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Experience of Space Geodesy Observations at Nuclear Facilities

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Abstract—The paper reviews observations of modern crustal movements (MCMs) using global navigation satellite systems (GNSS) at nuclear facilities (NF). In 1995–2002, observations were conducted at geodynamic test sites of the Novovoronezh, Kalinin, and Rostov NPPs. Following the results of GNSS observations, a conclusion was drawn about the stability of the Kalinin NPP test site: it was recommended that design solutions take into account deformation of the Earth's surface in the north–south direction. The creation of a geodynamic test site for observing the activity of the Rostov NPP area based on GPS technology promoted the passage of a state environmental impact assessment during the launch of the first NPP reactor in 2001. In the construction area of Russia's first deep-level radioactive waste disposal site (Krasnoyarsk krai), a geodynamic test site was created to observe MCMs, and a methodology was developed for processing and interpreting geodynamic observation data taking into account the large-scale spatiotemporal effect. For the first time, for the area at the junction of the largest tectonic structures—the Siberian Platform and the West Siberian Plate—the rates of horizontal crustal deformations were instrumentally measured and the cyclical nature of the geodynamic regime was established. Observations made in 2010–2016 showed that in 2010–2013, maximum changes in distances between observation points did not exceed 10 mm/year. In 2013–2014, the tectonic regime was activated, manifested by a change in the signs of compressional and extensional strain of the upper crust on the right and left banks of the Yenisei River. The annual rates of maximum change in the lengths of baselines during the activation period reached ±18 mm. The standard horizontal and vertical errors for 2012–2016 were 3.0–3.5 and 6.0–7.4 mm, respectively. To take into account the scale factor, methodological approaches to interpreting the observational data were developed, which made it possible to assess the extent of impact of MCMs on the stability of the natural insulating properties of rock massifs while substantiating the geoecological safety of radioactive waste disposal. Based on the observation results, the boundary conditions for modeling the stress–strain state of a rock massif were established and the site of the GKhK Mining and Chemical Combine was geodynamically zoned.

Keywords: space geodesy, satellite navigation systems, nuclear facilities, geodynamics, modern crustal movements, deformations

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INTRODUCTION

Nuclear facilities[1] (NFs) are extremely hazardous for the environment and people and are therefore subject to increased geoenvironmental requirements, such as the requirement on NF sites that there should be no hazardous external impacts in the form of modern slow differentiated (exogenic and endogenic) and fast (seismogenic) crustal movements (*NP* (Norms and Rules of Gosatomnadzor), 2006; *RB* (Safety Guidelines), 2017).

After the accident at the Chernobyl NPP, the requirements for accounting for modern fast and slow movements were significantly increased. In 1995, the Ministry of Atomic Energy was created by the sectoral seismic and geodynamic safety networks (order no. 160 of November 5, 1995), providing for the expansion of geodynamic test sites at all NFs. The mass application of classical geodetic methods for observing modern crustal movements (MCMs) in the 1990s was problematic because of the difficult economic situation, but a technology appeared based on the new possibilities for determining the motion coordinates of artificial satellites with centimeter accuracy, which made it possible to employ space geodesy for geodynamic monitoring of MCMs.

In 1995, under the supervision of G.A. Sobolev, staff members of the Geophysical Center, Russian Academy of Sciences (RAS), and the Schmidt Institute of Physics of the Earth, RAS, began work on implementing GNSS at the geodynamic test sites of a

[1] The term NF pertains to nuclear facilities, storage facilities for nuclear materials and radioactive substances, facilities for storage and underground isolation of radioactive waste, and other installations with radiation-hazardous technologies.

number of NPPs. They were conducted in parallel with field work under the global international projects *Reuseg*-95 and *Reuseg*-97. At this time, geodynamic test sites were created for observing MCMs and a method was developed for GPS observations and data processing, making it possible to isolate the trend component in weakly tectonically active regions, where the rates of MCMs were nearly comparable with the instrumental accuracy of the method.

One of the first tasks in organizing GNSS monitoring was to develop guidelines on the use of GPS/GLONASS technology for solving local geodynamic problems, as well as criteria for assessing the degree of hazard of differentiated movements at localized NF sites. Therefore, below we consider the regulatory and methodological aspects of using GPS/GLONASS systems and the main results over the 20-year period of their use at NFs.

REGULATORY REQUIREMENTS FOR FORECASTING THE DEVELOPMENT OF GEODYNAMIC AND TECTONIC PROCESSES AT SITES OF NUCLEAR FACILITIES

In the existing rules and regulations on ensuring the seismological and geodynamic safety of nuclear facilities (*NP*..., 2001a, 2001b, 2003, 2006; *RB*..., 2006, 2006b, 2017; *GKINP*..., 1984, 2002, 2003), the following are regulated:

(1) the nomenclature of natural processes, phenomena, and factors, their classification according to the degrees of hazard;

(2) requirements for engineering research and studying natural processes, phenomena, and factors;

(3) classes of NF sites according to the degree of hazard of the natural processes, phenomena, and factors;

(3) requirements for monitoring natural and man-made processes, phenomena, and factors.

The documents list the geological and engineering-geological processes and phenomena that should be studied in the area and at the NF site, namely: seismotectonic discontinuous displacements, seismic dislocations, seismotectonic uplifts, subsiding crustal blocks, modern differentiated crustal movements, tectonic creep, residual seismic deformations of the crust, earthquakes, etc.

Three degrees of hazard of natural processes, phenomena, and factors have been established according to the consequences of impact on the geological setting:

Degree I—a particularly hazardous process (phenomenon, factor) characterized by the maximum parameter values and characteristics for this type of process in a given time interval and accompanied by natural and/or man-made disasters.

Degree II—a hazardous process (phenomenon, factor) characterized by rather high (but no higher than the known maximum value for this type of process) parameter values and characteristics in a given time interval and accompanied by perceptible environmental consequences;

Degree III—a nonhazardous process (phenomenon, factor) characterized by low parameter values and characteristics in a given time interval and unaccompanied by perceptible environmental consequences.

Three classes of NF placement sites are defined:

(1) class A: a site where there are no external impacts of degree I and II hazard, but there are external impacts of degree III hazard;

(2) class B: a site where there are no external impacts of degree I hazard, but there are external impacts of degree II and III;

(3) class C: a site where there are external impacts of degree I, II, and III hazard.

To reveal and identify natural and man-made processes, phenomena, and factors, engineering surveys are regulated, including *geodetic observations of modern geodynamics of faults* (italics added), including high-precision leveling and observations of the rates of MCMs based on space geodesy (*RB*..., 2017).

At an NF site, monitoring of natural processes should be carried out, as well as periodic monitoring of anthropogenic factors at all stages of their life cycle. If natural processes and phenomena of degree I and II hazard are possible at the site, including hazardous MCM rates, then monitoring systems for assessing their parameters should be set up and functioning *before an NF is commissioned* (italics added).

The limiting quantitative boundaries of MCMs are very approximate and mainly for geological methods and large time intervals:

(1) Degree 1 hazard: slip along a fault is greater than or equal to 0.3 m, the presence of geodynamic zones with a velocity gradient of Quaternary movement of 10^{-6} 1/year or more;

(2) Degree 2 hazard: movement along a fault of less than 0.3 m, the presence of geodynamic zones with a velocity gradient of Quaternary movements from 10^{-9} to 10^{-6} 1/year, etc. (*RB*..., 2002).

In JV 11-104-97, SNiP 2.02.01, the following maximum permissible values were adopted when designing the foundations of buildings and structures: relative horizontal compression or tension, 10^{-3}; tilt 3×10^{-3}; relative nonuniformity of subsidence of the Earth's surface, 6×10^{-3}; base roll, 5×10^{-3}. Available publications indicate that if the average annual rates of relative deformations reach 5×10^{-4} to 5×10^{-5}/year, these areas are zones of increased geodynamic hazard (Kuzmin, 1999).

The main parameters describing modern differentiated movements of the crust and tectonic creep are the location of active tectonic faults and regional and other ruptures, including buried ones; the length and width of fault and rupture zones; the structure of active faults; the rate of uplift and subsidence of tectonic blocks and wedges; the rate of tectonic creep in different motion regimes (stable, variable, before and after an earthquake); displacement of structural tectonic blocks; and gradient movements. The publication (*NP*..., 2001a) contains recommendations on the content of engineering surveys for identifying tectonic structures and their movements (modern differentiated movements of the crust, seismic dislocations, earthquakes, etc.).

In (*NP*..., 2001b) a definition for *active fault* is given, meaning a tectonic fault in the zone of which during the Quaternary period of geological development, relative movement of adjacent crustal blocks by 0.5 m or more occurred, *or their relative displacements at modern movement rates of 5 mm/year or more are observed* (italics added). The concept of *geodynamic zone* is also introduced (tectonic structures active in the Quaternary period of geological development), as well as *gradient tectonic movements* (a change in amplitude of tectonic movement of a mark per unit distance and time).

To assess the possibility of activation of geodynamic processes, one should consider the results of monitoring tectonic movements, operation of local seismic networks, and other geophysical, hydrogeological, and geochemical networks, as well as *specialized geodynamic test sites* at NFs.

NP (Norms and Rules of Gosatomnadzor (2001b)) outlines the requirements on monitoring the stability of the geotechnical and hydrogeological parameters of soils used in feasibility (design) studies of building foundations (structures) important for the safety of the facility and to identify negative changes in the geological engineering environment that may affect the safety and stability of the facility during construction, operation, reconstruction, and expansion.

GKINP (2003) states the necessity of determining the parameters of all possible natural processes and phenomena capable of adversely affecting the safety of radioactive waste (RW), including *the values of amplitudes, rates, and velocity gradients of tectonic crustal movements along active faults and in geodynamic active zones; the values of landslide movements on slopes, taking into account tectonic disturbances, modern geodynamic processes* (italics added), ground conditions, groundwater influence, and seismic impacts with intensities up to and including the MCE.

RB (Safety Guidelines (2002)) regulates the hierarchical levels of operations on identifying probable Earthquake source (PES) zones. It is recommended that engineering surveys of NF sites within a radius of 300 km from an NF should identify and determine the characteristics of geodynamic zones and active faults on a scale of 1 : 500000, and sites within a radius of 3 km from NFs, on a scale of 1 : 5000. In the case of a complex geodynamic situation, it is recommended to carry out engineering studies of a nearby region (point) within a radius of 30 km on a scale of 1 : 50000.

Thus, the provisions in the regulatory documents relating to geodynamic monitoring indicate the need for:

(a) *instrumental determination* of the MCM parameters (vertical and horizontal displacement velocities of the Earth's surface and their gradients) in the near field (with a radius of up to 30 km) and at NF sites (with a radius of up to 3 km);

(b) creation of *permanent geodynamic test sites* for observing the spatiotemporal features of MCMs at all stages of an NF's lifetime;

(c) detection of negative changes in the geological engineering properties and the state of the geological setting that can affect the stability of NFs, based on instrumental methods *for predicting differentiated movements and deformations of the Earth's surface* (italics added).

GNSS observations were conducted at NFs taking these requirements into account. Let us consider some of the results of GNSS MCM monitoring at NFs.

RESULTS OF MCM OBSERVATIONS AT GEODYNAMIC TEST SITES OF NUCLEAR FACILITIES

In 1995–2002, studies were conducted at the test sites of the Novovoronezh, Kalinin, and Rostov NPPs (Morozov, 2001a, 2001b; Tatarinova, 2007). At the Kalinin NPP, GNSS observations began in October 1995 (Tatarinova, 2007). Within a radius of 10 km from the NPP, large-scale observation points were placed, consisting of paired adits, one of which contains a deep benchmark in undisturbed rocks at a depth of 30 m, and the second benchmark was placed fixed in soils in the upper part of the section at a depth of 5 m. The frame design (Fig. 1) of the inverted plumb line is a concrete-encased anchor connected by a vertical iron rod to a surface mark in a steel pipe casing. Measurements were carried out with Ashtech Z-XII dual-frequency GPS-receivers and Trimble 4000 SSE GPS receivers. Since the accuracy in determining the lengths of lines (L_b) between observation points is higher than in determining the coordinates, the assessment was carried out by comparing the changes in L_b.

Figure 2 shows the average annual rate of change in millimeters in the length of lines between GNSS points from 1996 to 2002. It was found that the displacements have a preferential north–south direction. Meridional distances increased by 18 mm over a span of 5 years. Based on the results of GPS observations, a conclusion was drawn about the overall tectonic sta-

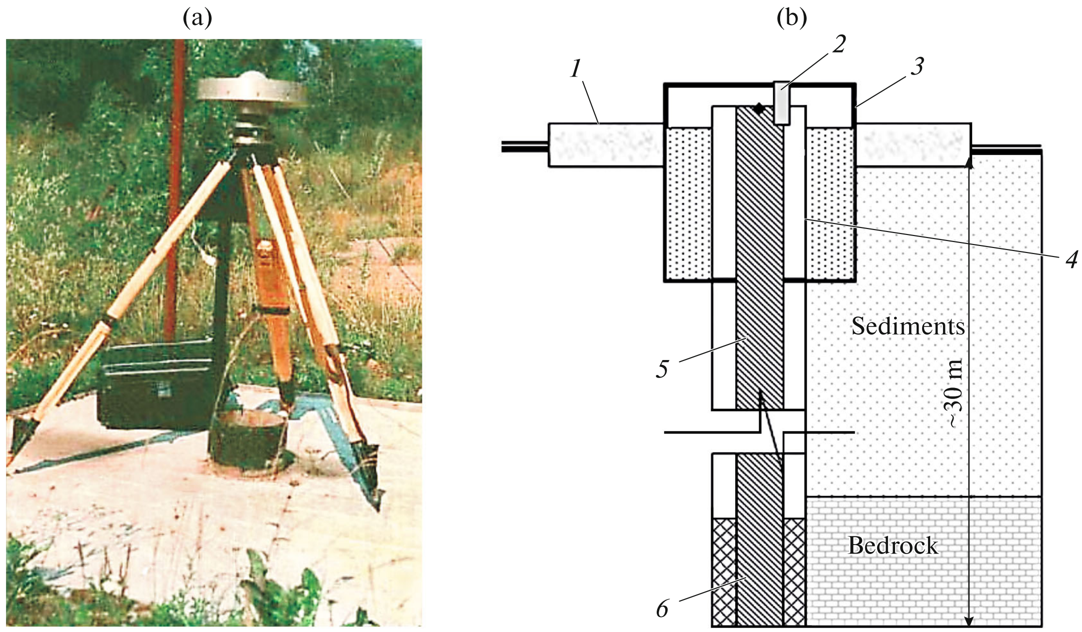

Fig. 1. GNSS observation point TA1 (a) of geodynamic network at Kalinin NPP site and observation point scheme (b): (*1*) cement area; (*2*) mounting for antenna; (*3*) protective cover; (*3*) casing; (*5*) drilling rod; (*6*) concrete-encased anchor.

bility of the Kalinin NPP site: the design solutions of the Atomenergoproekt Institute recommended attention to strain monitoring in the meridional direction, which could be caused by Valdai aulacogen structures.

For the Novovoronezh NPP, in parallel with GNSS observations, the vertical component of MCMs was measured by high-precision leveling. In the southwestern part of the site, multidirectional movements were established for tectonic faults with an offset >25 m in the last 20 ka (Morozov, 2001). A total of four GNSS observation cycles were carried out from September 1996 to October 2001. Figure 3 shows the vertical movement velocities for 1985–2001 based on leveling; Fig. 4, dilatation of the Earth's surface for 1996–2001 based on GNSS observations. The standard deviation in the calculations did not exceed 2.4 mm.

It can be seen that no significant MCMs were recorded at the Novovoronezh NPP site over 5 years. The configurations of the vertical and horizontal movement fields obtained by two independent teams and methods agree well with each other, which indirectly confirms the reliability of the results. Anomalous values were detected on the bank of the Don River and are most likely related to exogenic geodynamic processes (bank landslides).

The deformation models for the Kalinin and Novovoronezh NPP sites were introduced into the design solutions of Atomenergoproekt institutes (Moscow and Nizhny Novgorod) when validating the geodynamic and seismic stability of the sites and conducting expert examinations at the Federal Service for Environmental, Technological, and Nuclear Supervision.

The creation of a geodynamic test site and monitoring of activity of the Rostov NPP based on GPS technology also contributed to the state environmental impact assessment when the NPP's first reactor was commissioned in 2001.

At present, the construction of Russia's first deep highly radioactive waste disposal facility (DHRWDF) has commenced in the Lower Kan massif, south of the Yenisei Ridge. The task of safely removing highly radioactive waste from the biosphere has not currently been solved in any developed country. It is a unique problem, because it is necessary to guarantee the insulating properties of geological formations for the entire radiobiological hazard period of the highly radioactive waste, which is >10000 years.

As a partial solution to this problem, in 2010, a geodynamic test site was created for observing the rate of MCMs. In addition to the applied problem of predicting the lifetime of the insulating properties of rocks in the DHRWDF construction site, a fundamental result was obtained at the test site: the cyclical nature of geodynamic movements in the junction zone of the Siberian Platform and the West Siberian Plate (Tatarinov, 2014, 2015).

The main tectonic faults in the area are submeridional: the Muratov, Atamanov, Pravoberezhny, and Bolshetelsky. In accordance with the general trends of these faults, the scheme of observation points was chosen as a profile crossing the faults and the contact zone from west to east (Tatarinov, 2016) (Fig. 5).

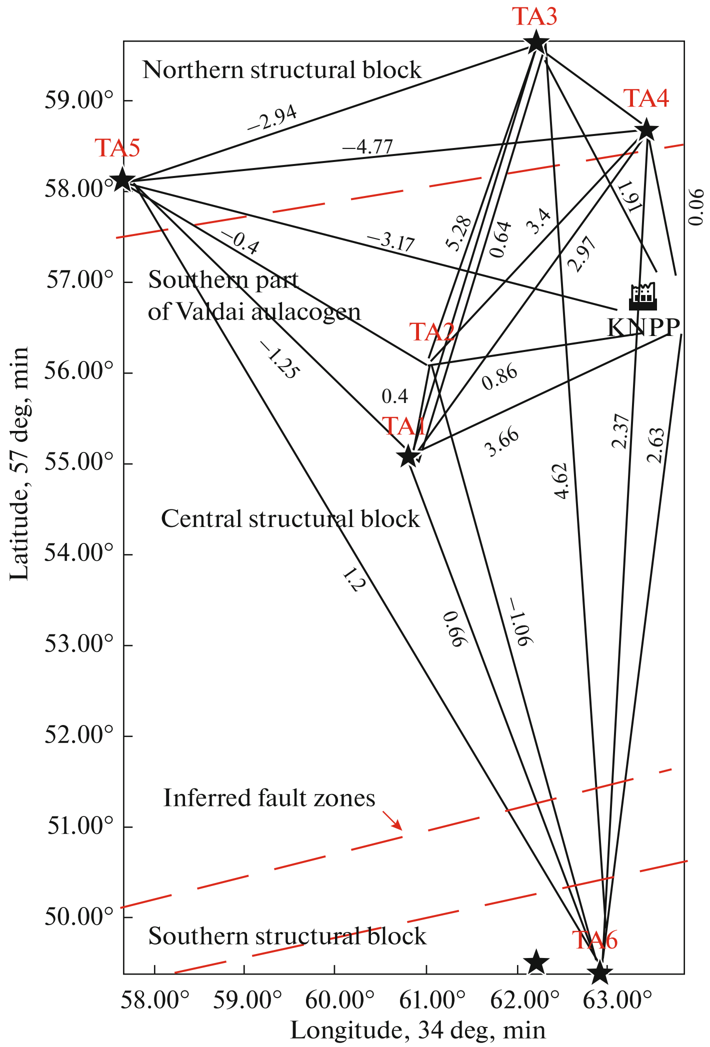

Fig. 2. Average annual rate of change in line lengths between GNSS points in mm for 1996 to 2002.

The position of the Yenisei area, within which construction of the DHRWDF is planned, has the following geological and tectonic features:

(1) It is located at the boundary of the Lower Kan massif and the Precambrian host strata; the exomorphic contact zones of magmatic bodies, as a rule, are characterized by increased fracturing and structural inhomogeneity. Not only gneisses and granitoids occur at the site, but also numerous irregular bodies, as well as dikes of mafic metamorphosed igneous rocks.

(2) The eastern edge of the area is cut off by the ancient, neotectonically activated Pravoberezhny normal fault, which forms the northeast slope of the Atamanov Ridge. The maximum offset of the faut, based on the data of (Lukina, 1999), is 400–580 m with a length of 20 km. The fault has been neotectonically rejuvenated; it was active in the Holocene and remains so (Anderson et al., 2011).

(3) The width of the Pravoberezhny faults zone of dynamic influence is from 300 m to 3 km. The Shumikhinsky strike-slip fault is located almost perpendicular to it, separating the subsided neotectonic block from the central part. Thus, these two faults divide the site into three structural blocks with different heights.

(4) The boundary of the Siberian Platform and the West Siberian Plate passes 2–3 km to the west of the area. The Muratov fault divides the territory into two parts, the plate has subsided, and the platform has been uplifted. The total vertical offset along the fault exceeds 3 mm/year, and the horizontal movement velocity based on GPS/GLONASS observations is 4–5 mm/year.

Figure 5 shows a diagram of the geodynamic test site and changes in the lengths of lines between observation points for 2010–2013. More detailed research results are given in (Tatarinov, 2014, 2016). The maximum MCM rates were recorded for the lines connecting points located in the dynamic influence zone of

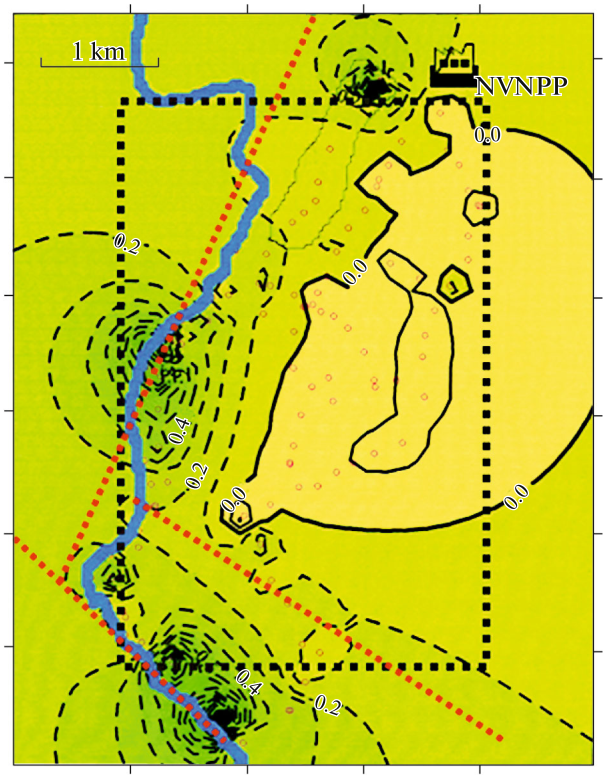

Fig. 3. Rates of vertical MCM at Novovoronezh NPP based on high-precision leveling data for 1985–2001 (black dotted line shows contour corresponding to site of GPS observations in Fig. 4).

the Muratov, Pravoberezhny, and Bolshetelsky faults. Calculation of dilatation Δ (strain rate) of the Earth's surface showed the presence of four abnormal areas:

(a) points 1204, 1205, 1206 ($\Delta = 5 \times 10^{-7}$/year), located in the zone of the Atamanovsky Fault, which is a contact suture between the Siberian Platform and the West Siberian Plate;

(b) an area on the left bank of the Yenisei River—point 1213 ($\Delta = -1.3 \times 10^{-7}$/year);

(c) compression and tension zones in the Yenisei area ($\Delta = 8 \times 10^{-8}$, $\Delta = -3 \times 10^{-8}$/year);

(d) an area near the Pravoberezhny fault, where points 1207, 1208, and 1209 are located ($\Delta = -7 \times 10^{-8}$/year).

If it is assumed that the stress has an impulsive nature, then it is more correct to focus on the rates of strain accumulated during the period of anomalous MCM values. In (Zubkov, 2002), based on the results of observations at 25 subsurface mines in the Urals, a pulse of tectonic stresses with a period of 1.5–3.5 years and an amplitude of 20–40% (10–40 MPa at depths of 400–600 m) of the measured gravitational–tectonic stress level was detected. In analogy with the possible cyclicity in the area, one can assume a similar change in stresses at the location depth of the DHRWDF: 500–600 m. If this is the case, then even with significantly smaller stress variations, due to the cyclical nature of geodynamic movements, they can have a significant impact on the stability of the insulating properties of the rock mass in the vicinity of subsurface operations of the DHRWDF.

A formula exists for calculating the limiting values of flexural deformations (Kuzmin, 2016):

$$\Theta < \frac{C\varepsilon_n}{T}, \tag{1}$$

where Θ is the average annual flexure rate; ε_n is the limiting flexural deformation; T is time; C is an empirical coefficient, which, based on the results of numerous, long-term, repeat geodetic observations, varies from 3 to 5.

Then, the limiting average-annual rates of relative flexural deformations should not exceed 5×10^{-5}–10^{-4}/year in the vicinity of the DHRWDF. Based on GNSS observations, the average annual strain rates in the region do not exceed (2–3) × 10^{-6}/year.

In (Anderson, 2001), it is emphasized that "long-term underground storage of radioactive waste is possible only outside the dynamic influence zones of active faults." This thesis was extended to the rules and regulations governing the choice of sites for the placement of NFs using Gosatomnadzor research results (*RB*..., 2002, 2017). Meanwhile, awareness of the uncertainty in estimating the size of the influence zones of tectonic faults envisages detailed studies of the specific tectonic conditions.

It is known that the dimensions of influence zones of faults depend on their lengths. Within the Lower Kan massif, the youngest faults have such zones with maximum width; e.g., the average width of the Lesser Itat fault reaches 2.1 km. The width of influence zones of faults is determined by the following relation as a function of length:

$$H\,(\mathrm{km}) = kL\,(\mathrm{km}). \tag{2}$$

The value of coefficient k on average is 0.05, but in some cases it reaches 0.08–0.1. Thus, based on this ratio, it should be recognized that the subsurface operations of the DHRWDF may theoretically be in the influence zone of the Atamanovsky Fault in the west and Right Bank in the east, as shown in Fig. 6 This will contribute to the destruction of the marginal part of the rock mass, as well as engineering barriers (bentonite, container walls) DHRWDF.

METHODOLOGICAL ASPECTS OF GNSS OBSERVATIONS AT LOCAL GEODYNAMIC TEST SITES

The experience of MCM observations at the geodynamic test sites near the locations of NFs showed that the reliability of the data largely depends on the

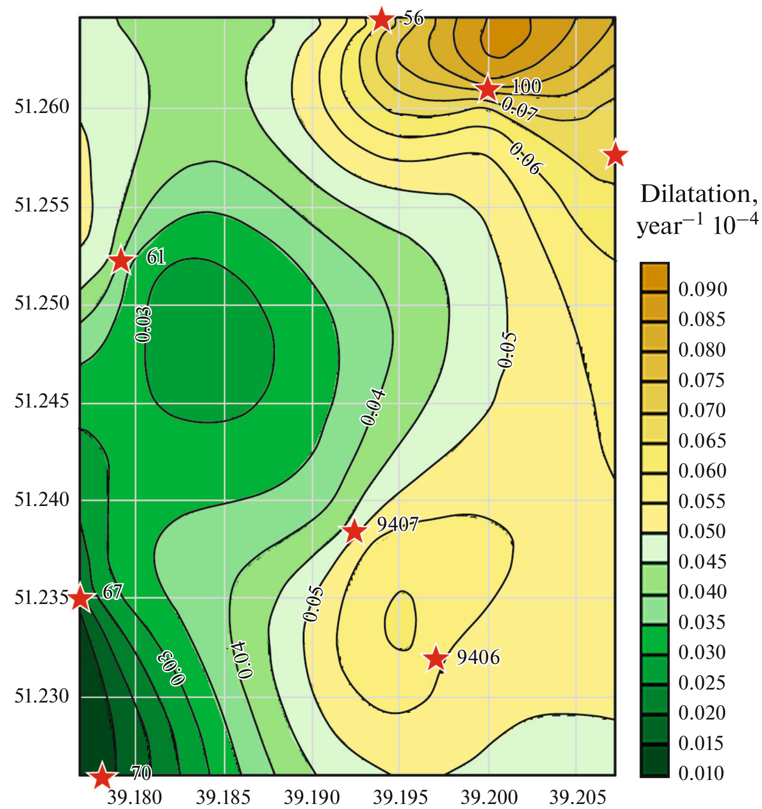

Fig. 4. Dilatation of Earth's surface at Novovoronezh NPP for 1996–2001.

operational methods, including the scheme of observation networks, field observation mode, data processing methods, etc. Therefore, in obtaining new knowledge, the methodology of GNSS observations at NFs has been constantly improved.

It is known that recorded displacements are an integral result of movements differing in scale and time of action; therefore, in interpreting them, it is necessary to take into account fundamental geodynamic laws: (a) the cyclical nature of movements; (b) the effect of decreased rates with increasing time interval for averaging the data; (c) the dependence of the movement rates and their derivatives on the distances between observation points.

The well-known success of GNSS observations on bases up to 1000 km or more created the illusion that the method is universal in solving purely local geodynamic problems, especially as applied to particularly important facilities (NPPs, radioactive waste storage facilities, hydroelectric power plants, etc.). The interpretation methodology has been massively extended from the global to the local level. In this case, interpreters adhere to two extreme hypotheses about the structure of the Earth's crust: one group uses a block model (discrete medium) (McCaffrey, 2005; Meade, 2007; etc.); the other group, a continual model (continuous medium) (Flesch, 2001, etc.). It should be noted that each group of adherents cites the results of GNSS observations as the decisive argument in defending their point of view.

However, long before the introduction of GNSS into geodynamic studies, it was known that the magnitudes and directions of recorded displacements of the Earth's surface are the result of *interference* of the force effect of various endogenic and exogenic sources of different scales and times. This is a fundamental property of the lithosphere, which Academician M.A. Sadovsky related to its hierarchical-block structure, is often ignored in GNSS observations. In the block crustal model, the boundaries of a block are faults identified as narrow zones of high-velocity MCM gradients. The distance between the observation points of the geodynamic network is usually much larger than the width of these zones; therefore, fault activity may be manifested in some cases (if the observation point is close to a fault) but not in others (Kuzmin, 1999).

This can be illustrated by the simple example in Fig. 7, where three tectonic blocks are shown conditionally: the middle block moves in a northerly direction, transferring forces to neighboring blocks and displacing them in the latitudinal direction. If we place the GPS observation points in the central block on either side of an NF, then the deformations at the time

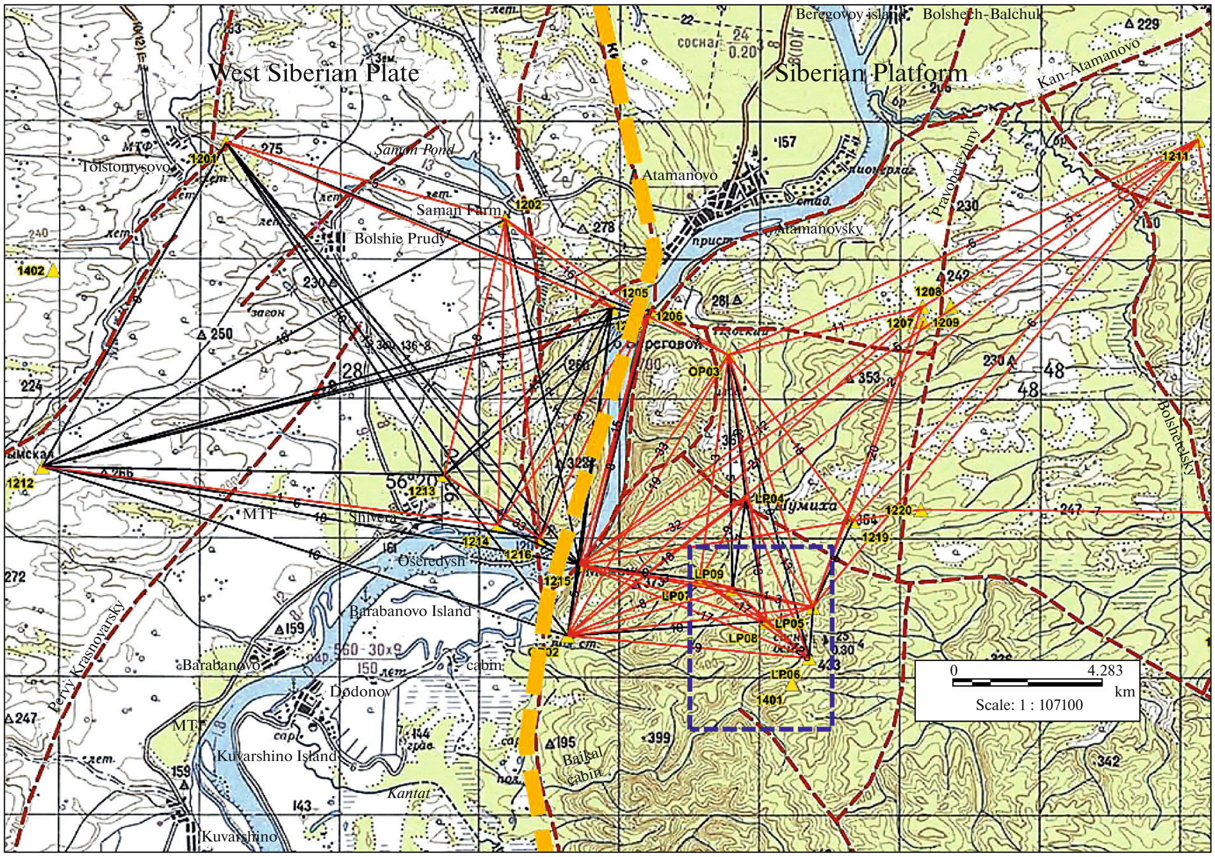

Fig. 5. Scheme of geodynamic test site in area of Lower Kan massif. Red lines show baselines, the lengths of which decreased in 2010–2013 (compression); black lines are lines the lengths of which increased (stretching). Position of Yenisei area is shown by blue dotted line; contact zone is shown by orange dotted line.

point t^1–T^0 will be 0, since the length of the base L_1 will not change. If we localize them in two adjacent tectonic blocks that have shifted in the latitudinal direction by Δx, the deformation will no longer be zero $\varepsilon = (L_2 - L_3)/L_2 = \Delta x/L_2$. Thus, our conclusions about the strain rates turn out to be scale-dependent (the length of the line connecting the observation points and crossing the block boundaries).

In a real situation, the movement kinematics of structural blocks are much more complicated when the spatial scale factor is also superimposed on the time factor (cyclical nature of movements). As seen in Fig. 8, the same strain value can be recorded for five completely different variants of the displacement directions of the observation points. In analogy with geophysics, "the inverse problem of geodynamics has several solutions in this case."

Accounting for the scale factor in interpreting GPS observations is also obvious. The use of the maximum possible strain at NF sites with a service life of up to 100 years (NPP reactors, radioactive waste storage facilities, hydroelectric dams, etc.) based on GNSS observations seems more reasonable than geological and geomorphological data, which typically provide information on time intervals of hundreds of thousands of years or more.

The study (Guseva, 1996), based on the data of repeat geodetic measurements at the local and global levels, clearly proved the pattern of reduction in the maximum values of horizontal deformations with increasing distances between observation points from meters to thousands of kilometers. Figure 9 shows the obtained distribution of the magnitudes of horizontal deformation velocities for different distances between observation points.

With these assumptions and limitations, the dependence of $|\dot{\varepsilon}|_{\max}$ on distance has been established as follows:

$$|\dot{\varepsilon}|_{\max\,\text{year}}\left[\text{s}^{-1}\right] \approx k \times 10^{-6} L^{b}\ [\text{m}],$$

where $k \approx 0.3$–3 and $b \approx -0.75$ to -0.85.

This graph can be used in solving geodynamic zoning problems to correct the strain rates when comparing distances of tens to thousands of kilometers (Tatarinov, 2006). According to the regulatory documents, when choosing locations for NFs, the sustainability of the geological setting should be analyzed in three

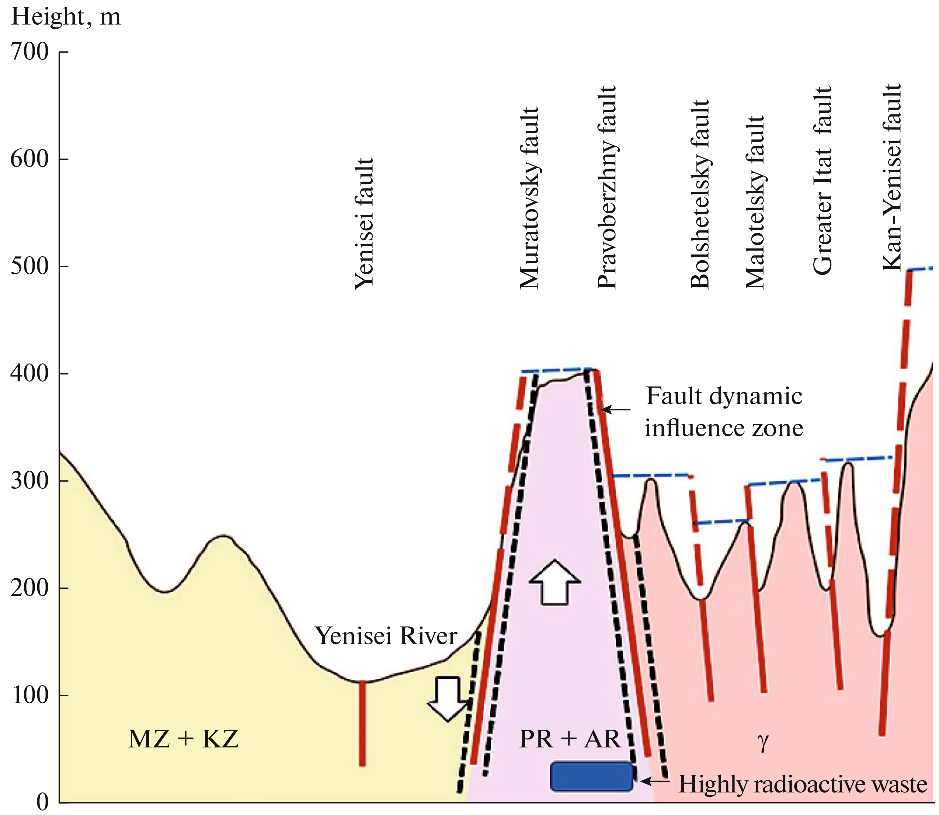

Fig. 6. Cross-sectional profile through Lower Kan massif (vertical scale is greatly enlarged), active faults are shown in red, and black dotted line indicates dynamic influence zone.

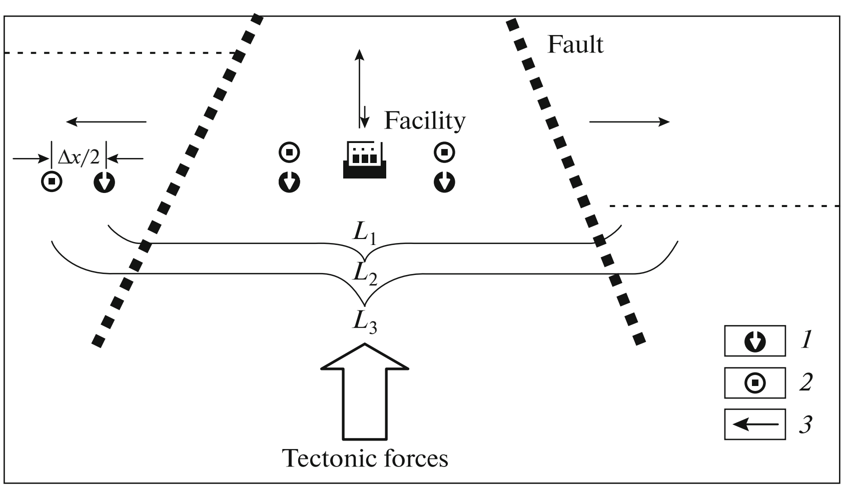

Fig. 7. Example of spatial scale effect with GPS observations: (*1*, *2*) position of point at time t_0 (*1*) and t_1 (*2*); (*3*) direction of tectonic block movement.

stages. First, the surrounding area is investigated ($L_3 = 3 \times 10^4$–5×10^4), then site ($L_2 = 3 \times 10^3$–10^4 m) and, finally, the marginal part of the rock massif ($L_1 = 1$–100 m). And at each stage, it is necessary to assess the degree of influence of MCMs and related deformations, determined from observations by GPS/GLONASS satellite systems, on the stability of NFs (*RB*..., 2017).

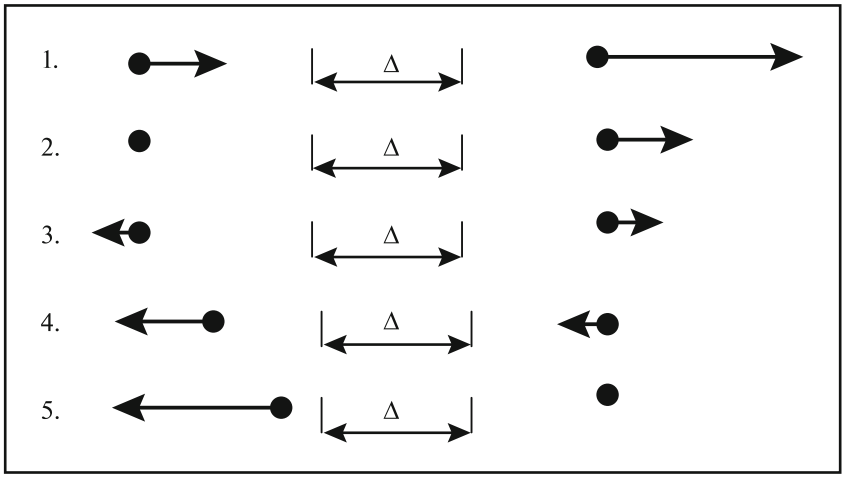

Fig. 8. Illustration of ambiguity in interpreting sources of deformations Δ for different variants of modern movements

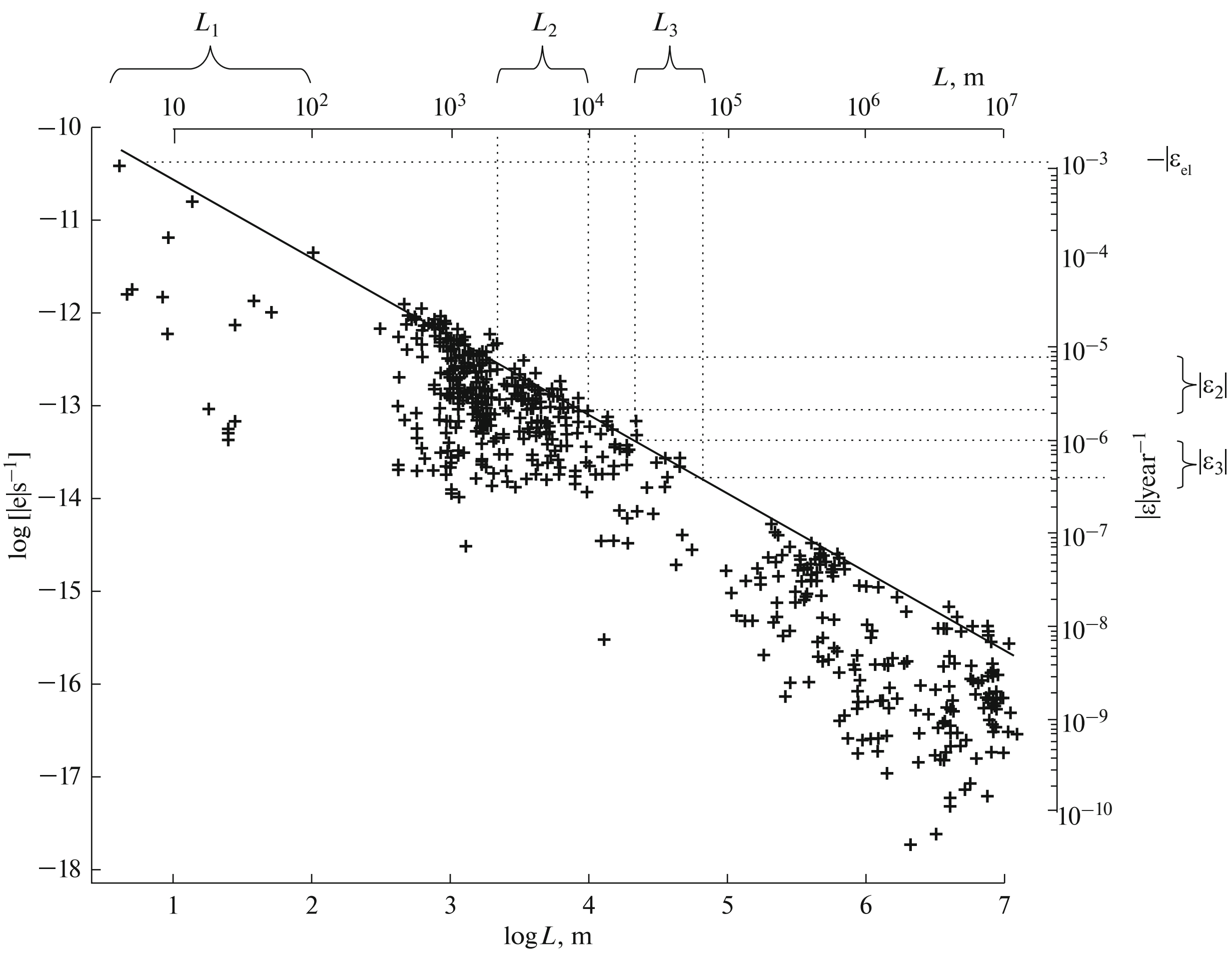

Fig. 9. Distribution of magnitudes of rates of horizontal deformations as function of distances between observation points taking into account (Guseva, 1996).

As a criterion for assessing the deformation hazard in geodynamic zoning, one can use the following estimated critical deformation values ε and their velocities $\dot{\varepsilon}$ (Fig. 9):

area $L_3 = 3 \times 10^4$–5×10^4 m, $|\varepsilon_3| = 10^{-6}$–$6 \times 10^{-7}$, $|\dot{\varepsilon}_3| = 3 \times 10^{-7}$–$10^{-6}$ year^{-1};

site $L_2 = 3 \times 10^3$–10^4 m, $|\varepsilon_2| = 10^{-5}$–$8 \times 10^{-6}$, $|\dot{\varepsilon}_2| = 3 \times 10^{-6}$–$10^{-5}$ year^{-1};

marginal part of the massif: $L_1 = 1$–100 m, $|\varepsilon_3| = 10^{-3}$–$6 \times 10^{-4}$, $|\dot{\varepsilon}_1| \geq (3$–$4) \times 10^{-3}$ year^{-1}.

CONCLUSIONS

Let us dwell on the main results of space geodesy technologies for predicting the stability of a geological setting in assessing the location and operation of NFs.

(1) In 1995–2017, an MCM monitoring system based on GPS/GLONASS was developed and implemented to measure differentiated movements of structural tectonic blocks and highlight active geodynamic zones in accordance with the requirements of the current standards and regulations of RF Gostekhnadzor for NFs.

(2) The accumulated observation experience based on GPS/GLONASS systems made it possible to correct the provisions of existing regulatory documents governing engineering surveys and studies at NF facilities. The March 2018 document (*RB*..., 2017), based on initial seismicity estimates, included GNSS observations in the mandatory set of methods for identifying geodynamic and PES zones. To assess the processes, phenomena, and factors of degree I and II hazards in the vicinity of and at NFs, the results of local monitoring observations should be applied in a timely manner. At the locations of NFs with category I and II radiation safety ratings, geodynamic monitoring of tectonic movements is recommended at specialized geodynamic test sites.

(3) When assessing the stability of the geological setting based on GNSS observations, it is necessary to take into account the large-scale spatiotemporal effect, which influences the absolute values of crustal deformation rates. The resulting kinematic characteristics of the geological setting make it possible to set boundary conditions closer to real conditions for modeling the stress–strain state.

(4) A methodology has been developed for estimating the maximum magnitude of the crustal deformation rate using GNSS observations at various scales, which allows geodynamic zoning of regions and areas hosting NFs, based on the kinematic characteristics of tectonic crustal blocks.

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