Spatial interpolation of intermediate strength properties of soil to determine the bearing capacity of the foundation

Aliya Aldungarova[1,2], *Nurgul* Alibekova[1,3], *Sabit* Karaulov[1*], *Zukhra* Yespolova[2], *Dametyk* Kurmanova[2], and *Gulmira* Baizakova[2]

[1]Solid Research Group, LLP, 010000 Astana, Kazakhstan
[2]D. Serikbayev East Kazakhstan technical university, Schools of Architecture and Construction, 070004, Ust-Kamenogorsk, Kazakhstan
[2]L.N. Gumilyov Eurasian National University, Department of Civil Engineering, 010008 Astana, Kazakhstan

Abstract. This study is aimed at determining the intermediate strength characteristics of soil at a given depth between boreholes using geoinformation systems. Changes in the strength characteristics of soils under the influence of load are studied, which is important for assessing the bearing capacity of the foundation and developing optimal solutions for its improvement and strengthening. A comparative analysis of Kriging and IDW methods in ArcGIS software package for determining the spatial variation of soil strength characteristics (c, φ) was carried out. The results showed differences in the values of specific cohesion and angle of internal friction varying depending on the chosen interpolation method. The proposed methodology for determining the intermediate soil strength characteristics takes into account the soil overlay, the thickness of the layers and the relative position of the known values obtained from the monolith selection. This is important for accurate determination of the bearing capacity of the foundation.
Keywords: specific cohesion, angle of internal friction, spatial interpolation, bearing capacity of the foundation, ArcGIS, IDW, Kriging.

1 Introduction

Given the global trend towards more efficient and environmentally sustainable production, as well as the desire to ensure the safest possible conditions, innovative technologies are being developed and widely used [1]. This ensures effective monitoring and management of structural reliability [2] and prevents and protects the environment from harmful factors through engineering systems [3], all this is interconnected with the correct design of the foundation of buildings and structures. The importance of proper foundation characterization emphasizes not only the safety of structures, but also their resistance to

* Corresponding author: sabit.altynbekovich.worldgis@gmail.com

 https://doi.org/10.1051/e3sconf/202455904040

external influences, such as precipitation and other natural phenomena, which ensures the stability and reliability of buildings and structures [4].

As we know, the strength of a soil is assessed by its ability to resist shear [5].

When considering soil strength as a function of moisture and normal stress, shear resistance depends on several factors [6].

In particular, these are the normal stress acting on the soil at a given surface, the angle of internal friction at a given moisture content, and the total cohesion, which is determined by the density and moisture content of the soil. It includes two components: cohesion due to water-colloidal bonding of the soil at a certain moisture content, and structural cohesion with the nature of irreversible bonds [7].

The first component of cohesion, mainly determines the strength of clay soils. Being of water-colloidal nature, it reflects the ability of mineral particles to interact with each other due to molecular forces. The value of this component varies widely and depends on various factors, including soil moisture, type of clay minerals, number and shape of active soil particles ≤0.001 mm in size, and the distance between them [8].

When clayey soils are compacted, the hydrate shells around mineral particles become thinner, which promotes their rapprochement and increases cohesive bonding by strengthening molecular forces [9].

However, when clay soils are overwatered, the value of this component is significantly reduced due to the thickening of hydrate shells, which leads to the separation of mineral particles and loss of contact between them. In this case, the internal friction forces of clayey soil cannot manifest themselves [8].

On the contrary, at significant dehydration of bound aqueous films there is a loss of plasticity and hardening of the soil. This phenomenon is explained by transformation of cohesion cohesion into its structural cohesion [10].

The second part of cohesion, characterizes the strength of rigid crystalline bonds between mineral soil particles. This mainly applies to rocky soils, where the structural cohesion almost completely determines the strength [11].

In clayey soils structural bonding is less pronounced, for example, in silt sediments structural bonds are in the initial stage of formation. In loose soils structural bonding is absent, but in dense loose soils some mutual interlocking of grains is observed, which can be considered as a manifestation of structural bonding [12].

The nature of structural bonding is explained by the processes of cementation and crystallization of substances in natural conditions [13].

When the natural soil structure is destroyed, the rigid structural bonds are broken and structural bonding becomes irreversible [14]. In contrast to cohesion, structural cohesion does not depend on soil moisture and remains practically constant at all soil moisture values [15].

Thus, the cohesion of cohesion of clayey soils is preserved at movement of mineral particles, but changes depending on their distance from each other: it decreases at swelling and swelling of the soil and increases at its compaction. The structural cohesion of the soil disappears irretrievably in the process of destruction of its natural structure by the movement of mineral particles. Consequently, the strength of foundation soils at different depths will be different as their shear resistance varies [16].

Obviously, the monolith sampling from one borehole will be different from another because the spacing and soil layering are different, resulting in a loss of the original structural cohesion [17].

In this regard, Geographic Information Systems (GIS) are now playing a key role in defining and tracking various aspects related to geotechnical data [18].

GIS enables analysis of soil and foundation strength, which is essential for engineering projects such as buildings, structures and roads. At the same time, robust GIS with distinguishing algorithms are being developed [19] capable of detecting hydrological and geological changes. The application of GIS is becoming more and more widespread and is developing every year, providing more accurate and efficient analysis of geographical data and helping to solve a variety of problems in the field of geotechnical and environmental engineering. Thus, the aim of the study is to determine the intermediate values of soil strength characteristics at a given depth between boreholes using Geographic Information Systems. This will allow a more accurate analysis of geotechnical data and determination of soil strength characteristics at specific points between boreholes, which will allow a correct assessment of the bearing capacity of the foundation, as well as the adoption of effective measures to improve the properties of the foundation.

2 Methods

The study area is a construction site in Astana, Saryarka district. Topographic survey at a scale of 1:500 is shown in Figure 1. The territory is located in the steppe zone. The settlement Esil has coordinates 51.18° north latitude and 71.44° east longitude. Altitude above sea level: 358 meters.

The average annual relative humidity is 67%, with annual fluctuations from 80% to 53%. The hydrographic shape of the region is characterized by a multitude of temporary watercourses, active during periods of spring snowmelt, with river runoff, which is mainly used for evaporation, saturation of alluvial deposits and partial recharge of lakes. The topographic plan is shown in Fig. 1.

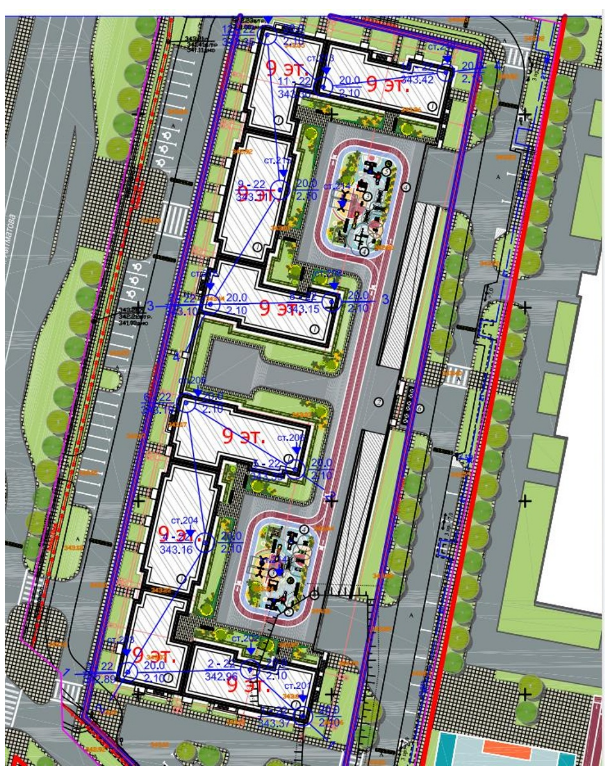


Fig. 1. Topographic survey

The results of determination of physical and mechanical properties of soils by engineering geological elements allowed to obtain an engineering geological section (Fig. 2) and determine the names and condition of soils.

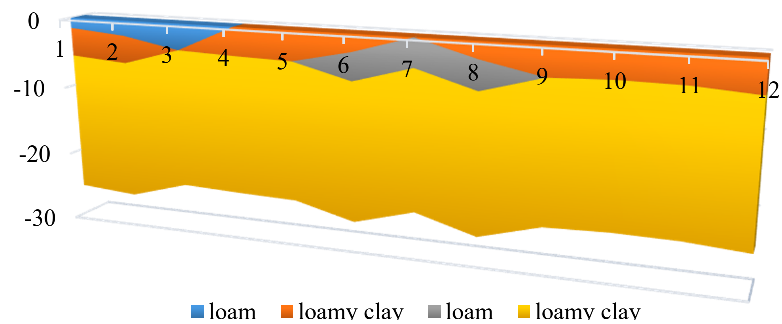


Fig. 2. Engineering-geological section

Engineering-geological element No. 1 (laQIII-IV) - Loam, light brown, hard and plastic consistency, with sand interlayers up to 20 cm thick, with organic matter admixture from 3.30% to 3.90%, average content 3.60%.

Engineering-geological element No. 2 (laQIII-IV) - Loam clay, light brown color, from hard to soft plastic consistency, with sand and loam interlayers up to 20 cm thick, with admixture of organic matter from 3.60% to 7.80%, average content 5.0%.

Engineering geological element No. 3 (eMZ) - Loam clay, reddish-brown, grayish-yellow and burgundy colors, of firm consistency, in some places of fluid and fluidity-plastic consistency, with spots of gelatinization and omarganization, with sand interlayers up to 20 cm thick, inclusions of sandy loam.

At the construction site 12 boreholes were drilled with varying depths from 1.5 to 20 meters. Many methods of calculating bearing capacity are based on the assumption of homogeneity and isotropy of the soil. However, analysis of the geologic section showed that the distance between the boreholes exceeded 20 meters, and monoliths were recovered from only 12 boreholes. The strength properties of the soil were determined by testing on samples taken from these boreholes. Tests on the entire monolith were not performed due to complexity and high cost. Representative samples from the monolith were selected to determine the mechanical properties of the soil.

Table 1 below shows that the strength characteristics of the soil were determined at different depths. However, this may not be an accurate way of determining the bearing capacity of the foundation, as the data on soil strength at different depths may differ significantly.

Table 1. Main physical and mechanical characteristics of IGE

№ IGE	Soil	Soil characteristics		Depth of sampling, m	Strength values	
		W, %	*e*		*c*	*φ*
1	Loam	15.45	0.492	1.2	21	22
		16.52	0.500	2.8	35	32
		18.87	0.492	33.4	31	23
2	Loamy clay	20.8	0.609	2.1	42	14
		19.08	0.545	2.0	13.5	31
		19.95	0.663	3.0	25	18.2
3	Loamy clay	19.2	0.594	9.5	86	13.7
		20.67	0.831	19	52	29.1
		7.46	0.328	8	49	28.2
		10.73	0.395	5	51	29.7
		18.34	0.629	15	49	28.8
		23.86	0.726	20	65	20.5
		26.93	0.863	11	37	25.2

 https://doi.org/10.1051/e3sconf/202455904040

Exposure to natural and anthropogenic factors can lead to changes in the structure of the foundation. The large distance between wells also affects the accuracy of determining the strength properties of the soil. A representative sample of samples for determining values of internal friction angle and specific cohesion will not always be equally representative of the entire engineering geologic element. This may lead to insufficiently accurate or unreliable values, which affects the assessment of the bearing capacity of the foundation and may lead to erroneous results in calculations.

The change in strength properties of the subgrade soils under loading is shown in Figure 3. This graph demonstrates that the soil properties change with time under load. This prediction gives a correct estimate of the bearing capacity of the foundation and for this purpose it is necessary to have information on the initial strength characteristics under natural conditions. Obtaining accurate strength characteristics will help to develop measures to improve the foundation. Based on these data, it is possible to determine the best methods of reinforcing the subgrade or making modifications to the structure to improve its reliability and durability. Such measures may include compensating for ground deformations, reinforcing the soil layer, or using special materials to improve the bearing capacity of the foundation.

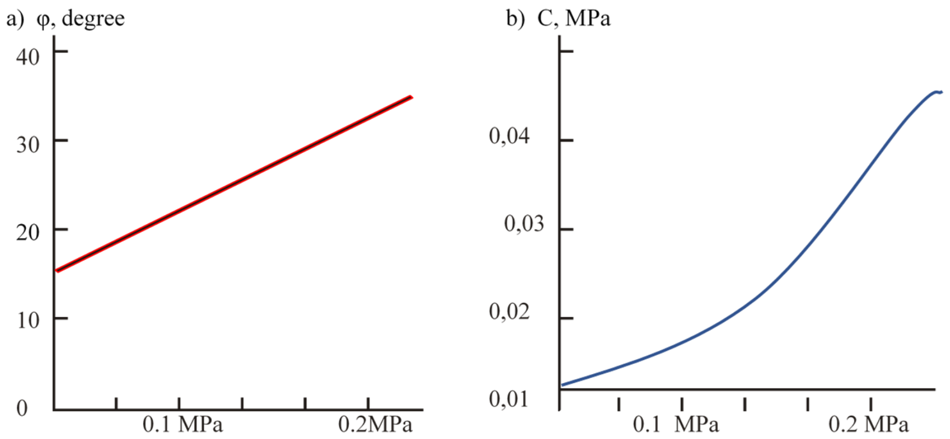


Fig. 3. Change of strength characteristics of foundation soils when they are loaded

3 Results and Discussion

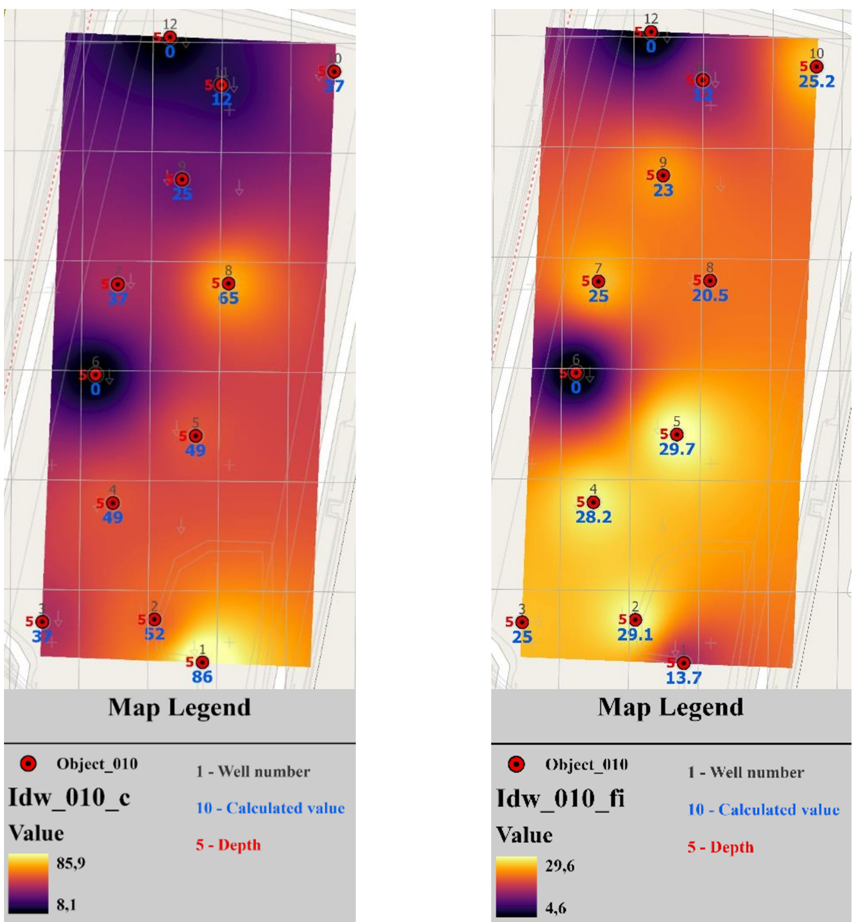
Modern GIS mapping techniques enable the creation of accurate maps by using digital data and analyzing information in real time. The integration of different types of data, such as geographic, demographic and environmental data, makes the mapping process more efficient. The digital format of data in GIS makes it easier to update mapping materials as new information becomes available. However, the use of GIS may require specialized knowledge and skills, which can be a barrier for some users. In addition, the effective use of GIS requires good quality and reliable source data, which may be difficult to ensure in some cases. Some GIS may also have limitations in functionality or data availability, which reduces its effectiveness and accuracy. Thus, the use of GIS for mapping soil properties has a number of advantages, but comes with certain limitations that should be considered.

Application of Kriging and IDW methods in ArcGIS software in the analysis of strength properties data allowed us to obtain more accurate and reliable predictions of the values of specific adhesion and internal friction angle for the entire study area. The results of the resulting maps are presented in Figs. 4-5.

Figures 4-5 show the distribution of soil over the study area at a depth of 5 m using a color scheme to visualize the results of the analysis of its strength properties (specific adhesion, angle of internal friction). These data were obtained by two interpolation methods – Inverse Distance Weighting (IDW) method and Kriging method - using ArcGIS software complex.

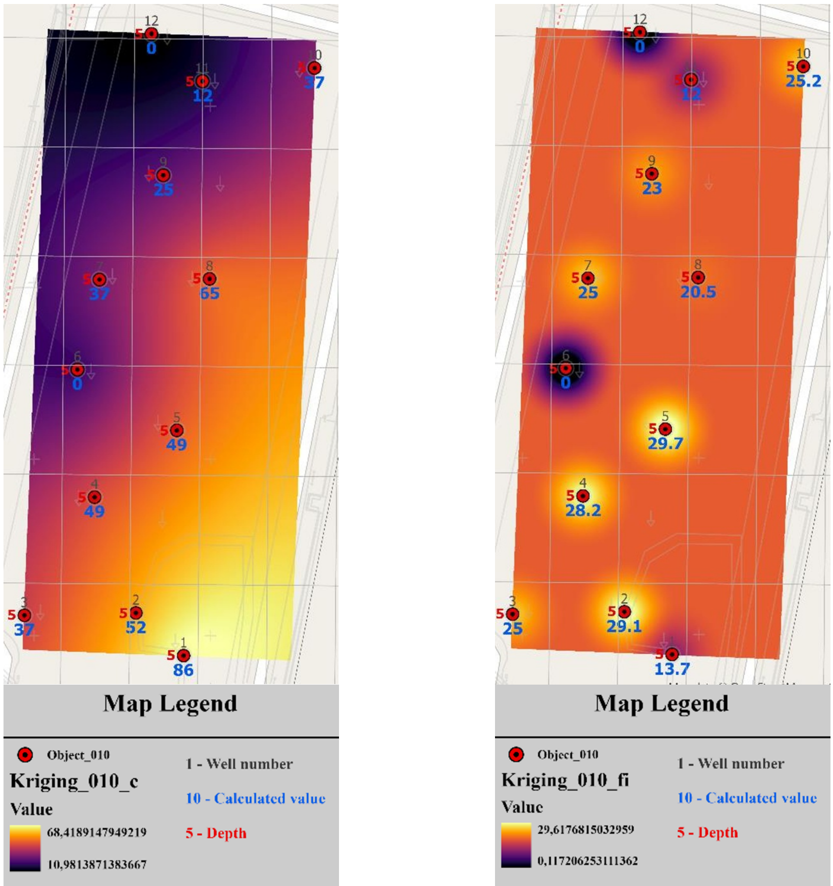
The software package allows to obtain a gradation of the variability of known values depending on the location of the soil. For example, in this case, a cutoff at a depth of 5 m was made, and the known values shown on the heat maps are obtained from different depths, depending on the depth of soil sampling to determine its strength characteristics.

Using ArcGIS software package, modeling of Kriging and IDW interpolation methods was performed to estimate the values of soil parameters in space. Taking into account the known values obtained during engineering surveys, their sampling depth and distance between boreholes, we obtained heat maps showing real values of soil strength characteristics. This means that, at any given depth, we can obtain more realistic intermediate soil strength characteristics based on the original known values obtained during the survey, while taking into account borehole spacing and soil stratification. Gradations of variability are displayed below each map: lighter colors correspond to near maximum values and darker colors to minimum values from known data.



Specific adhesion values – c Values of the angle of internal friction – φ

Fig. 4. Heat maps of spatial variability of known values obtained by IDW method



Specific adhesion values – c   Values of the angle of internal friction – φ

Fig. 5. Heat maps of spatial variability of known values plotted using the Kriging method

From the obtained gradation results, it can be seen that the comparative analysis of Kriging and IDW methods shows differences. For example, the values of specific grip vary from 8.1 to 85.9 by IDW method and from 10.98 to 68.41 by Kriging method. Similarly, the values of angle of internal friction range from 4.6 to 29.6 by the IDW method and from 0.117 to 29.61 by the Kriging method. These differences indicate the different effectiveness of these methods in assessing the spatial variation of soil strength properties. Further research will be continued to determine the most effective interpolation method to achieve a more accurate and reliable estimation of the spatial variation of soil strength characteristics. Nevertheless, the proposed methodology for determining the intermediate values of internal friction angle and specific cohesion takes into account the layered structure of the soil, the thickness of the layers and the relative position of the known values obtained from the monolith sampling. This is important for accurate determination of the bearing capacity of the foundation, since it allows taking into account the depth and layering in its different parts.

4 Conclusions

Based on the obtained results, the following conclusions were obtained:

• The use of interpolation methods to determine intermediate strength values at a given depth contributes to a more accurate assessment of the bearing capacity of the foundation;

• Taking into account soil stratification, thickness of layers and depth of sampling is important for accurate determination of intermediate strength values;

• The application of modern mapping methods using geographic information systems greatly facilitates the creation of accurate maps and real-time data analysis.

Thus, the determination of intermediate values of soil strength properties at a given depth plays a key role in ensuring accuracy and reliability in assessing the bearing capacity of the foundation for the construction of buildings and structures.

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).

Gratitude is expressed to “Geocenter Astana” LLP for providing the data from engineering-geological surveys used in this study.

References

1. Nwaila, G. T.; Frimmel, H. E.; Zhang, S. E.; Bourdeau, J. E.; Tolmay, L. C. K.; Durrheim, R. J.; et al. The minerals industry in the era of digital transition: An energy-efficient and environmentally conscious approach. *Resources Policy* **2022**, *78*, 102851. doi:10.1016/j.resourpol.2022.102851
2. Utepov, Y.; Aniskin, A.; Tulebekova, A.; Aldungarova, A.; Zharassov, S.; Sarsembayeva, A. Complex Maturity Method for Estimating the Concrete Strength Based on Curing Temperature, Ambient Temperature and Relative Humidity. *Applied Sciences* **2021**, *11*(16), 7712. doi:10.3390/app11167712
3. Utepov, Y. Potential application of an automatic sewer monitoring system based on sensors. *International Journal of GEOMATE* **2023**, *25*(109). doi:10.21660/2023.109.3929
4. Nuguzhinov, Zh. S.; Mukhamejanova, A. T.; Tokanov, D. T.; Koishybay, Z.; Zhumadilova, N. Z.; Beketova, M. S. Comprehensive study of the basses and foundations of furnaces No. 61, 63 of the melting shop No. 6 of the Aksu Ferroalloy Plant in connection with the renovation. In *Smart Geotechnics for Smart Societies*; CRC Press: London, 2023; pp 1309–1313. doi:10.1201/9781003299127-190
5. Ali, I.; Ahmed, S.; Khoso, S.; Sohu, S.; Bhatti, N.-K.; Naqash, M. T. Environmental impact assessment on shear strength characteristics of soil. **2023**, *30*(1).
6. Prolygin, A.; Dolgih, G.; Aleksandrov, A. Influence of Moisture Content of Loamy Soil on Shear Resistance Parameters. In *Networked Control Systems for Connected and Automated Vehicles*. Guda, A., Ed.; Springer International Publishing: Cham, 2023; Vol. 509, pp 863–872. doi:10.1007/978-3-031-11058-0_87
7. Khazratov, A. N.; Bazarov, O. Sh.; Jumayev, A. R.; Bobomurodov, F. F.; Mamatov, N. Z. Influence of cohesion strength in cohesive soils onchannel bed erosion. *E3S Web of Conferences* **2023**, *410*, 05018. doi:10.1051/e3sconf/202341005018
8. Malizia, J. P.; Shakoor, A. Effect of water content and density on strength and deformation behavior of clay soils. *Engineering Geology* **2018**, *244*, 125–131. doi:10.1016/j.enggeo.2018.07.028
9. Firoozi, A. A.; Firoozi, A. A.; Baghini, M. S. A Review of Clayey Soils. **2016**, *04*(06), 1319–1330.

10. Puzrin, A. M.; Burland, J. B. Kinematic hardening plasticity formulation of small strain behaviour of soils. *International Journal for Numerical and Analytical Methods in Geomechanics* **2000**, *24*(9), 753–781. doi:10.1002/1096-9853(20000810)24:9<753::AID-NAG97>3.0.CO;2-2
11. Magdi M. E. Zumrawi, M. E.; Mohammed, L. A. D. Scientific Research and Innovation for Sustainable Development in Africa. **2016**, No. 7th Annual Conference for Postgraduate Studies and Scientific Research.
12. Cai, G.-Q.; Zhao, C.-G.; Qin, X.-M. Structural bonding-breakage constitutive model for natural unsaturated clayey soils. *Acta Mechanica Sinica* **2010**, *26*(6), 931–939. doi:10.1007/s10409-010-0375-y
13. Rohrer, G. S. *Structure and Bonding in Crystalline Materials*; 1st ed.; Cambridge University Press, 2001. doi:10.1017/CBO9780511816116
14. Liu, E. L.; Shen, Z. J. Experimental Study on the Mechanical Behavior and Destructured Process of Artificially, Structured Soils in Triaxial Compression. In *Ground Modification and Seismic Mitigation*; American Society of Civil Engineers: Shanghai, China, 2006; pp 57–64. doi:10.1061/40864(196)9
15. Matsushi, Y.; Matsukura, Y. Cohesion of unsaturated residual soils as a function of volumetric water content. *Bulletin of Engineering Geology and the Environment* **2006**, *65*(4), 449–455. doi:10.1007/s10064-005-0035-9
16. Morozov, A.; Shapovalov, V.; Popov, Y.; Kochur, A.; Yavna, V. Effect of mechanical impact on the microstructure and IR spectra of cohesive soil. *Vibrational Spectroscopy* **2023**, *128*, 103582. doi:10.1016/j.vibspec.2023.103582
17. Ping, X.; Zhou, G.; Zhuang, Q.; Wang, Y.; Zuo, W.; Shi, G.; et al. Effects of sample size and position from monolith and core methods on the estimation of total root biomass in a temperate grassland ecosystem in Inner Mongolia. *Geoderma* **2010**, *155*(3–4), 262–268. doi:10.1016/j.geoderma.2009.12.009
18. Wan-Mohamad, W. N. S.; Abdul-Ghani, A. N. The Use of Geographic Information System (GIS) for Geotechnical Data Processing and Presentation. *Procedia Engineering* **2011**, *20*, 397–406. doi:10.1016/j.proeng.2011.11.182
19. Utepov, Y.; Neftissov, A.; Mkilima, T.; Shakhmov, Z.; Akhazhanov, S.; Kazkeyev, A.; et al. Advancing sanitary surveillance: Innovating a live-feed sewer monitoring framework for effective water level and chamber cover detections. *Heliyon* **2024**, *10*(6), e27395. doi:10.1016/j.heliyon.2024.e27395