Technobius, 2024, 4(3), 0062, DOI: https://doi.org/10.54355/tbus/4.3.2024.0062

Technobius

https://technobius.kz/

e-ISSN 2789-7338

Article

Examining intermediate soil properties variability through spatial interpolation methods in GIS

Aliya Aldungarova[1,2], Tymarkul Muzdybayeva[3], Assel Mukhamejanova[1,3*], Nurgul Alibekova[3], Khrystyna Moskalova[4], Sabit Karaulov[1]

[1]Solid Research Group, LLP, Astana, Kazakhstan
[2]Department of Mining, Construction and Ecology of S. Sadvakasov Agrotechnical Institute of Kokshetau University named after Sh. Ualikhanov, Kokshetau, Kazakhstan
[3]Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan
[4]Department Department for Research and Development, Development and Training Centre for the Metal Industry, Metal Centre Čakovec, Čakovec, Croatia
*Correspondence: assel.84@list.ru

Abstract. This study compares Kriging and Inverse Distance Weighting (IDW) spatial interpolation methods for estimating intermediate soil properties at a construction site in Astana, Kazakhstan. Using data from eight boreholes, seven engineering geological elements (EGE) were identified and analyzed at 6.5 m and 11.5 m depths. Kriging produced deformation modulus values ranging from -0.29 to 18.99 MPa at 6.5 m and -0.51 to 23.94 MPa at 11.5 m, capturing more spatial variability compared to IDW, which provided ranges of 3.3 to 18.99 MPa and 2.6 to 23.99 MPa, respectively. Kriging's ability to account for spatial correlations resulted in more accurate predictions, particularly in areas with complex subsurface variability. Meanwhile, IDW offered reliable localized results, effective in more uniform geological conditions. The findings demonstrate that both methods are valuable for geotechnical applications, with the choice depending on data density and site variability.

Keywords: Kriging, Inverse Distance Weighting, underground space, spatial interpolation, GIS, intermediate characteristics, foundation bearing capacity.

1. Introduction

In the process of urban infrastructure development, the study and analysis of the geological structure of the base of buildings and structures, as well as the overall optimal use of underground space, are of great importance [1], [2]

To ensure the strength and stability of the foundations, as well as to prevent the foundation from shifting on the footings and overturning, the bearing capacity of the foundations is calculated [3]. This calculation includes determining the design load on the foundation and the ultimate resistance force of the foundation [4]. The latter depends on the mechanical and strength properties of the soil, which are determined experimentally [5].

Currently, data from point excavations made at a specific depth and location are often used for calculations [6]. However, due to limited time and financial resources, the number of such excavations may be insufficient to fully analyze the subsurface. This makes it difficult to interpret the results correctly and can lead to a situation where layers of soil with low-strength characteristics are left unaccounted for between excavations. Such layers are difficult to account for or predict with existing data analysis methods. In this regard, it is important to properly account for, i.e., it is necessary to find intermediate mechanical characteristics of the soil to accurately predict settlement and ensure stability and strength of the foundations of buildings and structures.

The use of GIS is one of the key ways of exploring underground space [7]. GIS algorithms allow predicting values at unselected locations based on nearby measured data. Spatial interpolation methods in GIS are widely used in the world practice to obtain accurate values of geological characteristics of underground space [8], [9] The performance of these methods depends on several factors such as sample density, spatial distribution of the sample, data clustering, surface type, data variance, normality of data distribution, quality of archival information, data stratification, and grid resolution.

The [10] compared two interpolation methods, conventional Kriging and IDW, for groundwater quality assessment in the Lucknow district. The study identified high-risk areas with nitrate concentrations exceeding the permissible limits. The results of the analysis showed that the Ordinary Kriging method showed more accurate estimates compared to the IDW method.

The [11] discusses using multivariate analysis and geographic information systems for modeling and mapping foundation strength and land suitability in arid areas. The study used the IDW method in the ArcGIS 10.4 program to construct interpolation maps of soil properties.

The study [12] analyzed the effectiveness of interpolation methods such as IDW, ordinary Kriging, and co-Kriging for predicting soil properties in saline areas of northern China. The results confirmed that different methods provide similar spatial distributions of soil properties. However, the Kriging and co-Kriging methods showed more homogeneous results than the IDW method, indicating their higher accuracy and ability to account for the spatial autocorrelation of the data.

In this paper [13], an improved Kriging method was proposed, with the addition of spectral variables from high-resolution remote sensing images to the interpolation algorithm. This method was analyzed and compared with the traditional OK, co-Kriging, and KED algorithms. Applying the new algorithm to the soil moisture data produced soil moisture maps with a 30 m spatial resolution.

Thus, the study showed the need for further analysis and evaluation of spatial interpolation methods, such as IDW and Kriging, to determine intermediate geotechnical soil characteristics. Particular attention should be paid to identifying and accounting for soil layers with low-strength properties, which is critical to ensure the reliability and stability of the foundations of buildings and structures.

This study aims to compare IDW and Kriging spatial interpolation methods for determining intermediate geotechnical soil characteristics with a focus on optimizing their use in conditions of limited data, which may improve the accuracy of predictions and the safety of urban infrastructure.

2. Methods

The investigated territory is located in the capital of the Republic of Kazakhstan Astana City, located on the steppe plain in the central part of the territory of the Republic of Kazakhstan.

A distinctive feature of the climate of the Astana city territory is its sharp continentality, which is expressed in low precipitation, and significant amplitude between absolute maximum and minimum air temperatures.

Groundwater is confined to multigrained sands at the bottom of the layer with gravel and pebbles. The thickness of water-bearing sediments is 3-6 meters. From the surface, water-bearing deposits are overlapped with loams and clays with thicknesses of 2-4 meters. The main collectors of groundwater on the territory of the city are:

- aquifer in undivided alluvial alluvial sandy-gravel quaternary deposits of the Ishim River valley.

- water-bearing zone of fractured Ordovician rocks. Normative frost depth for Astana is 1.71 m (for loams and clays), 2.08 m (for sandy loams, sands, fine and dusty), 2.23 m (for gravelly, coarse, and medium sands) 2.53 m (for coarse clastic soils).

The average annual relative humidity is 67%. A topographic survey of the construction site is shown in Figure 1.

Figure 1 – Topographic survey of the construction site [14]

The figure shows the topographic survey of the investigated object. For the projected residential complex were drilled 8 wells with a maximum depth of 24 meters. Geomorphologically, the territory is confined to the left-bank floodplain terrace of the Ishim River. Groundwater level at the time of survey (01.12.2021) is fixed at depths of 3.8 - 4.0 meters, at absolute levels of 348.4...348.5 meters.

Based on the field description of soils, confirmed by the results of laboratory tests, composing the survey area, the following engineering geological elements (EGE) were identified [14]:

- EGE No. 1 (aQ/III-IV) - Loam, light brown and brown, from hard to soft-plastic consistency, with carbonate inclusions, with a mixture of organic matter up to 4.15%, with interlayers of sand and loam up to 20 cm thick.

- EGE No. 2 (aQ/III-IV) - Loam, light brown and brown, from hard to fluid consistency, with carbonate inclusions, with a mixture of organic matter up to 3.88%, with interlayers of sand and loam up to 20 cm thick.

- EGE No. 3 (aQ/III-IV) - Medium coarse sand of brown and dark brown color, water-saturated, polymictic composition, with lenses of loam and interlayers of sand of different coarseness up to 20 cm thick.

- EGE No. 4 (aQ/III-IV) - Coarse, brown, and dark brown, water-saturated, polymictic sand, with sand interlayers of various sizes up to 20 cm thick.

- EGE No. 5 (aQ/III-IV) - Gravelly sand, brown and dark brown in color, water-saturated, polymictic, with interlayers of sand of different coarseness up to 20 cm thick.

- EGE No. 6 (eC/I) - Clay, burgundy-colored, hard consistency, yellow-white in places, with spots of gelation and marganization, with interlayers of loam up to 20 cm thick.

- EGE No.7 (eC/I) - Burgundy-colored loam, hard consistency, with inclusions of dresva, in some places yellow-white color, with yellowish-white color, with spots of yellowing and marganization, with clay interlayers up to 20 cm thick.

ArcGIS Geostatistical Analyst provides statistical models and tools to provide accurate and reliable estimates of phenomena in places where measurements are not available. In our case, the use of geostatistical software provides a probabilistic basis for estimating intermediate mechanical properties of the EGE because only 8 boreholes were drilled in the study area, which is insufficient to fully characterize the entire area.

To realize the finding of intermediate values of deformation modulus, angle of internal friction, and cohesion, we used data from geological studies, presented in the form of a table similar to the one in Table 1.

Table 1 – Template for survey data aggregation

No.	E_1	c_1	φ_1	e_1	E_2	c_2	φ_2	e_2	…	E_j	c_j	φ_j	e_j	*Latitude*	*Longitude*
1															
2															
…															
i															

Note: *i* and *j* denote ordinal numbers of wells and soil layers (from top to bottom), respectively.

Using ArcToolbox tools in the ArcGIS Pro software package, we convert the ready Excel table with XY coordinates into points that will display the position of objects on the ground according to the specified coordinates. Thus, we mark the investigated underground space, which allows us to analyze and model the geotechnical characteristics of the ground more accurately.

We used IDW and Kriging interpolation tools to determine intermediate values of soil mechanical properties. IDW refers to deterministic interpolation methods because it is directly based on measured values falling in the neighborhood of the interpolated point and on specified mathematical formulas that determine the smoothness of the resulting surface. Kriging, on the other hand, is based on statistical models that include analysis of autocorrelation (statistical relationships between measured points). Geostatistical methods not only create a surface of predicted values but also provide measures of the validity or accuracy of the predicted values.

3. Results and Discussion

Based on the EGE data, an engineering-geological section of the construction site was constructed (Figure 2).

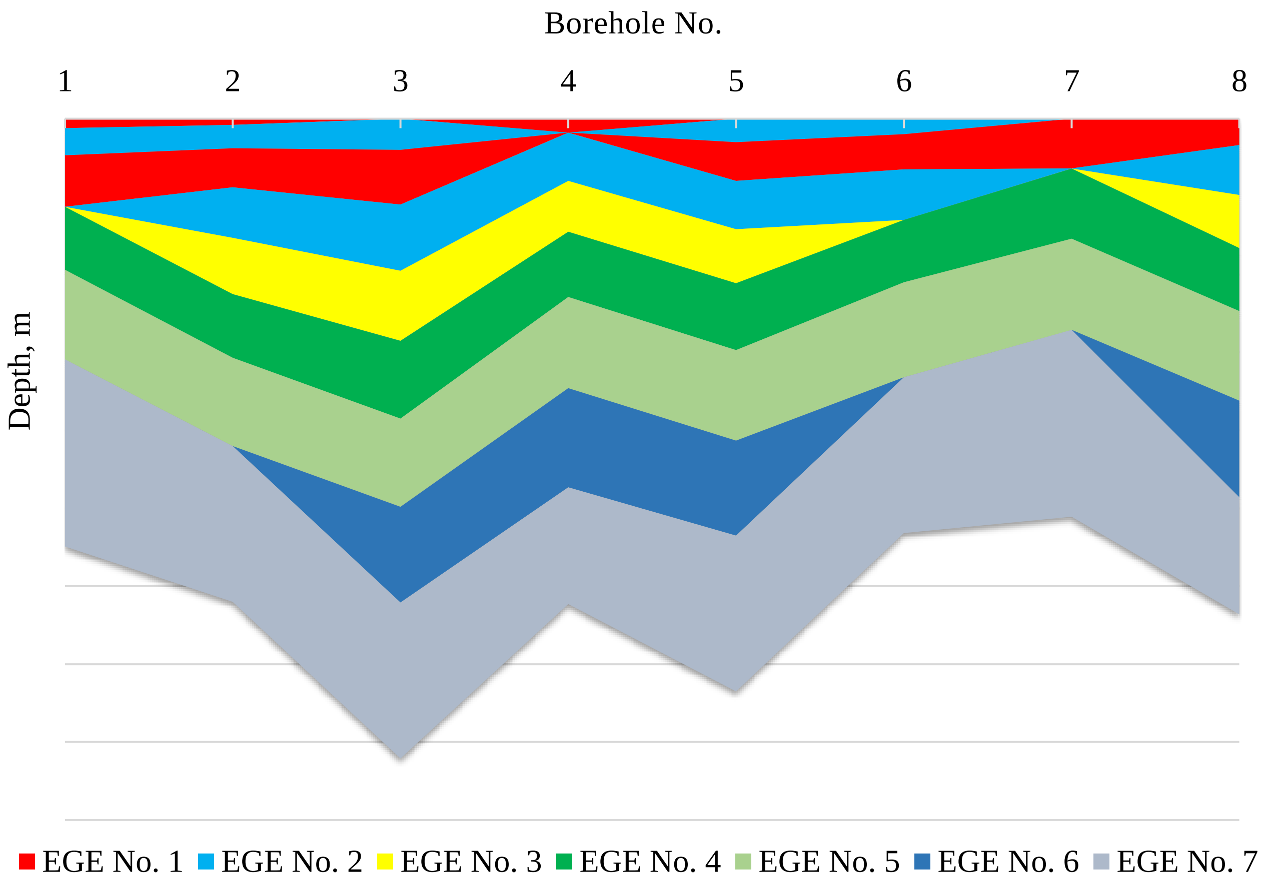


Figure 2 – Engineering-geological section

As can be seen from Figure 2, 7 EGEs were identified in 8 boreholes, ranging from loams in the upper layers, sandy soils in the middle layers, and clayey soils in the lower layers.

At a depth of 3 m, it can be seen from the visualization that layers of cohesive soils transition to non-cohesive soils, i.e., transitions from one class to another. At the same time, the opposite process is observed at a depth of 8 m: there is a transition from non-cohesive soils to cohesive soils. The lower layers of clayey soils are hard in consistency and smoothly transition to loams. In addition, several transitions are observed at greater depths. Thus, depths of 6.5 and 11.5 meters were selected for the study site (Figure 3). A raster image was plotted at these depths using ArcGIS to analyze the spatial variability of the soils in more detail.

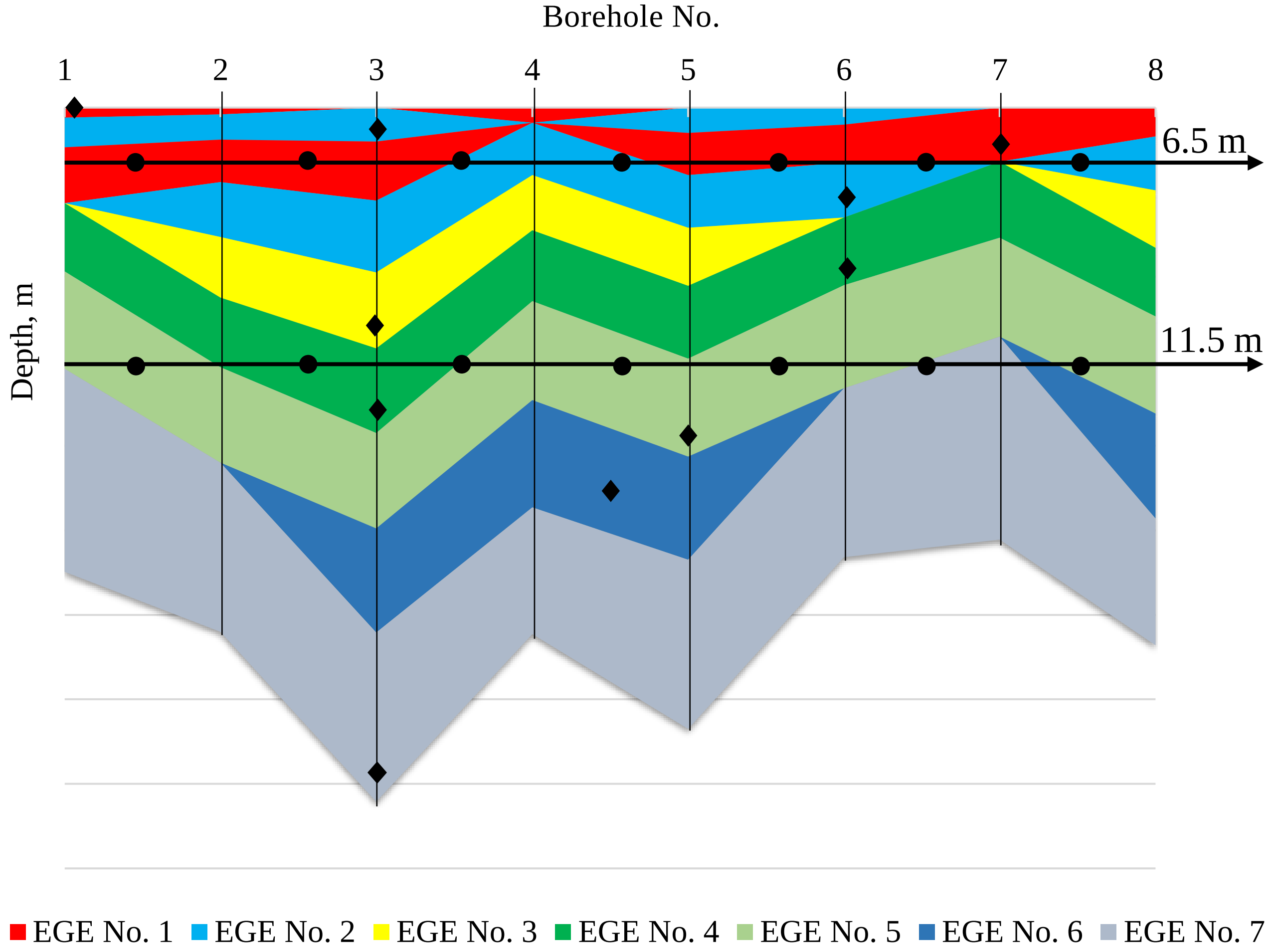
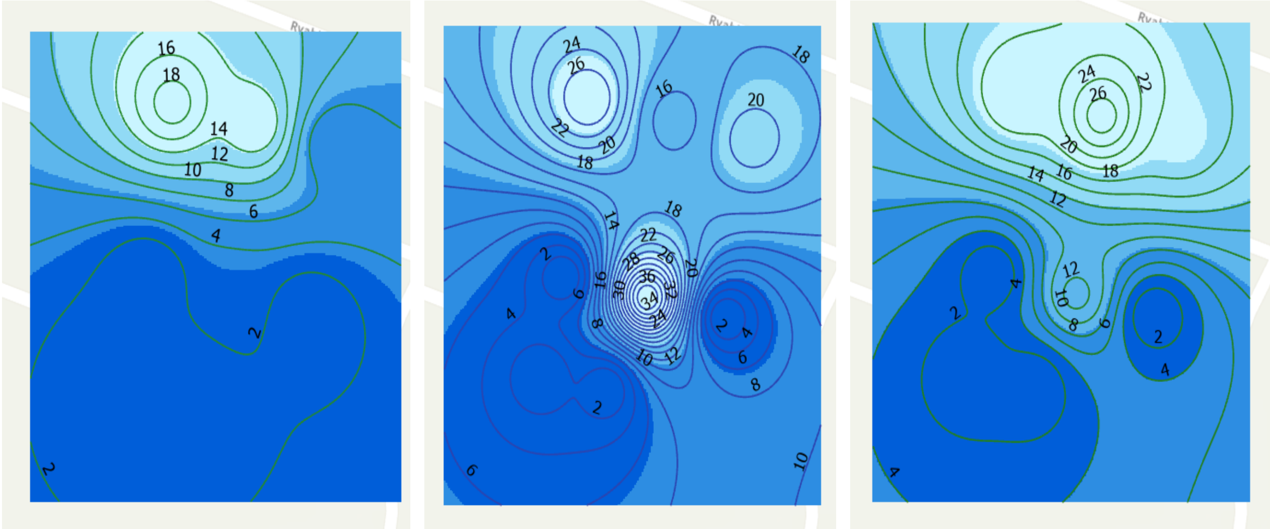


Figure 3 – Engineering-geologic section with an indication of the depth of interest

The figure above pint the locations of known points in boreholes where geotechnical characteristics have been determined by conventional methods (♦), as well as unknown points between wells assumed to be determined by the new methodology (●).

Using ArcGIS capabilities, raster images were acquired at a given depth of interest (Figures 4-7). These digital images are a finite set of small discrete elements called pixels, which are organized into a two-dimensional grid.

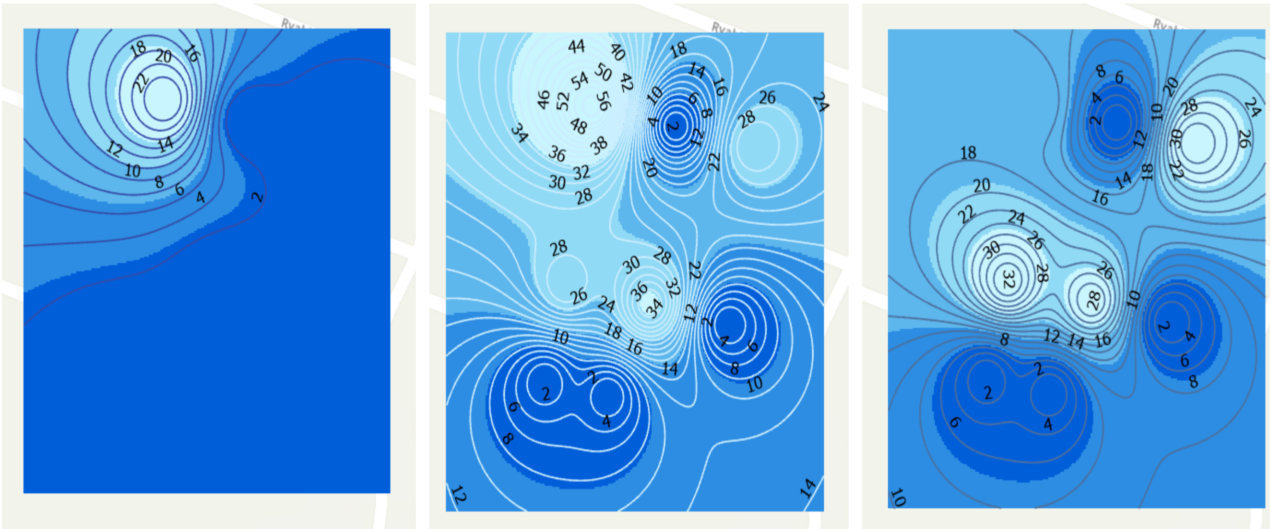
Using interpolation algorithms and adaptive pixel size control, the number of pixels per area of the considered object using Kriging and IDW methods was 68000, with dimensions of 0.66×0.66 meters. This indicates that this approach produces a more detailed image due to the smaller pixel size, which contributes to higher accuracy and greater coverage. This is particularly important when determining unknown intermediate mechanical properties of the soil at any given location [15].



Modulus of total deformation, *E* | Specific adhesion, *c* | Angle of internal friction, *φ*

Figure 4 – Raster images of the variability of mechanical characteristics of the soil of the considered territory using the IDW interpolation method at a depth of 6.5 m

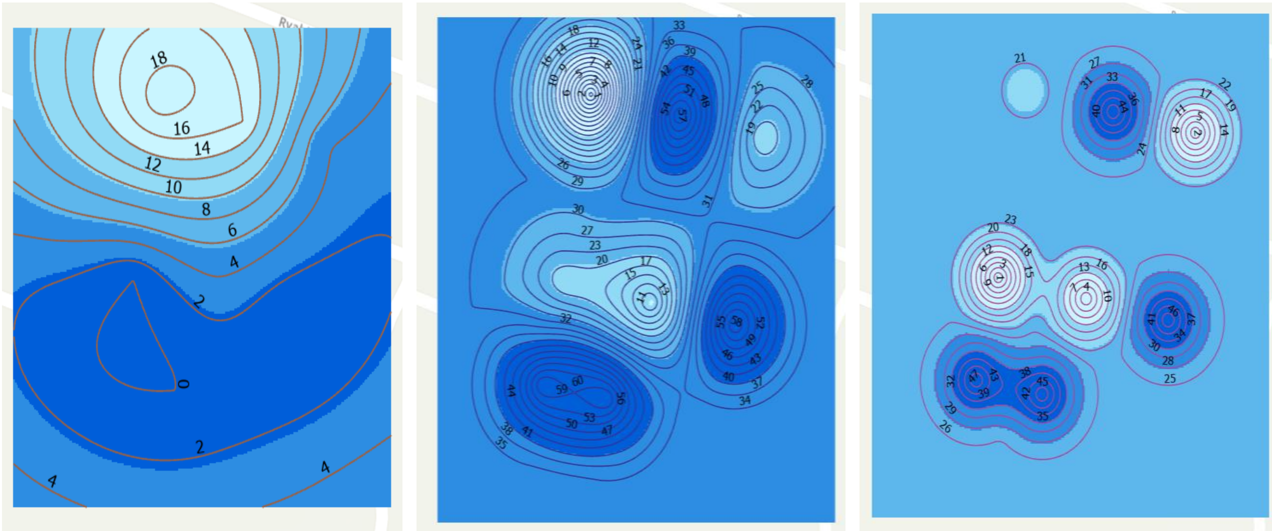
The image shows gradations with varying color shades at a depth of 6.5 m, displaying the values of various parameters. In the dark blue range, the values of total deformation modulus range from 3.3 to 10.13, specific adhesion ranges from 6.5 to 12.96, and the angle of internal friction varies from 4.02 to 14.18. In the pale blue range, the values of the total deformation modulus range from 10.13 to 18.99, specific adhesion ranges from 12.96 to 37.99, and the angle of internal friction range from 14.18 to 26.99.



Modulus of total deformation, *E* | Specific adhesion, *c* | Angle of internal friction, *φ*

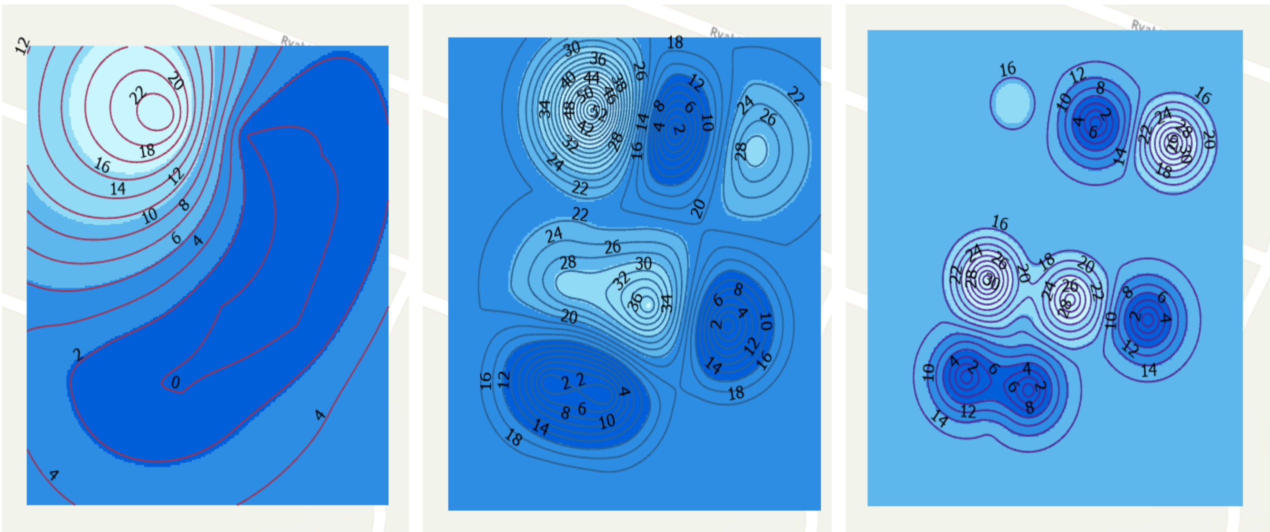
Figure 5 – Raster images of the variability of mechanical characteristics of the soil of the considered territory using the IDW interpolation method at a depth of 11.5 m

The image shows gradations with varying color shades at a depth of 11.5 m representing the values of various parameters. In the dark blue range, the values of total deformation modulus range from 2.6 to 12.04, specific adhesion ranges from 8.4 to 25.48, and the angle of internal friction varies from 6.93 to 19.19. In the pale blue range, the values of total deformation modulus range from 12.04 to 23.99, specific adhesion ranges from 25.48 to 56.99, and the angle of internal friction ranges from 19.19 to 33.99.



Modulus of total deformation, *E* — Specific adhesion, *c* — Angle of internal friction, *φ*

Figure 6 – Raster images of the variability of mechanical characteristics of the soil of the considered territory using the Kriging interpolation method at a depth of 6.5 m



Modulus of total deformation, *E* — Specific adhesion, *c* — Angle of internal friction, *φ*

Figure 7 – Raster images of the variability of mechanical characteristics of the soil of the considered territory using the Kriging interpolation method at the depth of 11.5 m

Table 2 below demonstrates the ranges of soil parameters variability in the Kriging method.

Table 2 – Variability of soil parameters at depths of 6.5 m and 11.5 m in the Kriging method

Parameter	Dark blue range (6.5 m)	Pale blue range (6.5 m)	Dark blue range (11.5 m)	Pale blue range (11.5 m)
Modulus of total deformation, *E*	-0.29 to 9.69	9.69 to 18.99	-0.51 to 11.37	11.37 to 23.94
Specific adhesion, *c*	0.093 to 18.63	18.63 to 37.32	0.06 to 27.66	27.66 to 56.83
Angle of internal friction, *φ*	-0.26 to 13.72	13.72 to 26.96	0.08 to 16.39	16.39 to 33.9

Now let us consider finding intermediate characteristics at depths of 6.5 and 11.5 m, e.g., for deformation modulus (Figures 8-11).

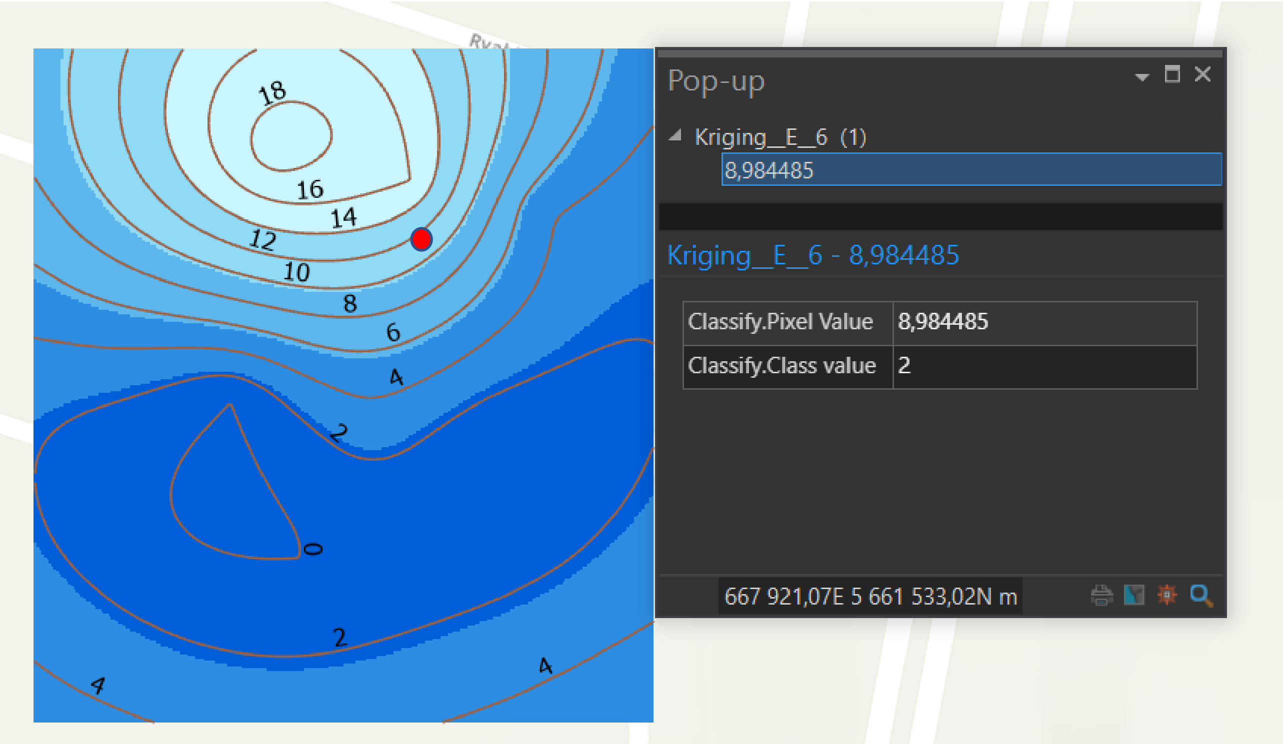


Figure 8 – Raster images of the variability of mechanical characteristics of the soil of the considered territory using the Kriging interpolation method at a depth of 6.5 m

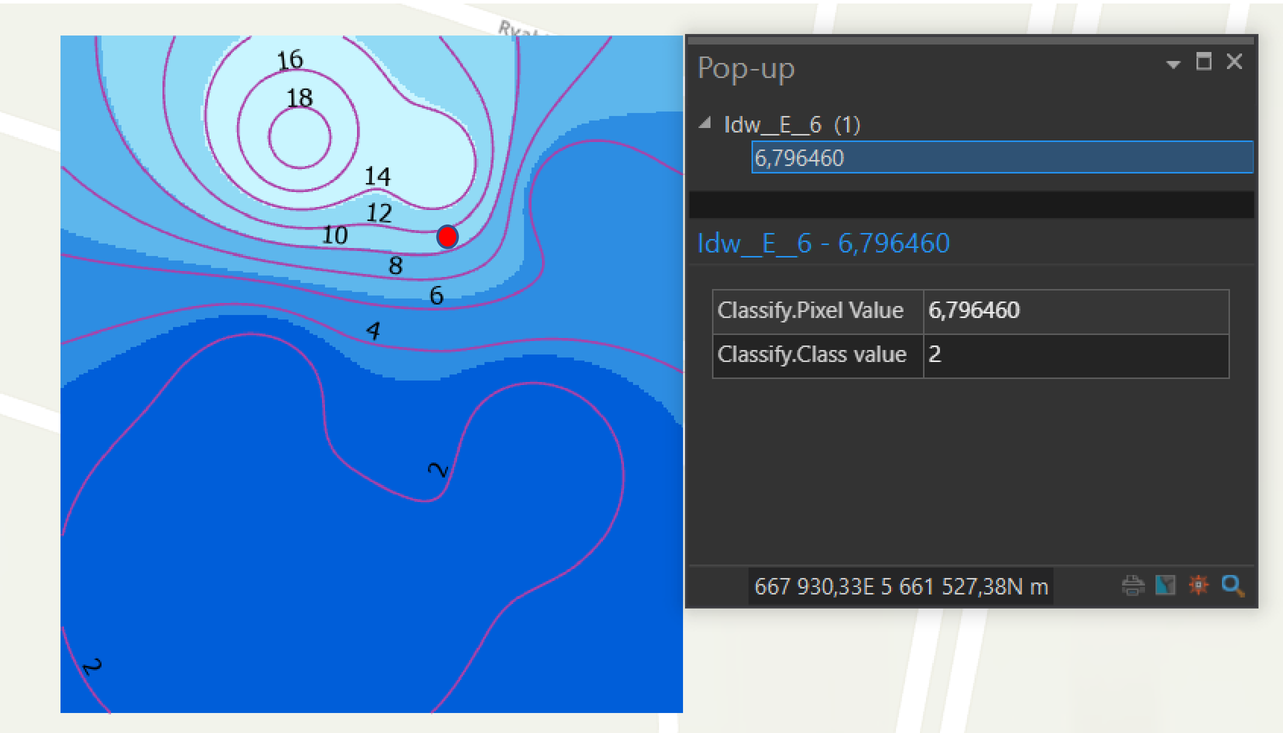


Figure 9 – Raster images of the variability of mechanical characteristics of the soil of the territory under consideration using the IDW interpolation method at a depth of 6.5 m

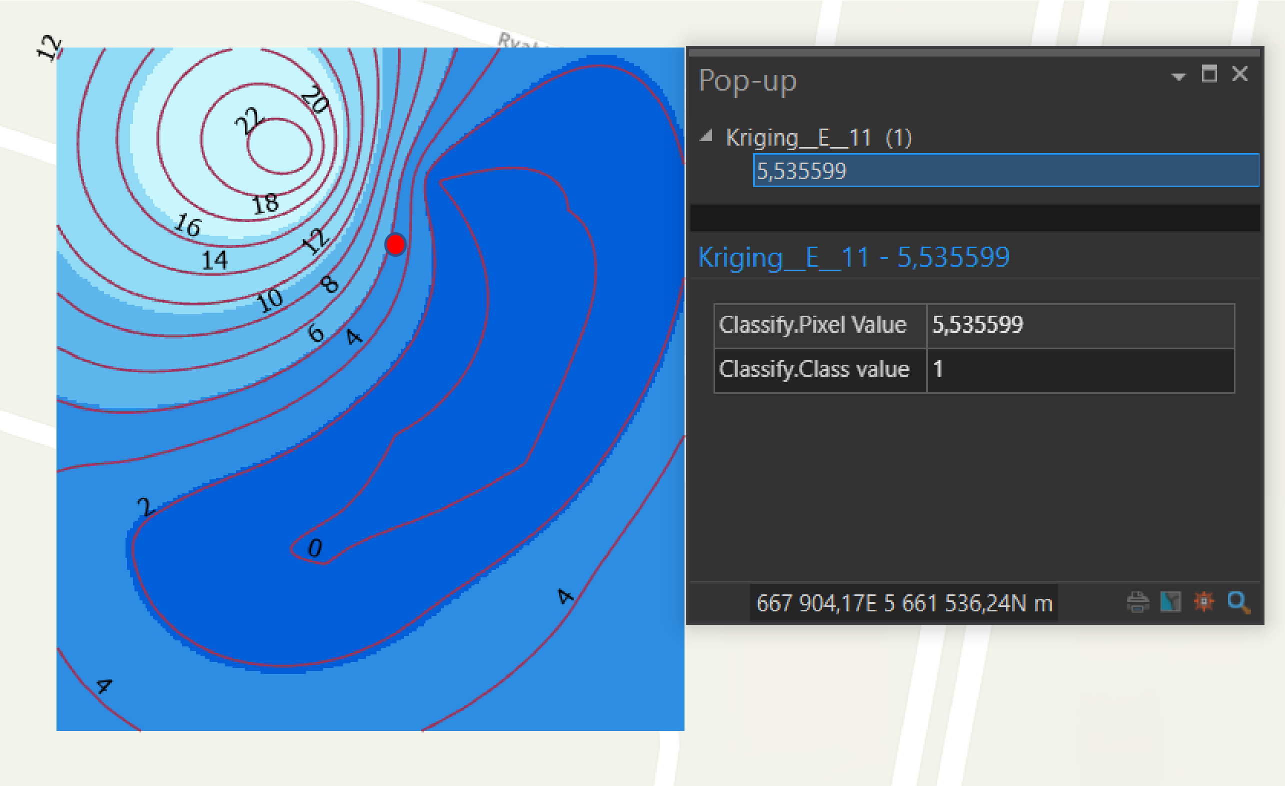


Figure 10 – Raster images of the variability of mechanical characteristics of the soil of the considered territory using the Kriging interpolation method at the depth of 11.5 m

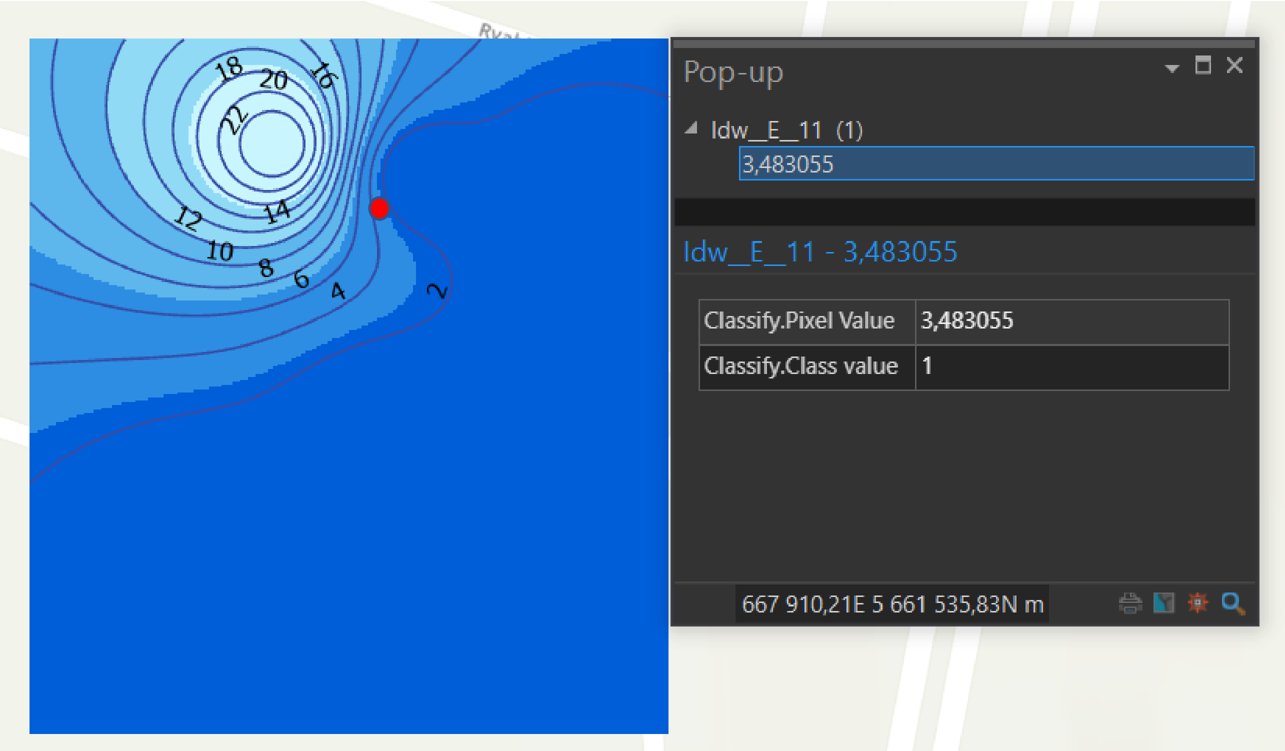


Figure 11 – Raster images of the variability of mechanical characteristics of the soil of the considered territory using the IDW interpolation method at the depth of 11.5 m

Raster images of the variability of soil mechanical characteristics at a depth of 6.5 m show that the strain modulus calculated by the Kriging interpolation method is 8.98, while by the IDW method, it is 6.79. At a depth of 11.5 m, the strain modulus by Kriging is 5.53, while by IDW it is 3.48.

A comparative analysis of the Kriging and IDW methods reveals key differences in their approaches to interpolation and value distribution. Both methods use raw data to produce intermediate values and cover the same number of pixels. However, conceptual differences in their approaches lead to different characteristics of the interpolated surfaces.

The IDW method relies on weighting the values according to the distance to the nearest points. This leads to a more localized distribution of values and consequently to more overlaps and gradations. Visually, this is expressed as undulating shadows and scattered values, reflecting the dependence of the interpolated values on individual points, without taking spatial correlation into account. This approach may not be accurate enough when modeling subsurface spaces, where soil layers typically lie on the same surface and have similar characteristics.

In contrast to IDW, the Kriging method combines the closest points to compute average values, taking into account the spatial correlation between them. This allows for a more correct representation of natural soil variability, especially in complex geologic settings. To demonstrate the effectiveness of Kriging, the pixel distribution was analyzed over a range of values from 15 to 18 (Figures 12 and 13).

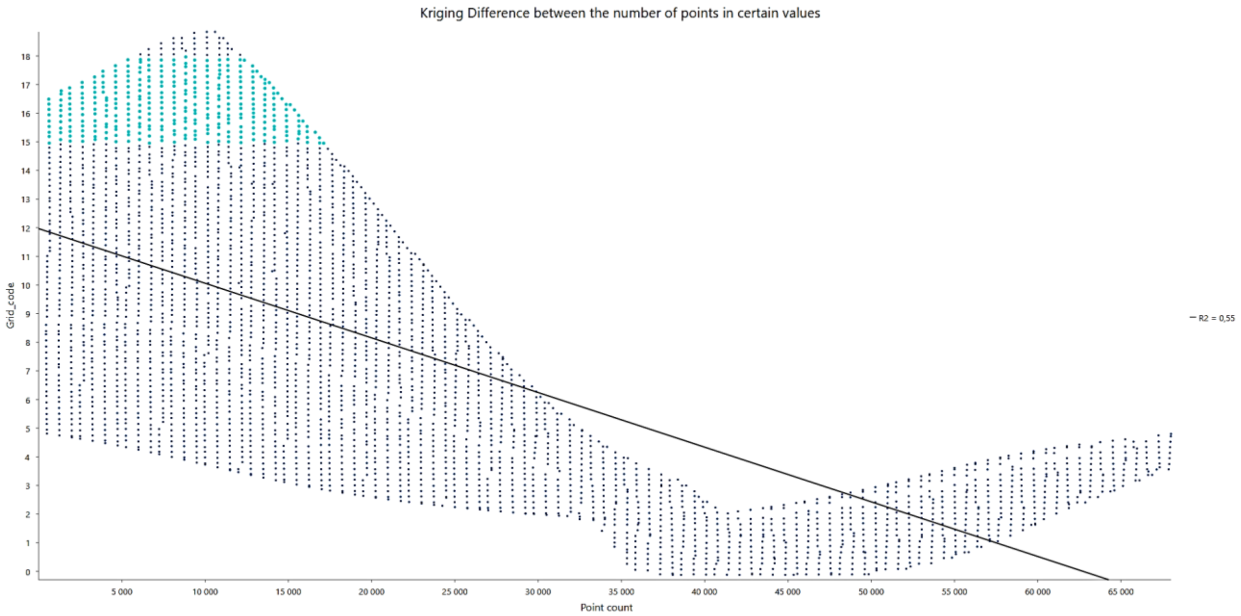


Figure 12 – Difference in the number of points in specified value ranges in Kriging

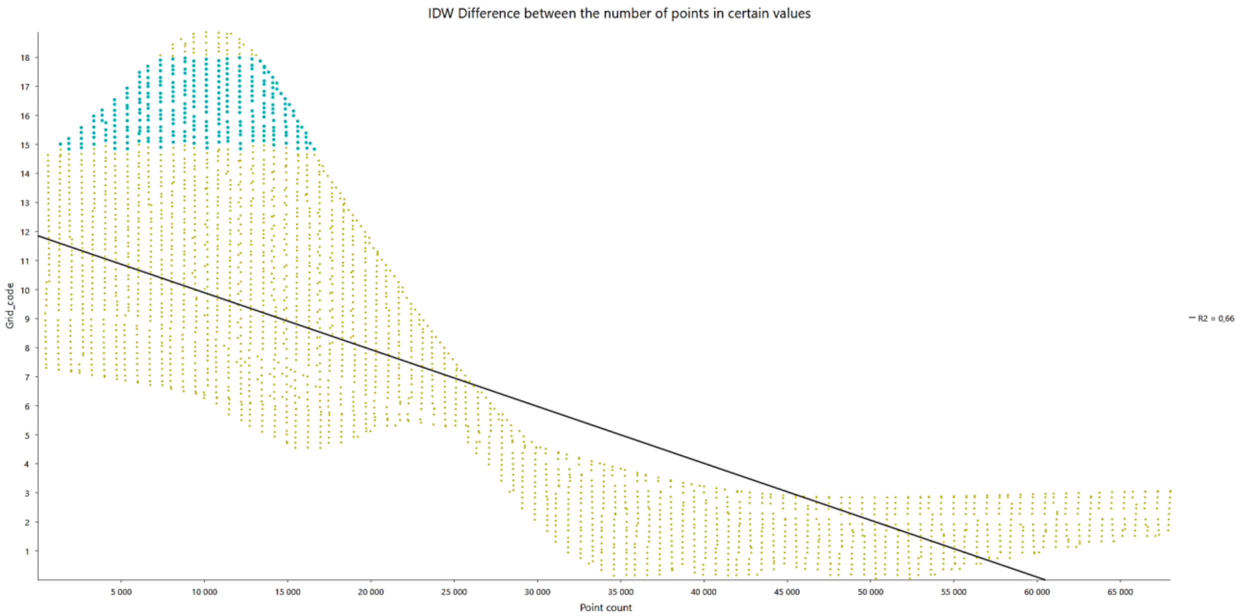


Figure 13 – Difference in the number of points in specified value ranges in IDW

The results showed that IDW covered 2962 pixels whereas Kriging covered 4935 pixels. This confirms that the Kriging method combines similar values more efficiently, increasing the spreading area of the extracted values. Unlike IDW, where the weight of the interpolated values comes from the point itself and results in a more localized distribution, Kriging provides a more uniform distribution of values. This makes Kriging the preferred method for interpolation when accurate modeling of spatial variations and accounting for natural variability in the subsurface is required.

4. Conclusions

This study used ArcGIS to produce detailed raster images of soil properties at depths of 6.5 m and 11.5 m using Kriging and IDW interpolation methods. Kriging provided a wider range of deformation modulus values, from -0.29 to 18.99 MPa at 6.5 m and -0.51 to 23.94 MPa at 11.5 m, capturing greater spatial variability. IDW, with ranges of 3.3 to 18.99 MPa at 6.5 m and 2.6 to 23.99 MPa at 11.5 m, offered localized results based on nearby data points, suitable for more uniform conditions.

Both methods are valuable for geotechnical analysis, with Kriging offering more accurate predictions in areas with complex soil variability, while IDW performs well in data-rich or less variable environments. The choice between methods should be guided by project needs, with both approaches contributing to better design solutions and reduced engineering-geological survey costs.

Acknowledgments

This study was funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP19676116).

References

[1] M. I. Wallace and K. C. Ng, “Development and application of underground space use in Hong Kong,” *Tunnelling and Underground Space Technology*, vol. 55, pp. 257–279, May 2016, doi: 10.1016/j.tust.2015.11.024.

[2] I. Vähäaho, “Underground space planning in Helsinki,” *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 6, no. 5, pp. 387–398, Oct. 2014, doi: 10.1016/j.jrmge.2014.05.005.

[3] Y. Li, W. Fan, X. Chen, Y. Liu, and B. Chen, “Safety Criteria and Standards for Bearing Capacity of Foundation,” *Math Probl Eng*, vol. 2017, pp. 1–8, 2017, doi: 10.1155/2017/3043571.

[4] V. N. Bukhartsev and N. T. Pham, “Assessing the Bearing Capacity of Foundation Soul Under Horizontal Load,” *Power Technology and Engineering*, vol. 52, no. 4, pp. 413–417, Nov. 2018, doi: 10.1007/s10749-018-0967-4.

[5] P. V. Loginov, Z. R. Salikhova, and K. S. Sultanov, “Experimental and Theoretical Method for Determining Mechanical Characteristics of Soils under Dynamic Loads,” *Mechanics of Solids*, vol. 54, no. 6, pp. 915–928, Nov. 2019, doi: 10.3103/S0025654419060074.

[6] M. P. Crisp, M. B. Jaksa, and Y. L. Kuo, “Effect of borehole location on pile performance,” *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, vol. 16, no. 2, pp. 267–282, Apr. 2022, doi: 10.1080/17499518.2020.1757721.

[7] W. N. S. Wan-Mohamad and A. N. Abdul-Ghani, “The Use of Geographic Information System (GIS) for Geotechnical Data Processing and Presentation,” *Procedia Eng*, vol. 20, pp. 397–406, 2011, doi: 10.1016/j.proeng.2011.11.182.

[8] A. Antonakos and N. Lambrakis, “Spatial Interpolation for the Distribution of Groundwater Level in an Area of Complex Geology Using Widely Available GIS Tools,” *Environmental Processes*, vol. 8, no. 3, pp. 993–1026, Sep. 2021, doi: 10.1007/s40710-021-00529-9.

[9] P. K. Srivastava, P. C. Pandey, G. P. Petropoulos, N. N. Kourgialas, V. Pandey, and U. Singh, “GIS and Remote Sensing Aided Information for Soil Moisture Estimation: A Comparative Study of Interpolation Techniques,” *Resources*, vol. 8, no. 2, p. 70, Apr. 2019, doi: 10.3390/resources8020070.

[10] P. Singh and P. Verma, “A Comparative Study of Spatial Interpolation Technique (IDW and Kriging) for Determining Groundwater Quality,” in *GIS and Geostatistical Techniques for Groundwater Science*, Elsevier, 2019, pp. 43–56. doi: 10.1016/B978-0-12-815413-7.00005-5.

[11] M. E. M. Jalhoum, M. A. Abdellatif, E. S. Mohamed, D. E. Kucher, and M. Shokr, “Multivariate analysis and GIS approaches for modeling and mapping soil quality and land suitability in arid zones,” *Heliyon*, vol. 10, no. 5, p. e27577, Mar. 2024, doi: 10.1016/j.heliyon.2024.e27577.

[12] T. Fu, H. Gao, and J. Liu, "Comparison of Different Interpolation Methods for Prediction of Soil Salinity in Arid Irrigation Region in Northern China," *Agronomy*, vol. 11, no. 8, p. 1535, Jul. 2021, doi: 10.3390/agronomy11081535.
[13] J. Zhang, X. Li, R. Yang, Q. Liu, L. Zhao, and B. Dou, "An Extended Kriging Method to Interpolate Near-Surface Soil Moisture Data Measured by Wireless Sensor Networks," *Sensors*, vol. 17, no. 6, p. 1390, Jun. 2017, doi: 10.3390/s17061390.
[14] Inzhenerno-geolgic report, No. 2021-12-IGI-60/ Geocenter Astana LLP. - 2021.
[15] Mukhamejanova, A., Aldungarova, A., Alibekova, N., Karaulov, S., Kudaibergenov, N., Yespolova, Z., Kurmanova, D., Baizakova, G., & Kazhimkanuly, D. (2024). Toward the use of an intermediate value of the modulus of deformation of soils in geotechnical design. E3S Web of Conferences, 559, 01008. doi: 10.1051/e3sconf/202455901008

Information about authors:

Aliya Aldungarova – PhD, Associate Professor, Solid Research Group, LLP, Astana, Kazakhstan; Department of Mining, Construction and Ecology of S. Sadvakasov Agrotechnical Institute of Kokshetau University named after Sh. Ualikhanov, Kokshetau, Kazakhstan, liya_1479@mail.ru
Tymarkul Muzdybayeva – PhD, Senior Lecturer, Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, tumar2304@mail.ru
Assel Mukhamejanova – PhD, Acting Associate Professor, Solid Research Group, LLP; Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, assel.84@list.ru
Nurgul Alibekova – PhD, Associate Professor, Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan, nt_alibekova@mail.ru
Khrystyna Moskalova – PhD, Assistant Professor, Senior Research Associate, Department for Research and Development, Development and Training Centre for the Metal Industry, Metal Centre Čakovec, Čakovec, Croatia, krisogasa@gmail.com
Sabit Karaulov – Junior Researcher, Solid Research Group, LLP, Astana, Kazakhstan, karaulovsabit1997@gmail.com

Author Contributions:

Aliya Aldungarova – concept, methodology.
Tumarkul Muzdybayeva – interpretation, drafting.
Assel Mukhamejanova – visualization, editing.
Nurgul Alibekova – resources, data collection.
Khrystyna Moskalova – analysis, testing.
Sabit Karaulov – modeling.

Conflict of Interest: The authors declare no conflict of interest.

Use of Artificial Intelligence (AI): The authors declare that AI was not used.

Received: 22.07.2024
Revised: 11.09.2024
Accepted: 14.09.2024
Published: 15.09.2024