Improving the reliability of the results of automated forecasting of emissions in geotechnical systems based on the bifurcation approach

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Abstract. To improve the reliability of the results of automated forecasting of anthropogenic emissions into the geological environment, an adaptive algorithm for spatial and temporal information processing of geotechnical monitoring data is developed in this article. The algorithm allows us to assess the trend in the stability of the geotechnical system during the bifurcation. 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 components of the geotechnical system, where technogenic emissions occur, and when the values of controlled parameters of the technical condition of construction objects exceed the limits.

1. Introduction
Active economic activity in urbanized territories, underground construction or unwise development of coastal territories, leads to the emergence and strengthening of dangerous geological processes [1-3]. Technogenic emissions of megacities and developed industrial production are associated with the load on the geological environment, violation of surface runoff conditions, technogenic increase in waterlogging of rocks, vibration loads, and others. Negative anthropogenic emissions have an even greater and unpredictable impact on the karst territories [4]. Karst water exchange systems, in contrast to similar systems in insoluble rocks, have a high natural and anthropogenic vulnerability of groundwater resources, an extremely low ability to self-purification and dispersion of pollutants. Technogenic emissions of industrial facilities have a strong effect on groundwater, distort the development of karst-suffusion processes. The combined effect of these technogenic processes has a negative impact on the stability of the geological environment, and hence urban structures, and requires continuous geotechnical monitoring in order to identify and prevent emergency situations.

The construction of automated geotechnical monitoring systems is based on local observations of selected geodynamically active zones for assessment and geodynamic forecasting. However, when evaluating and predicting the geodynamic state of the geological environment using automated monitoring methods, unexpected geodynamic changes may be omitted due to large discretization, which may later lead to errors in forecasts and unforeseen situations.

Increasing the reliability of the results of automated forecasting of technogenic emissions into the geological environment and the development of dangerous geodynamic processes in the geotechnical system is an important and complex task. For more effective geotechnical monitoring when analyzing
the data obtained about hidden processes of the geotechnical system, it is necessary to change the parameters of data collection and processing at bifurcation points. This requires the development of an algorithm for adaptive processing of heterogeneous geotechnical monitoring data.

The purpose of this article is to develop an adaptive algorithm for spatio-temporal information processing of data to increase the reliability of the results of automated forecasting of emissions in geotechnical systems based on a 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 system. It is based on the identification of key zones of the geotechnical system in which hidden geodynamic processes are manifested. You do not need to monitor every component of the geotechnical system.

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 [5]:

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

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

\[
H(z) = \frac{1}{1 + \sum_{i=1}^{k} \sum_{j=1}^{m} a_i z^{-j}}
\]

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

\[
\Psi(k) = \sum_{i=1}^{k} \left( \int_{\omega_{\text{min}}}^{\omega_{\text{max}}} (H(n) - H^*(n+i))^2 d\omega \right) \int_{\omega_{\text{min}}}^{\omega_{\text{max}}} (H^2(n)d\omega
\]

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 [6].

\[
K_i = G_i \{\Psi(k)\}
\]

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 [7].

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 [8]. 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 [9]:

\[ u_x(t) = K(\varphi_x + \omega_x(t)/G), \quad u_y(t) = K(\varphi_y + \omega_y(t)/G), \] (5)

where \( K \) is the conversion coefficient;
\( G \) is the reference harmonic signal;
\( \omega_x(t), \omega_y(t) \) is signal angular frequency;

\[ \varphi_x(t) = \varphi^*_x(t) + \Delta \varphi_x(t), \quad \varphi_y(t) = \varphi^*_y(t) + \Delta \varphi_y(t), \] (6)

where \( \varphi^*_x, \varphi^*_y \) - signal determined by the natural frequencies of a controlled building;
\( \Delta \varphi_x, \Delta \varphi_y \) - signal determined by frequency deviation of individual structural parts of an object;
\( \xi_{xy}, \xi_{yx} \) - random stationary processes that characterize noise-generating factors.

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

\[ S_a = \{u_{x1}(t), u_{x2}(t),..., u_{xn}(t), u_{y1}(t), u_{y2}(t),..., u_{yn}(t)\}. \] (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) [10]. Attribute is a separate measured property of an object. The \( a_k \) attribute can be represented as a function that displays the set of \( K \) and \( S \) 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 \( D(a_k) \) values, attributes are divided into nominal attributes that represent certain categories of the observed geotechnical monitoring component: \( D(a_k) = B_k \{ \beta_{k1}, \beta_{k2},..., \beta_{kn} \} \) 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 \( K \times x, S \times y_1 \) [11]:

\[ d = (a_1(x_i, y_1), a_2(x_i, y_1),..., a_k(x_i, y_1),..., a_p(x_i, y_1)) \quad k=1..p, i=1..z. \] (8)

The entire data set \( D \) is represented as an information field in a data matrix:

\[ d = (a_k(x_i, y_1))^T = \begin{pmatrix}
  a_1(x_1, y_1) & a_k(x_1, y_1) & a_p(x_1, y_1) \\
  \vdots & \vdots & \vdots \\
  a_1(x_z, y_1) & a_k(x_z, y_1) & a_p(x_z, y_1)
\end{pmatrix} \] (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: \( d = d_1 \cup d_2 \cup ... \cup d_n \), where \( d_n \) is the data submatrix located on the node of the \( n \) source.
Accordingly, each data submatrix $d_n$ is characterized by its own set of attributes $A_n$ and a set of vectors $K_{1:n}, S_{1:n}$.

Figure 1 shows a block diagram of an adaptive processing algorithm for heterogeneous geotechnical monitoring data.

![Block diagram of the algorithm for adaptive processing of heterogeneous data.](image)

**Figure 1.** Block diagram of the algorithm for adaptive processing of heterogeneous 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 $f' < 0$ [12]:

$$f(T_{ij}, \alpha) = 0$$  \hspace{1cm} (11)

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

$$f'(T_{ij}, \alpha) = 0$$  \hspace{1cm} (12)

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

$$t_{out} = \int_{t}^{t+2\Delta t} \Theta \left( \frac{|f(t) - f(t + \Delta t)|}{\Delta f} \right) f(t + \Delta t) d\Delta t$$  \hspace{1cm} (13)

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

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

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

3. Results and conclusion

Geotechnical monitoring was carried out in the Nizhny Novgorod region in the village of Chud. The territory is geodynamically unstable due to karst processes. The source of groundwater pollution characteristic of the studied territory of the village of Chud is the unauthorized release of municipal solid waste into the geological environment. Landfills are formed in natural depressions-ravines, sinkholes. During the spring flood period, surface and ground water accumulates in the areas of karst formation. Pollutants are filtered with surface water and precipitation and enter underground water used for non-centralized water supply, changing their chemical composition and increasing the overall mineralization and aggressiveness to karst rocks.
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. Figure 2 shows adaptive data collection in the study area.

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 zones. Zones were determined on the basis of forecast functions and according to GIS data. In periods when the level of the Oka River and groundwater decreased, and karst processes intensified, the frequency of polling of sensors increased. 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 to identify technogenic emissions and hidden destructive processes.

Acknowledgments
This paper is an output of the science project executed with the support of the grant of the President of the Russian Federation No. MD-1800.2020.8

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