Probabilistic seismic hazard analysis of the sites of critical objects

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Abstract. The work is devoted to the development of methods of probabilistic seismic hazard analysis, as one of the main stages in the engineering-seismological surveys for sites of critical objects, provides an overview of software and examples of calculations.

Keywords: PSHA, seismic hazard analysis, earthquake, seismic hazard parameters, software for PSHA.

1 Introduction

Seismic hazard assessment of the construction site is an integral part of the complex of geotechnical surveys in the design of critical objects. In the Russian Federation as in most countries of the world standard assessments of seismic hazard are probabilistic in nature. The general seismic zoning (GSZ) of the Russian Federation gives the estimated probability of not exceeding 90%, 95%, 99% over 50 years.

On November 26 2018 the Building Code of BC 14.13330.2018 "Construction Work in Seismic Areas" came into force. In accordance with paragraph 4.3 in order for refining the seismicity of the area of construction of critical objects it is necessary to conduct specialized seismological and seismotectonic studies – detailed seismic zoning (DSR). DSZ like GSZ, includes a set of studies that can conditionally be combined into two groups: compiling and parameterizing earthquake source zone (ESZ) model and preparing equations ground motion prediction equations (GMPEs). Probabilistic seismic hazard analysis (PSHA) is used to directly calculate probable seismic effects based on these data groups. Moreover, the correctness of the estimates obtained depends on the software used for the calculation.

In this paper, we calculated the seismic hazard for the Severomuisky tunnel – a railway tunnel in the Republic of Buryatia on the Baikal-Amur Mainline with a length of more than 15 km. The calculation was performed in specialized software systems in the Russian software package EAST-2016 [1] where PSHA is implemented on the basis of the Monte Carlo method and in the European software package OpenQuake Engine [2] where PSHA is based on the classic Cornell approach.

2 The main approaches for the probabilistic analysis of seismic hazard

The hazard assessment by the PSHA method consists in determining the level of seismic effects at the site which will not be exceeded with a fixed probability for a given period of time [3]. Seismic hazard according to PSHA is closely related to the concept of seismic shaking introduced by Yu.V. Riznichenko in 1965. As a computational procedure the PSHA approach was first introduced by Cornell (1968) for peak ground acceleration (PGA).

The probabilistic approach that Cornell proposed for assessing seismic hazard in modern literature is treated as a *classic* PSHA. According to this approach in order to calculate the probability of exceeding the specified ground motion amplitude at the investigated site the contributions of hazard are integrated over all magnitudes and distances for all ESZs according to the total probability theorem [4]. The classic approach for PSHA includes four basic steps:

1. Identification and parameterization of seismic sources. Sources can be represented as areas sources, faults sources, points sources, etc.
2. Characterization of the temporal and magnitude distribution seismicity for the source. The recurrence of earthquakes is statistically independent, earthquakes occur at a constant frequency and the recurrence of future events does not depend on the last earthquake that occurred.
3. Preparation of GMPE. The choice of GMPE is an important point because often GMPE is the main factor contributing to the uncertainties in the implementation of PSHA.
4. Implementation and accounting of various types of uncertainties. For example, in position, in magnitudes, in the occurrence of earthquakes.

The final result of the PSHA are hazard curves defined in the coordinates of the ground motion parameter and the probability of exceeding it in a given time interval.

Recently, there has been a tendency to solve the PSHA problem using Monte Carlo simulation. The Monte Carlo method is also known as the stochastic method. The PSHA procedure based on the Monte Carlo method can be divided into two stages:

1. Based on the ESZ model, an earthquake catalog is generated for a given time period T (years). Each earthquake is characterized by a set of parameters: magnitude; the length and width of the rupture; azimuth of its upper edge, angle of dip; geographic coordinates and hypocentral depth.

2. The intensity from each earthquake at the point of investigated site is calculated on the basis of the adopted GMPE and statistics are collected on the number of events of different intensities. The resulting statistics are translated into a cumulative form from which hazard curves are already calculated.

The use of a synthetic long-term earthquake catalog makes it possible to take into account the uncertainties in the random nature of the parameters of future earthquakes. This allows you to significantly simplify the logic tree to account for the uncertainties of the parameters of the ESZs.

3 Overview of modern PSHA software

The work on seismic hazard assessment and seismic zoning cannot be done without adequate mathematical software. Currently, computer programs for conducting PSHA are being actively developed and widely used in the world based on the classical approach such as the OpenSHA software module complex, the R-CRISIS software module complex, the OpenQuake Engine calculation module.

The OpenQuake Engine calculation module used in this work was developed on the basis of OpenSHA software modules (University of Southern California (USC) [5]) and implemented in the Python programming language [2]. The reason for the development was the implementation of the European scientific program Seismic Hazard Harmonization in Europe (SHARE). The main goal of SHARE was to provide a seismic hazard model for the Euro-Mediterranean region. The project was aimed at setting new standards in the practice of probabilistic assessment of seismic hazard through close cooperation of leading European geologists, seismologists and engineers [6]. OpenQuake Engine is freely available to users.

The Russian software package PRB-60 was developed in 1994-1995 as part of research to create a set of maps GSZ -97. The PSHA procedure implemented in it is based on the Monte Carlo method. The methodological foundations of the package and basic algorithms developed by A.A. Gusev with the participation of L.S. Shumilina and V.M. Pavlov, software implementation of the package by V.M. Pavlov. Software package PRB-60 was updated in 2003, 2010 and 2016. The last modification of this software was made in the Microsoft Visual Studio 2008 software environment and received the name EAST-2016 [1]. The main characteristics of the OpenQuake Engine and EAST-2016 are presented in the table [1].

Table 1. The main characteristics of the used software systems.

CHARACTERISTIC		Software	
		OQ Engine	EAST-2016
PSHA approach		Classic	Monte Carlo
Seismic Source Types			
Area		Yes	Yes
Fault	line (2D)	Yes	Yes
	Volume (3D)	Yes	Yes
Point		Yes	Yes
Allow to assign a depth distribution to each source		Yes	Yes
Allow to assign a style-of faulting to each source		Yes	Yes
Rupture length & width Modelling		Yes	Yes
Magnitude Frequency Distribution [MFD]			
Gutenberg-Richter		Yes	Yes
Gaussian		Yes	Yes
Customize MFD intervals		Yes	Yes
Ground Motion Prediction Equations [GMPE]			
Built-in		Yes	Yes
User Defined		Yes	Yes
Allow to assign different GMPEs per seismic source type		Yes	Yes
Allow to assign equation parameters for various soils		Yes	Yes
Logic Tree			
Allows to define a logic tree		Yes	No
Output			
Hazard Curves		Yes	Yes
Shake duration calculation		No	Yes
Hazard Maps		Yes	Yes
Uniform Hazard Spectra		Yes	Yes

4 Test calculation of seismic hazard for the Severomuisk tunnel

The Lineament-domain model of earthquake source zones contains two main structural elements. Lineaments (linear sources or planes falling at a given angle) serve as the basis for the model. In essence, lineaments are seismically active faults that are presented in the generalized form delineation which carry the bulk of seismic potential. Domains (area sources) cover the volumes of the geological environment within which earthquake ruptures of moderate and low magnitudes are scattered with equal density.

To demonstrate the capabilities of the PSHA software packages a test model of the ESZs of the Baikal rift zone was prepared. The Pliocene-Quaternary crustal faults of Baikal rift zone [7] (developed by the Institute of the Earth's Crust SB RAS, Irkutsk) was developed as the basis for constructing lineaments. The visualization of the elements of the ESZ model in the Severomuisky tunnel is shown in Figure 1.

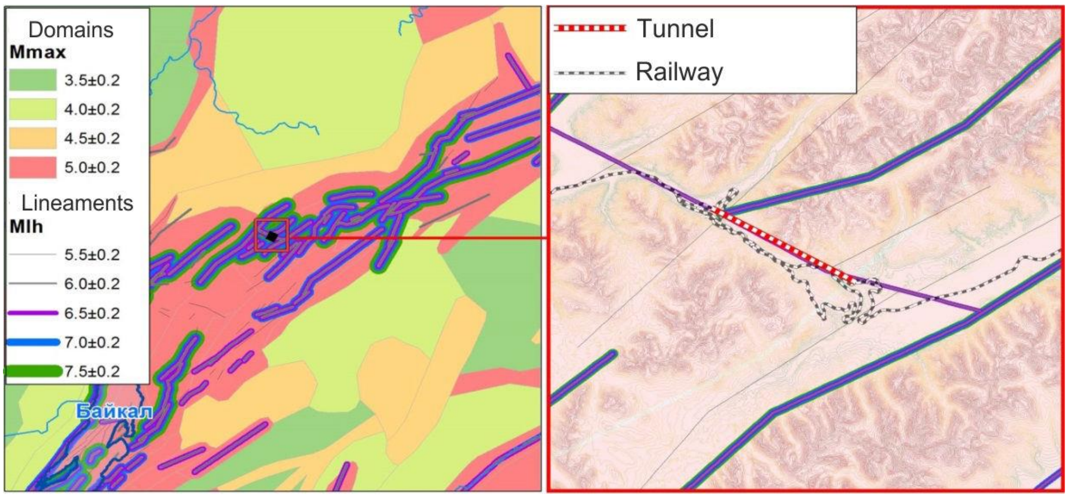

Figure 1. Elements of the ESZ model in the Severomuisk tunnel.

For each ESZs based on regional catalogs of earthquakes the magnitude-frequency distribution of earthquakes (i.e. the number of expected events per year for magnitude bins) is set.

To perform PSHA in the domestic software the GMPE F.F. Aptikaev [8]. OpenQuake Engine used GMPEs with equal weights to calculate PSHA: Campbell and Bozorgnia 2014, Chiou and Youngs 2014, Abrahamson et al. 2014. The calculation of PSHA in the used software was performed for rocky. As a result of the PSHA calculation for the Severomuisky tunnel the acceleration response spectra of soil were obtained. Figure 2 shows the calculated response spectra of rocky for a recurrence period of 1000 years (the probability of not exceeding 95% over 50 years) calculated using the OpenQuake Engine and EAST-2016.

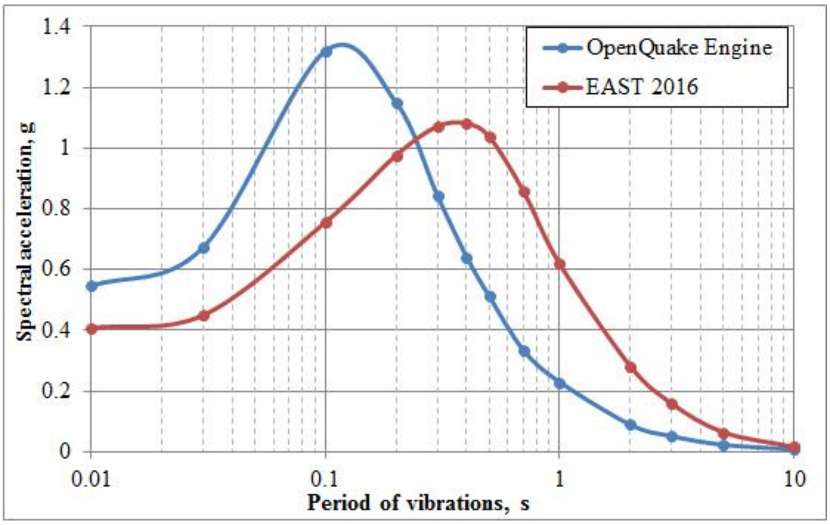

Figure 2. Response spectra for a recurrence period of 1000 years.

Peak ground acceleration (PGA1000) was 0.545 and 0.408 g units, the maximum values of the response spectra at the periods of vibrations of 1.25 sec. and 0.4 sec. for OpenQuake Engine and EAST-2016 respectively. In addition, in EAST-2016 the shake duration by F.F. Aptikaev was calculated. To convert PGA to macroseismic intensity the ratios

GOST R 57546-2017 were used.Figure 3 shows hazard curves in fractions of a point obtained as a result of PSHA according to EAST-2016 and OpenQuake Engine.

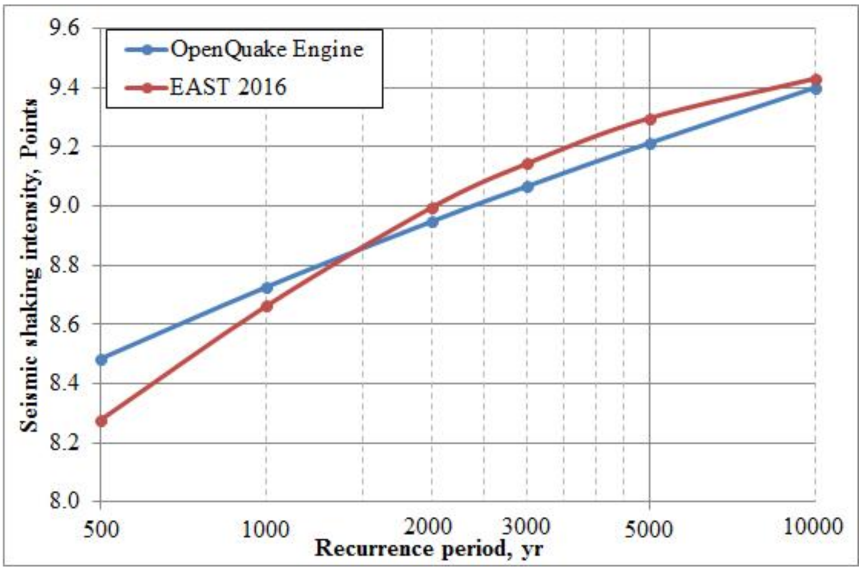

Figure 3. Hazard curves.

Figure 3 shows that the estimates obtained from both programs are generally consistent with each other. The maximum deviation for given periods corresponds to 0.2 percentage points. It should be noted that the performed PSHA calculations for the Severomuisky tunnel site are of a test nature and are intended to demonstrate the capabilities of software tools, therefore, the obtained estimates should not be considered absolutely reliable.

5 Conclusion

An urgent task is to obtain correct estimates of the seismic hazard of the territories for the construction and operation of facilities of varying degrees of responsibility. The choice of the program and algorithms on the basis of which PSHA is carried out is a very important point in research. It can be argued that the choice of the PSHA tool affects the correctness and reliability of the results.

Comparing the characteristics and the obtained results of the two programs we can conclude that EAST-2016 provides a reliable assessment of seismic hazard and is not inferior in functionality to the modern foreign OpenQuake Engine. At the same time, the EAST-2016 software package is focused on domestic standard documents (GOST R 57546-2017, BC 14.13330.2018) which makes its use more preferable during execution.

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