DOI: https://doi.org/10.5592/CO/EUROENGEO.2024.174

ANALYSIS OF THE SOIL PROPERTIES SPATIAL HETEROGENEITY BY MEANS OF ENGINEERING GEOLOGICAL MODELLING

GULMIRA AMANOVA [1,2,3], EUGENE VOZNESENSKY [1,2], PAVEL PATRIKEEV [3]

[1] *Sergeev Institute of Environmental Geoscience, Russian Academy of Sciences, Russia, 131597tupac@mail.ru*

[2] *Faculty of Geology, Lomonosov Moscow State University, Russia, eugene@geoenv.ru*

[3] *Atomenergoproekt, JSC, Russia, ilmarinnen@list.ru*

Abstract

The problem of soil properties heterogeneity in the massif and possible approaches of evaluating its regularities by means of three-dimensional numerical modeling of spatial fields of the studied parameters within the framework of geostatistical approach is considered. It can be demonstrated that the structure of geological parameters fields (a) differs for different stratigraphic-genetic complexes of soils and rocks, (b) can be simpler than the combination of engineering-geological units, (c) the proposed approach is able to identify and explain significant deviations from the normal or lognormal distribution in its upper and lower quartiles, presenting practically in any geological subdivisions of the section. These outbursts in the maximum and minimum ranges are themselves an additional characteristic of soil heterogeneity; they testify to the non-randomness of such "outbursts", their typicality. Unlike a formal approach of subdividing the soil profile into a set of engineering geological units the proposed differentiation is based initially on composing the geological model consisting of bodies with varying origin, age and lithology and separated by distinct boundary surfaces. Additional internal boundaries in these 3D bodies are, on the contrary, diffusive and based on the analysis of spatial fields of the studied soil parameters by means of appropriate geostatistical procedures.

Key words

heterogeneity, variability, soils, massif, geostatistics, parameter field, 3D modelling, engineering geological model

1 Introduction

One of the most important scientific problems of modern engineering geology is the problem of the nature of soil massif behaviour. The main components of our ignorance of this nature, which constitute the essence of this problem, include uncertainty of soil massif boundaries in space, impossibility of direct observation of geological processes occurring in soil massifs, uncertainty of correlation between the state and properties of the sample and the same soil in the massif, scale effect and heterogeneity of soil composition and properties in the massif. These summands define the main actual research tasks to overcome this scientific problem and require the development of an appropriate methodology. In this article, we will focus on the methodology of studying the heterogeneity of soil properties in their massifs.

The heterogeneity of soils is manifested in significant differences in their composition and properties between any two points, and the spatial heterogeneity of the considered attributes determines their variability which is characteristic for all soils. The heterogeneity and variability of soil properties within an arbitrary soil massif is caused by variations in such characteristics as composition, structure, texture, moisture, fracturing, weathering, soil stress state.

Back in the 60s of the last century, N.V. Kolomensky (1968) had postulated 3 types of variability of soil property parameters - discontinuously irregular, discontinuously regular and functional, examples of which are also given in our work (Amanova, Voznesensky, 2023). Later these ideas were developed in the works of G.K. Bondarik (1971) and I.S. Komarov (1972), who introduced the concept of "geological parameter field". This field, its structure is the main characteristic of soil heterogeneity and spatial variability of properties in the massif. And it is exactly this field that is unknown to us.

For scientific understanding of the nature and regularities of soil heterogeneity it is necessary to construct and analyse the fields of soil properties parameters. And these so far unknown to us regularities definitely exist, because the formation of soils and rocks is a regular process, it is governed by the laws of physics, chemistry, geology and other natural sciences. And it is necessary to start with methodology.

2 Methodology

In general, it can be summarized as following. The main methodological tool is engineering-geological modeling. At the first stage a spatial geological model of the investigated soil massif is developed. For this purpose, software specialized for spatial modeling of geological objects is used. Next, the variability of soils is assessed by plotting the fields of each investigated geologic parameter. Geostatistics, machine learning, neural networks or other models and approaches can be used for this purpose. This information field can then be analyzed in 2D or 3D representation for each indicator of soil composition and properties. Then the incorporation of these parameter fields in the geological model of the considered array using specialized software will allow to obtain an engineering-geological model of the array, explicitly reflecting ground conditions including their continuous heterogeneity, instead of a combination of "bricks" - engineering geological units, which are assumed to be homogeneous, but are not in reality. The most important aspect of such a combination of the parameter field with the spatial model of the array is the preservation of its geological sense, for which certain rules for creating boundaries of different ranks in the model must be followed, and they are described below in this paper.

2.1 Formation of stratigraphic and genetic boundaries in the model

The procedure for development of a soil massif engineering-geological model includes a sequence of the following logical operations.

At the first stage, a geological model of soil and rock massif (as understood by G.A. Golodkovskaya and other authors) or its part is developed. This model implies the allocation of the main structural zones - geological and genetic complexes - according to the signs of unity of age and genesis. Geological boundaries between them, with the exception of consonants, become the main structural surfaces within the massif, and the boundaries are rigid, definite, interrupting all other boundaries, for example, facies boundaries. These surfaces fix in the model the fact of a jump-like change of rock formation conditions in time, and therefore all other boundaries of higher rank - for example, isolines of soil property fields - can undergo a rupture on them. This is fully consistent with the stratigraphic and geological-genetic approaches in geology.

At the second stage, "facies" - volumes of soils and rocks of the same composition with even closer age and genesis - are distinguished within the main structural zones, making it possible to reveal the structure of each geological and genetic complex in detail. The boundaries between different facies of the same age are, on the contrary, non-rigid, diffuse in the model and should not be transformed into the next generation of structural surfaces, reflecting a gradual change in the conditions of, for example, sedimentation within a single sedimentary cycle. This detailing of geological and genetic complexes in the geological model is necessary for understanding and subsequent correct interpretation of the already engineering-geological model.

At the third stage, the geological model of the massif is transformed into the engineering-geological model of the soil massif by superimposing the fields of variability of essential attributes of soils - their engineering-geological properties - on the main structural zones. The structure of variability fields of these properties should inevitably reflect the facies distribution to some extent, and the boundaries of isofields of property parameters can either undergo a jump on the main structural surfaces, or correspond to the diffuse character of facies boundaries in the model and demonstrate a smooth change of parameters. Thus, when the values of the parameter in question are close to each other in the geological and genetic complexes of different age and genesis contacting on a rigid surface, its isofields can be characterized by smooth transitions.

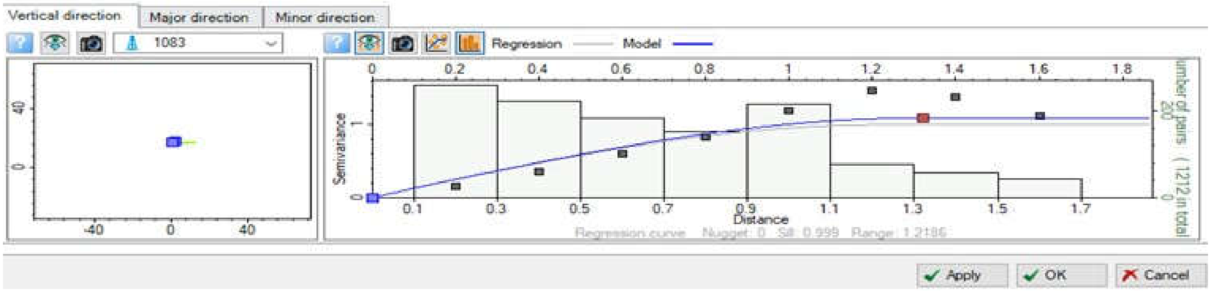
2.2 Spatial data analysis

Patterns of soil properties heterogeneity in general can be studied using various approaches, including:

- geostatistical models considering the spatial autocorrelation of data points to estimate values at unsampled locations;
- machine learning and artificial intelligence algorithms like random forests, support vector machines, and neural networks can be trained to predict soil properties based on input variables;
- process-based models simulating the physical and chemical processes that influence soil development and behavior;
- digital soil mapping involving spatial information from various data sources and data analysis techniques to create high-resolution soil property maps to predict soil properties;
- ensemble modeling approach combining multiple models to improve predictive accuracy.

In this research we used geostatistical approach based on variogram analysis and methods of statistical simulations. To implement the aggregate data analysis, Petrel software by Schlumberger was chosen, which is originally developed for petroleum geology tasks and has in its arsenal tools of statistical analysis, which can be used for engineering and geological modelling as well.

A variogram is a function of the variation of a spatial variable depending on the distance between the points at which the values of this variable are directly determined. Any variogram reaches an asymptote value (plateau) (Figure 1). The distance at which the variogram reaches the threshold of such a plateau is called the correlation radius. If the correlation radius for a data set is equal to, for example, 1 km, it means that to calculate a parameter at a point where its value has not been directly observed, all directly determined values (in our case, based on drilling results) within a sphere radius of 1 km should be taken into account.



Regression curve Nugget: 0 Sill: 0.999 Range: 1.2186

Figure 1. Example of a variogram for soil bulk modulus in Petrel variogram window.

Then within the specified correlation radius in the space between the tested points we can statistically develop parameter field for any indicator of soil composition and properties. We used Sequential Indicator Simulation (SIS) as a method for modelling lithological data, and Sequential Gaussian Simulation (SGS) for modelling soil properties parameters. SIS is a stochastic (cell-based) modelling algorithm that uses rescaled cells as a basis for relating the modelled lithological facies.

An approach known as Sequential Gaussian Simulation is often used to develop fields of continuous soil properties such as, e.g., porosity. The Sequential Stochastic Gaussian Simulation method assumes a joint normal distribution of the modelled random variable in the studied area. Real geological data, on the contrary, are usually not normally distributed, so the SGS method requires their preliminary preparation. This involves converting the original borehole data to a normal distribution.

Thus, both SIS and SGS stochastic operations are applied to each geological and genetic complexes in geological model within their fixed structural boundaries. This logic provides the preservation of the geological sense of the resulting engineering geological model. The detailed flowchart of model development process is presented in Figure 2.

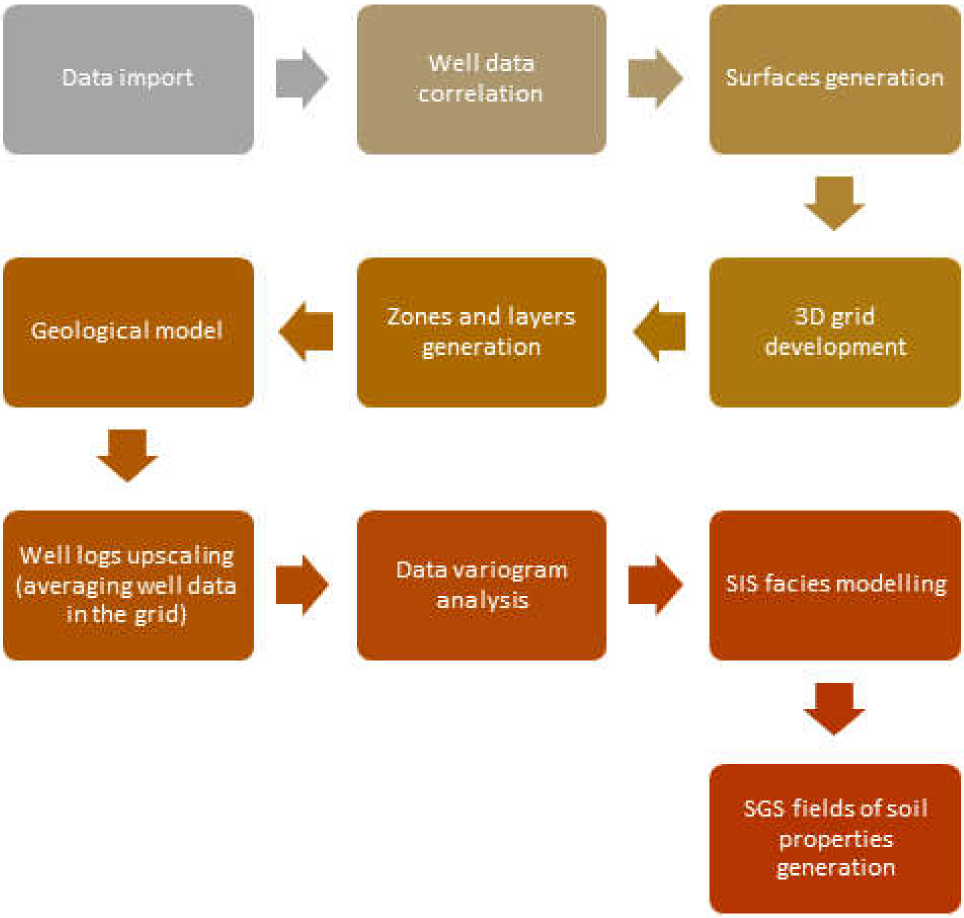


Figure 2. Modelling algorithm flowchart

About the resolution of the resulting model. In Petrel software rules of massif volume partitioning into cells should be set both laterally and vertically. If the model contains no faults, the cells have the same length and width. However, to correctly embed faults, it is necessary to modify the geometry of near-fault cells by "attracting" their vertices to the faults both horizontally and vertically. The horizontal resolution of the grid is determined by the increments of the horizontal projections of the cells and the correct choice of horizontal grid resolution - X and Y increments - is very important. It is usually desirable to have at least 2-3 cells between wells. For example, if the distance between wells is about 300 m, it is recommended to build a grid of cells no larger than 100 x 100 m. Grids in which several wells fall into the same or neighbouring cells should not be used and it is necessary to shift to smaller cells, if the wells are not too close to each other.

The model allows a certain smoothing. For example, lithological facies were modelled by averaging a set of stochastic SIS realizations and their subsequent smoothing. Smoothing is performed to remove noise (individual unrelated cells) while preserving values in well cells.

3 Results

The developed model is based on the following initial input data: geodetic survey data, engineering geological boreholes together with laboratory and field test results. Among the latter, the cone penetration test (CPT) data are of primary interest, since it provides such a massive, continuous and detailed distributed data set.

The object of modelling is the soil base of the nuclear industrial estate including different separate structures over a wide area. The site is located in the north-west of the European part of Russia. The structure of this massif up to a depth of 35 m is composed of Quaternary, mainly glacial and water-glacial soils on the top – loams, clays and quartz-feldspathic sands with gravel and pebble inclusions, as well as Cambrian sediments – sandstones and clays – at the bottom. There is a buried hollow in the site profile, associated with the pre-Valdaian palaeorelief stage and filled with younger sediments. In hydrogeological terms, water-bearing complexes confined to both Quaternary sediments and pre-Quaternary rocks are distinguished here. All Quaternary sediments represent water-bearing complexes and horizons. The groundwater level practically coincides with the day surface, hence all the considered soils are saturated in the massif, and all their properties, analyzed below, are characteristic for the saturated state. There is no permafrost.

Site investigations included more than 1500 boreholes of different depths. As a result of analysis of the data collected during engineering surveys, several dozens of engineering-geological units were identified in the massif profiles. At the same time, many of them are very similar to each other and, obviously, form single geological bodies, but differ in some features (e.g., variations in sand size), which, in fact, are a reflection of internal heterogeneity of these bodies. In general, the studied massif includes two quite homogeneous strata and a completely heterogeneous stratum of Quaternary sediments overlapping them. The formation has a rather complex structure, and in the geological profile appears as a set of numerous lenticular bodies. Some preliminary results discussing the variability of this massif are given in (Amanova, Voznesensky, 2023). Now we focus on the upper - the most variable and complexly composed - strata of Quaternary fluvio-glacial, alluvial and lacustrine-glacial sediments. For its detailed study 8 profiles were plotted using GeoSolution.Geology software. This software also allows to produce a set of structural surfaces – geological boundaries.

Consider the importance of these structural surfaces based on stratigraphic signs of age and genesis for correct representation of lithological facies in the model (Figure 3). Soil type is obtained from CPT data basing on the cone and friction sleeve resistances using standard geotechnical interpretation procedure and presented in this profile by sands, sandy silts, silts and clays, well corresponding with the direct soil description in the drill cores. In Figure 3a we observe overall random interlaying of facies replicating in general the shape of lower boundary of Quaternary deposits with the predominant occurrence of sands, which is not the case. Such chaotic interlacing, which is inconsistent with the geological regularities of formation of water and water-glacial origin strata, is an artefact of a simplified interpolation scheme that allows the inclusion of parameters of sediments formed at different time and in different conditions within the correlation radius of the variogram. The sharp-angled protrusions of the lower boundary and reflected higher in the strata are also not geologically meaningful and are related to the lack of actual data at individual points at the base of the strata.

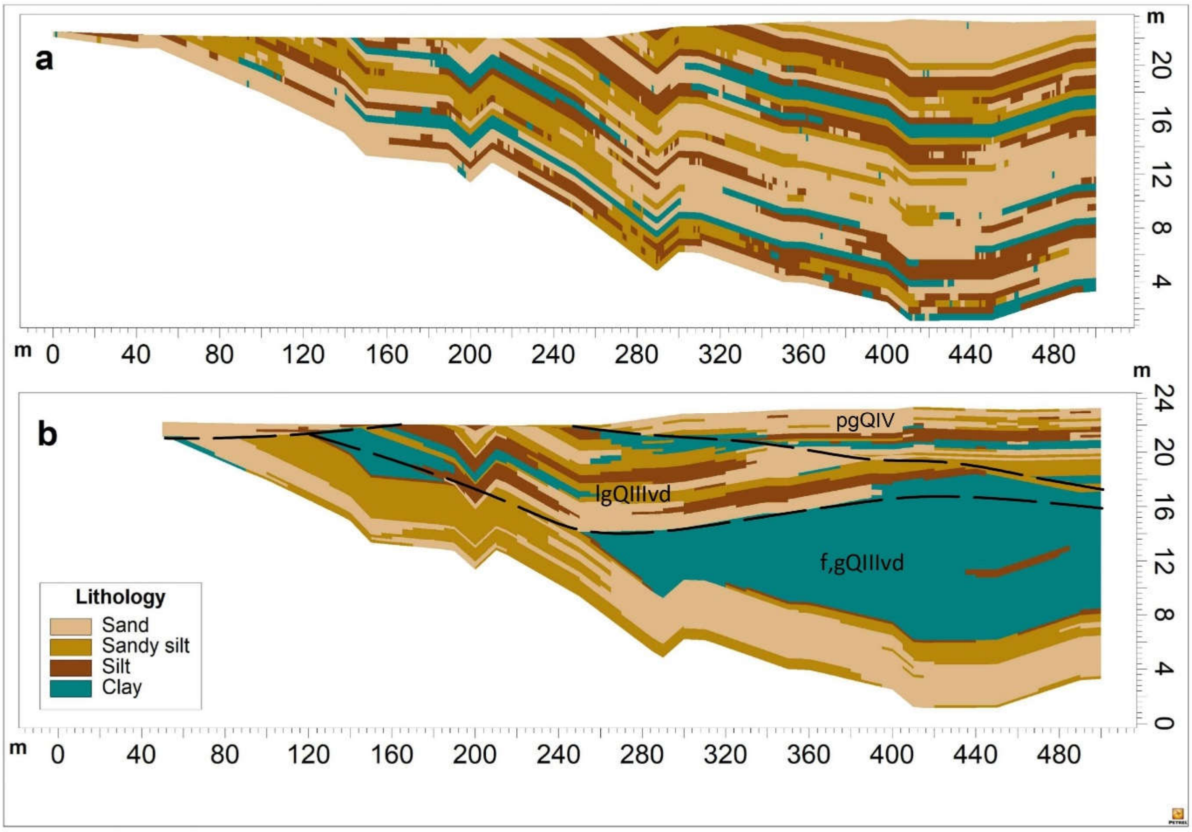


Figure 3. Spatial distribution of lithological facies in the model basing on CPT data: a – structural surfaces are ignored, b – geological boundaries are specified

On the contrary, in Figure 3b we observe geologically logic facies model with really observed soil lenses and predominance of clays in the central part of geological body. And diffusive boundaries of lithological facies are conformal to geological ones. Since soil properties depend primarily on composition, so the fields of their mechanical parameters (calculated for this model also from CPT data using generally adopted empiric relationships (Kulhawy, Mayne, 1990; Lunne, Robertson, Powell, 1997)) are expected to be also conformal to the facies spatial distribution.

This is what we really observe (Figure 4): on the top in Figure 4b there are mostly lacustrine-glacial sands and silt with bulk modulus generally below 150 MPa, whereas higher values – sometimes up to 350 MPa – occur in the lower fluvio-glacial clays and sands and the bottom. Interesting to note that in the upper Figure 4a, showing the modelling without taking into account structural surfaces, the distribution of the modulus is not just chaotic - the relatively thin (1-2 m thick) most rigid interlayers of loams and sands have been lost completely in this mess. We can also see that two different geological and stratigraphic complexes – upper lacustrine-glacial and lower fluvio-glacial – have different structure of parameter field, reflecting their deposition environment.

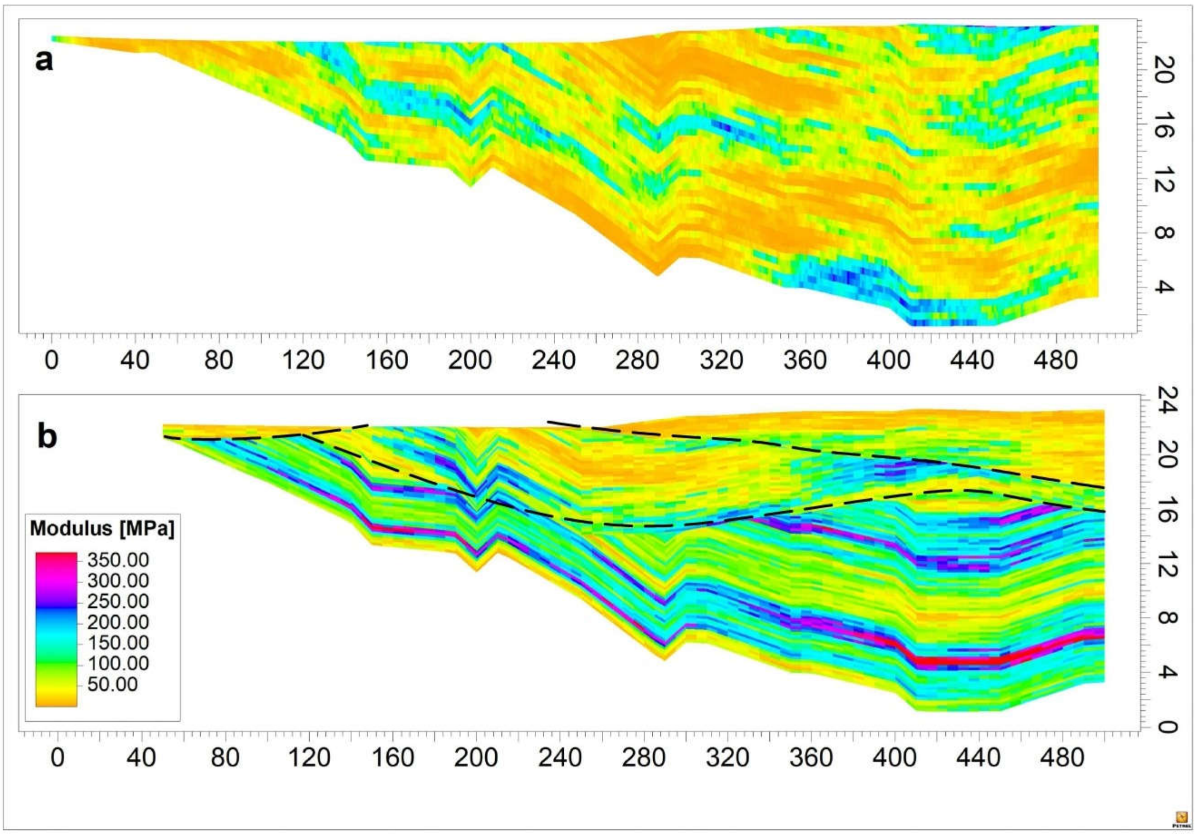


Figure 4. Spatial distribution of soil bulk modulus in the model basing on CPT data: a – structural surfaces are ignored, b – geological boundaries (black dashed lines) are considered

A similar situation is observed in the field of effective angle of internal friction (Figure 5): well-defined and generally conformal zones of this parameter for the model with fixed structural (geological) boundaries of stratigraphic and geological complexes (b) and haphazard distribution of "spots" with different values without this important consideration (a). It should be also noted that the structure of parameter field is also different for the soils of different origin. Considerably high absolute values for some facies (over 35^{o}) should be attributed to possible drawbacks of empirical correlations used for parameter calculations and coarse particles occurrence locally influencing cone resistance.

Thus, correct representation of the real relationship of geological bodies of different age and genesis within the studied massif is an absolutely necessary condition for correct modelling and the very possibility of studying the heterogeneity of soil properties with the help of the generated model. Moreover, only this approach gives the possibility to investigate specific features of this heterogeneity for soils of different origin.

Analysis of the presented herein model reveals considerable differences in the patterns of soil properties variability. Fluvio-glacial deposits have a somewhat regular alterations of both modulus and angle of friction with depth, probably due to their formation by water streams with different amounts of suspended clastic material of different size. Such variability both in vertical soil profile or in any horizontal section may be attributed to the discontinuous irregular type ("saw-rule" type) after N.V. Kolomensky (1968). On the contrary, lacustrine-glacial deposits, sedimented mostly in a still water environment, demonstrate much less regular, diffusive variability, which in certain sections of their profile – both vertical and horizontal – can hardly be associated with any of the known variability type. Further numerical studies of parameter field variability patterns for soils of various origin within the obtained engineering geological 3D models is an interesting and very promising future scientific task.

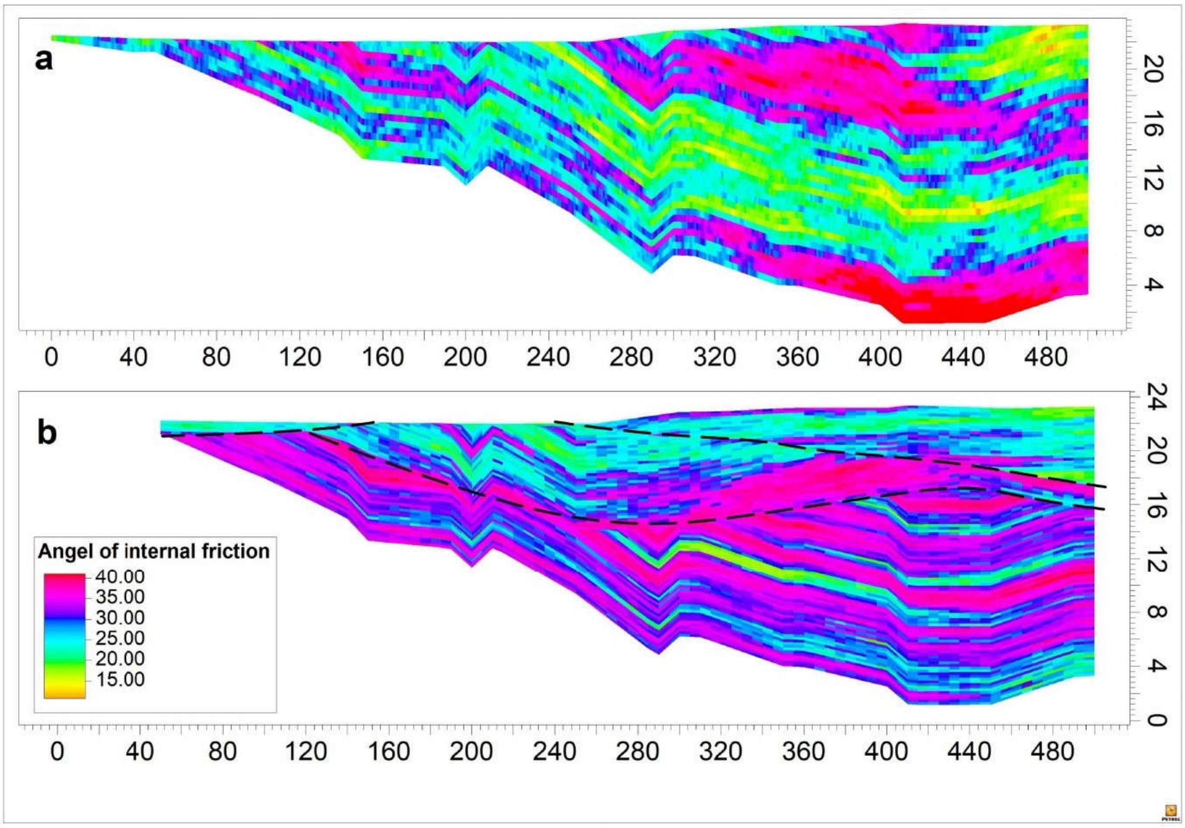


Figure 5. Spatial distribution of soil effective angle of internal friction in the model basing on CPT data: a – structural surfaces are ignored, b – geological boundaries (black dashed lines) are considered

Currently, in the practical field of engineering and construction activity this problem is circumvented by simplifying the real situation - by replacing a continuously inhomogeneous environment by its piecewise homogeneous model consisting of a set of engineering geological units (hereinafter referred to as EGU), all property indices of which are assumed to be constant within their boundaries, and on the basis of statistical processing of negligibly small sets of actual data. This approach was developed in 1960s for the possibilities of manual calculations and, in fact, has not changed so far. Many of the EGU boundaries are not unambiguous and abrupt in the geological space - on the contrary, they are often diffuse in nature, indicating gradual changes in some qualities of the soil, and only our subjective scheme of dividing the massif into EGU makes them some unambiguous lines on a profile or a map. Quantitative spatial analysis of soil massifs heterogeneity over large areas is complicated and requires a large volume of homogeneous and relatively uniformly distributed data. So, at present the solution of the above tasks seems to be expedient, primarily, for the bases of large and critical structures, the design of which requires the involvement of significant amounts of engineering geological information.

The development of the distribution fields of parameters allows not only to specify the geological boundaries of certain lithological facies, but also to identify deviations from their distribution law, which may be important for the operation of the structure, but are usually ignored in statistical processing. In addition, the fields of variation of parameters required for geotechnical calculations may not depend on the boundaries of the selected EGU, which opens up the possibility of improving this formal approach or even departing from it. Furthermore, the coupling of such engineering-geological model with the model (mechanical, thermal, hydraulic, etc.) of a foundation in the future will mean the emergence of a new type of geotechnical model of the structure base - with a continuous description of variations of key parameters instead of finite or boundary elements with discontinuous changes of corresponding parameters on their boundaries.

4 Conclusion

For scientific understanding of the nature and regularities of soil heterogeneity in a massif the parameters fields of soil properties should be generated and analysed. A methodology of such study based on engineering geological 3D modelling and geostatistical approach, including variogram analysis and methods of statistical simulations, is presented.

Correct allocation of the main structural zones within the model - geological and genetic complexes, separated by rigid, definite geological boundaries and diffusive, gradual boundary conditions between the facies is of crucial importance. The geological model of the massif is then transformed into its engineering-geological model by superimposing the fields of variability of essential attributes of soils - their engineering-geological properties - on the main structural zones.

The proposed methodology is demonstrated on the example of a variable and complexly composed strata of Quaternary fluvio-glacial, alluvial and lacustrine-glacial sediments within a single massif. Analysis of the presented model reveals considerable differences in the patterns of soil properties variability. Fluvio-glacial deposits have more or less regular alterations of both modulus and angle of internal friction with depth, probably due to their deposition by water streams with different amounts of suspended clastic material of different size and may be attributed to the discontinuous irregular type. Lacustrine-glacial deposits, sedimented mostly in a still water environment, demonstrate much less regular, diffusive variability, which hardly can be associated with any of the known variability type. Further numerical studies of parameter field variability patterns for soils of various origin within the obtained engineering geological 3D models is a very promising scientific task.

References

Amanova, G.S., Voznesensky, E.A. Engineering geological modelling of spatial heterogeneity of soils. *Gruntovedenie*, 2023, 2, 13-28. DOI:10.53278/2306-9139-2023-2-21-13-28

Bondarik, G.K. *Fundamentals of the theory of variability of engineering-geological properties of rocks*, Moscow, Nedra, 1971.

Kolomensky, N.V. *General methodology of engineering-geological research*, Moscow, Nedra, 1968.

Komarov, I.S. *Accumulation and processing of information in engineering-geological research*, Moscow, Nedra, 1972.

Kulhawy, F.H., Mayne, P.H. *Manual on estimating soil properties for foundation design*, Electric Power Research Institute, EPRI, 1990.

Lunne, T., Robertson, P.K., Powell J.J.M. *Cone Penetration Testing in geotechnical practice*, Great Britain, 1997.