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The Algorithm for Solution of the Inverse Task of the Inclinometric Control during Geotechnical Monitoring of the Foundation of Building

A V Grecheneva[1], O R Kuzichkin[1], A O Kovalenko[1], I A Kurilov[2]

[1]Belgorod National Research University, 85 Pobedy St, Belgorod, 308015, Russia
[2]Vladimir State University, 87 Gor'kogo St, Vladimir, 600000, Russia

E-mail: 1155464@bsu.edu.ru

Abstract. The article discusses the algorithm of the solving of the inverse problem of the determining of the load parameters of foundation during geotechnical monitoring using inclinometric control. The method of the inclinometric control of the foundation is based on the data of accelerometric sensors with using the phase-measuring principle of the control and the regression analysis to determine the load parameters of the foundation. The developed algorithm allows you to localize the foundation section with the violation of the balance of the forces in the "structure-foundation-soil" system, which leads to foundation deformations. The columnar type foundation is considered as an example.

1. Introduction

The necessary of the monitor of the condition of buildings, of the soil base and the surrounding area becomes in the process of construction and operation of buildings. The basic regulatory requirements, methodologies and necessary technical support are regulated by regulatory documents [1-5]. The deformation control is one of the effective methods used in geotechnical monitoring of structures, which is based on accelerometers [6–9]. The accelerometers allow measuring vertical and horizontal movements (precipitation, shifts, subsidence, rises, deflections, etc.), rolls (slopes), as well as fluctuations in the building and individual structural elements. The feature of systems of this class is the ability to indirectly estimate the deviation of parameter values from the "construction-foundation-soil" calculation model which was established in project. In append to this the feature is localization of the site of the initial manifestation of violations and the formation of the list of possible causes of deformations. In this case, it is possible to form forecast estimates of the transition of the structure to the pre-emergency state and it I possible to form forecast estimates of assess real resources (excess reserves) of the structural bearing capacity.

Thus, the work of automated systems of monitoring structures of buildings is based on the results of three-dimensional calculations of the interaction of elements in the "construction-foundation-soil" system, taking into account the nonlinearity and mechanical properties of the materials of individual structural elements. Design models should reflect not only the maximum design loads and impacts, but also dynamic ones characterizing the construction and operation period [10]. However, it becomes necessary to recalculate the parameters of the applied models for the correct interpretation of the data coming from the measuring equipment, i.e. solving the inverse problem [10-12]. In this case, it is rather difficult to accurately assess the possible places of deformation in the foundation and the

structure on the basis of inclinometry data due to the finite number of sensors, the uneven load on the foundation and the nonlinear properties of soils and their uneven reaction, and the complexity of the building structure. In solving the inverse problem the complexity of the interpretation of inclinometry data is also caused by subjectivity in choosing the "construction-foundation-soil" models, the lack of the unified calculation methodology and some inconsistencies in regulatory documents [11, 13-16].

The aim of this work is to develop the algorithm for solving the inverse problem of the inclinometric control, which carried out during geotechnical monitoring based on accelerometric sensors, on the example of the determining of changes in the load parameters of the foundation.

2. The inclinometric control technique

Systems are the most promising inclinometric control systems for buildings used in geotechnical monitoring which are built on the basis of accelerometers using the phase-measuring control method and the temperature correction algorithm [17, 18]. The use of the phase metric method of the control of space change of the position of the sensor allows measurements with an error of $\pm0.001°$ and the accuracy of registration of the settlement of the foundation $\pm0.1mm$ [17, 19, 20].

The settlement of the foundation ΔS_i is recorded at the i-th point by the change in the angles of inclination $\Delta\alpha_i$ of the axes of the accelerometers $\{x_i, y_i, z_i\} \rightarrow \{x_i^*, y_i^*, z_i^*\}$ (figure 1). In this case, it becomes possible to register the angular parameters of deflections and displacements at controlled points of the foundation together with the foundation draft.
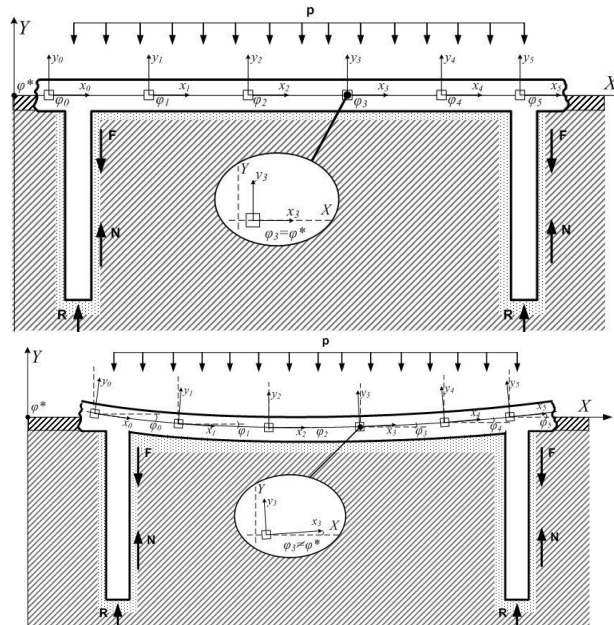
Figure 1. The scheme of the inclinometric control.

In this case, the total settlement of the foundation is defined as:

$$S_n = \sum_{i=1}^{n} \Delta S_i , \quad \alpha_n = \alpha_0 + \Delta\alpha_n, \qquad (1)$$

where α_0 is the angle of rotation of the support basis, $\Delta S_i = l_i \sin \Delta\alpha_i$.

It is possible of the localization of the place of possible deformation and of the exit of deformation parameters of the foundation beyond the permissible limits during the processing of the inclinometry data based on model data, as part of solving the inverse problem.

3. The algorithm of the solving of the inverse problem of the inclinometric control

Algorithms of the evaluating of deformation parameters can be considered within the framework of constructing of mathematical models of interacting processes during the dynamic influence of various factors on the construction-foundation-soil system. These models would allow indirectly to assess the imbalance of forces in the construction-foundation-soil system using the inclinometry data.

The change of angles of structural elements and the foundation can be represented in the vertical plane by the differential equation [21]:

$$mz'' + B_z z' + k_z z = F_z(j\omega),\tag{2}$$

where m is the mass of the foundation; B_z - the damping coefficient of the foundation base for vertical slopes and rotational vibrations; k_z - the stiffness factors of the base of the foundation with elastic uniform compression and shear, as well as with uneven compression; z - the displacement of the center of gravity and the vertical angle of rotation of the foundation; F_z - the vertical component of the effects; ω - frequency of exposure.

By analogy, horizontal and rotational vibrations can be described by independent systems of differential equations:

$$\begin{aligned}
&mx'' + B_x(x' - h\varphi_x') + k_x(x - h\varphi_x) = F_x(j\omega),\\
&\theta_x\varphi_x'' - B_x h(x' - h\varphi_x') - k_x h(x - h\varphi_x) + B_{\varphi x}\varphi_x' + (k_{\varphi x} - mgh)\varphi_x = M_x(j\omega)
\end{aligned}\tag{3}$$

$$\begin{aligned}
&my'' + B_y(y' - h\varphi_y') + k_y(y - h\varphi_y) = F_y(j\omega),\\
&\theta_y\varphi_y'' - B_y h(y' - h\varphi_y') - k_y h(y - h\varphi_y) + B_{\varphi y}\varphi_y' + (k_{\varphi y} - mgh)\varphi_y = M_y(j\omega)
\end{aligned}\tag{4}$$

where $\theta_{x,y}$ is the moment of inertia relative to the axes of rotation; B_x, B_y, $B_{\varphi x}$, $B_{\varphi y}$ - damping coefficients of the foundation foundation for horizontal and rotational vibrations; k_x, k_y, $k_{\varphi x}$ $k_{\varphi y}$ are the stiffness coefficients of the base of the foundation with elastic uniform compression and shear, as well as with uneven compression; $x, y, z, \varphi_x, \varphi_y$ - displacement of the center of gravity and the rotation angles of the foundation; h - the distance from the center of gravity to the base of the foundation; F_x, F_y, M_x M_y - horizontal components of the impacts; ω - frequency of exposure.

Expressions (2) - (4) describe the model of the foundation's behavior in the conditions of the linearly deformed soil foundation and under the condition of an uneven load. Equations (2) - (4) can be written in terms of the transfer function of the operator type $p = j\omega$ as:

$$H_z(p) = (mp^2 + B_z p + k_z)^{-1},$$

$$H_F^{x,y}(p) = -h_M^{x,y}(h_F^{x,y} h_M^{\varphi x,\varphi y} - h_M^{x,y} h_F^{\varphi x,\varphi y})^{-1}, \quad H_M^{x,y}(p) = h_F^{x,y}(h_F^{x,y} h_M^{\varphi x,\varphi y} - h_M^{x,y} h_F^{\varphi x,\varphi y})^{-1},$$

$$H_F^{\varphi x,\varphi y}(p) = h_M^{\varphi x,\varphi y}(h_F^{x,y} h_M^{\varphi x,\varphi y} - h_M^{x,y} h_F^{\varphi x,\varphi y})^{-1}, \quad H_M^{\varphi x,\varphi y}(p) = -h_F^{\varphi x,\varphi y}(h_F^{x,y} h_M^{\varphi x,\varphi y} - h_M^{x,y} h_F^{\varphi x,\varphi y})^{-1}$$

$$h_F^{x,y} = mp^2 + B_{x,y}p + k_{x,y}, \quad h_F^{\varphi x,\varphi y} = h_M^{x,y} = -(B_{x,y}hp + k_{x,y}h),$$

$$h_M^{\varphi x,\varphi y} = \theta_{x,y}p^2 + (B_{x,y}h^2 + B_{\varphi x,\varphi y})p + k_{x,y}h^2 + k_{\varphi x,\varphi y} - mgh$$

Measurement of the parameters of the acting external influences F_x, F_y, F_z, M_x M_y can be measured at monitoring points using strain gauge sensors. Thus, the damping coefficients of the foundation base and the stiffness coefficients of the foundation base are not determined when sharing the inclinometry and tensometry data in the described models. These coefficients are determined by solving the regression equation with the sufficient set of measurement data.

Imagine external influences in the form of decomposition of Fourier harmonics:

$$F_x(t) = \sum_{v=0}^{\infty} C_v^{FX} \cos(v\Delta\omega + \phi_v^{FX}), F_y(t) = \sum_{v=0}^{\infty} C_v^{FY} \cos(v\Delta\omega + \phi_v^{FY}),\ F_z(t) = \sum_{v=0}^{\infty} C_v^{FZ} \cos(v\Delta\omega + \phi_v^{FZ}),$$

$$M_x(t) = \sum_{v=0}^{\infty} C_v^{MX} \cos(v\Delta\omega + \phi_v^{MX}), F_y(t) = \sum_{v=0}^{\infty} C_v^{MY} \cos(v\Delta\omega + \phi_v^{My})$$

In accordance with the given presentation, we will limit the frequency range of the analyzed signals v_{max}, we will obtain $N = 5(v_{max} + 1)$ equations for the regression determination of the load parameters of the foundation:

$$\Psi(k_x, k_y, k_z, B_x, B_y, B_z, B_{\varphi x}, B_{\varphi y}) = \sum_{v=0}^{v\,max} \left(\mathbf{H_F} - \widetilde{\mathbf{H}}(\Delta\mathbf{x}, \Delta\mathbf{y}, \Delta\mathbf{z}, \varphi_{\mathbf{x}}, \varphi_y) \right)^2$$

4. The results of experimental studies

Studies were carried out during the construction of a low-rise structure with a columnar foundation in the period from May 1, 2018 to October 1, 2018. It is the practical verification of the developed algorithm for solving the inverse problem of inclinometric control. The studied structure has the following foundation characteristics d = 0.5 m, H = 1.8 m, L = 15 m, P = 14.3 t, the location of the pillars on average at a distance of 2 m.

Figure 2 (a) presents the average results of the inclinometric control for 7 sensors at 10 points of the analyzed period. The obtained results on the assessment of the foundation deformation correlate well with the calculated data. Figure 2 (b) shows the foundation deformation graphs in the last period of the study, that obtained by the developed algorithm (blue line) and averaging of inclinometry data (red line). The correlation coefficient is 0.96. The unevenness of the deflection of the foundation between the pillars (blue line in Figure 2 (b)) is explained by its uneven loading during operation of the structure under construction.
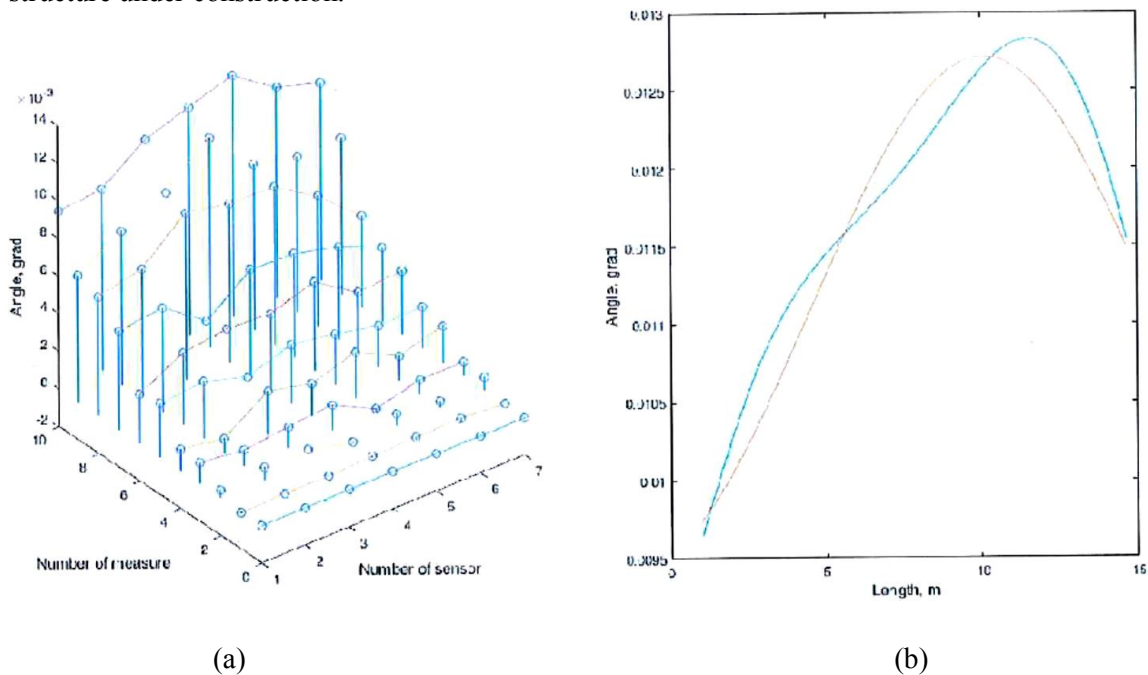

(a)   (b)

Figure 2. Research results.

5. Conclusion

Thus, as can be seen from the results of the interpretation of inclinometry data, the developed algorithm allows us to localize the place of violation of the foundation integrity, which leads to its deformations, to determine the places where the linear parameters of the foundation go beyond acceptable limits. With the joint use of strain gauges, it becomes possible to assess the torque and stress distribution in the foundation of the structure.

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