Toward the use of an intermediate value of the modulus of deformation of soils in geotechnical design

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Abstract. This study presents the results of a critical analysis of the existing methods of selecting the values of ground deformation modulus used in calculating the settlement of designed foundations. The importance of improving the reliability of the determination of the modulus of deformation for ensuring the reliability, economic efficiency and safety of structures is highlighted. It is revealed that the determination of the deformation modulus is not performed at the full depth of soil samples, which can lead to the risk of accidents at facilities. To increase the reliability of deformation modulus determination, a method of interpolation of values based on data from nearby wells is proposed. A new model for determining intermediate values of the deformation modulus is presented, which can be used in calculating the settlement of designed buildings. The results of test problems confirm the high efficiency of the proposed method not only for the calculation of foundation settlement using the values of ground deformation modulus, but also for the control determination of refined values of ground deformation modulus at the stage of geotechnical engineering surveys.

1 Introduction

When designing the geotechnical part of the building, it is important to take into account the deformations of the soil foundations in order to prevent foundation displacements, which may lead to disruption of normal operation or reduction of the service life of buildings and structures [1-2].

All existing foundation settlement assessment methods prescribed [3] by national and international standards use the modulus of total ground deformation as the main characteristic [4].

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Consequently, the accuracy of this characterization plays an important role to ensure the reliability, economic efficiency and safety of construction projects [5].

However, at the moment in the world practice of construction the solution of this important task mainly remains a subject of discussion among specialists and scientists [6].

The modulus of deformation is not considered to be a physical characteristic of the soil [7].

Frequent errors in determining the modulus of deformation of soils, which are allowed in engineering survey reports, are related to inaccurate determination of their values [8].

Thus, the accuracy of determining the values of ground deformation modulus directly affects the risk of accidents with constructed facilities [9]. There is still uncertainty in the choice of this characteristic due to the significant discrepancy between its values obtained by laboratory and field methods [10-11].

To solve this problem, interpolation techniques are often used to derive intermediate values from the available data.

Robust Geographic Information Systems (GIS) and simulation modeling equipped with specialized algorithms are now being actively developed [12], that allow us to understand the geomorphology of the earth structures [13–15]. A variety of mathematical and statistical analyses of the data received from IoT sensors enable rapid response to faults in engineering networks [16] and get a better understanding of the stability of the foundation [17], which in turn will affect the deformation characteristics of the soil. Thus, these methods provide an opportunity to analyze and model spatial data, which allows to get a more complete picture of the soil base and groundwater.

The use of different interpretation methods in ArcGIS software complex gives the possibility of more accurate determination of soil parameters and prediction of their changes in time and space, which helps to improve the efficiency of design and construction of engineering structures [18].

The purpose of this study is to clarify the values of soil deformation modulus and to develop a methodology for determining intermediate values of deformation modulus using the ArcGIS software package.

2 Methods

The study is conducted in the capital of the Republic of Kazakhstan, the city of Astana, located on the steppe plain in the central part of the territory. The climate of the city is characterized by sharp continentality, which is manifested in low precipitation and a significant amplitude between absolute maximum and minimum air temperatures. The relief of the territory is represented by low floodplain terraces of the Yesil (Ishim) River. The geological composition includes Paleozoic undivided sediments in the north and Middle Upper Quaternary sediments in the south and west.

Most of the city is built on sedimentary rocks, predominantly sandy loams. The average annual relative humidity is 67%, with annual fluctuations from 80% to 53%. The hydrographic appearance of the region is characterized by many temporary watercourses active during spring snowmelt, with river runoff, which is mainly used for evaporation, saturation of alluvial sediments and partial recharge of lakes.

Lakes in hollows and troughs are present along the Esil River valley, their depth varies from 1 to 2-3 meters, and they are all freshwater. Groundwater is largely formed by filtration of winter-spring precipitation and partly by filtration of surface runoff from temporary watercourses.

The main collectors of groundwater are the aquifer in the undivided alluvial sand and gravel Quaternary sediments of the Yesil River valley and the Ordovician fracture zone of the Ordovician rocks. The construction site is shown in Fig. 1.

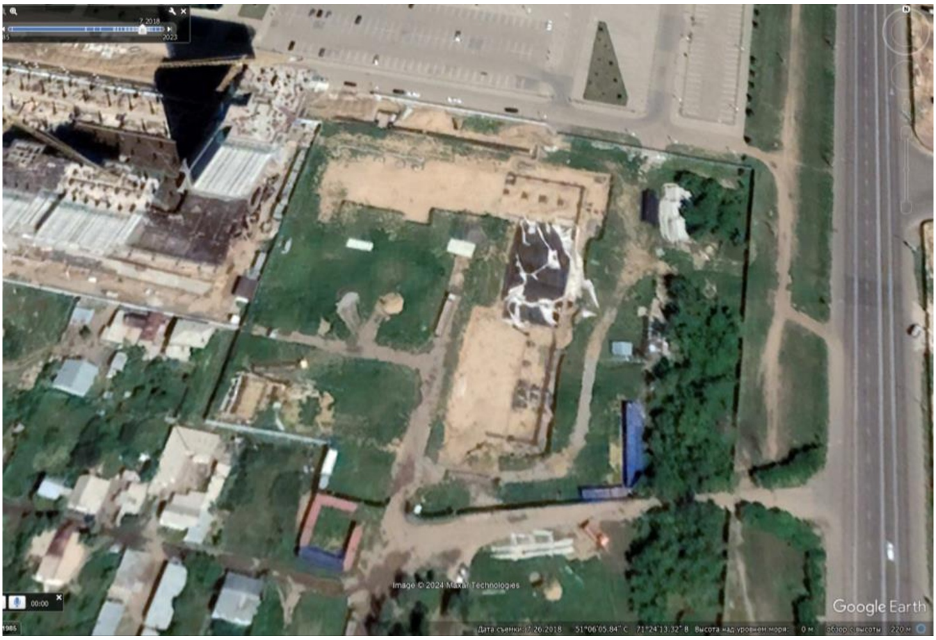

Fig. 1. Construction area.

Six boreholes were drilled at the construction site and soil samples were collected from various depths. The physical properties of these samples are summarized below (Table 1).

Table 1. Physical Characteristics of Soil Samples.

IGE number	Sampling depth, m	Particle size distribution, % Particle size, mm									Natural humidity, W, %	Plasticity, %			Fluidity rate, I_L	Density, g/cm^3			Porosity coefficient, e
			gravel		sand														
		> 10	10–5	5–2	2–1	1–0,5	0,5–0,25	0,25–0,1	0,1–0,05 (< 0,1)	< 0,002		yield point, W_L	rolling boundary, W_p	ductility number, I_p		natural, ρ	soil particles, ρ_S	dry ground, ρ_d	
1	1.6	12.3	4.1	2.7	14.9	–	–	12.6	53.4	–	5.27	24.9	17.2	7.7	-1.55	1.6	2.71	1.52	0.783
2	5.5	–	–	–	–	–	–	–	–	–	19.68	22.1	16.1	6.0	0.6	2.03	2.7	1.7	0.588
3	5.7	–	–	–	–	–	–	–	–	–	16.23	24.4	16.2	8.20	0.0	1.92	2.71	1.65	0.642
4	7.5	3.4	6.3	10.1	11.3	16.6	29.6	10.5	12.2	–	–	–	13.45	5.3	1.08	1.99	2.7	1.62	0.667
5	3	8.0	1.7	3.8	15.5	20.1	22.1	25.3	7.7	3.8	–	–	–	13.96	–	–	–	–	–
6	9.0	5.2	16.2	27.6	20.8	14.5	11.2	2.7	1.8	–	–	–	10.95	–	–	–	–	–	–
7	14.5	–	–	–	–	–	–	–	–	–	11.9	34.7	24.2	10.5	-1.17	2.12	2.72	1.89	0.439

Based on the results of the analysis, the following soil characteristics were obtained:

IGE 1 - The soil is a bulk material consisting of sandy loam with a sandy loam consistency, having a brown color, containing construction waste, and impurities of substances at the level of 4.0%;

IGE 2 - The sample is a brown-colored sandy loam, characterized by hard and plastic consistency, with interlayers of dusty sand and loam up to 20 cm thick. The content contains organic matter ranging from 3.6% to 4.1%, with an average of 3.9%;

IGE 3 - The sample is a brown-colored loam with a hard and semi-hard consistency, with interlayers of sand up to 20 cm thick. There are admixtures of organic matter up to 3.9%;

IGE 4 - The sample submitted is medium coarse grayish brown sand, is in a water saturated state, and has a polymict composition;

IGE 5 - The sample is a coarse grayish brown sand, also in a water saturated state, with a polymict composition;

IGE 6 - Sample represents a gravelly grayish brown sand, also in a water saturated state and with a polymict composition;

IGE 7 - The sample represents a loam of hard consistency, colored in mottled tones, with iron and manganese oxidation spots.

Based on our comprehensive studies of the mechanism of foundation-soil interaction, we have developed a new model that differs significantly from the existing ones. This model allows us to find intermediate values based on the available data. A comparative analysis based on the results of test problems has shown the high efficiency of this model in correcting the values of the compression modulus of deformation of the foundation soil.

In accordance with the methodology described in [19], in the process of processing the results of compression tests, the value of deformation modulus is defined as a constant value for a certain section of the compression curve at given intervals of compaction loads. However, this approach is tentative because it does not take into account the actual stress state of the foundation soil. In particular, this method takes into account only one factor - the slope angle of the secant line, which significantly differs from the real law of the compression curve of the investigated soil.

Our work has shown that the use of intermediate values can lead to significant errors in the calculations. For example, for a soft plastic sandy loam foundation, such distortions can result in a 15% reduction in settlement and a 17% to 34% reduction in the deformation of the foundation within its core, depending on the layering and known data.

The calculation schemes used in the methods for determining building code settlement [20], in the form of a linearly deformed half-space and a linearly deformed layer of finite thickness, do not correspond to the mechanical scheme of testing the specimen in a compression device. In the odometer, the soil is compressed under compression conditions, without the possibility of lateral expansion in a confined space. Therefore, the values obtained differ from the real foundation because the soil properties vary with the compressive thickness of the foundation.

However, by using intermediate characterizations of soil strength properties determined by our methodology, rather than from geotechnical engineering reports, which are determined at specific depths, we are able to determine with acceptable reliability the settlement of the designed foundation, which is close to real values. The engineering-geological section of the construction site is shown in Fig. 2.

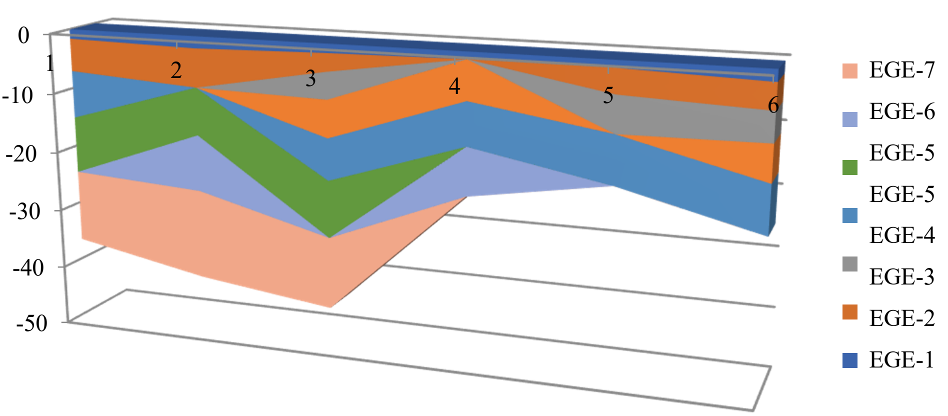

Fig. 2. Engineering and geological section of the construction site.

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Based on the available data, including the results of soil samples from 6 wells, using the Kriging and Inverse Distance Weighting (IDW) interpolation method in ArcGIS software to determine soil property values between these wells where data is unknown. This method allows us to predict soil property values at all other points in the study area.

Using ArcGIS software package, modeling of Kriging and IDW interpolation methods was performed to estimate the values of ground deformation modulus in space. Taking into account the known values obtained during engineering surveys, their sampling depth and the distance between boreholes, we obtained heat maps showing real values of the ground deformation modulus. This means that at any given depth we can obtain more realistic intermediate characteristics of the ground deformation modulus based on the original known values obtained during the survey, while taking into account the distance between the boreholes and the soil stratification.

3 Results and Discussion

Application of Kriging and IDW methods in ArcGIS software in the analysis of mechanical properties data allowed us to obtain more accurate and reliable predictions of deformation modulus values throughout the study area. The results of the resulting maps are presented in Figs. 3 and 4. Gradations of variability of values are displayed under each map: lighter colors correspond to near maximum values, and darker colors correspond to minimum values from known data.

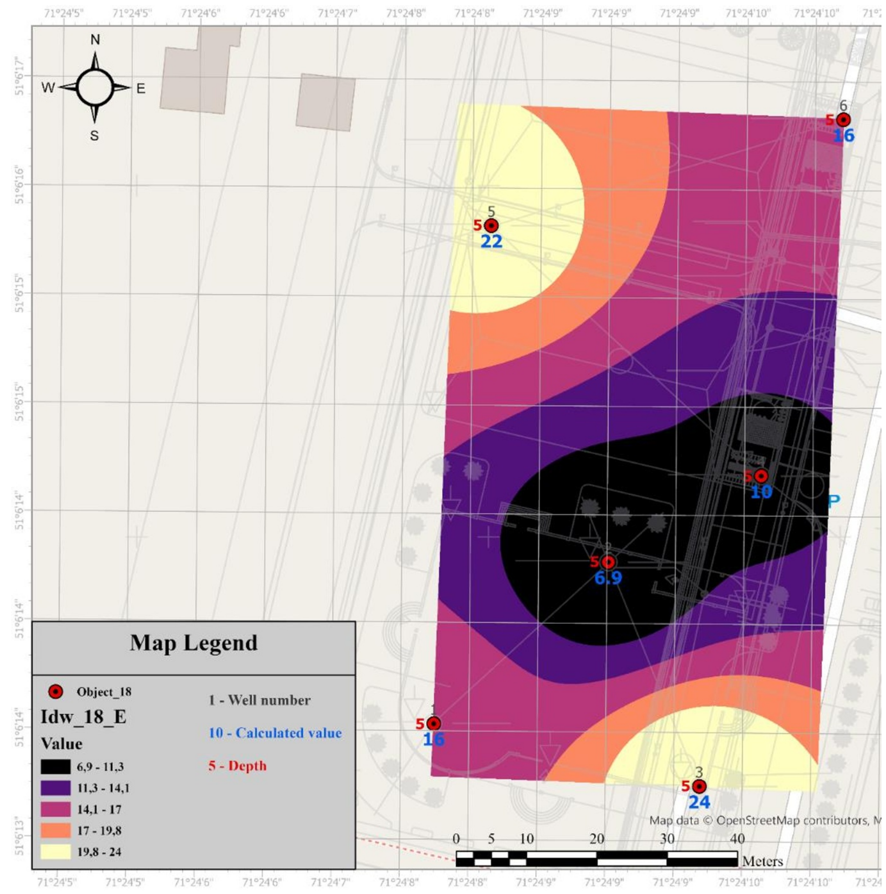

Fig. 3. Heat maps of spatial variability of known values obtained by the IDW method.

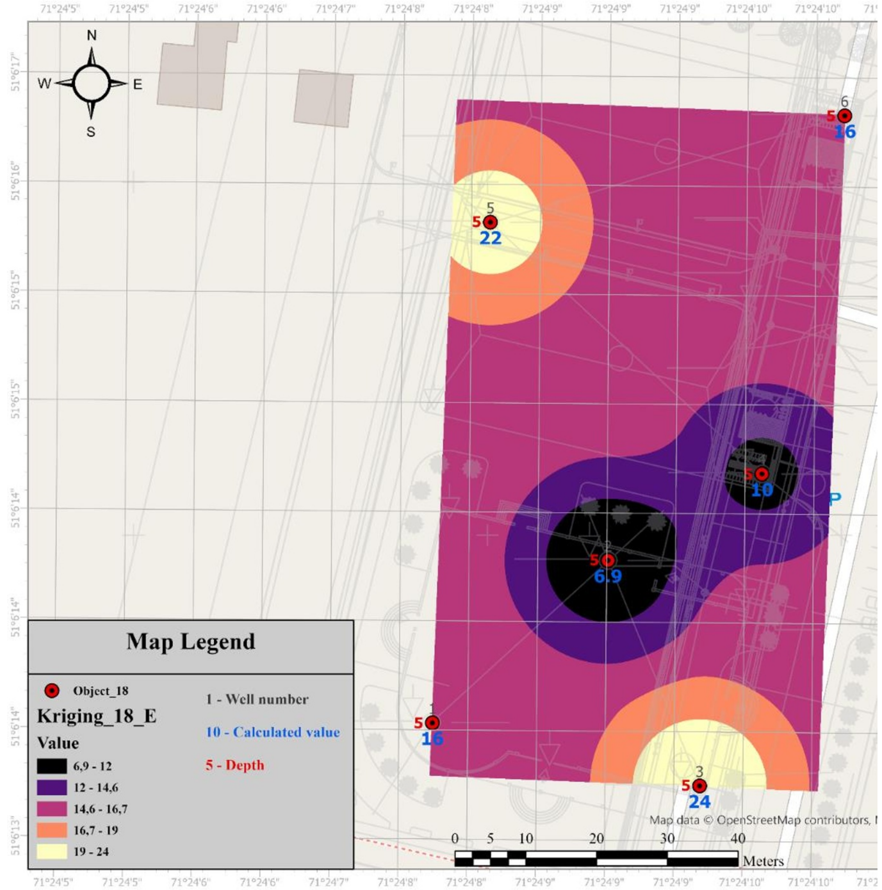

Fig. 4. Heat maps of spatial variability of known values plotted using the Kriging method.

Processing and loading the ground deformation modulus data into a map database allowed us to perform the comparative analysis presented in Table 2.

Using this approach allows us to reduce resource and time costs, while providing reliable results of the study.

By specifying the required depth and applying the recommended interpolation method, we can obtain intermediate values of the ground deformation modulus. This approach allows us to select any depth and obtain accurate characterization values, which greatly simplifies the correct assessment of geotechnical conditions at the construction site. This approach may also result in reduced costs for geotechnical investigations. In addition, by using soil condition information from known boreholes, we can obtain data not only for idealized conditions, but also for realistic scenarios of soil stratification.

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Table 2. Comparative analysis of soil deformation modulus.

№	Soil	Soil characteristics		Depth of sampling, m	Modulus of deformation, MPa	
		W, %	*e*		E_{fam}	E_{int}
1	Loam	96,7	0,561	4,8	6,9	8
2	Loamy clay	16,5	0,594	3,7	4,9	6,9
3	Medium coarse sand	14,5	0,6	7	30	23
4	Coarse sand	13,4	0,6	8,5	30	22

5	Gravelly sand	10,9	0,6	9	30	24
6	Loamy clay	11,22	0,417	11,5	6,1	8,1

Analysis of the data in Table 2 shows that the new methodology for determining refined values of ground deformation modulus includes the use of interpolation between known data points. This allows taking into account the distance between these points and obtaining intermediate values of the deformation modulus more accurately.

For example, using the old norm methodology, strain modulus values for clay 4.9 MPa and for sand 30 MPa were obtained, while using the new methodology, values of 6.9 MPa and 22 MPa were obtained, respectively.

This indicates a significant discrepancy between the known values of strain modulus. The new methodology allows taking into account this difference and finding intermediate values of the modulus of deformation using interpolation, which gives more accurate results.

This is important when evaluating the deformation properties of the soil when calculating settlement of foundations for structures. More accurate modulus of deformation data allows engineers to make more informed decisions about foundation design and reinforcement, minimizing the risk of undesirable deformations and damage to structures in the future.

4 Conclusions

The new model, based on comprehensive studies of the mechanism of foundation-soil interaction, allows to accurately determine the intermediate values of the ground deformation modulus.

Comparative analysis of the results of test problems confirmed the high efficiency of the new method for calculating foundation settlement.

The proposed method is effectively applied for the control determination of refined values of the ground deformation modulus at the stage of geotechnical engineering surveys.

More accurate data on the deformation modulus allow engineers to make informed decisions on the design and reinforcement of foundations, minimizing the risk of undesirable deformations and damage to structures in the future.

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