses in these regions. The short horizon of the prediction, based on statistical methods, can be attributed to the nonlinearity of seismic geodynamic processes. Fundamental laws of tectonic processes should be used as the scientific basis for long-term predictions for seismic hazard at the sites chosen for geological disposal of long-lived radioactive waste. These processes can be reflected in models for the migration of the seismically active boundaries of lithospheric plates and the occurrence of seismic activity in intraplate regions.

Keywords: seismic hazard; long-term prediction; radioactive waste; geological disposal; safety

Introduction

Earthquake prediction and the development of seismic hazard maps is a problem that has not yet been solved.

According to the period of time for which an earthquake prediction should be made, it is common to distinguish between long-term, medium-term, and short-term predictions (Sobolev, 1993). Each of them is based on its own specific theoretical propositions and formalized rules of processing observation data.

According to experts' opinion, long-term predictions are more reliable, medium-term predictions are less reliable, and short-term predictions are even less reliable (Mogi, 1985; Sobolev, 1993). The longer the prediction period, the more it can be considered as a seismic hazard prediction for the given region as a whole, rather than a prediction for a specific event. Here an analogy with climate and weather forecasts is appropriate. Climate is more reliably predicted for longer periods, although with a loss of specificity of the time and place of occurrence of separate events.

Seismic hazard maps are generated for the purposes of long-term prediction. Seismic zoning maps of the former Soviet Union compiled previously were in one way or another inadequate to the real environmental conditions. Considerable progress in detailing and refining the seismic hazard of the country is observed in the last GSZ-97 set of maps. However, it also involves a number of problems related to the reliability of predictions for long periods of time (Morozov et al., 2001; Seismotectonics..., 2009).

Obviously, existing methods of earthquake prediction are not fully suitable for long periods of time, although the need for such predictions exists and is associated, in particular, with the regulatory requirements for safety analysis of radioactive waste (RW) repositories containing long-lived radionuclides. In particular, the Russian regulations, which generally follow the internationally accepted guidelines, require ensuring reliable operation of geological repositories and protecting the population over the period of the potential danger of isolated radionuclides (Radioactive..., 2004). For high-level waste and spent nuclear fuel (HLW and SNF) and other types of RW

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containing long-lived radionuclides, the period of potential hazard is millions of years. A prediction for especially dangerous objects, such as nuclear power plants and radioactive repositories, with a reasonable probability of not exceeding a given earthquake intensity is calculated for a period of 10,000 years and is based on (GSZ-97D map). However, it is recommended that the stability of the geological environment that will ensure the reliability of the disposal system over the period of the potential hazard of long-lived RW should be evaluated for the whole of this period (Considering..., 2009; Kochkin, 2013; Methods..., 2012). Hence the need for long-term predictions of seismic hazard for periods of hundreds of thousands and millions of years and there is a question about the tools for predicting seismotectonic activity for such long periods. These predictions should be considered to be super-long-term even in geological terms, and considering tools for their development is the main purpose of the paper.

Safety of geological disposal of long-lived RW

The geological disposal of RW is a technology designed to ensure the reliable protection of the population and the biosphere from radioactive contamination (Falck and Nilsson, 2009). It is planned to dispose waste in special underground facilities (repositories) fitted with a multibarrier system of protection of the environment from radionuclides. First, this is a matrix comprising radionuclides. It is packaged in a metal can, which provides physical disposal of radionuclides from groundwater in the initial stages of isolation. Clay fillings of the chambers and tunnels are used for absorption slowing of the leakage of radionuclides due to the inevitable corrosion of the cans. The last barrier in this system is the geological environment. It is to minimize the dispersion of radionuclides for as long as they are a hazard.

Over millions of years, different events and processes will occur in the repository and its surrounding, and the rate and duration of these processes can vary within wide limits. In particular, the dangerous processes that can affect the stability of the isolating geological environment and deform the engineering barriers include the geodynamic processes occurring not only along the active margins of tectonic plates but also in intraplate blocks (Stein, 2007).

Obviously, it is best to place geological repositories in regions characterized by low seismicity and having no active faults. However, if such a region is turned out to be seismically hazardous, as is the case with the site for the Russian repository in Krasnoyarsk Krai (Lobanov et al., 2011), the location of active faults should be clearly established, and their seismotectonic activity should be predicted for the entire potentially dangerous period. The seismic hazard of the future disposal site in Krasnoyarsk Krai is estimated to be 8 points (GSZ-97D map) or according to the refined zonation of probable earthquake centers (PEC) for the territory of the Krasnoyarsk agglomeration developed in accordance with the methodology for constructing medium-scale GSZ maps is 7 points (Sibgatulin et al., 2004).

Dangerous consequences of seismic fault activation with magnitudes maximal for the south of the Siberian region ($M > 8$) are manifested mainly on the surface and near it as secondary faulting, slope processes, and other phenomena at distances up to tens of kilometers or more. At a distance from a seismogenic source, the frequency of dangerous geological processes decreases exponentially (Lunina et al., 2014). It is known that at a depth of hundreds of meters in rocks, the dangerous consequences of earthquakes (seismic intensity) are much weaker. This somewhat reduces the potential danger of high seismic activity for geological repositories.

Under the current regulations, sites in regions with possible seismic events of more than 9 points or with signs of active fault are considered unsuitable. Regions in which the seismicity is characterized by a maximum calculated earthquake intensity over 7 points are unfavorable (Radioactive..., 2004). Thus, seismogeodynamic processes at the site of the future repository in Krasnoyarsk Kari is to be studied in detail to assess its long-term safety.

Empirical foundations and theory of long-term prediction for seismic hazard

The seismicity of a region us usually assessed based on three main criteria: seismic activity, earthquake recurrence, and the maximum possible earthquake magnitude ($M_{\max}$) (Bune and Gorshkov, 1980; Ulomov and Shumilina, 1999).

Seismic activity is a stochastic variable. It is unstable both in time and in space.

Using the results of analysis of seismic activity in time and space, Fedotov (1968) introduced the concept of so-called "seismic gaps." He has shown that the regions of the sources of catastrophic earthquakes that occurred during the observation period occupy a significant part of a particular seismic zone but do not cover it completely and do not overlap one another. He assumed that the regions where strong earthquakes had not been observed for a long time are possible places of future major earthquakes. Sooner or later, strong earthquakes are believed to occur repeatedly in the same places. Fedotov proposed the term seismic cycle to refer to the course of the seismic regime at the same point of a seismogenic fault in the time interval between two earthquakes of maximum intensity. Thus, in the Kuril-Kamchatka zone, the average return period of catastrophic earthquakes $M > 7^3/_4$ is approximately 140 years. In less active regions, it is many hundreds and thousands of years. Instrumental monitoring for any region is performed only in the last 100 years or less, so that there are no data about any full seismic cycle. Even in the Kuril-Kamchatka zone, continuous instrumental monitoring of the seismic activity of individual sections during complete cycles will probably end only in about 2044 (1904 + 140 years). Fedotov believed that the seismic cycle is a common feature of seismic processes. Its typical characteristic is the long period of stabilization of the regime, which lasts for $^3/_4$ of the cycle or more. During this period, the seismic activity fluctuates around