Evaluation of Seismic Hazard Using Seismic Microzonation Techniques

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Abstract. It was shown the technique of seismic hazard assessment based on comprehensive use of methods of seismic microzonation.
This technique consists of four steps. The first step is to collect geological, seismological, geophysical and topographic information. Each layer according to geological engineering survey and geophysical work are assigned physical and mechanical properties (density, limit shear stress) and the P- and S- wave velocity. Next (step 2) after visualization and examination input data using GIS technologies 3D modelling of the geological environment is performed (it is created a grid each point of which is referred to coordinates of the site). The number and depth of soil are set in each point based on geological drilling data. Then (step 3) at each point seismic intensity are calculated using instrumental methods including the method of acoustic impedance and computer simulation (GRUNT program). At the last stage according to the analysis of the results of theoretical and instrumental methods seismic microzonation map are created using GIS technologies. The procedure of constructing maps uses different methods of selection areas with the same seismic hazard (kriging, spline interpolation).

Keywords: earthquake, seismic microzoning, seismic intensity, GIS.

1 Introduction

Seismic microzonation is performed to quantity the influence of soil properties on seismic vibration within the area of specific facilities and within the residential areas. Selection of areas with different seismicity is carried out using comprehensive study of seismic properties of soils, geotechnical, hydro-geological and seismotectonic features of the territory. As a result, after performing seismic zoning the map of microzonation is created.

The technique of carrying out seismic microzonation can be divided into four steps. The first step (preparing) includes acquisition of geological, seismic, geophysical and topographic data. According this data 3D site model is created (the second step).

The third step is calculation of seismic intensity in each model point of site using instrumental and calculation methods of soil seismic properties assessment [1, 2]. The following methods are used when seismic hazard is estimated:

- Seismic microzonation using acoustic impedance method
- Seismic microzonation using earthquakes and explosions records
- Seismic microzonation using microtremors

These methods are normative methods and are subjected in [2].

The basis of numerical simulation of the geological environment reaction to strong earthquakes is the concept of the heed to take into account more than one possible earthquake effect, so ensemble of earthquakes effect with different spectral characteristics is estimated. Therefore for each model point of site numerical simulation is implemented on the full range of accelerograms.

Numerical simulation lets us to carry out calculation of peak ground acceleration, time stress and strain changes, Fourier spectra and response spectra on the site surface for a given input motion.

The final stage of seismic microzonation is creation of seismic microzonation maps that displays the regions with varying seismic intensity. Seismic microzonation maps provide the basis for seismic resistant construction, public safety, environmental protection and other actions aimed to reducing the damage caused by strong earthquakes.

2 Data acquisition

Reliability of hazard estimates directly depends on the quality and completeness of the initial engineering-geological and engineering-geophysical information in study area. In this regard, in the first step of seismic microzonation are used a complex engineering geophysical method to determine the characteristics of the ground layer, necessary to the implementation of instrumental and calculation methods of seismic microzonation.

Geological information consists of drilling data: coordinates, absolute elevation, thickness and a number of layers, the groundwater level. This information is taken from the geological engineering survey reports.

Each layer is assigned a number of engineering-geological elements (EGE). The EGE is some amount of ground with the same name-bearing type and uniform in properties and state. According to the EGE number each layer is assigned physical and mechanical properties (density, critical shear stress, etc.) and velocity of P- and S- waves. The velocities are obtained by processing and interpretation of seismic exploration materials (complex method of refracted waves, vertical seismic profiling). The abovementioned data should be presented as database or spreadsheet for further work in GIS. The example of input data is shown in Table 1.

Table 1: Example of one borehole input data

Borehole	layer	EGE	X	Y	Z	depth, m	density	Vp	Vs
18	1	1	26436.6	21227.09	37.95	1.8	1.92	232	158
18	2	2	26436.6	21227.09	37.95	4.7	2.15	352	159
18	3	4	26436.6	21227.09	37.95	8	2.54	1025	488
18	4	5	26436.6	21227.09	37.95	10	2.72	2960	1968

At the same stage import and visualization of the boreholes data in the GIS environment are implemented. In addition to this information topographic data is displayed: lines of surface height, site boundaries, position of existing and planned buildings on site (Fig. 1).

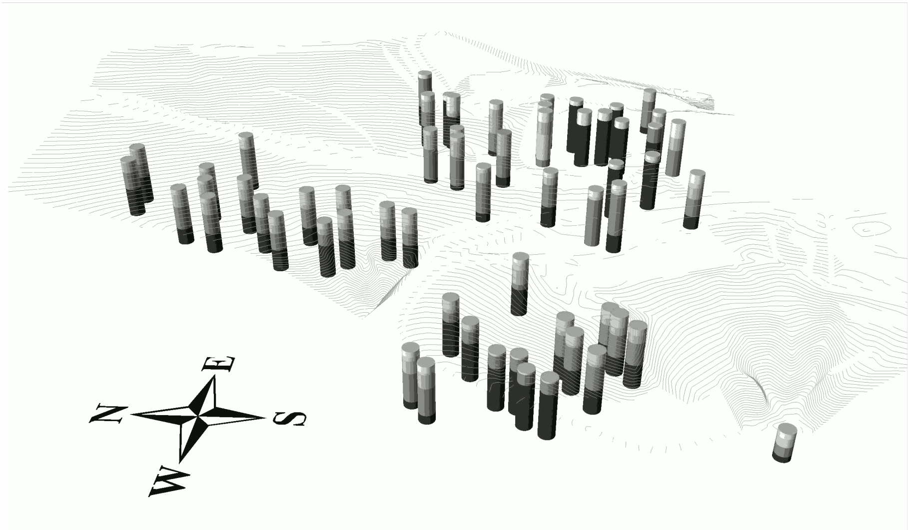

Fig. 1: Primary visualization of the input boreholes data

In most cases the input boreholes data may include data related to larger area than the area on which seismic microzonation is performed. Selection of the necessary data is carried out using GIS software tools which provide opportunities for the use of graphical tools, in particular, to highlight the geographical boundaries of site.

One more necessary data array for numerical simulation of the geological environment reaction to strong earthquakes is set of synthesized accelerograms or analogue accelerograms.

Calculated seismic impact can be modeled using accelerograms scaled to strength-level event (SLE) or ductility-level event (DLE). The accelerograms can be obtained from the following:

- from time-history of earthquakes obtained on building site or development area
- from time-history of earthquakes obtained on regions that have seismotectonic, geologic and other seismological conditions similar with area of site
- synthesized time-history of earthquakes based on parameters of seismic impact for SLE and DLE

Time-history of earthquakes obtained on building site or development area scaled to SLE and DLE.

During whole period of field geophysical works in area of building site is carried out registration of seismic events from nearby seismogenic zone. The time-history of earthquakes obtained on site are scaled to SLE and DLE.

Time-history of earthquakes obtained on regions that have seismotectonic, geologic and other seismological conditions similar with area of site.

Ensembles of digital accelerograms of real seismic events obtained on regions that have seismotectonic, geologic and other seismological conditions similar with area of site are selected on the basis of SLE and DLE parameters (hypocentral distance and magnitude) obtained in detail seismic zoning. For this purpose are used databases contained time-history of real seismic events, for example the database of accelerograms of Japan seismic station (`http://www.kik.bosai.go.jp/kik/search/index_en.html`). When the accelerograms are selected from the database engineering-geological conditions, hypocentral distance and magnitude are taken into account.

Synthesized time-history of earthquakes based on parameters of seismic impact for SLE and DLE.

Synthesized accelerograms are calculated using programs SMSIM [4] for modeling synthesized time-history of earthquakes. The programs SMSIM are based on simulation of ground motion using the stochastic method. It is very convenient for modeling ground motion on studied site in engineering frequency band from earthquake with given parameters hypocentral distance and magnitude of earthquake. This method is taken into account regional features of seismic source as well as influence of the features of the geological environment on the propagation of seismic waves from the source to the site.

3 Building of geological 3D model of site

For the further computation on the basis of aforementioned date building of 3D model points of geological environment is carried out with certain step.

Using GIS tools a grid is created and each point of which is geographically linked height and coordinates of the site. Then each point is defined by the thickness and a number of layers based on drilling data and engineering stratigraphic columns (Fig. 2). These data are input for the subsequent calculation of seismic intensity.

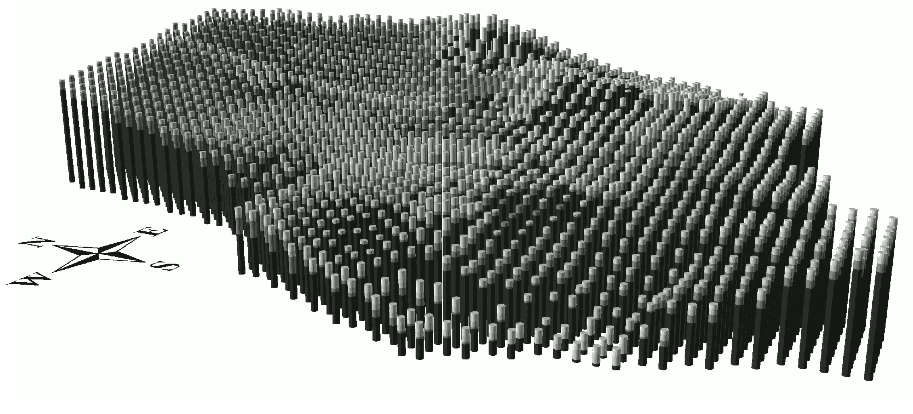

Fig. 2: 3D model of geological environment

4 Seismic intensity calculation

Seismic intensity calculation is carried out using acoustic impedance method and programs calculating the oscillation of surface. There are various methods for calculating the vibrations of layered soils based on linear equations [1] ; in this paper is used program GRUNT, which is based on the method of thin-layered media.

4.1 Seismic microzonation using acoustic impedance method

Instrumental evaluation of the velocity properties of site is considered as informational base for calculation of seismic intensity increment. Estimation of seismic intensity increments based on acoustic impedance method is carried out based on measuring the velocities of seismic waves and the density values in 10 meter soil thickness of studied aria and reference soil.

The calculations are carried out according to the equation:

$$I = I_0 + \mathit{\Delta} I_S + \mathit{\Delta} I_B, \tag{1}$$

where I is seismic intensity based on local conditions, I_0 is initial seismic in relation to the average ground conditions (II-category in seismic properties) according to the detail seismic zoning; I_S is seismic intensity increment because of acoustic impedance differences in the target and the reference soil:

$$\mathit{\Delta} I_S = 1.67 \log(V_{(p,s)} \rho_R / V_{(p,s)i} \rho_i), \tag{2}$$

where $V_{(p,s)}$ and $V_{(p,s)i}$ are weighted mean value of the propagation velocities of P- and S waves on the target and the reference soil, ρ_R and ρ_i are weighted mean value of density in the target and the reference soil; $\mathit{\Delta} I_B$ is seismic intensity increment because of deterioration of seismic properties caused by water saturation.

4.2 Seismic microzonation using earthquakes and explosions records

Synchronous registration of earthquakes on the different parts of site provides a simple way to compare some properties of ground motion. In this approach direct problem of seismic microzonation is solved, i.e. seismic intensity increment in some areas of site selected according to engineering-geological study is estimated.

After getting synchronous time-history of earthquakes frequency-domain characteristics and seismic intensity increment with respect to the recording station, located on the reference ground are estimated.

Seismic intensity increment assessment is carried out according to the equation [2]:

$$\varDelta I = 3.33 \log(\frac{A_i}{A_0}), \tag{3}$$

where A_i and A_0 are the average amplitude of ground motions (from one earthquake) on the target and the reference soil respectively.

In many cases such assessment is not enough spectral analysis of the events is carried out. The seismic intensity increment is defined for the entire frequency range from 0.1 to 10 Hz, and separately for the low, mid and high frequencies.

Figure 3a shows the three-component record of ground motion of the regional earthquake registered on the base station situated on I-category soil and station 4 situated on II-category soil. Figure 3b shows the Fourier spectra of these events (root mean square was taken from three component records).

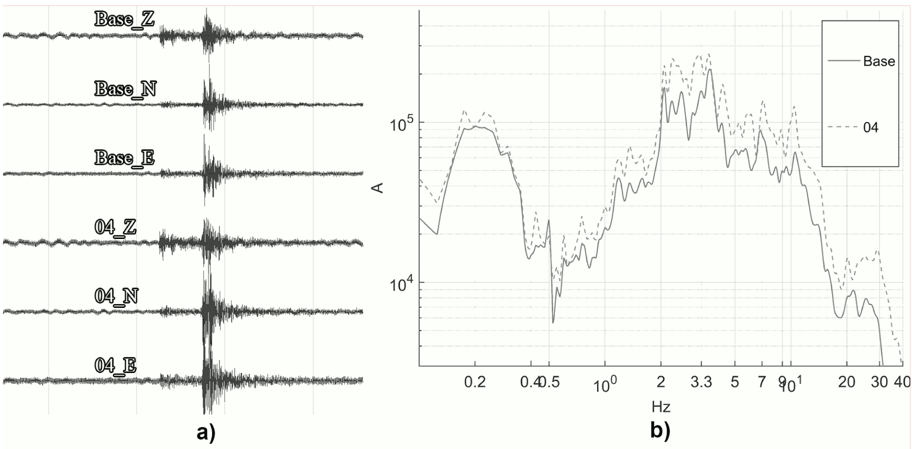

Fig. 3: Three-component record of ground motion on the two stations (a) and Fourier spectra of records (b)

4.3 Seismic microzonation using microtremors

This method is used as supplementary method in seismic microzonation.

To assess changes of strong earthquake intensity using peak of microtremors at a given period the following equation is used [2]:

$$\Delta I = 2\log(\frac{Amax_i}{Amax_0}), \tag{4}$$

where $Amax_i$ $Amax_0$ peak amplitude of microtremors on the target and the reference soil respectively.

All calculations are performed using the seismic processing program Geopsy (`http://www.geopsy.org`). Average Fourier spectra with duration from 40 to 60 second on the interval of 10 minutes or more (depending on the recording quality noisy areas can be excluded) are calculated. All spectra are previously smoothed by the Horse and Omachi window [Konno, K. and Omachi, T., 1998, Bull. Seism. Soc. Am., 88, 228-241.] with a coefficient characterizing the bandwidth, b = 90. Each piece of the recording also is multiplied by 5% weight cosine function to reduce boundary effects.

Based on analysis of the fundamental frequency of the site maximum value of spectra is selected in a particular bandwidth. The last step is to calculate the seismic intensity increment using equation (4) relative to the base point. It should be noted that in microtremors formation along with natural sources involved numerous artificial sources, the impact of which cannot be controlled. Inability to comply with the necessary conditions of registration microtremors and strong variation of maximum amplitude values limit the use of microtremors to calculate seismic intensity increment. Thus, the use of method of microtremors registration is only suitable in combination with other instrumental methods.

4.4 Numerical simulation

One of the simplest one-dimensional soil models is KelvinVoigt viscoelastic model. Shear stress τ in this case depends on the strain γ and its derivative $\dot{\gamma}$ as shown below:

$$\tau = G\gamma + \eta\dot{\gamma}, \tag{5}$$

where G is shear modulus, η is viscosity.

Schematic representation of KelvinVoigt model is shown in Figure 4.

The dynamics of the soil environment is described by the following equation:

$$\frac{\partial\tau}{\partial z} = \rho\frac{\partial^2 u}{\partial t^2} \tag{6}$$

Substitute the value τ from (3) and taking into account that $\gamma = \frac{\partial u}{\partial z}$,

$$\rho\frac{\partial^2 u}{\partial t^2} = G\frac{\partial^2 u}{\partial z^2} + \eta\frac{\partial^3 u}{\partial z^2 \partial t} \tag{7}$$

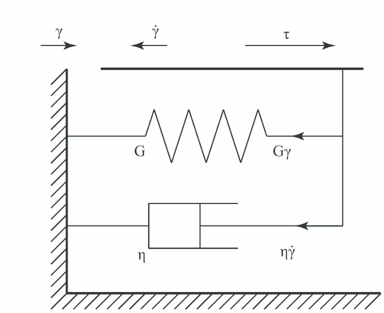

Fig. 4: Schematic representation of KelvinVoigt model

To calculate the spectral characteristics and accelerograms on the surface or in the interior of the multilayer inelastic (with absorption) media with plane boundaries is used thin-layered media (The Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences). It is solved the two-dimensional problem of propagation of plane bodily waves in nonelastic layer pack with free upper boundary and underlying elastic half-space. From half-space to the lower boundary layer thickness at an arbitrary angle it is fallen P- or S- wave with unit amplitude at a given frequency, or wave with a given arbitrary shape. The model parameters are thickness and density of layers, P- and S- wave velocity, damping ratio. It can be used different models of the absorption mechanism in the medium (linear dependence of the absorption coefficient on the frequency or dependence described a linearly inelastic Gurevich model).

Output data depending on the conditions of the problem are obtained as follows:

- The amplitude-frequency characteristics of a subsurface formation according to a predetermined model
- Accelerograms on the free surface or inside the medium
- Seismic intensity increments calculated using relationship of the amplitude-frequency characteristics of the studied and reference models
- Response spectrum corresponding to the calculated accelerograms

This method is implemented in Grunt software. The algorithms have been adapted for problems of seismic microzonation allowing counting large amounts of information in an automatic mode.

Geological section is described as a set of enumerated and numbered from top to bottom layers (including the half-space) each of which has its mechanical parameters. Each layer can be divided into sub-layers of equal power with its mechanical layer parameters to determine the properties of motion in certain depth (all calculations are executed in the program for the top of layer).

Input motion is read from formatted files. The nonlinear and inelastic soil behavior under loads caused by strong movements is described by change in the modulus of elasticity and damping, which are due to deformation. Their values are determined iteratively by leading maximum deformation to a uniform one to the entire layer.

For each model, automatic calculations are carried out using the synthesized accelerograms [3, 4], analogue accelerograms and regional records of earthquakes. The results of each calculation are numerical characteristics.

For each calculated pair (seismic event - model) are calculated set of characteristics including:

- Peak ground acceleration (PGA) expressed in g defined for a given return period (the maximum value of the modulus of the acceleration during earthquake)
- Response spectra calculated to the surface of site
- The duration of ground motion for a given return period;
- Period of oscillation with PGA;

To convert the peak acceleration in the seismic intensity the following equation is used[5]:

$$I = 2.5\log(PGA) + 1.25\log(d) + 1.05, \tag{8}$$

where PGA is peak ground acceleration expressed in g, d is duration of ground motion expressed in *second*.

5 Creation of seismic microzonation maps

The final stage of seismic microzonation is creation of seismic microzonation maps based on analysis of the results of numerical and instrumental methods.

Creation contour seismic microzonation maps is performed using the grid with certain step (usually 25x25 meters). Nodes of the grid are assigned design parameters of seismic effects corresponding to zoning areas.

Based on the grid interpolation is performed and then surface in geotif format is received. The user may make use of various options for surface contouring (e.g. kriging, spline) offered by the GIS software. Because of the uniform grid REGULARIZED type of spline is used. This type creates a smooth, gradually changing surface.

The next step is to reclassify a raster values. The interval of raster values is assigned the mean value. The step of interval is taken equal to integer value of seismic intensity, and 0.1 of one.

After receiving the parameterized raster conversion to GIS polygons of this raster is performed. Groups of raster pixels with the same values of seismic intensity are combined into a single polygon with assigning this value of seismic intensity (Fig. 5)

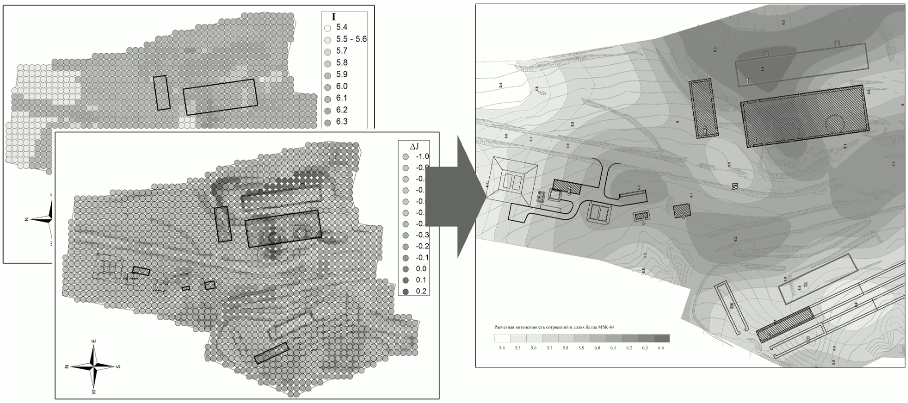

Fig. 5: Creation of seismic microzonation maps in GIS

6 Conclusion

The developed technique facilitates and accelerates research associated with seismic microzonation.

Creation of the 3D geological environment model lets us to increase the accuracy of defining seismic intensity of site.

Seismic intensity calculation is perfumed using instrumental methods and numerical simulation. GIS is the primary tool for creating seismic microzonation maps which is the final step of developed computational technique.

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