



The Forecasting of the Development of Suffusion Processes in Urban on the Basis of the Geoelectric Modeling by the Data of the Phasometric System of the Geodynamic Control

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Abstract

In this article, techniques and algorithms of the control and forecasting of the karst risk of the territory are considered. The formation of forecast assessments of the development of suffusion processes is carried out on the basis of the computer modeling with the correction of model data on the flexible schedule by results of the monitoring. To reduce the costs of the monitoring work, the resistive control method is proposed to use. This method is based on the phasometric principle of the control of the development of suffusion processes. In the article causes and stages of the development of suffusion processes are given, features of the development and the control of suffusion processes are described for urban territories. The modeling of suffusion processes is carried out on the basis of the geoelectrical model of the spherical cavity of the covered thickness of soil sediments. The description of the experimental setup is given for the modeling of the suffusion processes and for the control of their formation by the phase control method. The estimation of the adequacy of results is obtained.

The approbation of the proposed algorithm was carried out at the site of the alleged development of man-made suffusion processes. The identification and localization of the suffusion processes took place on the basis of the risk map and the phaseometric control method. The correction of the model was carried out by the data of the georadar survey of the investigated area. The proposed algorithm allows minimizing the costs of monitoring activities and increases the accuracy of forecast estimates during the modeling the geological environment on simple models.

Key words: forecasting, suffusion, urban, geoelectric, modeling, phasometric method, flexible schedule

1. Introduction

Currently, the negative dynamics of the number of emergency situations is observed, that occur during the operation of technical objects in conditions of the activation of suffusion processes. It is associated with an increasing technogenic burden on the geological environment. Engineering objects are at risk of the partial or of the complete destruction when these objects are located in the zone of the passage of suffusion processes [1, 2]. Various geophysical methods are used to control of the development of dangerous geological processes [3-6]. The most priority approaches of the quantitative forecast of the development of suffusion processes are based on quantitative assessments of karst holes on the area, quantitative and probabilistic assessments of parameters of hydrogeological conditions on the area, the estimation of the load of engineering objects on the geological environment, full-scale analogs, assessments of parameters of accidents on plumbings, the mathematical or the laboratory physical simulation [7]. In practice, several approaches are used to improve the accuracy of forecasting of the development of suffusion processes. To the specific geotechnical system the lack of information leads to the erroneous estimate of risks about the specifics of the development of suffusion processes. It is despite the complex approach to monitoring for the suffusion processes during geotechnical monitoring. Currently, normative documents regulate the regular execution of engineering-survey works during

the construction and operation of buildings and facilities. This works include karstological monitoring with the aim of the obtain short-term (from several months to an year) and operational (from several hours to days) forecasts of the estimate of karst risk [8]. However, in practice, for all buildings the constant carrying out of such works brings great costs and is often ignored. In this regard, the more flexible instrument is needed for the regular control and for the identification of dangerous pre-crisis situations, including the research and the development of more sensitive methods and algorithms for the geodynamic control.

The purpose of this work is the develop of the technique and of algorithms of the control and of the forecasting of the karst risk of the territory in urban conditions, which are based on the phaseometric method of the geoelectrical control and which allowed to correct the time and the area of the execute of additional works for minimize the risk of emergency situations on basic of the computer modeling of the geological section taking into account the observation data.

2. Karst Suffusion Processes and the Estimate of Geotechnical Risk

Karst suffusion processes are formed and are developed in the presence of several conditions: the presence of aggressive water, soluble rocks, the possibility of the arrival of water and the

possibility of water outlet with dissolved rocks. With the development of karst suffusion processes, the soluble rocks are washed out and the cavity is formed, the collapse of the arch of which occurs over time. The time of the collapse depend from the type of the summands of the arch of rocks and of the technogenic

load on the arch (Figure 1). With the formation of a hole, the process of "the raising" of the cavity is possible to certain layers, by the successively and the gradual collapse of rocks which are touched with the apical cavity.

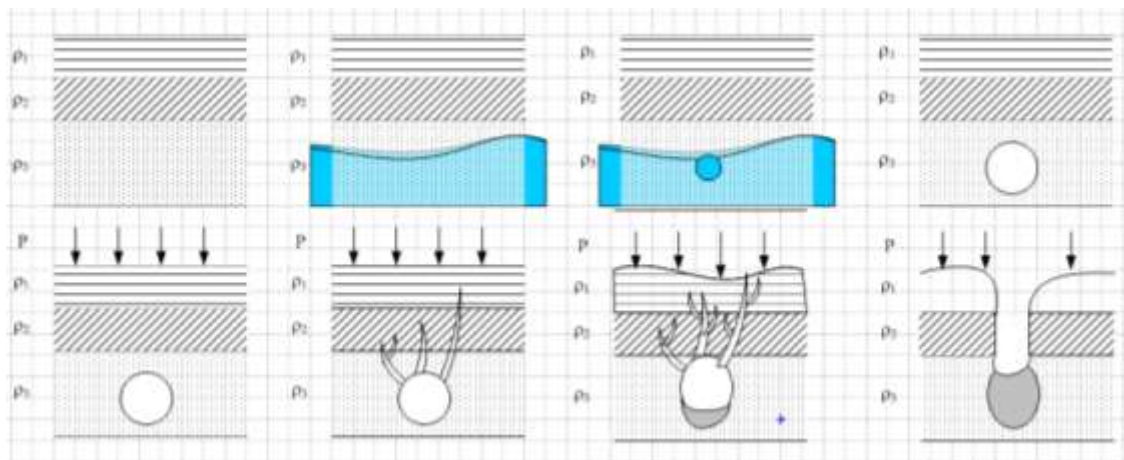


Figure 1: The process of the formation of the karst hole

It should be noted that in conditions of the urban environment, natural hydrological conditions of the terrain, accidents of the water supply and of sewerage networks, the pumping of groundwater and the violation of building codes are the reasons of the development of suffusion processes. Underground communications (which pass under buildings and the transport infrastructure) can lead to the formation of cavities, which are detected only after their development or their collapse which is the essential for the stability of the engineering object. It should be noted that in urban conditions the speed of the development of suffusion processes is significant even in the absence of a powerful unloading zone and the various degrees of dissolution (washing away) of rocks [9].

We also note that the stability of the sand arch (the backfilling of trenches and of communication routes are produced by the sand mix) is small, and when the vibrational load (constant or short-term) is applied to them, the stability of the arch is further reduced (it is due to the weak resistance of unbound earths to tensile stress). It is the important indicator for urban areas.

It was shown in [10, 11] that the development of the cavity can be approximated by a sphere, and its subsequent change due to the primary collapse of the lower rocks of the arch by a hemisphere. In turn, holes appear when the region of decompensation (cavity) reaches the height h and holes are described by a direct dependence in [12]. During modeling the process of activation of suffusion should be performed during periods of intense snowmelt and precipitation, as well as in emergency moments. To do this, the model parameters are set the flow of water from the surface or at the depth of 2 to 6 meters in accordance with the communication plan.

The stress-strain state of the analyzed area is evaluated when modeling the collapse of a rock massif with the development of suffusion processes. The polarization-optical modeling has been widely used among methods for estimating the stress-strain state. The polarization-optical modeling makes it possible to estimate the stress at any point in the rock massif without the introduction of measuring equipment [12]. The analysis of the results of modeling of the stress-strain state of karstic rocks allows us to understand the basic mechanisms and patterns of holes of forming and allows us to develop common methods for calculating the stability of the arch of the cavity for similar sections of the geological environment of the geotechnical system. It should be noted that in practice, approximate methods of calculation reflect the actual process of hole of formation often adequately than the exact methods. It is due to errors and mistakes in estimating of the

number and of values of parameters considered in the calculations. The statistical method is known and based on Poisson's law, which determines the distribution of the diameters of funnels and holes in a logarithmic normal law [13]. The formation and development of suffusion processes is accompanied by a change in the parameters (from mechanically deformed to electromagnetic) of the geological environment with subsequent failure of formation.

The forecasting of suffusion processes requires the greater degree of adequacy of the applied model to the real object in the method of laboratory physical modeling. It is quite complex or unrealizable in complicated geotechnical systems. From the real object the sufficiently large deviation of the applied physical model leads the accuracy and reliability of the predictive estimates to the level of statistical models or the level of the analogy method. The use of calculated deterministic models also requires in-depth analysis of the modeling object and the selection of a large number of design parameters. It significantly increases the costs of geodynamic monitoring.

Thus, for economic reasons the forecasting of suffusion processes is better to execute by statistical models and the analogy method in the urban environment at low hazard class (III, IV) objects. The disadvantage of the analogy method lies in the problematic nature of finding identical objects. This procedure can be simplified by applying together statistical models and neural network approaches, which can lead to a more accurate obtaining of the calculated parameters of the research object and the formation of a database of analogies.

In the urban environment the peculiarities of the development of suffusion processes lead to the need to move away from the geographic approach of the assessing of the karst risk (based on large-scale risk maps) to assessing the risk of the territories taking into account their intended use (using small-scale risk maps). In this case, to estimate the karst risk of the particular area it is necessary to analyze similar situations, various subtypes of karst danger, types of zones of territorial planning and engineering features of engineering facilities [14, 15]. At the same time, although the theory and methods of quantitative assessment of karst risks have been developed and successfully tested, due to the complex analysis and the need to involve specialists of different profiles, the quantitative risk assessment is rarely used in practice, even for objects of increased complexity [16]. The estimate of the risk of damage can be represented by the following expression in the case of development of suffusion processes in general form:

$$R=KEW \quad (1)$$

где R – the risk, $K=f(R_K, L, G, V, R_C)$ – the risk of development of suffusion processes in the controlled territory, f – the operator of risk assessment of development of suffusion processes, $R_K=\lambda K_S/N$ – the risk of damage to the territory under analysis, $\lambda=N/(S\Delta t)$ – the intensity of holes, N – the number of holes, S – the area, Δt – the time interval, $K_S=\Sigma S/S$ – the suffocation of territory by suffusion processes, ΣS – the total area of suffusion processes in the area S , L – the coefficient of remoteness of the territory from the main direction of development of suffusion processes on the rose chart, G – the coefficient that takes into account the geological and hydrological conditions of the terrain (according to the category of karst hazard), V – the average area of holes, $R_C=A\Sigma C/S$ – the degree of technogenic impact on the geological environment, A – the level of vibration, ΣC – the total area of water communications with a service life of more than T years, $E=v(E_W, E_L)$ – the economic vulnerability of the territory, E_W – the economic vulnerability of engineering object, E_L – the economic indicator that takes into account the trauma and death of people, as well as other tangible property, W – the value of the object before the development of suffusion processes.

3. The Geotechnical Monitoring of the Development of Suffusion Processes

Obviously, the costs of the organizing of the full-fledged monitoring of the development of suffusion processes should be lower than the cost of the compensating for the negative scenario at engineering objects. Otherwise, it is not expedient to conduct the full-fledged monitoring of the development of suffusion processes. To reduce the cost of monitoring works, the control of the development of suffusion processes is proposed using a flexible schedule using the phasometric system of geodynamic control and without the full-scale geophysical surveys. The algorithm for monitoring is as follows:

1. The map of the risks of damage occurrence is drawn up.
2. The most risk-prone areas are allocated, taking into account the economic feasibility of monitoring activities.
3. Simulation of selected sites and prediction of the development of suffusion is processed.
4. The period T of monitoring works is determined in accordance with the expression:

$$T=r(R, M, Z), \quad (2)$$

where, r – the operator for determining the monitoring period T , R – the risk of damage, M – the predictive evaluation of the time of negative development of suffusion processes on the analyzed site, Z – the cost of monitoring works.

5. Conducting monitoring works and correction of the parameters of the forecast model.

The choice of the resistance method is justified as the main one by its efficiency due to sensitivity to geodynamic changes and ease of application. This method is based on the phasometric principle of

the control of suffusion processes [17]. This method is based on recording the phase of the resulting signal $U(t)$ (2). The signal is formed by several alternating voltage sources. Phases φ_i of the N source of signals are shifted relative to each other by a constant value.

$$U(t) = \sum_N U_i \sin(\omega t + \varphi_i) + j \sum_N U_i \cos(\omega t + \varphi_i) \quad (2)$$

Changes of the electromagnetic parameters of the section of the controlled geological environment cause the deviation of the phase of the resulting signal. The direction of development of the geodynamic processes can be estimated by the magnitude and sign of the phase deviation of the resulting signal from the initial values to the changes in the parameters of the geological environment. And the geodynamic environment activation zone can be localized in the presence of a sufficient number of sources or signal receivers.

To demonstrate the phase-metric principle of the geodynamic control system, we present results of a laboratory experiment. The installation scheme is shown in Figure 2. As a geological medium, sand is used (specific electrical resistance in the dry state of $4.7 \text{ k}\Omega \cdot \text{m}$, with a moisture content of more than 50%, $2.3 \text{ k}\Omega \cdot \text{m}$) and was sandwiched in a dielectric box with dimensions of $95 \times 39 \times 27 \text{ cm}$.

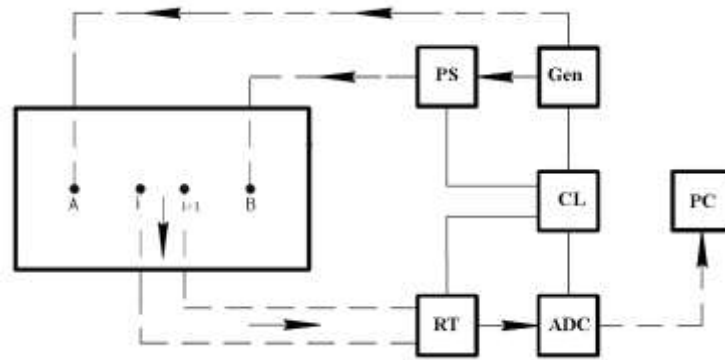
During the modeling of suffusion, the part of sand of different volumes was taken in different areas (both in depth and in place). In this case, increasing of the size of the cavity changes the electrical parameters of the medium and changes the value of the phase of the resulting signal recorded on the receiving electrode.

The results of the experiment are shown in Figure 3 in the presence of a cavity or suffusion processes in different areas of the geological environment. Figure 3a shows the displacement of the site of suffusion perpendicular to the line of electrode placement (in width), and in Figure 3b) displacement of the suffusion site parallel to the electrode placement line (along the length).

The obtained results show the correspondence of the computer model to the laboratory installation by 84%. From the obtained dependences it can be concluded that the value of the deviation of the phase of the total signal indicates the direction of the course of the suffusion processes. Thus, even if there are two sounding signals, one can find out the sector of development of suffusion processes, and with an increase in the number of radiating electrodes, it is possible to achieve the necessary localization accuracy of the suffusion processes.

Thus, the application of this system is possible without specialized trained personnel to identify the location of the course of suffusion processes, and its results are obtained in an automated mode without operator involvement. The cost of detecting negative changes in the geological environment with the use of this method of control is several orders of magnitude lower than the cost of conducting electrical exploration work.





A, B - radiating electrodes; $i, i + 1$ - position of the receiving electrode (in steps of 1); Gen - alternator; PS - phase shifter; RT - reception channel; ADC - type L-card; CL - common ground; PC - computer

Figure 2: The schematic representation of the laboratory installation

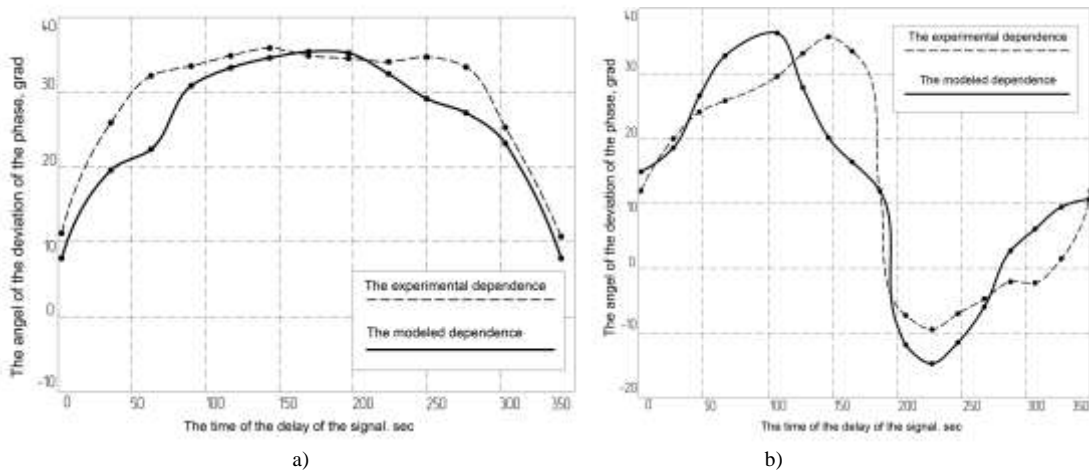


Figure 3: Results of a computer (solid line) and laboratory modeling (dotted line) of the phase deviation of the total signal of the phasometric device in the presence of suffusion

Geo-electric substitution schemes are used for determine areas of the geological environment, whose parameter values deviated from the original and for the subsequent correction of the model of the geological section by the phase data in the phase-measurement system of the geodynamic control. The sections of these schemes describe individual volumes of a geological medium with the

same parameters [18, 19]. When modeling the geological section by geoelectric models we are based on replacing a geological environment with a four-terminal network that interacts with neighboring sections. As the geoelectrical model, we used the model shown in Figure 4.

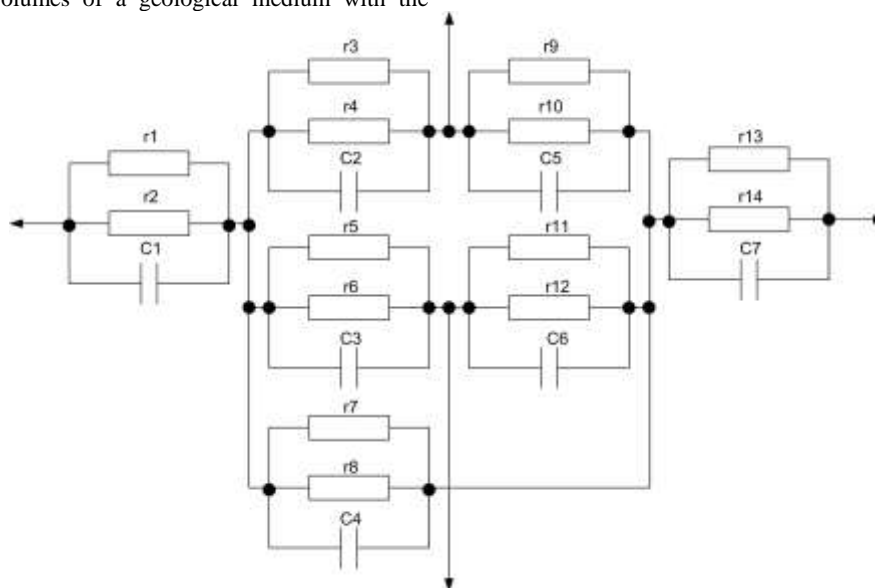


Figure 4: The block diagram of the elementary geoelectrical 2-D model

Each section of the circuit represents the complex resistance of the medium Z as the series-connected two resistors and the capacitor and it is characterizes the active and reactive

components, as well as the dielectric parameters of the medium.

The volume of the geological medium (that is replaced by the elementary geoelectric model) is determined by the necessary accuracy of the approximation of the geological section and the

minimum cavity size that must be detected with the available parameters of the geological section and the measuring installation (Figure 5).

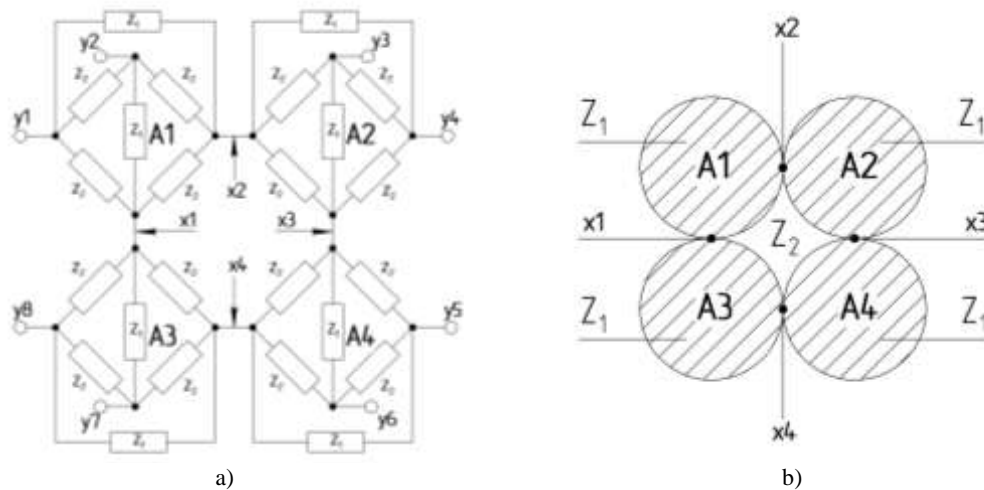


Figure 5: The example of the geoelectric circuit for replacing (a) of the geological environment, which is represented by the section of four media (b)

Suffusion processes are modeled by the decrease of the values of complex resistances at the area of the geoelectrical model which correspond to the place of their flow. In this case, the formation of the cavity is modeled by the maximum values of the resistances ($M\Omega$) or by the complete exclusion of sections of the geoelectric circuit and by the connection of the remaining ones. Thus, the distortion of the current lines and the flow of electric current around the cavity formed are simulated.

4. The Approbation and Experimental Results

The approbation of the proposed approaches was carried out at the site of the possible of the development of suffosive processes of technogenic origin. To analyze the territory, the risk map was drawn up on the basis of expression (1) (Figure 6). The simulation of the geological section was carried out on the basis of georadar data. In the future, the place of putative suffusion (highlighted by a green area) was determined as a result of the work of the phase-shift system of geodynamic control by the sharp phase deviation (Figure 7). During the monitoring system operation from August

to November 2017, the sharp change was recorded in the phase of the total signal. The sharp change of the phase of the signal coincided with the period of precipitation of heavy precipitation. As a result, the input parameters of the model of the geological section were adjusted. And for further monitoring the time was determined on the basis of expression (2). During the simulation, two corrections were made based on the georadar data. The results of the first georadar (Figure 8) sounding showed the development of the suffusion process and the disruption of the integrity of the near-surface layers, as also it indicated by a small subsidence of the roadway. The estimated size of suffusion was 4 meters in diameter (from the second to sixth meter of the georadarogram profile). The second passage of this area (by the georadar) showed a significant development of suffusion processes with the formation of a cavity filled with water (Figure 9). Further development of suffusion processes led to the formation of a cavity with the diameter of more than 4 meters, with the subsequent collapse of the arch of soils and the formation of the hole (Figure 10).

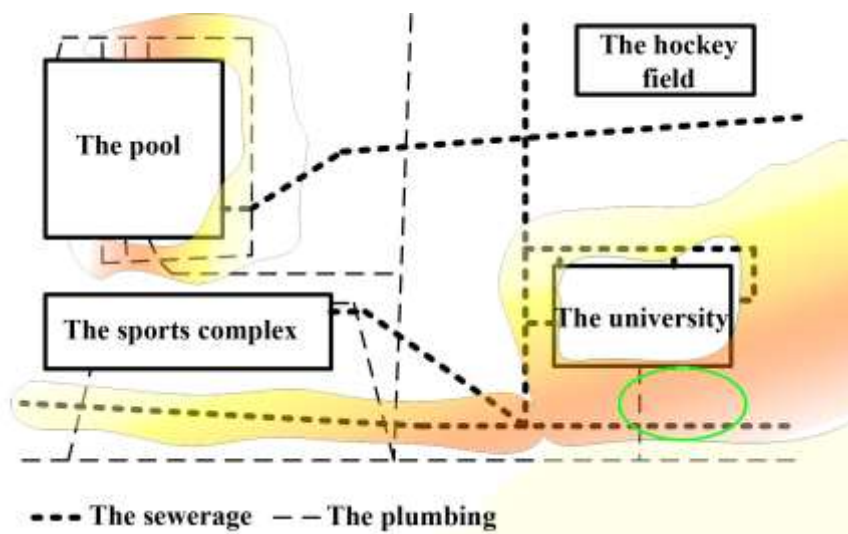


Figure 6: The map of the estimate of the risk

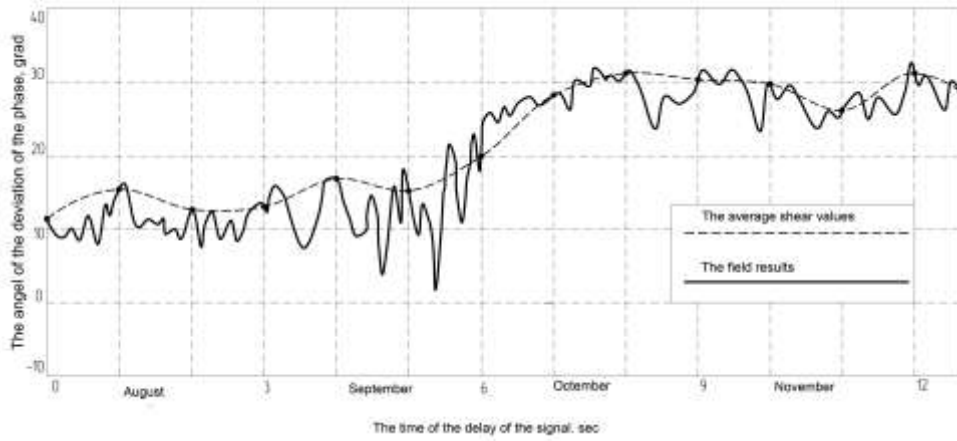


Figure 7: The results of the work of the phase-control system

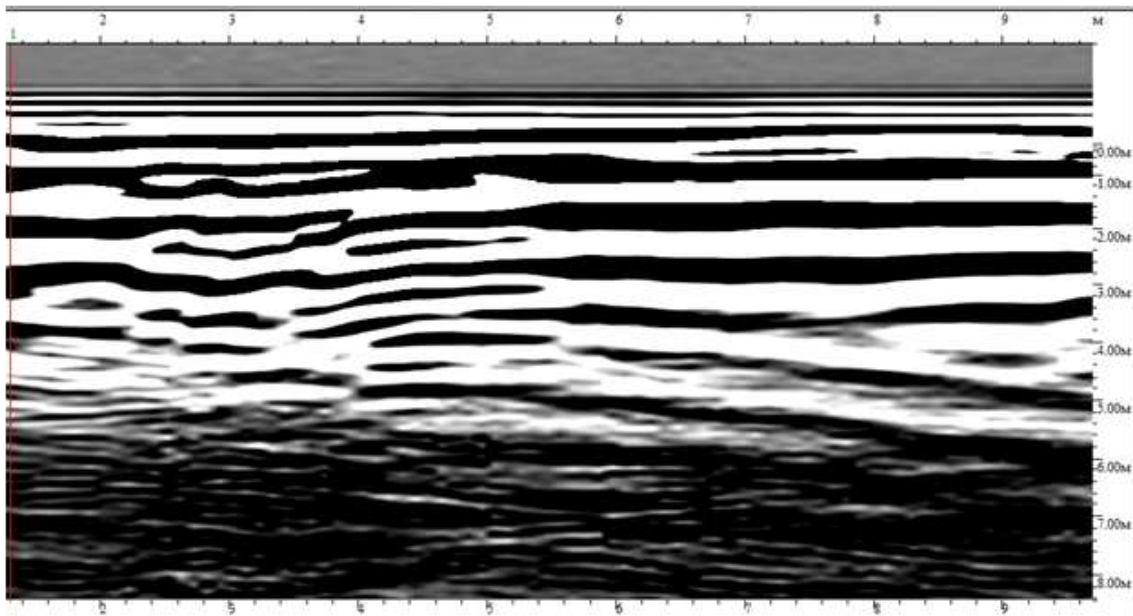


Figure 8: The georadarogram of the place of alleged suffusion. Type of georadar unit: OKO-2, 90 MHz

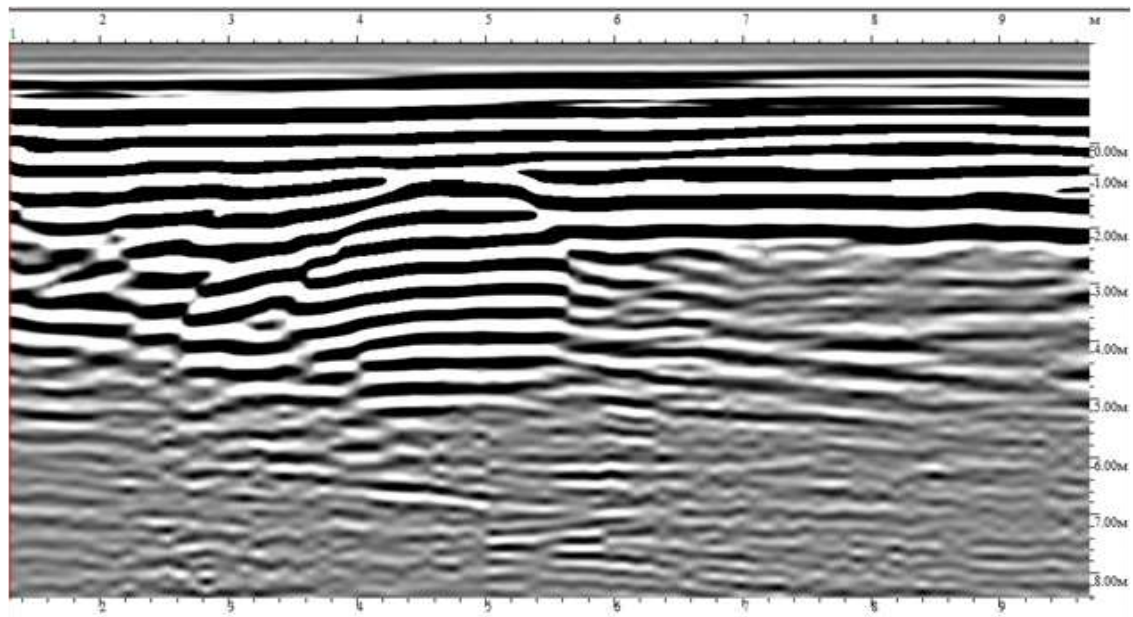


Figure 9: The georadarogram that reflect cavity formation



Figure 10: The hole in the flow of suffusion processes

The results of the obtained predictive estimates are shown on the model data in Figure 11. As can be seen from the schedule, the timely monitoring of the flexible schedule allowed the model parameters to be corrected in advance and to be predicted the

occurrence of the failure. The discrepancy is between the forecast estimate and the actual situation. It indicates about the application of an inaccurate model of the geological section, an assessment of the development of suffusion, and collapse of the cavity.

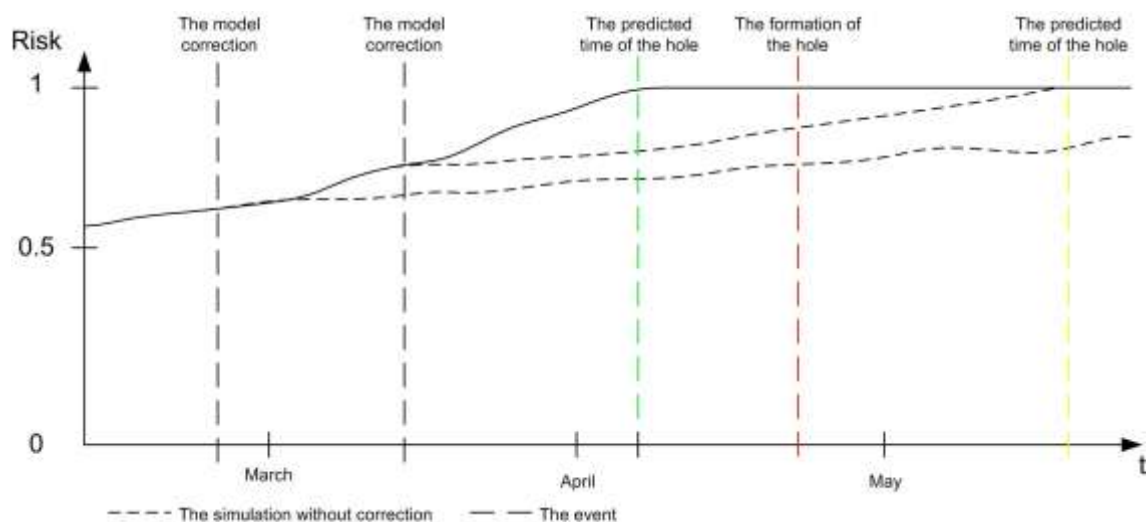


Figure 11: Simulation results

5. Conclusion

Thus, proposed methods and algorithms of the monitoring and of the predicting of the karst risk of the territory are based on the phaseometric method of geoelectrical control. It allow to correct the time and area of the executing of additional works for the minimize of the risk of emergencies in urban conditions by the computerized modeling of the geological section taking into account the observation data. The joint application of the phase control method and of the proposed geoelectrical scheme of substitution of the geological section made it possible to detect and localize the suffusion process. In turn, the complex approach of the formation of flexible monitoring schedule allowed to reduce costs, improve the accuracy of forecast estimates (simulation results), which allowed to predict in advance the further development of negative near-surface geodynamic processes.

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