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Methods for Assessing the Layered Structure of the Geological Environment in the Drilling Process by Analyzing Recorded Phase Geoelectric Signals

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Citation: Abzhanova, A.; Bykov, A.; Surzhik, D.; Mukhamejanova, A.; Orazbayev, B.; Svirina, A. Methods for Assessing the Layered Structure of the Geological Environment in the Drilling Process by Analyzing Recorded Phase Geoelectric Signals. *Mathematics* **2024**, *12*, 2194. <https://doi.org/10.3390/math12142194>

Academic Editors: Longjun Dong, Daoyuan Sun, Ju Ma, Weiwei Shu, Qiong Wu, Rui Yong, Tao Wen and Kun Fang

Received: 23 May 2024
Revised: 24 June 2024
Accepted: 10 July 2024
Published: 12 July 2024



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Abstract: Assessment of the current state of the near-surface part of the geological environment and understanding of its layered structure play an important role in various scientific and applied fields. The presented work is devoted to the application of phasometric modifications of geoelectric control methods to solve the problem of the detailed complex study of the underground layers of the environment in the process of drilling operations with the use of special equipment. These studies are based on the analysis of variations in phase parameters and characteristics of an artificially excited multiphase electric field to assess poorly distinguishable details and changes in the layered structure of the medium. The proposed method has increased accuracy, sensitivity and noise proofness of measurements, which allows for extracting detailed information about the heterogeneity, composition and stratification of underground geological formations not only in the zone where the drill makes contact with the medium, but also in the entire control zone. This paper considers practical mathematical models of phase images for basic scenarios of drill penetration between the layers of the near-surface part of the geological medium with different characteristics, obtained by means of approximation apparatus based on continuous piecewise linear functions, and also suggests the use of modern machine learning methods for intelligent analysis of its structure. Studying the phase shifts in electrical signals during drilling highlights their value for understanding the dynamics of soil response to the process. The observed signal changes during the drilling cycle reveal in detail the heterogeneity in soil structure and its response to changes caused by drilling. The stability of phase shifts at the last stages of the process indicates a quasi-equilibrium state. The results make a significant contribution to geotechnical science by offering an improved approach to monitoring a layered structure without the need for deep drilling.

Keywords: near-surface part of geological environment; layered structure; drilling process; phasometric methods; geoelectrics; phase images; approximation; continuous piecewise linear functions; machine learning; intellectual analysis

MSC: 86-10

1. Introduction

Assessment of the current state of the near-surface geological environment and understanding of its layered structure play an important role in various scientific and applied fields, ranging from geophysics to geotechnical and environmental engineering and others. For example, in geotechnical engineering, accurate knowledge of the properties and characteristics of the environment is necessary for designing foundations, analyzing the stability and stability of slope areas to ensure the overall structural integrity of the engineering and technical facilities being constructed, etc. In applied geo-ecology, a deep understanding of the composition of underground layers helps in assessing groundwater movement, analyzing and predicting the mechanisms of oil pollutant transportation, taking measures to eliminate adverse environmental effects, etc. Understanding the structural composition of the geological environment is also extremely important for soil treatment in agriculture [1].

In the context of the detailed complex study of underground layers of the environment, especially in the process of drilling operations with the use of special equipment, the use of phasometric modifications to geoelectric methods of control is an effective tool for their study. These studies are based on the analysis of the variations in phase parameters and characteristics of an artificially excited multiphase electric field for the evaluation of weakly distinguishable details and changes in the layered structure of the surface part of the geological medium. The choice of the phasometric method of control is conditioned by its increased accuracy, sensitivity and noise immunity during measurements, and the electric field—by the significant sensitivity of the electrical properties of the medium to the presence of surface inhomogeneities and ongoing geodynamic processes [2,3].

In this control method, the study of variations in phase parameters and characteristics of geoelectric signals recorded during drilling is aimed at extracting valuable information about the heterogeneity, composition and stratification of underground geological formations. The proposed method provides detailed information not only about the zone of drill contact with the medium, but also allows for obtaining extended information about the structure of underground layers in the whole control zone [4,5].

In this aspect, it is extremely important to have easy-to-use mathematical models of phase images for basic scenarios of drill penetration between layers of the near-surface part of the geological medium with different characteristics, as well as to use modern methods of machine learning for the intelligent analysis of its structure [6–15].

The study [2] aims to investigate the influence of the interaction between the near-surface geologic environment and reinforced concrete (RC) structures and their vulnerability to seismic effects. The study involved the design and modeling of a group of reinforced concrete structures placed on three different soil types. The interaction between the near-surface portion of the geological environment and the foundation was modeled using a non-equilibrium Winkler-based technique. Non-equilibrium static analysis and incremental dynamic analysis were performed to evaluate the seismic behavior and vulnerability of the reinforced concrete structures, taking into account the assumptions of rigid and flexible foundations.

The numerical analysis revealed that soil–structure interaction (SSI) has a significant impact on the vulnerability and stability characteristics of structures installed on rigid soils. This emphasizes the importance of considering SSI in the design and construction of buildings and structures, especially in seismically active regions. In the course of the study, a methodology for direct determination of the stability level of soil foundations was developed. It involves modifying the acceleration spectrum of the main mode. This approach provides engineers with an effective tool to better assess risks and design measures to strengthen structures, ultimately contributing to their safety and reliability. This paper contributes to the understanding of the seismic vulnerability of the interaction between the near-surface geologic environment and reinforced concrete structures by providing practical results for assessing the vulnerability of reinforced concrete structures under different soil types.

This paper explores the fundamental role of soil in maintaining ecosystem functions and its contribution to the agricultural sector [16], flora growth, fauna viability, biodiversity conservation, carbon sequestration and overall environmental health. Soil, as a critical component of the Earth's critical zone, is experiencing global degradation caused by anthropogenic and natural processes such as contamination, erosion, and increased salinity and acidity [17,18]. These changes negatively affect groundwater quality and stability of earth foundations, which in turn affect agriculture and infrastructure construction. In the context of global aspirations by 2030, the need to move towards sustainable soil management practices that will ensure soil conservation and restoration, as well as support sustainable agricultural sector and infrastructure development, is emphasized.

The study by Hou et al. [15] emphasizes the importance of soil conditions. The authors emphasize the interdisciplinary links between soil and key environmental aspects, including biodiversity and climate change, offering an integrated approach to address these issues. Recognizing that soil is a major terrestrial carbon reservoir, as well as a significant source of greenhouse gases and water, the study highlights the need to develop methods to monitor the condition of soil structure. The importance of agriculture in maintaining the required soil condition is highlighted as a critical factor requiring improved information management and knowledge sharing to encourage sustainable practices among land users. In the context of decreasing government funding for soil data collection, new technologies such as data mining algorithms [19] offer new opportunities for integrated data collection and analysis [20]. The study also highlights the relationship between soil sustainability and the sustainability of soil foundations, which has direct implications for construction and infrastructure, emphasizing the need to integrate soil research into the development of sustainable soil use strategies.

Groundwater at an optimal level can improve the stability of building foundations and prevent their deformation. Considering the importance of groundwater for the stability of soil foundations [20] and agricultural efficiency, it should be noted that the level and quality of groundwater can have a significant impact on the structural and functional characteristics of soils [21,22]. Also, there are studies describing the influence of water regime on the properties of soils used in the base of highways [23].

In agriculture, effective groundwater management and utilization can increase crop productivity and improve yield, which is critical for food security [22].

As part of the monitoring of the drilling process, research by Nielson et al. and Liu et al. presents a technique to monitor changes in the electrical characteristics of the signal caused by drill movement. The monitoring system, operating at 166 Hz and 500 V amplitude, provides reliable data transmission to depths of up to 250 m. The use of deep learning techniques, including capsule neural networks, allows for signal data to be analyzed with high accuracy. The WFT-2D-CapsNet modification showed 99% accuracy in identifying transitions between different rock formations, outperforming traditional MWD and LWD methods. These results emphasize the potential of applying advanced technologies in drilling process monitoring to obtain accurate data on ground conditions and drilling progress [24,25].

The study by Bykov et al. in [26] focuses on the use of the phasometric method to control the drilling process. A comprehensive review of the technical aspects of vertical electro-tomography using the phasometric method is provided. The study presents details of a laboratory experiment evaluating the effectiveness of drilling process control by using phasometry and demonstrating the dynamics of phase signal changes in the receiving lines of electrodes as the drill passes through soil layers with different characteristics. The results of the study, supported by graphical material, confirm the metrological capabilities of the proposed phasometric method, emphasizing its potential in the optimization of drilling parameters in real time.

Mathematical justification of the application of seismoelectric and phasometric methods of geoelectric control to detect defects and deformations at the early stages in the integrity of the foundation of railroad tracks was carried out in [27] (Bykov et. al). The

study considers laboratory modeling of the natural–technical system “railroad track” in order to assess the prospects of these methods. The results of laboratory studies demonstrate high efficiency in registration of weak useful electrical signals against the background of significant external interference. The obtained phase images in the course of laboratory modeling confirm the presence of a transient process causing the initial phase shift and allowing to detect the initial stage of defect formation in the soil base of the railway track.

As a result of the analysis of scientific works on the research topic, it was revealed that in the conducted research, insufficient attention is paid to the study and analysis of variations in the phase shifts of registered geoelectric signals in the process of drilling in order to assess the structure of the near-surface part of the geological environment. In addition, a mathematical description of the phase images of the basic scenarios of drilling transition between layers is required. This motivated the conduct of this study, aimed at investigating and addressing these issues.

2. Study Area

This study was carried out in a flat area, which, at the same time, is characterized by a complex structure and varied geological conditions. Within the study area, layers with different physical characteristics can be identified, including porosity, moisture content and composition. The thickness of the layers varies from 30–50 to 100–130 cm, which significantly affects the electrical properties of soils. There are no geodynamic processes, such as karst formations, that can affect the accuracy of measurements.

3. Materials and Methods

It is known [22,23] that measurements of phase parameters and characteristics have increased information content, accuracy and noise immunity in comparison with amplitude ones. At the moment, phasometric methods and geodynamic control devices are successfully used in the electromagnetic control of various geodynamic objects, in geotechnical monitoring of engineering buildings and structures, in goniometric control based on accelerometric transducers, etc.

The methods and devices of phasometric control are based on continuous measurements of instantaneous values of phase shift angles between oscillations of fields of equal frequency and the determination of their parameters and characteristics. For a pair of signals of the same angular frequency ω , the phase shift $\Delta\varphi = \varphi_2 - \varphi_1$ can be determined through the time delay $\Delta t = t_2 - t_1$ (time shift) as follows:

$$\Delta\varphi = \omega\Delta t = 2\pi f\Delta t = \frac{2\pi\Delta t}{T} = \frac{360^\circ\Delta t}{T},$$

where T is the signal period.

According to the provisions of measurement theory, the problem of determining the phase difference of a pair of oscillations $\Delta\varphi$ can be solved in various ways that allow for their implementation, both in analog and digital form. At the same time, the main classification of methods involves their differentiation according to the type of signals being compared, dividing them into methods for comparing the phases of quasi-harmonic and pulsed signals, with the second group of methods being less preferable for practical implementation. This is due to the appearance of additional measurement errors in the presence of high-frequency noise; useful or spurious amplitude modulation of the compared signals; shifting their zero level; as well as those caused by the loss of information due to the processes of converting quasi-harmonic signals into pulsed ones.

In relation to the tasks of automated monitoring of the layered structure of the geological environment, the use of phasometric control methods involves isolating, analyzing and monitoring the dynamics of the phase $\Delta\varphi(j\omega, x, y, z)$ transfer function of the controlled zone of the environment in real time (x, y, z —spatial coordinates).

At the same time, the general methodology for applying geoelectric modification of phasometric methods and active geodynamic control devices includes the following stages:

- Generation of sounding signals to create the necessary multiphase field structure in the controlled zone of the near-surface part of the geological environment;
- Excitation in the controlled zone of the near-surface part of the geological medium of a multiphase field using point radiating source poles;
- Adaptive control of the parameters of the probing signals and the positioning of the monitoring system to carry out its initial calibration and balancing according to the recorded field vectors;
- Reception and primary conversion of measuring signals recorded by point field receiver poles, necessary to eliminate existing interference and amplify measuring signals to the required level;
- Secondary processing of converted signals, aimed at forming phase images, determining their parameters and characteristics, as well as eliminating the geodynamic trend;
- Interpretation of the information obtained at the previous stage.

This experimental study was carried out using a specially designed rig for smooth and continuous drill immersion. The setup was designed in a radial configuration and equipped with eight receiving electrodes and two emitting electrodes. A moving average filtering method was used for signal processing. The size of the averaging window was 2000 samples (about two seconds). The digital-to-analog converter (DAC) operated in generation mode at a frequency of 166 Hz. The amplitude at the DAC output was set at 0.03 V. The data collected during the experiment were processed using sampling with a sampling rate of 1001 Hz. This ensured high accuracy and reliability of the results obtained.

Different color designations for the displayed phases of the recorded signals were used in the following graphical designation: Red (M1N1), Green (M2N2), Blue (M3N3) and Turquoise (M4N4). The input configurations of the experiments included three types of signals. The generated signals, represented by red and green, were generated during the experiment. Receiving signals, represented by blue and turquoise colors, corresponded to M1N1 and M2N2, respectively. The phase signals, represented by yellow and purple colors, represented M3N3 and M4N4, respectively. Thus, each experiment used three types of signals: generated input signals, received signals that were processed, and received phase signals.

Input Generated Signals. These signals represent electrical signals that were created and generated by the research equipment during the experiment. In this study, the red and green signals were activated and monitored to determine their effect on the sensing process and their influence on the acquired data.

Input receiving signals. These signals represent the input signals received from the receiving electrodes (M₁N₁, M₂N₂, M₃N₃ and M₄N₄) that responded to the probing electrical signal generated in this study. They recorded changes in the electric field as a result of the impact of the drill on the soil structure. These signals are the basis for further analysis and evaluation of soil structural characteristics.

Phase signals. Phase signals refer to the changes in phase of the signal received from different pairs of electrodes (e.g., Red M₁N₁, Green M₂N₂, Blue M₃N₃ and Turquoise M₄N₄). The phase characteristics of the signals can contain important information about soil properties such as soil composition, depth and other parameters. Analyzing these phase signals helps in deciphering the structure of the subsurface and evaluating its characteristics during the drill sinking process. All signal data were converted to text files with geometric details:

The distance between the transmitting electrodes A and B, through which a signal with a phase difference of 90 degrees is applied to the soil, was set to 1 m (see Figure 1).

The diameter of the "circle" for the receiving electrodes (M₁M₂M₃M₄N₁N₂N₃N₄) was 40 cm.

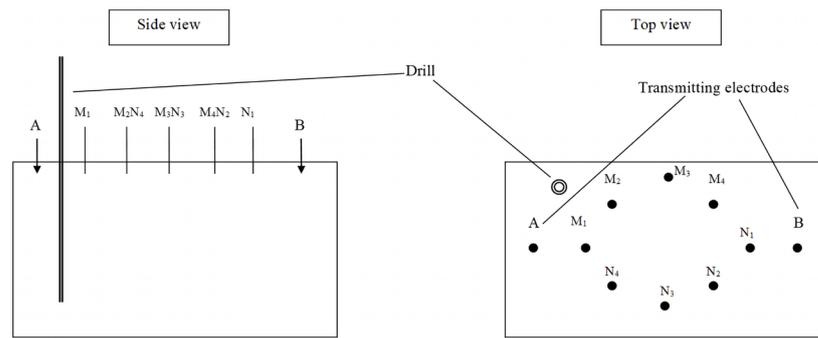


Figure 1. First experiment.

4. Results

4.1. Progress of the Experiment

This experiment involved preparing equipment, calibrating measuring instruments, registering phase geoelectric signals during the drilling process, and processing of the received data, including real-time monitoring. The experiment included uniform vertical immersion of the drill and immersion at an angle (approximately 45%). The corresponding results from these experiments were obtained and analyzed.

Experiments.

Immersion was performed both vertically (Experiments 1 and 2) and at an angle of approximately 45 degrees (Experiments 3 and 4).

Experiment 1 (Figures 2–4):

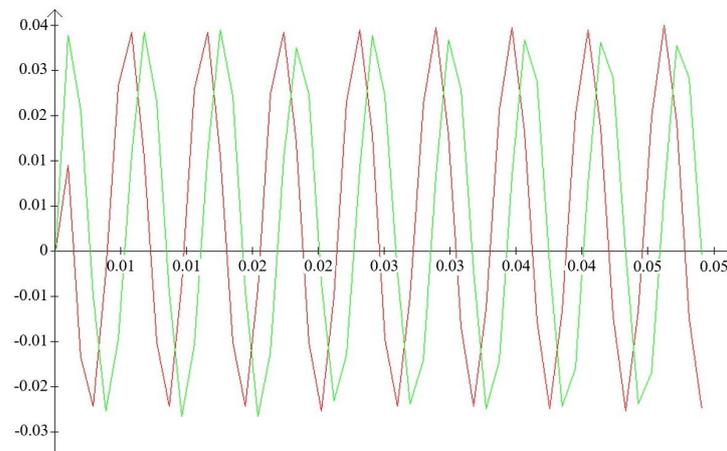


Figure 2. Input generated signals (first experiment).

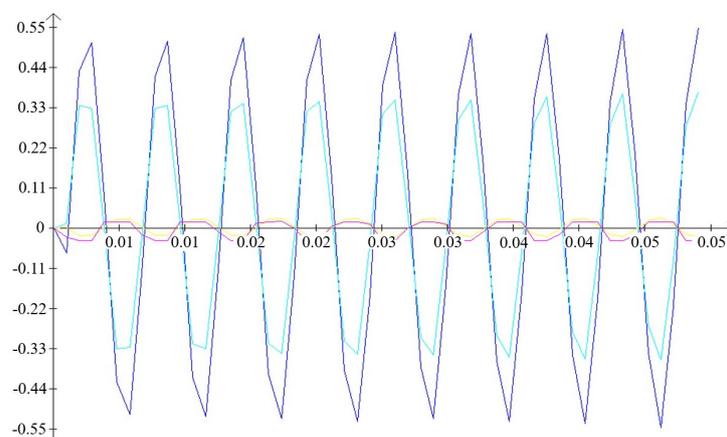


Figure 3. Input receiving signals (first experiment).

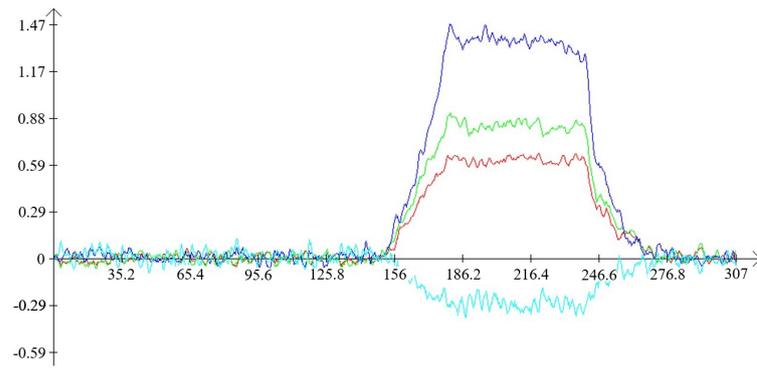


Figure 4. Phase signals (first experiment).

Diving: start—140 s; end—180 s.

Ejection: start—250 s; end—270 s.

Experiment 2 (Figures 5–8):

- Immersion: start—70 s; end—145 s.
- Extraction: start—220 s; end—260 s.
- Depth: 72 cm.

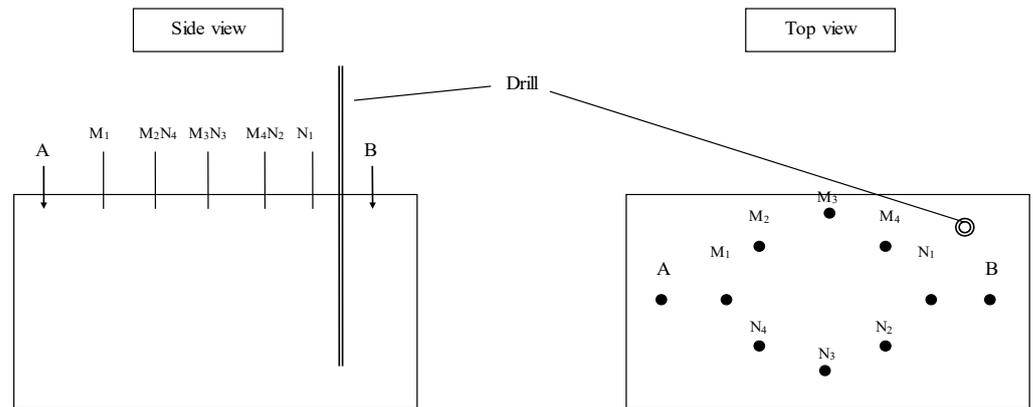


Figure 5. Second experiment.

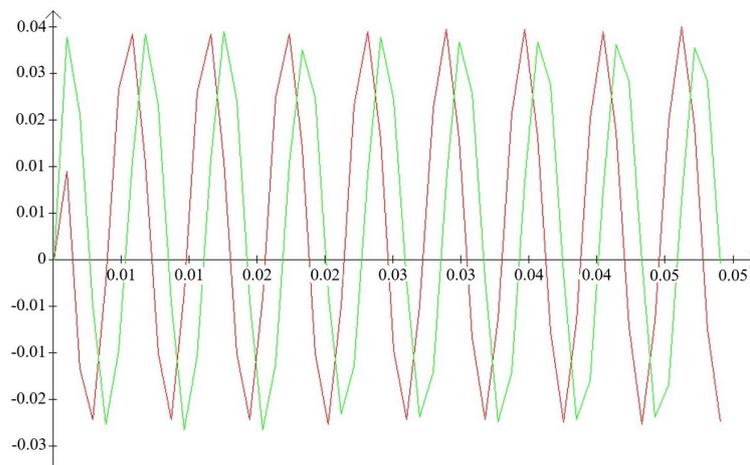


Figure 6. Input generated signals (second experiment).

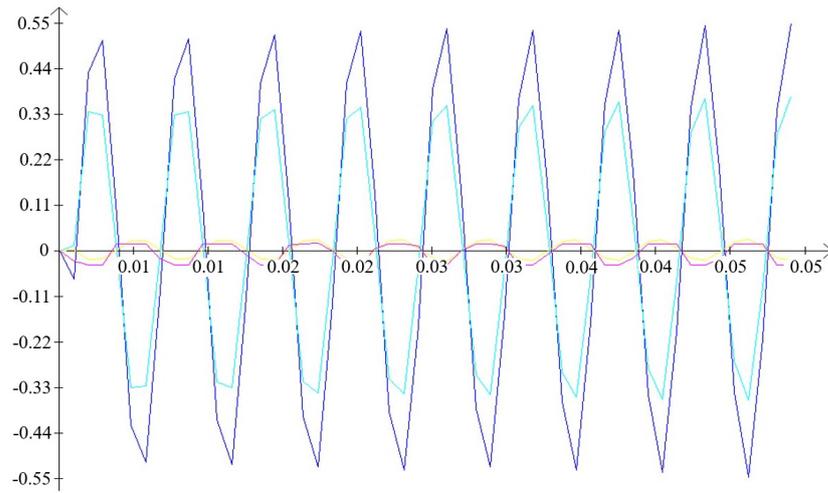


Figure 7. Input receiving signals (second experiment).

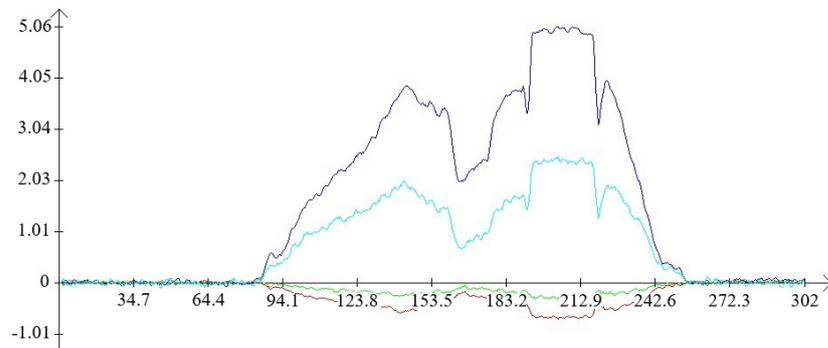


Figure 8. Phase signals (second experiment).

Diagonal dipping and extraction:
Experiment 3 (Figures 9–12):

- Immersion: start—60 s; end—140 s.
- Extraction: start—180 s; end—210 s.
- Depth: 140 cm.

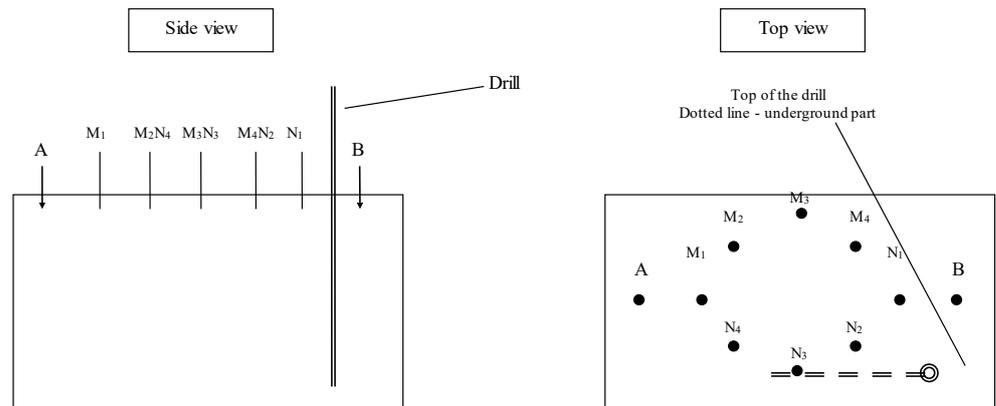


Figure 9. Third experiment.

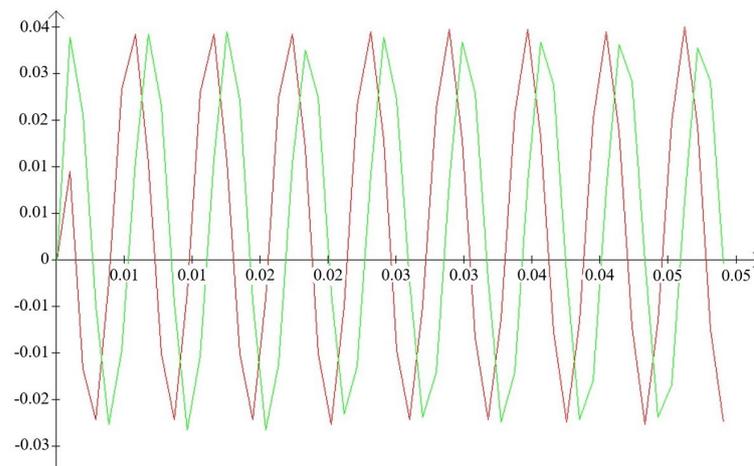


Figure 10. Input generated signals (third experiment).

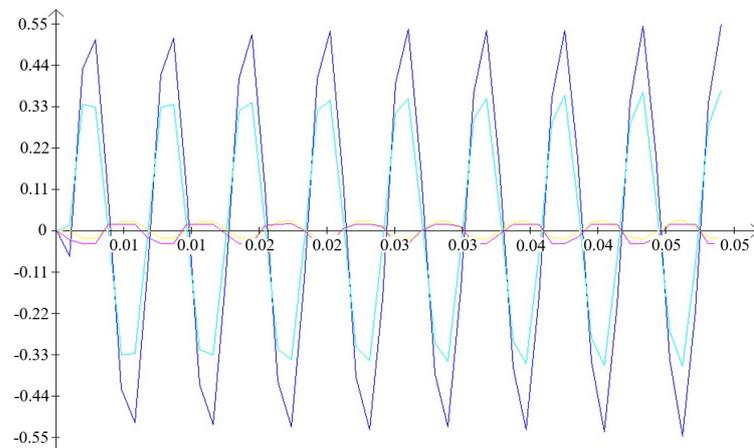


Figure 11. Input receiving signals (third experiment).

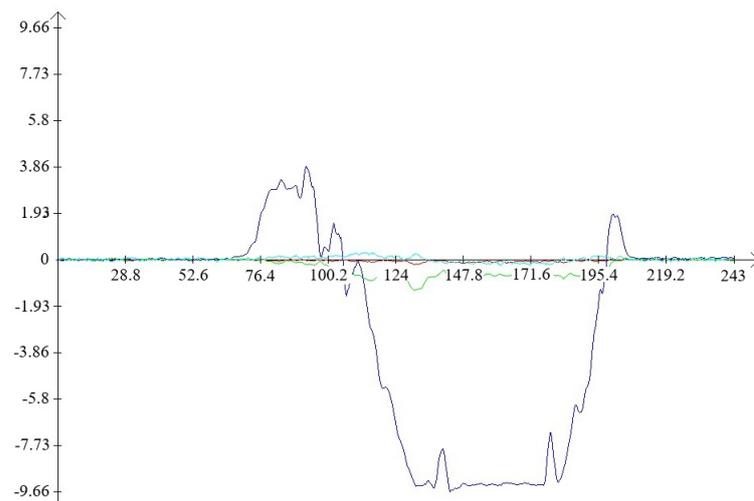


Figure 12. Phase signals (third experiment).

Experiment 4 (Figures 13–16):

- Immersion: start—70 s; end—125 s.
- Extraction: start—180 s; end—200 s.
- Depth: 140 cm.

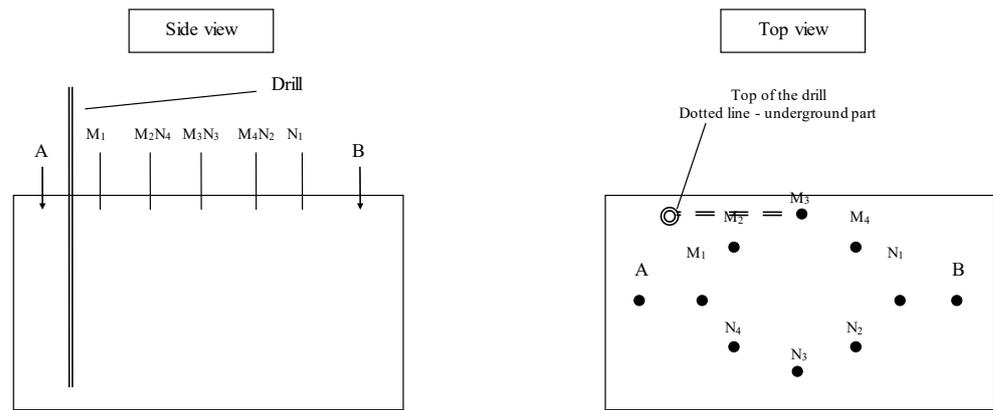


Figure 13. Fourth experiment.

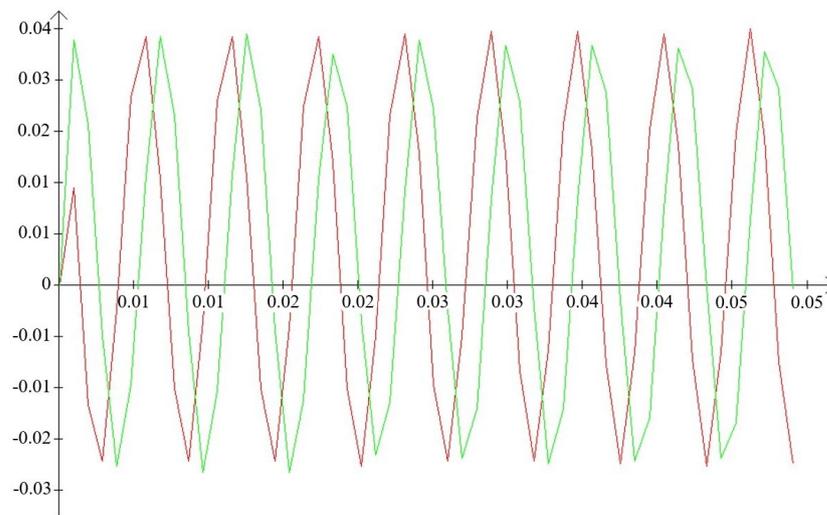


Figure 14. Input generated signals (fourth experiment).

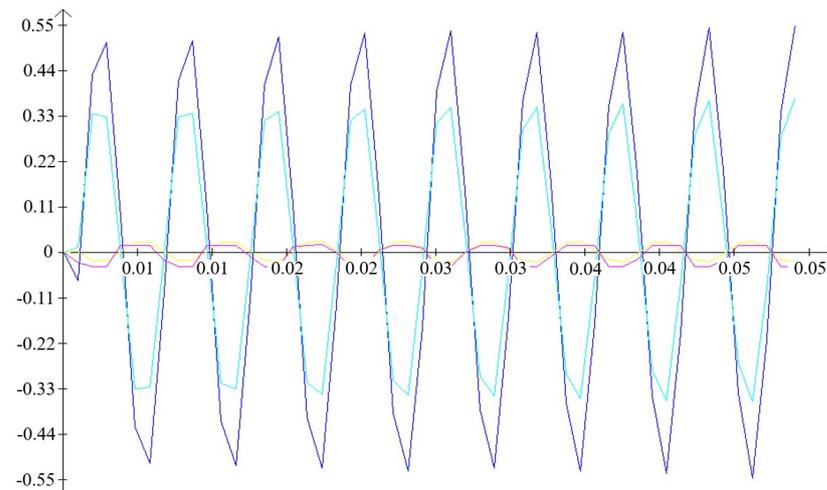


Figure 15. Input receiving signals (fourth experiment).

Intermediate analysis results allow for quickly identifying changes in the geological environment and making the necessary adjustments to the drilling process, which ensures high accuracy in assessing the structure of geological layers (see Figure 17).

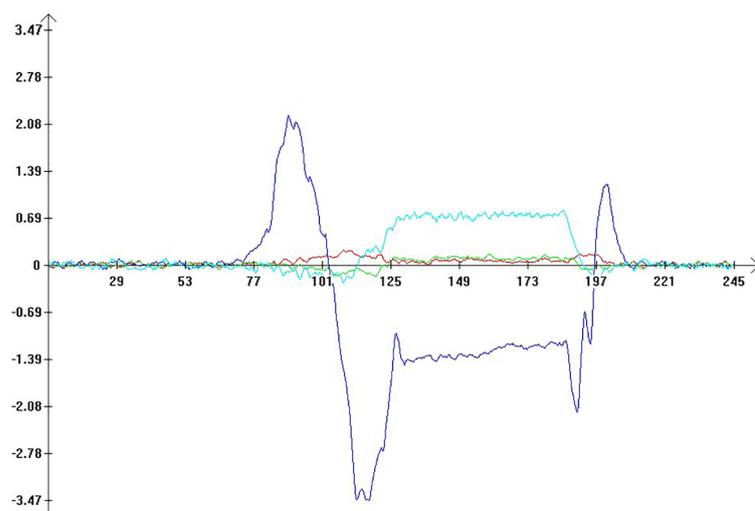


Figure 16. Phase signals (fourth experiment).



Figure 17. Geophysical control data collection point.

To assess the possibility of using geoelectric modification of phasometric methods and devices in the tasks of monitoring the layered structure of soils using an experimental installation, a full-scale study of the process of drilling through layers of the subsurface part of the geological environment with various electrical characteristics was carried out. The following parameters of the experimental setup were used in the experiment: the distance between the emitting electrodes AB 800 m; the distance between the receiving electrodes M_1N_1 —700 m; the distance between the receiving electrodes M_2N_2 —600 m; the distance between the receiving electrodes M_3N_3 —500 cm; the distance between the receiving electrodes M_4N_4 —400 m.

During the research, a well was drilled, while a metal drill was immersed in the ground to a depth of 250 m with registration of changes in the phase characteristics of electrical signals.

Brass rods with a length of 1 m driven into the ground were used as emitting and receiving electrodes, with the help of which an artificial electric field was created and recorded. The frequency of probing electrical signals was 166 Hz, the amplitudes of probing electrical signals were 500 V. Digital generation and signal processing were carried out using a data acquisition system based on the multifunctional ADC/DAC module

E-502-P-EU-D. The registration of changes in the electric field was carried out at a sampling frequency of ADC 10,101 Hz.

According to the results of the experimental studies, it was found that a change in the phase characteristics of the signals provides information about the depth of drilling and about the electrical characteristics of the soil layers into which the drill is immersed, which allows, in particular, for judging the degree of its moisture saturation.

4.2. Mathematical Models of Phase Images of Basic Scenarios of Drill Transition between Layers

To solve the problem of monitoring the soil structure in the near-surface part of the geological environment, it is recommended to apply an approach based on the creation of a group of basic mathematical models of typical phase images. These models can be used for subsequent calculation of their mutual correlation function with real phase images obtained as a result of processing of measurement signals from each channel of the monitoring system. The same approach can be applied to detect ground layers differing in their physical properties.

Such model phase images include reference (in the absence of geodynamic processes); reference in the presence of destabilizing factors of natural, climatic and anthropogenic character; reference in the presence of geodynamic processes; and reference in the presence of geodynamic processes and the impact of destabilizing factors of natural, climatic and anthropogenic character.

To compose these mathematical models, we can use the assumption of additive model of interaction of useful and interfering components of phase images and apply the approximation apparatus on the basis of continuous piecewise linear functions (CPLFs) [28], which have a simple typical analytical form of recording for complex signals of arbitrary form. Such functions include the switching (Figure 18a), including (Figure 18b) and combined NCLFs (Figure 18c).

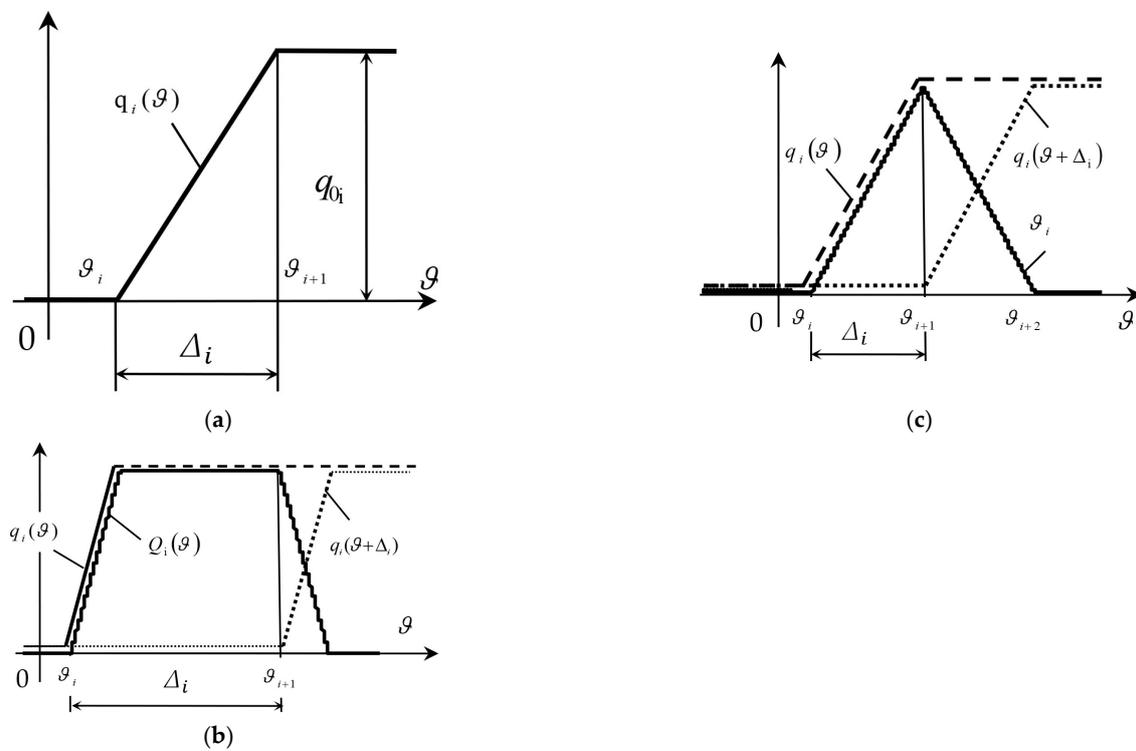


Figure 18. Approximating NCLFs for building phase image models: switching (a), including (b) and combined (c).

The switching NCLF can be analytically written in the following form:

$$q_i(\vartheta) = \frac{q_{0_i}}{2\Delta_i} (|\vartheta - \vartheta_i| - |\vartheta - \vartheta_i + \Delta_i| + \Delta_i),$$

where i —is the number of NCLFs, q_{0_i} —is the height of the function, ϑ , ϑ_i —is the value of the argument at the beginning and end of the slope section and Δ_i —is the length of the slope section.

The characteristics of switching NCLFs of different shapes can be obtained by summation of several modules.

A switching NCLF is obtained by subtracting two switching NCLFs:

$$Q_i(\vartheta) = K_\sigma \sum_{\lambda=0}^1 \sum_{\gamma=0}^1 (-1)^{\lambda+\gamma} \left| \vartheta - \vartheta_i - \gamma\Delta_i - \frac{\lambda}{2K_\sigma} \right|,$$

where K_σ is the steepness of the lateral components; λ , γ —identifiable parameters.

The combined NCLF, having the form of a triangular function, is analytically given as follows:

$$\hat{Q}_i(\vartheta) = \frac{1}{2\Delta_i} \sum_{\lambda=0}^1 \sum_{\gamma=0}^1 (-1)^{\lambda+\gamma} |\vartheta - \vartheta_i - (\lambda + \gamma)\Delta_i|.$$

However, from this aspect, it seems more promising to use an intelligent approach based on the use of artificial neural networks [19,29,30]. The idea of the method is to recognize and classify individual layers of the near-surface part of the geological environment, as well as transitions between them, by the type of graphs of phase images over time. Methods such as capsule networks (CapsNets), generative adversarial networks (GANs) and convolutional neural networks (CNNs), especially 1D-CapsNet, 2D-CapsNet, Basic-DCNNs and VGGNet-16, have proven effective in analyzing such data [31]. For example, the work [19] describes the use of a CapsNet to convert graphs of the frequency spectrum of phase signals into two-dimensional images and their subsequent analysis, which allows for achieving high accuracy of classification of geological layers [27]. The presented models can be used to optimize the drilling process parameters in various situations.

In addition, the use of neural networks can significantly reduce the time for data processing and increase the accuracy of interpretation of results. With the ability to process large quantities of data in parallel, neural networks provide high performance even when working with massive geophysical data. Artificial neural networks also make it possible to take into account nonlinear dependencies and relationships in the data, which helps to more accurately identify hidden patterns and anomalies in the geological environment. The introduction of these technologies into drilling and geological exploration processes helps to improve the safety and economic efficiency of projects, thanks to a more accurate assessment of the structure and composition of geological layers. Thus, the integration of machine learning and artificial intelligence methods into geophysical research opens up new opportunities for improving the quality and speed of data analysis, which is an important step in the development of modern technologies in the field of geology and drilling.

In particular, previous work [19,30,31] showed how the use of the CapsNet and GAN methods can achieve significant results in increasing the accuracy and speed of data analysis. The use of these technologies allows for more efficient management of the drilling process, which ultimately leads to reduced costs and increased safety of operations.

5. Discussion

Discussion and Results. In the experiment, the observed change in phase signals during the transition from drill immersion to drill retrieval provides important insights into the electrical response of the soil structure. Consider the following scientific explanation:

1. Before the dive:

- Behavior of the phase signals: The phase signals were fixed near zero before the dipping process began.
- Scientific explanation: Before the immersion process began, the soil–electrode interaction was in a relatively stable state.

The electrical properties of the soil may have caused the phase signals to oscillate around zero, indicating a ground state or equilibrium.

2. Start of dive:

- Behavior of phase signals: Phase signals began to deviate from zero with the onset of immersion (positively or negatively).
- Scientific explanation: Drill penetration into the soil and interaction with subsurface materials resulted in changes in the electrical properties of the soil, which was reflected in the phase signal deviation.

3. End of immersion:

- Phase signal behavior: The phase signals reached a stable value with some fluctuations.
- Scientific explanation: As the maximum diving depth was reached, the electrical properties of the soil stabilized. The observed fluctuations may indicate dynamic interactions or fluctuations in the soil structure.

4. Start of extraction:

- Phase signal behavior: Phase signals returned to near zero.
- Scientific explanation: The extraction process leads to the restoration of electrode–soil equilibrium, reflected in the return of phase signals to near-zero values.

In general, the observed changes in phase signals during the dip–retrieval cycle indicate the sensitivity of the electrical response to changes in soil structure. Oscillations in the phase signals at the end of the dipping process may be due to dynamic interactions between drilling equipment and heterogeneous subsurface layers, providing valuable insights into heterogeneity and drilling-induced temporal effects on soil electrical properties.

The detected oscillations in the phase signals at the end of the sinking process can be explained by dynamic interactions between the drilling equipment and the heterogeneous subsurface. As the drill penetrates different soil layers with different characteristics such as density and moisture content, the electrical response undergoes periodic fluctuations. These oscillations are likely due to a complex interplay of factors, including changes in the electrical conductivity of different soil horizons, dynamic changes in soil structure during drilling, and the effects of moisture redistribution. The periodic nature of the oscillations can provide valuable insights into the heterogeneity of the subsurface and the drilling-induced temporal effects on soil electrical properties.

To optimize the subsequent analysis of the obtained time series, a mathematical method based on finite field and polynomial theory can be used, as described in [32]. This approach allows for approximating the data with high accuracy and determining the inflection points of the function. Thus, it is possible to draw conclusions about changes in the characteristics of the probed soil section during drilling.

6. Conclusions

In conclusion, the analysis of the probing electrical signals and their variations in phase shift during drilling provides valuable research data on the dynamics of soil response. The observed signal variations during the drilling cycle provide a subtle understanding of soil structure, revealing its heterogeneity and response to drilling-induced changes. The stability revealed in later stages of the process indicates a quasi-equilibrium state. The results obtained contribute to the geotechnical and environmental sciences by proposing an improved approach to the characterization of subsurface layers. The presented methodology and results emphasize the potential for wider application in soil investigations, enriching our knowledge of geological formations and contributing to the practice of engineering solutions. However, it should be noted that the effectiveness of the phasometric method may

be reduced in conditions of high humidity and in the presence of strong electromagnetic interference [22].

An important aspect of research is monitoring structural changes in various objects over a long period of time. For example, in the tasks of control and prediction [32] of the state of engineering structures and monitoring of deformations and stress changes caused by temperature gradients and concrete shrinkage, the results of phasometric control can serve as a source of primary information. This allows for the application of phasometric data for analysis and prediction, as described in the article on monitoring a self-supporting concrete beam suspension bridge [33,34], highlighting the importance of integrating different methods to improve the accuracy and reliability of the assessment of changes in engineering systems [35,36].

In the context of further research, the authors intend to continue studying the changes in phase shifts of the probing electrical signal during the drill's passage through soil layers characterized by different physical and electrical properties. In the future, it is also planned to develop methods to compensate for these interferences to further improve the accuracy and reliability of our methods. The aim is to estimate the soil structure during drilling under complicated conditions, as well as under conditions of uncertainty and vagueness of the initial information.

In addition, it is planned to develop models that will allow for describing the drilling process under different modes of drill plunging and retrieval. This will take into account the scarcity and vagueness of the initial information. As a result, the authors intend to develop a decision support system that will contribute to a better understanding of the soil structure based on the data obtained during the drilling process. The research conducted contributes to effective soil probing to detect inhomogeneities and the presence of groundwater and cavities. This significantly improves the reliability of the soil bases of roads and engineering structures. As a result, more accurate planning and construction of infrastructure is possible, leading to reduced risks and increased durability of structures. In addition, improved understanding of soil structure and groundwater availability can contribute to more efficient use of groundwater in agriculture. This can lead to increased crop yields and resilience of agricultural systems to climate change.

Author Contributions: Conceptualization, A.A. and D.S.; methodology, A.A.; validation, A.A. and B.O.; formal analysis, B.O. and A.B.; investigation, D.S.; resources, D.S. and A.M.; data curation, A.B. and A.M.; writing—original draft preparation, A.B. and A.S.; writing—review and editing, B.O. and A.S.; visualization, D.S.; supervision, B.O.; funding acquisition, D.S. All authors have read and agreed to the published version of the manuscript.

Funding: The study was supported by the Russian Science Foundation grant No. 23-29-10126, <https://rscf.ru/project/23-29-10126/> (accessed on 20 May 2024).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Nunes, M.R.; Karlen, D.L.; Moorman, T.B. Tillage intensity effects on soil structure indicators—A US meta-analysis. *Sustainability* **2020**, *12*, 2071. [CrossRef]
2. Or, D.; Keller, T.; Schlesinger, W.H. Natural and managed soil structure: On the fragile scaffolding for soil functioning. *Soil Tillage Res.* **2021**, *208*, 104112. [CrossRef]
3. Tahghighi, H.; Mohammadi, A. Numerical evaluation of soil–structure interaction effects on the seismic performance and vulnerability of reinforced concrete buildings. *Int. J. Geomech.* **2020**, *20*, 04020072. [CrossRef]
4. Erktan, A.; Or, D.; Scheu, S. The physical structure of soil: Determinant and consequence of trophic interactions. *Soil Biol. Biochem.* **2020**, *148*, 107876. [CrossRef]
5. Olsen, T.; Kasper, T.; de Wit, J. Immersed tunnels in soft soil conditions experience from the last 20 years. *Tunn. Undergr. Space Technol.* **2022**, *121*, 104315. [CrossRef]
6. Jong, S.C.; Ong, D.E.L.; Oh, E. State-of-the-art review of geotechnical-driven artificial intelligence techniques in underground soil-structure interaction. *Tunn. Undergr. Space Technol.* **2021**, *113*, 103946. [CrossRef]

7. Zhang, W.; Zhang, R.; Wu, C.; Goh, A.T.C.; Lacasse, S.; Liu, Z.; Liu, H. State-of-the-art review of soft computing applications in underground excavations. *Geosci. Front.* **2020**, *11*, 1095–1106. [[CrossRef](#)]
8. Cheng, Z.L.; Zhou, W.H.; Ding, Z.; Guo, Y.X. Estimation of spatiotemporal response of rooted soil using a machine learning approach. *J. Zhejiang Univ.-Sci. A* **2020**, *21*, 462–477. [[CrossRef](#)]
9. Cheng, Z.L.; Zhou, W.H.; Garg, A. Genetic programming model for estimating soil suction in shallow soil layers in the vicinity of a tree. *Eng. Geol.* **2020**, *268*, 105506. [[CrossRef](#)]
10. Li, C.; Jiang, S.H.; Li, J.; Huang, J. Bayesian approach for sequential probabilistic back analysis of uncertain geomechanical parameters and reliability updating of tunneling-induced ground settlements. *Adv. Civ. Eng.* **2020**, *2020*, 8528304. [[CrossRef](#)]
11. Wang, Y.; Hu, Y.; Zhao, T. Cone penetration test (CPT)-based subsurface soil classification and zonation in two-dimensional vertical cross section using Bayesian compressive sampling. *Can. Geotech. J.* **2020**, *57*, 947–958. [[CrossRef](#)]
12. Hu, Y.; Wang, Y. Probabilistic soil classification and stratification in a vertical cross-section from limited cone penetration tests using random field and Monte Carlo simulation. *Comput. Geotech.* **2020**, *124*, 103634. [[CrossRef](#)]
13. Peerun, M.I.; Ong, D.E.L.; Choo, C.S.; Cheng, W.C. Effect of interparticle behavior on the development of soil arching in soil-structure interaction. *Tunn. Undergr. Space Technol.* **2020**, *106*, 103610. [[CrossRef](#)]
14. Shi, C.; Wang, Y. Nonparametric and data-driven interpolation of subsurface soil stratigraphy from limited data using multiple point statistics. *Can. Geotech. J.* **2021**, *58*, 261–280. [[CrossRef](#)]
15. Hou, D.; Bolan, N.S.; Tsang, D.C.; Kirkham, M.B.; O'Connor, D. Sustainable soil use and management: An interdisciplinary and systematic approach. *Sci. Total Environ.* **2020**, *729*, 138961. [[CrossRef](#)] [[PubMed](#)]
16. Giannitsopoulos, M.L.; Burgess, P.J.; Rickson, R.J. Effects of conservation tillage drills on soil quality indicators in a wheat–oilseed rape rotation: Organic carbon, earthworms and water-stable aggregates. *Soil Use Manag.* **2020**, *36*, 139–152. [[CrossRef](#)]
17. Nielson, T.; Bradford, J.; Pierce, J.; Seyfried, M. Soil structure and soil moisture dynamics inferred from time-lapse electrical resistivity tomography. *Catena* **2021**, *207*, 105553. [[CrossRef](#)]
18. Wang, S.; Guo, P.; Li, L. Numerical simulation revealing the impact of drilling-based mining equipment structure on water ice extraction from lunar soil. *Acta Astronaut.* **2023**, *213*, 431–437. [[CrossRef](#)]
19. Osipov, A.; Pleshakova, E.; Bykov, A.; Kuzichkin, O.; Surzhik, D.; Suvorov, S.; Gataullin, S. Machine Learning Methods Based on Geophysical Monitoring Data in Low Time Delay Mode for Drilling Optimization. *IEEE Access* **2023**, *11*, 60349–60364. [[CrossRef](#)]
20. Makhmudova, D.; Ikramova, F. Water regime effect on soils of the motor roads subgrade. *AIP Conf. Proc.* **2023**, *2612*, 040024. [[CrossRef](#)]
21. Alnaim, M.A.; Mohamed, M.S.; Mohammed, M.; Munir, M. Effects of Automated Irrigation Systems and Water Regimes on Soil Properties, Water Productivity, Yield and Fruit Quality of Date Palm. *Agriculture* **2022**, *12*, 343. [[CrossRef](#)]
22. Soothar, R.K.; Singha, A.; Soomro, S.A.; Chachar, A.U.; Kalhor, F.; Rahaman, M.A. Effect of different soil moisture regimes on plant growth and water use efficiency of Sunflower: Experimental study and modeling. *Bull. Natl. Res. Cent.* **2021**, *45*, 121. [[CrossRef](#)]
23. Tang, W.; Ma, H.; Wang, X.; Shao, Z.; He, Q.; Chai, H. Study on the Influence of Sponge Road Bioretention Facility on the Stability of Subgrade Slope. *Water* **2021**, *13*, 3466. [[CrossRef](#)]
24. Tian, Y.; Zhang, J.; Zhang, W.; Xu, B.; Duan, Z. Drill-soil penetration model and its application to lunar exploration. *Adv. Space Res.* **2022**, *70*, 3436–3449. [[CrossRef](#)]
25. Liu, T.; Zhou, J.; Liang, L.; Bai, Z.; Zhao, Y. Effect of drill bit structure on sample collecting of lunar soil drilling. *Adv. Space Res.* **2021**, *68*, 134–152. [[CrossRef](#)]
26. Bykov, A.; Surzhik, D.; Vasilyev, G.S.; Kuzichkin, O.R.; Bondarik, K.V. Application of the Phase-Metric Method in the Problems of Geotechnical Control of the Drilling Process. *Int. Multidiscip. Sci. GeoConf. SGEM* **2022**, *22*, 593–597.
27. Bykov, A.; Grecheneva, A.; Kuzichkin, O.; Surzhik, D.; Vasilyev, G.; Yerbayev, Y. Mathematical Description and Laboratory Study of Electrophysical Methods of Localization of Geodeformational Changes during the Control of the Railway Roadbed. *Mathematics* **2021**, *9*, 3164. [[CrossRef](#)]
28. Boldyrev, V.I. Piecewise linear approximation method for solving optimal control problems. *Differ. Equ. Control Process.* **2004**, *1*, 28–123.
29. Zou, J.; Han, Y.; So, S.S. Overview of Artificial Neural Networks. In *Artificial Neural Networks; Methods in Molecular Biology*; Humana Press: Totowa, NJ, USA, 2008; Volume 458. [[CrossRef](#)]
30. Mijwil, M.M. Artificial Neural Networks Advantages and Disadvantages. *Mesop. J. Big Data* **2021**, *2021*, 29–31. [[CrossRef](#)]
31. Jaiswal, A.; AbdAlmageed, W.; Wu, Y.; Natarajan, P. CapsuleGAN: Generative Adversarial Capsule Network. In *Proceedings of the Computer Vision—ECCV 2018 Workshops, ECCV 2018, Munich, Germany, 8–14 September 2018*; Springer: Cham, Switzerland, 2019; Volume 11131.
32. Abdymanapov, S.; Turusbekova, U.; Altynbek, S.; Turginbayeva, A. Research of Irreducible Normal Polynomials Special Type over a Field of Characteristic 2. *IAENG Int. J. Appl. Math.* **2020**, *50*, 777–782.
33. Wang, X.F.; Peng, P.; Yue, W.V.; Shan, Z.G.; Yue, Z.Q. A case study of drilling process monitoring for geomaterial strength assessment along hydraulic rotary drillhole. *Bull. Eng. Geol. Environ.* **2023**, *82*, 295. [[CrossRef](#)]
34. Dong, L.; Pei, Z.; Xie, X.; Zhang, Y.; Yan, X. Early Identification of Abnormal Regions in Rock-Mass Using Traveltime Tomography. *Engineering* **2023**, *22*, 191–200. [[CrossRef](#)]

35. Zhou, G.P.; Li, A.Q.; Li, J.H.; Duan, M.J. Health monitoring and comparative analysis of time-dependent effect using different prediction models for self-anchored suspension bridge with extra-wide concrete girder. *J. Cent. South Univ.* **2018**, *25*, 2025–2039. [[CrossRef](#)]
36. Kahraman, E.; Hosseini, S.; Taiwo, B.O.; Fissha, Y.; Jebutu, V.A.; Akinlabi, A.A.; Adachi, T. Fostering Sustainable Mining Practices in Rock Blasting: Assessment of Blast Toe Volume Prediction using Comparative Analysis of Hybrid Ensemble Machine Learning Techniques. *J. Saf. Sustain.* **2024**, *in press*. [[CrossRef](#)]

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