Assessment of Adverse Engineering Geological Conditions during Seismic Microzonation of the Sentachan Mining and Refining Facility (Eastern Yakutia)

N N Grib¹,⁴, V S Imaev²,³, A A Syasko⁵, G V Grib¹, I I Kolodeznikov⁴

¹Technical Institute (branch) of North-Eastern Federal University named after M. K. Ammosov, 16 Kravchenko St., Neryungri 678960 Sakha Republic, Russia
²Diamond and Precious Metal Geology Institute, Siberian Branch of the Russian Academy of Sciences, 39 pr. Lenina, Yakutsk 677000, Russia
³Institute of the Earth’s crust, Siberian Branch of the Russian Academy of Sciences, 128 Lermontova St., Irkutsk 664033, Russia
⁴Academy of Sciences of the Republic of Sakha (Yakutia), 33 pr. Lenina, Yakutsk 677007, Russia
⁵Neryungri Geophysics, 42 Geologov St., Neryungri 678960 Sakha Republic, Russia

E-mail: grib@nfygu.ru, imaev@crust.irk.ru

Abstract. In this study, the authors used complex seismotectonic, geological and geophysical methods when carrying out scientific research, identifying unfavourable engineering geological conditions for the designed mining facility located in the cryolithozone, as well as when determining the level of basic seismic hazard and performing seismic microzonation. The seismotectonic methods consisted in establishing the relationship between the distribution of local earthquake epicentres and active geological structures. The geophysical studies employing the methods of near-surface seismic tomography and electrical resistivity tomography allowed obtaining of detailed and reliable information on the features of the engineering geological structure of the studied site required to assess the influence of soils on the seismic wave attenuation of possible earthquakes in the region, thus solving the issue of seismic microzonation.

Seismotectonic studies consisted in determining the level of basic seismic hazard and were based mainly on previous field studies summarised in a number of published works, some of whose conclusions were used in this article.

The analysis of geophysical data allowed the authors to establish probable location of the distributions of ice and ice-rich permafrost, as well as the heterogeneity of soil conditions that affect their behaviour under dynamic loads.

The calculated values of probable earthquake intensities allowed the authors to determine the level of maximum earthquake intensity at the designed industrial sites of the mining and refining facility.

1. Introduction
At the present stage, mineral deposit development constitutes a system represented by alternately changing stages of creating the mining industry infrastructure. One of the key stages of this system consists in providing an engineering geological substantiation of the area for the designed construction
of a mining facility. The basic seismic hazard level of the designed mining facility (Sentachan) is established using seismic microzonation primarily on the basis of studying the engineering geological structure of the facility sites and introducing corresponding corrections related to the features of soil conditions determined via geophysical observations.

2. Geological structure of the research subject: a brief overview

The subject of research, Sentachan, is located in the Taryn metallogenic zone of the East-Yakutia metallogenic belt (central Verkhoyansk-Kolyma orogenic region). Local seismic situation is influenced by a large and seismically active Adycha-Taryn fault, which separates the Kular–Nersky terrane from the western part of the Verkhoyansk fold-and-thrust belt and plays a structure-determining role in the control and formation of the studied structures [14].

Tectonic stresses caused by the North American and Eurasian lithospheric plates moving towards one another are represented by the Kolyma-Omolon terrane and extend to the northwest, forming linear folds that changed repeatedly during subsequent tectonic activities [4, 14].

The proximity of the large Adycha-Taryn faulted zone (structure), within which excessive tectonic stresses are generated during the interaction of large tectonic structures, undoubtedly affect the high tectonic and, accordingly, seismic hazard of the Sentachan research subject [7].

The intensity of possible seismic vibrations equals 8 points on the MSK-64 scale for the Sentachan region, which is in contact with the active Adycha-Taryn fault; and is contoured with an 8-point isoseismal line.

The studied area is characterized by continuous permafrost (more than 300 m thick). According to the annual cycle of temperature dynamics, there is a layer of seasonal thawing and a stratum of permafrost soils [5, 14]. For the period of research, the soils of the seasonal thawing layer were in a thawed state extending to a depth of 0.3–1.2 m. Below this depth, the soils were frozen solid, having massive, layered and crustal cryogenic texture. In the course of thawing, the soils having medium degree of saturation became water saturated, whereas highly plastic loamy soils became free flowing.

The temperature of soils at a depth of zero annual amplitude varies from minus 6.0 ºС to minus 7.8 ºС. The standard depth of seasonal thawing is 1.6 m in wetlands and 2.5 m in dry areas.

3. Results of detailed geophysical studies

The studies performed at the mining and refining facility (Sentachan gold-antimony deposit) were aimed at identifying and estimating the spatial distribution of unfavourable engineering geological conditions in the area of technical and production sites for the further development of measures ensuring trouble-free operation of the above-mentioned system. Moreover, in this work we set out to establish the influence of soil conditions on the behaviour of ice and ice-rich permafrost under dynamic loads, as well as on seismic hazard assessment (seismic microzonation) [6]. A complex of geophysical methods was used in order to achieve this aim [3, 8, 16, 19, 20, 18].

Engineering and geophysical studies, one of which consisted in determining the intervals of exceedingly ice-rich permafrost and buried ice, allowed us to obtain more detailed information on the geological structure of the area, as well as to identify potential dangers for the functioning of the designed structures manifested through adverse engineering geological processes.

Geophysical studies, including methods of shallow seismic survey and electrical resistivity tomography, allowed obtaining of detailed and reliable information on the features of the engineering geological structure of the site under study [2].

For an integrated assessment of the ice content in the cross-section, initial data containing information on the electrical resistances of rocks at depths from 0 to 30 m were processed. During recalculation, the resistance of a point on the map was estimated as the mean resistance in this point for the entire depth interval, i.e. the mean resistance of a 30 m rock stratum. The resulting map is shown in Figure 1, a.

The integrated contour map of the 30 m thick stratum (Fig. 1, a) allowed us to establish probable location of ice and ice-rich permafrost intervals. The most dangerous places are highlighted in blue,
corresponding to an average electrical resistance of 10,000 Ω⋅m and above. The intervals of rocks having resistance above 3,162 Ω⋅m (isoline of resistivity logarithm of 3.5 in Figure 1, a) are also considered potentially dangerous.

At this stage of the analysis, the identified intervals were seen as potentially dangerous. The data analysis of near-surface seismic refraction tomography allowed us to determine the hazard level of the intervals more precisely.

When analysing the results of near-surface seismic tomography, maximum attention was paid to the areas of probable distributions of ice-rich permafrost and buried ice, previously identified according to the data of electrical resistivity tomography. Significantly, horizon-oriented analysis of elastic wave propagation velocity revealed that these areas coincide with the low-velocity zones. A velocity map, made on the basis of average indicators for a 30 m thick stratum, confirmed the conclusion that there was a good agreement between high-resistivity anomalies and low-velocity anomalies (Fig. 1, b).

Considering that the velocity of elastic wave propagation is a function of rock density, it should be noted that the previously identified intervals both have anomalously high electrical resistances and are characterised by low rock density. Loose or highly fractured rocks containing a high percentage of ice and, obviously, buried ice, possess such physical characteristics.

For a more accurate identification of intervals having minimum velocity indicators and maximum resistances, the map of elastic wave propagation velocity was standardised against the logarithmic resistivity scale. As a result, a contour map was generated, the physical meaning of which is as follows: minimum isoline values correspond to intervals characterised by very low elastic wave propagation velocity and high values of rock resistivity, or, very likely, to intervals containing buried ice or ice-rich permafrost. The averaged characteristics of a 30 m thick strata were used for the normalisation (Fig. 1, a-b).

The resulting map is shown in Figure 2. The boreholes which revealed buried ice are marked with red dots in this figure. The result analysis shows that potentially dangerous (in terms of a high probability of ice and ice-rich permafrost being present in the section) should be considered areas with the standardised indicator of less than eight (from the contour line 8 and less; in Figures 1 and 2 they are contoured in red).

Assuming a one-point increase in seismic activity corresponds to the doubling of seismic vibration amplitude, the seismic intensity increment in the linearly elastic range (weak earthquake oscillations) is calculated according to oscillation recordings using the formula [9, 15, 10, 11, 1].

We calculated the seismic intensity increment as the total increment in points: increment induced by the water (ice) content of soils and by the increase in resonant oscillations in the layered stratum.

According to the results of processing microseism recordings, the prevailing periods and the amplitude level of micro-oscillations, necessary for evaluating the resonant properties of soils, were determined. When calculating the seismic point increment, the ratio of oscillation amplitudes was used in order to estimate the soil response.

In order to assess changes in the intensity of a strong earthquake by the maximum amplitude of micro-vibrations in a particular prevailing period, the following formula [1] for calculating is used:

\[ \Delta J = 2 \lg \frac{A_{\text{max}}}{A_{\text{max}}}, \]  

where \( \Delta J \) is the seismic intensity increment; \( A_{\text{max}} \) and \( A_{\text{max}} \) are the maximum amplitudes of micro-vibrations for the tested and reference soil, respectively.
Figure 1. Averaged geophysical parameters for the 30 m thick strata:
(a) a contour map of the resistivity logarithms; (b) a contour map of elastic wave propagation velocity.

Figure 2. A contour map showing the standardised indicator V/R for a 30 m thick stratum.

The seismic intensity increment induced by the difference in soil conditions ($\Delta J_c$) was determined using the following formula [1]:

$$\Delta J_c = 1.67 \log \frac{\bar{V}(p,s) \cdot \bar{\rho}_s}{\bar{V}(p,s) \cdot \bar{\rho}_r},$$

(2)

where $\bar{V}(p,s)\bar{\rho}$ and $\bar{V}(p,s)i\bar{\rho}$ are the weighted means of the propagation velocities of longitudinal or transverse waves for the studied soil thickness at the reference and test site, respectively; $\bar{\rho}$ and $\bar{\rho}$ are the weighted means of soil density for the calculated thickness of the soil at the reference and test site, respectively.

The thickness of the stratum was chosen in accordance with the requirements outlined in [12, 13].

The propagation velocities of longitudinal and transverse waves in soils are determined in the course of interpreting the data of seismic refraction tomography.
The density values taken into account when calculating seismic impedance were obtained from laboratory data on the study of the physical and mechanical properties of soils (on the basis of core material) during engineering geological studies.

In addition to estimating the increment of surface seismic effects, the seismic impedance method allows assessment of intensity changes when the upper layer of loose sediments is removed.

The detailing of the predicted increment in seismic hazard for the studied area allowed obtaining of more accurate information on the seismic hazard level of designed facilities. The predicted seismic intensity in points of the MSK-64 scale is given for each section in Table 1.

The data presented in the table are calculated for the soils of the second category, structures of a high level of responsibility (OSR-97B map).

Difference in the determination of the predicted intensity in points for different methods does not exceed 0.5 points, which is in line with the regulatory requirements.

### Table 1. Predicted seismic hazard intensity of designed facilities in points of the MKS-64 scale.

| Section No. | Seismic impedance method | Microseism registration | Difference in average values | Difference in medians |
|-------------|--------------------------|-------------------------|-----------------------------|-----------------------|
|             | Average value | Median | Average value | Median |                      |                      |
| 4–6         | 7.09          | 7.10   | 6.67          | 6.61   | 0.42                  | 0.49                  |
| 7           | 7.06          | 7.05   | 6.78          | 6.66   | 0.28                  | 0.39                  |
| 8           | 7.13          | 7.14   | 6.82          | 6.82   | 0.31                  | 0.32                  |
| 11          | 7.12          | 7.09   | 6.86          | 6.80   | 0.26                  | 0.29                  |

### 4. Conclusion

The results of special geophysical studies carried out at the designed mining facility (Sentachan) using the methods of near-surface geophysics [3, 11, 17] revealed unfavorable areas in the geological cross-sections of the territory. These areas determine the stability of openings and mines, as well as further behavior of foundation soil and changes in its temperature, which is very likely to result in such extremely dangerous engineering-geological phenomena as thawing and liquefaction of soil due to subsiding foundation of engineering constructions.

Identification of such areas is of great importance for determining the level of seismic hazard to the designed facility, since they increase the level of seismic threat by 1–2 points.

Using electrical resistivity tomography, we were able to identify the intervals of buried ice and ice-rich permafrost. From the standpoint of seismic microzonation, thawing of foundation soil will cause a significant increase in the intensity of predicted seismic impacts. In fact, the soils which at the time of the study in terms of seismic characteristics were classified as soils of first category, when thawed, can be assigned the second or third category. Consequently, the seismicity of construction sites will be increased by one or even two points.

### 5. References

[1] Aleshin A S 2010 *Seismic Microzonation of Vital Facilities* (Moscow: Svetoch Plus Publ.) 304
[2] Bobachev A A, Modin I N, Pervago E V and Shevnin V A 1996 Multi-electrode electrical sounding in horizontally inhomogeneous media *Overview of Geophysical Exploration* issue 2 (Moscow: Geoinformmark) 50
[3] Voronkov O K 2009 *Engineering Seismicity in the Cryolithic Zone: Study of the Structure and Properties of Frozen and Thawed Rocks and Massifs* (St. Petersburg: VNIIG Publ.) 401
[4] Imaev V S, Imaeva L P, Mackey K G et al. 2009 The geodynamics of some segments of lithospheric plates in the North-East Asia *Geophysical Research* 10(1) 5–17
[5] Imaev V S, Imaeva L P and Kozmin B M 2000 *Seismotectonics of Yakutia* (Moscow: GEOS) 226
[6] Ishihara K 2006 *Soil Behaviour in Earthquake Geotechnics* translated from English, ed. A B Fadeev, M B Lisyuk (St. Petersburg: NPO Georeconstruction-Foundation project) 383
[7] Kolodeznikov I I and Gusev G S 2015 A *Seismotectonic Map of Eastern Siberia: Explanatory Note* (Neryungri: TI NEFU Publ.) 168
[8] Kobrunov A I 2009 *Mathematical Basics of the Theory of Geophysical Data Interpretation* (Moscow: TsentrLitNefteGas Publ.) 288
[9] Medvedev S V 1968 International scale of seismic intensity *Seismic Zoning of USSR* (Moscow: Nauka) 151–162
[10] RSM-73 Recommendations on seismic microzonation *Problems of Engineering Seismology* 1973 15 6–34

[11] Recommendations on Seismic Microzonation in Geotechnical Investigations (Moscow: USSR Gosstroy) 1985 72

[12] *SP 11-105-97 Engineering Geological Site Investigation for Construction. Part 6. Code of Practice for Geophysical Research* http://www.internet-law.ru/stroyka/text/45007/

[13] *SNiP II-7-81* Construction in Seismic Regions (Moscow: CPP GUP, Gosstroy of Russia) 2000

[14] *Tectonics, Geodynamics and Metallogeny of the territory of the Sakha Republic (Yakutia)* (Moscow: Maik Nauka/Interperiodica Publ.) 2001 571

[15] Sherman S I, Berzhinsky Yu A, Pavlenkov V A and Aptikaev F F 2003 *Regional Scales of Seismic Intensity: a Seismic Intensity Scale for Baikal* (Novosibirsk: Geo Branch, SB RAS Publ.) 189

[16] Zaalishvili V B and Rogozhin E A 2011 Assessment of seismic hazard of territory on basis of modern methods of detailed zoning and seismic microzonation *The Open Construction and Building Technology Journal* 5 30–40

[17] Fedorov A A and Syasko A A 2016 Seismic micro zoning of industrial sites at Nezhdaninsky deposit *News of the Higher Institutions. Mining Journal* 7 81–85

[18] AliElahi H and Mojtabazadeh H 2015 A review of studies on seismic geotechnical Zoning and micro-zoning urban areas *Journal of Novel Applied Sciences* 4 190–196

[19] Horike M, Zhao B and Kawase H 2001 Comparison of site response characteristics inferred from microtremors and earthquake shear waves *Bulletin of the Seismological Society of America* 91 1526–36

[20] Kuriyama T, Enomoto T and Mochizuki T 2000 *Proc. 12 WCEE* (New Zealand: Auckland) 1–7