The Method of the Registration of Parameters of a Geotechnical System Based on Data of the Technical and Economic Analysis

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Abstract.

This article proposes the method of the registration of the parameters of a geotechnical system. This method is designed to increase the efficiency of the functioning of geotechnical monitoring systems in the condition of the risk of the disturbance of the geodynamic stability and in the condition of technical and economic restrictions when monitoring works are organized. The proposed method allows you to select the technical parameters of the monitoring system and it allows you to select monitoring points in the geotechnical system based on economic indicators. The selection criterion is the criterion of minimizing the costs of introducing the geotechnical monitoring system with respect to possible damage, which is expressed in monetary terms, in case of the disturbance of the stability of the geotechnical system or its analyzed area. The costs of implementing of the geotechnical monitoring system are determined based on its cost, fixed costs for its maintenance, as well as technical parameters. Costs of introducing of the geotechnical monitoring system are determined by the next technical parameters: the costs are highlighted in the case of missing destructive geotechnical processes, costs are in case of false operation of the system and costs of registering one parameter of the geotechnical system at one point by a specific method. It is proposed to carry out measurements at key control points for reduce the number of monitored parameters and measurement points. The choice of controlled parameters is carried out on the basis of the bifurcation approach. The practical check of the developed method of the registration of parameters of the geotechnical system was carried out during the detecting of suffusion processes in urban areas in the city of Murom, Vladimir Region, Russian Federation. The proposed method allowed to significantly reduce of the cost of monitoring work while maintaining the accuracy of results of the work of the monitoring system.

Keywords: registration, monitoring, geotechnical system, technical and economic analysis

1. Introduction

The development of the technosphere is accompanied by a change in the quantity and strength of the relationships between components of the natural and of the technical environment. Changes lead to accidents and disasters of various sizes when these changes negatively affect the stability of geotechnical systems (Inozemtsev & Redkov, 2017; Telichenko et al., 2006; Sosunov, 2010). Systems of the monitoring of the condition of geotechnical systems are built on two main approaches. One approach is to organize observations of changes in the geological environment, to isolate and predict the initial stage of the development of dangerous geodynamic processes. This approach takes into account hydrological, geological, climatic and other parameters. Another approach is to monitor technical and operational parameters of structures, identify and predict destructive processes, and evaluate the stability parameters of structures (Vasilyev et al., 2018; Kostarev et al., 2013; Bondarik, 2012). Different of technical, of organizational and of economic issues always arise in practice despite the advantages and disadvantages of both approaches. For example, what parameters of the geotechnical system need to be registered, what technical means should be used to register selected parameters, how to place technical means and how to collect data, how many sensors are needed and what places it is necessary to measure, what costs will be incurred, what will be the benefit, and etc.

The purpose of this work is to increase the efficiency of geotechnical monitoring systems in the conditions of the risk of the disturbance of the geodynamic stability and economic restrictions on the organization of monitoring work by developing the method of registering parameters of a geotechnical system based on data of the technical and economic analysis.

2. The method and approaches

The economic efficiency of the applying of the geotechnical monitoring system is achieved by reducing damage from the negative development of processes in the geotechnical system by reducing the measurement error and the probability of the false detection of precrisis situations in the geotechnical system, by increasing the likelihood of the correctly detecting of precrisis situations and predicting them at an earlier stage (Leonov & Shkaruba, 2012). Thus, the economic efficiency of the introducing of the geotechnical monitoring system depends on the metrological, methodological and algorithmic support of the latter.

It should be noted that the economic efficiency from implementation will differ in the case of the organization of monitoring work on the basis of the monitoring system of the same type in various geotechnical systems. This difference can be several orders of magnitude. This is due to individual characteristics of the functioning of geotechnical systems and processes occurring in them, which (individual features) are not reflected or which are not fully reflected in the functioning of geotechnical monitoring systems. As a rule, geotechnical monitoring systems are developed for a specific object (geotechnical system) and have low adaptability to qualitative and quantitative changes in the geotechnical system (Kuzichkin et al., 2018, A).

At the beginning of the technical and economic analysis the mapping of economic damages is developed with the division into zones of significance and with the combining of components of the geotechnical system on objects of various levels (local, local, regional). For each zone, the possible economic damage and the significance of this zone are determined for the functioning of the geotechnical system taking into account the possible social criteria (1) and (2). Clustering of the map of zones is based on an expanding neural gas algorithm (Sledge & Keller, 2008).

$$C_{GD} = \sum_{i=1}^{n} C_{iD}\,, \tag{1}$$

where C_{GD} – is the total economic damage in the geotechnical system; C_{iD} – is the economic damage of the separate area of the geotechnical system; n – is number of zones.

$$C_{iD} = \sum_{j=1}^{m} (C_j(W_j)P_j r_j + S_j(r_j)), \tag{2}$$

where C_j – is the significance of the *j*-th component in the *i*-th zone in the depending on its wear W_j, P_j – is the cost of the *j*-th component in the *i*-th zone; r_j – is the the risk (probability) of destruction, that characterize the possible degree of destruction, while 0 – is the absence of damage, 1 – is the complete destruction; S_j – is the social damage expressed in cash.

In the event of a malfunction of each zone the calculated possible economic damage is the determining criterion for the implementation of the geotechnical monitoring system. The cost of implementing of the monitoring system should be lower than possible economic damage, while the costs of maintaining a geotechnical monitoring system for a certain time and it are set based on its technical parameters:

$$C_{DG} \geq C_I = C_S + \sum_{t=0}^{\Delta} (C_M + kC_S(1 - e^{-t/T_0})) + \sum_p \sum_b (p_{1\to 0} C_p + p_{0\to 1} C_{SM})\,, \tag{3}$$

where C_I – is the cost of implementing of the geotechnical monitoring system; C_S – is the cost of geotechnical monitoring system; *t* – is time of the operation of the monitoring system, Δ - is allowed period of the implementation of the geotechnical monitoring system; C_M – is fixed costs of the maintaining of the geotechnical monitoring system; *k* – is the correction factor in the range from 1.1 to 1.4; T_0 – is the mean time between failures in the geotechnical monitoring system; *p* – is unfavorable factor (analyzed parameters of the geotechnical system); b – is bifurcation points for each parameter *p*; $p_{1\to 0}$ – is the probability of the skipping of the transition of the parameter p in bifurcation point b by geodynamic monitoring system; C_P – is the damage in case of missing an adverse event *p*; $p_{0\to 1}$ – is the probability of false triggering of the geodynamic monitoring system when a transition of the parameter p to the bifurcation point is detected b; C_{SM} – is the cost of the work done to eliminate the adverse event *p* in the event of the false positive.

Taking into account the individual characteristics of the geotechnical system, the geotechnical monitoring system is accepted for consideration of the issue about implementation in case if this system satisfies the following conditions:

$$\min(C_{\cos t}), C_{\cos t} = \{\forall C_I \mid (C_I \leq C) \cap (\Delta \geq T)\}\,, \tag{4}$$

where C – is eligible costs over the period of time T.

The complex nature of the functioning of geotechnical systems is described by a large number of heterogeneous parameters, some of which are interdependent. It is necessary to control the change in the values of these parameters over a large area. It is for assess the current state and predict of the stability of the geotechnical system. It is proposed to determine the parameters by the degree of dependence on each other, the degree of influence on the stability of the geotechnical system and the costs of measuring these parameters. It is for reduce of monitored parameters and, accordingly, reduce of the cost of implementing of the geotechnical monitoring system.

Based on the modular construction principle, the model of the geotechnical system or its individual areas is formed (Grecheneva et al., 2018). Based on this modular model, parameters *p* are determined for the assessment of the stability of the geotechnical system S_t (Kuzichkin et al., 2018, B). Based on the analysis of variance, the degree of influence of the parameters p is estimated on the stability of the geotechnical system $S_t 1$. The result of the assessment is a vector

$$St_1 = \{f(p_1),..., f(p_n)\}, \tag{5}$$

where $f(p_i)$ – is the degree of influence of the *i*-th parameter on the stability of the geotechnical system.

By analogy, for all parameters of the geotechnical system, the matrix Pij of the dependence of the *i*-th parameter on the *j*-th $f(p_i, p_j)$ is compiled, such that

$$P_{ij} = \begin{cases} f(p_i, p_j), i \neq j \\ 0, i = j \end{cases}. \tag{6}$$

Vectors of the stability of the geotechnical system St_i are compiled based on the matrix of mutual dependencies of the parameters P_{ij} by successively replacing the values of degrees of influence of the vector *St* of dependent parameters *p* on the set of corresponding parameters from the row of the vector P_{ij} for parameter *p*. Replacement is carried out until the values of the degrees of influence of the replacement parameters are greater than the set threshold ε when replacing the replaced ones.

Bifurcation points are determined for each vector parameter based on bifurcation diagrams for all parameters of the *St* vectors (Petrochenko and Petrochenko, 2019; Inozemtsev et al., 2010; Nazarov, 2015). The degree of significance of the parameter is determined and the remoteness of the current state of the system is determined from these points. It is determining as well as bifurcation points. For the control, the parameters are selected from vector that satisfies the following conditions:

$$\min\left(\sum_p \frac{\left(\left|b_p - \overline{p}\right| - D\right)\Delta SKC_{ME} St_i\{p\}}{DS}\right), \tag{7}$$

where p – are all elements (parameters) of the vector St_i; b_p – is the the value of the bifurcation parameter, while $b_p = \min(\left|b_{pi} - p(t)\right|)$, b_{pi} – *i*-th bifurcation point for parameter *p*; $\overline{p}$ – is the current average value of the measured parameter *p*; *D* – is the variance of the measured parameter *p*; ΔS – is the area of the influence of the parameter *p*; *S* – is the total area of the analyzed area; *K* – is the required number of parameter measurement points *p* on area *S*; C_{ME} – is the cost of introducing one measurement point; $St_i\{p\}$ – is the degree of influence of the parameter *p* on the stability of the geotechnical system.

In expression (7) the C_{ME} parameter determines the cost of measuring the parameter by the specific method, which is selected based on the technical and operational capabilities of the application at the particular measurement point. If it is possible to carry out measurements by several methods, the method is selected for the implementation that which (the cost of the installed equipment and work) requires less cost.

It is possible to reduce the cost of implementing of the geodynamic control system by applying the control method based on monitoring the stability of key points (Dorofeev et al, 2016). In accordance with this method, the control of hazardous processes is carried out at points that are most sensitive to the development of the initial phase of destructive processes and the manifestation of their precursors. Each key control current determines the general trend of parameter changes over a certain area. The increased sensitivity of these points allows you to record negative processes at earlier stages and changes in the control area.

It should be noted that posterior data and dependencies between the parameters of the geotechnical system may be absent at the initial time when monitoring the stability of the geotechnical system. In this case, the robust model of the analyzed sections of the geotechnical system is built and critical parameters and monitoring points are determined on its basis. As data is accumulated and dependencies are identified, the model is refined, and the functioning of the geotechnical monitoring system is adjusted.

Thus, the proposed method of the registration of parameters of the geotechnical system is based on the results of the technical and economic analysis. The method includes the following steps:

1. The assessment of risks and possible damages in case of disturbance of the stability of the geotechnical system and its individual sections, as well as the classification and allocation of the most significant monitoring zones.

2. The formation of a list of measured parameters.

3. The formation of a modular model of the geotechnical system or its analyzed area.

4. The assessment of the degree of mutual dependence of one parameter on another and the assessment of the degree of influence of each parameter on the stability of the geotechnical system.

5. The determination of bifurcation parameters and assessment of the significance of parameters in the analysis of the stability of the geotechnical system.

6. The founding of key control points and the definition of controlled parameters and methods for their registration.

7. The estimation of the cost of the geotechnical monitoring system with various configurations (number and types of measuring sensors)

8. The choice of the complete set of the geotechnical monitoring system according to economic and technical criteria.

3. Results of the practical test

In order to verify the developed approaches, data of the detection of the suffusion process were processed during geotechnical monitoring, which was carried out under urban conditions in the city of Murom, Vladimir Region, and the Russian Federation (coordinates 55.557282, 42.056503) from August 2017 to May 2018. The monitoring area was 150x250 meters. As the result of data processing, key control zones were identified (yellow and green zones in Fig. 1), which covered the most vulnerable sections of the geotechnical system, and the soil electromagnetic parameters (electrical resistance and permittivity of the medium) were selected as controlled parameters. According to the results of monitoring the suffusion process (red zone) developed in one of the identified zones, which provoked the collapse of the arch of the soil with the formation of the hole with the diameter of 4 meters (Fig. 2).

Figure 1: The identification of key control zones

Figure 2: The hole in a key control zone

The monitoring system was selected from the following systems: georadar of the type OKO-2, system based on constant current of type Meduza-48 and phase-measuring system of type S-1. Formed costs are shown in Fig. 3 taking into account their cost, operation, probability of detection and forecasting, as well as reliability. In the geotechnical system the total economic damage was estimated at 85.7 thousand dollars. Costs of monitoring work are shown in Fig. 4. These costs are without the application of the proposed method of registration of the parameters of the geotechnical system, and without the allocation of key zones and technical and economic analysis. These costs are for all analyzed area. The comparison of the costs is summarized in Tab. 1. It is incurred over 5 years.

Figure 3: The cost comparison using the developed method

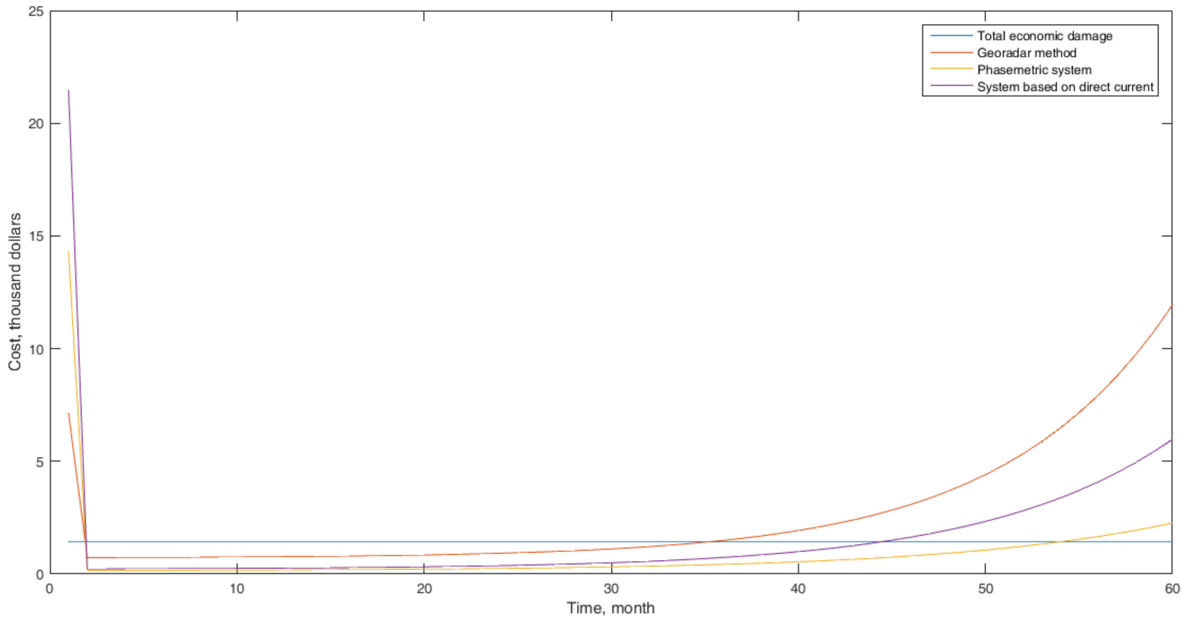

Figure 4: The cost comparison without a developed method

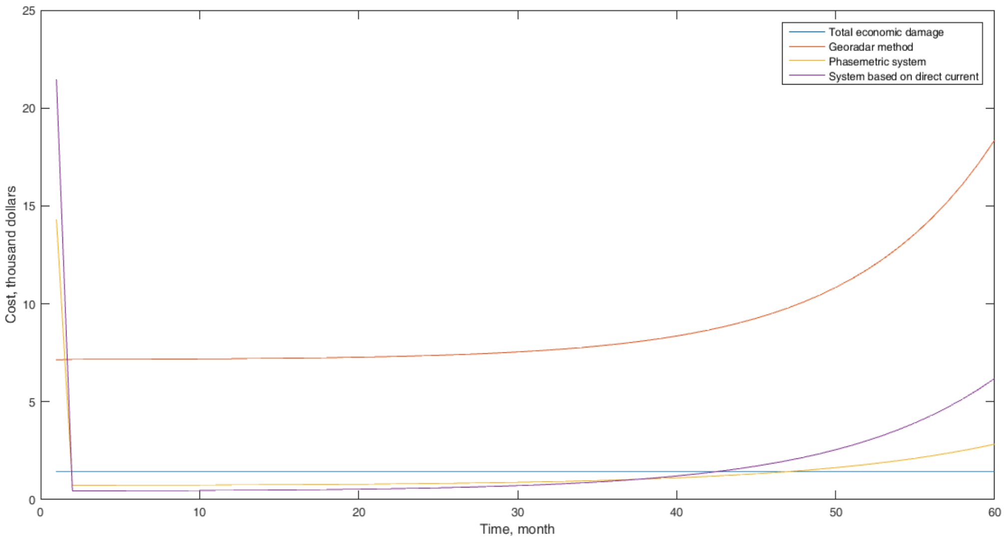

Table 1: The cost comparison for various measurement methods over 5 years

Type of the monitoring system	Without the developed method, thousand dollars	With the developed method, thousand dollars
Georadar	535,2	155,8
System based on constant current	107,1	94,5
Phase-measuring system	82,8	49,0

4. Conclusion

The regular monitoring of the most important sections of the geotechnical system is governed by regulatory documents in the field of construction and operation of structures. However, in practice, for all buildings the constant conduct of such work is expensive and often ignored. As can be seen from the results described in this article, the developed method of the registration of parameters of the geotechnical system can reduce the cost of monitoring work, while maintaining the accuracy of forecast estimates, which will improve technological safety. To further reduce costs, it is possible to build a flexible monitoring schedule based on data on the period of development of destructive processes and a combination of various measurement methods. This approach is in good agreement with the objectives and goals of geotechnical monitoring.

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