UDC: 621.039.75

UNDERGROUND RESEARCH LABORATORY: PROBLEMS OF GEODYNAMIC RESEARCH

Tatarinov V. N.[1,2], Morozov V. N.[1], Kaftan V. I.[1], Manevith A. I.[1], Tatarinova T. A.[1,2]

[1]Geophysical Center RAS, Moscow, Russia

[2]Institute of Physics of the Earth. RAS, Moscow, Russia

Article received on February 26, 2019

Geodynamic aspects of research are considered in connection with the start of construction of an underground research laboratory at the territory of the Yenisei Nizhnekanskiy massif. The goal of observations of modern movements of the Earth's crust is formulated based on the methods of space geodesy and high-precision leveling for the period 2019—2024.

In the area of the Yeniseisky Rige, a geodynamic testing area has been created for observing recent movements of the Earth's crust, which includes 30 observation points. For the period from 2010 to 2016 were carried out 5 epochs of observation at the geodynamic test area using global navigation satellite systems (GNSS). To make reliable conclusions on the stability or mobility of the territory, the period of such observations must be at least 10 years. Preliminary observation data processing for 2012—2016 showed that it is also necessary to take into account the cyclical effect of movements of the Earth's crust on the boundary of the West Siberian platform and the Siberian Plate, which consists in the alternation of long periods of weak tectonic movements with short-term periods of activation.

The scheme of development of the geodynamic test area in the south direction from the Yeniseisky section is shown. A design of priority research using GNSS-methods and a method of high-precision re-leveling, aimed at predicting the stability of the insulating properties of rocks of the structural-tectonic block containing the underground research laboratory is proposed.

The data of testing GNSS receivers at the reference geodetic baseline of the Federal Center for Geodesy, Cartography and Spatial Data Infrastructure of the Federal Register of State Register are presented. The accuracy of determining the ethalon distances is estimated to be an error of 0,3 mm. Comparison results showed high GNSS measurement accuracy. The root mean square error was 2,4 mm with a 3,0 mm device declared by the manufacturer of GNSS equipment for short baselines less than a kilometer length. The average difference of 0,8 mm does not exceed 30% of the value of the standard error, which indicates the absence of a statistically significant systematic error in the measurements.

The monitoring of the horizontal and vertical components of the movements of the Earth's crust will allow to evaluate the geodynamic regime of the Yeniseisky section. The results will also be useful in organizing geomechanical studies in mine workings of the underground research laboratory, adjusting the space-planning layout of workings and wells to accommodate containers with high-level radioactive waste.

Introduction

Maintaining the isolation properties of the geological environment for the entire period associated with high-level waste (HLW) radiobiological hazard is seen as a fundamental condition ensuring safety of its underground isolation. Such period exceeds 10—100 thousand years. Tectonic mode in the region should be stable, thus, deformations of the Earth's crust (quickly occurring due to seismic activity or slow creep) should not result in its destruction and massive release of radionuclides. Forecasts on the geodynamic stability of the territory are based on the evaluation of Earth's crust movements using geological methods covering extended time periods. Monitoring of present-day crustal motion (PDCM) carried out at geodynamic testing sites (GTS) is seen in its essence as a direct and effective method enabling to evaluate the tectonic activity of a region.

In 2010, a GTS was established in the siting region of the first Russian HLW deep disposal facility to demonstrate the safety of FSUE MCC's isotope-chemical plant to be constructed there. In 2010 – 2016, monitored were the horizontal and vertical components of PDCM, as well as the strain rate of the ground surface.

In the course of research conducted, for the first time ever knowledge was obtained on the geodynamic mode of the region located in the contact zone of largest tectonic structures: the Siberian Platform, the West Siberian Plate and the Sayan Orogen. The research was performed using global navigation satellite systems (GNSS) [24—26]. It was found that at the boundary of these geological structures PDCM is cyclical in its essance. In 2013—2014, geodynamic regime activation was recorded, which manifested itself in a sharp change in the sign of compression and tensile strains on the western and eastern banks of the Yenisei River.

Maximum PDCM rates were recorded in the zone of Muratov and Right-bank faults' dynamic influence. According to geomorphological data, these sections are characterized by most pronounced relief gradient in the region [1], which confirms the inherited nature of modern movements, at least starting from the Quaternary. In this regard, an objective need arises suggesting that observations in the Yeniseiskiy site region should be continued to obtain data on the stability of the geodynamic mode of the territory. This data is believed to be essential for international peer review on the suitability of the site for underground RW disposal facility construction.

The paper seeks to define the priority objectives of geodynamic research in the URL for 2019—2024, as well as the ways of addressing them in keeping with the provisions set up in the Strategy for the Development of Deep Disposal Facility [22], Strategic Master Plan [4] and Program [18], as well as in relevant decisions of the Scientific and Technical Council № 10 Ecology and Radiation Safety of the State Corporation Rosatom of October 10, 2018.

It should be emphasized that the tasks considered surely need and will be adjusted in some way taking into account the views of specialists and new knowledge on the region. Let's focus on the existing regulatory requirements governing geodynamic research at nuclear facilities (NF).

The need for geodynamic research in the URL

The need for geodynamic research at NFs is provided for in a number of existing norms and rules [14—17]. In keeping with their provisions, including those of the Federal law № 190-FZ (Article 26, p. 1) activities on forecasting *geodynamic and tectonic processes* are seen as a must, as the stability of geological environment under external impacts involving modern slow (exogenous and endogenous) *differentiated geodynamic movements,* should be guaranteed.

Displacements of GTS nods are measured and deformations immediately at the boundaries of structural tectonic blocks where they have greater extent of free run and can be seen as indicators of tectonic processes occurring in the subsoils are calculated to study the differentiated movements. Moreover, stress-strain state (SSS) inside the structural block incorporating RW repository integrally reflects the kinematic effect of neighboring blocks, including those located at a sufficiently large distance from the URL.

Federal norms and rules specify:

- List of naturally occurring features, events and processes, their classification based on the degree of hazard;
- Requirements to engineering surveys and studies of naturally occurring features, events and processes;
- Classes of NF sites based on relevant hazard rates of naturally occurring features, events and processes;
- Requirements to the monitoring of naturally occurring and technogenic features, events and processes.

These specify geological and engineering processes and events that should be studied in NF siting region and its site: seismotectonic discontinuous displacements, seismic dislocations, seismotectonic uplifts, *modern differentiated movements of the earth's crust, tectonic creep,* residual seismic deformations, karst outcropping, permafrost-geological processes, etc.

Requirements for conducting certain surveys, including *geodetic observations over modern geodynamics of discontinuous disturbances,* involving high-precision repeated leveling and methods of space geodesy are set forth to identify naturally occurring and technogenic features, events and processes.

If naturally occurring processes and phenomena of hazard class I and II, including hazardous present-day crustal motions, can potentially occur at the NF site, then monitoring systems aimed at evaluating their parameters should be developed and operated before the NF commissioning.

According to the outcomes of the impacts, three hazard classes for naturally occurring features, events and processes have been established:

I class — especially hazardous process (phenomenon, factor) characterized by the maximum possible values of parameters and characteristics for a given type of process in a given time interval and accompanied by natural and / or man-made disasters;

II class – hazardous process (phenomenon, factor) characterized by rather high (but not higher than the known maximum value for this type of process) values of parameters and characteristics in a given time interval and accompanied by tangible consequences for the environment;

III class – a non-hazardous process (phenomenon, factor) characterized by low values of parameters and characteristics in a given time interval and not accompanied by any tangible consequences.

The following boundary parameters — *modern differentiated movements of the earth's crust* are defined:

First hazard level — displacement along the discontinuity is more than or equal to 0.3 m, presence of geodynamic zones with a speed gradient of Quaternary movements of 10^{-6} per year or more;

Second hazard level — displacement along the discontinuity of less than 0.3 m, presence of geodynamic zones with a speed gradient of Quaternary movements from 10^{-9} to 10^{-6} per year.

It should be noted that these documents do not provide sufficiently clear data on quantitative criteria enabling to zone the territory according to the hazard level for horizontal movements. There are only a few publications on this subject. For example, Yu. O. Kuzmin [10] provides criteria for average annual strain rates for areas with increased geodynamic hazard. The horizontal strain rate accounts for $\Delta \geqslant \pm(5{\cdot}10^{-4}—5{\cdot}10^{-5})$.

The key parameters describing modern differentiated movements of the earth's crust and tectonic creep are as follows:

- location of tectonically active faults, regional and other faults;
- length and width of fault and discontinuity areas;
- structure of tectonically active faults;
- tectonic blocks' raising and lowering rate;
- tectonic creep rate in different modes of motion (stable, cyclical, as well as before and after distant earthquakes);
- displacement (raising and lowering, shift, inclination) of tectonic blocks;
- motion gradient — the ratio of the displacement amplitude to the width of the deformation zone and the unit of time;
- age and amplitude of displacement given the youngest tectonic creep and the nature of their topographical manifestation.

[13] provides a definition for *active fault* seen as a tectonic fault with a relative displacement of by 0.5 m or more that occurred during the Quaternary period *or if relative displacements of the blocks are observed and their modern movement rate is over 5 mm/year.* Concept of a geodynamic zone (tectonic structures being active in the Quaternary period) and *gradient of tectonic movements* (change in the amplitude of marking surface's tectonic movement per unit distance and time) are also introduced. "Active fault" and "dangerous fault" should be distinguished. Active fault is characterized by presence of abnormal movements compared to background ones. These may not be dangerous for the repository. *"Modern Active Fault"* is seen as an area that accumulates dangerous deformations.

If we take into account that deformations are pulsating in their nature (which was proved for many regions of the globe and for this region in [26]), then it is necessary to use the assumptions on the periodic nature and not on the monotonous accumulation of deformations. In this case, C coefficient is introduced taking into account the cyclic nature of the strains. Then the criterion for identifying a dangerous fault may look as follows:

$$\theta < \frac{C\varepsilon_i}{t}, \quad (1)$$

where ε_i are the calculated strains; C is the empirical coefficient, which, according to the results of lengthy, repeated geodetic observations, ranges from 3 to 5; t is time.

[14] provides the criteria enabling to evaluate the deformation rate via observations of present-day crustal motion (PDCM) based on GPS/GLONASS systems. In particular, Appendix 1 of the document contains a nomogram that can be used to estimate the rates of dangerous horizontal deformations depending on the observation line length (Fig. 1, Table 1).

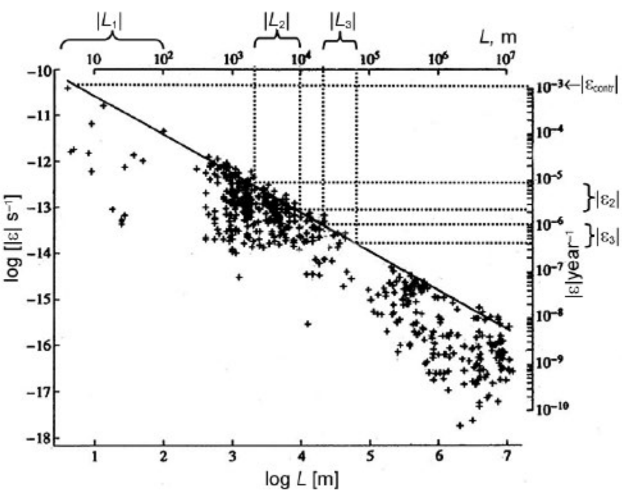

Fig. 1. Distribution of horizontal strains velocity modules depending on the observation line length taking into account data from [3]

Table 1. Hazard assessment criteria for measured crustal deformations

	Size of monitoring area, m	Maximum speed of deformations, year^{-1}
Region	$L_3 = 3{\cdot}10^4 - 5{\cdot}10^4$	$\lvert\varepsilon_3\rvert = 2{\cdot}10^{-6} - 3{\cdot}10^{-7}$
Site	$L_2 = 3{\cdot}10^3 - 10^4$	$\lvert\varepsilon_2\rvert = 10^{-5} - 5{\cdot}10^{-6}$
Marginal part of repository massif	$L_1 = 1 - 10^2$	$\lvert\varepsilon_1\rvert = 10^{-3} - 3{\cdot}10^{-5}$

Regulations specify the following needs in this domain:

a) Instrumental measurements of PDCM parameters (velocities of vertical and horizontal displacements of the ground surface and their gradients) in the near field (with a radius of up to 30 km) and directly at NF site;

b) Establishment of constantly operating GTSs enabling to monitor PDCM parameters at all stages of NF life cycle;

c) To identify negative factors potentially affecting NF safety and stability based on instrumental geodetic methods to study differentiated movements and deformations of the earth's crust upper part;

d) To take into account the large-scale space-time factor in the interpretation of monitoring data.

Monitoring PDCM

The purpose of PDCM observations is seen in estimating quantitative parameters of modern vertical and horizontal movements of the earth's crust caused by tectonic processes within a radius of 15 km from the repository (far field). These estimates are necessary for:

a) identifying active tectonic structures and geodynamic zones;

b) determining the magnitude and direction of modern movements associated with large tectonic disturbances and at the boundaries of structural units;

c) forecasting strain rates at the Yeniseyskiy site;

d) identifying kinematic boundary conditions for the numerical simulation of the stress-strain state in the near field of repository's underground excavations.

Two types of instrumental observations are sufficient to achieve this goal:

1 Monitoring of horizontal components using global navigation satellite systems;

2 Monitoring of vertical PDCM components by means of high-precision repeated leveling of the first accuracy class.

Simultaneous use of the two methods is required as each of them has approximately an order of magnitude greater accuracy in measuring horizontal (GNSS) and vertical (leveling) displacements of the ground surface.

Geo-dynamic testing site is available in the Yeniseiskiy site area. It was established in 2012—2016 jointly with the specialists of FSUE MCC to monitor PDCM using GNSS with 30 major GNSS stations (Fig. 2). In 2010—2016, 5 epochs of GNSS observations were performed at the GTS [24, 26]. Over the entire observation period, only in rare cases did the horizontal velocities of PDCM exceed 5 mm/year. Comparison of strain rates and existing criteria enabling to identify dangerous geodynamic areas [11] showed that the region is quite stable in terms of its geodynamics since the maximum strain rates were found to be equal to $5{\cdot}10^{-7}$ year^{-1}.

Evaluation of GNSS results presented in [17] and other literature sources allows to state that:

(a) to make a final conclusion, further research is necessary to obtain a longer time series of data on PDCM;

(b) when identifying dangerous deformation zones some discrepancies are observed in different calculation methods, which is obviously caused by the spatial-temporal scale effect which should be taken into account in the future.

Obviously, PDCM monitoring shall be resumed before the start of mining operations. Firstly, this will eliminate the gaps in the time series of data on PDCM and in skipping anomalous values. Secondly, it is necessary to fix the “zero” position of GTS stations as their changes will be monitored in the future.

In 2019—2025, the following efforts are expected to be completed (Fig. 2):

1) initial survey of the stations pertaining to the existing network (2019);

2) development of designs on fitting GTSs with additional equipment (2019);

3) establishment of additional stations in the southern part of the area (2019);

4) conducting annual (if sufficient funding is available, bi-annual) cycles of GNSS observations (2019—2025);

5) data processing, mapping of strain rates, comprehensive interpretation of the results (2025).

It should be noted that according to the guideline, following the establishment of new GNSS stations some "settling" period should be provided for. Therefore, given the actual state-of-art associated with relevant contracts that have to be signed, the implementation of the first cycle of observations may be postponed to 2020.

Based on GNSS monitoring accounting for comprehensive interpretation of geodesic and geophysical data the following items are to be identified:

Fig. 2. Geodynamic observations in 2019-2024 The yellow triangles represent the existing GNSS stations, the red circles — new GNSS stations, the black dotted line — existing re-leveling profile No. 1, the red dotted line represents the new re-leveling profile No. 2

- speeds of horizontal and vertical PDCM will be identified;
- dilatation of the ground surface at the Yeniseyskiy site will be calculated;
- kinematic and dynamic characteristics of the main faults will be identified;
- PDCM influence on the stress-strain state in repository's near field will be evaluated;
- a more precise picture on the configuration of the block structure in repository's siting area will be obtained.

Monitoring over vertical movements of ground surface using high-precision re-leveling method

Leveling of the line crossing the main tectonic disturbances in repository region was carried out in 2011—2015 under the program of leveling class I performed by experts from JSC Geolcom and FSUE MCC. Previously, measurements in the region were performed in irregular manner. Therefore, based on previous results it was practically impossible to evaluate the dynamics of modern vertical PDCM [12].

Class I leveling technique is characterized by the parameters given in Table 2 [19—22 and others]. Current leveling profile [12] presents a line extending from east to west spreading from the east wing of the Minzhul-Sidelnikovsky discharge area to the east up till the east wing of the Bolshetelsky discharge area (Fig. 2). To cover the Yeniseyskiy site with observation stations it was proposed to lay down the leveling line No. 2 to the south of line No. 1.

Total actual length of the leveling lines accounts for some 45 km with the estimated number of stations being equal to 70. The distance between the stations is identified based on the availability of

Table 2. Leveling parameters of class I [19]

Parameter	Characteristic
Level	TrimbleDINI 12 (standard deviation of leveling ±0.3 mm per 1 km of double stroke)
Leveling rods	3- meter, invariant, code
Minimum length of a collimating ray	15 m
Maximum length of a collimating ray	50 m
Inequality of collimating ray lengths at the station	less than 0.3 m
Measurement of collimating ray length at the station	steel tape, cable wire
Accumulation of inequalities of collimating ray lengths in a section	Less than 1.0 m
Height of a collimating ray above the underlying surface	Less than 0.8 m
Number of horizons	1
Number of leveling lines	2 (left and right)
Number of directions	2 (front and back)
Meteorological conditions	measurement of air temperature at a leveling level performed once an hour
The discrepancy between the first and second rod reading	0.3
Discrepancy in the excess value on the left and right lines (mm)	$2\sqrt{L}$ (km)
Discrepancy in the excess value in the section front and back (mm)	$1\sqrt{L}$ (km)
Discrepancy in loop traverse (mm)	$1\sqrt{L}$ (km)

existing faults and the block structure of the area, but should not exceed 2 km.

Geodetic network stations are [19] steel tubular signs with a diameter of 150—180 mm, recessed by 3 m and protruding above the ground by 1.2 m with a casing pipe being 400—500 mm in diameter filled with insulation (glass wool, expanded clay) over which a 10-centimeter waterproofing layer is poured (bitumen, tar). A centering device is welded to the upper part of the pipe with an anchor (corner, pipe, reinforcing wire) welded to its bottom part.

Locations of the monitoring network stations should provide optimal conditions for observations, safety, the possibility of round-the-clock access to the stations themselves and their operation all year round. Fig. 2 shows the layout of high-precision leveling lines of class I, taking into account additional observation stations. The position of the new line No. 2 is shown according to 2017 GSPI design project [19]. Observations are performed on a yearly basis.

In 2019—2025, the following activities are scheduled:

1) preliminary survey of existing networks (2019);
2) design development to fit the leveling lines with additional equipment (2019);
3) establishing additional stations along the line No. 2 (2019);
4) conducting annual observations based on two leveling lines (2019—2024);
5) data processing, drawing schemes and cross-sections of vertical displacements along the profile, integrated interpretation of the results with due account of GNSS observations (2025).

The correctness of the conclusions drawn about the nature of the geodynamic activity in the region is judged by the quality of the field PDCM measurements and data processing, and also depends on the qualified geological and geodynamic interpretation of the results obtained. In this regard, let's take a closer look on the accuracy of PDCM parameter measurements by GNSS methods.

Ways to improve the accuracy of PDCM parameter measurements in URL vicinity

The reliability of estimates regarding the speeds of horizontal PDCM can be improved in three ways: by applying modern equipment, using special methodological techniques allowing to perform field observations and data processing.

To ensure higher accuracy of geodynamic monitoring, two-frequency and predominantly two-system GNSS receivers of the geodetic class are used. Such receivers record signals from two GLONASS and GPS navigation systems simultaneously. Today, such a configuration of GNSS equipment provides accuracy in identifying horizontal and vertical displacements at first millimeter level [7, 8].

From methodological perspective, to improve the quality, “classical” methods are used: forced centering, uniform installation of antennas and receivers for different periods of observation, increased duration of observation sessions, etc. Each observation cycle contains several GNSS receiver layouts drawing up fragments of a single network with cross-strapping. Such a layout is established due to the number of GNSS equipment sets being involved in the observations and at the same time helps to achieve higher measurement accuracy.

In 2012—2016, 12 sets of Hyper dual-frequency GNSS receivers (7 pcs) with MarAnt+ and TopconGR-3 antennas (5 pcs) were used for observations. Recently, under RSF project No. 18-17-00241 (run by the Member of the Academy of Sciences A.D.Gvishiani), SC RAS has been upgrading PDCM monitoring hardware and software with 3 Delta-3N JAVAD GNSS receivers purchased. Configuration of new GPS/GNSS receivers will enable to obtain the maximum currently possible accuracy in recording horizontal displacements at the first millimeter level [9].

Deformations of the ground surface are determined by mathematical processing of the temporary differences in the current and initial cycles' measurements. When processing repeated GNSS measurements at the GPS, the method enabling difference equalization of the kinematic satellite geodetic network is used [22]. It is known that in determining the vectors of geodetic station spatial displacements, separate equalization of measurement cycles in kinematic geodetic networks is less effective than equalization of repeated observation differences. Significant uniformity of measurements' physical conditions during each cycle, which, when processing the differences of observations, provides more effective estimates, explains the latter. Uniformity of the observation conditions in each cycle is due to some local features, such as constant obstruction to the passing radio signal, items causing its re-reflection, design features of geodetic centers, seasonal atmospheric conditions, etc. These factors give rise to one-sided errors in measurements that are significantly attenuated in their time differences.

It should be noted that the radio signal is recorded simultaneously by two GLONASS and GPS satellite systems. It was found that if GLONASS group is brought in line with the current GPS setup, the accuracy of observations may be increased by about one and a half times [7, 9].

It should be noted that deformations of ground surface within the finite element (triangle) of a GTS with GNSS stations seen as its vertices are inversely proportional to its area. This somewhat complicates the interpretation of strains spatial distribution inside an inhomogeneous network. With equal displacements of stations in unequal triangles, the strains will not be equal which can be interpreted as geodynamic mode anomalies. To eliminate this drawback, deformations scaling method is used to reduce them to average or given standard area of the triangle. In doing so the values of primary strains are multiplied by scale factors $m = P_i / P_m$, where P_i is the area of the i-th triangle, P_m is the average (standard) area of the triangle.

Actual accuracy of GNSS measurements depends on a big number of natural and instrumental factors, including those that cannot be rigorously corrected. Accuracy in determining the coordinates and lengths of the baselines between the observation stations is considered to be crucial in geodynamic studies with the PDCM speed being only slightly higher than the resolving power of the equipment. An experiment was conducted to test GNSS receivers using a reference one. GNSS receivers available at the State Center of the Russian Academy of Sciences were tested at a reference geodetic basis of the Federal Center for Geodesy, Cartography and Spatial Data Infrastructure of the Rosreestr [2, 10]. The line lengths of this basic reference standard are measured regularly by high-precision electronic measuring instruments: laser rangefinders and tacheometers. The accuracy in determining the basis distances was estimated by the mean square error of 0.3 mm.

Layout of the reference basis located in the northern part of the Moscow region is shown in Fig. 3, and the appearance of the centers is shown in Fig. 4.

Fig. 3. Reference basis of the Federal Center for Geodesy, Cartography (Moscow Region). The red lines represent the basis lines. Yellow markers represent equipment installation stations

Figure 4. Reference basis center during an experiment

Centers of the site are concrete monoliths buried in the soil at distances exceeding the freezing depth. In the upper part of the concrete monoliths, centering devices are mounted. These provide centering with an error of some 0.1—0.2 mm (Fig. 4).

GNSS equipment testing method suggests its installation on the basis centers and measurement of the baseline vectors between these centers followed by measurement comparison with the reference values. The measurements were carried out in 4-hour static sessions on different segments of the basis. At the same time, GPS and GLONASS

Table 3. Comparison of measured horizontal distances with reference values

Numbers of basis centers	Measured distances, m	Exceedance, m	Reference horizontal distances, m	Slope corrections, mm	Measured horizontal distances, m	Discrepancies, mm
1–3	599.796	−2.97	599.7913	−7.3	599.7887	−2.6
3–5	887.221	−1.43	887.2227	−1.2	887.2198	2.9
1–5	1,487.018	−4.48	1,487.014	−6.8	1,487.0112	2.8
2–4	575.329	−2.83	575.3320	−7.0	575.3220	0
Mean						0.8
RMS						2.4

satellite data was recorded. As the result, the lengths of the baselines and their horizontal positions were calculated. Table 3 presents the comparison of the measurements with the standard values.

The comparison results demonstrated high measurement accuracy. The mean square error (RMS) accounted for 2.4 mm (Table 3) with 3.0 mm declared by GNSS equipment manufacturer for short base lines being less than a kilometer long. The average difference of 0.8 mm does not go beyond 30 % of the mean square error. It means that no statistically significant systematic error exists in the measurements.

Previously obtained RMS for the Nizhnekanskiy massif region in plan and height were 3—4 mm and 6—7 mm, respectively, for 6 epochs of observations [24]. Therefore, it can be argued that for the obtained values reflecting the changes in the baseline lengths ΔL in the region of the Nizhnekanskiy massif (Fig. 5) [26], RMS allows to identify abnormal values for horizontal PDCM and slightly exceeds 2.4 mm level obtained for the reference standard and measurements performed under the "ideal" conditions.

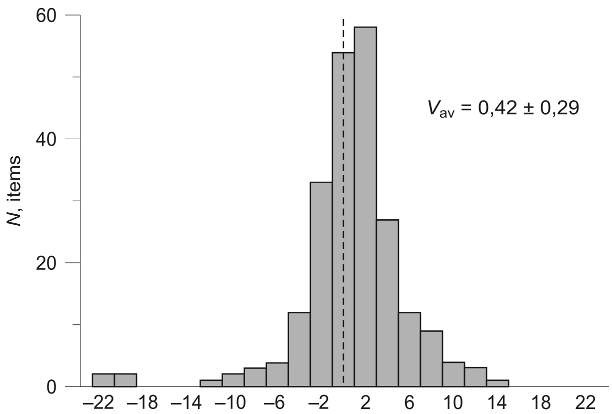

Fig. 5. Bar chart showing the distribution of changes in the lengths of the baselines within Nizhnekanskiy massif's GTS covering a time period from 2010 to 2016

Deformation analysis of GNSS observations

Geological and geodynamic interpretation of GNSS observations based on the differential description of deformations in continuum mechanics, referred to as the finite element method [5] is seen as a most important element of geodynamic monitoring. Methods allowing to determine deformations within the finite elements of spatial geodetic networks were developed and described in [6]. To date, separate analysis of lateral and vertical deformations based on the results of repeated satellite observations is considered as the most effective one. For this purpose, the following technique is used [25].

The vectors showing spatial displacements of control network stations obtained from the adjustment of the differences in the measurements are converted into differences in the geodetic coordinates ΔB, ΔL and ΔH. For this purpose, the following differential formulas are used:

$$\begin{cases} \Delta B = \dfrac{1}{M+H}\left(-\Delta X \sin B \cos L - \Delta Y \sin B \sin L + \Delta Z \cos B\right) \\ \Delta L = \dfrac{1}{\left(N+H\right)\cos B}\left(-\Delta X \sin L + \Delta Y \cos L\right) \\ \Delta H = \Delta X \cos B \cos L + \Delta Y \cos B \sin L + \Delta Z \sin B \end{cases} \qquad (2)$$

where $M = \dfrac{a\left(1-e^2\right)}{W^3}$, $N = \dfrac{a}{W}$, $W = \sqrt{1-e^2 \sin^2 B}$,

where a is the semimajor axis and e^2 is the eccentricity square of Earth-wide ellipsoid.

For each triangle in a flat rectangular coordinate system, values of the its vertices' coordinates x, y and the differences of coordinates (horizontal displacements) Δx, Δy obtained from equalizing repeated satellite measurements are available. Then, horizontal strains γ_1, γ_2, Δ and ω can be calculated based on the following equations [5]:

$$\begin{aligned}
\gamma_1 &= \frac{x_2(\Delta y_3-\Delta y_1)+y_2(\Delta x_3-\Delta x_1)-x_3(\Delta y_2-\Delta y_1)-y_3(\Delta x_2-\Delta x_1)}{x_2y_3-x_3y_2}\\
\gamma_2 &= \frac{x_2(\Delta x_3-\Delta x_1)+y_2(\Delta y_3-\Delta y_1)-x_3(\Delta x_2-\Delta x_1)-y_3(\Delta y_2-\Delta y_1)}{x_2y_3-x_3y_2}\\
\Delta &= \frac{x_2(\Delta y_3-\Delta y_1)-y_2(\Delta x_3-\Delta x_1)-x_3(\Delta y_2-\Delta y_1)+y_3(\Delta x_2-\Delta x_1)}{x_2y_3-x_3y_2}\\
\omega &= \frac{-x_2(\Delta x_3-\Delta x_1)-y_2(\Delta y_3-\Delta y_1)+x_3(\Delta x_2-\Delta x_1)+y_3(\Delta y_2-\Delta y_1)}{2(x_2y_3-x_3y_2)}
\end{aligned} \quad (3)$$

Maximum and minimum tensile strains can be calculated using the formula presented below:

$$E_1=\frac{1}{2}\left(\Delta+\sqrt{\gamma_1^2+\gamma_2^2}\right),\quad E_2=\frac{1}{2}\left(\Delta-\sqrt{\gamma_1^2+\gamma_2^2}\right), \quad (4)$$

Azimuth of the principal deformation axis can be calculated from the expression:

$$\operatorname{tg} 2\theta_0=\frac{\gamma_2}{\gamma_1}. \quad (5)$$

Accuracy of the strain components within each triangle is calculated via their covariance matrix:

$$Q_{(\gamma_1,\gamma_2,\Delta,\omega)}=f_{(\gamma_1,\gamma_2,\Delta,\omega)}Q_{dx}f^T_{(\gamma_1,\gamma_2,\Delta,\omega)}, \quad (6)$$

where Q_{dx} stands for covariance matrix of displacement vector components obtained from the equalization of the differences in satellite measurements. The matrix of partial derivatives associated with the desired deformation components based on horizontal displacement arguments (6) can be presented as follows:

$$f_{(\gamma_1,\gamma_2,\Delta,\omega)}=\frac{1}{x_2y_3-x_3y_2}\begin{pmatrix} -y_2+y_3 & x_2-x_3 & -y_3 & -x_3 & y_2 & x_2\\ -x_2+x_3 & y_2-y_3 & -x_3 & -y_3 & x_2 & -y_2\\ y_2-y_3 & -x_2+x_3 & y_3 & -x_3 & -y_2 & x_2\\ x_2-x_3 & y_2-y_3 & x_3 & y_3 & -x_2 & -y_3 \end{pmatrix}.$$

Here, the coefficient indexes are shown as numbers of the triangle's vertices to which the corresponding strain components refer to.

Then mean square errors of the deformation components are calculated based on the expression provided below:

$$m_{(\gamma_1,\gamma_2,\Delta,\omega)}=\mu\sqrt{\operatorname{diag} Q_{(\gamma_1,\gamma_2,\Delta,\omega)}}. \quad (7)$$

Similarly, the accuracy of deformations corresponding to the maximum and minimum tensile stresses and their axes' azimuth is calculated as functions of the four main deformation characteristics.

Conclusion

Studies aimed at investigating geological and environmental safety of RW underground disposal facility performed in URL at the Yeniseyskiy site cannot be limited to the study of the state of the rock mass conducted exclusively in underground excavations. In this case, we limit ourselves to a significant extent in discovering the true reasons that can lead to the possible destruction of the structural block incorporating the repository and the engineered barrier system. Due to its energy power, the kinematics of structural and tectonic blocks at the Yeniseyskiy site and the adjacent areas is decisive among all other naturally occurring factors.

Evaluation of GNSS observations in areas considered tectonically similar to the Nizhnekansky massif shows that a reliable conclusion on the stability or abnormality of the territory can be drawn if the period of instrumental observations lasts over 10 years. Preliminary evaluation of observation data processing covering PDCM in 2012–2016 showed that it is also necessary to take into account the cyclic effect of movements at the border of the West Siberian Platform and the Siberian Plate which consists in alternating relatively long periods of weak tectonic movements with short periods of sharp activization.

The field observation technique applied has been tested at GTS. It allows to identify abnormal values of horizontal PDCM and dilatation of the ground surface. The calculated values of the mean RMS at GTSs in the region of the Nizhnekanskiy rock mass were found to be slightly exceeding the 2.4 mm level which was derived based on reference standard measurements.

It is considered necessary to continue the observations launched in 2012 over vertical and horizontal PDCM components enabling stable identification of abnormal PDCM parameters. An objective need in expanding the GTS network, establishing additional observation stations and a leveling line seems quite obvious: these activities shall be completed before the start of mining efforts on URL construction in 2019.

Observations over horizontal and vertical PDCM components will enable to evaluate the geodynamic regime at the Yeniseyskiy site. These are also required to arrange for geomechanical studies in URL excavations, adjust the space-planning location of excavations and boreholes for RW package emplacement, as well as for the successful implementation of international peer review covering NKM URL investigation results.

The paper was written as part of a State task on addressing the topic titled as “Development of forecasting and monitoring methods for the geological environment to prevent geological and ecological threats from nuclear facilities”.

References

1. Anderson E. B., Belov S. V., Kamnev E. N., Kolesnikov I. Yu, Lobanov N. F., Morozov V. N., Tatarinov V. N. Underground isolation of radioactive waste. M.: Gornaya Kniga, 2011. 592 p. (In Russian).

2. Gvishiani A. D., Tatarinov V. N., Morozov V. N. Systematic assessment of factors affecting stability of geological medium in disposal of high-level radioactive waste. *X International conference “Monitoring of nuclear tests and their consequences”*. Almaty. Kazakhstan. Kurchatov: NNC RK, 2018. pp. 105–106. (In Russian).

3. Guseva T. V., Mishin A. V., Skovorodkin Yu. P. Modern horizontal movements at various scales. *Fizika Zemli,* 1996, no. 12, pp. 86—91. (In Russian).

4. Dorofeev A., Bolshov L., Linge I., Utkin S. S., Savelyeva E.A.. Strategic Master-Plan for R&D demonstrating the safety of construction, operation and closure of a deep geological disposal facility for radioactive waste. *Radioactive waste,* 2017, no. 1, pp. 33—42. (In Russian).

5. Geodesic methods of studying Earth crust deformations at geodynamic sites (Guidlines). Moscow, TsNIIGAiK, 1985. (In Russian).

6. Esikov N. P. Modern movements of Earth surface from the viewpoint of deformation theory. Novosibirsk. Novosibirsk, Nauka publ., 1991. 226 p. (In Russian).

7. Kaftan V. I., Ustinov A. V. Enhancing the accuracy of local geodynamic monitoring by application of global satellite navigation systems. *Gorny journal,* 2015, no. 12, pp. 32—37. (In Russian).

8. Kaftan V. I., Krasnoperov R. I., Yurovsky P. P. Graphical presentation of the results of identification of movement and deformation of ground surface by means of global navigation satellite systems. *Geodesy and Cartography,* 2010, no. 11, pp. 2—7. (In Russian).

9. Kaftan V. I., Sidorov V. A., Ustinov A. V. Comparative monitoring accuracy analysis for local movements and deformations of ground surface using global navigation satellite systems GPS and GLONASS. *Vulkanologiya i seysmologiya,* 2017, no. 3, pp. 50—58. DOI: 10.7868/S020303061703004. (In Russian).

10. Kaftan V. I., Gviashini A. D., MorozovV. N., Tatarinov V. N. Identification of movements and deformations of Earth crust based on GNSS data at Nizhnekansk geodynamic site in the vicinity of potential radioactive waste disposal site. *Sovremennye problemy distantsionnogo zondirovaniya Zemli iz kosmosa,* 2019, no. 2. (In Russian).

11. Kuzmin Yu. O. Modern geodynamics and assessment of geodynamic risk in subsoil use. Moscow, Economic News Agency publ., 1999. 220 p. (In Russian).

12. Morozov V. N., Tatarinov V. N., Kaftan V. I., Manevich A. I. Underground research laboratory: geodynamic and seismotectonic aspects of safety. *Radioactive Waste,* 2018, no. 3 (4), pp. 16—29. (In Russian).

13. GKINP 01-271-03. Guidelines for setting up and reconstruction of urban geodesic networks using GLONASS/GPS satellite systems. Moscow, 2003. (In Russian).

14. RB-019-17. Federal codes and standards. Assessment of the initial seismicity of nuclear facility site under of engineering surveys and studies. Moscow, 2017. (In Russian).

15. NP-064-17. Federal codes and standards. Accounting of external impacts of natural and man-induced origin on nuclear facilities. Moscow, 2017. (In Russian).

16. NP-055-14. Federal codes and standards. Disposal of radioactive waste. Principles, criteria and main safety requirements. Moscow, 2014, 29 p. (In Russian).

17. NP-100-17. Federal codes and standards. Requirements to the content of safety analysis report for radioactive waste disposal facilities. Moscow, 2017, 122 p. (In Russian).

18. Program of studies in the underground research laboratory (URL) in the Nizhnekansk rock mass to confirm the design parameters of safety for class 1 and class 2 RW disposal: Decision of section No. 1 “Environmental and radiation safety of facilities for long-term storage, conservation and disposal of RW” of STC № 10 of State Corporation “Rosatom” of 06.04.2016. (In Russian).

19. Development and justification of geodynamic monitoring network of modern movements of Earth crust in the vicinity of potential DRWDF (Krasnoyarsk

kray, Nizhnekansk massif). Technical Report. GSPI. Zhelznogorsk, 2017. 78 p. (In Russian, unpublished).
20. Staritsyna L. I., Khafizov R. R., Zabrodin S. M. Technical report on the results of geodynamic and seismic monitoring at nuclear facility sites in the first half of 2014, stage 2, in 2 volumes. Zheleznogorsk, LLC "GEOLKOM", 2014. 285 p. (In Russian, unpublished).
21. Staritsyna L. I. Technical report on the results of geodynamic and seismic monitoring at nuclear facility sites in the first half of 2015, stage 4, in 2 volumes. Zheleznogorsk: LLC "GEOLKOM", 2015, 317 p. (In Russian).
22. Strategy for establishment of a deep radioactive waste disposal facility. *Radioactive Waste,* 2018, no. 2 (3), pp. 114—120. (In Russian).
23. Tatarinov V. N., Tatarinova T. A. Account for scaling effect in observation of deformation of Earth surface by satellite navigation systems. *Mine Surveying Magazine,* 2012, no 5, pp. 15—19. (In Russian).
24. Tatarinov V. N., Morozov V. N., Kaftan V. I., Manevich A. I. Modern geodynamics of the southern part of Yeniseysky Ridge based on satellite observations results. *Geophysical research,* 2018, vol. 19, № 764, p. 64—79. DOI: 10.21455/gr2018.4-5. (In Russian).
25. Kamnev E. N, Morozov V. N., Tatarinov V. N., Kaftan V. I. Geodynamiccal aspects of investigations in underground research laboratory (Niznekansk massif). *Eurasian mining*, 2018, no. 2, pp. 11—14. DOI: 10.17580/em.2018.02.03.
26. Tatarinov V. N., Kaftan, V. I., Seelev, I. N. Study of the Present-Day Geodynamics of the NizhnekanskMassif for Safe Disposal of Radioactive Wastes. *Atomic Energy,* Springer. 2017, vol. 121, issue 3, pp. 203—207. doi:10.1007/s10512-017-0184-5.

Information about authors

Tatarinov Viktor Nikolaevich, doctor of Technical Sciences, Head laboratory, Geophysical Center, Russian Academy of Sciences (3, Molodezhnaya str., Moscow, 119296, Russia), e-mail: v.tatatrinov@gcras.ru.

Morozov Vladislav Nikolaevich, prof, doctor of Technical Sciences, Chief Researcher, Geophysical Center of RAS (3, Molodezhnaya str., Moscow, 119296, Russia), e-mail: v.morozov@gcras.ru

Kaftan Vladimir Ivanovich, doctor of Technical Sciences, Chief Researcher, Geophysical Center of RAS (3, Molodezhnaya str., Moscow, 119296, Russia), e-mail: v.kaftan@gcras.ru

Manevich Alexander Iliych, researcher. Geophysical Center of RAS (3, Molodezhnaya str., Moscow, 119296, Russia), e-mail: ai.manevich@yandex.ru

Tatarinova Tatyana Aleksandrovna, researcher, Geophysical Center RAS (3, Molodezhnaya str., Moscow, 119296, Russia) , e-mail: tata@wdcb.ru.

Bibliographic description

Tatarinov V. N., Morozov V. N., Kaftan V. I., Manevith A. I., Tatarinova T. A. Underground Research Laboratory: Problems of Geodynamic Research. *Radioactive Waste*, 2019, no. 1(6), pp. 77—89. (In Russian)