Information Systems in Geotechnics - BIM Geotechnics

Boldyrev G.G., Doctor of Technical Sciences, Director for Research and Innovation, NPP Geotek LLC, Penza, Russia, g-boldyrev@geoteck.ru

Barvashov V.A.

Ph.D., Leading Researcher, NIIOSP named after N.M. Gersevanova, Moscow, Russia

Idrisov I.Kh. Ph.D., General Director of NPP Geotek LLC, Penza, Russia

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Abstract

Results of the development of a comprehensive technology of geotechnical investigation and design of foundations that are the basis for BIM geotechnics are presented in the paper. It is shown that the currently existing information systems for data transmission and processing, information and measuring systems allow not only to manage soils testing and processing of test data, but also to simultaneously perform calculations for the foundations using analytical and numerical solutions.

Modern methods of in-situ research of soils, such as static, dynamic and drilling sounding, allow to obtain continuous information on the physical and mechanical properties of soils in depth. Using well-known or local correlation equations and sounding data, the soil characteristics are found in depth and bases are calculated directly in the field in the process of soil sounding.

The proposed integrated technology combines geotechnical investigation and the design of foundations of structures into a single production process. The result is the reduction in survey time due to the application of soil testing methods with automated process control and interpretation of test data. In this case, the result of geotechnical investigation is not only information about the properties of soils, but also an assessment of the heterogeneity of the base and its effect on the behavior of the designed building or structure.

1. Introduction

This article is a continuation of research aimed at the use of digital technologies in engineering-geological, geotechnical investigation and designing the foundations of buildings and structures [15,16,19,20,24,25].

In order to increase the efficiency of construction, it is proposed to combine the stages of geotechnical investigation and the design of the foundations of buildings and structures in a single whole. Existing information systems for data transmission and processing, information and measuring systems allow solving the problem under consideration in a similar formulation. In 2012, at a conference of engineer-geologists in Kaluga [38], for the first time in Russia, the task was set of creating an integrated technology for geotechnical investigation, which is shown in the form of a diagram on Fig. 1. It was noted that current computer technologies provide tremendous opportunities for geotechnical

Fig.1. From the presentation in 2012

data processing and engineering calculations with the possibility of visualization. But the main obstacle to further progress remains the lack of interaction between prospectors and designers, which is constantly mentioned in numerous speeches at conferences of prospectors and a number of publications [6,26].

Currently, both in domestic and foreign practice, the foundations base of buildings and structures are being designed using analytical and numerical solutions. Analytical solutions are given in the corresponding sets of rules (SP) [44,45,46,58 and others], they are simple, easily programmable, require the determination of the minimum number of soil characteristics, and long-term practice of their application indicates their reliability. Numerical methods for calculating the foundation bases are much more complicated, in most cases it is necessary to determine a larger number of characteristics/parameters of soil models during investigation, and often the reliability of the calculations has to be verified using analytical solutions. Due to the fact that it is still mandatory to comply with the requirements of the joint venture in the Russian Federation, when developing a complex technology, we propose using the appropriate analytical solutions for calculating the foundation bases in regulatory documents. At the same time, the structure of the proposed technology allows the use of numerical methods of solutions implemented in various geotechnical software, such as Plaxis, Flac, Z-Soil, Geo-Slope, Geo-5, etc.

2. The use of digital technology in building design

In general, a digital model of a construction facility should include not only structures, but also a 3D model of the foundation base with the necessary set of soil parameters. This can be implemented as the following sequence: 3D architecture - Digital terrain model - 3D geotechnics - 3D construction. If you perform the calculation of the foundations together with above-ground structures, then the third and fourth stages of digital modeling can be combined.

As a rule, 3D digital modeling is performed for the first, second and fourth stages. In geotechnical investigation [43], determination of soil parameters and calculation of the foundation base are performed sequentially as information is received. Moreover, the data of geotechnical investigation are transmitted to the designer in the form of reports in docx or pdf format. The designer is forced to manually create a digital model of the foundation base, for example, in the Plaxis software and enter soil parameters into it. It should be borne in mind that geotechnical report soil parameters only for analytical methods for calculating the bases given in existing joint ventures [44,45,46] or EN 19972-2 [58]. In the case of using numerical solutions, it is necessary to determine additional soil parameters that are not regulated by GOST and ASTM for soil testing. However, all these problems can be solved if, as a result of the geotechnical investigation, a digital three-dimensional model of the base is created, the necessary soil parameters are determined and the foundation bases are calculated according to the deformation and bearing capacity.

The aim of the work is to develop a comprehensive digital geotechnical technology, which includes not only the creation of a digital three-dimensional model of the foundation base, determination of parameters for various soil models, but also the calculation of the foundations bases using analytical or numerical solutions. In fact, the proposed integrated digital technology is one of the elements of building information modeling (Building Information

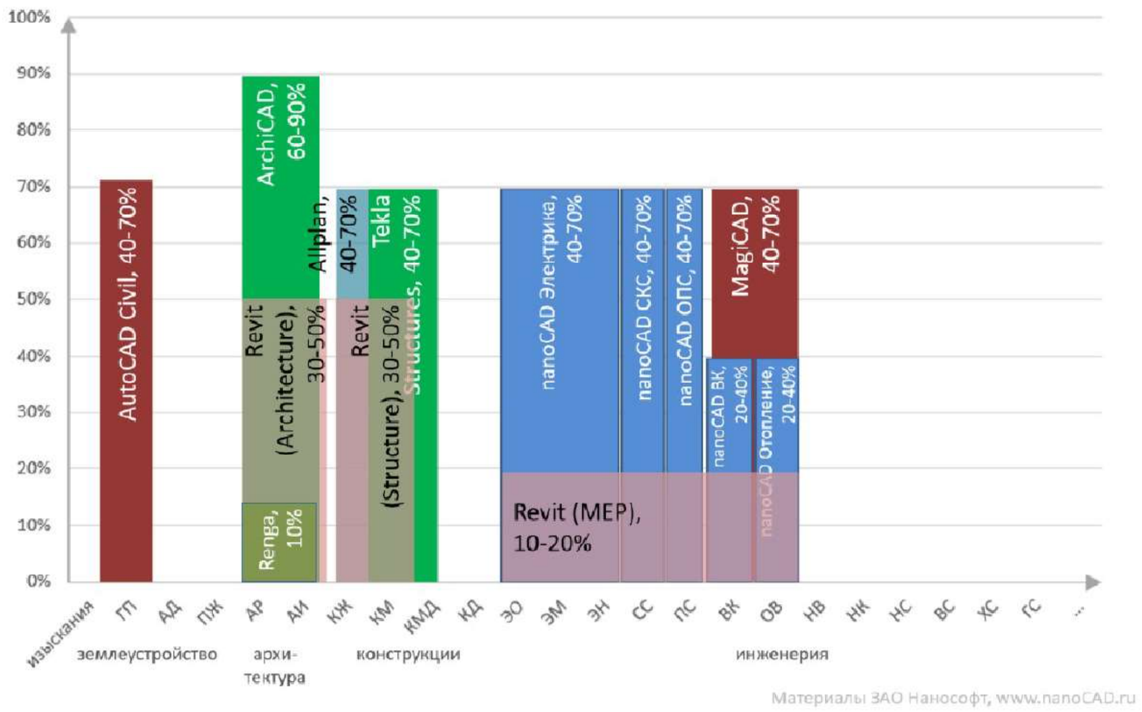


Fig. 2. Russian market of BIM solutions (www.nanoCad.ru)

Modeling - BIM) and includes geotechnical and foundation calculation in conjunction with building structures. Together, this is all the subject of 3D geotechnics. Currently, BIM technologies are being developed for many sections of the design and construction projects, with the exception of the empty section in Fig. 1, which are surveys.

Consider the possibility of realizing the task using well-known digital technologies.

3. 3D digital modeling of the surface relief of the construction site

At present, geologists in the preparation of engineering geological surveys, in the vast majority of cases, do not use a digital model of the surface topography of the earth, replacing it with a situational plan of the designed facility in order to place boreholes for the selection of soil monoliths and places for in-situ testing of soils (static or dynamic penetration, tests with a pressiometer or screw stamp). A situational plan is created after topographic and geodetic work is carried out and is carried out in the form of a scheme that is not the basis for design and construction work. At the same time, the data of 3D digital modeling of the surface topography can be used both for the purposes of geotechnical investigation, and for the direct design of construction facilities.

Digital modeling of the surface topography can be performed according to topographic data with processing, for example, in the following software: Topocad (Adtollo AB, Sweden, www.topocad.ru), ArcGIS (www.), AutoCAD Civil 3D 2012, ZWCAD 2019 (https://www.zwsoft.ru/zw-about), Credo Topographer (https://credo-dialogue.ru), GeoniCS RGS, RgsPl (http://www.csoft.ru/catalog/soft/geonics-rgs/geonics-rgs-rgspl-10.html), etc.

These or similar software allow to create a digital elevation model and are a means of representing the topographic surface during computer processing of the results of geotechnical investigation. Using a digital model of the surface topography, you can snap the designed facility on a given construction site.

4. 3D digital modeling of buildings or structures

As a technology for constructing a three-dimensional model based on GIS applications, the most frequently used software is ArchiCAD to build a digital terrain and create a three-dimensional model of building structures. ArchiCAD is a software package for architects, designers, and civil engineers based on Building Information Modeling (BIM) technology created by Graphisoft [1].

No less powerful CAD system of Russian production is T-FLEX. A computer-aided design system that has all the modern tools for developing projects of any complexity. The software combines the powerful parametric capabilities of three-dimensional modeling with the means of creating and design documentation [32,33,39]. The twenty most popular software include, in addition to the products listed above, Bentley (https://www.bentley.com/), Civil 3D (https://www.autodesk.ru/), Allplan (http://www.allbau-software.de/), Autodesk Revit (https://financesonline.com/building-information-modeling/).

In [47], the possibility of using various software products in the Revit-LIRA-PLAXIS-LIRA bundle within the framework of BIM technology was considered. Recently, not only LIRA SOFT companies (https://lira-soft.com), but also Bentley (https://bentley.com) began to use a similar approach to building design.

The digital model of the building [47] created in the Revit software is transmitted to the LIRA, where the base calculation is performed using the coefficient

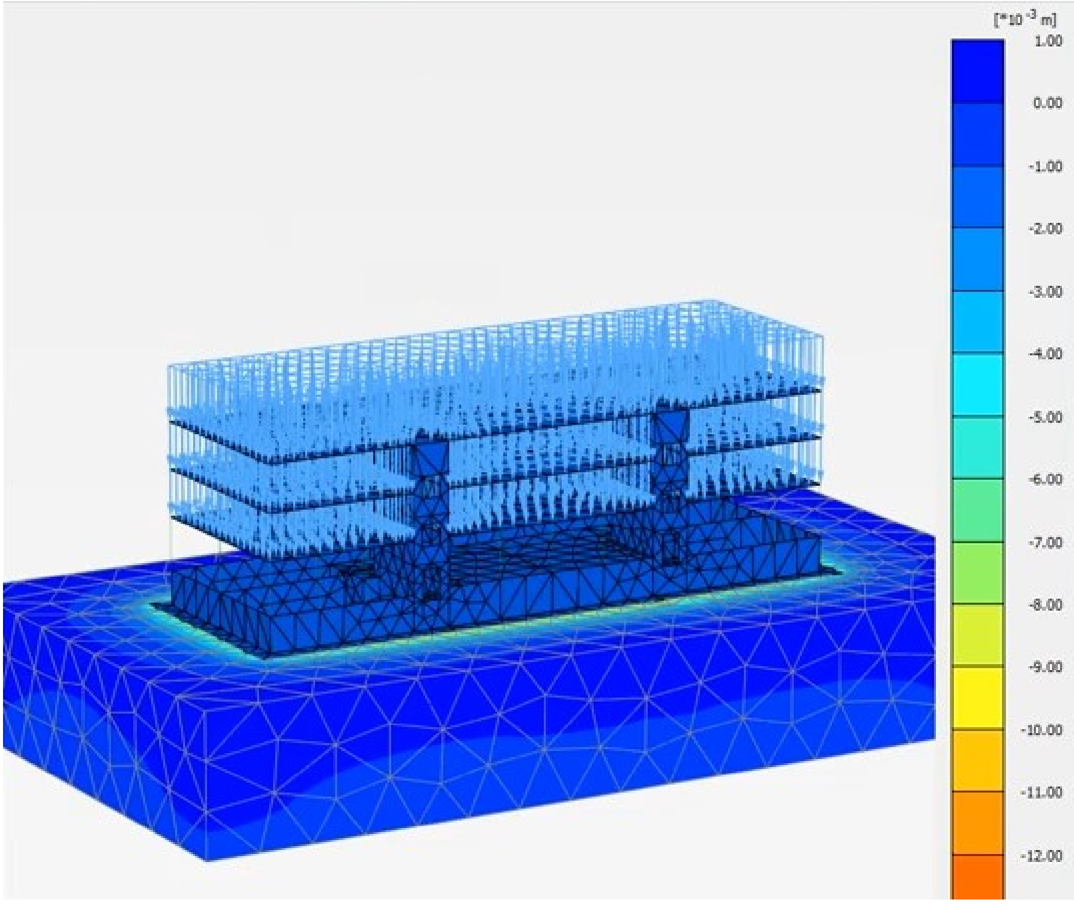


Fig. 3 General view of the model of the building slab Foundation with vertical movements in the PLAXIS, transmitted from the LIRA model [47]

bed or with the Plaxis software for non-linear soil models. Then, the results of calculating the stress-strain state of the foundation base are transferred to the LIRA software for calculating the structures of the designed building (Fig. 3).

Thus, the data transfer is implemented in the LIRA 10 software in conjunction: 3D modeling of building structures (Revit) - geotechnical calculations (LIRA, Plaxis) - design of foundations and above-ground building structures (LIRA).

5. 3D geotechnics

5.1. Introduction

Input data for digital modeling of building foundations and construction are from the geotechnical investigation. The standard geotechnical procedure is presented in SP 47.13330 [43] and includes the determination of stratigraphy with the allocation of geological elements, the construction of a geomechanical model (GOST 20522-2012 [30]), the determination of the parameter soil for calculating the deformation and bearing capacity of the foundation bases using analytical methods of calculation. The latter is determined by the fact that the relevant

GOSTs for soil testing are focused on domestic Code of Rules [44,45,46] . In the case of using numerical methods, the solution of the problem is somewhat more complicated, since in GOSTs [27,28,29,31] there is no methodology for determining the parameters of many soil models.

The general procedure, including the stages of geotechnical investigation and design, was previously proposed by Paul Maine [61] in the form of a circuit, which is shown in Fig. 4. As can be seen from Fig. 4 to calculate the foundations using analytical or numerical solutions, it is necessary to carry out a complex of geophysical, laboratory and in-situ tests of soils. As noted above, the soil testing methodology is formalized in the form of various GOSTs, ASTM, ISO and others. And, it is quite easy to determine the soil parameters necessary for the analytical solutions that are given in Code of Rules SP [42,43.44] or EN 19972-2 [58]. In the case of using numerical solutions, the task of determining the parameters is somewhat more complicated, since the existing standards does not spell out the methodology for determining them, and the parameters themselves depend on the adopted soil model, type of stress state and stress trajectory.

Determination of soil model parameters is carried out using various instruments and devices in laboratory [29] and in-situ [28,31]. As a rule, the results of the corresponding tests are presented in digital form in ASCII, Excel format. At the same time, the results of determining stratigraphy of soils are presented in the graphic format JPEG, BMP, etc. in the form of lithological columns and sections.

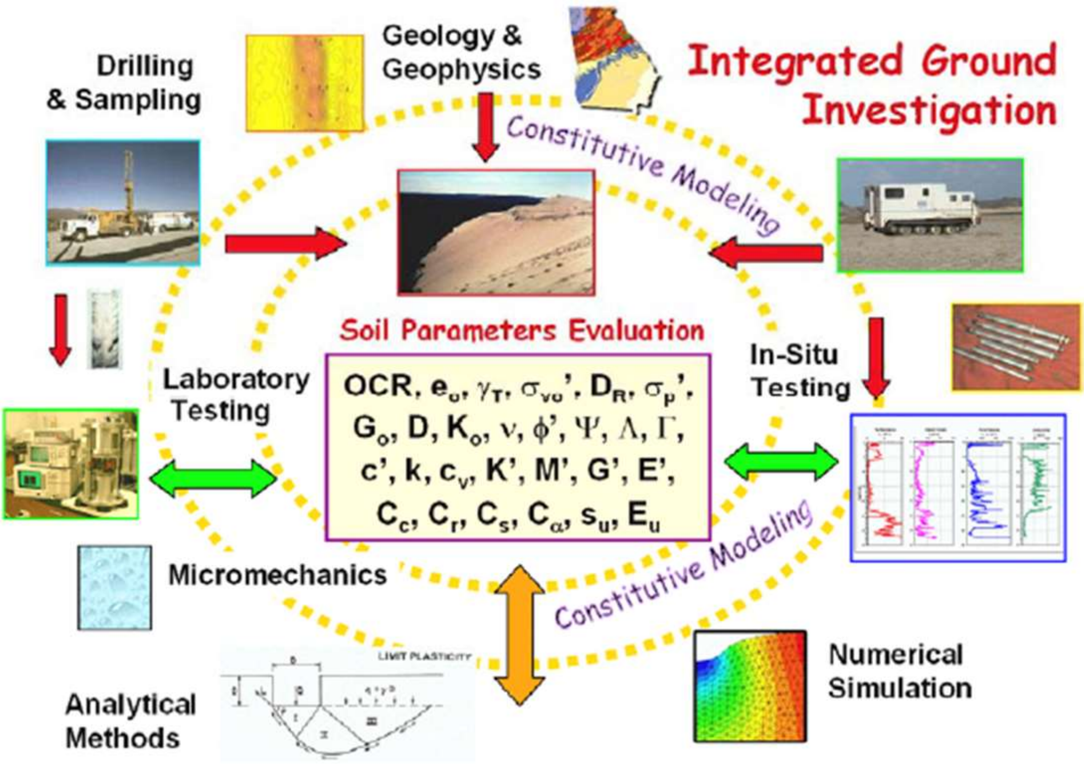


Fig. 4. The General procedure for investigation and design of foundations [60]

The publication on the Geoinfo website (www.geoinfo.ru) provides an overview of software for engineering geology compiled by M. Prokhachev [40]. The author notes that among the most commonly used software among geologists are: CREDO geology, GEOSimple, EngGeo, GEOTECH Geologist + GeoDraw (www.uniservice-europe.co.uk), GeoniCS GEODirect.

The GeoSimple software is intended for entering archive data from field logs, as well as converting static penetration data obtained using various equipment into the GXL format for transmission to the GeoExplorer software (http://geotest.ru/complect/GeoSimple/).

GGS processing in the CREDO software package (https://credo-dialogue.ru/tekhnologii/geologiya.html) is performed with the following tasks: input data on the initial boreholes; determination of physical, mechanical and chemical properties of soils; formation of geological models, sections, geological columns; data processing of in-situ tests of soils.

The LOGDRAFT software processes the results of laboratory and in-situ tests of soils and provides initial information for geotechnical design, includes the DXF format for transferring data to the Autocad software (http://geosystemsoftware.com/products/ld5/index.html).

The GeoniCS Engineering Geology (GEODirect) software allows to: to process and interpret the results of laboratory tests and static penetration of soils; perform statistical processing of information on selected engineering-geological elements (EGE), the calculation of the normative and calculated characteristics of the physico-mechanical properties of soils; build graphical dependencies to carry out the construction of engineering-geological sections and engineering-geological columns; calculate the ultimate resistance and bearing capacity of piles; carry out the formation of reporting documentation (https://cad.ru/support/bz/archive/82/geonics-inzhenernaya-geologiya-geodirect-2014/).

It should be noted that in most of the noted software, AutoCAD, MicroStation, and nanoCAD are used to graphically construct a two-dimensional or three-dimensional model of the base massiv.

All noted and other well-known software for geologists are focused on storing engineering-geological and geotechnical investigation data, as well as processing laboratory and in-situ test data.

An analysis of the software mentioned above for geologists shows that they all have the following disadvantages:

- data from in-situ and laboratory tests are entered into the software for interpreting test data manually in the appropriate tables or through Excel;
- lack of a procedure for automatically determining the parameters of soils from geological and geotechnical investigation necessary for calculating the foundations bases using analytical solutions;

- the lack of a procedure for determining the parameters of soil models from geological and geotechnical investigation necessary to calculate the stress-strain state of the bases using numerical methods;
- lack of communication between geotechnical investigation and of the foundation base calculation software;
- lack of assessment of heterogeneity of the natural mass of the soil and its impact on the behavior of construction facilities;
- the traditional representation of a three-dimensional model in the form of soil layers, rather than a digital field of soil parameters;
- presentation of investigation data in the form of a report on paper in docx or pdf format.

However, a more significant drawback is the impossibility of digitally transmitting geotechnical investigation data from geological software to geotechnical software.

Programs at the geotechnical level perform the calculation of foundations using data from engineering-geological surveys and geotechnical investigation. As a rule, the solution of various boundary value problems in geotechnical software is associated with the manual entry of soil parameters directly into the software or using the corresponding procedure of a specific finite element software.

The most popular geotechnical software are GEO5 - (www.finesoftware.ru), Plaxis (www.nipinfor.ru), GeoSet (www.geoset.pro/programs), Flac (www.itascacg.com/software/flac3d), Z-soil (www.zsoil.com), MidasGTS (www.ru.midasuser.com), etc.

In a number of software, for example Plaxis, Ansys (www.cadfem-cis.ru), there is an internal procedure for creating scripts using its own editor, which allows you to use the software as a calculator in the main software.

5.2. Engineering-geological and geotechnical investigation

The main task of engineering-geological and geotechnical investigation is the creation of geomechanical model of the foundation base [30,43]. Traditionally, the geomechanical model is a three-dimensional array of soil (base) from various engineering geological elements (EGEs) and a set of soil parameters.

Most of the required parameters of soils for designing the foundations of buildings and structures using Code of Rules be determined both in laboratory and field conditions. As a rule, laboratory tests are labor intensive and last for weeks. As a result, complete information about the properties of soils can be obtained no less than a few weeks after the start of the survey.

It is more attractive to determine the properties of soils in the field, for example, using methods of static and dynamic penetration, drilling sounding, testing with a screw stamp, a vane shear, etc. The first two methods are known and widely used in the practice of geotechnical investigation [12,14,19,59,60,62,63], the method of drilling sounding (Russian drilling test - RDT) is little known and is still rarely used in domestic practice in determining mechanical characteristics of soils and the division of the soil stratum into separate layers, despite its shown effectiveness [11,17,56,57].

Nevertheless, the method of static sounding (CPT - cone penetration test), which is used not only for dividing the soil stratum (EGE) into engineering-geological elements, but also for determining the strength and deformation characteristics of soils, is still finding wider application in both domestic and mainly foreign practice [19,59].

In determining the deformation and strength properties of soils, correlation dependencies are used between the parameters measured during the introduction of the probe into the soil and the data from laboratory tests of soils [19,59,61,62,63]. The measured parameters of static penetration are: cone tip resistance, A friction sleeve, pore pressure, shear and longitudinal wave velocity, soil temperature. The shear wave velocity is used to determine the elastic shear modulus, and the transverse and longitudinal waves to determine the Poisson's ratio. Using sounding parameters and correlation equations, physical and mechanical characteristics of soils are found [41,59,61,62,63].

In the study of the properties of frozen soils, the soil temperature is a mandatory measured parameter. Currently, the Russian Federation has completed discussion of a new standard for static penetration of frozen soils [27]. The standard provides for testing frozen soils with probe heating and measuring soil resistance to penetration and soil temperature, both during immersion and during thawing and freezing.

Despite a number of advantages of the CPT method and its widespread use over many decades, compared with other in-situ test methods, it is laborious in frozen and inapplicable in rocky and coarse clastic soils. When exploring sandy and gravel soils or at great depths, its capabilities are also limited, since it requires the use of more durable probes and machines with a large net weight or anchoring of the machine.

The standard dynamic sounding method (SPT - standart penetration test) is used to determine soil resistance by driving a hollow steel cylinder into the soil with sampling of the broken structure for soil classification. In Russia, this method is practically not used, tests are carried out by shock immersion of a cone in soil [31]. Unlike static penetration, this method is applicable in sandy, gravelly and coarse soil.

The method of drilling sounding allows you to research the properties of almost all types of soils like sand, clay, gravel, rocky and frozen soils. In this method, well drilling is performed by a screw with a drilling tool, the type of which depends on the type of soil [11,13,14,17,56,57]. Due to the fact that the auger plunges into the ground almost effortlessly, this allows the use of conventional drilling rigs massively used in geotechnical investigation without their modernization.

5.3. Assessment of heterogeneity of the research site and determination of the number of workings

The reliability of geotechnical investigation depends on the quality and volume of investigation, especially in the presence of specific soils and their heterogeneity. The determining factors here are the engineering-geological element and its physical and mechanical characteristics (parameters soil). According to Code of Rules SP 47.13330 [43] and EN 1997-2 [59], the distances between the nearest workings/borehole are assigned in the range from 20 to 100 m.

Due to this sparseness, very often the geological features do not fall into the field of view of the geologist: wedging out layers, soil lenses, etc. In addition, if their presence was revealed in one or several workings, then their boundary is assigned based on the experience of the geologist. Determining the properties of soils by selecting monoliths in the workings does not provide complete information about the properties of the array of the studied soil due to the artificially large distance between the workings and the small volume of the test soil. With this approach, the use of complex soil models and numerical solutions is not justified due to the ambiguity in determining their parameters.

Given the heterogeneous properties of soils and the ambiguity of the construction of sections V.Sheinin et al. [42,49-53] proposed to evaluate the heterogeneity of the base by calculating the settlement and tilt with determining the function of the elast modulus at various points of the foundation plan, where settlement is calculated. The elast modulus is determined for each workings by selecting soil monoliths and laboratory tests.

At the same time, modern methods of in-situ research of soils, such as static and dynamic penetration, drilling soundings, provide continuous information on the physical and mechanical properties of soils in depth and are fairly cheap with an increase in the number of test sites within the study site. The data recording of sounding parameters can be performed at any interval in depth. Using the well-known correlation equations and sounding data, one can find the soil characteristics in depth. Further, by introducing reliability factors, it is possible to obtain the calculated values of the soil characteristics, and then perform the calculation of the foundation bases for deformation and/or bearing capacity. All this can be done in the field directly in the process of soils sounding.

In the proposed survey technology, the controlled parameters are the settlement and the tilt of the designed building, the values of which are normalized in SP 22.13330. The sounding of soils within the spot of the designed building continues until the calculated values of settlement and the tilt cease to change significantly. Thus, we are moving away from the normative setting for assigning the number of workings in SP 47.13330 (EN 1997-2) to their determination, based on the hypothesis of the assumed a priori heterogeneity of the studied soil massif [18]. Naturally, for a soil mass uniform in its properties, a smaller number of workings will be required than for a heterogeneous one. It is quite advisable to use geophysical methods at the first stage of surveys to assess the heterogeneity of natural soil masses and, based on their data, to adjust the programm of engineering-geological and geotechnical investigation.

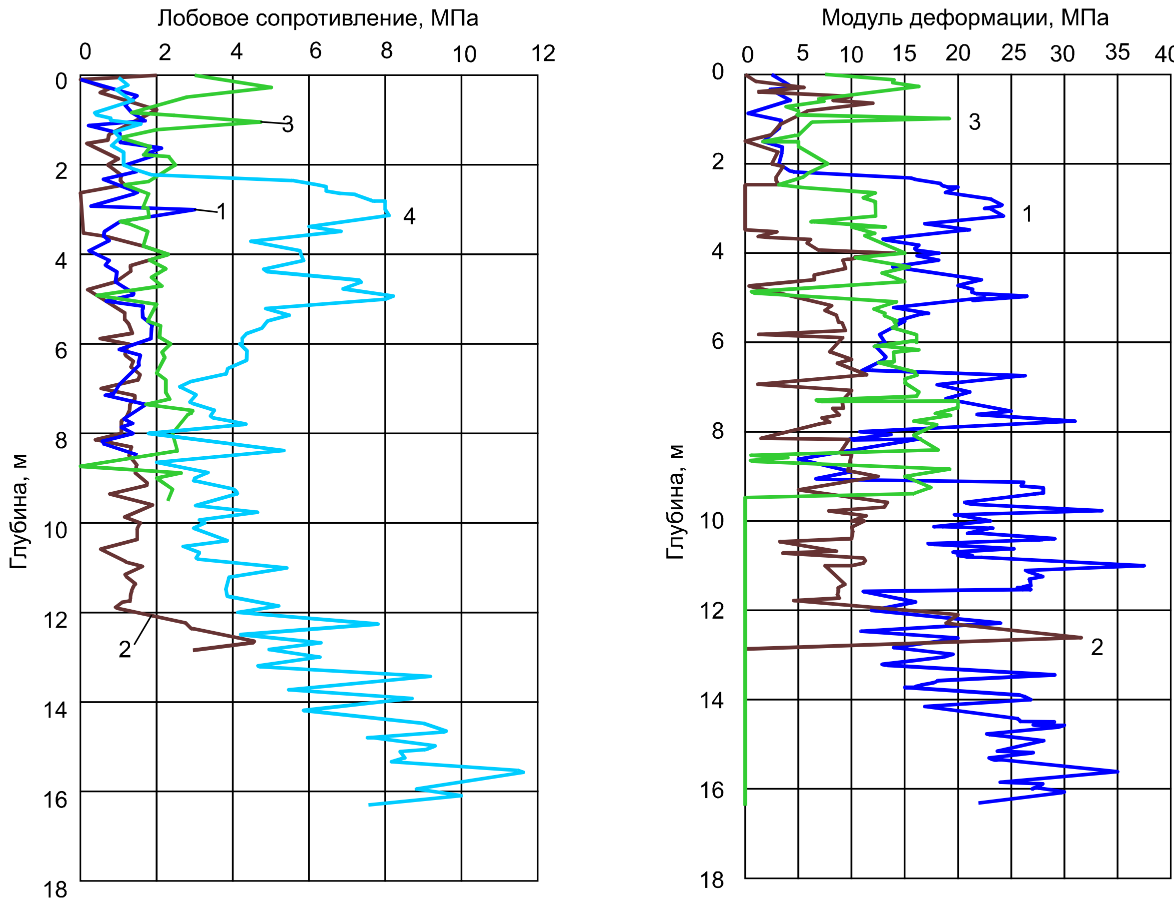
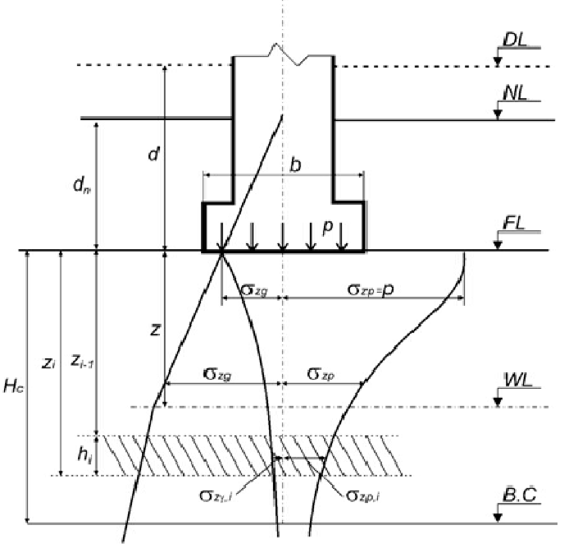


Fig.

Fig. 5. Profiles of cone tip resistance and stiffness: 1,2,3,4 - numbers of sounding points at a distance of not more than 2 m from each other

In the process of sounding, on the screen of the drillmaster’s computer after driving each sounding point, the values of the depth of the compressible thickness, settlement and tilt of the structure appear and the profiles of the physical and mechanical characteristics of soils are displayed (Fig. 5). This allows to analyze incoming information to make a decision on the completion of investigation at the survey site under consideration. The sounding depth is determined from the calculation of the compressible stratum according to one of the conditions of SP 22.13330 and is monitored during the probing, which allows to stop probing when the depth of the compressible stratum is reached, plus 1-2 m. The depth of the compressible stratum depends on the pressure under the sole of the foundation and the compressibility of the soil of the foundation base and, accordingly, the sounding depth may be different within the area of the designed building, and not normative as adopted in Code of Rules SP 47.13330 or EN 1997-2.

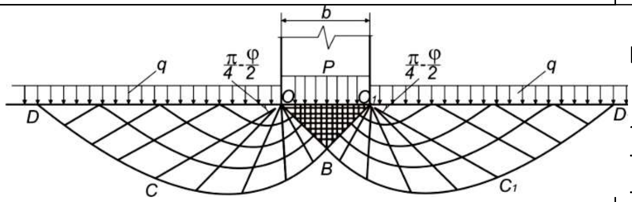
Table 1. Analytical methods of calculation in SP 22.13330

<table>
<tr><th>Method of calculation</th><th>The calculation scheme of the method</th><th>Test method and parameters soil</th></tr>
<tr><td>Settlement calculation SP 22.13330</td><td>


$$s = \beta \sum_{i=1}^{n} \frac{(\sigma_{zp,i} - \sigma_{z\gamma,i}) h_i}{E_i} + \beta \sum_{i=1}^{n} \frac{\sigma_{z\gamma,i} h_i}{E_{e,i}}$$
</td><td>
Laboratory tests:
1. Compression:
- elast modulus, E
- elastic modulus during unloading, E_e
- Poisson's ratio, ν

2. Physical characteristics:
- density, ρ

In-situ Tests:
1. Plate test
- elast modulus, E_{PLT}

2. Static penetration
- elast modulus, E_{CPT}
</td></tr>
<tr><td>Bearing capacity SP 22.13330</td><td>


$$F = b'l'\left(N_y \xi_y b' \gamma_{\mathrm{I}} + N_q \xi_q \gamma'_{\mathrm{I}} d + N_c \xi_c c_{\mathrm{I}}\right)$$
</td><td>
Laboratory tests:

1. Direct shear/triaxial compression:
- cohesion, c
- angle of internal friction, φ

2. Physical characteristics:
- density, ρ
</td></tr>
</table>

The calculation of the deformation and bearing capacity of the foundations base of buildings can be calculated using analytical solutions given in the corresponding Code of Practice or using numerical solutions (Table 1) and more complex soil models (Table 2) in the software Plaxis, Flac, etc.

The use of analytical solutions for calculating the deformations and bearing capacity of substrates is preferable to numerical, since they are easily programmed, do not require a license, and are tested by many years of construction practice.

It is simple enough to carry out the calculation of settlement from the average pressure of the bed foundation by the method of elementary layer-by-layer summation (SP 22.13330) taking into account the heterogeneity of soils, revealed as a result of in-situ tests. Such calculations are performed for each sounding point, and not under the entire sole of the foundation. Then, the stiffness coefficients of the base (bed coefficient) are determined over each sounding point, which are then extrapolated to the entire surface of the base, and calculation options are considered for various values of the Shepard extrapolation function [8,54,55]. To assess the reliability of the used correlation dependencies, reference workings are assigned with the selection of soil monoliths and laboratory tests of soils are performed. The data obtained are used to assess the reliability of the information received and recalculate, if necessary, the settlement and tilt of the designed buildings.

5.4. Method for determining the parameters of soil models

The study of the stress-strain state of structures of buildings and structures together with soil bases has recently been performed using numerical methods, in particular the finite element method (FEM). FEM is the basis of many commercial software that are used today in calculating the strength of foundations base and structures. Most of this software was designed to calculate strength in the field of mechanical engineering and do not, as a rule, take into account the peculiarities of the deformation of building materials, especially such as soils or concrete.

In this regard, all known calculation software can be divided into two groups. The first group is software designed to solve the problems of structural strength in mechanical engineering and the second group is software for solving problems in the field of geotechnics and construction.

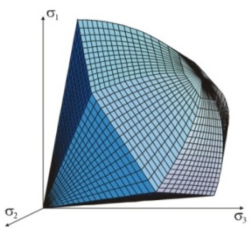
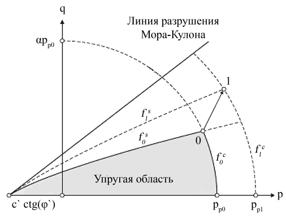
Online: www.engr.usask.ca posted a list of the most popular software, both the first and second groups, and on the sites: www.geotech.civen.okstate.edu; www.ggsd.com lists software for solving problems in the field of geotechnics.

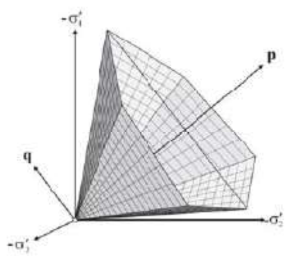
The most famous software of the first group are: Abaqus, Adina, Ansys/LS-Dyna, Lira, Nastran, etc.

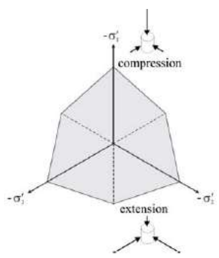
In the field of geotechnics, the following software is most often used: CivilFem, Flac, Geo-Slope, Plaxis, Z-Soil, Geo-5, etc.

All of these and many other calculation programs include determining equations or models of the material (Table 2), which determine the behavior of the

Table 2. Example, some models of soils

<table>
<tr><th>Programs</th><th>Name of soil model</th><th>Test method</th></tr>
<tr><td rowspan="2">Plaxis
FLAC
ABAQUS
LS-DYNA</td><td>Hardened models



$f^c = \frac{q^2}{\alpha^2} - p^2 - \sigma_p^2$
$f^s = \frac{1}{2E_{50}} \frac{q}{1-q/q_a} - \frac{2q}{E_{ur}} - \gamma_p$</td><td>Triaxial compression:
- secant elast modulus, E_{50}
- elastic modulus during unloading, E_{ur}
- Poisson's ratio, ν
Compression:
- pre-compaction pressure, σ_p
- odometric modulus E_{oed}
Direct shear/triaxial compression:
- cohesion, c
- angle of internal friction, φ
- angle of dilatancy, ψ
Physical characteristics:
- initial porosity coefficient e_0 - minimum and maximum porosity coefficient e_{max}, e_{min}
- density, ρ</td></tr>
<tr><td>Elastic-Plastic Models
$f^s = \frac{1}{2}(\sigma_1 - \sigma_3) - \left[\frac{1}{2}(\sigma_1 + \sigma_3)\sin\varphi + c\cos\varphi\right] = 0$



</td><td>Triaxial compression:
- elastic modulus, E
- Poisson's ratio, ν
- cohesion, c
- angle of internal friction, φ
- angle of dilatancy, ψ
Physical characteristics:
- density, ρ</td></tr>
</table>

base or elevated structures during their loading. In most cases, with the exception of elastic models of materials, the process of determining model parameters is complex and ambiguous. This is due to the following main reasons.

1. It is necessary to carry out material tests using appropriate devices and a known or newly developed test procedure.

2. The obtained parameters of material models must be calibrated by optimization methods by modeling the testing process and numerical calculation for various loading conditions.

To solve these problems, in most cases is quite difficult due to the lack of appropriate equipment and methods for testing samples of materials and identification of parameters.

Despite this, quite successful attempts to solve this problem by using auto-

mated systems for laboratory testing of soils and the subsequent interpretation of test data [35,36].

5.5. Laboratory automated soil testing system

LLC NPP Geotek offers to solve the problem of determining the parameters of soil and rock models using the test results of samples of materials using the ASIS Geotek Studio measuring system with static, kinematic and dynamic loading of soil samples (Fig. 6.7). The measuring system is certified by the State Standard of the Russian Federation as a means of measurement and is included in the register of industrial products.

The object of measurement of ASIS Geotek Studio is the deformation and stresses that occur when loading soil samples, in the corresponding devices with different types of stress state force loading. Currently, ASIS Geotek Studio is a

Fig. 6 The main types of devices in the ASIS Geotek Studio under static and kinematic loading

combination of measuring instruments and a set of control and computational software for measuring physical quantities and interpreting laboratory tests of soils.

Fig. 7 The triaxial compression device in the composition of the ASIS Geotek Studio under dynamic loading

An example of the determination of some characteristics of soils and parameters of soil models is shown in Fig. 8-10.

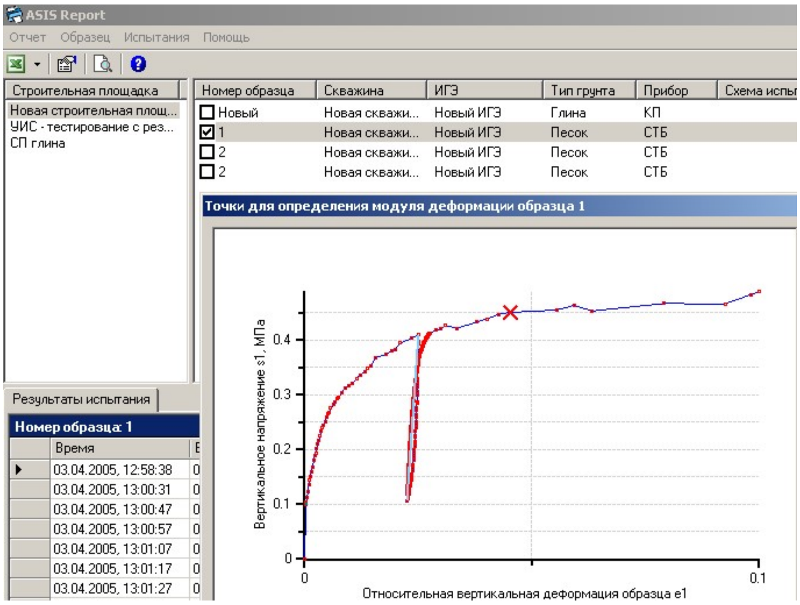


Fig. 8. The dependence of the axial strain from the axial stress, with the lateral pressure $\sigma_2 = \sigma_3 = 100$ kPa: the stiffness modulus at loading E = 55,78 MPa; elastic modulus of deformation (when unloading) E = 120,28 MPa; ultimate load σ_1 = 0,45 MPa (cross on the graph)

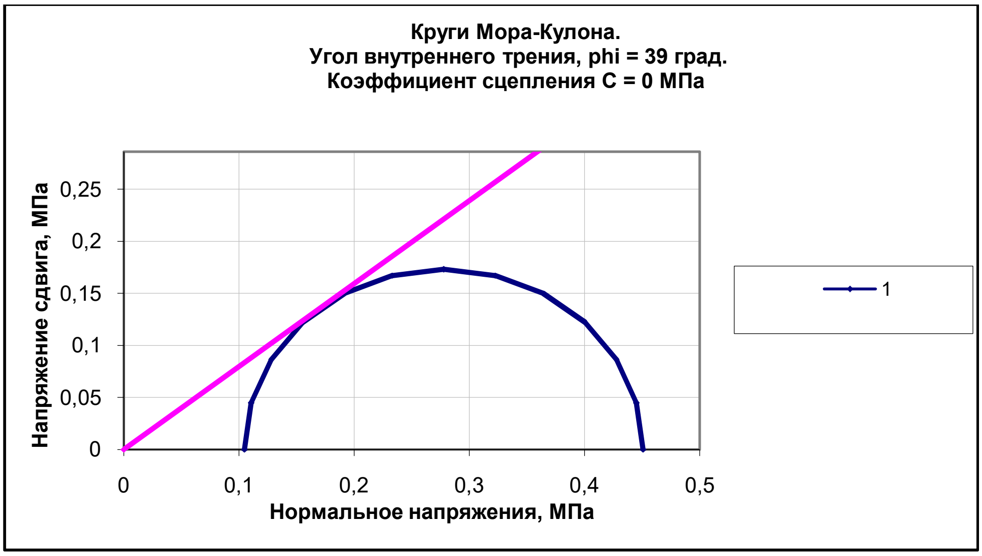


Fig. 9. Strength parameter φ for sand

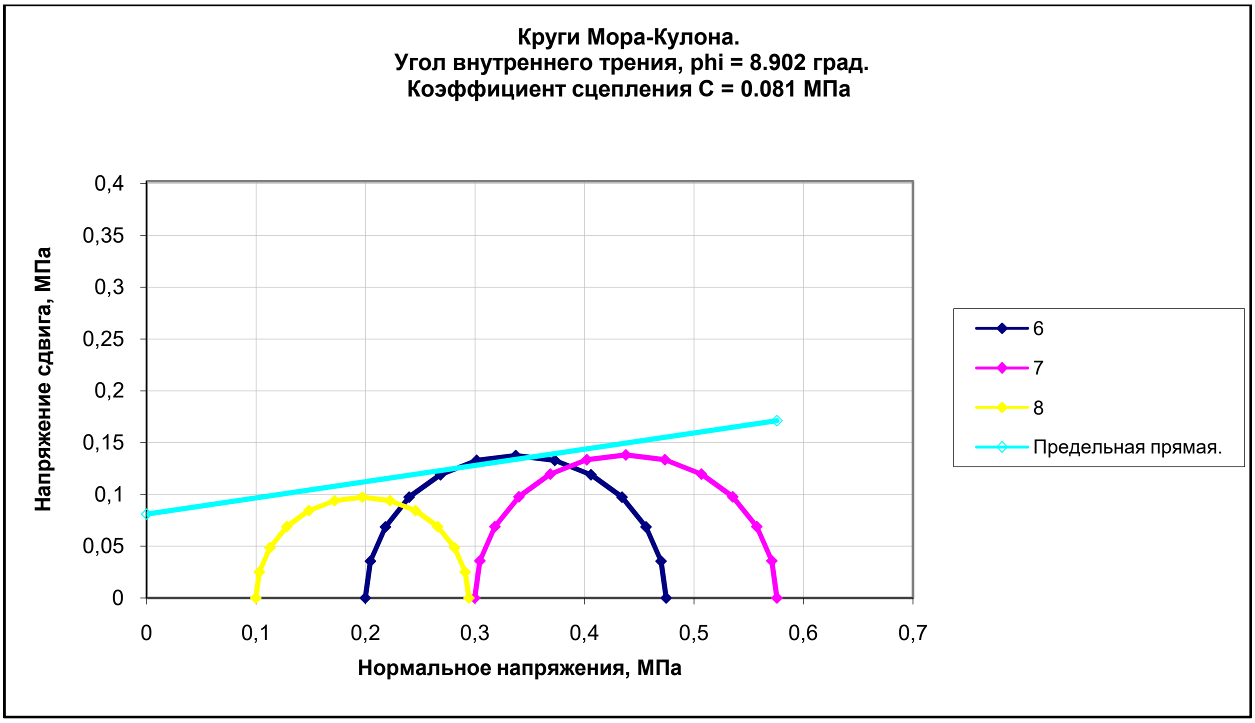


Fig. 10. Strength parameter φ for clay

The test results are stored in a database for each type of test and are used in the process of calibration/identification of parameters by the optimization method.

5.6. Automated soil testing system in the in-situ test

LLC NPP Geotek is currently developing hardware and software for solving the problem of in-situ testing of soils in the setting discussed above [12,13,15,16,18]. If the task is successfully solved, geotechnics will be freed from the need to perform a large amount of office work, since the processing of test data, the determination of a number of soil characteristics and the calculation of the foundations base will be carried out during geotechnical investigation at the site of the designed building and structures.

Currently, the ASIS Field measuring system for in-situ soil tests is a combination of measuring instruments (instruments and devices) and a set of control and computing software (Geotek Field) for measuring sounding parameters and interpreting in-situ test data (Fig. 11).

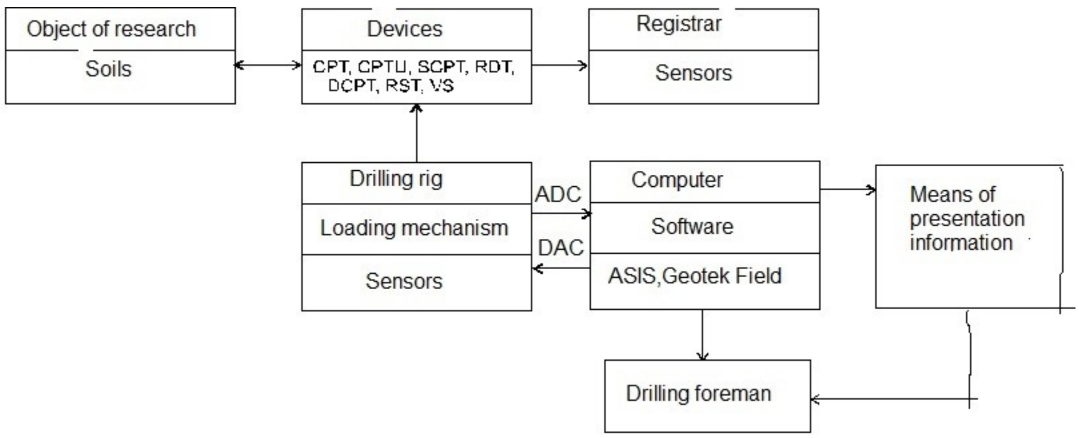


Fig. 11. Block Diagram of ASIS Field

ASIS Field receives digital signals from sensors of sensing devices (CPT, CPTU, SCPTU, SPT, DCPT, etc.), converts them into physical quantities, performs a basic interpretation in terms of the type of soil behavior [19,60,62], defines different physical and mechanical characteristics/parameters of soils and performs the calculation of the deformation of the foundations base of buildings and structures in accordance with the requirements of SP 22.13330 or EN 1997-1 during the entire process of immersion of sensing devices in the ground. Linear immersion speed, rotational speed, feed force and other parameters of force action are monitored and controlled through feedback from the drilling rig mechanism using the ASIS Field software.

In-situ test include: static (CPT - cone penetration test, CPTU - piezocone test, SCPT - seismic cone penetration test) and dynamic (SPT - static penetration test and DCPT - dynamic cone penetration test) penetration; drilling sounding (RDT - Russian drilling test); tests with screw (RST - Russian screw test) and flat dies (PLT - plate load test); vane shear tests (VS - vane shear), etc.

As noted earlier, estimated values of soil characteristics/parameters are found using the corresponding correlation equations. The correlation equations in the

Geotek Field software are based on the work of domestic and foreign researchers [19,59,60,61,62,63]. It should be borne in mind that the correlation equations are presented only as a guide to geotechnical use and should be carefully analyzed and adjusted for local varieties of soils. The values of the obtained soil characteristics/parameters are estimates and should be clarified by conducting appropriate laboratory tests of soils. At the same time, the Geotek Field software has a "Statistics" module, which is used to construct local correlation equations according to laboratory and in-situ tests of soils. The structure of the Statistics module is based on the guidelines for compiling regional tables of normative and calculated indicators of soil properties [41] and GOST 20522 [30].

5.7. Determination of stratigraphy and soil characteristics

The determination of stratigraphy is carried out using the methodology proposed by Robertson in 1986 and developed by him and other researchers later [62].

When determining the mechanical characteristics of soils, correlation dependencies are used between the parameters measured in the process of static and dynamic penetration and data from laboratory tests of soils. Using the penetration parameters (q_c, f_S, u_2, N) and correlation equations, the physical and mechanical characteristics of soils are found. During dynamic penetration, the number of hammer blows (N) or conditional dynamic resistance is determined for a given movement of the probe [19,31].

Currently, the Geotek Field software includes several calculation modules: settlement and tilt of foundations/building; stiffness coefficient of the base; bearing capacity of piles using analytical solutions, statistical processing of test data, geometrization of soil characteristics [8,19,20,25].

The Geotek Field software can be used both as an interpreter of test data, and as part of the ASIS Field, directly during in-situ testing of soils.

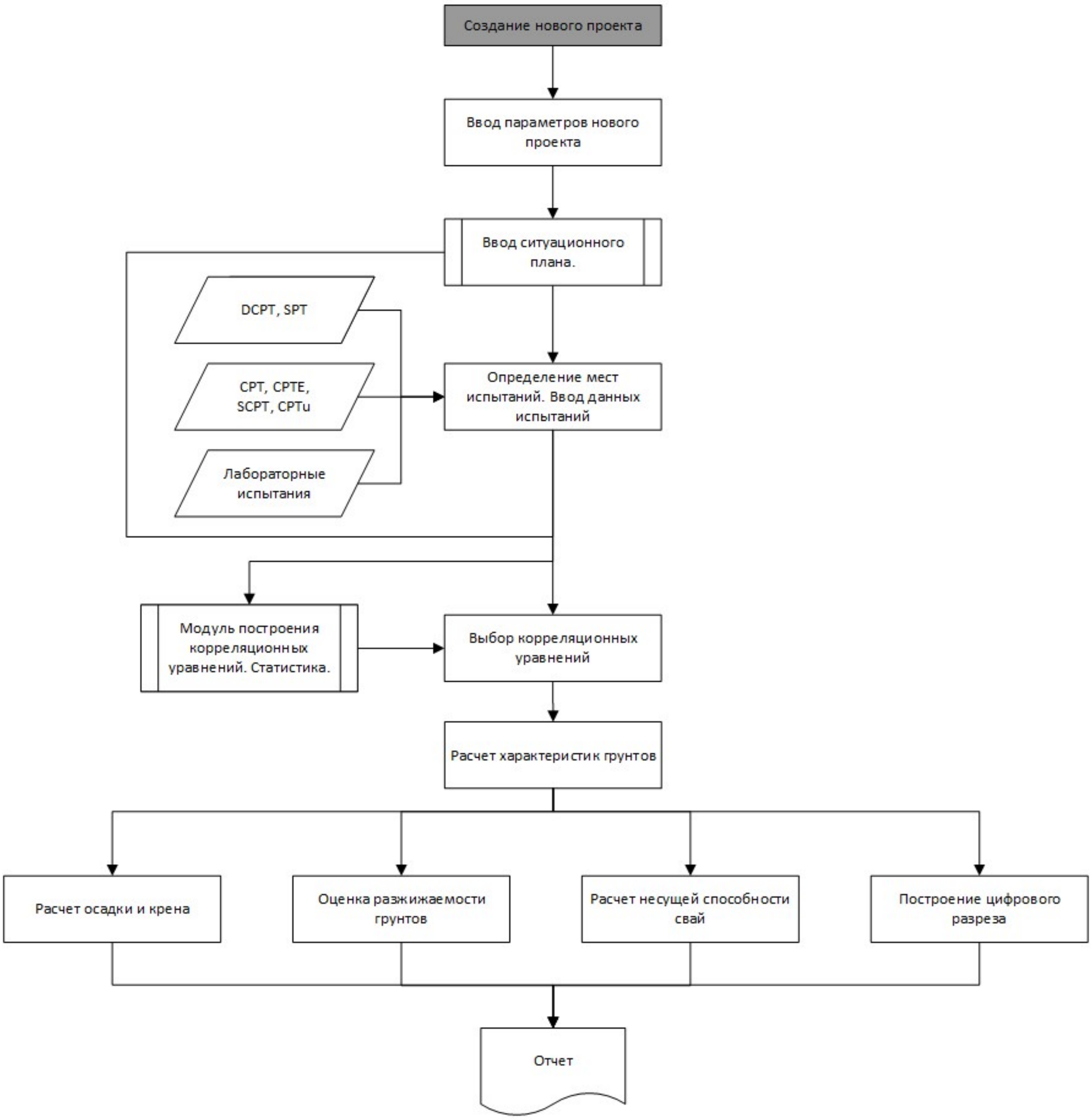


Fig. 12. Block diagram of the Geotek Field software

The block diagram of the Geotek Field software is shown in Fig. 12. In Fig. 13 shows the results of determining the type of soil behavior and constructing a lithological column according to the data of static penetration.

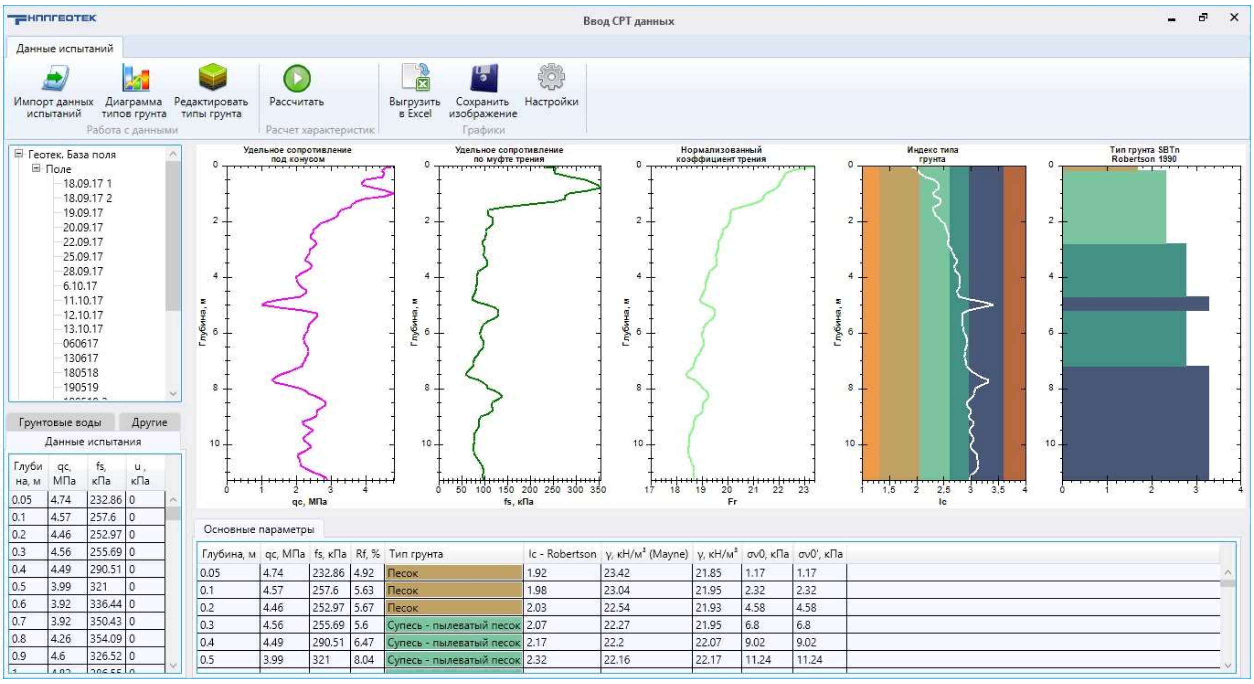


Fig. 13. Results of determining the type of soil behavior

5.8. Model parameter optimization

The optimization problem can be formulated as follows [48]. Find such set of parameters x that the scalar objective function $f(x)$ is minimal. Most often, when calibrating the parameters of material models, the least squares method is used, the essence of which is to minimize the sum of squares of the difference between the prediction of the mathematical model and the observations:

$$F(x) = \frac{1}{2}\sum_{i=1}^{n}\omega_i[f(x,t_i) - y(t_i)]^2, \qquad (1)$$

where $f(x,t_i)$ are model values; $y(t_i)$ is relevant experimental value; n is total number of measurement points in the experiment; t_i is sign of experiment (for example, experiment number); ω_i are weights associated with the test point i.

By minimizing $f(x)$ changing x in the interval $x_{\min} \le x \le x_{\max}$, so that the condition

$$g_j(x) \le 0, j = 1, n_g \qquad (2)$$

finds the best set of model parameters x^* close to the experimental data. Here g is the constraint vector used to limit or relate the experimental data to the calculated values.

From the test results, we have the data of stress and strain measurements in the form of functions whose parameters are the subject of identification (Fig. 3):

$$\sigma_{ij}^* = f(\varepsilon_{ij}^*; k^*), \qquad (3)$$

where σ_{ij}^*, ε_{ij}^* are stresses and strains, respectively, and k^* are identifiable parameters of the material model. Therefore, expression (1) can be written as:

$$\min \sum_{i=1}^{n} [\omega_i (\sigma_{ij} - \sigma_{ij}^*)]^2 , \qquad (4)$$

where σ_{ij} are stresses calculated using the material model.

The objective function $F(x)$ depends on the measured and calculated data and can be very complex and contain errors due to both the material model and the measurement results during material testing. In such cases, the solution may diverge or converge slowly, so you should choose an optimization method that gives stable convergence based on the required accuracy and efficiency.

In the local optimization method, the accuracy of the solution is determined by the expression

$$F(x^*) < F(x) \qquad (5)$$

provided that $\left\| x - x^* \right\| < \varepsilon$.

The block diagram for identifying the parameters of the material model is shown in Fig. 14. The obtained parameters are offered to the user for use when entering structures or foundations into the calculation software [9,10,37].

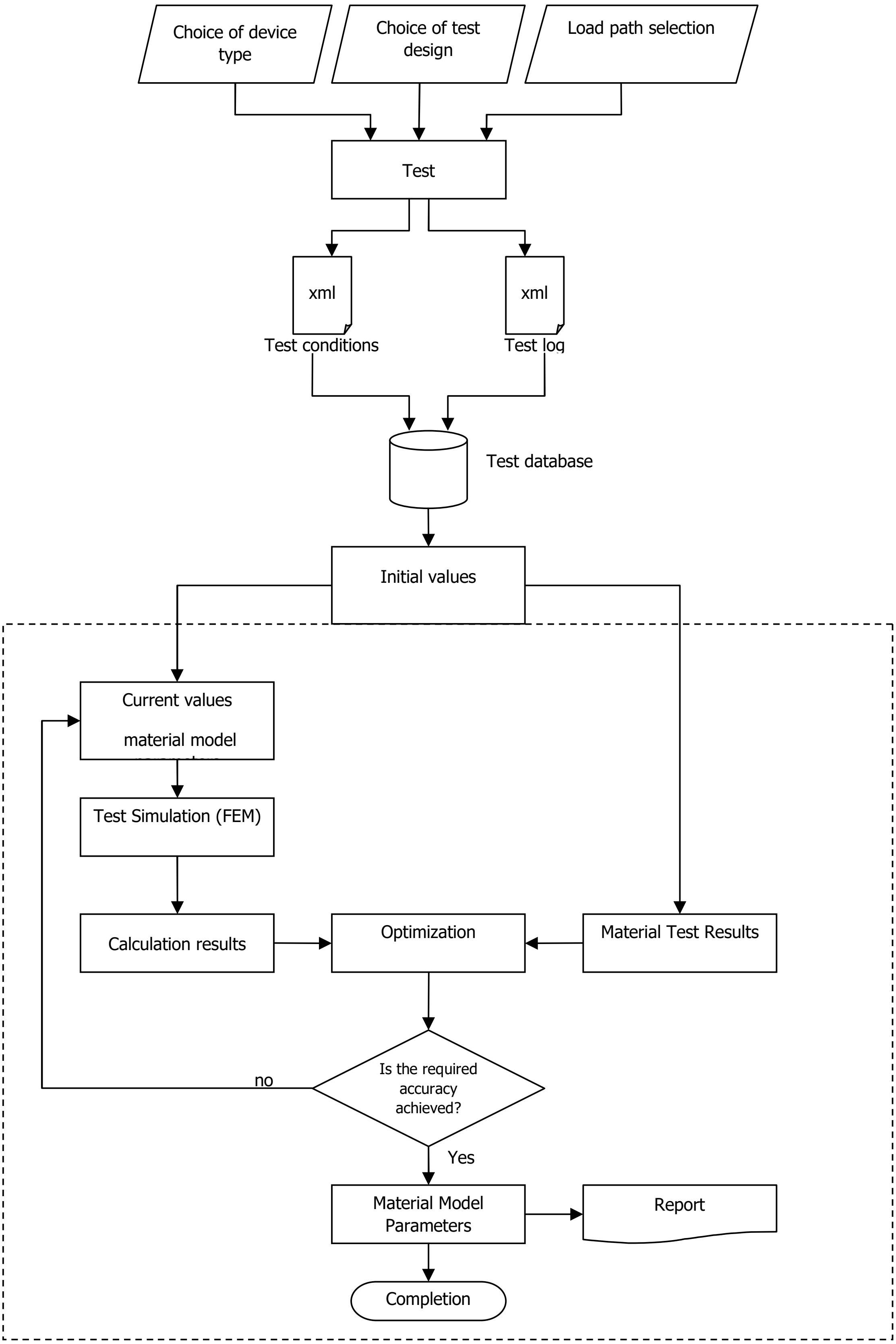


Fig. 14. Block diagram of material testing and identification of material model parameters [10]

5.9. Geometrization of geotechnical investigation data

The algorithm for the preparation and computer formalization of geotechnical data and schematization of the soil mass was proposed by V. Sheinin. et al. [51] and allows one to perform of the foundation base calculations when the degree of uncertainty is associated with an insufficient amount of initial information and can be increased. Such approach makes it possible to significantly facilitate and automate the processing of geotechnical research materials and provides more reliable and comprehensive information. Later V. Barvashov [2,5,8] suggested using the D. Shepard function [64] to interpolate the parameters of soil models in the massif between the borehole and the phenomenon of concentration of shear strain (crack) along the perimeter of the foundations. Taking this phenomenon into account leads to a decrease in internal efforts in the construction of foundations [4].

5.9.1. To the construction of engineer geotechnical elements (EGEs)

To calculate settlement and determine the calculated soil resistance in accordance with the existing Code of Rules [44,45], it is necessary to find the modulus of elasticity E, cohesion c, angle of internal friction φ and know the position of the groundwater table in the base. Geotechnical investigation give the values of these characteristics in a limited number of points, in places of workings/boreholes. Within each EGE E, c, φ are taken constant. The boundaries of EGEs are drawn manually at several sections passing through the workings. Between the workings of the boundary, EGEs remain uncertain, and geologists choose these boundaries at their discretion, based on their experience.

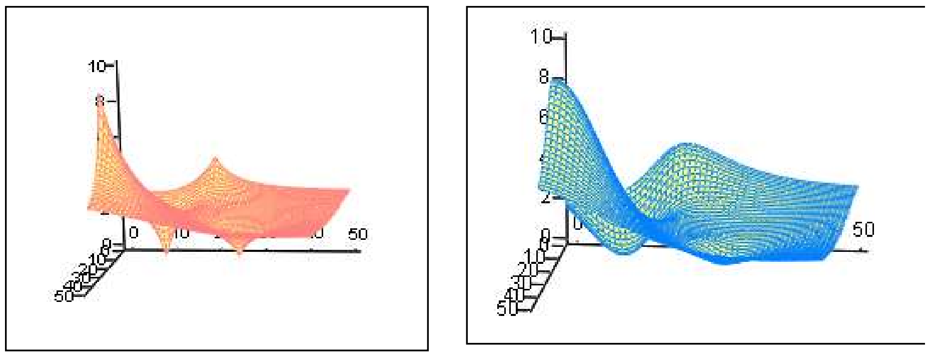
The manual construction of EGE boundaries requires considerable labor and extensive experience, and outside the sections it often turns out to be impossible, because EGEs are numbered on sections without a clear sequence according to the precedence of genesis, therefore young EGEs may be lower than older ones by geological age in the section. Very often, lenses and wedging of soil layers are applied to geological sections subjectively.

The construction of EGE boundaries can be automated if we use two-dimensional interpolation functions of D.Shepard [5,64], which are a generalization of the well-known one-dimensional Lagrange interpolation polynomial to the case of a function of two coordinates:

$$F(x,y)=\frac{\sum_{i=1}^{n}\frac{F_i}{R_i^{\,p}}}{\sum_{i=1}^{n}\frac{1}{R_i^{\,p}}}, \qquad (6)$$

where $R_i = (x-X_i)^2+(y-Y_i)^2$; X_i, Y_i are coordinates of the i-th point at which the function F takes a given value F_i; p is the shape parameter of the function $F(x, y)$.

The application of Shepard's functions makes it possible to perform the selection of the EGE geomass on a computer, but the ambiguity problem remains. An example of such an ambiguity is given in Fig. 15, which shows computer graphs of functions constructed at the same given points, but for different values of the parameter p of equation (6).

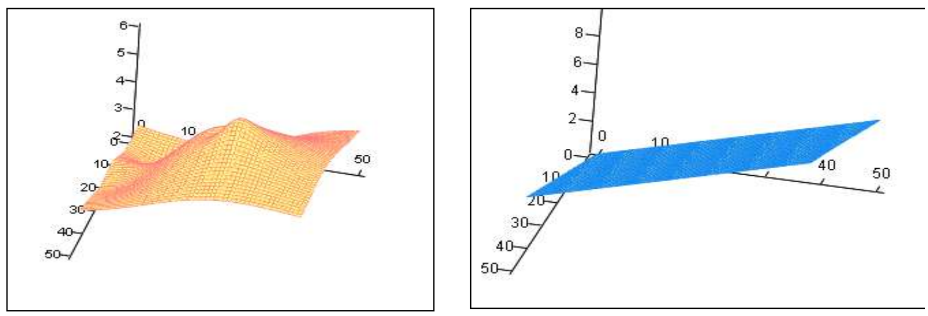


Z0 Z1

Fig. 15. *Z0* is the surface at $p = 0.5$; *Z1* - surface at $p = 1$ [5]

Figure 15 shows that, at $p = 0.5$, the boundaries of the EGE have discontinuities of derivatives at the collocation points, where the interpolation function has the form of conical vertices, and such a shape is unlikely in nature. Mathematical modeling in Matcad [5] showed that for the boundaries of the EGE it is advisable to take $p = 4$, because when $p > 4$, another uncertainty arises: the constructed function graph has a stepped shape near the collocation points.

Another example of significant ambiguity is shown in Fig. 16. Where the function values at the collocation points belong to the same plane. When using formula (6), we obtain not a plane, but a curved surface *Z0*. For comparison, the *Z1* plane is drawn at the same points.



Z0 Z1

Fig. 16. *Z0* - surface constructed by the formula (1), *Z1* - plane passing through three points [5]

If the stratigraphy of the soil mass is characterized by any global trends in the form of falling layers or clinoforms, then it is advisable to first identify these trends, for example, construct planes using the least squares method, and then finish building these trends using formula (6). This procedure is described in detail in [5].

Interpolation formula (6) can be generalized to an *n*-dimensional coordinate space as follows [5]:

$$F(x_1, x_2, ..., x_n) = \frac{\sum_{j=1}^{m} \frac{F_j}{R_j^{\ p}}}{\sum_{j=1}^{m} \frac{1}{R_j^{\ p}}}, \qquad (7)$$

where x_i is the *i*-th coordinate of the *n*-dimensional coordinate space ($i = 1, 2,.., n$); $R_j = \sum_{j=1}^{m} \cdot \alpha_j (x_i - X_{i,j})^q$, $X_{i,j}$ is the *i*-th coordinate of the *j*-th value of the function *Fj* from the set of points (i = 1, 2,..., n); *p* and *q* are surface shape parameters.

By setting $\alpha_i = 0$ for certain *i*, it is possible to simulate shapes having a dimension less than *n* (for *n* = 2 these are features like “ridges”, “depressions” and “channels” are absent.

The interpolation function *F* has the following properties:

1) equal to the given values at the given points;
2) equal to the arithmetic mean of the values at the collocation points at a point equidistant from these points (if one exists) and at infinity;
3) if F_j = const for all *j*, then the function *F* = *const* itself everywhere;
4) if $p \to \infty$, then the function *F* tends to a step function;
5) if $p = 0$, then the function *F* is equal to the arithmetic mean of the given values everywhere except the collocation points, where it undergoes a removable gap;

6) if it is known that the interpolated function is everywhere smooth, the value of p should be taken as an integer greater than one.

The distribution functions E, c, and φ, depend on three coordinates *(x, y, z)*, i.e. $n = 3$, and if there are no "ridges" and "depressions", i.e. $\alpha = 1_i$ then formula (2) takes on the simplest form

$$F(x,y,z)=\frac{\sum_{j=1}^{m}\frac{F_j}{[\ (x-x_j)^2+(y-y_j)^2+(z-z_j)^2\ ]^p}}{\sum_{j=1}^{m}\frac{1}{[\ (x-x_j)^2+(y-y_j)^2+(z-z_j)^2]\ ]^p}}, \qquad (8)$$

The most simple formula (8) looks at $p = 1$. To interpolate the groundwater table, the function of two coordinates *(x, y)* is used, just like for interpolating the boundaries of the EGE.

Any approximation is ambiguous, but a positive construction experience shows that despite the inevitable errors:

- determination of soil characteristics/parameters and the spread of engineering-geological and geotechnical investigation data;

- ambiguity of the interpolation of EGE boundaries;

- use of various design models of the foundation base and various assumptions, the behavior of buildings and structures as a rule does not cause concern during their operation. This indicates a low sensitivity of the stress-strain state (SSS) structures to variations of many initial data. But to the variations of some initial data, the base-foundation-building (SOFS) system has an increased sensitivity [4,54].

For this reason, the numerical geometrization of geo-arrays can be significantly simplified by eliminating operations that, without increasing accuracy, complicate the procedure as a whole. Such operations include the construction of EGE boundaries, which, among other things, is also subjective.

It is much easier to perform geometrization numerically without isolating EGE [5,7,34,51]. For this, it is necessary to calculate the spatial distribution of soil characteristics/parameters from the discrete values of these characteristics obtained in geological workings/boreholes, for example, using the interpolation formula (3). The initial data for such a calculation can be presented in electronic form, for example, in the form of Excel tables, which can be immediately entered into the computer. Having found the distributions $E = E\ (x, y, z)$, $c = c\ (x, y, z)$ and $\varphi = \varphi\ (x, y, z)$, we can use them in electronic format to calculate the bases and foundations in compliance with current regulations without visualization or printout.

In fig. 17,18 shows examples of color visualization of the distribution *E = E (x, y, z)* along the section between the workings number N1 and N5 built in the Geometrization module of the Geotek Field software. A similar visualization can be obtained both for distributions *c*, *φ*, and other characteristics of soils.

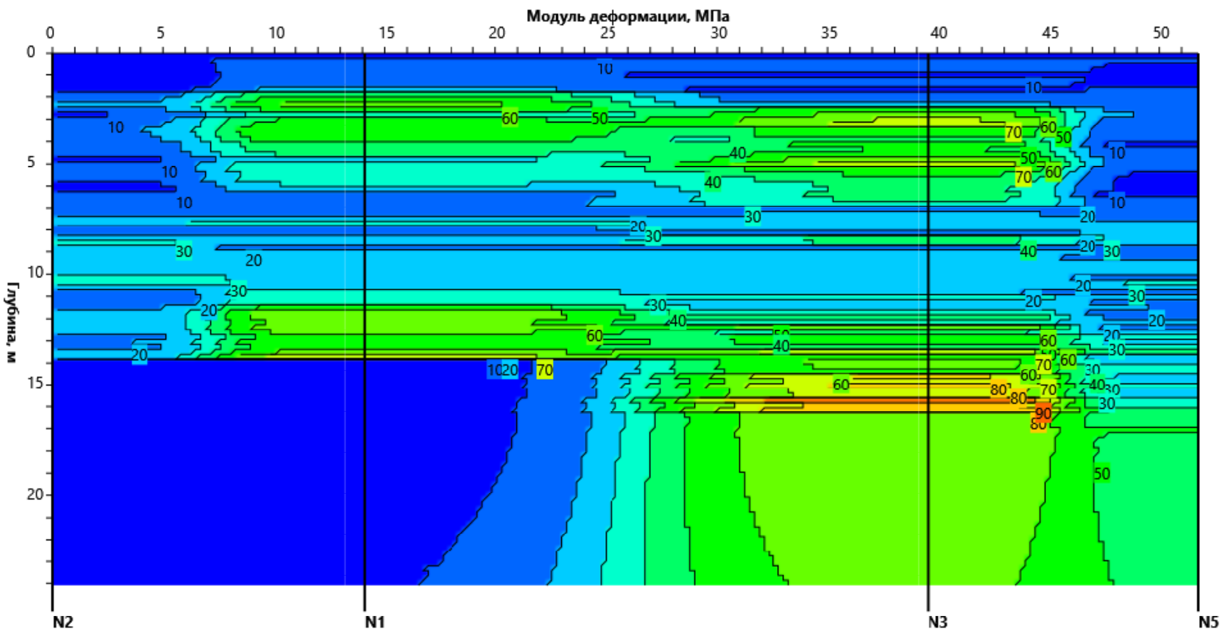


Fig. 17. To visualize the values of the modulus of elasticity E=E(x,y,z) obtained by the 2D function of Shepard

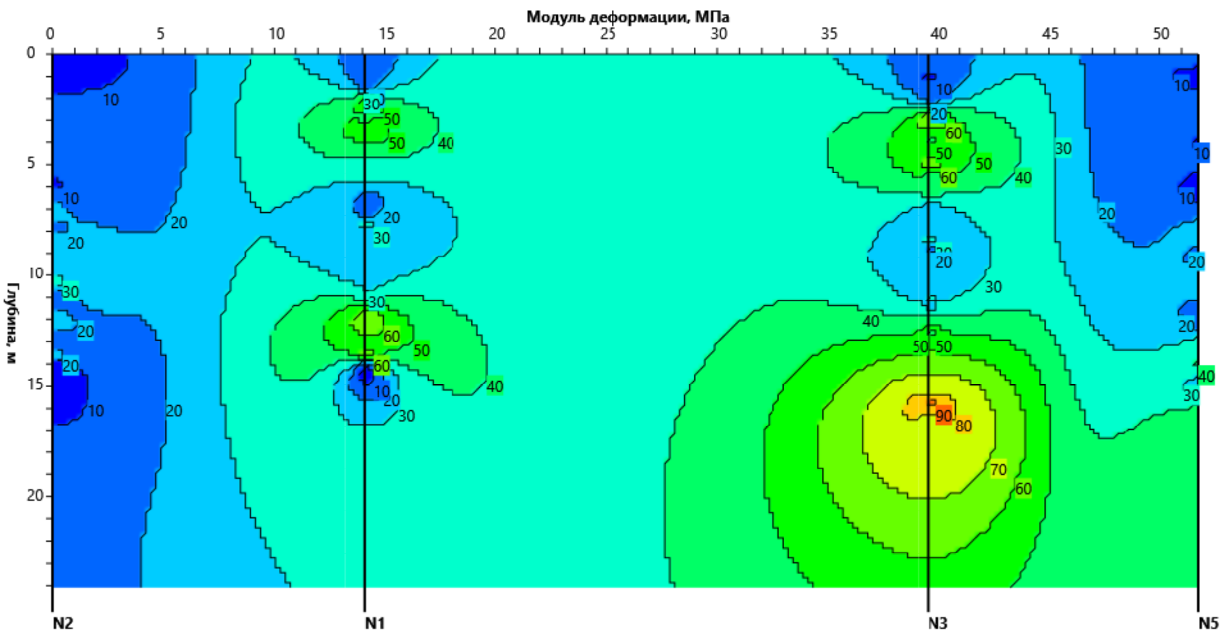


Fig. 18. To visualize the values of the modulus of elasticity E=E(x,y,z) obtained by the 3D function of Shepard

As can be seen from fig. 17,18 in the case of two-dimensional approximation (2D), a more uniform distribution of the deformation modulus between the support workings is obtained. The modulus of elasticity values on the support workings are clearly visible in the 3D distribution graph.

5.9.2. Assesment of the ambiguity of the geometrization

For such an assessment, it is necessary to determine how SOFS is “sensitive” to the inevitable ambiguity of the digital data [4,54,55].

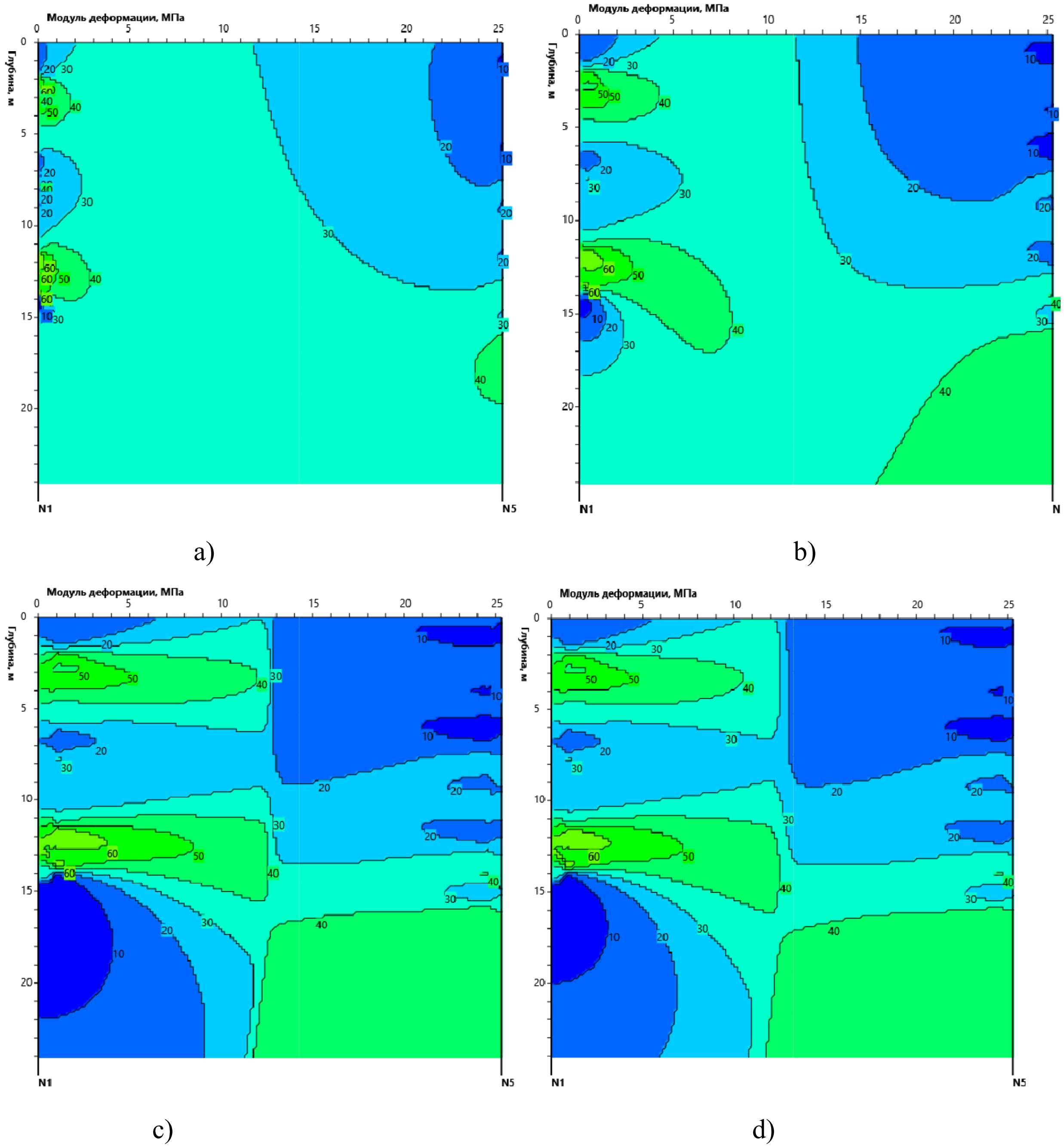


Fig. 19. To 3D visualize the values of the modulus elasticity E=E(x,y,z) obtained by the function of the Shepherd (8) at different values of its argument of the form, p: a – 1; b - 4; c – 10; d – 10 to 20

In specific cases, the ambiguity of geometrization can be modeled by varying the free parameters in formulas (6-8). In the simplest case, the shape parameter p in formula (8) varies. The results of such a simulation are shown in Fig. 19.

The sensitivity of SOFS to the ambiguity of the interpolation data can be estimated by introducing virtual workings between existing ones and calculating the settlement at this point of the foundation base. From the point of view of reliability, the minimum value of the modulus elasticity should be used when calculating the settlement on a virtual working. Similar calculations can be performed on a variety of virtual workings with the determination of the average settlement of the foundation.

If such variations lead to significant changes in the behavior of SOFS, it is necessary to increase the volume of geotechnical data due to additional geological workings, or to increase the reliability of the structure by increasing the strength of structures. This issue was analyzed in [4] using mathematical modeling using exact solutions for SOFS standards (simplified models).

We note the following important question in this connection. It was shown in [4] that bending moments and transverse forces in the foundation slabs substantially depend on the depth of development of the soil destruction zones ("plastic zones or crack") under the edges of the foundation. In the current design standards (SP 22.13330), the development of these zones is limited to a depth equal to one quarter of the foundation width, but this depth is not taken into account in foundation calculations, which leads to serious distortion and ambiguity of the results of such calculations.

To clarify the calculations of foundation slabs, data are needed on the distribution of strength parameters c and φ under the edges of the foundation to a relatively shallow depth, but at a larger number of points than is accepted in standard geotechnical and geological surveys. Therefore, it is necessary to increase the number of geological workings in these marginal zones, the depth of which can be limited to one quarter of the width of the foundation.

With any approximation, inaccuracies and scatter of geotechnical and geological data are inevitable, and as a consequence, the ambiguity of interpolation of the EGE boundaries, but experience has shown that, despite the inevitable errors in the definitions, the use of different calculation models of the base and various assumptions, the sensitivity of the SSS structures to variations of many initial data is usually small.

Conclusion

1. The proposed integrated technology combines geotechnical investigation and design of the foundations of structures into a single production process and can be used as one of the elements in the digital information systems of buildings and structures.

2. Integrated technology can reduce the time of geotechnical investigation due to the automation of the laboratory and in-situ testing of soils and the simultaneous interpretation of test data.

3. The result of geotechnical investigation is not only information about the properties of soils, but also an assessment of their impact on the behavior of the designed building or structure.

4. The proposed procedure for determining the parameters of various soil models allows you to calibrate known soil models and take into account the influence of the type of stress state and stress trajectories on the parameters of soil models.

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