Diagnostics of changes in the stress-strain state of the massif after earthquakes by geodetic methods

A A Panzhin* and D A Koptiakov
Institute of Mining, Ural Branch of the Russian Academy of Sciences, Yekaterinburg, 620144, Russia

E-mail: panzhin@igduran.ru

Abstract. The results of diagnostics of changes in the stress-strain state of the massif during the earthquake in the region of Katav-Ivanovsk in September 2018 are presented. The data were obtained as a result of a study of regional geodynamics using permanent stations of the Global Navigation Satellite System (GNSS) of the Urals. The numerical values of the amplitudes of changes in coordinates, the distribution of displacements and deformations of the rock mass have been determined.

1. Introduction

The modern seismicity of the Ural region is mainly characterized by a large number of shallow-focus events with a magnitude of 2–3 [1, 2]. In September 2018, a series of earthquakes with magnitudes 4.2–4.5 occurred in the South Urals. The epicenter of the earthquakes was 7 km to the northwest of the city of Katav-Ivanovsk, Chelyabinsk Region, at a depth of 10 km (figure 1).

Previously, geodynamic research in the Urals was carried out mainly by geophysical methods. Deformation studies of the geodynamics of the Northern and Middle Urals by geodetic methods, according to GPS data, were first carried out under the leadership of V.I. Utkin (IGF UB RAS) in 2009–2010. When redetermining the coordinates of points of geodetic networks, the changes in the stress-strain state (SSS) of the massif was determined. Based on the results of the work performed, the following conclusions were drawn [3]:

- the Ufa ledge of the East European Platform is a tectonic formation, which continues to slowly move eastward in modern times wedging into the Ural structure;
- the movement of the Ufa ledge will inevitably occur in the future and lead to the accumulation of elastic stresses at the boundaries of the ledge, which can cause sufficiently strong earthquakes when discharging;
- it was noted the need to organize a comprehensive detailed geodynamic monitoring in the area of the Ufa ledge of the East European Platform in order to predict the possible next major tectonic event.

However, later, the monitoring of the SSS of the Urals has not been organized and studies have not been carried out by the Institute of Geophysics of the Ural Branch of the Russian Academy of Sciences by the number of reasons. Nevertheless, the Institute of Mining of the Ural Branch of the Russian Academy of Sciences has been researching regional geodynamics for several years using the...
initial data of permanent stations of the GNSS of the Northern, Middle and Southern Urals [4]. At the same time, periodic, four times a year, calculations of their spatial coordinates from IGS points in the ITRF-2014 system, determination of annual displacement rates, construction of displacement and deformation fields based on speed differences are performed.

![Scheme of the network of permanent GNSS stations in the Southern Urals in the area of the earthquake epicenter](image)

**Figure 1.** Scheme of the network of permanent GNSS stations in the Southern Urals in the area of the earthquake epicenter.

2. Research methods

In connection with the earthquake that occurred in September 2018, an experiment was carried out to diagnose changes in the stress-strain state of the rock mass in the area of Katav-Ivanovsk. The dimensions of the study area were 280x250 km. The experiment involved 9 permanent GNSS stations of the Southern Urals, using the data accumulated by the stations in the RINEX format. Cameral processing was carried out in the Bernese Software (by the Precise Point Positioning (PPP) method) and Waypoint GrafNet (by the Double Difference (DD) method) with the determination of the spatial coordinates of the points for each daily series.

A sample of the initial data was made for the period from 15.08.2018 to 15.10.2018, to record movements and deformations before, during, and after the earthquake.
The experiment program included:

- determination of the absolute coordinates of points and their changes along the coordinate axes daily, for 61 days, by referencing them from 10–12 reference points of IGS in the ITRF-2014 system;
- processing and adjustment of the GNSS network in order to study the trend movements by comparing the spatial coordinates of points obtained in various series of monitoring measurements.

3. Research results

As a result, numerical values were determined:

- daily amplitudes of changes in coordinates along three coordinate axes, amplitude and trend components before an earthquake, between series of earthquakes and after ones (figure 2);
- distribution of horizontal displacements and deformations of the rock mass in the area – in the form of displacements to the east with amplitudes of 7–10 mm (figure 3);
- distribution of horizontal deformations of the rock mass in the area – extension and compression with an amplitude of up to 2.4·10⁻⁷ (figure 4).

![Figure 2](image)

**Figure 2.** Amplitudes of changes in the spatial coordinates of the GNSS network point KTIV before and after the earthquake.
Figure 3. Horizontal displacements to the east along the axis of IGLI–KTIV stations with amplitudes of 7–10 mm.

To construct the field of horizontal displacements and deformations, the finite element method was used, as the initial data were the values and directions of the displacement vectors measured at the GNSS points.

Vertical movements were also recorded, which are manifested in the form of a uniform inclination: uplifts in the southwestern part, subsidence in the northeast. Tensile deformations were noted in the southwestern and western parts of the site at azimuths of 135° and 45°, with compressive deformations prevailing in the eastern part of the study area.

Also, according to the measurement results, the azimuth diagrams of displacements were built for all possible ΔN, ΔE, ΔH, 2D, 3D between the points of the GNSS network. Both correspondence and inconsistency have been established for the main directions of the prevailing orientations of the faults in the Ural region.
4. Research prospects

One of the promising areas of research of modern geodynamic movements of the upper part of the Earth's crust is the method of radar interferometry.

The studies were carried out on the territory of Kuzbass, where the earthquake of magnitude 4.9 occurred on August 12, 2021, at a depth of 10 km, not far from the cities of Prokopyevsk and Kiselevsk, as a result of the development of coal deposits.

A test study conducted used C-SAR images from the Sentinel-1 mission. The mission is a group of two satellites in a near-polar sun-synchronous circular orbit, performing C-band synthetic aperture radar (C-SAR) imagery in 4 data acquisition modes [5]. Scenes were selected for research and pairs were compiled covering the area of interest in the area of the earthquake epicenter. As a result, the
The seismic deformation field, located at the epicenter of the event, was identified. Figures 5a and 5b show the fields of coseismic deformations obtained from interferograms. The shape, location and values of the deformation fields are different. This is due to the difference in dates, satellite courses and angles of incidence of the interferogram axis.

![Interferogram Images](image)

**Figure 5.** Vertical displacements obtained from two pairs of images (a) and (b) with profile plots for AA' and BB'.

### 5. Conclusion

As a result of the studies, it has been confirmed that at present in the Southern Urals there is a slow movement to the east of the Ufa ledge of the East European Platform. The result of such a movement is the accumulation of elastic deformations, which can cause earthquakes when discharging.
Further directions of the research are determination of new data on the rates of displacement of points of the GNSS network of the area located in the zone of changes in the stress-strain state of the massif during an earthquake in the vicinity of Katav-Ivanovsk, for the period 2018–2019 and further years, during the period of stabilization of the geodynamic situation.

One of the directions of research is the establishment of the main characteristics of the vector field of modern movements [6], in particular divergence [7], which will determine the distribution patterns of its characteristics and identify the sources of the formation and flow of deformation processes.

Also, within the framework of the indicated experimental studies, work continues on the creation of a database of modern geodynamic movements of the upper part of the Earth's crust in the Ural region [8]. The initial data for filling the database are spatial displacements and their velocities, determined from the results of processing geodetic measurements of more than 60 GNSS points located in the Northern, Middle and Southern Urals.

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