Journal of Engineering and Applied Sciences 12 (Special Issue 3): 6628-6634, 2017
ISSN: 1816-949X

The Results of Joint Processing of Geotechnical and Geodynamic Monitoring Data of Karst Processes

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Abstract: The research is dedicated to addressing the issue of joint processing of geotechnical and geodynamic monitoring data of Karst processes. Based on geotechnical monitoring of the real object which is located in the Karst terrain, it highlights the main problems affecting the quality of the forward-looking estimates. It was found that for increasing the sensitivity of detecting the initial phase of destructive processes in the "geological environment engineering facility" system, it is necessary to use the several informative control methods (geoelectrical, inclinometric, strain gauge). The structural scheme and algorithm of joint processing of geotechnical and geodynamic monitoring data. The block-diagram assumes allocation of the key geodynamic objects, the algorithms of distributed processing of the heterogeneous data and the formation of forward-looking estimates. The techniques of the registration and initial processing of physical parameters on the basis of selected informative methods are described. The numerical solution of the deformation interaction problem in the "subsoil-foundation-structure" system is carried on the basis of geotechnical and geodynamic monitoring data.

Key words: Karst processes, geotechnical monitoring, geoelectrical, inclinometric, strain gauge, data

INTRODUCTION

At present moment there is a large-scale development of new territories including Karst areas due to the necessity of building production and technical facilities. Construction and operation of buildings and structures in Karst areas affects the activation of exogenous geodynamic processes. As a consequence, there are Karst cavities in the ground under the engineering structures (Korolev, 1995). At the beginning of construction, the geological surveys may indicate a lack of Karst cavities under foundation. However, at the technogenesis process can be implemented the conditions for emergence and growth of Karst cavities. Activation of Karst processes can lead to unacceptable deformations of the soil and the destruction of facilities (Sharapov and Kuzichkin, 2014).

One of the most effective ways to timely predict the beginning and activation of deformation processes in the "geological environment-engineering facility" system is using the complex of informative physical methods of geotechnical and geodynamic monitoring. This approach involves the real-time automatic measurement of deformation parameters and post-processing of heterogeneous data. Conclusion about the patterns of deformation conditions and forecast assessment of their future dynamics is based on the analysis of the evolution of the measured parameters data and mathematical modeling of deformation processes in "foundation soil-foundation-construction" complex (Kuzichkin, 2008a, b; Dorofeyev and Orekhov, 2013).

The aim is to develop an approach for joint processing of geotechnical and geodynamic monitoring data of Karst processes. This approach aims the processing of geodynamic data, in combination with the parameters of the dynamics of deformation processes of engineering structures for further prediction and prevention of technogenic catastrophes.

MATERIALS AND METHODS

Description of the monitoring object: Geotechnical and geodynamic control was carried out in an area Chud village of Nizhny Novgorod region (55°46'9"N, 42°19'36"E). The main characteristic of the geological environment in this area is the dominant stratum of carbonate (limestone, dolomite, marl) and sulphate (gypsum, anhydrite) rocks. Chloride breed (chloride or salt

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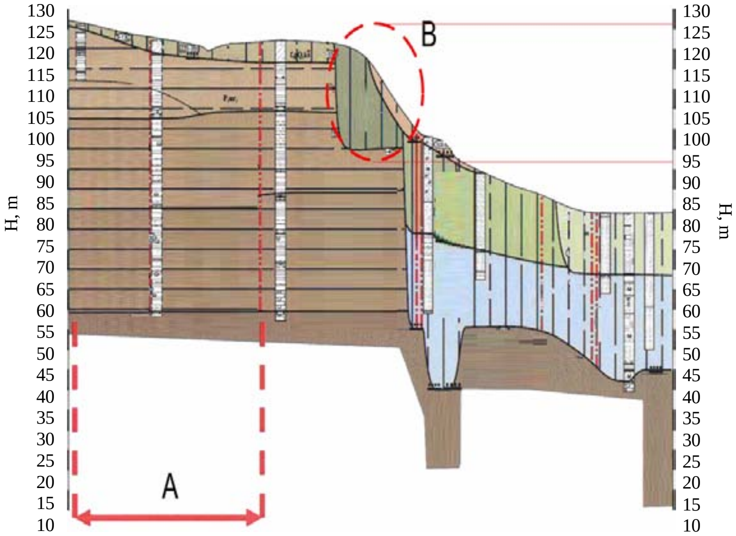

Fig. 1: The geological features of the site and the selection of the geodynamic control zones: A) Zone development; B) The optimal zone of geoelectric monitoring

Karst) in the Nizhny Novgorod region lie at great depths (over 450 m) and as a rule did not have a practical effect on the conditions of construction. Karst rock in the Nizhny Novgorod Region occur, usually at depths ranging from 5 and 70-80 m. As a result, the destruction of Karst cavities on the earth's surface occurs mainly in the central, Western and South-Western parts of the Nizhny Novgorod Region.

The organization of the geodynamic control should take into account that there are two main types of geodynamic movements of the Karst environment. This cyclic variation with varying intensity and duration of the period characterized by cyclical changes in the structure of the medium. In addition, the period characterized by the trend of variation which are pronounced character and having a constant direction for a long time with the result that they are the main source of mechanisms of technological disasters (Izrael, 1985). In addition, geoelectric monitoring data supplemented by stationary observations including the monitoring of hydrogeological regime fracture-Karst aquifer and overlying and geodetic monitoring of surface subsidence, changes in morphometric characteristics of the relief, failures and deformations.

Therefore, based on geological data, the optimum geoelectric zone control which will be geodynamic more pronounced than in other areas, for the same man-caused load was determined. Geodynamic monitoring of the local area in combination with the deformation monitoring of engineering structures will provide more accurate forecasts of geodynamic activity surrounding area (Fig. 1).

The data of routine observations indicate that due to the Karst strain at various times there have been several major accidents in the Nizhny Novgorod Region. It was noted that in all cases the cause of accidents are errors in various stages of building development: site selection, engineering survey, design, construction or operation of facilities. To avoid such situations should be a thorough study of the Karst process, specifics of the natural and man-made environment, the development and use of integrated measures of anti Karst protection and improvement of geodynamic control systems with use the new algorithms and data processing approaches.

The structure of joint processing of geotechnical and geodynamic monitoring data: Applying the multiple informative control methods (geoelectrical, inclinometric, strain gauge) to increase the sensitivity of detection of the initial phase of destructive processes in the "geological environment-engineering facility" system suggests the need to consider multiple types of heterogeneous data. The task of building predictive functions based on the dynamics of the recorded data is quite complex and is multi-criteria character (Kuzichkin and Dorofeev, 2015).

The solution to this problem is the implementation of joint processing of the heterogeneous data of geotechnical and geodynamic monitoring on three levels: physical, data link and network that is taken into account when designing the block diagram (Fig. 2).

The physical layer is the hardware and is a combination of physical methods of obtaining information (inclinometric, geoelectric, strain gauge). This level

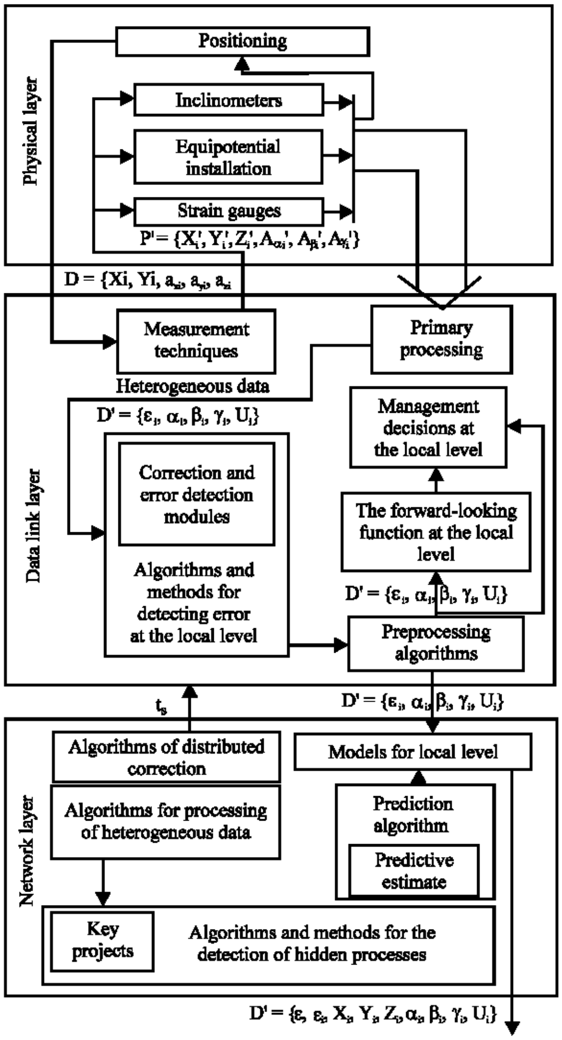

Fig. 2: The structure of processing of the geotechnical and geodynamic monitoring data. X_i, Y_i, Z_i are the initial coordinates measuring equipotential installation; X_i', Y_i', Z_i' are the required coordinates of the measuring equipotential installation; a_{x_i}, a_{y_i}, a_{z_i} are the acceleration values of i-accelerometer on the corresponding coordinate axes; A_{α_i}, A_{β_i}, A_{γ_i} are the tensor transformations matrix; α_i, β_i, γ_i are the angles of the control object; α_i', β_i', γ_i' are the angles after primary treatment; U_i is the resistance of strain gauge; ε_i is the geoelectric method data; ε'_i is the geoelectric method data after preprocessing; t_s is the total time of the system

contains a description of the placement techniques and positioning of the primary transducers (electrodes, accelerometers, strain gauges) that determine the coordinates X_i, Y_i, Z_i and a_{x_i}, a_{y_i}, a_{z_i} of measuring devices.

The link layer is carried out pre-processing of heterogeneous data, presentation and storage of primary D_i and D_i' processed data, supporting information: methods of measurement and processing of the local level, the model required X'_i, Y'_i, Z'_i, A_{α_i}, A_{β_i}, A_{γ_i} and recorded X_i, Y_i, Z_i, a_{x_i}, a_{y_i}, a_{z_i} by, the situation of primary converters in the space. Moreover, this level requires a predictive module.

The network layer is represented by software modules for distributed processing and correction of the data at the local level, identifying and predicting the initial phases of the latent deformation processes as well as the correlations in the "geological environment-engineering facility" system. For the coordinated work of measuring systems at the local level network layer generates clock signals t_s.

Registration and preprocessing of data: The block diagram of joint processing of geotechnical and geodynamic monitoring heterogeneous data includes the several informative testing methods (there are geoelectrical, inclinometric, strain gauge) which is reflected in Fig. 3.

The rational use of the accelerometer method for inclinometry survey of buildings and structures are the provisions described by Dorofeev *et al.* (2016) and Grecheneva *et al.* (2016). The operating principle of inclinometers in geotechnical monitoring systems is based on the determination of deflection angles of the object from the vertical in different planes and determination of the rotation angle relative to the reference coordinate system associated with the Earth. At the same time, the basic coordinate system related to the non-collinear vectors is adopted: a vector acceleration of gravity which is oriented orthogonally to the horizontal plane and directed towards the center of the Earth $\vec{g}$; a vector of Earth's angular velocity $\vec{\omega}$.

Figure 3 shows the principle of the inclinometric control with the use of accelerometer transducers and phase-measuring method algorithm (Dorofeev *et al.*, 2015). In the normal position of the control object, the acceleration values coincide with the acceleration of the free fall. Once the control object deviates from its normal position, an angles α and β form between the accelerometer axes and the direction of the gravitational acceleration vector. For each accelerometer the projection of acceleration vector on the axis OX and OY will be equal, taking into account the conditions of the stationary objects of control and exposure to a constant gravitational acceleration g:

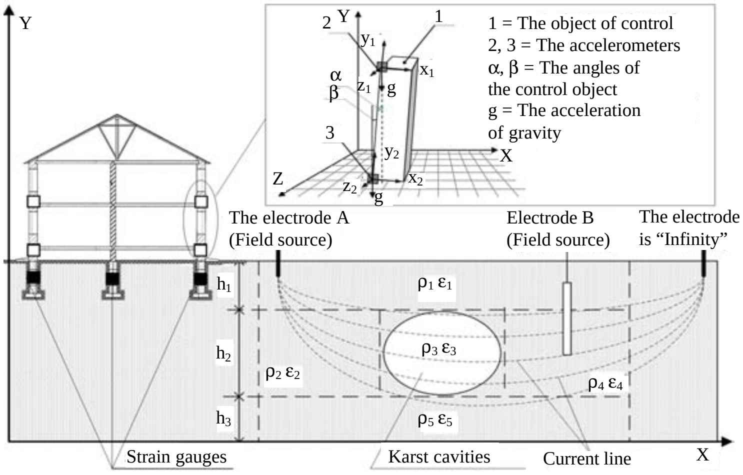

Fig. 3: The principle of joint organization of the geotechnical and geodynamic monitoring

$$a_y^i = -g\times\cos\alpha_i;\ a_x^i = g\times\sin\alpha_i \tag{1}$$

Where:

a_x^i, a_y^i = The acceleration values on the respective axes of i-accelerometer
g = The acceleration of gravity
α_i = The angle of the coordinate system OX_i and OY_i of the ith accelerometer relative to an idealized coordinate system OX' and OY'

On the basis of the phase measuring principle, the signals from the accelerometer are represented in the form of harmonic signals by multiplying them by the reference oscillator signals sin ωt and cos ωt:

$$U_y^i = a_y^i\times\sin\ \omega t;\ U_x^i = a_x^i\times\cos\ \omega t \tag{2}$$

Substituting Eq. 1 in Eq. 2, respectively, we will have the following relationship:

$$U_y^i = -g\times\sin\ \omega t\times\cos\alpha_i;\ U_x^i = g\times\cos\ \omega t\times\sin\alpha_i \tag{3}$$

Summing up the signals, we obtain an expression for determining the angle of tilt:

$$U_\Sigma^i = -g\times(\sin\ \omega t\text{-}\alpha_i) \tag{4}$$

For determination of the angle the time of referral to the zero reference signal $U_o = \sin.\omega t$ and the summed signal U_Σ^i must be registered. The time τ between the zero signal values in each period will be proportional to the angle of rotation α_i of the accelerometer coordinate system relative to an idealized coordinate system (Fig. 4).

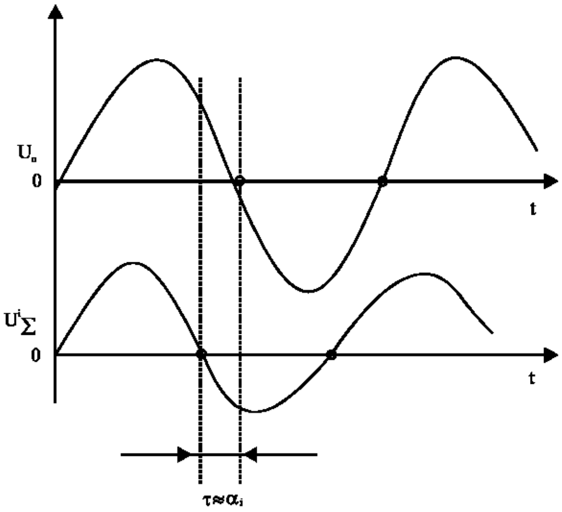

Fig. 4: The phase measuring principle for determining the angle of rotation

In case of using the phase-measuring method described in the article, the measurement error can be substantially reduced by using the following expressions:

$$\Delta\alpha = \frac{\pi}{2}\times\frac{\Delta k_y\text{-}\Delta k_x}{(1+\Delta k_y)\times(1+\Delta k_x)} \tag{5}$$

$$\Delta\beta = \frac{\pi}{2}\times\frac{\Delta k_x\text{-}\Delta k_y}{(1+\Delta k_y)\times(1+\Delta k_x)} \tag{6}$$

As a result, the measurement accuracy will be significantly reduced Δα, Δβ ≈ $0, 3.10^{-2\circ}$ at $k_x = 0.5\%$.

In conjunction with inclinometric control of engineering constructions was carried geodynamic control of subgrade and the surrounding area based on the application of the geoelectric method. This method is characterized by a heightened sensitivity to the hidden geodynamic processes. High sensitivity control is achieved due to the fact that the source of the probing signals in the test environment is created in accordance with the principle of superposition of spatially-distributed signal which forms the total zero signals on the sensors of geoelectric field.

Geoelectrical control method is based on the linear principle and stationary of the geoelectric section, the transfer function $\Delta H_{ij}(p, \alpha_1, ..., \alpha_l)$ is determined by the set of spatial functions of the control object $\Psi_{ij}(p)$ with the nominal geodynamic parameters α_i^0 :

$$\Delta U_i(p) = \sum_{j=1}^{n} \Delta H_{ij}(p) I_j(p) \, \Delta H_{ij}(p, \alpha_1, ..., \alpha_l) = \frac{K(p)}{S_i(p)} \sum_{k=1}^{l} \left[\frac{\partial \Psi_{ij}(p, \alpha_1^0, ..., \alpha_l^0)}{\partial \alpha_k} \Delta \alpha_k \right] \tag{7}$$

Where:

I_j = The probe signal of ith source
Δu_i = The response of ith source
$K(p)$ = The contrast ratio environments
$S_i(p)$ = The dependence of the measurement channel gain

In this case, the control signals of initial setting and positioning of geoelectric measuring systems are formed in accordance:

$$\bar{U}_i(t_0) = F_U(M_{Si}, \bar{U}^*(t_0)) \tag{8}$$

Where:

F_U = The option forming of primary positioning on the control vector
$\bar{U}^*(t)$ = The system of space-time processing data control at start time
$t = t_0$, M_{si} = The vector of model parameters

Later the geoelectric measuring system is functioning directly, in the semi-automatic mode using the following algorithm:

$$\bar{U}_i(t) = \bar{U}_i(t_0) + \Delta U(M_{Si}, \Delta\bar{\alpha}_i) + F_U(\Delta M_{Si}, \bar{U}^*(t)) \tag{9}$$

Where:

$\Delta U(M_{Si}, \Delta\bar{\alpha}_i)$ = The ongoing management of the positioning of the electrical installation of the vector of geodynamic variations
$\Delta\bar{\alpha}_i$; ΔM_{Si} = The correction model

Increase of sensitivity leads to an increase in noise level caused by thermal and tidal deformation effects. In addition, operational management of electro location signals is the presence of the trend component in the recorded signals which is determined by the structural changes of the object.

These relations (Eq. 7-9) make it possible to solve the inverse problem-selection of properties of the local geodynamic object by adjusting the parameters of sensintive sources which is a key aspect of the organization of geodynamic control. However, increased sensitivity leads to an increase in noise level caused by thermal and tidal deformation effects. In addition, operational management of the electrolocation signals is the presence of the trend component in the recorded signals which is determined by the structural changes of the object (Bykov and Kuzichkin, 2014). These factors confirm the feasibility of sharing the several informative testing methods (there are geoelectrical, inclinometric, strain gauge) to improve the accuracy and efficiency of the prediction of the destructive processes in the “geological environment-engineering facility” system.

Furthermore, for improving the evaluations of the reliability forecast is necessary to control the physical and mechanical properties of materials and design elements of the building. It is known, that the physical and mechanical properties of the building foundation and are considered elastic. With the development of Karst cavities in the soil based on changes of the stress-strain state, formed in the elements of the engineering object before it appears. In this case, the most promising method of control is loaded-strain state is the use of the classical strain measurement in conjunction with the already described informative methods of geotechnical and geoelectrical control.

RESULTS AND DISCUSSION

Proposed in this study an approach of joint processing of heterogeneous geotechnical and geodynamic monitoring data was tested in the monitoring of the dynamics of the Karst areas in the area Chud village of Nizhny Novgorod region (55°46'9"N, 42°19'36"E).

In the experiments assessed the effects of the Karst cavity dynamics to the change of the stress-strain state in the elements of the system “ground-foundation-building” as a change in the inclination angle (rotation) at some points bearing walls of the building and the mechanical tension of design foundation (Fig. 5).

It should be noted that the greatest dynamics of destructive processes in the foundation structures are correlated with changes in soil dielectric permittivity, caused by seasonal changes in the hydrological regime. The satellite observations confirm the depending covering the period from the formation of Karst cavity (Fig. 6) to the total destruction of a residential building located in a dangerous geodynamic zone (Fig. 7).

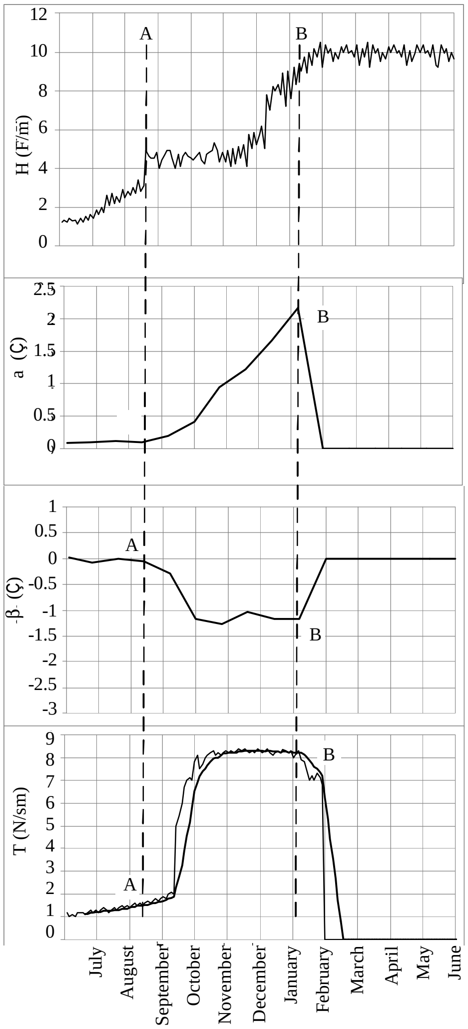

Fig. 5: The results of the joint monitoring data of the dynamics of the Karst cavity near the engineering buildings: the time dependence of the values of the rotation angles α and β top of the building along its length, the time dependence of H factor when changing of the soil permittivity, the time dependence of mechanical tension T with changes loaded-strain state of the building foundation; A the starting point of building destruction; B the final point of the building destruction

The picture of May 2015 (Fig. 7) shows that the diameter of the crater widened to 26 m, the border can be easily seen is seen fresh soil. By the fall of the crater sizes increased slightly due to subsidence, the influence of the hydrological regime of groundwater. The depth of the crater was more than 10 m.

Fig. 6: Satellite image of the area, the 09/05/2014

Fig. 7: Satellite image of the area, the 09/05/2015

CONCLUSION

The experimental studies have shown that the geoelectric monitoring is the most sensitive method to predict in advance of the initial phase of the hidden destructive processes in the complex "foundation soil-foundation-engineering facility". However, the proposed approach is the integrated application of several informative physical methods of control and follow-up of joint processing of the heterogeneous data of geotechnical and geodynamic monitoring allows timely predict the onset and activation of deformation processes in the system "geological environment-engineering facility". Based on the analysis of geotechnical and geodynamic monitoring data the results of the evolution in the measured parameters and mathematical modeling of deformation processes in complex "foundation soil-foundation-structure" was formed opinion on the laws of the deformation as well as prognosis estimation of their future dynamics.

ACKNOWLEDGEMENT

This research was supported in part by the Ministry of Education and Science of the Russian Federation under Grant No. 5.3606.2017/P4.

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