Modelling and forecasting of soil deformations in karst-hazardous areas

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Abstract

In the context of constructing and operating buildings and engineering structures in karst-prone areas, detailed monitoring and analysis of the processes affecting soil base stability are crucial. In such regions, the formation of karst cavities and sinkholes is often observed, leading to significant deformations and the potential destruction of foundations. This article presents a comprehensive study of the "soil base - foundation - structure" system to identify and predict the initial stages of soil base failure. The article details the results of a laboratory experiment that simulates soil deformation and failure under load. Machine learning methods for processing time series of electrical signals recorded during the experiment are also presented. These methods enabled the detection of areas indicating soil integrity violations, opening new prospects for predicting and preventing man-made accidents. The proposed approach to monitoring data analysis enhances the prediction and prevention of man-made accidents, thereby increasing the reliability of engineering structures.

Keywords

soil foundation, geoelectric methods, deformation monitoring, stress-strain modelling

1. Introduction

For the construction of facilities in areas with existing urban and industrial development, it is necessary to carry out geotechnical forecasting and monitoring. When designing foundations for new or reconstructed structures in built-up areas, it is crucial to assess the impact of construction on the stress-strain state of the surrounding soil mass, including the foundations of adjacent buildings. In karst-prone areas, the construction and operation of buildings may trigger the activation of exogenous geodynamic processes [1], leading to the formation of karst cavities and sinkholes, which can cause soil deformation and the failure of foundations [2].

A complex of interconnected natural, natural-technogenic, and technogenic objects forms a single geotechnical system, the "soil-foundation-building," whose state is determined by a wide range of natural and technogenic factors [3, 4]. It is also essential to accurately and promptly predict the activation and development of deformation processes.

Monitoring the geological environment in the development area using direct geophysical methods is technically and economically impractical [5]. In this case, to obtain information about the main elements of the geological environment, as well as its physical and mechanical properties, it is necessary to use shallow engineering geophysical monitoring methods [6, 7]. The objects of geotechnical monitoring in this context are: foundations, building structures, retaining structures of

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excavations, the soil mass surrounding the underground parts of structures, and soil foundations of roads, including those for railway transport [8].

During their operation, buildings are exposed to both external and internal influences—such as radiation, temperature, precipitation, chemical processes, biological factors, frost heaving, and the hydrogeological influence of soils—which significantly impact the durability of buildings and structures [1, 2, 8].

One of the main reasons for the reduction and loss of bearing capacity in the structures of technological facilities is the adverse natural and man-made impacts on the "soil-foundation-building" system [1, 2, 8]. These impacts cause deformations in the soil base, leading to damage to the foundation and the superstructure. To assess the technical condition of the foundation, it is necessary to measure the mechanical and physical properties of the soil, as well as the parameters of the applied loads, and to calculate the stress-strain state (SSS). Timely detection of deformation processes and control over the impact of additional loads on the foundation allow for tracking changes in the technical condition of structures, which is crucial for preventing emergencies that can cause serious damage, including the complete loss of the foundation's bearing capacity and the inability to continue its operation [9].

The most promising method for organizing automated control of geodynamic objects is the use of geoelectric probing techniques, which ensure effective monitoring of geological objects, assessment of their condition, and forecasting of their development, owing to their advanced technology [6, 7, 9]. The combined use of geoelectric and seismic methods, i.e., the application of the seismoelectric method for monitoring the geological environment, will enhance the efficiency of geological research by reducing the ambiguity in the interpretation of geophysical data [9, 10, 11].

In general, the geological environment under study can be represented as a dynamic system [11, 12] (Fig. 1). The output signal received from the geodynamic monitoring system is a cumulative response to atmospheric influences, operational loads, and the temperature and hydrological regime of the geological environment. Any exogenous or endogenous impact results in changes to the parameters of the geological environment.

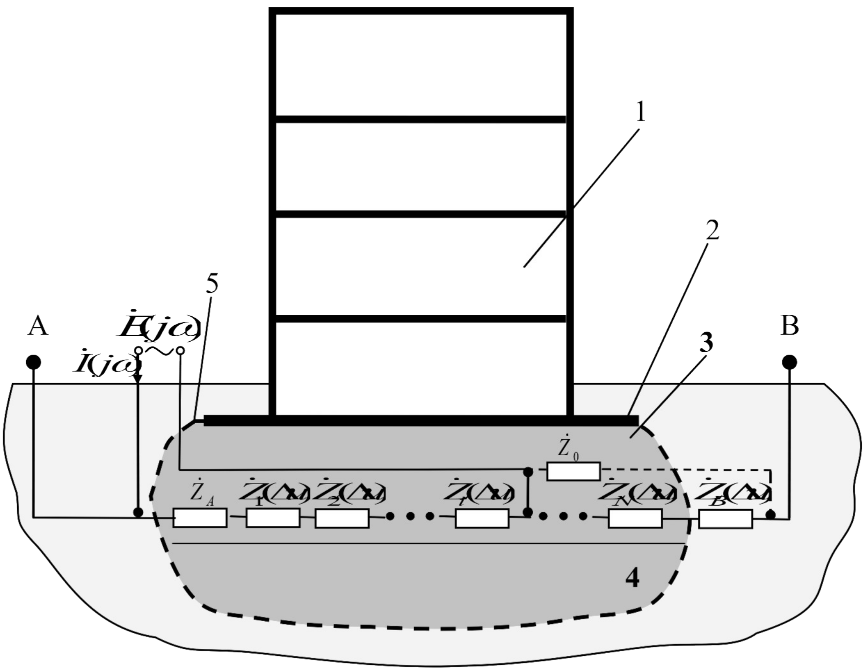

Figure 1: Geotechnical system "soil-foundation-building"; 1 - building, 2 - building foundation, 3 - bearing layer of the foundation base, 4 - the underlying layer of the foundation base, 5 - the deformable area of the foundation base.

The aim of this work is to substantiate and explore an integrated approach to solving the challenges of geotechnical monitoring within the "soil base – foundation – structure" system. This approach will enable the identification of the initial stages of foundation failure by combining geoelectric and seismic methods for monitoring the geological environment.

2. Application of seismoelectric method of monitoring the soil-foundation-building system

The Mohr-Coulomb elastic-plastic model is used to assess the stress-strain state of soils at the base of structures [13]. This model combines Hooke's law with the Coulomb failure criterion, accounting for elastic behavior under low loads and plastic behavior at failure. A notable feature of this model is its simplification in determining soil shear resistance near the limit state. In practice, Young's modulus and Poisson's ratio are typically treated as constants [9, 13].

The main physical and mechanical characteristics of soil for applying this model in the geotechnical monitoring of structures are the elastic modulus (E), the internal friction angle (φ), and the cohesion coefficient (c). Shear deformations in the soil lead to a redistribution of stresses within the foundation elements of the structure. The shear resistance of soils is strongly influenced by their density, moisture content, mineral composition, and stress state [14, 15]. It is also well-known that these characteristics significantly affect the geoelectric properties of soil, which are measured using geoelectric methods.

When a seismoacoustic signal $x_s(t)$ is applied to the studied medium, its parameters change [9]. In this case, it is described by the impulse response $h_{es}(t)$, the transfer function $H_{es}(j\omega)$, and the received signal $y_{es}(t)$ and its spectrum $Y_{es}(j\omega)$ are the result of seismoelectric conversion.

Since the geological environment under study, in the presence and absence of elastic action, is unambiguously described by the impulse response he(t) or hes(t), the presence of inhomogeneities, karst cavities and deformation processes in it can be assessed by the mutual correlation of these characteristics.

$$B_{es}(\tau)=\int_{-\infty}^{\infty} h_e(t)h_{es}(t-\tau)dt \tag{1}$$

Since the most informative is not the time domain, but the frequency domain, it is possible to move from the mutual correlation function to the mutual energy spectrum $W_{es}(\omega)$ of these characteristics, which is related to the mutual correlation function by the Fourier transform

$$W_{es}(\tau)=\int_{-\infty}^{\infty} B_{es}(\tau)e^{-j\omega\tau}d\tau \tag{2}$$

Based on (1) in (2), we obtain a generalized expression for the mutual energy spectrum of impulse characteristics of the geological environment in the presence and absence of elastic action

$$W_{es}(\tau)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_e(t)h_{es}(t-\tau)e^{-j\omega\tau}dtd\tau \tag{3}$$

Soil strength indicators are the resistance to soil shear. For rocks with structural strength, the relationship between tangential σ_τ and normal σ_n stresses on the shear area is described by the control of a straight line and is determined from Coulomb's law:

$$\sigma_\tau=\sigma_n\cdot tg\,\phi+c \tag{4}$$

Parameters such as the angle of internal friction φ and the coefficient of adhesion c are determined experimentally for each case. When monitoring the bearing capacity of soil, these properties are difficult to measure accurately, so laboratory tests on samples are used. Geoelectric methods allow tracking dynamic changes in these parameters through the complex resistance of the geological environment, which improves the accuracy of the assessment [11, 16]:

$$\dot{H}(j\omega,\Delta u)=\frac{\dot{E}(j\omega)}{\dot{I}(j\omega)}=\dot{Z}_A(j\omega)+\dot{Z}_B(j\omega)+\sum_{i=1}^{n} Z_i(j\omega,\Delta u) \quad (5)$$

where $\dot{Z}_A(j\omega),\dot{Z}_B(j\omega)$ - grounding resistance; $E(j\omega),I(j\omega)$ - parameters of the electric field source; ω - frequency of the probing signal; $\dot{Z}_i(j\omega,\Delta u)$ - resistance of the *i*-th element of the studied section of the geological environment under seismoacoustic influence Δu.

The representation of the transfer function (5) of the studied section of the geological environment in the form of a geoelectric model of series-connected complex resistances allows us to use the model of an *N*-layer imperfect dielectric. The given model contains *N* elements with layer thickness *d* and electrical parameters of the *i*-th element: permittivity ε_i, specific electrical resistance ρ_i. In this case, the transfer function of the studied section of the geological environment can be represented in the form of series-connected *RC*-circuits with parameters [9]:

$$C_i=\varepsilon_i S(j\omega,\Delta u_i)/d(\Delta u_i),\ R_i=\rho_i d(\Delta u_i)/S(j\omega,\Delta u_i), \quad (6)$$

where $S(j\omega)$ - the effective area of an element of the environment, determined taking into account the skin effect.

The transfer function of a geoelectric section without taking into account the grounding parameters can be expressed through the electrical parameters of a layered imperfect dielectric (6):

$$\dot{H}(j\omega,\Delta u)=\sum_{i=1}^{N}\frac{R_i}{1+x_i^2}-j\sum_{i=1}^{N}\frac{R_i x_i}{1+x_i^2}, \quad (7)$$

where $x_i=\omega R_i C_i=\omega\varepsilon_i\rho_i$.

3. Methodology of experimental research on the model

To evaluate the application of the seismoelectric effect in monitoring the condition of building foundations, a laboratory model of the 'soil base - foundation - structure' system was developed [4, 15]. The study aimed to analyze the behavior of this geotechnical system under the influence of karst processes and to assess the efficiency of the seismoelectric method. The laboratory setup simulates natural processes such as changes in moisture content, suffusion, and karst collapses. The setup includes: a model of a geodynamic object representing a reservoir with sand to simulate karst collapses; sources of probing signals for generating and recording seismic and electrical pulses; sensors for measuring current variations and seismic characteristics; and a data processing device for complex signal analysis to identify the initial stages of destruction.

Various scenarios involving the occurrence and development of karst processes accompanied by soil collapse were simulated during the experiments. These scenarios were accompanied by recording changes in the characteristics of seismic and electrical signals. Based on the obtained data, key parameters indicating the onset of irreversible subgrade destruction were identified.

The results of the experimental studies demonstrate that the combined processing of seismic and electrical monitoring data allows for more accurate and timely detection of the initial phases of destructive processes. However, for a deeper understanding and interpretation of the results, additional data processing is required to identify specific patterns in the time series. This approach will improve the methods for predicting the activation of deformation processes and for effectively preventing man-made accidents within the 'soil base - foundation - structure' system [4, 15, 16]. To fully reveal the patterns in the data, the use of advanced processing algorithms is necessary. These algorithms include machine learning and time series analysis methods capable of detecting complex hidden dependencies and patterns in large volumes of data [17].

The use of intelligent algorithms can significantly improve the accuracy of forecasting deformation processes in the «soil base - foundation – structure» natural-technical system by processing large volumes of data and identifying subtle changes in signals that indicate the initial stages of destruction. These methods are also effective for analyzing dynamic changes and uncovering hidden patterns, which is critical for the timely detection and interpretation of destructive processes. The integration of intelligent algorithms into monitoring systems optimizes data analysis and enhances the efficiency of early warning systems for potential threats, contributing to more accurate monitoring of soil conditions and the prevention of man-made accidents [14, 15, 16].

4. Processing the results to detect the time of soil integrity violation

Particularly important is the analysis of time series using modern data processing methods to detect the moment when soil integrity is compromised. The efficiency of data processing algorithms, such as the construction of envelope functions for time series and machine learning methods, is critical for accurately identifying the initial phases of destruction and ensuring the reliability of monitoring systems. A machine learning method, such as Isolation Forest, was employed to accurately detect anomalies and critical moments in the time series.

The data were loaded from a dataset containing soil electrical resistance measurements obtained from six electrodes. During the filtering process, the first 3 seconds of the experiment and the last 50 seconds were excluded to analyze only the relevant time series.

To visualize the data, graphs were constructed to show changes in electrical signals over time (Fig. 2). The first graph displays the signal time series, enabling a visual analysis of trends and anomalies in the data. Additionally, an envelope function was constructed for the time series, which helps to identify significant changes and allows for the visual detection of potential anomalies related to soil integrity violations. The envelope was constructed using the Moving Average (MA) and Standard Deviation (STD) methods. This approach allows for the visualization of upper and lower boundaries, which aid in identifying anomalies and significant changes in the data.

The moving average was calculated to smooth the time series to reduce the influence of random fluctuations. The standard deviation at time t was calculated to assess the variability of the data:

$$SDT_t = \sqrt{\frac{1}{\omega - 1} \sum_{i=t-\frac{\omega}{2}}^{t+\frac{\omega}{2}} \left(x_i - SMA_t\right)^2},$$

where SMA_t — the value of the moving average at time t, ω — window size (in our case - 1000 values).

Then, the upper (UE) and lower envelope (LE) functions were constructed based on the moving average and standard deviation:

$$UE_t = SMA_t + T \cdot STD_t$$
$$LE_t = SMA_t - T \cdot STD_t,$$

where T - the coefficient that determines how far the upper and lower envelopes are from the moving average (in this case 2).

This allows for the detection of significant changes in the data, as values outside the upper and lower envelope of the function may indicate the desired anomalies. In some cases, polynomial approximation is used to improve the accuracy of time series approximation, which can be optimized by various methods [18]. These approaches improve the quality of detecting anomalies in data.

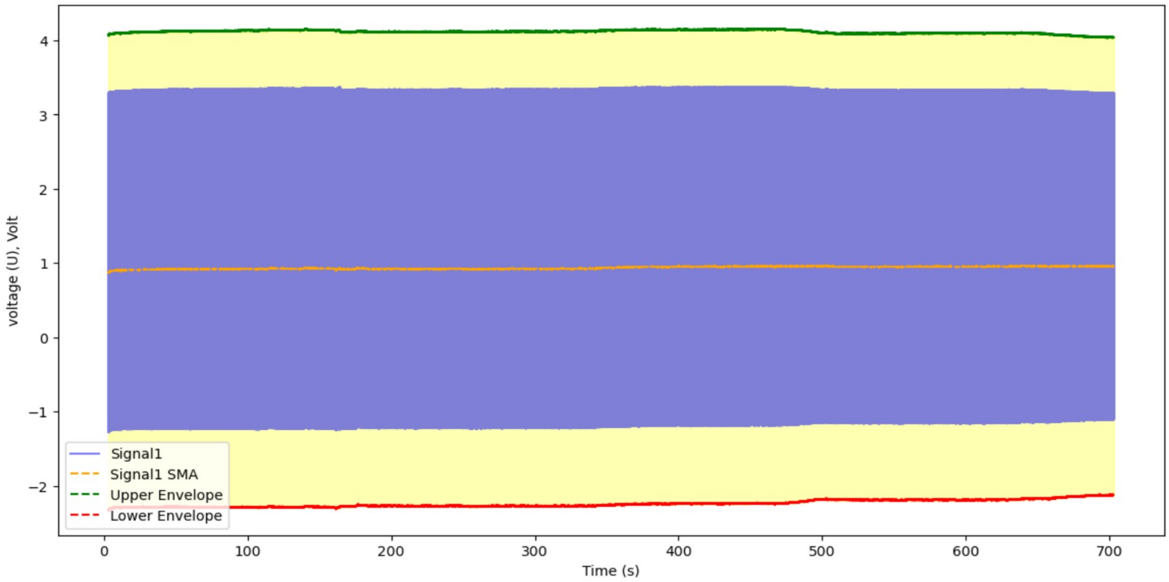

Figure 2: Change in voltage on the electrode.

The next step was to apply intelligent data processing using machine learning techniques. The Isolation Forest algorithm, designed to detect anomalies in large datasets, was applied for time series analysis. The Isolation Forest algorithm is based on the concept that anomalous data points (outliers) are easier to isolate than normal points. Each data point is isolated by randomly selecting a feature and a random split value. This process is repeated until every data point is isolated. The depth of the isolation tree (the number of splits required to isolate a point) is used as a measure of the 'anomalousness' of a data point:

1. For a point x in a data set X, a random feature fj and a random partition value v_j are selected:

$$x_{i,j} < v_j \text{ or } x_{i,j} \geq v_j.$$

2. The depth of the tree $h(x)$ required to isolate a point x serves to assess its "anomaly".
3. The anomaly of a data point is estimated using the formula:

$$s(x,n) = 2^{-\frac{E(h(x))}{c(n)}},$$

where $E(h(x))$ — average tree depth, $c(n)$ — constant depending on the number of data points n, defined as:

$$c(n) = 2H(n-1) - \frac{2(n-1)}{n},$$

where $H(i)$ — is the harmonic number used to normalize the average depth of isolation trees, $E(h(x))$, by the number of data points n.

The smaller $s(x,n)$, the more anomalous is the point x.

In our case, the Isolation Forest algorithm helps to identify anomalies that may indicate soil failure. By analyzing the isolation depth measured by this algorithm and the corresponding anomaly values, it is possible to pinpoint sections of the time series with potentially dangerous changes. Thus, the algorithm enables the identification of sections within the time series where significant changes related to soil integrity violations occur, which can be visualized and used for further monitoring. This algorithm also uncovers hidden patterns and anomalies that may not be apparent using traditional analysis methods (Fig. 3).

The results of intelligent data processing and time series analysis allowed us to identify critical moments indicating possible violations of soil integrity. The identified anomalies and changes in the data were interpreted to determine their significance and connection with soil failure. Optimization of monitoring systems based on the obtained results will help to improve existing monitoring methods and develop new approaches to forecasting and managing geotechnical risks.

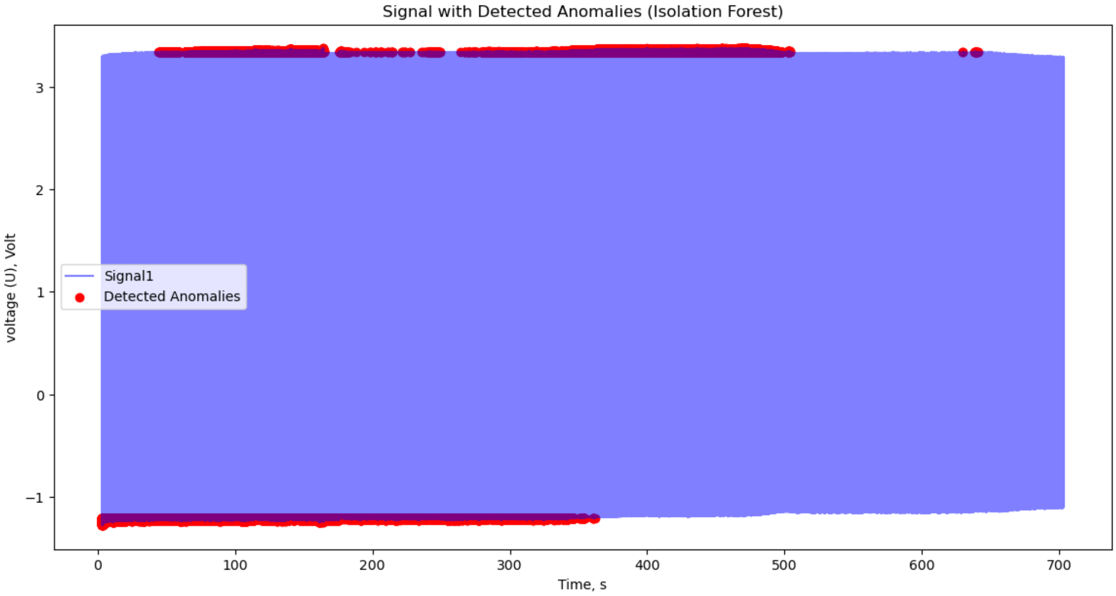

Figure 3: Graph of electrical voltage change over time with specific areas

5. Features of the implementation of the seismoelectric method in field geotechnical studies

Currently, various methods are employed for monitoring karst processes, each with its own advantages and limitations. Traditional geotechnical investigations involve drilling and soil sampling to obtain direct information about subsurface conditions. Although these methods provide accurate local data, they are invasive, labor-intensive, and cover limited areas, making them impractical for continuous monitoring over large regions [19].

Remote sensing techniques utilizing aerial or satellite imagery are used to detect surface manifestations of karst phenomena such as sinkholes or subsidence. While useful for large-scale monitoring, these methods are unable to detect subsurface anomalies before they become apparent at the surface, limiting their effectiveness in early warning systems.

Geophysical methods such as electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) are often employed to monitor karst-prone areas. ERT enables the mapping of resistivity variations to identify voids or moisture changes but is susceptible to external electromagnetic interference. GPR provides high-resolution imaging for shallow subsurface objects; however, its effectiveness decreases in conductive soils, and its penetration depth is limited [20].

Seismic methods are most effective at great depths but have limited resolution at shallow depths. They are also sensitive to external acoustic noise, which can compromise data quality [21].

The proposed seismoelectric monitoring method combines seismic and electrical measurements, enhancing sensitivity to changes in the mechanical and electrical properties of the soil. This integrated approach offers several advantages: early detection of deformation processes, non-invasive monitoring, and cost-effectiveness due to the use of intelligent data processing and machine learning algorithms. However, when applying the proposed monitoring method under real-world conditions, certain challenges may arise. Natural soils are significantly more heterogeneous and complex than laboratory models, exhibiting variations in moisture content, density, stratification, and the presence of various inclusions [22]. To address this issue, field calibration of the laboratory models is necessary. This can be achieved by conducting pilot studies in selected karst areas. Comparing these field data with laboratory results will allow for adjustments to the models to account for real-world conditions.

The scale of monitoring in practical applications is also considerably larger. Therefore, the following parameters for the experimental setup and probing signals are proposed: the use of 1-

meter-long brass rods driven into the ground as emitting and receiving electrodes; probing electrical signals with a frequency of 166 Hz, an amplitude of 500 V, and a harmonic waveform.

Signal generation and processing are intended to be performed using the multifunctional ADC/DAC module E-502-P-EU-D, a data acquisition system based on USB and Ethernet interfaces. Recording changes in the electric field will be conducted with an ADC sampling frequency of 10,101 Hz. To monitor the seismic background during measurements, a network of several highly sensitive digital short-period seismometers ZET 7156 is planned.

When processing real data, issues such as the presence of various interferences from natural and anthropogenic sources may occur. Data processing algorithms need to be adapted to handle large volumes of information and to account for potential noise.

Thus, despite the existing challenges, the seismoelectric monitoring method has significant potential for application under real-world conditions. Its ability to provide early warnings makes it a valuable tool for detecting and predicting karst-related ground deformations, complementing existing approaches and enhancing the safety of engineering structures.

6. Conclusion

The study employed an integrated approach to modelling soil loads and failures, which provided a deeper understanding of the dynamics of deformation processes within the soil-foundation-building system. The modelling demonstrated that an increase in operational loads significantly intensifies deformation processes, potentially foreshadowing future foundation failures. The analysis of the geological environment's responses to seismic and electrical effects enabled a more precise determination of the depth and location of potential failure zones within the foundation base, thereby confirming the necessity of specialized monitoring of these zones during operation.

In laboratory experiments, changes in electrical voltage in the soil under load were recorded. Using intelligent algorithms, these changes made it possible to identify anomalies indicating soil integrity violations and to develop a method for more accurately predicting collapses and monitoring deformation processes.

Thus, the application of time series analysis and intelligent data processing methods played a key role in enhancing the accuracy and efficiency of soil foundation condition monitoring. The developed methods improve the precision of identifying the initial stages of destruction, thereby enhancing safety and preventing man-made accidents in geotechnical systems. These methods also hold the potential for further improvement of monitoring processes and ensuring the reliability of structures in a changing geological environment.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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