Встановлення розподілу міцнісних характеристик по глибині і порівняння з аналітично встановленими значеннями дозволяє отримати данні про глибину залягання різних морфологічних горизонтів, наявність пустот і включень. Проходження процесу зондування пов'язано з зміцненням ґрунту, що було враховано при аналітичному визначенні зміни зусилля пенетрації. Сучасний етап розвитку засобів визначення властивостей ґрунтів характеризується застосуванням мехатронних систем, що дозволяє встановити данні з високою точністю, надійністю і продуктивністю. Для розробки експериментального зразка розроблені головні підходи створення геомехатронного комплексу для моніторингу верхніх шарів ґрунтової поверхні, які визначають головні задачі, область використання, критерії якості. Наявність геотехнічних відхилень у ґрунтовому масиві супроводжується зміною зусилля пенетрації, яку запропоновано вимірювати тензорезистивним динамометром з фіксацію глибини занурення щупу шляхом створення масиву даних. Запропонований алгоритм роботи програми представляє собою циклічну структуру, в якій послідовно виконується реєстрація даних з датчика зусилля і кроку переміщення щупа, який визначає його положення. Реалізація розробленого алгоритму дозволяє визначати зусилля пенетрації і зміну міцнісних параметрів ґрунтового масиву з високою точністю (0,05 %), що дає можливість шляхом порівняння з аналітично вставленим розподілом встановити положення геоаномалій

Ключові слова: геомехатронний комплекс, зусилля пенетрації, міцносні параметри

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INVESTIGATION OF THE CHANGE IN THE STRENGTH PROPERTIES OF A SOIL MASS BY MECHANICAL SENSING

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1. Introduction

Among various types of surface soil studies (archaeological, geological, environmental, forensic and military-humanitarian), one of the most common methods is mechanical sensing [1–5]. The main purpose of these studies is to solve the problem of search for small-size objects in surface soils. The method allows obtaining data on strength characteristics of soils, depth of various morphological horizons, presence of voids and inclusions.

Despite the widespread application of the method of mechanical sensing of soils, the main problem is low productivity and insufficient reliability of the results. Thus, during the rod sounding of the soil surface, the productivity is within 20–50 m^2/h depending on the researcher's qualification with a significant performance reduction after long work. At the same time, the method of mechanical sensing of soils remains the only one that meets the requirements of the UN International Mine Action Standards – IMAS [6].

However, the present stage of development of means for determining the properties of soils is characterized by the use of mechatronic systems. These systems are based on knowledge in the field of mechanics, electronics and microprocessor technology, computer science and computer control of machines and units [7].

Such geomechatronic complexes are successfully used in geotechnical studies to reduce labor intensity and improve the quality and productivity of data [8–11].

The principle of operation of the geomechatronic complex for surface soil monitoring is similar to means for determining the strength characteristics of soils – ground penetrometers, consisting of a force measuring device and a push rod with a tip. Direct application of existing designs of soil penetrometers for the mechanized search of voids and inclusions is impossible for a number of reasons. In most cases, movement of the soil penetrometer push rods occurs due to the operator's force, which makes the process long and low-productive. The penetration depth of the penetrometer tip with a diameter of 0.01 m is not more than 1 m, which is not enough to search for voids and inclusions. Data recording is carried out using an indicating gage or electronic device with the recording of a single maximum or average value, which does not allow determining the depth of inhomogeneities [12]. Existing designs of penetrometers with the penetration depth recording according to the Yu. Revyakin principle require the presence of the operator, high (0.01 m) data discreteness and have no warning means in the case of objects in the search area [13]. The penetration force is proportional to the indenter diameter. Therefore, for cases where a minimum impact on the environment is required, rods with a diameter of less than 0.006 m are used.

For the automated process of localization of voids and inclusions, it is necessary to develop an algorithm of operation of the geomechatronic complex. The operation of the geomechatronic complex is based on the real-time, highly accurate comparison of analytically calculated and real diagrams of penetration forces. Therefore, the analytical study of the processes of soil penetration by small-diameter (less than 0.006 m) indenters with experimental verification of the obtained dependences is an important scientific problem.

2. Literature review and problem statement

In the study of the processes of interaction of working bodies with deformable media, the determination of the contact interaction mechanics is decisive for the determination of force parameters [14]. One of the main indicators of the force of indenter penetration into the soil surface are strength and tribotechnical parameters of soils. When considering the fundamental theories of contact interaction of a narrow wedge and cone indenters with a plastic surface, it is necessary to determine a group of studies considering the tribotechnical parameters with slipping of contact surfaces [15, 16]. A special case of contact interaction is adhesion of the deformable material to the indenter surface [17]. In the case of interaction between the rod and the soil mass, a simultaneous presence of adhesion areas in the anterior part and slipping of the remaining contact surfaces can be noted. Also, the majority of the known analytical studies of the interaction of the indenter with the deformed medium relate to the study of mechanical properties of metals by indentation [18–20].

When modeling the mechanical properties of metals, various soil description models are used: elastic-plastic [18], plastic [19, 20]. In such interaction, the indenter penetration is commensurate with the contact width [18–20], which significantly differentiates contact conditions during the rod penetration into the soil, in which the penetration depth is tens of times larger than the rod diameter. Also, the shape of indenters applied differs substantially, which in most cases has the form of a sphere [18, 19] or a cone [20] (a round end cone indenter), in contrast to a filament rod (filament rod indenter) of the penetrometer. The main difference lies in the developed deformation zone in the front part of the rod with changes in the material strength and the presence of a friction zone along the indenter. For modeling the penetration process, a preliminary identification of deformation zones is useful. Thus, in [18, 19], the zone of plastic deformation has been represented in the form of a sphere. When modeling the process of penetration of the material layer [20], deformation zones are limited by the boundaries of materials.

A special exception close to the conditions of rod penetration is the penetration of bodies of various shapes into the soil with comparable geometric parameters [21–25].

In [21], the process of penetration of an axisymmetric body in an elastoplastic medium at a speed about 1,000 m/s has been considered in order to determine the depth of penetration of bodies of various shapes into the soil with the known initial speed. The soil penetration resistance in the proposed model is determined from the elastic, plastic and inertial components of the soil reaction from external impact. For the case of rod penetration, this can be used taking into account the plastic component. The process of high-speed soil penetration is characterized by the separation of the material flow from the indenter surface with the formation of a contact geometry different from the indenter shape, which essentially affects calculations.

In [22, 23], the results of the numerical solution to the problem of penetration of a spherical striker into the soil using local interaction models to determine the connection between kinematic and force factors have been presented. These studies allow determining strength parameters of soils, depending on the initial and final conditions of the system. The disadvantage is the underestimation of the penetration force values when using the hypothesis of incompressibility.

In [24], the results of the striker shape optimization to ensure maximum penetration have been presented. The advantage of this study is the possibility of modeling the interaction of indenters of various shapes with various structural materials due to the proposed model of the medium. The disadvantage is that the calculation model does not consider friction between the indenter and the medium, which will significantly affect the results of the case of interaction between the rod and soil.

The work [25] deals with investigating the interaction of a penetrating rigid shell in an incompressible elastic-plastic model. The peculiarity of this study is the focus on the direction of deformation under the indenter impact. Thus, the study considers radial deformations and radial forces of inertia relative to the shell axis. This observation may be useful in describing the interaction between the rod and soil. The disadvantage of the study is that the calculation model does not consider friction between the indenter and the medium.

The specified features of [21–25] do not allow direct application of high-speed penetration calculation models for describing the interaction between the rod and soil.

Cases close to the static interaction are a static puncture of soil by a cone-tip working body in order to determine strength parameters [26, 27] and trenchless laying of communications [28, 29].

When modeling the contact interaction [28, 29], the case of soil deformation in the direction perpendicular to the motion direction of the working body, which is suitable for the conditions with the sharp and thin indenter has been considered. At the same time, with the wedge angles greater than the angle of soil friction on the contact surface, as well as the spherical tip, formation of adhesion zones and pressure bulb is possible.

When modeling the piercing process, it is particularly important for quality to determine the stress distribution in the material, taking into account the speed, mandrel shape, physical and mechanical properties of metals [30–32].

In [30, 31], when modeling the piercing process in order to determine the optimum shape of the mandrel by the criterion of the minimum value of the roll force, the principle of fluid-flow analogy has been used. In this study, when determining the axial resistance force of the mandrel, attention is paid to tangential stresses in the contact area, which significantly affect the roll force. At the same time, the assumption concerning the lack of radial deformations and viscous medium model does not allow using the results of the work to describe soil penetration.

In [32], mechanical properties of metals have been presented as an ideal plastic model. When describing the contact interaction of the mandrel, tangential contacts that arise between the mandrel and the material have been taken into account, which allows using the proposed approach for determining the energy-power parameters of the penetration process. It should be noted that the plastic model used requires clarification regarding the processes of strengthening the medium during the indenter penetration.

For all of the above models, the indenter penetration force is determined by integrating the contact pressure on the contact surface. The analysis of the problems related to penetration of materials allows using the approaches of the description of contact interaction of the indenter during metal piercing and static puncture of soils. The existing models of contact interaction require consideration of geometric parameters, namely, small wedge angle and length of the cylindrical zone, as well as characteristics of soil behavior associated with the formation of compression zones.

3. The aim and objectives of the study

The aim of the work is to develop an algorithm of operation and to create an industrial-experimental sample of the geomechatronic complex for surface soil monitoring based on the analytical description of the sensing process.

To achieve this aim, the following objectives were formulated:

– to create the program algorithm of the geomechatronic complex for surface soil monitoring;

– to describe analytically the process of surface soil monitoring by rod penetration;

– to carry out experimental studies of the geomechatronic complex for surface soil monitoring for the verification of the theoretical developments.

4. Development of the program algorithm of the geomechatronic complex for surface soil monitoring

The analysis of possible situations in the study of surface soil by penetration allows determining the main problems to be solved in geotechnical monitoring:

– determination of strength characteristics of soils;

– determination of the depth of various morphological horizons;

– identification of voids and inclusions.

The distribution of the determined strength values in the plan, the presence of voids and inclusions can be applied as additional parameters that allow better application of the results obtained.

The areas of application of the geomechatronic complex are:

– initial stages of archaeological and geological research;

– forensic research;

– military and humanitarian.

The geomechatronic complex can be adapted, if necessary, for the solution of related problems, for example, the diagnosis of the ecological state of the ecotope [4].

The main criteria when developing the program algorithm of the geomechatronic complex for surface soil monitoring, taking into account the objectives and application areas, are:

– penetration depth;

– monitoring process speed;

– reliability of the geomechatronic complex.

Among the main requirements to be considered when creating geomechatronic complexes for surface soil monitoring, the following should be noted:

– low cost of design and maintenance of the complex;

– monitoring safety;

– design simplicity, no adjustment at the application site is required;

– resistance to high humidity and dust;

– mobility;

– transportability.

When determining the key parameters of the penetration process, it is necessary to determine stress distribution patterns, as well as the nature and values of deformations caused by the working body of the geomechatronic complex – a rod. In the case of surface soil monitoring, the rod is an indenter with a diameter of 0.004 to 0.006 m and length up to 0.4 m with wedge angles of 15–20 degrees. In some cases, blunting by creating a spherical part of the rod end is advisable in order to increase the force, as in the case of weak soils. Under the impact of the rod on the soil mass, the treated medium, depending on the values of deformations of the contact surface, exhibits the elastic and plastic properties. For cohesive soils, the process of rod penetration occurs with the strengthening of the contact zone, as evidenced by the formed openings almost equal to the rod diameter. For non-cohesive soils, openings are closed immediately after removing the rod. In the process of penetration, the soil mass, depending on the deformation degree, has zones of plastic and elastic deformation.

Consider the case of a cone indenter with a long cylindrical part with a diameter d and the cone half-angle φ (Fig. 1). During the rod penetration, the cone part pushes soil aside with the appearance of the plastic deformation zone of length l_1 and radius r_y (zone – I). The advancement of the cylindrical part (zone – II) is carried out under the influence of inverse elastic deformation of the compacted soil layer in the case of cohesive soil or under the influence of horizontal stress caused by soil weight. In general, at the beginning of contact between the indenter and soil, deformations are within the limits of elastic values, which is important for the interaction of small-diameter indenters. For the case of the mechatronic complex rod, this phenomenon will not significantly affect the penetration force, due to the small stresses that precede plastic deformation. With further penetration, deformed and strengthened soil tries to return to its original state, showing elastic properties (zone – II).

When considering the zone I (Fig. 1), in the direction perpendicular to the rod movement, it is possible to identify the area of plastic, elastic-plastic and elastic deformations, whose influence on the penetration force decreases as the distance from the rod axis. Thus, in order to determine the resistance, it is essential to determine the contact pressure in the area of plastic deformations of the zone I and elastic deformations of the zone II.

The contact pressures arising in plastic deformation of soil can be determined using the equation describing the penetration of the cone mandrel in a half-space [32]:

$$p = 2\tau(1+\omega), \quad (1)$$

where τ is the shear strength of the material; ω is the angle of rotation of slipping lines:

$$\omega = \frac{\pi}{2} + \varphi, \qquad (2)$$

where φ is the cone half-angle.

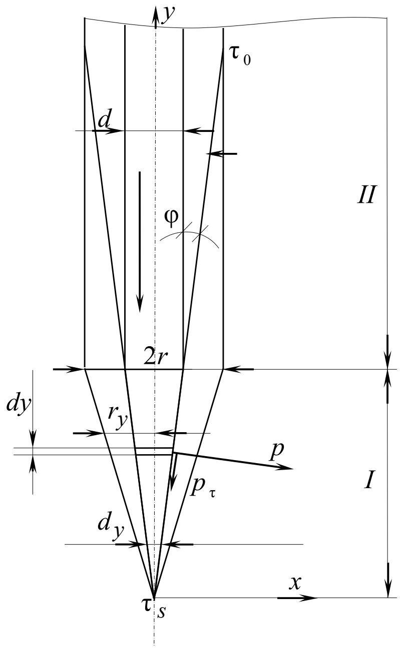

Fig. 1. Scheme of action of a cone indenter with a long cylindrical part

Taking into account friction along the zone I [33]:

$$p = 2\tau(1+\omega)(1+f\operatorname{ctg}\varphi), \qquad (3)$$

where f is the coefficient of friction of contact surfaces.

When solving contact problems, it is particularly difficult to determine geometric parameters of zones by the type of deformation distribution. The analysis of compression curves of cohesive soils indicates the predominance of plastic deformations over elastic ones, which allows neglecting the action of the latter when considering the problems with the developed deformation zone. Thus, it can be assumed without much loss of calculation accuracy that deformations in the radial direction of the zone I will be determined from the condition:

$$\varepsilon_x = \left(\frac{d_y}{2r_y}\right)^2, \qquad (4)$$

where r_y is the radius of the plastic deformation zone; d_y is the rod thickness depending on length:

$$d_y = \frac{d}{l_1} y = 2y\tan\varphi. \qquad (5)$$

Normal stresses σ are proportional to linear deformations ε, which are bound by the lateral pressure coefficient K:

$$\sigma = E\varepsilon, \qquad (6)$$

$$K = {}^{\sigma_y}\!/_{\sigma_x}, \qquad (7)$$

where E is the soil deformation modulus.

The maximum stresses under the action of the indenter with a small half-angle are perpendicular to the contact plane, as evidenced by the opposite movement of the material. Using the Tresca conditions for a material in a fluid state and the equation (7), we have

$$\sigma_x = \frac{2\tau_s}{1+K}, \qquad (8)$$

where τ_s is the soil shearing strength.

Based on the equations (5) and (7), the radius of the zone of plastic deformation along the height is equal to

$$r_y = \frac{d_y}{2}\sqrt{\frac{E(1+K)}{2\tau_s}} = y\tan\varphi\sqrt{\frac{E(1+K)}{2\tau_s}}. \qquad (9)$$

The radius of the plastic deformation zone:

$$r = \frac{d}{2}\sqrt{\frac{E(1+K)}{2\tau_s}}. \qquad (10)$$

Determination of the sizes of the plastic deformation zone allows revealing the distribution of strength characteristics and the width of the rod coverage area, which is necessary in determining the distance between adjacent punctures during the study by the method of mechanical sensing.

The strength properties of soil under the action of the rod change due to compaction, which will change the contact pressure along the tip generatrix. Depending on the rod tip geometry, sizes and wedge angle, the contact layers of soil are compacted with varying intensity and to certain values. Thus, the action of relatively large (more than 0.1 m) tips leads to limited values of the deformations arising in the contact area and the zone of constant value of the material strength. Under the action of a sharp small-diameter (less than 0.01 m) cone tip, there is a partial compaction and strengthening of soil along the tip generatrix. To reveal the distribution of changes in the material strength, the linear dependence of changes in soil strength along the indenter generatrix with the increase to the boundary of the plastic deformation zone is proposed.

For the case of interaction of the cone tip, a linear change in the shear strength of the material is proposed:

$$\tau = \tau_s + \frac{(\tau_0 - \tau_s)}{r} y\tan\varphi = $$
$$= \tau_s + 2\frac{(\tau_0 - \tau_s)}{d}\sqrt{\frac{2\tau_s}{E(1+K)}} y\tan\varphi. \qquad (11)$$

The contact pressure under the action of the rod on soil consists of two components of normal p and tangential p_τ. The tangential component of normal pressure is caused by rod friction on the soil surface and can be presented by the following expression:

$$p_\tau = fp. \qquad (12)$$

The total penetration force from the action of contact pressures of the zone I is calculated considering the interaction between the elementary section with the height dy (Fig. 1) and soil by projecting the forces on the vertical axis:

$$dP_1 = p\pi d_y \sin\varphi \frac{dy}{\cos\varphi} + p_\tau \pi d_y \cos\varphi \frac{dy}{\cos\varphi}. \quad (13)$$

After integration and transformation, we get:

$$P_1 = \frac{\pi d^2 (f/\tan\varphi + 1)\left(3\tau_s + 2\sqrt{\frac{2\tau_s}{E(1+K)}}(\tau_0 - \tau_s)\right)}{6}. \quad (14)$$

Similarly, for the cylindrical zone, provided that soil strength acquires the maximum value at the end of the zone I:

$$dP_2 = p_\tau \pi d_y dy,$$

$$P_2 = 2\pi d f l_2 (\tau_s + 2\sqrt{\frac{2\tau_s}{E(1+K)}}(\tau_0 - \tau_s)), \quad (15)$$

where l_2 is the length of the zone II.

The total penetration force during the rod penetration to a depth greater than the wedge length:

$$P = P_1 + P_2. \quad (16)$$

The presented dependences characterize changes in the penetration force at constant values of strength properties of soil as linear. A deviation to the smaller or larger values of the force indicates a change in strength characteristics, the presence of voids or inclusions.

To verify the obtained dependences, the information-measuring system of soil penetration was developed (Fig. 2).

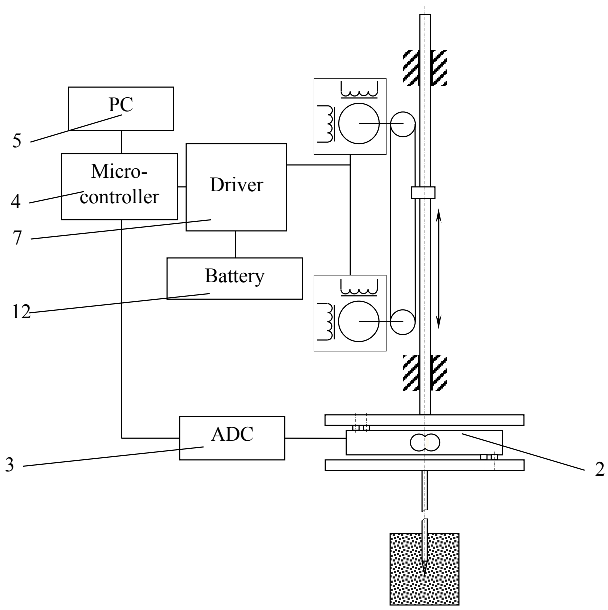

Fig. 2. Scheme of the information-measuring system of soil penetration

The main components of the experimental stand to measure the soil penetration force are force measurement and rod movement units. The force measurement unit allows recording the soil penetration force at an arbitrary time in different positions of the rod. The main components of the force measurement unit are: rod – 1, strain gauge-force sensor – 2 connected to a 24-bit analog-to-digital converter (ADC) HX711 – 3, microcontroller based on ATmega328 (ATmega16U2) – 4 and personal computer – 5. The rod movement unit consists of two high-torque twin stepper motors 14HS4401 – 6 powered by the BL-TB6560-V2.0-7 driver and transmitting the traction force through the timing belt – 8 on the push rod – 9. The timing belt – 8 is connected to the push rod – 9 by the coupling – 10. As guides to set the translational motion of the push rod – 9, spherical roller bearings were used.

For the power supply of the experimental stand, to measure the soil penetration force, two power supplies were used. The push rod drive is powered by a lead-acid battery with a voltage of 12 V and a capacity of 80 A·h. The microcontroller, the analog-to-digital converter are powered through a USB port of the personal computer. Thus, the information-measuring system developed is a stand-alone mobile mechatronic complex.

Table 1

Key parameters of the developed mechatronic complex for the surface soil study

Indicator, unit	Value
Rod force, N	140
Rod speed, m/s	0–0.6
Step, mm	0.1
Penetration force measurement range, N	0–100
Force measurement accuracy, N	0.01
Rod diameter, mm	5.8

Data for constructing sample load diagrams is a two-dimensional array. It contains data about the push rod movement and the penetration force of the sample. The resulting data are stored in the computer memory with the possibility of further processing.

The developed program algorithm is a cyclic structure. The algorithm has the following steps:

1. Beginning of the program;
2. Setting of variables;
3. Connection of libraries to control engines and the analog-to-digital converter;
4. Setting of the required number of cycles;
5. Reading of data from the force sensor at each cycle;
6. Recording of data with displaying on the PC;
7. Return of the rod to the original position;
8. End of the program.

The program is written in C/C++ and compiled with the AVR library, which allows using any of its functions. Each cycle of the program occurs when the stepper motor is rotated to an angle of 1.8° with recording the value of the force that occurs in the strain gauge sensor. Thus, during penetration at a depth of 0.3 m, an array of 1,500 force values is formed. This accuracy allows using the developed system with high reliability for surface soil monitoring for localization of objects by changes in the penetration force.

The frame of the mechatronic complex is a vertical board, on which elements of the force measurement and rod movement units are mounted (Fig. 3). The weight of the complex without a power supply is about 7.4 kg.

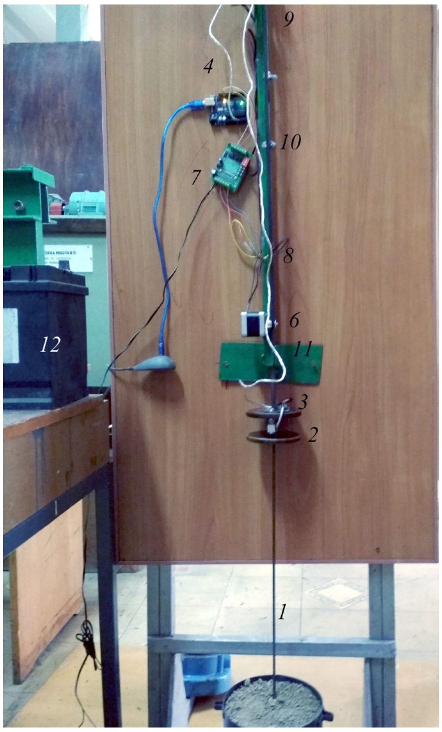

Fig. 3. Appearance of the information-measuring system of soil penetration (designation according to Fig. 3)

For the study, heavy sandy loam, which shows more strengthening effects and has the highest strength values is used. The material was pre-crushed and brought to a moisture content of 18 % and compacted to a compression coefficient of 0.81. Before the test, the samples were kept in sealed containers for a day.

The designed mechatronic complex develops the force within 100 N, which is sufficient for penetration of most types of cohesive soils.

5. Discussion of the results of experimental studies

The advantage of the research is that the proposed method for determining changes of force allows determining real values with distribution over the depth with a high accuracy and speed. Comparison of the obtained data with the analytical distribution allows revealing the presence of changes in geomechanical parameters and, if necessary, stopping the process in order to prevent damage to the object or means of research. This significantly reduces the cost of research with the possibility of automation.

In order to determine the effect of speed on the penetration process, the rod penetrated at different speeds of 0.1 and 0.6 m/s, with the difference in force increase being less than 2 %, which allows neglecting the influence of speed on the process of mechanical rod sensing in this range of speeds.

Fig. 4 shows analytically and experimentally determined graphs of changes in the soil penetration force *P* depending on the rod penetration depth. Experimental data are obtained by transforming the array of data that contains force values on a particular step of the stepper motor. The solid line shows the analytical distribution of the penetration force, the broken line – experimental values. The parameters of the indenter and soil: d=0.005 m, φ=8°, f=0.3, τ_s=10,500 Pa, τ_0=17,500 Pa, K=0.3, E=1.1·107 Pa.

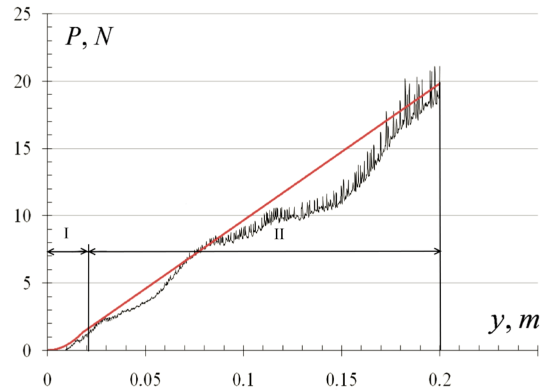

Fig. 4. Analytically and experimentally determined changes in the soil penetration force

We note the high coincidence of the theoretical and experimental values in general over the depth of penetration (deviations within 10 %) with different values in separate zones. In particular, a high coincidence can be observed in the zone I (deviations within 5 %). The greatest deviation is observed in the penetration of the lower zone of the sample, which is explained by the uneven compaction of the sample along the height during the compaction with decreasing penetration force. Further increase of the force to the calculated value is due to the wall effect, which is the reason for the increased strength of samples on the periphery.

The graph of changes in the penetration force (Fig. 4) indicates a high sensitivity (0.05 %) to changes in the geotechnical parameters of the sample studied. This allows using the proposed program algorithm to create electromotive mechatronic search devices, which basically use the contact methods of research.

The obtained data when moving the complex in the plane allow revealing the distribution of strength characteristics both over the depth and in space to obtain data on the anisotropic characteristics of soils.

The advantage of the proposed method for studying changes in strength properties over the known ones is the high accuracy of the data obtained, both on the depth of penetration (0.1 mm), and the values of the penetration force, with the possibility of their analysis in the process of penetration.

The developed analytical dependencies and the program algorithm of the mechatronic complex can be used to increase reliability, safety, performance and accuracy in different types of research. So, for the case of archaeological search, the analysis of data on changes in strength in the rod penetration process will prevent the destruction of the object of search from the force.

It should be noted that the proposed method for studying changes in the strength properties of soils can be used only for disperse soils with particle sizes smaller than the rod diameter (0.5 mm), which do not have large fragmental inclusions. The presence of large inclusions in the soil will lead to an increase in the penetration force and complicates the analysis of changes in strength properties by this method. A possible solution for conducting studies of soils containing fragmental inclusions is repeated penetration of the study area with the exception of diagrams with increased force values from the analysis. Also, the presence of large fragmental inclusions can lead to the destruction of elements of the information-measuring penetration system. In order to prevent damage to the elements, it is necessary to improve the program algorithm by limiting the force required for the study of this type of soil.

The research is carried out within the framework of the project of creating an electromotive mechatronic complex for monitoring the ecological status of hard-to-reach areas. These studies allow developing a unit of localization of dangerous underground objects by means of the most reliable method of search – the method of mechanical soil sensing.

6. Conclusions

1. Based on the developed basic approaches for the creation of geomechatronic complexes for surface soil monitoring, which determine the main tasks, application scope, quality criteria, the program algorithm is developed. The developed program algorithm of the geomechatronic complex allows determining the dependence of changes in force depending on the depth of penetration. The program algorithm has a cyclic structure in which the data from the force sensor and the rod step with the recording and displaying of the data on the PC are sequentially executed. The program algorithm provides the recording of force changes from movement with high sensitivity due to a small step of the rod (0.1 mm).

2. To predict real forces that occur in the rod penetration, the mathematical model considering the effect of partial strengthening of disperse cohesive soils and friction of contact surfaces is developed. The increase in the soil shearing strength is due to compaction in the front part of the rod and, depending on the rod diameter, can increase to 40 %, which directly affects the penetration force.

3. To implement the developed basic approaches for the construction of geomechatronic complexes for surface soil monitoring and checking the analytical model based on the developed program algorithm, an experimental sample that provided high-accuracy of measurements was created. The experimental sample of the geomechatronic complex provides a high accuracy (0.05 %) of determining the penetration force, depending on the indenter penetration depth. The measurement accuracy is ensured by the use of a high-precision electronic dynamometer (0.01 N), which records the force at each step of the rod. The high coincidence of the theoretical and experimental values in general over the depth of penetration (deviation within 10 %) is noted.

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