Integrated technology of the geological surveys and design foundations

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ABSTRACT: The results of integrated technology of engineering-geological and geotechnical investigations and foundation design are presented in the article. The current information systems of data transmission and processing, information-measuring systems allow not only to control the process of soil testing and to process testing data, but also to perform simultaneous calculations of deformation and strength of foundations. Modern in-situ soil investigation techniques, such as static and dynamic penetration tests, and boring sounding, allow to get full information on the physical and mechanical properties of soils in depth. It is rather cheap with an increase in the number of test sites within the surveyed site. The recording of the sounding parameter data may be performed at any depth interval. Using known or local correlation equations and sounding data we can find soil depth characteristics. Then deformation and strength of foundations are calculated directly in in-situ conditions during soil sounding.

Keywords: in-situ test; correlation equations; soil parameters; settlement and tilt calculation

1. Introduction

Currently, foundations of buildings and structures are designed using analytical and numerical solutions. Analytical solutions are given in the corresponding sets of rules (SR) [1, 2] They are simple, easily programmable, require determination of the minimum number of soil characteristics. And many years practice of their application testifies to the reliability of these solutions. Numerical methods of foundation calculation are much more complicated. In most cases it is necessary to determine more characteristics/parameters of soil models during engineering-geological and geotechnical investigations.And very often their validity has to be checked using analytical solutions. Due to the fact that it is still obligatory to comply with the requirements of the SR, in the development of integrated technology we propose to use the appropriate analytical solutions for calculating the foundations on deformations and bearing capacity given in the sets of rules. The structure of the proposed technology allows to apply numerical methods of solutions implemented in various programs such as PLAXIS, FLAC, etc. However, it is not yet clear how to determine all the parameters of soil models directly in the field.

The aim of our research is to develop an integrated technology of engineering and geological investigation, which includes not only the determination of physical and mechanical characteristics of soils but also foundation calculation by limit states at the same time. Modern information-measuring systems allow you to do this.

2. Soil testing methods

Most of the required physical and mechanical characteristics of soils for the design of buildings and structures bases can be determined both in laboratory and in-situ conditions. More attractive is the determination of physical and mechanical characteristics of soils in in-situ conditions, for example, using static and dynamic penetration tests, boring sounding, vane shear test, etc. The first two methods are known and widely used in practice of engineering and geological investigations [3]. Boring sounding (Russian drilling test – RDT) is little known and is still rarely used in domestic practice in determining mechanical characteristics of soils and fragmentating the soil thickness into separate layers, despite its shown efficiency [4].

One of the calculated parameters of drilling sounding is the mechanical power of the rotational load at the current drilling depth, kJ/s:

$$A = M \cdot 2\pi\omega \tag{1}$$

where M is the current torque, Nm; ω – rotational speed of the drilling tool, s^{-1}.This parameter characterizes the work spent per unit of time while drilling a well.

In 1965, R. Teale [12] proposed using a parameter called specific energy to control the well drilling process. Specific energy is understood as the amount of work required to drill a unit volume of soil:

$$E = \frac{(Qv + M\omega)\frac{s}{v}}{As} = \frac{Q}{A} + \frac{M\omega}{Av} \tag{2}$$

where Q is the axial force applied to the tool in the bottom of the well, kN; A – cross section of the well, m^2; M – torque, kNm; ω is the rotation speed, rad/s; v – translational speed of the drilling tool, m / s.

Never the less CPT – cone penetration test is widely used in domestic and mainly in foreign investigation practice. It is used not only for dismembering of soil thickness into engineering-geological elements, but also for determining of strength and deformation characteristics of soils [5].

When determining mechanical characteristics of soils, correlation dependence between parameters measured during cone penetration into soil and laboratory tests data are used. Measured parameters are: the cone resistance, the sleeve friction, pore pressure. Vertical deviation control is determined by built-in inclinometer and speed of shear waves by accelerometer. Shear waves velocity to determine the elastic shear modulus. And as shear and longitudinal waves are used to determine the Poisson coefficient. Using measured parameters of the penetration and correlation equations, physical and mechanical characteristics of soils are found.

2.1. Soil testing by boring sounding

Boring sounding method allows to carry out investigations of soil properties of practically all types similar to sandy, clay, gravellous soil, rock and frozen soils. In this method, the well boring is performed by a screw with a boring tool, the type of which depends on the type of soil. Due to the fact that the screw almost without force penetrates into the ground, it allows to use conventional drilling machines.These machines are widely used in carrying out engineering- geological and geotechnical investigations without their modernization. It will be shown later, combining the static penetration and boring sounding method allows a significant increase in the number of measured parameters, which is useful in constructing correlation dependencies.

In our opinion a more promising method of in-situ studies of soil properties is the method of boring sounding method [4, 6]. First, this method is applicable, in contrast to the method of static penetration, not only in clay and sandy soils, but also in gravellous, rocky and frozen soils. Second, the method allows to determine the modulus of soil deformation and force resistance to shear without using correlation dependencies. At the same time, other soil characteristics can be found using correlation dependencies, as in the case of static and dynamic penetration. The boring deviceis shown in Fig. 1. In this figure, the device for boring measurement is located at the top of the screw column. Another variant of the device position at the bottom of the hollow screw column is discussed below.

Figure 1. Boring sounding

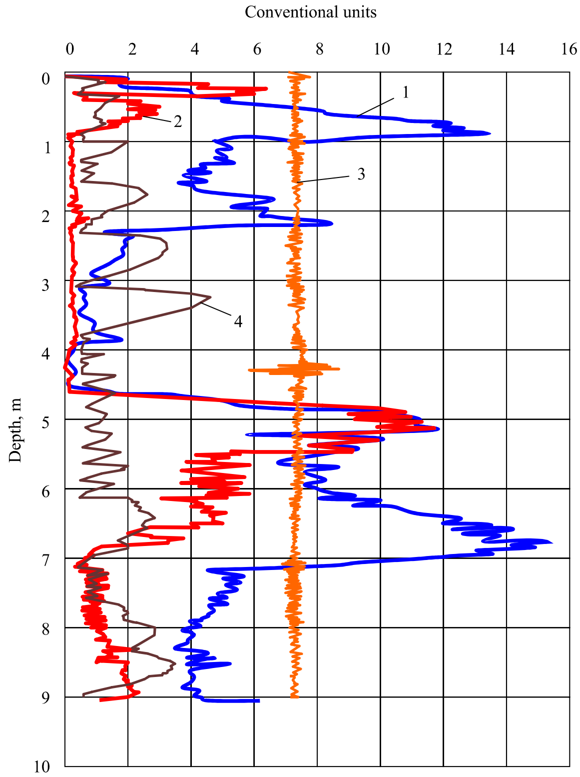

Figure 2. Parameters of sounding: 1 – Torque; 2 – Feed force; 3 – Rotational speed; 4 – Linear speed

Boring sounding method involves testing of dispersed and frozen soils by means of measuring a number of parameters during well sounding with a solid or hollow screw, which are given in Table 1 and Fig. 2.

The device of boring sounding is measuring system including sensors, amplifiers of signals and analog-to-digital converter which are structurally located in the steel cylinder having standard shafts in end faces (Fig. 3).

Sensors of force, moment, slope angle and rotational speed are connected to analog-to-digital converter (ADC) boards powered by a built-in accumulator. ADC boards are connected to the wireless RS-485/ZigBee modem by RS-485 interface. The modem antenna is brought to an upper part of the device. There is a modem for wireless ZigBee communication from the managing computer. It is connected by means of USB port.

Table 1. The parameters measured by boring sounding

Measured parameter	Dimen-sion	Range	Measurement accuracy, % of a range
Torque	kHm	0-0,5	1,0
Feed force/thrust force	kH	0-50	1,0
Hoisting force/ weight of a boring column with soil on flanges	kH	0-50	1,0
Rotational speed	RPM	0-300	1,0
Depth	m	30	0,5
Vertical deviation	degr.	0-60	0,5

For data exchange between ADC and computer boards ModBus RTU recording is used. The block which is electronic and transforming with RS-485 interface for the range finder which is located on a mast of the boring device is connected to a computer. The process of registration and visualization of boring parameters is carried out by ASIS program. Penetration depth measurement of a boring column and a line speed is carried out by a potentiometer range finder. Range finder indications are transferred by means of interface RS 485 and registered in a cmputer database.

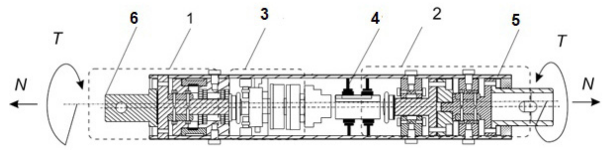

Figure 3. Boring measurement device: 1 – torque sensor; 2 – force sensor; 3 – electronics unit; 4 – battery; 5 – housing; 6 – shank

The boring measurement apparatus operates as follows. The upper part of the device is connected to drilling rig rotator, and the lower part of the device is connected to a column augers. Range finder is fixed on mast and its cable is fixed on rotator housing. By means of a button on the upper part of the device, the power supply is switched on and signals from sensors (forces, torque, rotation, movement, inclination) begin to enter the computer in digital form by wireless communication. Then boring master activates the rotator and the well boring process begins. Torque and axial load simultaneously transmitted to the upper part of the device. The torque is measured by a torque sensor and an axial force is measured by a bidirectional force sensor. At the same time, only torque is transmitted to the moment sensor, and only the axial force is transmitted to the force sensor. The rotation speed of the device is measured by the rotation speed sensor located in the electronics unit. The movement of the boring column is measured by a laser or potentiometric range finder. The slope of the boring column is measured by an inclination sensor located in the electronics unit. The same sensor can be used for monitoring the angle of inclination of the boring mast. Torque and axial force from the lower shank of the device are transmitted to the boring column sounding the ground.

The described boring sounding device is located in the upper part of the auger column above the soil surface. Therefore, the measured boring parameters are influenced by column bending, friction forces between the surface of the auger flange and the soil, friction forces between the moving soil and the well walls, and also other factors. However, these disadvantages can be avoided if the boring sounding device is placed in the first link of the hollow auger string by penetrating an extensible static penetration cone into the structure. An example of implementation of such the multi-parameter sensing device is shown in the Fig. 4.

The similar combined device of boring sounding and static penetration allows to measure not only boring parameters (torque, axial load, rotation speed, movement, pressure upon soil under the boring tool, tension relaxation), but also, at the same time, parameters of static penetration (the cone resistance, the sleeve friction, pore pressure, temperature of the soil, time in the course of stabilization of the process of heating and thawing frozen soil; heating power and heating temperature; speed of shear and longitudinal waves).

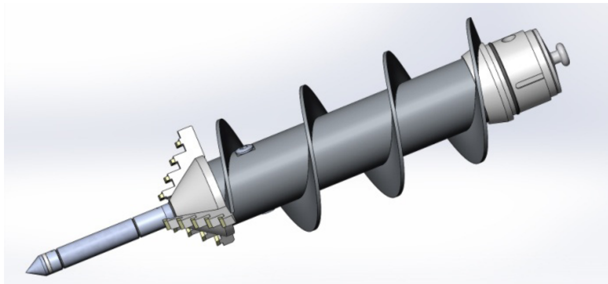

Figure 4. The multi-parameter sensing device

Due to the fact that parameters measurement of combined penetration parameters (sounding and penetrating) is performed during well penetration, similar type of boring is possible in almost all soils, both in dispersed and in rock and frozen soils.

2.2. Test procedure by method of the combined penetration

The soil test procedure by the combined penetration includes the following operations:

1. Installation of site situation plan, laying depth, loads and other data into the control program.
2. Installation of the drilling rig on the site and its preparation for operation.
3. Attachment of the multi-parameter sensing device to a rotator of the drilling rig.
4. Starting of electronic devices power and measurement control program. Recording of zero readings of the measuring system.
5. Starting the rotator drive and penetration of the multi-parameter sensing device into the soil.
6. Automatic logging of measurement data of boring sounding and static penetration.
7. Determination of the type of soil behavior according, calculation of soil characteristics using correlation equations [3,7], calculation of settlement at the penetration point [1] and calculation of the base stiffness coefficients [8]. Penetration at another point of the foundation plan with carrying out operations according to items 6,7.

9. Determination of difference of settlement and tilt, and of the base stiffness coefficients.
10. Carrying out operations according to items 5-9 at the other point of foundation plan until the specified value of non-uniformity of foundation/structure sediments and tilt is achieved.

The procedure for testing soils to determine the deformation modulus by means of boring sounding includes the following additional operations.

1. Well boringis stopped at the specified test depth.

2. The boring column rises 10-20 cm above the bottom of the well by means of the drilling rig drive and scrolls to remove friction forces between the well wall and the flange of the auger.

3. Using the bidirectional force sensor, the weight of the string of auger and soil on the flanges is determined.

4. The boring columnis lowered into the well bottom hole. Rotation is activated and the boring tool is penetrated into the soil 5-10 cm below the well bottom hole.

5. Step-by-step diving of the boring column into the soil is carried out with measurement of settlement and pressure on the soil under the boring tool.

6. Using the solution of elasticity theory and the "settlement-pressure" relationship, the soil deformation modulus is located at the specified depth.

Interpretation of measurement data is considered in the paper [3, 4, 5, 6].

3. Evaluation of investigation site inhomogeneity

The reliability of engineering-geological and geotechnical investigations depends on the quality and scope, especially in the presence of specific soils and the the heterogeneity of soils mass. The determining factors here are engineering-geological and geotechnical element and its physical and mechanical characteristics. According to SR 47.13330 [9] and EN 1997-2 [2] distances between the nearest soil workings/boreholes are assigned in the range from 20 to 100 m. Due to such sparseness very often features of geological structure do not come into view of a geologist: clipping of layers, lenses of soils, etc. In addition, if their presence has been detected for one or more soil workings, their boundary is assigned on the basis of the geologist's experience. Determination of soil properties by selection of monoliths in outputs does not give complete information about properties of the mass of the investigated soil due to artificially large distance between soil workings and small volume of the tested soil.

At the same time, modern in-situ soil investigation techniques, such as static, dynamic penetration tests and boring sounding, allow to get continuous information on the physical and mechanical properties of soils in depth and are quite cheap with an increase in the number of test place within the surveyed site. The recording of the penetration parameter data may be performed at any depth interval. Using known correlation equations and penetration data, soil depth characteristics can be found. Further, by entering reliability factors, it is possible to obtain calculated values of soil characteristics, and then to calculate deformations and/or bearing capacity of the base. All this can be done in the field directly during soil penetration.

In the proposed engineering-geological and geotechnical investigation technology, the controlled parameters are the values of the settlement and tilt of the designed building, the values of which are normalized in SR 22.13330 [1]. Soil penetration within the area of the designed building continues until the estimated values of settlement and tilt stop to change significantly. Thus, we break off the normative setting of assignment of the number of outputs according to SR 47.13330 [9] to their determination, based on the hypothesis of assumed to a priori heterogeneity of the surveyed soil mass. Naturally, a homogenous soil mass will require fewer soil workings than a non-homogenous one.

During penetration values of compressible thickness depth appear on the screen of a computer of the boring master after penetration of each probing point. Settlement and tilt of the structure and profiles of physical and mechanical characteristics of soils are displayed. This allows it to analyze visually the incoming information to make a decision on the completion of the penetration at the surveyed site. Penetration depth is determined from the calculation of compressible thickness by one of the conditions of SR 22.13330 and is monitored during penetration. That allows to stop penetration at reaching the depth of the compressible thickness plus 1 – 2 m. The depth of the compressible thickness depends on the pressure under the foundation base and deformation properties of the base soil and accordingly the depth of penetration may be different within the area of the designed building, rather than the normative one as in SR 47.13330 or EN 1997-2.

Settlement is calculated from the average pressure of the structure on the base by the method of layer-by-layer elementary summation taking into account the inhomogeneity of the soil revealed as a result of the tests. Such calculations are performed for each penetration point, not under the entire base of the foundation. Then base stiffness coefficients above each penetration point are determined, which are then extrapolated to the whole surface of the base, at that calculation variants are considered at different values of Shepard extrapolation function [8,10]. Support boreholes with selection of soil monoliths are assigned to assess validity of used correlation dependencies. And laboratory tests of soils are performed. The obtained data are used to estimate reliability of the received information and recalculation in case of necessity of settlement and tilt of the designed buildings.

4. Implementation of the proposed technology

Currently, technical and software tools are being developed to solve the problem in the previously considered formulation. If the task is successfully solved, geologists will be exempted from the need to carry out a large volume of chamber works, as the processing of test data and, most unusual, the determination of a number of soil characteristics, calculation of foundations will be carried out during the investigation on the site of the designed object.

For the implementation of this technology is developed measuring and computing complex ASIS Field (ASIS). Currently, ASIS is a set of measuring instruments/devices and a set of control programs and computing programs for measuring the parameters of sensing and interpreting in-situ data and laboratory tests of soils (Fig. 5). In-situ tests include the cone

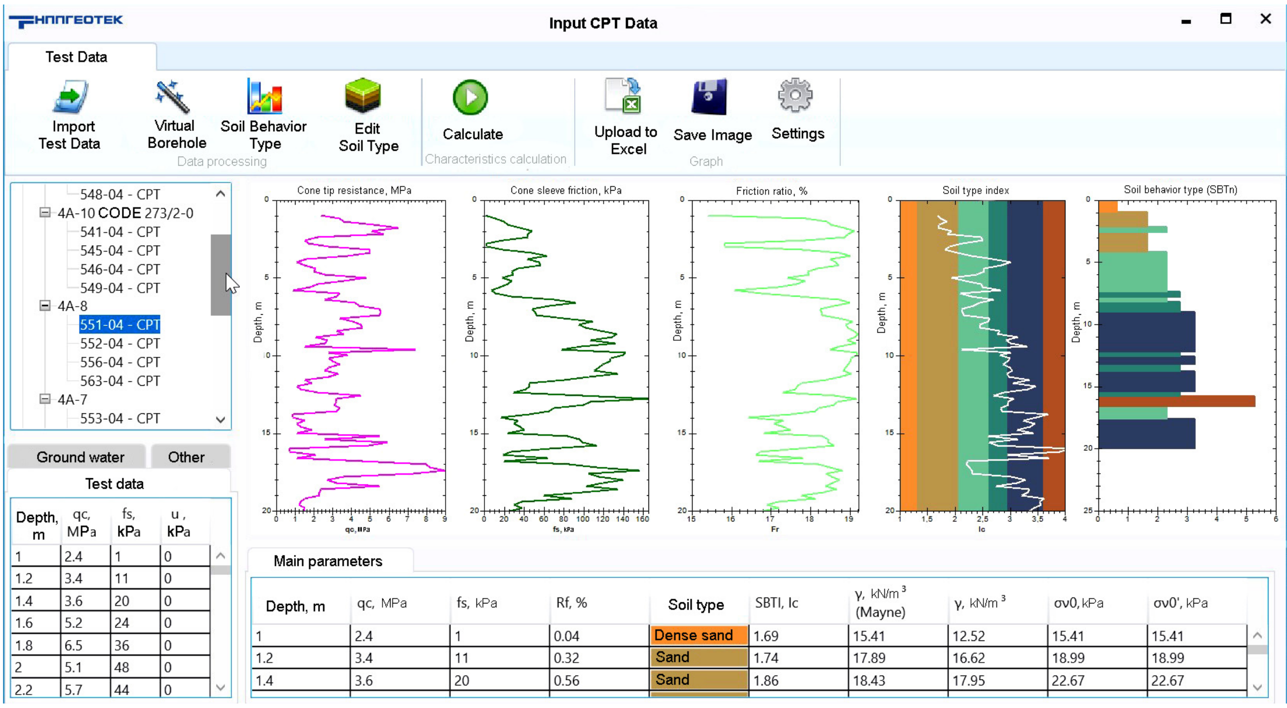

Figure 5. Interpretation of static penetration data

penetration test (CPT), piezocone test (CPTU), seismic cone penetration test (SCPTU) and dynamic staticpenetration test (SPT) and dynamic cone penetration test (DCPT)); boring sounding (RDT – Russian drilling test); screw tests (RST – Russian screw test) and plate load test (PLT); vane shear test (VS), etc.ASIS receives signals in digital form from sensors of penetration devices (CPT, CPTU, SCPTU, SPT, DCPT, etc.) converts them to physical values performs basic interpretation from the point of view of soil behavior [3,7], determines various physical and mechanical characteristics of soils and calculates deformation of bases of buildings and structures in accordance with the requirements of the Set of Rules [1, 11] during the whole process of penetrtion of sensing devices into soil. The linear penetration speed, rotational speed, input force and other force parameters are monitored and controlled by means of feedback to the drilling rig mechanism by the ASIS program.

As it was noted earlier, the estimated values of soil characteristics are based on the corresponding correlation equations. Correlation equations, in ASIS program, are based on the works of domestic and foreign investigations. Note that correlation equations are presented only as a guide to geotechnical use and must be carefully analyzed and adjusted for local soil varieties. The values of the obtained soil characteristics are estimated and should be clarified by carrying out the corresponding laboratory tests of the soils. At the same time, ASIS has a module "Statistics," which is used to build local correlation equations according to laboratory and field soil tests.

Now ASIS program includes several modules of calculation of the foundations bases: settlement and tilt; liquefaction of the soils; determination of base stiffness coefficient; bearing capacity with use of analytical solutions. The program can be used as the interpreter of in-situ tests, and as a part of ASIS information-computing system, directly when carrying out in-situ soil tests.

5. Conclusion

The proposed complex technology combines geotechnical investigations and design of foundations bases into a single production process. The result is the reduction in investigation time due to the use of soil penetration methods with automated control of the investigations is and not only information on soil properties, but also assessment of their impact on the behavior of the designed building or structure.

The main advantage of the combined method of penetration soils is a significantly larger number of measured parameters compared to standard static penetration method and the possibility of studying the properties of not only dispersed and rocky soils, but also frozen soils.

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