Russian Geology and Geophysics © 2020, V.S. Sobolev IGM, Siberian Branch of the RAS
Vol. 61, No. 8, pp. 929–936, 2020 DOI:10.15372/RGG2019123 *Geologiya i Geofizika*

The Spectral Behavior of Ground Coseismic Motion in the Baikal Region: Effect of Seasonal Thawing–Freezing Cycles

V.I. Dzhurik✉, E.V. Bryzhak, S.P. Serebrennikov, A.Yu. Eskin

Institute of the Earth's Crust, Siberian Branch of the Russian Academy of Sciences, ul. Lermontova 128, Irkutsk, 664033, Russia

Received 21 November 2018; received in revised form 20 March 2019; accepted 22 May 2019

Abstract—Reliable solution of theoretical and applied seismological problems requires the knowledge of natural factors that influence ground motion induced by earthquakes. The effect of seasonal freezing and thawing on the behavior of coseismic ground motion in the Baikal region has been studied using data on local geology, earthquake source parameters, seismogeology, and seismic risk zoning for East Siberia. East Siberia, including the highly seismic Baikal region, is located in a temperate and cold, sharply continental climate, with the mean annual air temperature locally falling below –10 ºC. In this respect, the knowledge of seasonal variations in the ground motion spectra in different seismic-climatic zones of the region is of special importance. We study the dynamic parameters of seismic signals and their variations caused by seasonal thawing and freezing of the ground, using calculated spectra of selected earthquakes that were recorded by 0.5–20 Hz digital seismic stations at a sampling interval (Δ) of 0.01 s. Spectral analysis was applied to three-component records of more than two hundred $M = 2.8$ ($K = 9$–14) earthquakes that occurred in the region for the past twenty years at distances from 32 to 280 km from the stations. The influence of seasonal temperature variations on the frequency responses of coseismic ground motion is discussed for the case of two seismic stations in zones of continuous and sporadic permafrost. The results are complemented by generalized data from other seismic stations located in different permafrost conditions within the Baikal region. The effect of seasonal freezing and thawing turns out to be the most prominent at frequencies above 5–6 Hz and depend on the properties and thermal state of soils beneath the stations. At the same time, they are more prominent in thawing than in freezing curves for any soil, including relatively solid bedrock. The spectral behavior of earthquake-induced ground motion is associated with variations in wave amplitudes, which correlate with seasonal temperature variations. The reported results have implications for geophysical prospecting, seismic-risk zoning, and prediction of shaking intensity of large earthquakes, which require due regard for local permafrost conditions.

Keywords: seismic climatic zones, earthquakes, ground motion, amplitude, frequency, spectra, permafrost, mean annual temperature, Baikal region

INTRODUCTION AND PROBLEM FORMULATION

The Baikal region comprises three administrative entities of the Russian Federation adjacent to Lake Baikal: the **Irkutsk and Transbaikalian areas and the Republic of Buryatia** (Fig. 1). The region is located in a temperate continental climate (Rogatyuk, 1996), and most of its territory belongs to the Subarctic permafrost zone (Melnikov, 1984). The seismicity level corresponds to a potential shaking intensity range of 6 to 10 according to the updated general seismic risk zoning (Seismic…, 2015).

The spectra of coseismic ground motions are exposed to natural climatic effects which have to be taken into account in theoretical and applied seismology. The issues concerning earthquake records by permanent stations on permafrost-affected soils with different mechanical and thermal properties are especially important in this respect. They include various corrections to raw data (most often amplitudes, frequencies, and phase spectra of seismic waves), seismic risk zoning, and estimation of potential macroseismic effects of large earthquakes (Pavlov, 1988). The necessity of due regard for the effect of seasonal temperature variations on the amplitudes and frequencies of earthquake-induced vibrations of engineering structures on permafrost was discussed in a number of earlier publications (Dzhurik et al., 2000; Li et al., 2015) and has been confirmed by recent results (Briggs et al., 2017; Gupta and Trifunak, 2018). The latter cited studies characterize the behavior of different permafrost layers during large earthquakes and justify the importance of predicting their responses to temperature variations associated with seasonal freezing and thawing, industrial activity, or global change.

This study aims at detection of changes in amplitudes and frequencies of coseismic ground motion caused by seasonal ground freezing and thawing in permafrost-affected areas, with seismic risk implications. These effects are especially prominent in the uppermost ground.

✉Corresponding author.
E-mail address: dzhurik@crust.irk.ru (V.I. Dzurik)

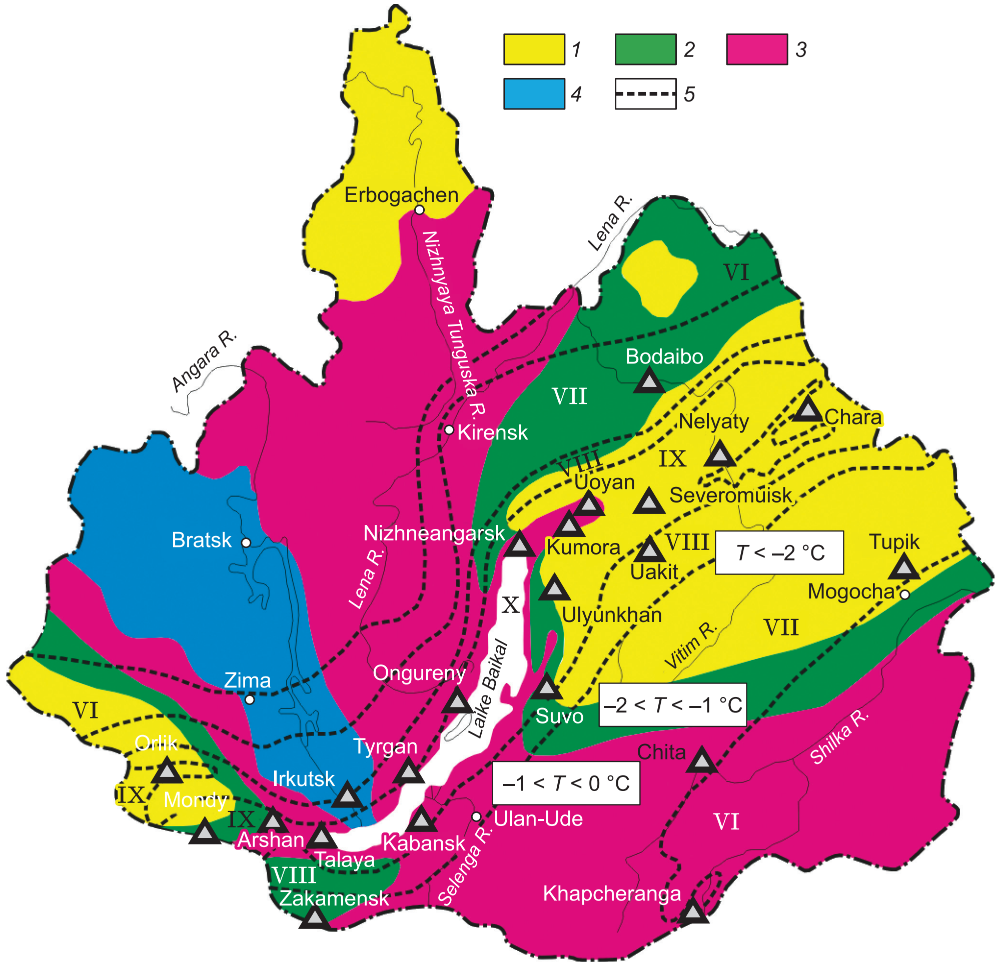

Fig. 1. Combined maps of permafrost and seismic zoning of the Baikal region. *1,* continuous permafrost; *2*, discontinuous permafrost; *3*, sporadic permafrost; *4*, no permafrost; *5*, boundaries of seismic zones. Numerals show shaking intensity. Triangles are seismic stations.

METHODS AND DATA

Spectral patterns were studied for earthquakes that occurred for the past twenty years and were recorded at 24 stations (Fig. 1). Data from two stations located in zones of continuous (Orlik) and sporadic (Nizhneangarsk) permafrost were reviewed most thoroughly and comprehensively. The Orlik station is situated in the Oka area (Buryatia) at an elevation of 1376 m asl, in a narrow intermontane basin of the East Sayan Mountains, on the right bank of the Oka River, upstream of the Orlik River inlet (Fig. 1). The climate is sharply continental: long and very cold winters with little snow and no winds, and short hot summers. The mean annual air temperature is –4.8 °C, with January and July monthly means of –22.6 °C and +12.6 °C, respectively. The area around Orlik Village has diverse landscapes with glaciers, volcanoes, and hot springs (Kravets, 2006). The Nizhneangarsk station is located on the northern shore of Lake Baikal, in the southwestern part of Nizhneangarsk community, 23 km northeast of Severobaikalsk Town, near the Syroi Molokan Creek inlet into Lake Baikal. The climate is sharply continental in the mountains but milder on the Baikal shore, at 475 m asl. The mean annual air temperature is –3.2 °C, and the January and July monthly means are –23 °C and +15 °C, respectively (Solonenko, 1985). The area belongs to the zone of sporadic permafrost, but the station is built upon a talik subject to deep seasonal freezing, with the ground locally remaining frozen in some summers as well (Nekrasov and Klimovskii, 1978).

The ground temperature at the depth of zero annual amplitude roughly corresponds to the mean annual temperature at the permafrost top and varies seasonally above this depth. The mean annual ground temperature may be variable (+/–2 °C) within 15 m in any locality depending on snow depth and vegetation patterns (Washburn, 1979). The seasonal freezing and thawing of permafrost and active layer above 15 m controls the variations in the behavior of coseismic ground motion.

The data used for analysis included records of the two stations acquired during warm and cold seasons and may obviously differ from those over the whole region. The selected records refer to the time of positive and negative

Table 1. Seismic properties of ground at seismic station sites for the period of thawing (August–September) and freezing (February–March, in brackets)

Seismic station	Geotechnical conditions	h, m	ρ, g/cm^3	v_P, m/s	v_S, m/s
Orlik	Frozen boulder-pebble-sand deposits	7	2.5	2800 (3100)	1460 (1630)
	Limestone and dolomite limestone	—	2.6	3800	2000
Nizhneangarsk	Blocks, debris, and weathered bedrock	5	2.0	800 (2200)	380 (1100)
	Heavily fractured bedrock	6	2.5	2700	1400
	Medium-grained gneissic biotite granitoids	—	2.6	3850	1950

mean monthly air temperatures: May through September (5 months) and October through April (7 months), respectively, with different specific values for the two stations (Kravets, 2006). The two stations were chosen because they stand on the soils of similar lithology but different thermal states. The layer above the depth of zero annual temperature amplitude consists of weathered and fractured bedrock over relatively solid bedrock dolomite limestone and granitoids with seismic velocities approximately v_P = 3800 m/s and v_S = 1950 m/s (Table 1).

The collection of selected earthquakes included events recorded by seismic stations of the Geophysical Surveys of the Siberian Branch of the Russian Academy of Sciences (Baikal Filial, Irkutsk) which occurred for the past twenty years with magnitudes M > 2.8 (energy class K > 9) at epicentral distances within 300 km, depending on magnitude. Altogether we have analyzed 77 acceleration records (41 and 36 from the Orlik and Nizhneangarsk stations, respectively) by digital instruments at a sampling rate of $\Delta = 0.01$ s, with plateau-shaped frequency responses in the range 0.5–20.0 Hz (extended lately).

The effects of ground temperature variations on the spectral composition of earthquake records were studied from amplitudes and frequencies of ground motion responses within the depth of seasonal freezing and thawing. The frequency responses were calculated either using the *H*/*V* spectral ratios based on earthquake records at one station (Nakamura, 1989) or by velocity modeling for thin-layer near-surface structures (Pavlov, 1988).

In the former case, the spectra for the selected earthquakes (Jenkins and Watts, 1969; Dzhurik et al., 2018) were calculated using 20 s ground acceleration records at each station (Dzhurik et al., 2015). The calculated frequency responses represent the spectra of the *NS* and *EW* horizontal components and the *Z* vertical component, because the amplification components U_{NS} and U_{EW} or their vector sum $U(x)$ are used to estimate earthquake source parameters and seismic effects (Kaliberda, 1988).

Thus, the U_{NS}, U_{EW} and $U(x)$ responses were calculated with the equations

$$U_{NS} = (H_N/V_Z);\ U_{EW} = (H_E/V_Z);\ U(x) = (H_N^2+H_E^2)^{1/2}/V_Z, \quad (1)$$

where H_N and H_E are the earthquake spectra along the horizontal *NS* and *EW* components, and V_Z is that for the vertical *Z* component.

In this case, the approach to studies of ground motion spectra recorded at the two stations in different permafrost zones (Fig. 1) consists in using only digital instrumental data. The method is based on the assumption that the effect of ground temperatures on the vertical component is minor, except for surface waves (Nakamura, 1989). However, the estimates of "true" frequency responses are problematic, because the spectral composition of motions can vary considerably as a function of ray path, emergent angle, and other parameters. Thus, the ground responses may depend on the types and intensity of source *P* and *S* waves and on the heterogeneity of their propagation medium.

For this reason, obtaining the frequency response with the *H*/*V* spectral ratios is not quite appropriate, unless the *NS* and *EW* records are considered separately because the ratios can somehow compensate random noise effects and yield reliable estimates of predominant ground motion periods.

The true frequency responses would be recoverable if seismographs were installed immediately at the zero annual amplitude depth. Otherwise, one can obtain relative spectral curves for each component, in the first approximation, using reference ground properties comparable with those in deeper layers (Pavlov, 1988; Drenov and Dzhurik, 2005). The latter approach, however, neglects the effect of the uppermost reference bedrock ground on the amplitudes of seismic waves, though this situation is considered acceptable for practical applications of engineering seismology, such as in seismic risk zoning within construction areas (Solonenko, 1985).

In our case, the *H*/*V* spectral ratios can be used to study spectral variations in ground motion caused by seasonal freezing and thawing cycles in the Baikal region if they are estimated for each component and as the sum over three components. The results, with regard to the above drawback, will be useful for theoretical and practical applications for predicting the effects of large earthquakes on the permafrost-affected areas in the Baikal region.

RESULTS AND DISCUSSION

Further analysis is performed using calculated spectra of selected events (Fig. 2). Most of the spectra recorded by the Orlik and Nizhneangarsk stations for the past twenty years comprise a low-frequency ascending branch, a flatter middle part, and a high-frequency descending branch, but some

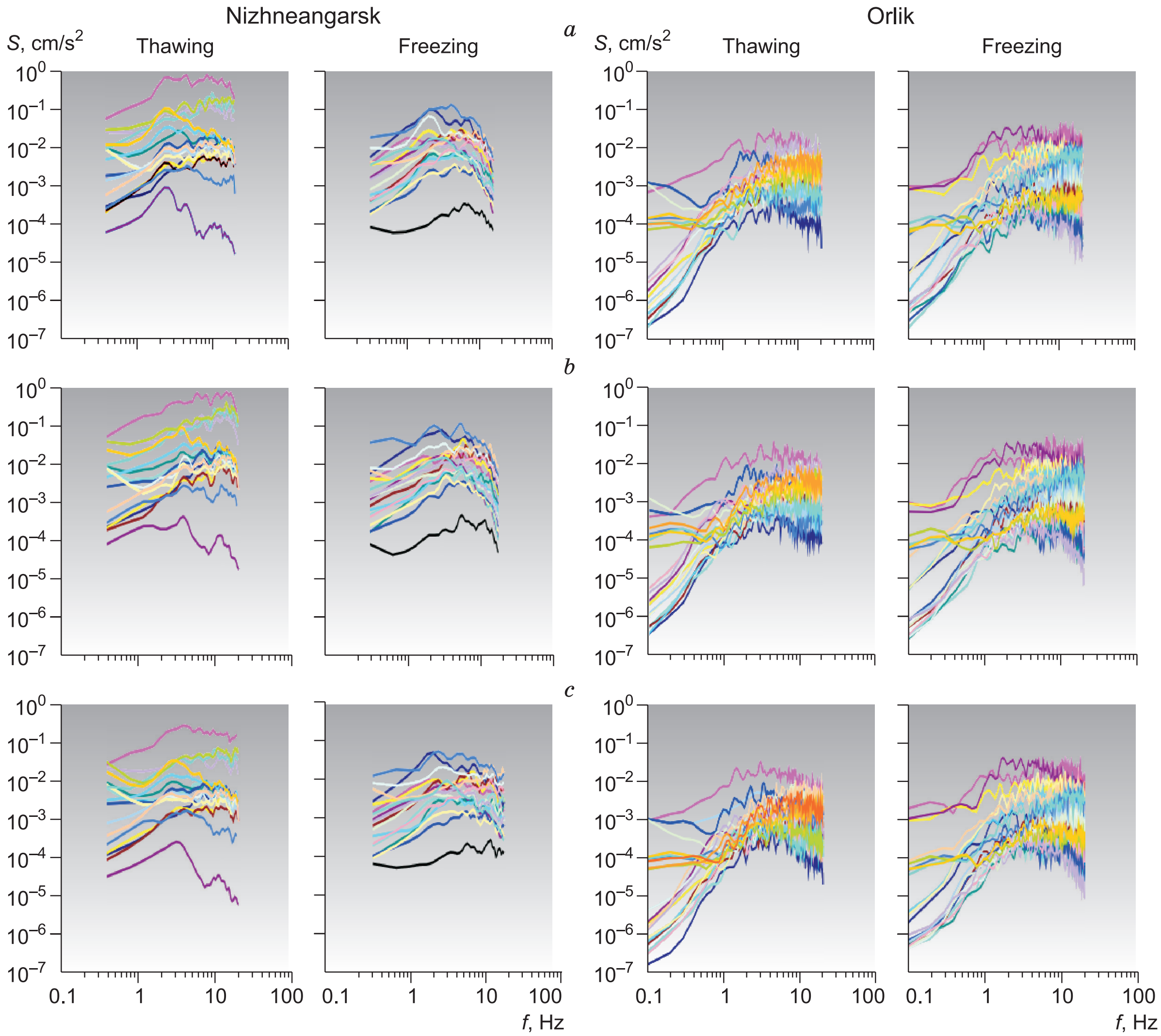

Fig. 2. *NS* (*a*), *EW* (*b*) and *Z* (*c*) components of earthquake spectra recorded by the Nizhneangarsk and Orlik stations in thawing and freezing seasons.

spectra miss the high-frequency portion. The wave amplitudes may differ by factors of 100 to 10,000, which correspond to the chosen ranges of magnitudes, epicentral distances, and other earthquake parameters. The frequency variation range is at 0.7 of the maximum level, which is important for estimating the energy class of earthquakes and for the reconstruction of source seismic signals in the area (Dzhurik et al., 2015). In our case, this range is from 2 to 14 Hz.

The effects of temperature variations are more prominent in the spectra recorded in the thawing season than in those of the freezing period, at both stations (Fig. 2) but especially at the Nizhneangarsk one located on sporadic permafrost. This difference is better pronounced in the *NS* and *EW* components than in the *Z* records. The quantitative estimates of these relationships for two seismic stations are especially spectacular for calculated frequency responses. The spectra (Fig. 2) and frequency responses (Fig. 3) show notable variance in shapes and levels for different earthquakes. Therefore, average frequency responses were obtained for each station. The variance of responses calculated using spectral ratios (Nakamura, 1989) was estimated according to frequency-dependent *U* values as an r.m.s. error of the average (thin lines in Fig. 3). Averaging over all selected events gives smoother curves (heavy lines in Fig. 3).

The responses calculated using the three equations (1) agree well in the frequency patterns: the peaks fall within the same frequency intervals for thawing and freezing seasons, in both continuous and sporadic permafrost areas. However, the amplitudes differ markedly between the two areas, especially at frequencies >8–10 Hz, e.g., the maximum at 16–18 Hz may reach 6–10 in the summer season but approaches 1 during maximum freezing.

Obviously, the amplitude difference is the greatest in the vertical component; it may be minor in the zone of sporadic

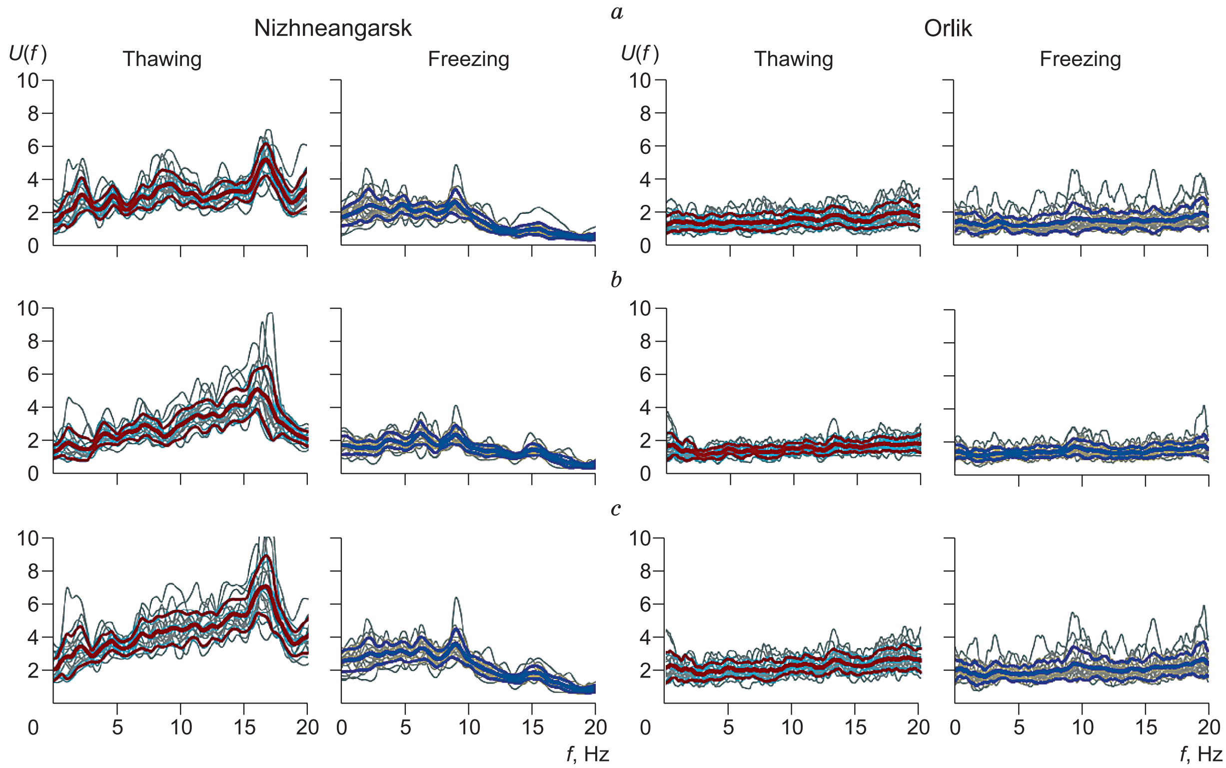

Fig. 3. Frequency responses of ground calculated using spectral ratios for the Nizhneangarsk and Orlik stations located in zones of sporadic and continuous permafrost, respectively, for thawing and freezing seasons. *a*, H_N/V_Z; *b*, H_E/V_Z, *c*, $(H_N^2 + H_E^2)^{1/2}/V_Z$. Lines are described in text.

permafrost at low frequency (0–5 Hz) and during freezing at relatively high frequency, while the difference for the warm season may reach 2–4 times.

Thus, the spectrum of a specific earthquake that occurred in a warm or a cold season can be corrected in the first approximation by normalizing it to the bedrock foundation response. This may be necessary to solve problems concerning parameters of seismic waves (e.g., attenuation) or engineering issues (Pavlov, 1988), or to reconstruct the source seismic signals (Dzhurik et al., 2015).

This regularity in frequencies and amplitudes of ground motion during thawing and freezing seasons is confirmed by comparison of frequency responses calculated by the two methods (Fig. 4). The panels for spectral ratios (Fig. 4*a*) show combined average frequency responses for thawing and freezing periods for the two stations (Fig. 3). The curves

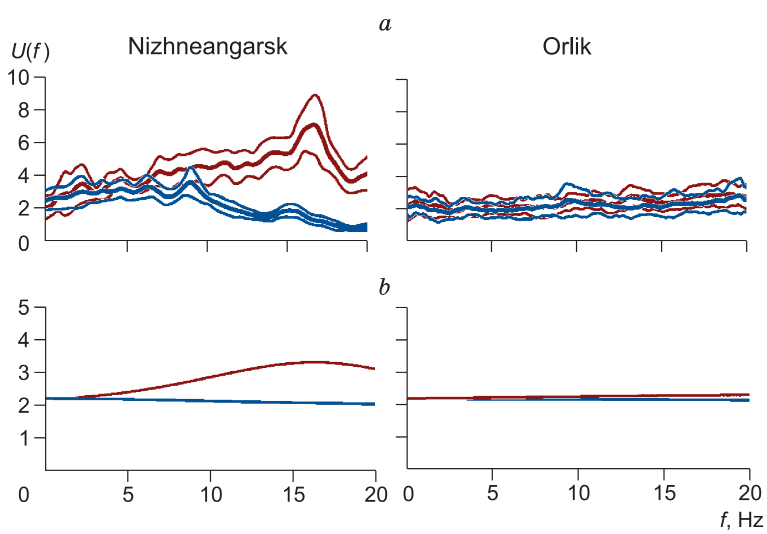

Fig. 4. Frequency responses of ground at the Nizhneangarsk and Orlik stations calculated using spectral ratios (a) and *P* and *S* velocities in a thin-layer Earth (*b*). Purple and blue lines are for thawing and freezing periods, respectively.

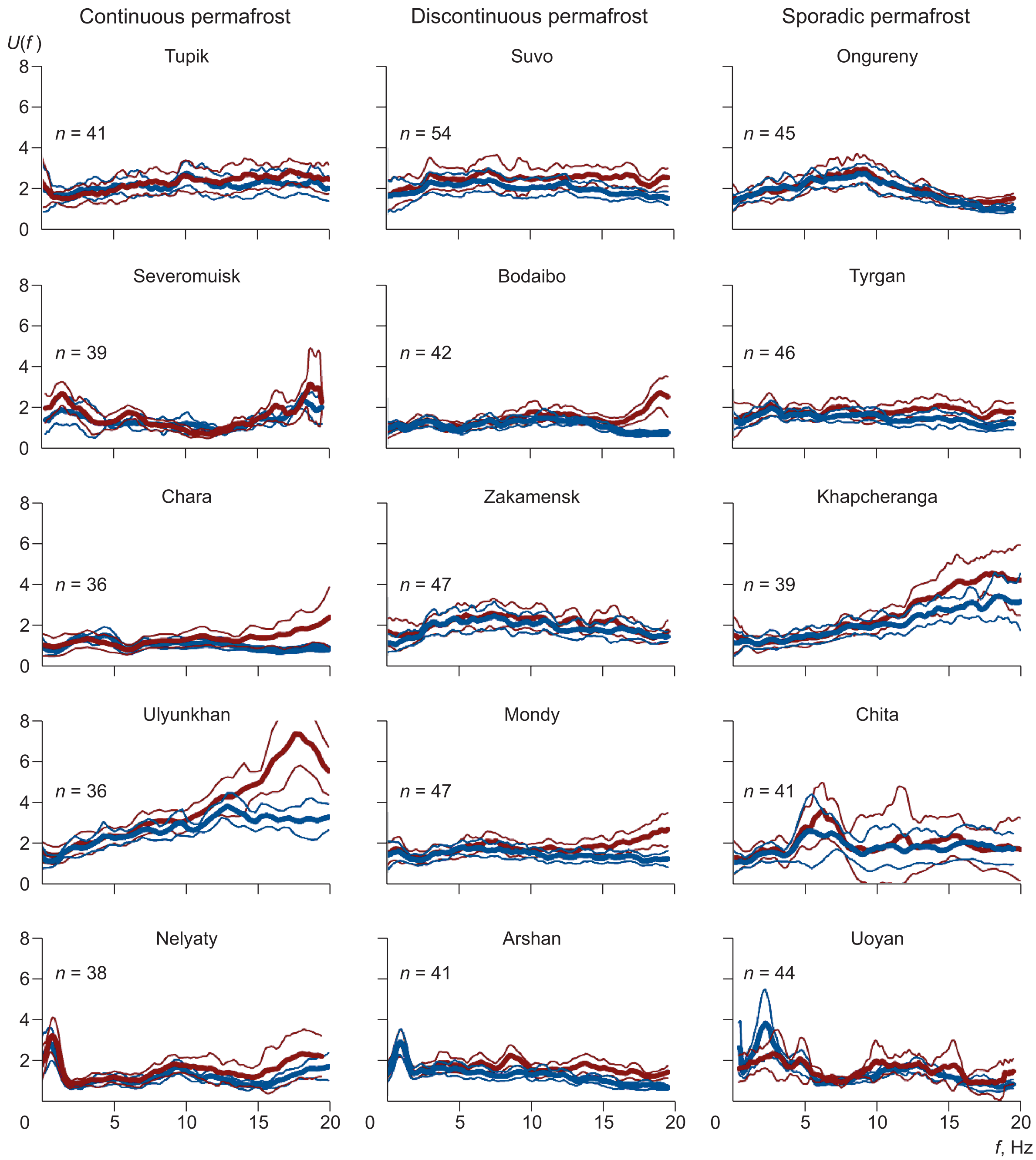

Fig. 5. Frequency responses and rms errors. Minimum errors for freezing (blue) and maximum for thawing (purple) conditions in continuous and sporadic permafrost in the Baikal region. *n* is the number of selected earthquakes.

for the thin-layer structures (Fig. 4*b*) are based on velocities v_P and v_S as in Table 1, likewise for the periods of thawing and freezing. The results show good agreement, especially in frequencies (the peaks fall within the same frequency range); the general pattern in amplitudes is the same but their ranges (within 5 to 20 Hz frequencies) differ: 2.3 to 6.5 for the method of spectral ratios and 2.2 to 3.6 in the case of thin-layer model calculations. The difference is due to dissimilarity of ground volumes in the two methods and to the assumptions on ground parameters in the latter method.

Note that the frequency responses calculated by the two methods are almost identical for the time of maximum freezing. Frozen consolidated rocks agree in both the amplitude and frequency patterns (the effect of surface waves is minor), which justifies the chosen calculation approach.

However, the warm season data show larger variance. Monitoring of v_P and v_S is required to outline anomalous zones for better justification of spectral responses of ground subject to seasonal temperature variations, which are calculated by the thin-layer method. Theoretical calculations should take into account that the parameters in these zones beneath each station may vary with positive or negative gradients.

The approach applied to the data from the two stations was extrapolated to all stations shown in Fig. 1. The frequency responses calculated using the vector sum $U(x)$ are presented (Fig. 5) for the same number of stations located in the zones of continuous, discontinuous, and sporadic permafrost. The physics behind the calculated responses for the selected stations is that the minimum and maximum r.m.s. errors for the freezing season correspond, respectively, to the greatest frost depth or the beginning of the thawing cycle and the greatest thaw depth or the beginning of freezing.

The revealed variations as a function of permafrost conditions are hard to compare among most of the stations, because they differ in the type and properties of soils. Nevertheless, such comparison may be possible in the first approximation for a few station pairs, as it was done for Orlik and Nizhneangarsk where the seismographs were installed on similar soils.

The annual variation range can be comparable for some of the analyzed stations (e.g., Tupik, Zakamensk, Tyrgan) upon the most consolidated (frozen or bedrock) soils, irrespective of their location in areas of continuous, discontinuous, or sporadic permafrost. In some other stations (Severomuisk, Bodaibo, and Khapcheranga) the difference may reach 2–4 times at relatively high frequencies due to dissimilarity of permafrost conditions (Fig. 5).

Note that low-frequency ground motion is more intense during seasonal thawing at some stations (Severomuisk, Neliaty, Uoyan), presumably because ice connection between large blocks loosens during thawing. The same explanation may be valid for stronger motions at stations installed on relatively solid bedrock in which ice fills fractures and voids. However, low-frequency motions at most of the stations have comparable variation ranges in the thawing and freezing cycles.

The reported results based on the two methods, which are imperfect though in providing true frequency responses of the dynamic uppermost crust, show some ambiguity in the expected earthquake-induced changes to the spectral composition, despite the revealed seasonal amplitude and frequency trends. The ambiguity is due to specific conditions (lithology, structure, and thermal state of soils) at each station located in continuous or discontinuous (sporadic) permafrost which have to be analyzed separately in terms of their effect on the final results.

At the same time, the obtained frequency responses can be used to update the calculation methods to further predict distance-dependent changes in the spectra of recorded earthquakes for each component. This prediction is relevant to seismological problems (spectral analysis of seismic records affected by shallow and deep crustal heterogeneities), as well as to seismic risk zoning in permafrost areas (Dzhurik et al., 2015).

In this respect, further work can include either determination of frequency responses from measured earthquake parameters (origin depth, mechanism, etc.), if statistically sufficient data are available, or combined temperature and geophysical monitoring in the outlined seismic-climatic zones of the Baikal region. The expected results, along with the suggested calculations of relative frequency responses by two methods, will improve the reliability of inferences on the changing spectral composition of ground motion within the depth of seasonal temperature variations.

CONCLUSIONS

The reported study using more than 200 three-component earthquake records from permanent stations operated by the Geophysical Surveys of the Russian Academy of Sciences (Baikal Filial, Irkutsk) has confirmed the correlation between the intensity of ground motion in different permafrost-affected areas of the Baikal region and ground temperature variations associated with seasonal freezing and thawing cycles.

The ranges of effects from the seasonal temperature variations on the amplitudes and frequencies of ground motion have been constrained at the level of r.m.s. errors for each station. These effects mainly appear at frequencies above 4–6 Hz and depend on the properties and thermal state of soils beneath the stations. At the same time, they are more prominent in thawing than in freezing curves for any soil, including relatively solid bedrock.

The frequency responses calculated using spectral ratios and velocities in thin-layered shallow Earth behave almost identically in the periods of freezing, i.e., the results of the two methods agree well in amplitudes and frequencies of motion for frozen consolidated ground. The results of the spectral ratio method for the thawing period are especially sensitive to temperature variations. The theoretical spectra calculations can be used in practice if monitoring data of P and S velocities till the depth of the zero annual temperature amplitude become available beneath each station. In our case, such calculations have been performed for certain measured velocities at selected stations.

Eventually, the reported results contribute to understanding of permafrost effects on the spectral behavior of ground motion during earthquakes in the Baikal region and have theoretical and applied implications for imaging shallow structures, seismic risk zoning, and predicting macroseismic effects of large earthquakes.

The study was carried out as part of Project 0346-2018-0001 of the Research Foundation (IX. Geosciences) and was partly supported by the Russian Foundation for Basic Research (Project 19-05-00232).

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Editorial responsibility: V.S. Seleznev