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Article

Spatial interpolation of the latest Quaternary and older Mesozoic sediment soils

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Abstract. The paper presents a comparison of three methods of interpolation of engineering-geological parameters of soils: Empirical Bayesian Kriging (EBK), ordinary Kriging, and Inverse Distance Weighting (IDW). The initial data were obtained from bored wells on the territory of the residential complex in Astana city. Interpolation was performed along a horizontal section at a depth of 10 m for the parameters: cohesion, modulus of deformation, and friction angle. The results were visualized as heatmaps. Comparative analysis showed that the EBK 3D method provides a higher degree of detail and robustness to insufficient data density compared to IDW and Kriging, making it the most preferred method for 3D modeling of soil mechanical properties.

Keywords: soils, mechanical properties, spatial interpolation, GIS, lithology.

1. Introduction

The current state of engineering-geological surveys is increasingly determined by the need to integrate classical methods of field and laboratory studies with digital technologies of spatial analysis [1], [2]. Increase in urban density, intensification of urban planning processes, implementation of large-scale infrastructure projects, especially in conditions of cramped city development and complex engineering and geological conditions, impose new requirements for accuracy, detail, and reproducibility of subsurface space modeling [3], [4], [5], [6].

One of the most promising approaches to solving these problems is three-dimensional modeling of the geological environment [7]. Unlike traditional stratigraphic, block, or surface models, 3D structures form a regular grid covering the study area with a given spatial resolution [8]. This is especially important when modeling natural environments characterized by pronounced heterogeneity and anisotropy [9], [10]. A key step in building a 3D model is interpolation, a procedure for estimating parameter values at points not covered by direct measurements [9]. This task presents significant challenges given the limited and irregular spatial distribution of field observations (e.g., boreholes) and because of the stochastic nature of engineering geologic properties in the natural environment [11]. Under such conditions, the choice of interpolation method becomes crucial: it determines the accuracy and reliability of the generated model and, consequently, the validity of design and engineering decisions made on its basis [12].

Despite the widespread use and development of the mathematical apparatus of these methods, the comparative effectiveness of their application to real geotechnical data remains an open question in geotechnical engineering practice [13], [14]. This is especially true under conditions where observations are limited and the spatial structure of the massif under study is complex and poorly defined [15]. The available literature presents mostly theoretical justifications of interpolation algorithms, such as Inverse Distance Weighting (IDW), ordinary Kriging, and Empirical Bayesian Kriging 3D (EBK); or individual practical examples of their application without a comprehensive analysis of accuracy, robustness to outliers, sensitivity to density, and configuration of observation points [16], [17]. In geotechnical engineering applications, where each estimate may have critical implications for strength, stability, or settlement calculations, such analysis takes on applied significance [18], [19], [20].

This study aims to conduct a comparative analysis of interpolation methods: IDW, Kriging, EBK, from the perspective of their applicability for estimation of intermediate values of geotechnical properties in a complex and heterogeneous geological structure.

2. Methods

2.1 Initial data

The materials of engineering-geological surveys and the results of the topographic survey of the territory intended for the construction of a multifunctional residential complex located in Astana, Saryarka district, Republic of Kazakhstan, were used as input data. In the course of survey works, 5 engineering-geological boreholes were drilled, the results of which established the occurrence of five engineering-geological elements (EGE) formed in the conditions of the latest Quaternary and older Mesozoic sediments. The lithology composition and engineering-geological characteristics of each element are described below (Figure 1).

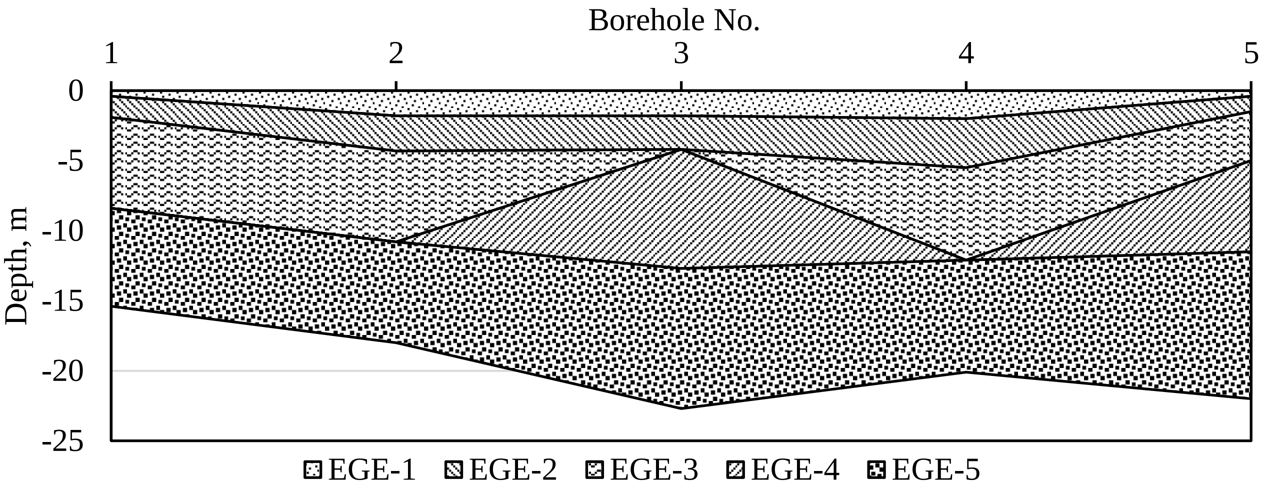


Figure 1 – Lithology section of surveyed site

EGE-1 (laQIII-IV) is represented by water-saturated loams of light brown color. The consistency varies from hard to soft plastic. It contains organic inclusions up to 4.10%. There are interlayers of sand and sandy loam. It was formed under conditions of alluvial-deluvial sedimentation. EGE-2 (laQIII-IV) is composed of light-brown and brown-colored water-saturated sandy loam. The consistency varies from solid to fluid. The content of organic matter reaches 3.20%. There are interlayers of sand and loam. The sediments are of alluvial origin. EGE-3 (laQIII-IV) is represented by sands of medium coarseness, light brown and brown, saturated with water. Interlayers of sand of different coarseness are noted in the composition. It was formed under alluvial conditions with a variable hydrodynamic regime. EGE-4 (laQIII-IV) is composed of gravelly sands of light-brown and brown color, water-saturated. It has inclusions and interlayers of sands of different coarseness. Deposits characteristic of channel and near-channel alluvial facies. EGE-5 (eMZ) is represented by clays of light brown and light yellowish-brown color, in some places with a dark gray tint. The clays are water-saturated, of hard consistency, with areas of iron and manganese, inclusions of tar sands, and interlayers of loam. Lower Mesozoic sediments are characterized by significant density and low filtration capacity.

The data presented in tabular form were used for spatial analysis. Thus, Table 1 contains engineering-geological data obtained from the results of borehole drilling. For each borehole, the coordinates (latitude and longitude in the WGS 84 coordinate system), as well as the main mechanical characteristics of the soils in the selected EGEs, were indicated.

Table 1 – Borehole soil characterization data template

Borehole No.	Latitude	Longitude	Soil type 1				Soil type 2				Soil type m			
			φ_1	E_1	c_1	h_1	φ_2	E_2	c_2	h_2	φ_n	E_n	c_n	h_n
1	71.42976435	51.06208017	0	1.3	20	5	6	14	14	3	0	0	0	6
2	71.43025677	51.06210828	0	0	0	10	3.3	20	12.7	9	0	0	0	8
3	71.4307321	51.0619152	0	5	12	15	0	0	0	12	0	0	30	13
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
n	71.43086928	51.06203564	0	5	12	20	8	15	17	18	21	30	30	19

Interpolation was done in ArcGIS Pro using the Spatial Analyst and Geostatistical Analyst tools using three methods.

2.2 IDW interpolation

The IDW principle is that the values of the interpolated parameter at an unknown point are defined as a weighted average of the values at known points, with the weight inversely proportional to the distance to the power of p (Eq. (1)) [21].

$$z_{(x_0)} = \frac{\sum_{i=1}^{n} \gamma_i z(x_i)}{\sum_{i=1}^{n} -\gamma_i}, \gamma_i = \frac{1}{d(x_0,x_i)^p}, \tag{1}$$

where: $z_{(x_0)}$ – value at interpolated point; γ_i – weight; $z(x_i)$ – value at existing point i; $d(x_0, x_i)^p$ – distance between points; p – degree of influence (commonly is 2); n number of nearest points.

2.3 Ordinary Kriging interpolation

Ordinary Kriging is based on constructing a spatial autocorrelation model using variograms and minimizing the variance of the estimation error (Eq. (2)) [22].

$$z(x_0) = \sum_{i=1}^{n} \lambda_i z\,(x_i), \sum_{i=1}^{n} \lambda_i = 1, \tag{2}$$

where the coefficient λ_i determined by solving the system of linear equations based on the variogram model (Eq. (3)).

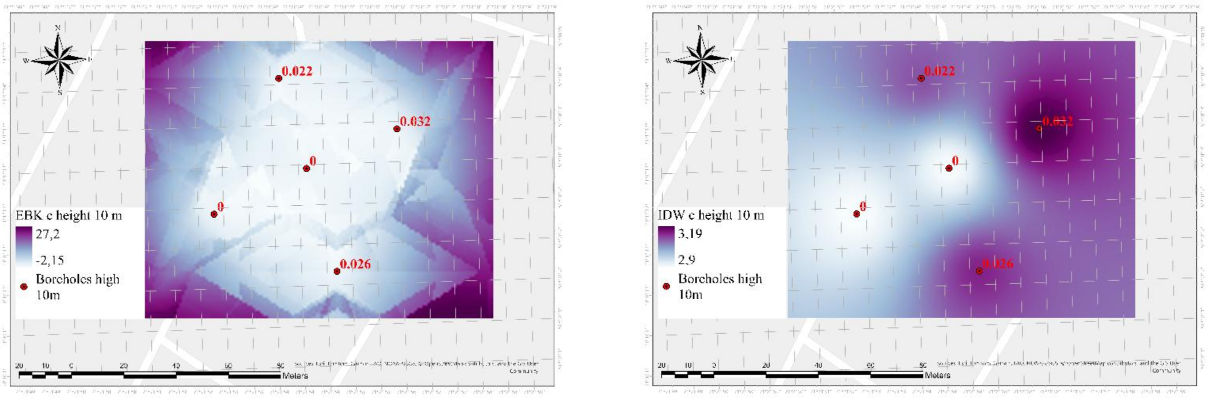
$$\gamma(h) = \frac{1}{2} E\left[\left(Z(x) - Z(x+h)\right)^2\right] \tag{3}$$

2.4 EBK 3D interpolation

EBK uses a Bayesian approach to variogram generation, where model parameters are estimated not once, but over multiple subsamples with subsequent averaging: automatic variogram generation; accounting for model uncertainty; more robust to localized outliers and unstable data structure. A special feature of the EBK method is the automatic accounting of boundary conditions and model uncertainty through the use of Extents, which allows for a more accurate description of parameter distributions in areas with sparse data. The spatial location of wells is fixed in the WGS 84 (or UTM Zone) coordinate system of the corresponding region [23].

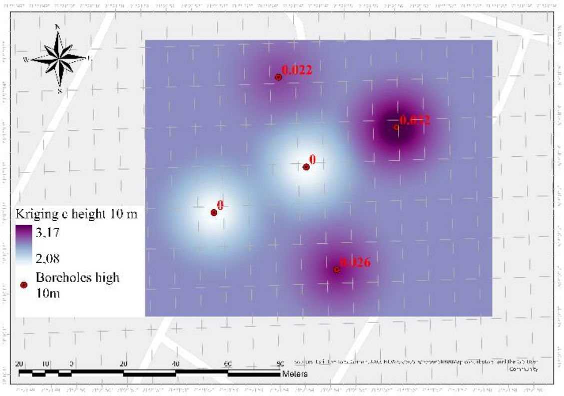
3. Results and Discussion

As a result of processing of field data obtained during engineering geological surveys, heatmaps of the spatial distribution of key mechanical characteristics of soils at a depth of 10 m were constructed through interpolations of EBK, Kriging, and IDW. Thus, Figures 2a, 2b, and 2c show the distributions of specific cohesion (*c*), where the range of values varies from -2.15 to 27.2 kPa. Figures 3a, 3b, and 3c show the distribution of strain modulus (*E*), where the values range from 0 to 33 MPa. Figures 4a, 4b, and 4c show the interpolation of the angle of internal friction (*φ*), whose values range from 0 to 25 degrees.



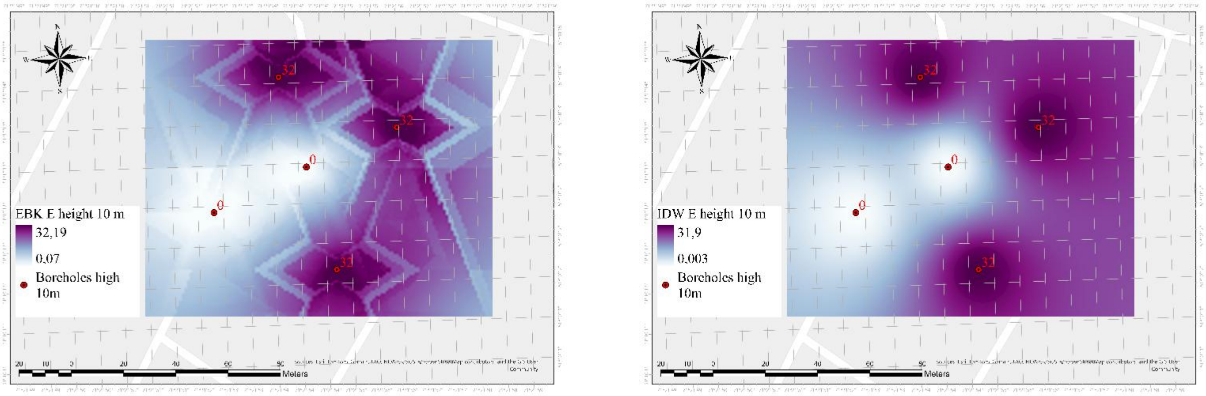
a) EBK

b) IDW



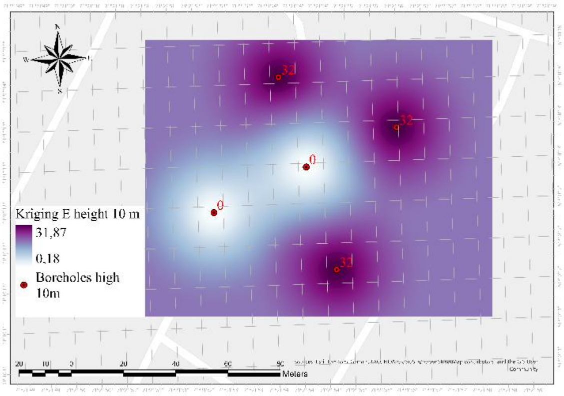
c) Ordinary Kriging

Figure 2 – Distribution of *c* at 10 m depth



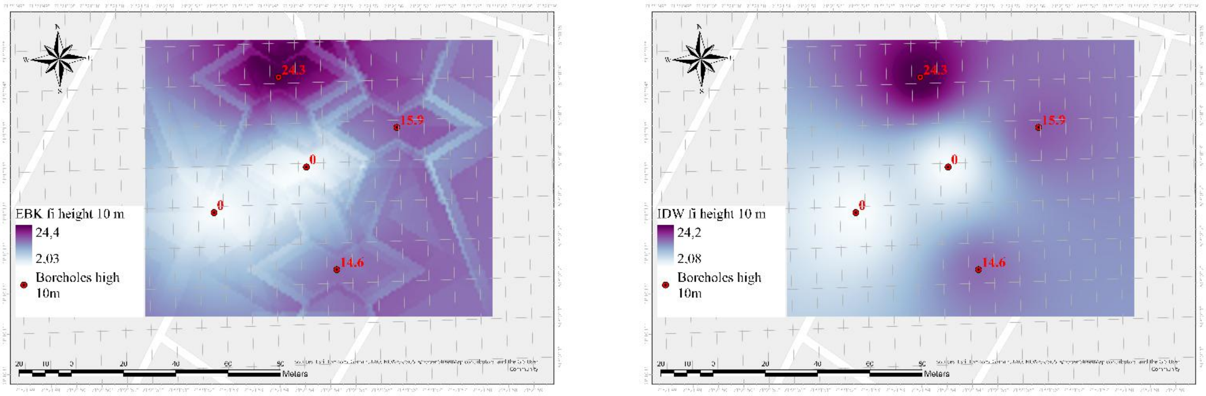
a) EBK

b) IDW

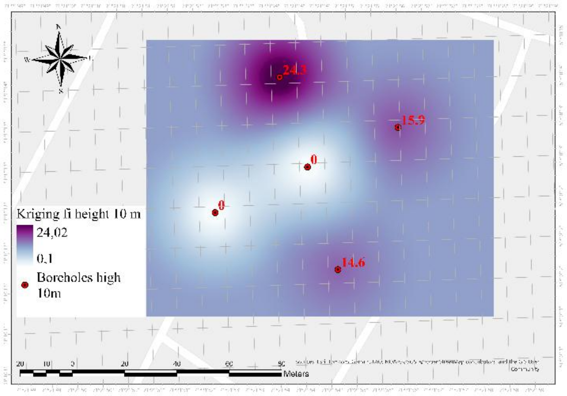


c) Ordinary Kriging

Figure 3 – Distribution of *E* at 10 m depth



a) EBK b) IDW



c) Ordinary Kriging
Figure 4 – Distribution of φ at 10 m depth

Visual examination of the interpolated data obtained in the form of heatmaps revealed several qualitative differences between the models. The IDW model was characterized by pronounced zonality and local variability. The most noticeable were artifacts in the form of "spots" in zones with low density of points (wells), which reflects the excessive influence of the nearest measurements and lack of consideration of spatial correlation. The model based on ordinary Kriging showed a smoother distribution of values over the volume. However, over-simplification was observed in areas devoid of observational data: the method tended to average values, losing the ability to detect local anomalies. In addition, the quality of the result depended significantly on the accuracy of manual variogram adjustment, which increases the subjectivity of the model. The best structural consistency was achieved using the EBK method. The Bayesian stochastic approach underlying the algorithm allowed not only to automate the stage of variogram construction, but also to take into account spatial heterogeneity in poorly studied areas. Visually, the model was characterized by a high degree of detail, especially in the zones of abrupt parameter changes, and at the same time by the absence of over-averaging. The obtained results are consistent with those of previous studies [17], [19] and supplement strengthen them with additional case at the Quaternary and Mesozoic soils.

4. Conclusions

The study demonstrated the possibility of defining the mechanical properties of soils at unknown positions in the subsurface between the known ones (i.e., intermediate) with a certain quality extent using various methods, including the Inverse Distance Weighting, ordinary Kriging, and Empirical Bayesian Kriging.

Analysis of the interpolated models revealed fundamental differences in the behavior of each method. The IDW method showed the greatest sensitivity to local values and point density, which was reflected in pronounced fragmentation and artifacts in the form of spots in areas poorly represented by wells. The Kriging method provided a more uniform distribution of parameters, but demonstrated a tendency to average values, especially in zones with low data density, which reduces its ability to detect local anomalies. The most balanced and structurally consistent results were obtained using the EBK method, which achieved a high degree of detail without excessive fragmentation or smoothing.

EBK 3D method can be recommended as the most reliable tool for spatial modeling of engineering-geological characteristics of soils, especially in conditions of a sparse well network and pronounced geological heterogeneity.

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Nurgul Alibekova – testing, data collection.
Sabit Karaulov – methodology, drafting, visualization.

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