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АНАЛИЗ СУЩЕСТВУЮЩИХ МЕТОДОВ ОПРЕДЕЛЕНИЯ ПРОМЕЖУТОЧНЫХ ГЕОТЕХНИЧЕСКИХ ХАРАКТЕРИСТИК ГРУНТОВ

ТОПЫРАҚТЫҢ АРАЛЫҚ ГЕОТЕХНИКАЛЫҚ СИПАТТАМАЛАРЫН АНЫҚТАУДЫҢ ҚОЛДАНЫСТАҒЫ ӘДІСТЕРІН ТАЛДАУ

ANALYSIS OF EXISTING METHODS FOR DETERMINING INTERMEDIATE GEOTECHNICAL CHARACTERISTICS OF SOILS

Abstract. *This article presents an overview of the main methods for determining the intermediate geotechnical characteristics of soils, emphasizing the importance of strict adherence to the testing regime. Deterministic and stochastic interpolation methods such as Thiessen polygons, inverse distance weighting (IDW), Spline and Kriging are discussed. Special attention is given to the problem of determining strength properties at various points, where only certain areas are to be investigated and intermediate values are obtained by interpolation methods. The analysis of geotechnical reliability using Kriging numerical models and methods of using geographic information systems for processing and presenting geotechnical data are also discussed.*

Keywords: *construction, geotechnical engineering, intermediate characteristics, interpolation, geographic information systems, spline, kriging.*

Аңдатпа. *Мақалада сынақ режимін қатаң сақтаудың маңыздылығына назар аудара отырып, топырақтың аралық геотехникалық сипаттамаларын анықтаудың негізгі әдістеріне шолу жасалады. Тиссен көпбұрыштары, қашықтықты кері өлшеу (IDW), Сплайн және Кригинг сияқты детерминирленген және стохастикалық интерполяция әдістері қарастырылады. Тек белгілі бір учаскелер зерттелетін және аралық мәндер интерполяция әдістерімен алынған әртүрлі нүктелердегі беріктік қасиеттерін анықтау мәселесіне ерекше назар аударылады. Сондай-ақ, скринингтік сандық модельдерді қолдана отырып, геотехникалық сенімділікті талдау және геотехникалық деректерді өңдеу және ұсыну үшін геоақпараттық жүйелерді пайдалану әдістері қарастырылады.*

Түйін сөздер: *құрылыс, геотехника, аралық сипаттамалар, интерполяция, геоақпараттық жүйелер, сплайн, кригинг.*

Аннотация. *Статья представляет обзор основных методов определения промежуточных геотехнических характеристик грунтов с акцентом на важности строгого соблюдения режима испытаний. Рассматриваются детерминированные и стохастические методы интерполяции, такие как многоугольники Тиссена, обратное взвешивание расстояний (IDW), Сплайн и Кригинг. Особое внимание уделяется проблеме определения прочностных свойств в различных точках, где лишь определенные участки подлежат исследованию, и промежуточные значения получаются методами интерполяции. Также рассматривается анализ геотехнической надежности с использованием Кригинговых численных моделей и методы использования геоинформационных систем для обработки и представления геотехнических данных.*

Ключевые слова: *строительство, геотехника, промежуточные характеристики, интерполяция, геоинформационные системы, сплайн, кригинг.*

Introduction. All structures are built on the ground, which serves as their foundation. A key role is played by the foundation, which must transfer the load from the building to the ground in such a way that the strength of the foundation is not compromised. Calculations are based on two groups of limit states: strength and stability, as well as deformations, including settlement of the foundation and its base. It is impossible to calculate the foundation without knowledge of the physical and mechanical properties of the soils. Selection of optimal foundation designs and methods of work is a complex engineering task. The deformation characteristics of soils are best determined by field methods. Strength characteristics of soils should be determined in the field when it is difficult to take samples or when the soils contain many large inclusions.

The strength characteristics of soils in the field should be determined when it is difficult to take samples or the soils contain many large inclusions [1]. In practice, even under favorable engineering and geological conditions, more than 50% of the research time at the construction site is spent on field work to study soil properties [2]. When determining the mechanical characteristics of soils, it is necessary to strictly observe the testing regime, first of all, the nature of soil loading. The strength properties are not determined over the entire thickness of the foundation, which is a critical factor in design [3].

Determination of soil strength properties is carried out at various points, but not all of them are subject to investigation [4]. Measurements are made at one particular point, while values at intermediate locations can be obtained by interpolation methods [5]. This practice raises questions about the lack of representativeness of the data, as geologic features such as changes in soil composition can lead to significant distortion gradients [6]. Interpolation methods are diverse, and each has advantages and disadvantages. Despite their use to fill data gaps, it should be considered that they can introduce errors, especially when there are significant changes in geologic structure [7]. Thus, to ensure the accuracy and reliability of geotechnical analysis, the choice of interpolation method should be carefully considered and their limitations should be taken into account.

The purpose of this paper is to conduct a literature review of various methods for determining the intermediate physical and mechanical characteristics of phenomena, including the foundations of buildings and structures.

The main objective was to analyze the current research in the field of geotechnical engineering in order to identify sufficiently reliable and accurate methods that take into account the geological structure.

Main part. The paper [8] presents a comprehensive analysis of geotechnical investigation and determination of design shear strength for the construction of breakwater. The paper deals with the important engineering problem of determining the design shear strength for the intermediate soil layer. Intermediate soil characteristics between boreholes are determined by conventional interpolation methods, and the accuracy of these characteristics depends on the number of boreholes drilled and the quality of the cores.

However, there are several potential drawbacks or limitations that were not addressed in the study:

– The study focuses on the specific method used to determine the design strength of the intermediate soil. However, it would have been useful to discuss alternative construction methods or materials that could potentially improve the long-term performance and cost-effectiveness of the breakwater.

– The study is based on a specific location (Sakai Port) and may not fully consider the generalizability of the results to other coastal or offshore construction projects. A discussion of the applicability of the results to different geologic and environmental conditions would enhance the significance of the study.

The author of [9] notes that the actual values of 130 measured values of soil deformation properties obtained as a result of geotechnical investigations often did not coincide with the tabulated values by 52% - this creates a risk and threat to the safety, reliability and proper operation of any building or structure design. Traditional interpolation methods do not reflect accurate data of soils located between boreholes because average data between neighboring boreholes is taken, which does not always reflect actual data (Fig. 1). Incorrect estimation and distorted geologic site investigation data can lead to accidents of the erected or constructed building, as well as large economic losses.

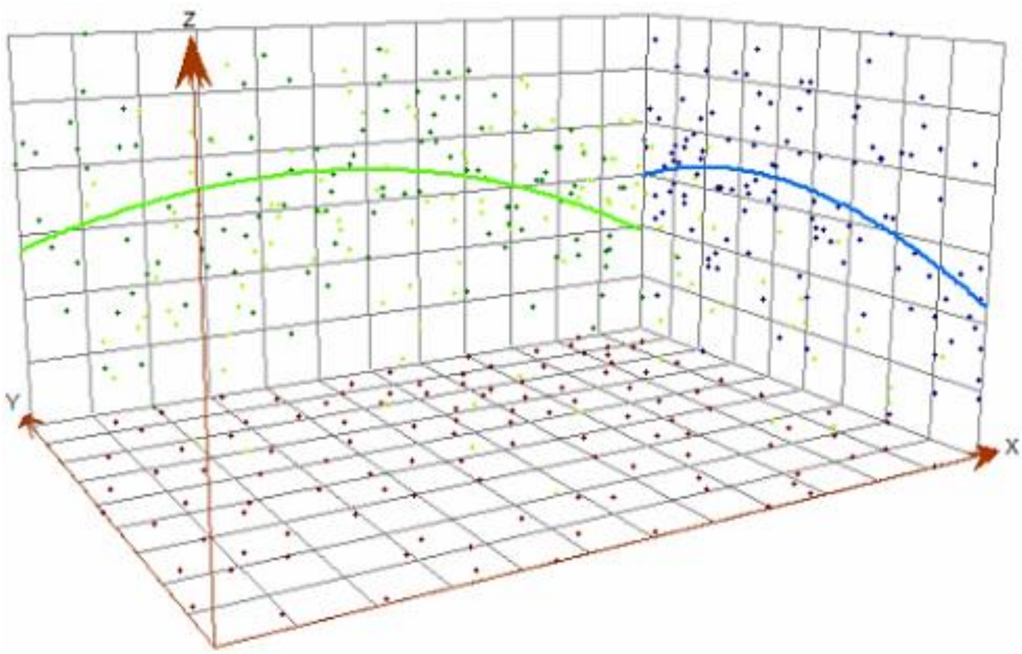

Figure 1. Spatial distribution of points

The authors did not consider potential limitations or uncertainties associated with the geotechnical investigation process. They did not consider the potential variability of soil properties within a single geologic unit or the potential effect of seasonal changes in soil moisture on deformation characteristics. In addition, the authors did not consider the influence of construction methods and materials on the actual deformation of the subgrade soil, which may affect the reliability of the estimated settlement of the structure.

The paper [10] deals with geotechnical reliability analysis using kriging numerical models. It focuses on the problems of combining deterministic numerical analysis with reliability analysis and proposes a method of reliability analysis based on kriging approximation of a deterministic geotechnical model. The authors illustrate the process of calibrating the kriging model to approximate the deterministic numerical model and then estimating the failure probability based on the kriging model (Fig. 2). The paper also describes the use of the first-order reliability method (FORM) for reliability assessment and provides practical applications and examples.

The paper does not discuss in detail the assumptions and limitations associated with the use of kriging models for reliability analysis. The authors have not explicitly discussed sensitivity analysis in the context of using kriging models for reliability analysis. Although the article describes the process of calibrating a kriging model, there is no in-depth consideration of model validation. Consideration of the validation process and potential sources of model errors would enhance the robustness of the proposed method. The authors did not discuss potential problems and limitations in implementing the proposed method in real geotechnical projects, such as data availability, model complexity, and software compatibility.

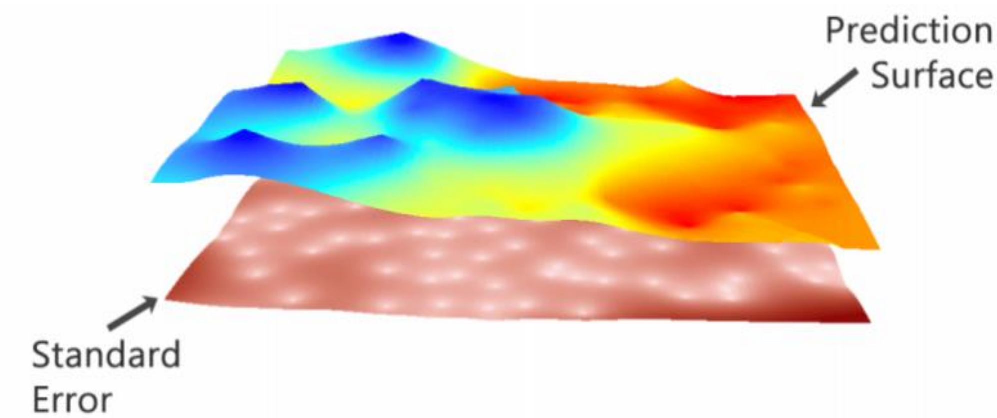

Figure 2. Kriging Interpolation

The paper [11] discusses interpolation methods for modeling spatial phenomena in a GIS environment. It presents an overview of basic and commonly used modeling methods suitable for modeling spatial objects and phenomena. The paper discusses deterministic interpolation methods such as Thiessen polygons, inverse distance weighting (IDW) and spline (Fig. 3), as well as stochastic interpolation methods such as Kriging. The author emphasizes the importance of selecting and using modeling methods correctly, understanding how each method works, and being aware of their strengths and weaknesses. The article also emphasizes the importance of analyzing and planning the use of simulation methods to achieve accurate results in scientific experiments.

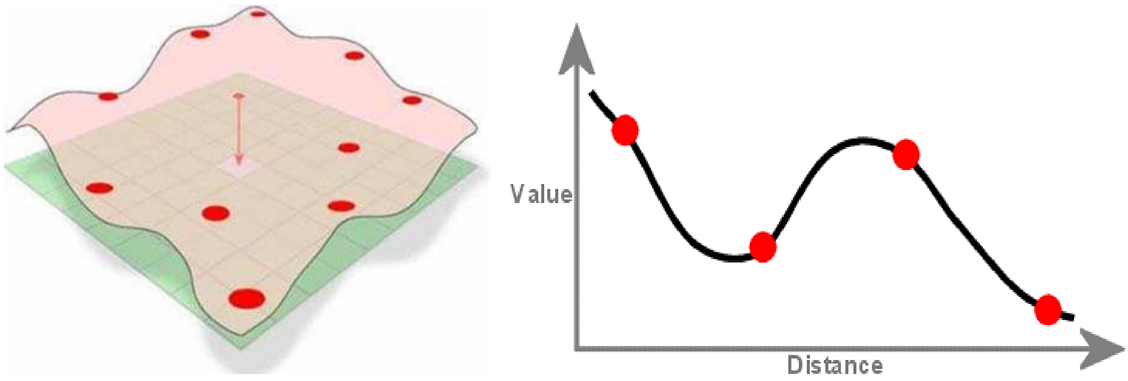

Figure 3. Spline

Although the article provides an exhaustive overview of interpolation methods for spatial modeling in a GIS environment, there are several potential weaknesses or areas that the author has not addressed. The article focuses on the theoretical aspects of interpolation methods. However, it could have benefited from the inclusion of practical examples or case studies to demonstrate the real-world application of these methods in GIS projects. The author could have included a comparative analysis of the accuracy and limitations of different interpolation methods. The article does not discuss the importance of data quality and preprocessing steps before applying interpolation methods. The article does not discuss the computational complexity and resource requirements of different interpolation methods. While the article touches on the importance of understanding the strengths and weaknesses of modeling methods, it could have delved into the topic of uncertainty and error analysis associated with interpolation, especially in the context of stochastic methods such as Kriging.

The article [12] discusses the use of geographic information systems (GIS) in various scientific disciplines, including soil science. The authors emphasize the importance of GIS for the collection, storage, analysis and visualization of spatial data related to soils. They also highlight methods and tools for processing and disseminating soil properties in a map-based format.The study emphasizes the accuracy of interpolation methods for creating maps of physical and hydrophysical properties of soils. It involves the use of various interpolation methods to create maps based on soil samples collected from specific locations in the Nitra, Wagh and Gron river basins. The study utilizes 112 disturbed and undisturbed soil samples collected from agricultural land at a depth of 15-20 cm. The paper describes in detail the methodology used, including the process of collecting and analyzing soil samples, as well as the criteria for assessing the accuracy and reliability of the interpolation methods. The results section discusses the spatial distributions of the interpolated values of available water holding capacity, soil organic carbon content and clay fraction content.

Although the article provides a comprehensive review of the evaluation of interpolation methods for mapping soil physical and hydrophysical properties, there are several potential shortcomings. The authors did not discuss the potential impact of sampling density on the accuracy of interpolation methods. The paper does not address the potential spatial autocorrelation of soil properties that may affect the performance of interpolation methods. Understanding the spatial dependence of soil properties can provide insight into the suitability of different interpolation methods. While the article discusses the accuracy and reliability of interpolation methods, it does not discuss the uncertainty associated with interpolated maps. A discussion of the uncertainty and potential errors associated with the maps would have improved the completeness of the study. The authors did not discuss potential external factors that may affect the accuracy of interpolation methods, such as changes in land use, anthropogenic activities, or natural phenomena. Consideration of these external factors could have provided a more holistic understanding of the limitations of interpolation methods. The article did not provide a detailed comparison of the results obtained with those of other similar studies conducted in different geographic regions or under different environmental conditions.

The aim of the study [13] is to analyze and model the geotechnical characteristics of soils in Erbil city using Geographic Information Systems (GIS) and Artificial Neural Networks (ANN). The study collected data from 102 boreholes in the study area and analyzed soil characteristics such as fines content, moisture content, soil plasticity, shear strength parameters, compressibility, standard penetration test (SPT) and bearing capacity. The results showed that the soil classification was silty clay with small amount of sandy gravel (CL) in most of the study area. The study also predicted the SPT-N value and bearing capacity based on the geotechnical properties of the soils using ANN methods. The methodology involved field data collection, processing and analysis using GIS and ANN. During the study, GIS maps with soil properties including the distribution of different soil characteristics at different depths were generated. ANN models were also developed to estimate the SPT-N values and ultimate bearing capacity. The results of the study showed that ANN models can accurately predict the geotechnical parameters of soil types in the study area.

There is no explicit discussion in the article of possible limitations or biases of data collected in the field. It would have been useful for the authors to consider any potential limitations in the data collection process, such as variations in sampling methods, potential measurement errors, or representativeness of well locations. Although the article discusses the development of ANN models for predicting SPT-N and bearing capacity values, it does not address the validation of these models. The study does not address the uncertainty associated with GIS mapping and ANN modeling. The authors did not discuss potential external factors that may affect the geotechnical performance of soils, such as climate change, anthropogenic activities, or natural disasters. Consideration of these external factors could have provided a better understanding of the soil properties.

The paper [14] discusses methods for determining the intermediate characteristics of foundation soils using the interpolation method. The authors distinguish three main approaches to this process:

– within the selected design geologic elements (DGE) design characteristics of soils are set;

– specification of normative soil characteristics within the selected RGEs (e.g. Eurocode 7 - Design approach 1, Combination 1).

– discrete setting of values of soil properties within the whole foundation, which is based on the idea of building a field of properties distribution in the foundation on the basis of known and actually measured data on soil properties.

The choice of a particular approach depends on the conditions and requirements, as well as on the characteristics of the object under investigation. However, regardless of the chosen method, in order to ensure the safety and reliability of buildings and structures, it is important to take into account the complexities associated with the interpretation of geological data and soil characteristics, and strive for more accurate and reliable estimates of foundation stability. The third scheme of distribution of soil properties differs from other approaches in that it moves away from the statistical processing of laboratory data in the construction of the calculation model and is used to take into account the heterogeneity of geological bodies, since even the smallest geological layers can be heterogeneous. In domestic practice, heterogeneity is taken into account by lowering the average value of the characteristic for the selected layer. While abroad, the average value (or mathematical expectation) is applied, and heterogeneity can be taken into account by means of probability distribution functions of physical and mechanical characteristics of soils.

The methodology for landslide hazard assessment and prediction [15] discusses the shortcomings of traditional schemes in delineating a geologic section and assigning statistically treated characteristics to layers. The authors note that in these schemes, values for a layer may depend on data obtained elsewhere when analyzing the sections. This can lead to errors in estimating the physical and mechanical properties of the layer, especially in the case of anthropogenic soils.

Let us consider the known methods of spatial interpolation, evaluating their essence, advantages and disadvantages (Table 1).

Table 1. Advantages and disadvantages

Spatial interpolation methods	Essence of the method	Advantages	Disadvantages
Thyssen method	Thiessen polygons are formed so that each contains only one measured point, and all other points within the polygon are closer to that measured point than to any other measured point.	is the basis of some other interpolation methods such as TIN or natural neighbors.	each estimate is based on only one value.
Natural Neighborhood Method (NaN)	Delaunay data triangulation is based on the construction of triangles where vertices belong to sample points in neighboring Thiessen polygons (Dirichlet tiles). To compute the value at an unknown point, x0 is inserted into the mosaic structure and its neighbors (points inside the bounding Dirichlet tile) are used for interpolation.	– combines the best features of NN and TIN; – is good at producing discontinuous math functions; – predicts actual values at measured points.	when calculating noisy data the method gives unacceptable results.
Inverse Distance Weighting (IDW)	The basic concept is to use the inverse of the distance to the point to be determined. This distance is further modified by an exponent.	In the IDW method, the mean value cannot be greater than the largest or less than the smallest input value because it is a weighted average of the distances [16].	- formation of concentric isolines (bull's eyes) around the input points is a disadvantage of the IDW method due to the strong influence of these points on their surroundings at large exponent values.
Spline	Estimation of unknown quantities using mathematical functions is performed using the spline method. This method is a system of	Multivariate spline is among the interpolation methods that try to find such a function [17]. When applying the	- at the basic shape of the thin plate spline (TPS), abrupt changes may occur in its first surface derivative

Spatial interpolation methods	Essence of the method	Advantages	Disadvantages
	low degree polynomials separated by different intervals, which are connected at the input data points.	spline method, the following conditions must be met: the mathematical function passes through the measured points and has minimal curvature.	(slope) in the vicinity of the measured points, which limits its use for estimating the second surface derivative (curvature).
Trend method	The trend method estimates the unknown values of a phenomenon by representing them as the sum of trend and random error. The purpose of the method is to approximate the input points by a polynomial, usually of the first to third order. When choosing the degree of the polynomial, it is recommended to take into account that each section of the polynomial can have at most p-1 alternating maxima and minima. For example, a first-order polynomial describes an inclined plane, while a second-order polynomial describes a simple hill or valley.	This method can be used to globally estimate the trend of the phenomenon under study by using a single function for the entire area of interest.	The trend method is an approximating method, so inconsistent results may be obtained in extrapolated areas. In the case when there are low values of measured points the method may give negative estimates, which cannot satisfy essentially the phenomenon under study
The Kriging Method	Kriging is a modern and efficient method for modeling spatial phenomena, perfectly reflecting their frequency vector form. This geostatistical approach is categorized into several types such as ordinary, simple, universal and lognormal kriging. It is used to analyze spatial variability. The main step is the calculation of experimental variogram, which studies the structure of spatial distribution of soil properties through basic instrumental variograms.	Kriging is a geostatistical method that takes into account the spatial distribution of measured points, in contrast to IDW. In organic carbon analysis, kriging proved to be more effective. Universal Kriging (UK) is better than other methods in representing the water table. In crustal thickness estimation in Mojo regions in Brazil and in DGPS imaging, kriging outperformed conventional and other interpolation methods, provid-	

Spatial interpolation methods	Essence of the method	Advantages	Disadvantages
		ing accurate and adaptive results [18-19].	
Topo to Raster	The Topo to Raster method, based on the ANUDEM program (version 5.3 in ArcGIS), presents a discretized spline to create hydrologically correct digital elevation models [20-21]. This method adapts DEMs to abrupt elevation changes using an iterative finite difference interpolation method. The interpolation programs are tuned to maximize the use of data and known characteristics of relief surfaces [22].	Topo to Raster interpolation programs make the best use of the data and known terrain characteristics. The method uses an iterative finite difference method, providing computational efficiency comparable to local interpolation methods (e.g. IDW), but retains the surface continuity characteristic of global methods (e.g. Spline).	

Based on the analysis of these methods, we can conclude that among the spatial interpolation methods, the Kriging method is the most accurate. Also, the Topo to Raster method uses iterative finite difference interpolation method, which allows spatial interpolation without loss of surface continuity.

With the development of technological advancements, spatial data has become widely used with a variety of software applications and high levels of internet security. GIS, in particular, has shown significant advantages in analyzing geotechnical characteristics, predicting shear strength, settlement and bearing capacity of soil based on its properties [23].

The article in [24] presents a comprehensive review of the use of GIS for processing and presenting geotechnical data for construction and infrastructure projects. The authors discuss the importance of geotechnical information for safe and cost-effective design and emphasize the difficulties in obtaining disparate data from different sources. A case study of Seri Iskandar, Malaysia, shows how GIS can be used to store, process and present geotechnical data in a useful format for engineers, planners and land managers. The article also discusses the benefits of using GIS to store and retrieve geotechnical information such as reducing time and increasing efficiency. Overall, this article provides valuable insight into the use of GIS for processing and presenting geotechnical data and highlights the potential benefits of this technology in land management projects.

GIS, being a powerful tool, takes time to develop the raw data for modeling at different spatial scales. They are not just a means of organizing data, but an important tool for integrating, analyzing and visualizing information to identify relationships, patterns and trends. Many researchers have successfully applied GIS to analyze a variety of data [25–28]. ArcGIS software is designed for a full cycle of work with geographic data - from collection and storage to processing and analysis [29].

GIS are actively used to identify potential problems in the early stages of design, thus contributing to efficient construction management and avoiding wasted time. They are a modular tool supporting geotechnical site evaluation, land preparation management and integration of field data with existing information [30].

Despite the extensive review of the use of GIS for geotechnical data processing, there are some shortcomings in the presented works that are worth considering.

These papers lack sufficient attention to the problems related to the spatial representation of soil strata in the form of MRD. It is important to take into account that this method involves the use of non-linear interpolation and extrapolation, which may entail additional difficulties in data processing and require more detailed analysis.

The papers do not provide details on what specific algorithms will be used to transform vector discrete data. The proposed algorithms for determining intermediate features require thorough testing and verification on real geotechnical data. The lack of information on testing plans may raise doubts about the effectiveness and accuracy of the proposed methods.

It is recommended to pay attention to the possibilities of implementing modern cloud-based GIS solutions to provide a more flexible and extensible approach. When using spatial non-linear interpolation to calculate intermediate pixel values, possible errors should be considered and their impact on the final results should be assessed.

Conclusion. From this review of geotechnical soil characterization methods, it is clear that proper selection and use of modeling methods, understanding of their operating principles, and consideration of their strengths and weaknesses are key aspects in assessing their applicability.

Traditional soil strength methods have limitations, especially when analyzing man-made soils, and can lead to distortions in the estimation of soil properties.

The use of geographic information systems represents an important tool for collecting, storing, analyzing, and visualizing spatial data related to the geotechnical characteristics of soils.

Thus, consideration of local features in the delineation of the geologic section and the use of modern interpolation techniques are essential to obtain accurate and economically feasible data on the geotechnical characteristics of soils.

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