The Algorithm for Complex Processing of Heterogeneous Data at the Local Level in an Automated Geotechnical Monitoring System*

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Abstract. The paper analyzes features of the organization of automated systems of control and monitoring parameters of geotechnical systems. The authors describe a generalized structural scheme of the interaction of the geotechnical system and the environment. The applied approaches briefly describe the processing and analysis of the measured data. The authors propose an algorithm for the complex processing of heterogeneous data at a local level based on a bifurcation approach to assessing the significance of the analyzed parameters. This algorithm should increase the efficiency of automated systems for monitoring and controlling the parameters of geotechnical systems. The geotechnical system stability assessment is carried out based on a modular approach and analysis of bifurcation points. The authors describe an algorithm of choosing key points of control, conduct the results of the practical verification of the developed algorithm, and compare its results with the previous processing algorithm results. Based on the analysis results, they conclude the development and possibility of using the developed algorithm for the complex processing of heterogeneous data.

Keywords: Monitoring · Geotechnical system · Complex processing · Modular approach · Bifurcation

1 Introduction

Currently, technical means of automation, monitoring, and control are rapidly introduced in all sectors. Automated monitoring systems identify and control hidden and unpredictable processes at the important military, industrial, and civilian facilities by intelligent sensors and subsystems of technical vision. However, technical facilities alone will not solve the problem of detecting and predicting adverse conditions in a controlled system without using specialized methods and algorithms to collect, process, and analyze measurement information.

This is especially noticeable in automated geotechnical monitoring systems. The efficiency of monitoring systems of this class remains at a low level due to the complex and poorly studied processes occurring in geotechnical systems. It is confirmed by accidents and natural and human-made disasters constantly occurring in geotechnical systems (Inozemtsev & Redkov, 2017; Sosunov, 2010; Telichenko, Gutenev & Slesarev, 2006). Thus, the urgent goal is to develop new methods, models, and algorithms that recognize a negative change in geotechnical systems at early stages.

The research aims to reduce the risk in making managerial decisions and increase the automated geotechnical monitoring systems efficiency. It could be achieved by developing the algorithm of the complex processing of heterogeneous data of geotechnical monitoring at a local level based on the bifurcation approach.

Geotechnical systems are the dynamic system of interacting technical, natural (components of the geological environment), and natural-technical components. Their composition and parameters are varied. The scale of geotechnical systems is varied from the locative (within the same building or enterprise) and local levels (small area or city) to the regional level. Geotechnical systems are open systems – they interact with the environment (Fig. 1) (Dorofeev, 2017).

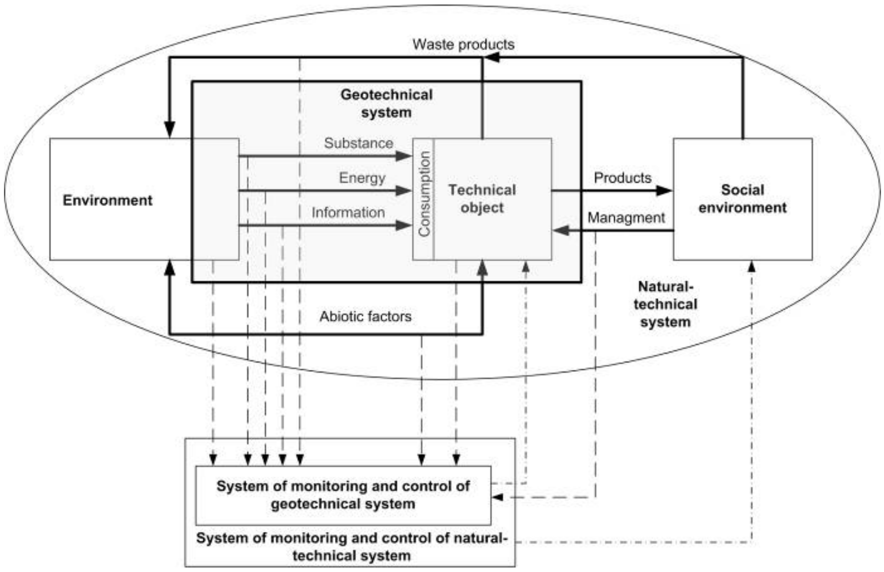

Fig. 1. The generalized structural scheme of the interaction of the geotechnical system with the environment. *Source:* (Dorofeev, 2017).

Geodynamic processes (internal or endogenous, and external or exogenous) influence the state of the geotechnical system. These processes can occur in the geotechnical system or the environment. It should be noted that some geodynamic processes are cascading in nature – the development of some adverse geodynamic processes provokes the development of other adverse geodynamic processes.

The implementation of the monitoring and control parameters in geotechnical systems has the following features:

- The need to control a large number of heterogeneous spatiotemporal parameters of the geotechnical system;
- The limited volume of measuring equipment and, as a result, the limited set of monitored parameters that are measured at a finite number of measurements points;
- The estimation of parameter values between measuring points is based on the theory of function approximation, numerical methods of analysis, probability theory, and statistics, as well as based on the use of indirect control methods (geophysical and geotechnical), which allow one to obtain averaged or apparent values;
- Management decisions are made based on measurement information and applied models, the adequacy of which is not always sufficient and may decrease over time due to the inappropriate reflection of changes in the geotechnical system in them;
- The automated collection, processing, and analysis of information are combined with a manual way of making and executing management decisions;
- The quality of the entire monitoring and control system of geotechnical systems is deteriorating due to the presence of the human factor, administrative and legal problems.

Thus, various errors and mistakes occur when evaluating the parameters of the geotechnical system, adoption, and implementation of control decisions. In this case, the generalized structural scheme of the monitoring and control system of geotechnical systems is presented as follows from the geo-cybernetic approach point of view (Bondarik, 2012; Kostarev, Sereda & Mikhailova, 2013) (Fig. 2).

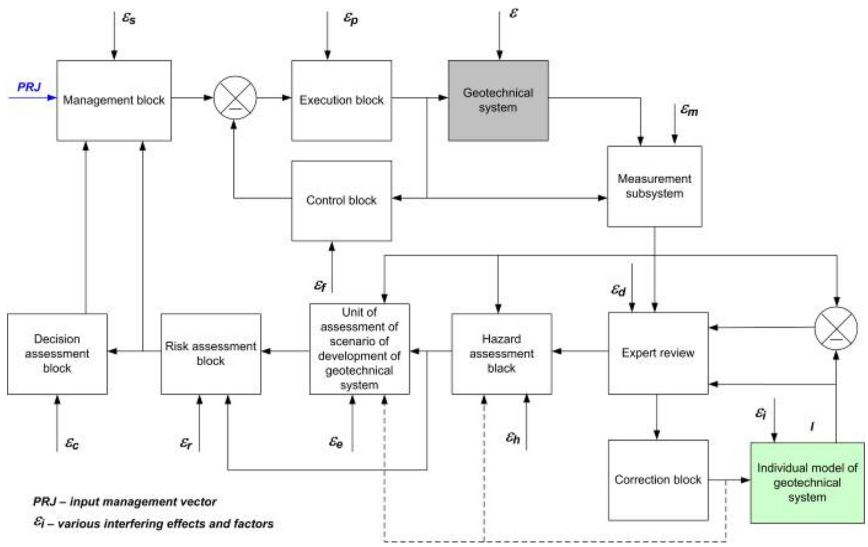

Fig. 2. The generalized structural scheme of the monitoring and control system of

geotechnical systems. *Source:* Compiled by the authors.

Automated systems control the stability of the geotechnical system and its individual components in several ways:

- Based on an assessment of changes in the state of engineering facilities foundations and adjacent territory. The disadvantage of this approach is the late identification of negative changes in the geological environment;
- Based on forecast estimates of the development of adverse geodynamic processes and risks of geotechnical stability disturbance. The disadvantage is the weak accounting of changes in the state of engineering objects.

Thus, these shortcomings of automated systems do not allow predicting sudden changes in the geotechnical system in advance, which leads to beyond design basis emergencies.

2 Materials and Methods

Methods of quantitative, qualitative, and probabilistic-statistical assessment of the geotechnical system state and its forecasting are applied when processing and analyzing the measurement results. In practice, one uses complex data processing and analysis methods, including various types of modeling (deterministic, stochastic, and mixed), system analysis, graph theory, and theory of dynamical systems (Benuj, 2010; Sainov, 2019; Vitiuk, 2012).

Data processing is carried out to obtain more reliable values of the geotechnical system parameters and identify new relationships and dependencies that are not considered when modeling at the analysis stage. In this case, the detection of dangerous geotechnical processes and, accordingly, the violation of the stability of the geotechnical system occurs by analyzing the vector of regulation errors (Inozemtsev & Zhestkova, 2018; Mikhnevich, Bogoslavchik & Volodko, 2013; Petrochenko & Petrochenko, 2019; Shipovsky & Tsivinsky, 2012) (Fig. 2).

The research proposes to use a modular approach as the algorithm for processing heterogeneous data to assess the stability of the geotechnical system, its individual components, and bifurcation points to use as stability criteria (Inozemtsev, Inozemtseva & Strelnikova, 2012; Nazarov, 2015; Poluyanov, 2011; Potapenko, 2017; Pradhan & Guha, 2019). Fig. 3 presents the generalized block scheme of the algorithm of the complex processing of heterogeneous data of the geotechnical control.

Following the modular approach, the analyzed section of the geotechnical system is presented in the form of a structure based on unitary modules. In this process, the controlled parameters of the geotechnical system area and the transfer functions of each module are determined. In this case, the interaction of modular components is represented by the vector:

$$\boldsymbol{I} = (\boldsymbol{P}, \boldsymbol{R}), \tag{1}$$

where:

$\boldsymbol{I}$ – the vector that describes the state of the geotechnical system;
$\boldsymbol{P}$ – the vector that contains the current values of the analyzed parameters provided $\boldsymbol{R_{ij}} \neq \varnothing \Rightarrow \boldsymbol{P_i} \in \boldsymbol{I}$;
$\boldsymbol{R}$ – the vector that describes the state of the relationship between the components of the geotechnical system based (2).

$$\boldsymbol{R_{ij}} = (\boldsymbol{T}, \boldsymbol{A}, \boldsymbol{Ch}, \boldsymbol{M}, \boldsymbol{E}), \tag{2}$$

where:

$\boldsymbol{R_{ij}}$ – the vector that describes the relationship between the *i*-th and *j*-th parameter. Wherein $\exists\ \boldsymbol{R_{ij}} \neq \varnothing \Rightarrow \exists\ \boldsymbol{R_{ji}} \neq \varnothing$ otherwise $\boldsymbol{R_{ij}} = \boldsymbol{R_{ji}} = \varnothing$;
$\boldsymbol{T}$ – the vector that describes the type of connection;
$\boldsymbol{A}$ – the vector that defines communication properties;
$\boldsymbol{Ch}$ – the vector that describes communication parameters;
$\boldsymbol{M}$ – the vector that describes possible effects on communication;
$\boldsymbol{E}$ – the vector that describes the stage of processes that are activated when the connection changes.

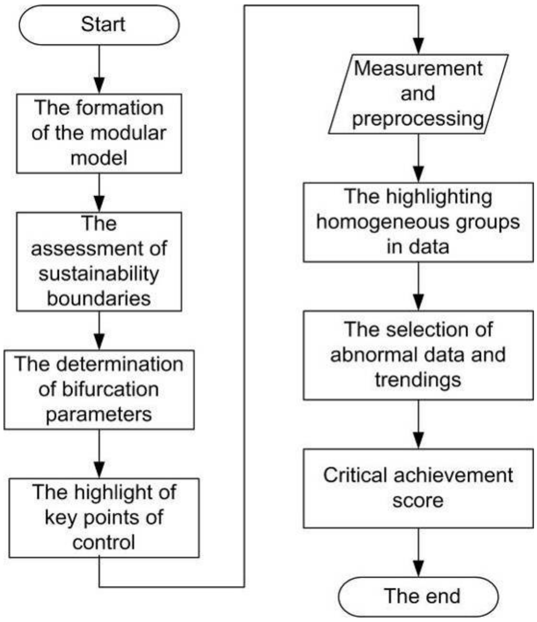

Fig. 3. The generalized block scheme of the algorithm of the processing of heterogeneous data of the geotechnical monitoring. *Source:* Compiled by the authors.

The stability condition of each module is estimated based on the following expression:

$$H(z) = 1 \Big/ (1 + \sum_{i=1}^{n} a_i z^{-i}) \quad , \qquad (3)$$

where:

$H(z)$ – a module transfer function;
a – model parameters;
z – complex variable.

It is necessary to study the behavior of individual modules and model for all possible parameter values since the last one is included in the model and the number of significant parameters for frequent is not known. In this case, the equilibrium points of the analyzed module and the geotechnical system model are determined according to the bifurcation theory. The equilibrium positions are found from formula (4), and the stability of the equilibrium positions are determined from condition (5) under the condition f ' < 0:

$$f(\boldsymbol{T_{ij}}, \boldsymbol{\alpha}) = 0, \qquad (4)$$

where:

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

$$f'(\boldsymbol{T_{ij}}, \boldsymbol{\alpha}) = 0, \qquad (5)$$

Stable positions form the vector $\boldsymbol{S_{ij}}$ based on which the key control points are determined by the algorithm indicated in Fig. 4.

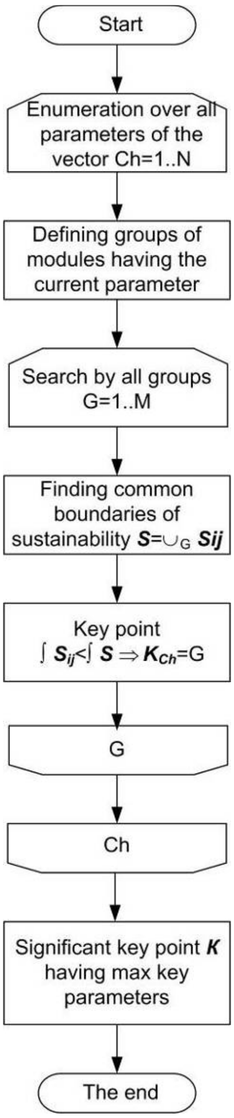

Fig. 4. The algorithm of the selection of key points. *Source:* Compiled by the authors.

Measurements are made at key control points by critical parameters after compiling the basic model of the geotechnical system, determining the main parameters of monitoring, and the stability of individual areas and the entire geotechnical system. The measured data undergo a quick exploratory analysis to obtain the distribution structure and uniformity of the data, to detect anomalous data after the initial processing, including the stages of electrical conversion, filtration, etc.

The division into homogeneous populations is based on the distance analysis of the currently measured data from the average value of the available sample:

$$\left\| x - \overline{x} \right| - D_i \right| \leq \Delta_i \Rightarrow x \in X_i \quad , \tag{6}$$

where:

x – current measurement;
$\overline{x_i}$ – mean of X_i aggregate;
D_i – data variance in X_i aggregate;
i – the number of the aggregate;
Δ_i – set deviation threshold.

In the formed aggregates, the distribution structure is analyzed for the presence of anomalous data and distribution asymmetry based on the median, lower and upper quartile, and interquartile range.

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

$$t_{out} = \int_{t}^{t+\Delta} \left(\Theta\left(\frac{|f(t) - f(t+\Delta t)|}{\Delta_f} - 1 \right) f(t+\Delta t) d\Delta t \right), \tag{7}$$

where:

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

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

In spectral form, assessment of the trend over the acceptable limits is determined following the formula:

$$F(k) = \sum_{i=1}^{k} \left\{ \int_{\omega_{\min}}^{\omega_{\max}} \left(H(n) - H^*(i+n) \right)^2 d\omega \Big/ \int_{\omega_{\min}}^{\omega_{\max}} \mathrm{H(n)}^2 d\omega \right\}, \tag{8}$$

where:

$H(n)$ – a transfer function of the module according to preliminary data;
$H(i + n)$ – the value of the transfer function in step $i + n$; k = 1..n;
ω_{min}, ω_{max} – a minimum and maximum frequency.

The authors checked measured data, including those related to abnormal and average values for proximity to critical parameters' values. At the same time, an assessment is made of the rate of change in trends and its approximation to the stability boundaries.

If the measured parameters are closer to critical values than acceptable, the frequency of anomalous data increases and the trend approaches acceptable tolerance limits, then one should carry out expert analysis of suspicious sections of the geotechnical system and correct models in case of a false positive of the automated system.

3 Results

The proposed algorithm was tested based on processing data on fixing the development stages of technogenic origin's suffusion process with a diameter of 4 meters (Fig. 5). These data are obtained in the research of 2018 (Dorofeev, Kuzichkin, Grecheneva & Baknin, 2018).

Fig. 5. The resulting failure at the site of the development of suffusion. *Source:* (Dorofeev, Kuzichkin, Grecheneva & Baknin, 2018).

The development stages of the suffusion process were periodically recorded by the OKO-2 georadar with a sounding frequency of 90 MHz (Fig. 6), relying on the results of the operation of the phasometric geodynamic control system (Fig. 7).

It was possible to simulate the appearance of a failure at an earlier stage (Fig. 8) due to applying an algorithm based on the bifurcation approach with the identification of the most significant parameters.

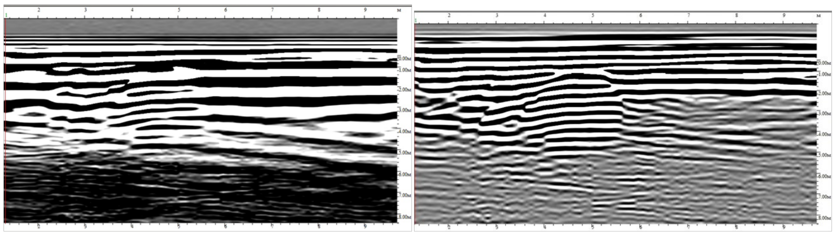

Fig. 6. The example of georadarogramm of the development of the suffusion. *Source:* (Dorofeev, Kuzichkin, Grecheneva & Baknin, 2018).

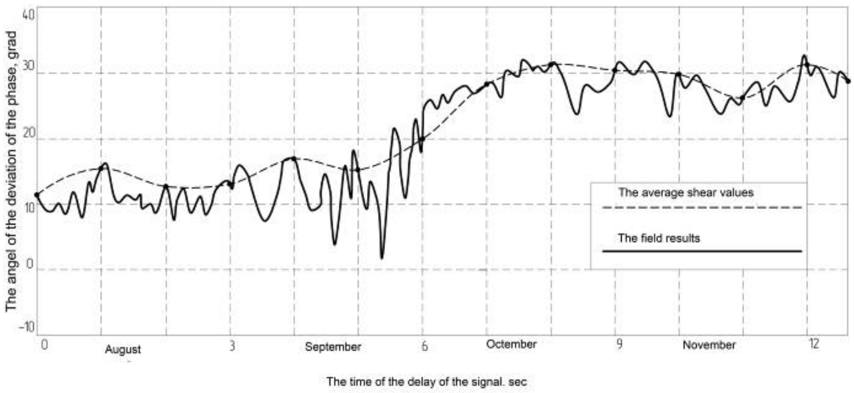

Fig. 7. The results of the phase monitoring system. *Source:* (Dorofeev, Kuzichkin, Grecheneva & Baknin, 2018).

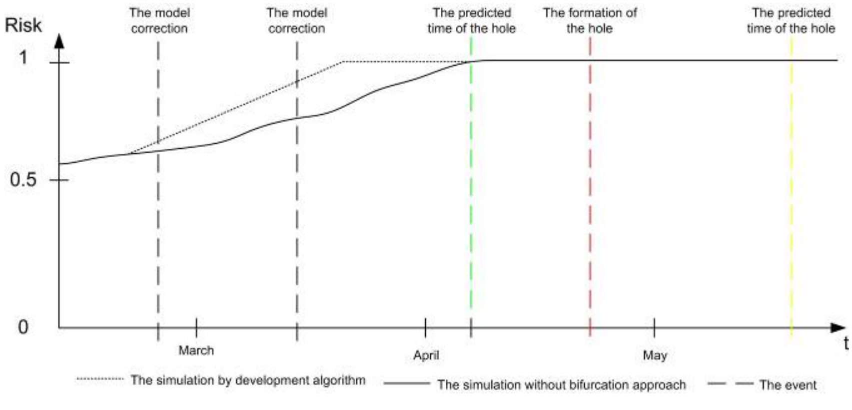

Fig. 8. Result of simulation. *Source:* Compiled by the authors.

4 Discussion

It should be noted that models and the period of monitoring work were corrected twice (measurement period) in predicting the development of suffusion by the old algorithm. Application of the developed algorithm was carried out without model correction based on the bifurcation approach to allocate significant parameters. Although the formation of failure was predicted at an earlier stage, the proximity of forecast estimates to the real situation is better with the old algorithm. A premature failure decision may be associated with using crude models of the geological environment and the development of suffusion processes.

5 Conclusion

Thus, it is possible to use the developed algorithm based on the bifurcation approach to improve the efficiency of automated systems of geodynamic control. However, more research is needed to test the developed algorithm. Besides, the improvement of the developed algorithm is possible by timely correction of the model data.

Acknowledgments

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References

Benuj, A. A. (2010). A model for assessing the quality and forecasting the state of the environment by a system of differential equations. *Vestnik MGSU*, *2*, 105-109.

Bondarik, G. K. (2012). Geokibernetika – A tool for diagnosing and predicting the state of natural and natural-technical systems. *Geoecological, Enginering Geology, Hydrogeologycal, Geocryology*, *4*, 364-370.

Dorofeev, N. V. (2017). Generalized informational structural diagram of natural-technical systems. *Information Systems and Technologies*, *1*(99), 5-12.

Dorofeev, N. V., Kuzichkin, O. R., Grecheneva, A. V., & Baknin, M. D. (2018). The forecasting of the development of suffosion processes in urban on the basis of the geoelectric modeling by the data of the phasometric system of the geodynamic control. *International Journal of Engineering and Technical (UAE)*, *7*(4.7), 268-275.

Inozemtsev, V. K., & Zhestkova, S. A. (2018). General stability of a system with a high center of gravity. *Bulletin of the Volga Regional Branch of the Russian. Academy of Architecture and Building Science*, *21*, 156-159.

Inozemtsev, V. K., & Redkov, V. I. (2017). Geotechnical problems of the construction and operation of buildings in landslides with landslide processes. *Bulletin of the Volga Regional Branch of the Russian. Academy of Architecture and Building Science*, *20*, 170-179.

Inozemtsev, V. K., Inozemtseva, O. V., & Strelnikova, K. A. (2010). The bifurcation criterion for stability of the “object-base” system based on the incremental base model. *Construction. and Reconstruction*, *27*(1), 16-22.

Kostarev, S. N., Sereda, T. G., & Mikhailova, M. A. (2013). Development of an automated monitoring and management system for natural-technical waste disposal systems. *Fundamental Research*, *6*(2), 273-277.

Mikhnevich, E. I., Bogoslavchik, P. M., & Volodko, E. A. (2013). Ensuring the stability of the slopes of the dubm for flood protection on the Goryn River. *Science and Technics*, *5*, 39-44.

Nazarov, D. I. (2015). Destruction of the structures of the mining building, energy and bifurcation analysis. *Mining Inf. and Analytical Bulletin (Science and Technic. Journal)*, *7*, 95-100.

Petrochenko, V. I., & Petrochenko, A. V. (2019). Optimization of design solutions for flood protection in river basins. *Reclamation*, *88*(2), 26-33.

Poluyanov, V. P. (2011). Scenarios of the development of energy phenomena in natural and technogenic processes. *Bulletin of the Belgorod State Technological University*, *4*, 156-160.

Potapenko, A. V. (2018). The use of a synergistic approach to the tasks of territorial planning. In G. I. Rogunova (Ed.), *Collect. of Science papers of the Russian. Academy of Architecture and Building Science. Fundamental, search and applied research RAASN on Scientific support of architecture, urban planning and construction industry of the Russian Federation in 2017* (pp. 501-508). Moscow, Russia: ASV Publishing House.

Pradhan, K., & Guha, A. (2019). Fluid dynamics of a bifurcation. *International Journal of Heat and Fluid Flow*, *80*, 1-29.

Sainov, M. P. (2019). Methodology for modeling nonlinear deformation of dam soils. *Bulletin of the Volgograd State University of Architecture and Civil Engineering. Series: Construction and Architecture*, *75*(2), 20-36.

Shipovsky, K. A., & Tsivinsky, D. N. (2012). Optimization of the drilling of directional and horizontal wells based on monitoring of technological, geological and geophysical parameters. *Construction of Oil and Gas Wells on Land and at Sea*, *11*, 9-15.

Sosunov, I. V. (2010). *Actual issues of emergency prevention, scientific and methodological publication*. Moscow, Russia: Institute of Civil Defense and Emergencies.

Telichenko, V. I., Gutenev, V. V., & Slesarev, M. Yu. (2006). Approaches to the interpretation of environmental safety management systems in construction. *Ecology of Urbanized Territories*, *2*, 6-11.

Vitiuk, E. Yu. (2012). *Mathematical methods in architectural theory.* Yekaterinburg, Russia: Architecton.