МАРКШЕЙДЕРСКОЕ ДЕЛО. ГОРНОПРОМЫШЛЕННАЯ ГЕОЛОГИЯ

DOI: 10.21440/0536-1028-2023-1-55-65

A method of seismic microzoning based on the vulnerability coefficient

Lev N. Senin[1]*, Tatiana E. Senina[1]
[1] Institute of Geophysics UB RAS, Ekaterinburg, Russia
e-mail: selenik@rambler.ru

Abstract

The research objective *is to develop a new method of seismic microzoning (SMZ) based on the spectral ratios between seismic signal's horizontal and vertical components, i.e. on the vulnerability coefficient of the topmost soil stratum.*

Methods of research. *The HVSR spectral ratio analysis has been used for a long time in various modifications. However, in author's opinion, what's new is the approach to seismic hazard zoning proposed in this research. It uses the vulnerability indices and subsequent recalculation into seismic intensity increments. The SMZ method based on the vulnerability coefficient considered in this article is not mandatory, although it is a variation of the spectral ratio method. It may be regarded as an addition to the mandatory seismic stiffness method. The combination of these SMZ methods will arguably increase the capabilities of the method as a whole and improve the accuracy and adequacy of a schematic map of seismic intensity increments. One of the advantages of both spectral ratio method and SMZ method based on the vulnerability index, is that they allow to take into account inelastic and nonlinear deformation processes when strong wave movements impacts on soils.*

Research results. *Based on the calculated spectral characteristics of soils, the method makes it possible to construct schematic SMZ maps for different frequency ranges. Another advantage of the proposed of seismic microzoning method is that it eliminates the requirements for the synchronic microtremor measurements on the studied and reference soils. Moreover, the fact that there is simply no need for reference soils is a prerequisite for the method. The local vulnerability can therefore be assessed using only one seismic recorder with a 3-component sensor ignoring the location of microseismic motions sources and their characteristics variation over time.*

Keywords: *seismic microzoning; spectral ratios; vulnerability index; seismic signal recorder; seismic station; seismic intensity.*

Introduction. By definition, seismic microzoning (SMZ) is the main tool for seismic hazard assessment. The aim of seismic microzoning is to specify the parameters of seismic loads at a construction site and the parameters of buildings and structures operation depending on the local conditions, namely, soil, geomorphological, hydrogeological and geophysical conditions [1].

In seismic microzoning, in contrast to general seismic zoning (GSZ) (*General seismic zoning of the Russian Federation GSZ-2016. A set of maps and other materials for construction norms and regulations (SNiP)*), it is not the seismic hazard sources that are studied, but soil response to seismic load. The properties of the 10–30 m topmost soil stratum have major influence, which is confirmed by the empirical research by Y. Nakamura and his colleagues [2].

Methodically, seismic microzoning is divided into instrumental and computational. Instrumental SMZ almost always contains elements of computational SMZ, both when carrying out SMZ by the seismic stiffness method (SSM), and when using microseismic motions, as noted in "National Construction Norms RSN-65-87. Engineering survey for construction. Seismic microzoning. Technical requirements for the performance of works".

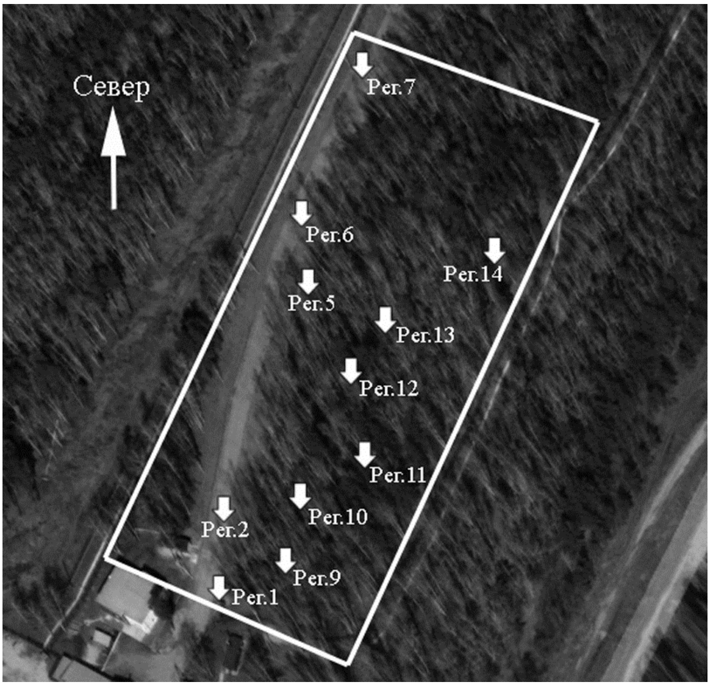

Figure 1. Contours of the study area against the background of a satellite image of the territory with SSR installation points placed on it (Рег. = Reg.)

Рисунок 1. Контуры участка исследований на спутниковом снимке территории с вынесенными на него точками установки регистраторов сейсмических сигналов (РСС)

The method of seismic stiffness is the most common. Developed by S. V. Medvedev as far back as in the middle of the 20th century [3], it has remained one of the mandatory methods used when assessing the seismicity of territories plotted out for residential development and industrial facilities. One of the main disadvantages of the method is extremely weak and unsatisfactory dependence of the results on the elastic vibrations frequency characteristics. The main advantage of the method is it's rich case history of application for civil and industrial construction sites.

A method of research, that mainly takes into account the soil frequency properties, was proposed by Y. Nakamura at the end of the last century [4] and has been under serious theoretical investigation for a long time [5].

The research objective is to develop a new method of seismic microzoning based on the spectral ratios between the horizontal and vertical components of the seismic signal, that is based on the vulnerability coefficient of the topmost soil stratum.

Originally, his method became widespread as the method of spectral ratios. One of the advantages lies in the fact that it allows to take into account inelastic and nonlinear deformation processes when strong wave movements impact on soils. Based on the calculated spectral characteristics of soils, the method makes it possible to construct schematic SMZ maps for different frequency ranges. Another advantage of the Y. Nakamura's method is that it eliminates the requirements for the synchronic microtremor measurements on the studied and reference soils [4]. Moreover, the fact that there is simply no need for reference soils is a prerequisite for the method. The local vulnerability can therefore be assessed using only one seismic recorder with a 3-component sensor ignoring the location of microseismic motion sources and their characteristics variation over time. However, it is worth noting that there are some assumptions, the disregard for which results in distorted estimates of the local vulnerability of soils. Therefore, the Y. Nakamura's method is advisable in conjunction with other SMZ methods.

Table 1. Geographic coordinates of the SSR installation at the site
Таблица 1. Географические координаты точек установки РСС на участке

Point number	N	E
Reg.1	57°0'31.46"	60°43'46.77"
Reg.2	57°0'32.27"	60°43'46.94"
Reg.3	No point	
Reg.4	No point	
Reg.5	57°0'34.45"	60°43'48.54"
Reg.6	57°0'35.14"	60°43'48.37"
Reg.7	57°0'36.57"	60°43'49.45"
Reg.8	No point	
Reg.9	57°0'31.81"	60°43'48.14"
Reg.10	57°0'32.43"	60°43'48.43"
Reg.11	57°0'32.82"	60°43'49.54"
Reg.12	57°0'33.60"	60°43'49.31"
Reg.13	57°0'34.07"	60°43'49.90"
Reg.14	57°0'34.71"	60°43'51.75"

Methods of research. ***Problem statement and proposed solution.*** The research objective is to implement the seismic microzoning method based on vulnerability indices in theory and practice. The prerequisites outlined in work [6] form the basis for the problem's solution.

It should be assumed that the Nakamura's method can be considered as a variant of the spectral ratios method, which is based on the concept that the influence of the fine structure of the object under study is more related to transverse waves, which are enhanced by this structure and scarcely change longitudinal waves. In this case, the ratio of the resulting horizontal component spectrum to the spectrum of the vertical one will characterize the so-called H/V transfer function, which strictly depends on the fine structure of the object under study. The resulting spectrum of the horizontal component H in this case can be determined by any of the following relations:

$$H = \frac{X+Y}{2}; \quad (1)$$

$$H = \sqrt{X \cdot Y}; \quad (2)$$

$$H = \sqrt{X^2 + Y^2}; \tag{3}$$

$$H = \sqrt{\frac{X^2 + Y^2}{2}}, \tag{4}$$

because in work [7] these relations were subjected to statistical analysis, which revealed that the calculation of the resulting value of the spectrum horizontal component scarcely depends on the calculation method.

We use the empirical formula by S. V. Medvedev [3] to calculate the increment of seismic intensity based on the microseismic motions measurement results:

$$\Delta I = 2\lg \frac{\left(A_{\max}\right)_i}{\left(A_{\max}\right)_0}, \tag{5}$$

where $(A_{\max})_i$, $(A_{\max})_0$ are the maximum amplitudes of microseismic motions for the studied and weighted average (reference) soils, respectively. With its help, it is possible to obtain a ratio to calculate ΔI through the transfer function H/V, as shown, for example, in work [6].

Since the Nakamura's technique allows to obtain spectral graphs of the H/V transfer function, i.e. graphs of shaking amplification at dominant frequencies, it becomes possible to calculate the values of the vulnerability coefficients at any microseismic motion measuring point using the formula [8]:

$$K_{\text{vulner.coef}} = \frac{A_{\max}^2}{f}, \tag{6}$$

where $A_{\max}$ is the maximum value of the amplification factor in accordance with the spectral characteristic H/V; f is the frequency corresponding to this value.

Thus, using relations (5) and (6), it is possible to calculate the seismic intensity increment [9]:

$$\Delta I = 2\lg \frac{\left[\left(K_{\text{vulner.coef}}\right)_{\max}\right]_i}{\left[\left(K_{\text{vulner.coef}}\right)_{\max}\right]_0} = 2\lg \frac{\left[\left(A^2/f\right)_{\max}\right]_i}{\left[\left(A^2/f\right)_{\max}\right]_0}, \tag{7}$$

where $\left[\left(K_{\text{vulner.coef}}\right)_{\max}\right]_i$ is the maximum value of the vulnerability coefficient at the measuring points on the soils under study; $\left[\left(K_{\text{vulner.coef}}\right)_{\max}\right]_0$ is the weighted average maximum value of the vulnerability coefficient over the entire area of the studied soils.

Since SMZ based on the vulnerability coefficient is based on field observations of microseismic motions, field instruments that provide long-term 3-component recording of seismic signals are usually required, for example, the "Registr" seismic signal recorder (SSR) [10]. An integral part of the device is a 3-component electrodynamic velocimeter on two "GS-ONE Horizont" horizontal sensors and a "GS-ONE Vertical" vertical sensor manufactured by Geospace Technologis Eurasia [11]. Geophones increased sensitivity, exceeding 85 V/(m/s), is within the capability of modern 24-bit recorders.

SSR seismic sensors can be placed both on the day surface and in shallow delves, depending on the external conditions at the time of registration.

It is appropriate to provide a further description of the SMZ based on the vulnerability coefficient on the example of experimental research and based on actual seismic data.

General characteristics of the study area and methods of field observations. The site in a wooded area near the town of Verkhnyaya Pyshma, Sverdlovsk Region, was selected. The location is typical in terms of the Middle Urals geology within the western margin of the West Siberian Plate, which is mainly represented by volcanogenic-sedimentary strata of the Early and Middle Paleozoic age with the presence of fault zones filled with serpentinites [12] and overlain by thin (1–5 m average) soil cover of the Mesozoic-Cenozoic crust of weathering. Rocky pre-Quaternary soils are represented by metamorphosed volcanogenic-sedimentary formations hosting intrusive bodies of ultrabasites, serpentinites, gabbroids, granitoids, dikes of acidic and basic rocks, and quartz veins [13]. In terms of physical and mechanical properties, slightly weathered varieties of pre-Quaternary formations of low and medium strength, as well as the strong ones, can be attributed to the most favorable, in terms of engineering and seismicity, soils of the first category of seismic properties according to the classification in Code Specification 14.13330.2018 "Construction in seismic regions. Updated edition of SNiP P-7-81*". Their density is 2.53–3.01 g/cm^3, the velocity of longitudinal seismic waves is from 1 to 4 km/s [14].

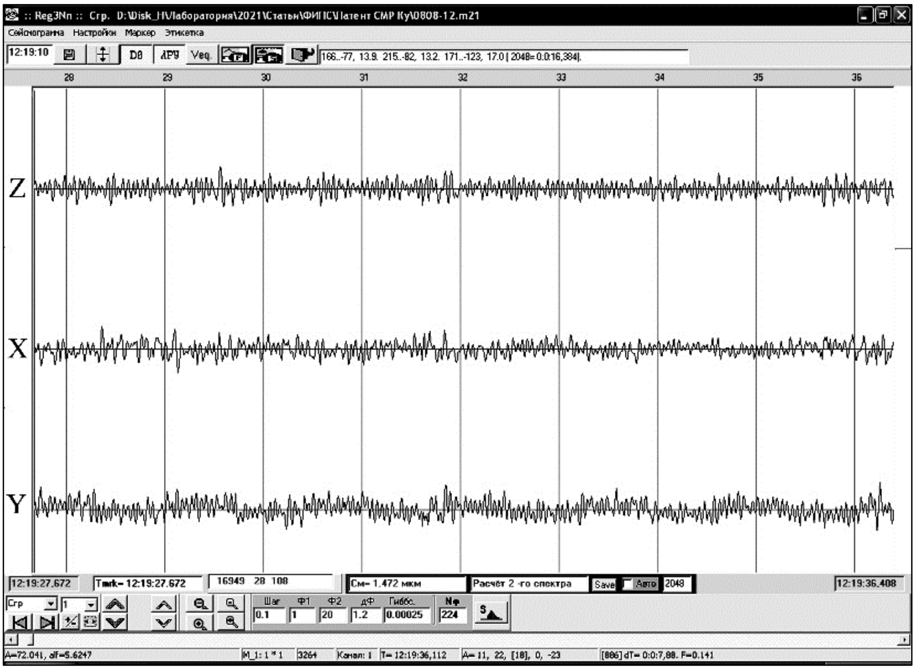

Figure 2. An example of the microseismic motions record at the observation point Reg.2
Рисунок 2. Запись микросейсмических колебаний в точке наблюдения Рег.2

The seismic regime in the areas adjacent to the study area is determined by seismic shaking during palpable natural earthquakes that rarely occur in the Middle Urals, the magnitude of which does not exceed 5–6 points on the MSK-64 scale.

The contours of the study area in Google Earth coordinates with points (Reg.1–Reg.14) of the seismic signal recorders installed are shown in Figure 1. All seismological observation points are fixed with a "Garmin Dakota 20" navigation device [15]. Table 1 shows the geographic coordinates of the recorder installation points (denoted by white arrows in Figure 1).

At each of the marked observation points, a 3-channel recording of microtremors was carried out. The seismogram was read, transferred to a computer and processed with specialized software. Figure 2 shows an example of a microseismic motions seismogram recorded at the Reg.2 point.

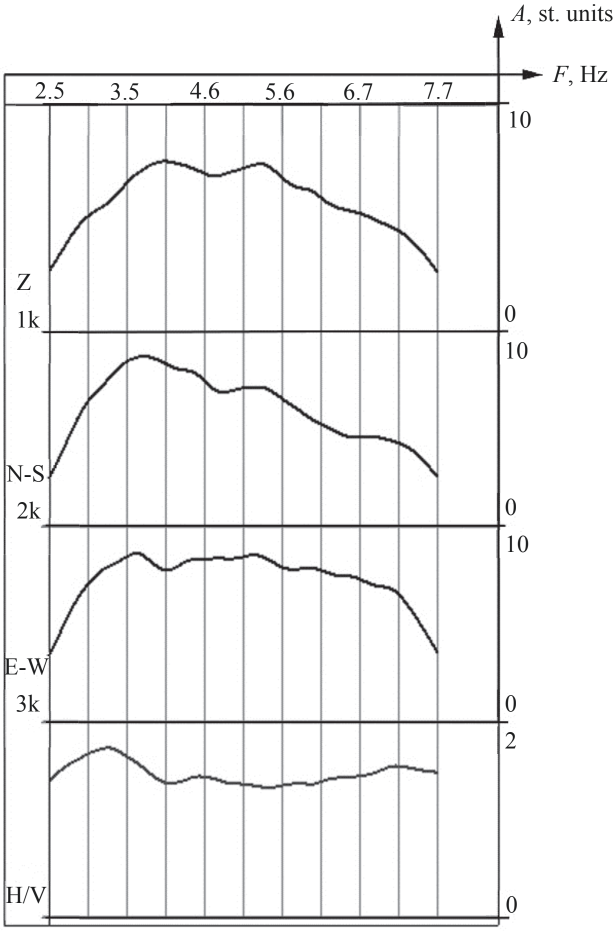

Figure 3. The amplitude-frequency spectra of the *X*, *Y*, *Z* components and the *H*/*V* transfer function for the seismic record shown in Figure 2

Рисунок 3. Амплитудно-частотные спектры компонент *X*, *Y*, *Z* и передаточная функции *H*/*V* для сейсмической записи, показанной на рис. 2

Processing of seismograms and calculation of vulnerability coefficients and seismic intensity increments. At the initial stage of seismograms processing, the amplitude-frequency spectra for the seismic signal components *X*, *Y*, *Z* were calculated. Calculations can be performed, for example, by mean of the spectral analysis using non-recursive digital filtering [16].

Amplitude-frequency spectra of microtremor records make it possible to reveal the maximum signal amplitudes at certain frequencies [17]. Using the spectra of the seismic signal components, the *H*/*V* transfer function can be calculated. The resulting spectrum of horizontal components through one of the relations (1)–(4). Plots of the spectral characteristics of the X, Y, Z components and the H/V transfer function for the seismogram from Figure 2 are shown in Figure 3.

Such spectra and spectral ratios are calculated for each observation point. After that, the vulnerability indices $(K_{vulner})_i$ and weighted average coefficients for the entire study area $(K_{vulner})_0$ are calculated using formula (6). By substituting the obtained values of K_{vulner} into formula (7), the values of the intensity increments ΔI are calculated for each measurement point. As a result, it becomes possible to construct a schematic map of seismic intensity increments that takes into account the resonant properties of the topmost soil stratum. Such a map for the study area (Figure 1) is shown in Figure 4. Computational data for this map are given in Table 2.

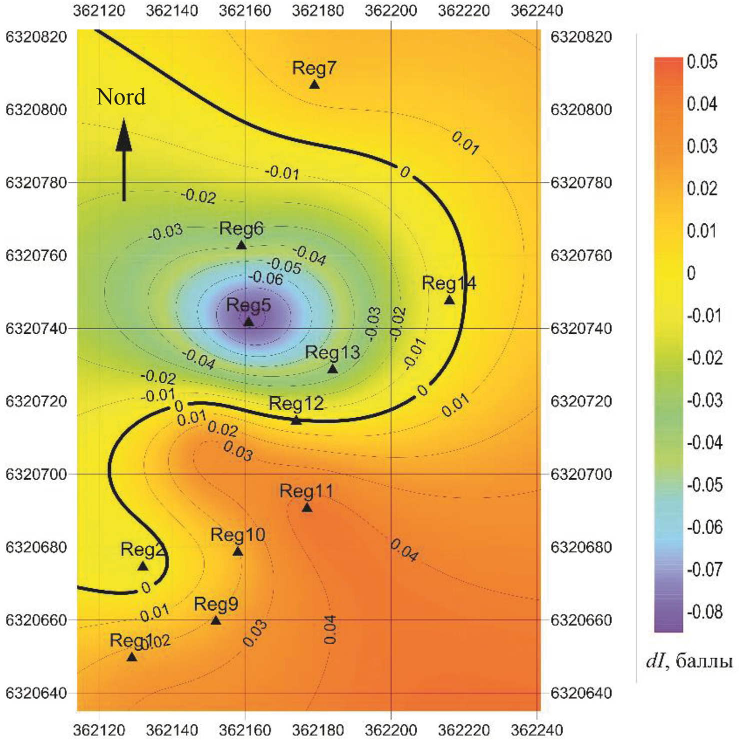

Figure 4. Schematic map of the SMZ using the vulnerability index
Рисунок 4. Схематическая карта сейсмического микрорайонирования (СМР) с использованием индекса уязвимости

Results and discussion. In this research, the main objective the authors set has been solved, that is a new method of SMZ has been developed. The new method is based on the vulnerability coefficients of the topmost soil stratum, i.e. on the transfer function H/V. The spectral ratios in the calculation of seismic intensity increments ΔI, intended for constructing SMZ schematic map, make it possible to take into account the frequency-dependent relationships between the soils of the study area and the intensity of elastic impacts from endogenous and exogenous processes.

The schematic map of seismic microzoning obtained and shown in Figure 4 describes the study area as homogeneous, both in the area of positive increments ΔI, and in the area of negative increments. The most vulnerable zone of the study area in terms of increased frequency dependence of the topmost section under the influence of transverse waves on the soil stratum is its southern part. However, in quantitative terms, the range of changes in ΔI parameter from –0.06 to +0.05 points is so insignificant that it shouldn't be taken into account. This emphasizes the geological homogeneity of the area selected for experimental and methodological studies.

Table 2. Design values of ΔI. A method of SMZ using vulnerability coefficient
Таблица 2. Расчетные значения ΔI. Метод СМР с использованием коэффициента уязвимости

Point number	$(A_{max})_{H/V}$, st.units	$(f_{max})_{H/V}$, Hz	K_{vulner}	ΔI, numbers
Reg.1	1.30	2.84	0.592	0.0247
Reg.2	1.37	3.28	0.572	–0.0051
Reg.3	No point			
Reg.4	No point			
Reg.5	1.37	3.58	0.516	–0.0946
Reg.6	1.40	3.56	0.551	–0.0376
Reg.7	1.49	3.80	0.585	0.0144
Reg.8	No point			
Reg.9	1.36	3.14	0.590	0.0218
Reg.10	1.49	3.82	0.589	0.0203
Reg.11	1.38	3.18	0.605	0.0436
Reg.12	1.43	3.50	0.576	0.0009
Reg.13	1.39	3.50	0.552	–0.0360
Reg.14	1.43	3.58	0.573	–0.0036

Conclusions. The SMZ method considered in the article belongs to the field of seismic research and can be used in engineering seismology to assess seismic motions intensity taking into account soil resonant properties. It is well known that various modifications of the method of spectral ratios *HVSR* are common in practice [18, 19]. However, in author's opinion, what's new is the approach to seismic hazard zoning proposed in this research. It is based on the vulnerability indices and subsequent recalculation into seismic intensity increments.

The SMZ method based on the vulnerability coefficient considered in this article is not mandatory, although it is a variation of the spectral ratio method. It may be regarded as an addition to the mandatory seismic stiffness method. The combination of these SMZ methods will arguably increase the capabilities of the method as a whole and improve the accuracy and adequacy of a schematic map of seismic intensity increments.

REFERENCES

1. The Nakamura's method: advanced technologies of seismic microzoning at the construction sites of urban land. Available from: https://www.geoygservis.ru/publishing/metod-nakamury-sovremennye-tekhnologii-seysmicheskogo-mikrorayonirovaniya [Accessed: 28 November 2022] (In Russ.)

2. Nakamura Y. Gurler E. Dilex, Saita J. et al. Vulnerability investigation of Roman Coliseum using microtremor. In: *Proceeding, 12th WCEE 2000 in Aucland. NZ.* P. 1–8.

3. Medvedev S. V. (ed.) Seismic microzoning. Moscow: Nauka Publishing; 1977. (In Russ.)

4. Nakamura Y. Method for dynamic characteristic estimation of subsurface using microtremor on the ground surface. *Quarterly report of Railway Technical Research Institute.* 1989; 30(1): 25–33.

5. Fah D., Kind F., Giardini D. A theoretical investigation of average H/V ratios. *Geophysical Journal International.* 2001; 145: 535–549. Available from: https://doi.org/10/1046/j.0956-540x.2001.01406.x [Accessed: 02.06.2022]

6. Senin L. N., Senina T. E. *Method of seismic microzoning*. Patent RF 2686514; 2019. (In Russ.)

7. Lunedei E., Malishewsky P. A Review and some new issues on the theory of the H/V technique for ambient vibrations. In: Ansal A. (ed.) *Perspectives on European Earthquake Engineering and Seismology, Geotechnical and Earthquake Engineering.* Springer, Cham.; 2015. Vol. 39. P. 371–394.

8. Nakamura Y. Seismic vulnerability indices for ground and structures using microtremor. In: *World Congress on Railway Research*. Florence; 1997. P. 1–7.

9. Senin L. N., Senina T. E. *Method of seismic microzoning based on the vulnerability coefficient.* Patent RF no. 2771156; 2022. (In Russ.)

10. Senin L. N., Senina T. E. The «Registr» seismic signal recorder. *Pribory i tekhnika eksperimenta = Instruments and Experimental Techniques*. 2005; 6: 141–142. (In Russ.)

11. *Geospace Technologies Eurasia.* Available from: www.geospace-ufa.ru [Accessed: 28 November 2022]

12. Kuzovkov G. N., Dvoeglazov G. A., Vagshal G. S. *Schematic geological map of Ekaterinburg*. Ekaterinburg: Uralgeologia; 1987. (In Russ.)

13. Guliaev A. N., Osipova A. Iu. *Zoning of the central part of the Ural region according to the value of the seismic load design force*. Ekaterinburg: Institute of Geophysics UB RAS; 2020. (In Russ.)

14. Griaznov O. N., Guliaev A. N., Ruban N. V., Savintsev I. A., Cherkasov S. A. Factors of engineering and geological conditions of Ekaterinburg. *Izvestiia Uralskogo gosudarstvennogo gornogo universiteta = News of the Ural State Mining University*. 2015; 3(39): 5–20. (In Russ.)

15. *Garmin Dakota 20 (RF maps, water reservoirs)*. Available from: http://www.geo-planet.ru/tovar.php?tid=542 [Accessed: 28 November 2022] (In Russ.)

16. Hamming R. W. *Digital filters*. Translation from English. M: Sovetskoe Radio; 1980. (In Russ.)

17. Berezhnoi D. V. et al. *Analysis of microtremor spectral characteristics as a method of studying the structure of geological environment.* Kazan: KSU; 2008. p. 360–386. (In Russ.)

18. Anosov G. I., Drobiz M. V., Konovalova O. A., Sotnikov D. S., Chugaevich V. Ia. Evalution of seismic stability of the educational building 3 of Immanuil Kant Russian State University using the Nakamura method. *Vestnik KRAUNTs. Nauki o Zemle = Bulletin of KRAESC. Earth sciences.* 2010; 1(15): 223–231. (In Russ.)

19. Haghshenas E., Bard P. Y., Theodulidis N. SESAME WP04 Team. Empirical evaluation of microtremor H/V spectral ratio. *Bulletin of Earthquake Engineering.* 2008; 6(1): 75–108. Available from: https//doi.org/10.1007/s10518-007-9058-x [Accessed: 02.06.2022]

Received 8 August 2022

Information about the authors:

Lev N. Senin – DSc (Engineering), Head of the Laboratory of Seismometry, Bulashevich Institute of Geophysics UB RAS. E-mail: selenik@rambler.ru; https://orcid.org/0000-0003-1534-2292
Tatiana E. Senina – leading researcher, Laboratory of Seismometry, Bulashevich Institute of Geophysics UB RAS. E-mail: selenik@rambler.ru; https://orcid.org/0000-0001-5889-368X

УДК 550.34.012 DOI: 10.21440/0536-1028-2023-1-55-65

Способ сейсмического микрорайонирования с использованием коэффициента уязвимости

Сенин Л. Н.[1], Сенина Т. Е.[1]
[1] Институт геофизики УрО РАН, Екатеринбург, Россия.

Реферат

***Цель исследований**, представленных в настоящей статье – разработка нового способа сейсмического микрорайонирования (СМР), основанного на спектральных отношениях горизонтальной и вертикальной компонент сейсмического сигнала, т. е. на использовании коэффициента уязвимости верхней части грунтовой толщи.*

***Методология.** Несмотря на то, что метод спектральных отношений HVSR применяется давно в различных модификациях, новым, по мнению авторов, является предложенный в работе подход к районированию сейсмической опасности с использованием индексов уязвимости и последующим пересчетом в приращения сейсмической интенсивности. Рассмотренный в статье метод СМР с использованием коэффициента уязвимости не относится к обязательным, хотя и является разновидностью метода спектральных отношений, он может рассматриваться как дополнение к обязательному методу сейсмических жесткостей. Можно сказать, что комбинация этих методов СМР обеспечит расширение возможностей метода в целом и позволит повысить точность и адекватность построения схематической карты приращений сейсмической интенсивности. Одно из*

достоинств метода спектральных отношений, как и его разновидности – метода СМР с использованием индекса уязвимости, заключается в том, что он позволяет учитывать неупругие и нелинейные деформационные процессы при воздействии на грунты сильных волновых движений.
Результаты. *На основе рассчитанных спектральных характеристик грунтов метод дает возможность построения схематических карт СМР для разных частотных диапазонов. Предложенный способ сейсмического микрорайонирования исключает требования к синхронности измерений микросейсм на исследуемых и эталонных грунтах. Более того, предпосылки метода таковы, что в эталонных грунтах вообще нет необходимости, в связи с чем оценку локальной уязвимости можно проводить, используя всего один сейсмический регистратор с 3-компонентным датчиком, не учитывая ни расположение источников микросейсмических колебаний, ни изменение их характеристик во времени.*

Ключевые слова: *сейсмическое микрорайонирование; спектральные отношения; индекс уязвимости; регистратор сейсмических сигналов; сейсмостанция; сейсмическая интенсивность.*

БИБЛИОГРАФИЧЕСКИЙ СПИСОК

1. Метод Накамуры: современные технологии сейсмического микрорайонирования стройплощадок на урбанизированных территориях. URL: https://www.geoygservis.ru/publishing/metod-nakamury-sovremennye-tekhnologii-seysmicheskogo-mikrorayonirovaniya (дата обращения: 28.11.2022)

2. Nakamura Y., Gurler E. Dilex, Saita J. et al. Vulnerability investigation of Roman Coliseum using microtremor // Proceeding, 12th WCEE 2000 in Aucland. NZ. P. 1–8.

3. Сейсмическое микрорайонирование / под ред. С. В. Медведева. М.: Наука, 1977. 248 с.

4. Nakamura Y., Method for dynamic characteristic estimation of subsurface using microtremor on the ground surface. Quarterly report of Railway Technical Research Institute. 1989. Vol. 30. No. 1. P. 25–33.

5. Fah D., Kind F., Giardini D. A theoretical investigation of average H/V ratios // Geophysical Journal International. 2001. No. 145. P. 535–549. URL: https://doi.org/10/1046/j.0956-540x.2001.01406.x (дата обращения: 02.06.2022)

6. Способ сейсмического микрорайонирования: пат. Рос. Федерация. № 2686514. опубл. 29.04.2019. бюл. № 13.

7. Lunedei E., Malishewsky P. A Review and some new issues on the theory of the H/V technique for ambient vibrations // Ansal A. (ed.) Perspectives on European Earthquake Engineering and Seismology, Geotechnical and Earthquake Engineering. Springer, Cham. 2015. Vol. 39. P. 371–394.

8. Nakamura Y. Seismic vulnerability indices for ground and structures using microtremor // World Congress on Railway Research. Florence, 1997. P. 1–7.

9. Способ сейсмического микрорайонирования с использованием коэффициента уязвимости: пат. Рос. Федерация. № 2771156; опубл. 27.04.2022. бюл. № 12.

10. Сенин Л. Н., Сенина Т. Е. Регистратор сейсмических сигналов «Регистр» // Приборы и техника эксперимента. 2005. № 6. С. 141–142.

11. Geospace Technologies Eurasia. URL: www.geospace-ufa.ru (дата обращения: 28.11.2022)

12. Кузовков Г. Н., Двоеглазов Г. А., Вагшаль Г. С. Схематическая геологическая карта Екатеринбурга. Екатеринбург: Уралгеология, 1987. 170 с.

13. Гуляев А. Н., Осипова А. Ю. Районирование центральной части Уральского региона по величине расчетной силы сейсмического воздействия. Екатеринбург: УрО РАН; Институт геофизики, 2020. 89 с.

14. Грязнов О. Н., Гуляев А. Н., Рубан Н. В., Савинцев И. А., Черкасов С. А. Факторы инженерно-геологических условий города Екатеринбурга // Известия УГГУ. 2015. Вып. 3(39). С. 5–20.

15. Garmin Dakota 20 (ТОПО карты РФ, водоемы). URL: http://www.geo-planet.ru/tovar.php?tid=542 (дата обращения: 28.11.2022)

16. Хэмминг Р. В. Цифровые фильтры / пер. с англ. М.: Советское Радио, 1980. 224 с.

17. Анализ спектральных характеристик микросейсм как метод изучения структуры геологической среды / Бережной Д. В. [и др.]. Казань: КГУ, 2008. С. 360–386.

18. Аносов Г. И., Дробиз М. В., Коновалова О. А., Сотников Д. С., Чугаевич В. Я. Оценка сейсмической устойчивости учебного корпуса № 3 Российского государственного университета им. И. Канта с применением методики Накамуры // Вестник КРАУНЦ. Науки о Земле. 2010. № 1. Вып. 15. С. 223–231.

19. Haghshenas E., Bard P. Y., Theodulidis N. SESAME WP04 Team. Empirical evaluation of microtremor H/V spectral ratio // Bulletin of Earthquake Engineering. 2008. No. 6(1). P. 75–108. URL: https// doi.org/10.1007/s10518-007-9058-x (дата обращения: 02.06.2022)

Поступила в редакцию 8 августа 2022 года

Сведения об авторах:

Сенин Лев Николаевич – доктор технических наук, заведующий лабораторией сейсмометрии Института геофизики им. Ю. П. Булашевича УрО РАН. E-mail: selenik@rambler.ru; https://orcid.org/0000-0003-1534-2292
Сенина Татьяна Егоровна – старший научный сотрудник лаборатории сейсмометрии Института геофизики им. Ю. П. Булашевича УрО РАН. E-mail: selenik@rambler.ru; https://orcid.org/0000-0001-5889-368X

Для цитирования: Сенин Л. Н., Сенина Т. Е. Способ сейсмического микрорайонирования с использованием коэффициента уязвимости // Известия вузов. Горный журнал. 2023. № 1. С. 55–65 (In Eng.). DOI: 10.21440/0536-1028-2023-1-55-65
For citation: Senin L. N., Senina T. E. A method of seismic microzoning based on the vulnerability coefficient. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal = Minerals and Mining Engineering*. 2023; 1: 55–65. DOI: 10.21440/0536-1028-2023-1-55-65