The Algorithm for Adaptive Processing of Heterogeneous Geotechnical monitoring data

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Abstract.

When conducting geotechnical monitoring, it is necessary to timely detect early negative changes in areas of the geotechnical system to prevent emergency situations and assess the accuracy of forecasts. This article has developed an adaptive algorithm for spatio-temporal information processing of geotechnical monitoring data, which allows us to assess the trend in the stability of the geotechnical system during the bifurcation period. For early detection of negative changes and identification of mechanisms for assessing the transformation of the geotechnical system during the bifurcation period, the parameters of the data collection and processing are changed in the algorithm. These parameters change depending on the selected key zones of the components of the geotechnical system , in which hidden geodynamic processes occur and when the values of the controlled parameters of the technical condition of construction objects are exceeded. The article presents the layout of key objects of the geotechnical system distributed over the observed area. A block diagram of the adaptive processing of heterogeneous geotechnical monitoring data is presented that implements the processing and combining of heterogeneous data to predict the initial phase of development of dangerous destructive processes. The algorithm was used for geotechnical monitoring in the village of Chud in the Nizhny Novgorod region in the period from may 2018 to February 2019. The algorithm allowed to increase the efficiency of early detection of hidden destructive processes and their harbingers.

Keywords: geotechnical system, adaptive algorithm, heterogeneous data processing, bifurcation approach

1. Introduction

Intensive deformation processes are widespread in the territories of large and small cities. Their activity is provoked by both new construction and the reconstruction of existing buildings, which bring the geological environment out of equilibrium. Deformation processes are ubiquitous, but they are most noticeable in the lowlands (Kuzmin, 2014; Fedoseyev, & Yegorchenkova, 2010). Active economic activity in urban areas, underground construction, or unreasonable development of coastal areas, leads to the emergence and strengthening of dangerous geological processes (Lobazov, 2009; Osipov, & Medvedev, 1997; Sheshenya, & Kozlovsky, 2010; Smirnov, 2018). Technogenic effects of megacities and developed industrial production are associated with changes in the relief, the load on the geological environment by buildings and structures, violation of surface runoff conditions, anthropogenic increase in water cut of rocks, vibration loads from working mechanisms and moving vehicles, etc.

The combined impact of these man-made processes has a negative impact on the stability of the geological environment, and therefore urban buildings, and requires continuous geotechnical monitoring to identify and prevent emergencies.

Under geotechnical monitoring refers to a system of observations and control of the state and changes in natural and man-made conditions during the construction and operation of the facility (TBC 30-307-2002, 2002). Geotechnical monitoring is necessary to assess the reliability of the geotechnical system, accepted calculation methods and design decisions, timely detection of defects, prevention of emergency situations and assessment of the accuracy of forecasts. Geotechnical monitoring should be carried out continuously using automated systems, the basic requirements are spelled out and regulated in the standards (GOST R 22.1.12-2005; Federal law of the Russian Federation No. 384-FZ, 2009).

When assessing the stability of a geotechnical system, it is very important to identify hidden precursors of destructive processes. To do this, the geotechnical monitoring system must take into account the behavior of both the geological environment and the structures of buildings and structures themselves, since they are mutually influenced. The early identification and prediction of the initial phase of the development of dangerous geodynamic processes in the geotechnical system is an important and difficult task. However, for more effective geotechnical monitoring when analyzing the data obtained on hidden deformation processes of the geotechnical system, it is necessary to change the data collection and processing parameters. This requires the development of an adaptive processing algorithm for heterogeneous geotechnical monitoring data.

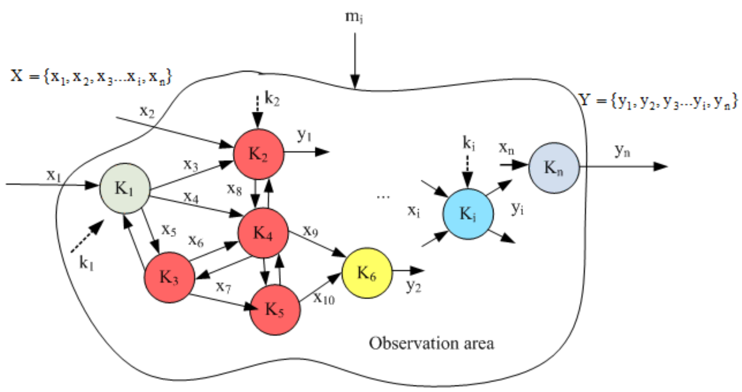
The purpose of this article is to develop an adaptive algorithm for spatio-temporal processing of geotechnical monitoring data to assess the trend in the stability of the geotechnical system based on the bifurcation approach.

2. Applied Methods and approaches

When observing in large areas and local areas, the authors propose a new approach for identifying hidden precursors of destructive processes in the geotechnical monitoring system. It is based on the identification of key areas of the geotechnical system in which hidden geodynamic processes are manifested. You do not need to monitor every component of the geotechnical system.

Figure 1 shows the layout of the key objects of the geotechnical system distributed over the observed territory.

Figure 1: Schematic layout of key objects



The components that make up the geotechnical system can be distributed over a large area. Moreover, in the geotechnical system, the state of the components K_2, K_3, K_4, K_5, K_i, K_n may depend on the state of the component K_1, and also depend on the same or similar conditions. Among the components K_2, K_3, K_4, K_5, K_i, K_n there are components that are most sensitive to changes in their input parameters, their reaction time is the lowest. Sensitivity in this case understands the noticeable response of the component to the input parameters (the strength of the connection between the components and their parameters) (Kashyap, 1983; Dorofeev et al., 2018). This does not mean that the reaction time is longer the further away the dependent component is from the influencing factors. By identifying key zones, it is possible to detect and identify hidden precursors of violations of geodynamic stability of geotechnical systems.

The key zone $K_i = \{x_i, y_i, \Delta x, \Delta y\}$ in the space of temporary geodynamic states can be described by a stochastic autoregressive model, where the current state depends on the internal geodynamic trend with depth *k* and external influence *m*.

The geodynamic process is described as follows (Grecheneva et al., 2017):

$$y[n] = -a_1 y[n-1] - \ldots - a[k]y[n-k] + x[n] \text{ or } X(z) = (1 + \sum_{i=1}^{k}\sum_{i=1}^{m} a_i z^{-i})Y(z) \quad (1)$$

Then the transfer function describing the stability condition in this key zone x_i:

$$H(z) = \frac{1}{1 + \sum_{i=1}^{k}\sum_{i=1}^{m} a_i z^{-i}} \quad (2)$$

The forecast function for the key zone of geodynamic control for the frequency range $\omega_{\max}$ $\omega_{\min}$, in spectral form, can be defined as the ratio:

$$\Psi(k) = \sum_{i=1}^{k}\left(\int_{\omega min}^{\omega \max} (H(n) - H^*(i+n))^2 \partial\omega \Big/ \int_{\omega min}^{\omega \max} (H^2(n)\partial\omega \right. \quad (3)$$

where *H(n)* is the transfer function according to preliminary data;

$H(i+n)$ the value of the transfer function that is determined as a result of regression forecasting at the current step, k=1,n.

In accordance with this approach, it is possible to determine the key points of geodynamic control in a geotechnical system based on forecast functions taking into account the *Gi* of the preliminary assessment of the control zone according to GIS data (Romanov, 2013; Dorofeev et al., 2012).

$$K_i = G_i\{\Psi(k)\} \quad (4)$$

Thus, observing the state of only the most sensitive components of the geotechnical system, it is possible to predict in advance the change in the state of similar dependent components in the study area and reveal hidden destructive processes.

To control the parameters of the engineering structure, it is proposed to analyze the angles of deviation from the vertical axis of the structure and the amplitude-frequency characteristics of vibrations (Kuzichkin et al., 2018).

To identify the direct values of the dominant natural frequencies of controlled objects using vibration velocity sensors (accelerometers), the phase-metric method of inclinometric control is used (Dorofeev et al., 2018; Grecheneva et al., 2019). The application of the phase-metric angle measurement method involves registering a time interval proportional to the angle of mutual rotation of the accelerometers. When applying the phase-metric measurement method, the output signal of the primary transducer in a rectangular coordinate system has the form (Kuzichkin et al., 2019):

$$u_x(t) = K(\varphi_x + \omega_x(t)/G) \ , u_y(t) = K(\varphi_y + \omega_y(t)/G), \tag{5}$$

where K is the conversion coefficient;

G is the reference harmonic signal;

$\omega_x(t)$, $\omega_y(t)$ is signal angular frequency;

$$\varphi_{xi}(t) = \varphi_x^*(t) + \Delta\varphi_{xi}(t) + \xi_{\varphi x}, \ \varphi_{yi}(t) = \varphi_y^*(t) + \Delta\varphi_{yi}(t) + \xi_{\varphi y} \tag{6}$$

where φ_x^*, φ_y^* – signal determined by the natural frequencies of a controlled building;

$\Delta\varphi_{xi}$, $\Delta\varphi_{yi}$ – signal determined by frequency deviation of individual structural parts of an object;

$\xi_{\varphi x}$, $\xi_{\varphi y}$ – random stationary processes that characterize noise-generating factors.

As a result of converting signals from accelerometers, a vector is formed:

$$S_a = \{u_{x1}(t), u_{x2}(t),..,u_{xn}(t), u_{y1}(t), u_{y2}(t),..,u_{yn}(t)\}. \tag{7}$$

To conduct more effective geotechnical monitoring, the controlled parameters should be recorded in the most dangerous and characteristic areas. the frequency of observations should be determined by the intensity (speed) and duration of the processes of deformation of building structures and their bases. If any deviations are recorded, the frequency of polling sensors in this network segment should increase.

Data analysis is performed on a variety of heterogeneous analyzed objects K (controlled parameters of key zones) and S (data from nodes of the sensor network). Each of the objects is characterized by a set A consisting of p attributes (predictive functions for assessing a specific zone, criterial evaluation of a control zone according to GIS data, amplitude-frequency characteristics of objects) (Bishop, 2006). Attribute is a separate measured property of an object. The a_k attribute can be represented as a function that displays the set of K_i and S_a objects in the set of valid values for this attribute $D(a_k): K \cap S \rightarrow D(a_k)$.

Depending on the set of $D_{(ak)}$ values, attributes are divided into nominal attributes that represent certain categories of the observed geotechnical monitoring component: $D(a_k) = \mathrm{B}_k\{\beta_{k1}, \beta_{k2} ... \beta_{kn}\}$ and numerical attributes of measured values represented in integer or real values. $D(a_k) = R$.

Each object is described by a p- dimensional vector of attribute values $K \in x_i$, $S \in y_i$ (Hastie et al., 2001):

$$d = (a_1(x_i, y_i), a_2(x_i, y_i),..., a_k(x_i, y_i),..., a_p(x_i, y_i)) \ \ k=1..p, i=1..z. \tag{8}$$

The entire data set D∈d is represented as an information field in a data matrix:

$$d = (a_k(x_i, y_i))^{zp} = \begin{vmatrix} a_1(x_1, y_1) & \dots & a_k(x_1, y_1) & \dots & a_p(x_1, y_1) \\ \dots & & \dots & & \dots \\ a_1(x_i, y_i) & \dots & a_k(x_i, y_i) & \dots & a_p(x_i, y_i) \\ \dots & & \dots & & \dots \\ a_1(x_z, y_z) & \dots & a_k(x_z, y_z) & \dots & a_p(x_z, y_z) \end{vmatrix} \quad (9)$$

Each row of the data matrix is called a vector, each column is called an attribute. In distributed processing and storage, data are parts of a data matrix: $d=d_1,\cup d_2\cup\ldots\cup d_n$

where d_n is the data submatrix located on the node of the n source.

$$d_1 = \begin{vmatrix} x_{1.1} & \dots & x_{1.p} \\ \dots & \dots & \dots \\ x_{z.1} & \dots & x_{z.p} \end{vmatrix} \quad \dots \quad d_n = \begin{vmatrix} x_{n+1,1} & \dots & x_{n+1,p} \\ \dots & \dots & \dots \\ x_{n+z,1} & \dots & x_{n+z,p} \end{vmatrix} \quad (10)$$

Accordingly, each data submatrix d_n is characterized by its own set of attributes A_n and a set of vectors $K_{i..n}$,$S_{a..n}$.

Figure 2 shows a block diagram of an adaptive processing algorithm for heterogeneous geotechnical monitoring data.

This algorithm includes:

- processing of data obtained when monitoring key objects in large areas and local areas of geotechnical monitoring;

- processing of data of inclinometric control obtained from a deployable sensor network.

The equilibrium points of the analyzed module and the model of the geotechnical system in accordance with the theory of bifurcation and the equilibrium position are found from expression (11), and the stability of the equilibrium positions are determined from condition (12) under the condition f ' < 0 (Rudiger, 2010):

$$f(T_{ij}, \alpha) = 0 \quad (11)$$

where f is a function that describes the relationship i and j of the parameter T_{ij}; a is the vector of model parameters.

$$f^{'}(T_{ij}, \alpha) = 0 \quad (12)$$

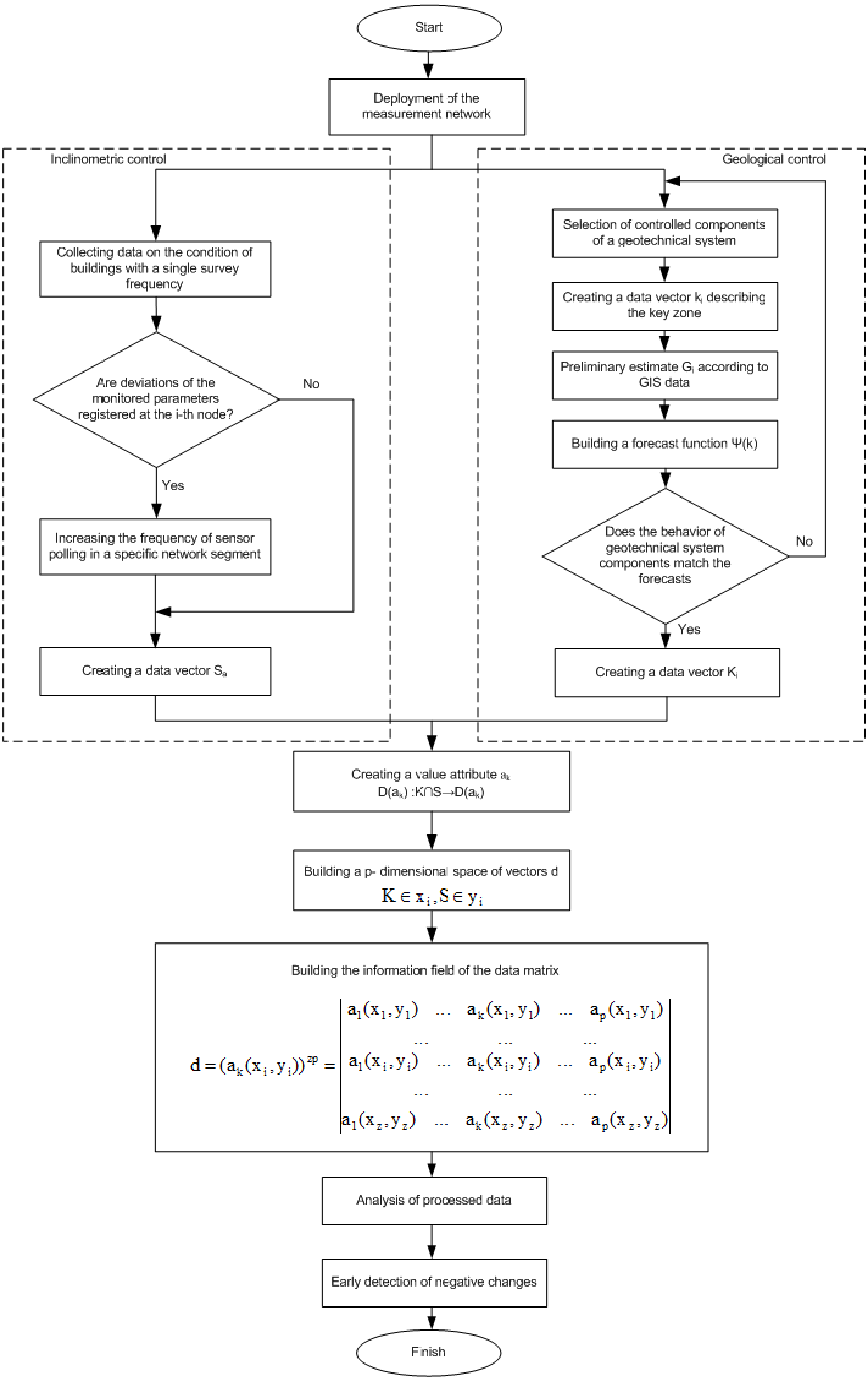
The resulting data trends of each population are evaluated in the time and frequency domains:

$$t_{out} = \int_{t}^{t+\Delta} \left(\Theta\left(\frac{|f(t) - f(t+\Delta t)|}{\Delta_f} - 1 \right) f(t+\Delta t) d\Delta t \right) \quad (13)$$

where t_{out} is the moment the trend goes beyond the permissible limits; $f(t)$ is the observed trend at time t; Δt – next point in time at an interval Δ; Θ – Heaviside function; Δ_f – permissible trend deviation.

The deviation in this case is defined as $e = t_{out} - \Delta_f$.

Figure 2: Block diagram of the algorithm for adaptive processing of heterogeneous data



Stable positions form a vector of data on the basis of which key control points are determined.

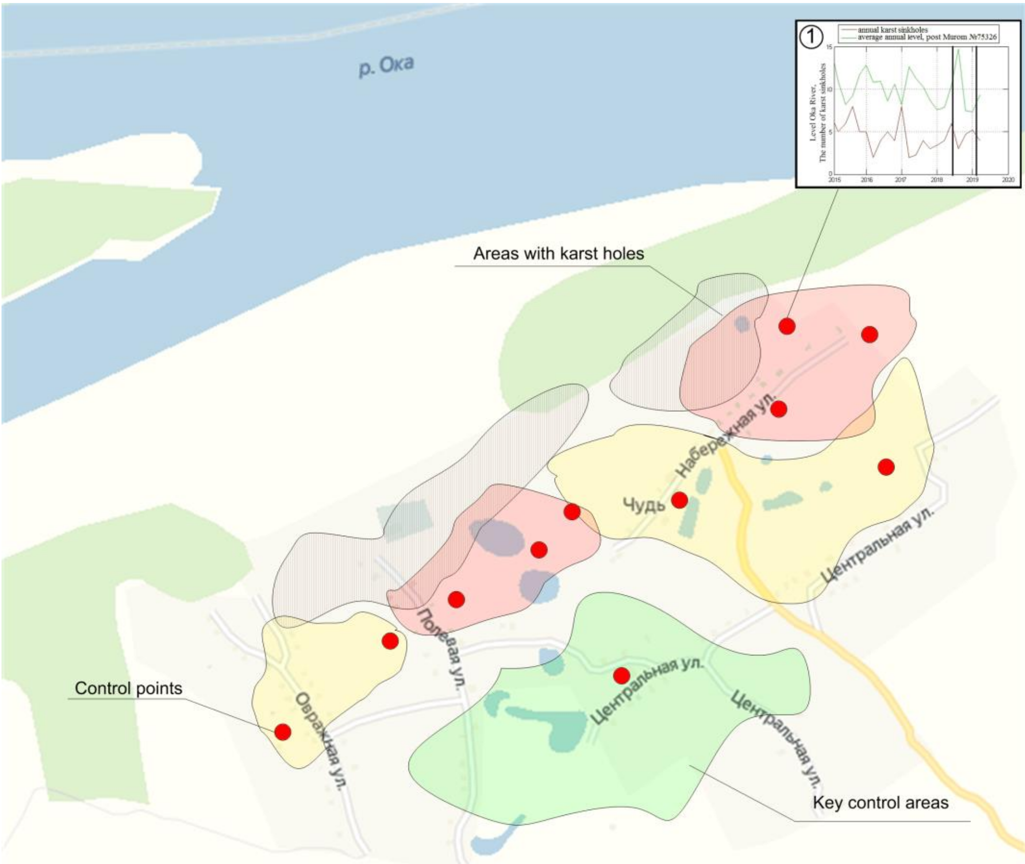
3. Results

Geotechnical monitoring was carried out in the Nizhny Novgorod region in the village of Chud. The territory is geodynamically unstable due to karst processes. These processes are especially activated during the spring flood on the Oka River. Between the time series of the annual number of sinkhole and the average annual water level in the river. Oka (the level in the Oka River above the 67.2 m BS mark) recorded at a post in the city of Murom, there is a clear, almost one hundred percent negative correlation (Figure 3).

In the period from May 2018 to February 2019, geotechnical monitoring of the territory of the village of Chud was carried out on the basis of an integrated approach with the allocation of mechanisms for assessing the transformation of the geotechnical system in the period bifurcation. To assess the trend of changes in the stability of the geotechnical system, an adaptive algorithm of spatio-temporal information processing of geotechnical monitoring data was used.

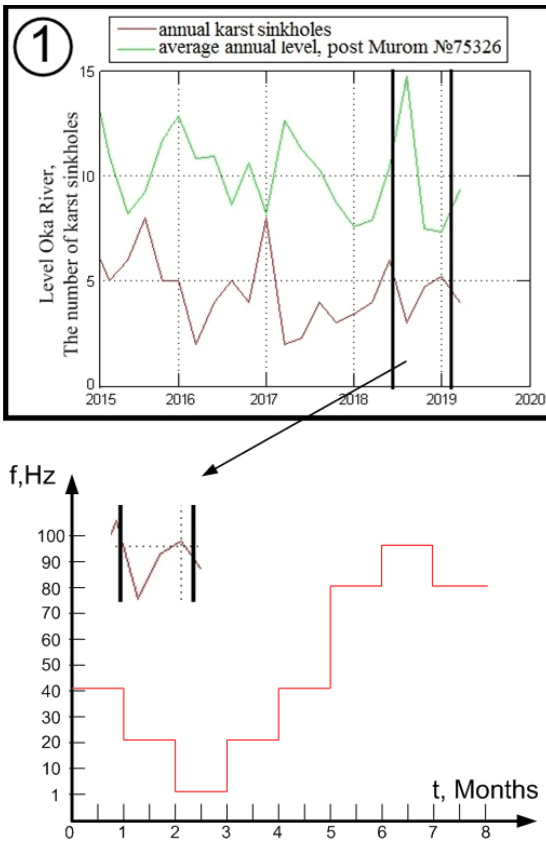
Monitoring was conducted on predefined key areas. Zones were determined on the basis of forecast functions and according to GIS data.

Figure 3: Study area for geotechnical monitoring



During periods when the level of the Oka River and groundwater decreased and karst processes intensified, the frequency of interrogation of sensors increased (Figure 4).

Figure 4: Adaptive sensor acquisition



The application of this algorithm made it possible to predict in advance the change in the state of the geological environment and geotechnical objects in the study area and reveal hidden destructive processes.

4. Discussions and conclusions

As a result, this article developed a heterogeneous data processing algorithm. The algorithm is adaptive, because on the basis of preliminary GIS data and forecast functions, key control zones and the most sensitive components of the geotechnical system are identified. This makes it possible in advance to predict a change in the state of similar dependent components in the study area and to reveal hidden destructive processes.

When you exit from the specified boundaries of the values of the monitored parameters of the technical condition of construction objects, the frequency of polling sensors in this network segment increases. Then a more detailed control is carried out, as well as informing the monitoring services about the disbalance of the geotechnical system. The algorithm was tested during geotechnical monitoring on the territory of the village of Chud and allowed to increase the effectiveness of early detection of hidden destructive processes and their precursors.

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