UDC 624.132.3
DOI: 10.15587/1729-4061.2018.131838

DETERMINATION OF THE RESISTANCE OF THE CYLINDRICAL-TUBULAR DRILL FOR TRENCHLESS LAYING OF UNDERGROUND COMMUNICATIONS

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В основі визначення сил опору заглибленню в ґрунт кільцевого наконечника було покладено уявлення про зміну пружного стану ґрунту при його ущільненні, який визначається компресійним модулем деформації ґрунту. Цей показник пов'язує усі фізико-механічні властивості кожного з типів ґрунтів, та дає можливість встановити закони нормального тиску опору ґрунту на поверхні конусної та циліндричної частині робочого органу.

Запропоновані теоретичні моделі процесів, що протікають під час заглиблення в ґрунт кільцевого наконечника, дозволили встановити для кожного з випадків виконання робіт вплив його параметрів в залежності від фізико-механічних властивостей ґрунту на сили його опору. Встановлено, що максимальна довжина кільцевого наконечника визначається з умови руху (незабиваємості) ґрунту, яка наприклад при діаметрі циліндру 28 мм складає 0,87 м, 1,04 м та 1,16 м відповідно для твердого супіску, напівтвердого суглинку та тугопластичної глини. Також можна констатувати, що збільшення внутрішнього діаметру в 2 рази призводить до збільшення довжини ґрунтового керну в 1,75 рази.

Визначено, що двоконусний наконечник не сприяє пропусканню ґрунту крізь себе, є причиною його забивання та утворення ґрунтових ядер ущільнення на фронтальних площинах, що призводить до збільшення опору переміщенню. Тому для протискування труб, щоб не було забиваємості ґрунтом, наконечник потрібно виконувати з одним зовнішнім конусом.

Отримані результати роботи можуть бути використані при обґрунтуванні раціональних параметрів робочого обладнання при утворюванні горизонтальної свердловини в різних типах ґрунтів

Ключові слова: аналітична модель, безтраншейна технологія, інженерні комунікації, горизонтальна свердловина, технологія продавлювання

1. Introduction

One of the methods of trenchless laying of underground communications is pipe jacking or shield tunnelling method. It is employed for constructing tunnels of relatively large diameters from 300 mm to 800 mm and larger ones. In this case, a borehole is usually formed by a steel pipe, which serves as a protective casing. When the pipe is pushed into the ground under the thrust force of hydraulic jacks, the spoil enters the interior and undergoes further pneumatic, hydraulic or mechanical removal. To reduce soil cutting resistance and to adjust movement direction, the end of the pipe is equipped with a pointed annular drill. This process requires a lot of effort. Therefore, the improvement of the calculation methods, as well as the selection of rational parameters of the annular drill, is a topical issue.

2. Literature review and problem statement

The process of soil punching using pointed annular drills is described in the works [1–3]. According to the work [1], the process of punching the soil with the annular drill can be accompanied by its compaction into the inner face of the pipe or vice versa, depending on the angle of the cutting edge [2, 3]. In the former case, the external stress in the soil decreases and this results in reducing the risk of damage to the road surface and the surrounding communications [1]. In the latter one, it is possible to enlarge the path and reduce the cost of removing soil from the pipe by using an auger, for instance [2, 3]. However, these studies do not allow the determination of frictional forces on the surface of the working body.

The analysis of the studies [4–6] has shown that the main emphasis is, as a rule, placed on separate cases of the soil excavation process, and problem-solving methods are of a rather empirical nature. Thus, in the work [1], the effect of rotation on the cone penetration resistance is under consideration. The same issues are dealt with in [2] taking into account the vibration of the working body. The problem of reducing frictional forces on the surface of the working body is addressed in the work [3]. The theoretical basis of the failure mechanics in the soil under puncturing and expanding by means of the conical drill bit is given in the work [4]. In the works [5] and [6], the results of experimental research on improvement of the working equipment for soil punching are presented. However, these methods cannot be used to provide a general picture of the process of soil punching using the cylindrical-tubular drill.

Advances and experiences with pipelines and trenchless technology for water, sewer, gas and oil applications are considered in the work [7]. Methods of trenchless laying of underground communications are presented in the works [8, 9]. Methods of horizontal directional drilling and ways for their improvement are investigated in the work [10], and a detailed technical review of technologies for the continuous development of new installations is presented in the work [11]. However, the specified methods do not fully determine the influence of drilling bit parameters for various physical and mechanical properties of soils on the process.

The procedure for calculating the axial pullback distributions in pipes during directional drilling installations and determining loads and stresses is described in [12, 13]. The above-mentioned studies deal with the stresses associated with pipelines installed by horizontal directional drilling. Guidelines for selecting rational parameters of borehole drilling are given in the work [14]. An analytical model for determining the frontal resistance to penetration with the annular drill is presented in the work [15]. The obtained results can be used in substantiating the choice of installations for trenchless laying of underground communications using the soil punching method. However, these works do not provide guidelines for rational parameters of the drill depending on the type of soil being punched. Therefore, the problem of determining the resistance to penetration of the cylindrical-tubular drill for trenchless laying of underground communications requires further research.

3. The aim and objectives of the study

The aim of the work is the theoretical determination of the total resistance to penetration of the cylindrical-tubular drill and determination of the influence of the parameters of the working body and the soil environment on it.

To achieve the aim, the following tasks are to be solved:

– to describe the processes occurring during borehole formation and develop new approaches to improving the calculations;

– to specify the laws of the normal pressure of penetration resistance acting on the surface of the conical and cylindrical parts of the working body according to the suggested model of the pipe jacking process;

– to develop a mathematical model for calculating the total penetration resistance and determine the influence of the constituents and physicomechanical properties of the soil on its values;

– to obtain a rational shape and parameters of the head of the working body for the formation of the borehole using the pipe jacking method according to the results of theoretical studies.

4. Substantiating the approach to the theoretical determination of penetration resistance forces

The development of trenchless laying of underground communications has recently gained global interest, which is associated with the current needs for the active development and reconstruction of engineering networks. All this has been reflected in the creation of new special technologies and machines, which require improvement of their calculations [7–14].

One of the most widespread methods is pipe jacking. According to this method, laying of underground communications is carried out by the following stages:

1) the cylindrical-tubular drill is pressed into the soil;
2) the removal of spoil forms a borehole;
3) the pipeline is drawn into the created borehole.

During the pushing process, the pointed cylindrical-tubular drill is subjected to frontal resistance and frictional forces acting along the outer and inner surfaces of the cylinder. The strength of frontal resistance to penetration of the cylindrical-tubular drill with double-sided cutting edges can be determined by the following formula [15]:

$$P_{2c} = \pi E_S \left(1 + f ctg\beta\right) \times$$
$$\times \left[\frac{\gamma^2 - 1}{4} - \frac{\gamma^2 - 2\gamma - 1}{16\left[1 - \left(\frac{\gamma+1}{2\gamma}\right)^2\right]} - \frac{(\gamma+1)^4}{128\left[1 - \left(\frac{\gamma+1}{2\gamma}\right)^2\right]\gamma^2} - \left(\frac{\gamma+1}{32}\right)^2 + \frac{1}{2(\gamma+1)^2} \right] \frac{D^2}{\gamma^2}, \quad (1)$$

where

$$E_S = \frac{(1+\omega)\cdot\rho_{SOL}}{C_C \cdot \rho_{IP}}$$

is the compression deformation modulus of the soil; γ is the ratio of the inner and outer diameters of the annular drill,

$$\gamma = \frac{D}{d};$$

ρ_{SOL} is the density of the soil solid phase in the absence of pores; ω is the soil moisture; ρ_{IP} is the in-place density of the soil; C_C is the compression index of the soil; 2β is the cutting angle of the annular drill.

In case of using a single-sided cutting edge, the resistance is calculated from the relation [15]:

$$P_c = \pi E_S \left(1 + f ctg\beta\right) \times$$

$$\times\left(\frac{3\gamma^2-2\gamma-1}{16} - \frac{\gamma^2-2\gamma-1}{16\left[1-\left(\frac{\gamma+1}{2\gamma}\right)^2\right]} - \frac{\frac{(\gamma+1)^4}{\gamma^2}}{128\left[1-\left(\frac{\gamma+1}{2\gamma}\right)^2\right]}\right)\frac{D^2}{\gamma^2}. \quad (2)$$

The received approach to calculating the annular drill with its pressing into the soil is the foundation for further solution of the problems set in the work.

5. Determination of the resistance of the cylindrical-tubular drill

For determining the resistance to the frictional forces of the soil, an elementary soil cylinder of length ∂x is allocated on the lateral cylindrical (inner) surface at a distance X from the cutting edge of the drill (Fig. 1). The transverse sections of this cylinder are subjected to internal stresses in the soil, which are normal according to the direction of motion σ_x and $\sigma_x + \partial\sigma$. In the radial direction, the side walls of the inner cylinder of the drill are subjected to the normal pressure $\xi\sigma_x$, where ξ is the lateral pressure coefficient [16].

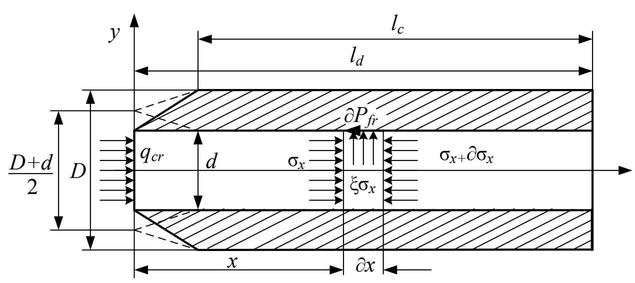

Fig. 1. Analytical model of the external cone drill

Let us define the law of normal stress distribution σ_x and soil friction force acting on the side walls of the inner cylinder along its length. For this purpose, all elementary forces are projected on the X-axis:

$$\frac{\pi d^2}{4}\sigma_x - \pi d f \xi \sigma_x \partial x - \frac{\pi d^2}{4}\left(\sigma_x + \partial\sigma_x\right) = 0, \quad (3)$$

where d is the inner cylinder diameter; f is the soil friction coefficient [16].

After transforming the equation (3), we obtain the differential equation (4):

$$\frac{\partial\sigma_x}{\sigma_x} = -\frac{4f\xi}{d}\partial x. \quad (4)$$

After solving this equation, we have:

$$\ln\sigma_X = -\frac{4f\xi}{d}x + c \text{ or } \sigma_X = e^{-\left(\frac{4f\xi}{d}\right)x+}. \quad (5)$$

Using the boundary condition, we obtain:

$$\sigma_{X/x=0} = e^c = q_{cr},$$

$$\sigma_X = e^{-\left(\frac{4f\xi}{d}\right)x} e^c = q_{cr} e^{-\left(\frac{4f\xi}{d}\right)x} = \frac{q_{cr}}{e^{\left(\frac{4f\xi}{d}\right)x}}, \quad (6)$$

where q_{cr} is a critical pressure on the soil according to its bearing capacity. After integrating the expression (6), we obtain the soil friction force as follows:

$$P_{fr}^{in} = \pi d f \xi \int_0^{l_d} \sigma_X \partial x = \pi d f \xi \int_0^{l_d} \frac{q_{cr}}{e^{\frac{4f\xi}{d}x}} \partial x = \frac{\pi d^2}{4} q_{cr}\left(1 - \frac{1}{e^{\frac{4f\xi l_d}{d}}}\right), \quad (7)$$

where l_d is the drill length.

Taking into account the gravity force of the core, the condition of soil movement (unplugged condition) can be calculated by the following equation:

$$q_{cr}\frac{\pi d^2}{4} > \frac{\pi d^2}{4} q_{cr}\left(1 - \frac{1}{e^{\frac{4f\xi l_d}{d}}}\right) + \frac{\pi d^2}{4} l_d \gamma_s, \quad (8)$$

where γ_s is the core specific gravity.

Hence, the condition of movement can be determined as follows:

$$l_d \cdot e^{\frac{4f\xi l_d}{d}} < \frac{q_{cr}}{\gamma_s}. \quad (9)$$

The graphical representation of the maximum length of the drill according to its internal diameter for different soils is obtained from the inequality (9) and is shown in Fig. 2.

Dependences of the soil friction force acting along the inner cylinder of the drill are given in Fig. 3–5 for different soils and ratios $\frac{l_d}{D}$ and $\frac{D}{d}$ according to (7).

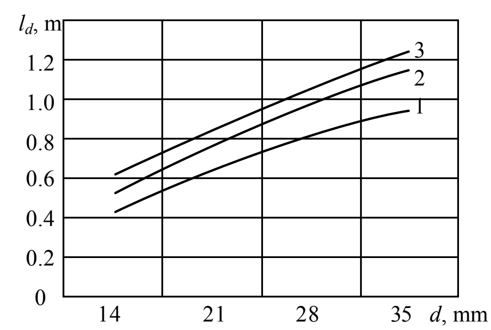

Fig. 2. Dependence of the maximum length of the drill on its internal diameter: 1 — for sandy clay; 2 — for semi-solid loam; 3 — for tough clay

Since the maximum friction force acting on the side walls of the inner cylinder of the drill depends on its maximum filling, we analyze the dependence of the length of the soil core on the diameter of the cylinder and its length (Fig. 2). It has been calculated that its maximum length, for example, with a cylinder diameter of 28 mm, is 0.87 m, 1.04 m and 1.16 m respectively for sandy clay, semi-solid loam and tough clay. It is now clear that a 2-fold increase in the internal diameter leads to an increase in the core length by 1.75 times.

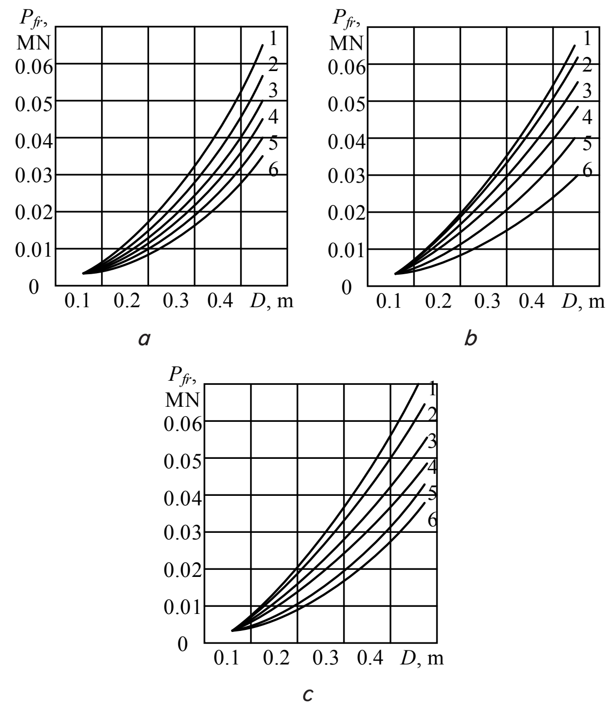

Fig. 3. Dependence of the friction force acting along the inner cylinder P_{fr} on D for different values γ: 1 – for γ=1.2; 2 – for γ=1.3; 3 – for γ=1.4; 4 – for γ=1.5; 5 – for γ=1.6; 6 – for γ=1.7 for semi-solid loam: *a* – for l_d/D=1.5; *b* – for l_d/D=2.0; *c* – for l_d/D=3.0

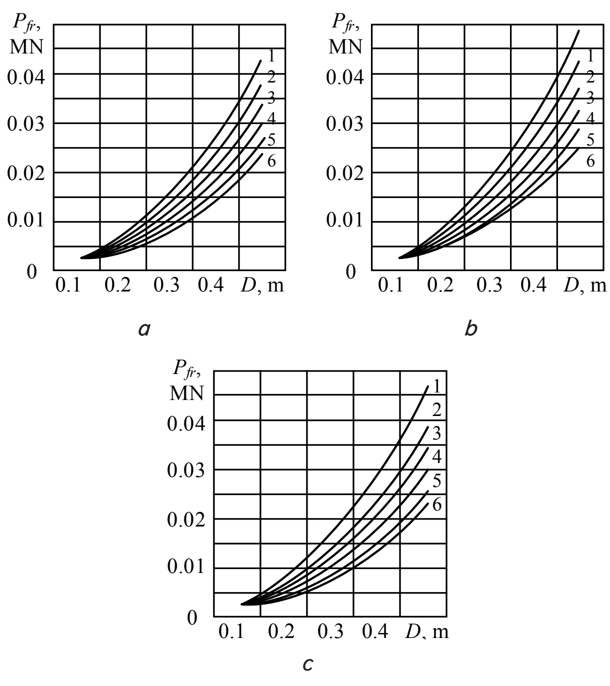

Fig. 4. Dependence of the friction force acting along the inner cylinder P_{fr} on D for different values γ: 1 – for γ=1.2; 2 – for γ=1.3; 3 – for γ=1.4; 4 – for γ=1.5; 5 – for γ=1.6; 6 – for γ=1.7 for sandy clay: *a* – for l_d/D=1.5; *b* – for l_d/D=2.0; *c* – for l_d/D=3.0

Taking into account the calculated cylinder length of the drill, we analyze the action of the friction force during the pressing process and while filling its internal cavity within the calculated maximum length of the core (Fig. 3). The graph shows that the value of the resistance due to the soil friction with the increase of the cylinder length from 1.5 *D* to 3.0 *D* in all types of soils increases by 10–12 %.

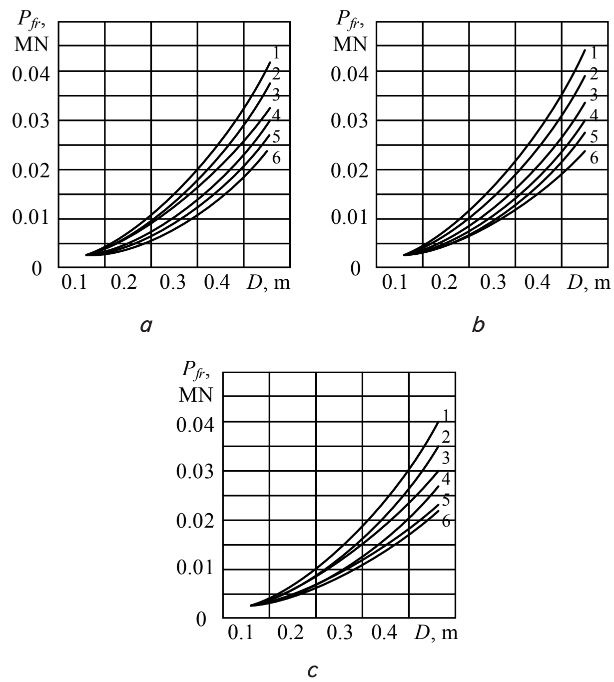

Fig. 5. Dependence of the friction force acting along the inner cylinder P_{fr} on D for different values γ: 1 – for γ=1.2; 2 – for γ=1.3; 3 – for γ=1.4; 4 – for γ=1.5; 5 – for γ=1.6; 6 – for γ=1.7 for tough clay: *a* – for l_d/D=1.5; *b* – for l_d/D=2.0; *c* – for l_d/D=3.0

The obtained graphs also show that the friction force is greatly influenced by the ratio of outer and inner diameters of the cylinder. So, when the value changes from γ=1.2 to γ=1.7, the friction forces are nearly twice reduced.

The friction force on the inner surface of the drill essentially depends on the type of soil. Thus, the difference of the calculated data between the tough clay and the semi-solid loam reaches 30–35 % according to the calculations (7).

If the drill has two cones – the external and the internal ones, as shown in Fig. 1 by the dashed line, then the internal cone compresses the soil of size $\frac{D+d}{2}$ to size d. The relative deformation equals:

$$\varepsilon=\left(\frac{D+d}{2}-d\right)/\frac{D+d}{2}=\frac{D-d}{D+d}=\frac{\gamma-1}{\gamma+1}, \quad (10)$$

where $\gamma=\frac{D}{d}$ is the ratio of outer and inner diameters of the drill.

Due to elastic deformations, the soil applies pressure to the inner surface of the drill and an additional force of friction occurs:

$$P_{df}=\pi d l_c f E_v \varepsilon=\pi d l_c f E_v \frac{\gamma-1}{\gamma+1}, \quad (11)$$

where E_v is the modulus of elastic volumetric deformation of soil, l_c is the length of the cylindrical part of the drill.

Then the total friction force of the soil acting on the inner lateral surface of the drill equals:

$$P_{\text{fr}}=\frac{\pi d^2}{4}q_{\text{cr}}\left(1-\frac{1}{e^{\frac{4f\xi l_c}{d}}}\right)+\pi dl_c fE_v\frac{\gamma-1}{\gamma+1}. \quad (12)$$

The condition of soil movement (unplugged condition) can be shown as follows:

$$\frac{\pi d^2}{4}q_{\text{cr}}\geq\frac{\pi d^2}{4}q_{\text{cr}}\left(1-\frac{1}{e^{\frac{4f\xi l_c}{d}}}\right)+\pi dl_c fE_v\frac{\gamma-1}{\gamma+1}. \quad (13)$$

On the condition that the inequality (13) is written in the following form:

$$\frac{4l_{\text{d}}fE_v}{dq_{\text{cr}}}\cdot\frac{\gamma-1}{\gamma+1}-\frac{1}{^{4fql_{\text{d}}/d}}\leq 0 \quad (14)$$

or

$$e^{-\frac{4f\xi l_{\text{d}}}{d}}\geq\frac{4fE_v}{q_{\text{cr}}}\cdot\frac{\gamma-1}{\gamma+1}\cdot\frac{l_{\text{d}}}{d}. \quad (15)$$

After taking the logarithm of the equation (15), we get:

$$\frac{4l_d fE_v}{dq_{cr}}\cdot\frac{\gamma-1}{\gamma+1}-\frac{1}{e^{4fql_d/d}}\leq 0 \quad (16)$$

The inequality (16) is not fulfilled under any conditions.

Thus, the design of the two-cone drill does not facilitate passage of soil through itself and it causes soil plugging as well as formation of soil plugs on the frontal planes, which causes an increase in drag force.

Therefore, to provide unplugged conditions during pipe jacking the drill with a single external cone should be used.

The total force for pressing such a drill equals:

$$P_{\Sigma}=P_{\text{c}}+P_{\text{fr}}^{\text{in}}+P_{\text{fr}}^{\text{out}}, \quad (17)$$

where P_{c} is the force of pressing a single-sided external cone, which is determined by the equation (2); $P_{\text{fr}}^{\text{in}}$ and $P_{\text{fr}}^{\text{out}}$ are frictional forces on the inner and outer cylinders, which can be calculated according to (7):

$$P_{\text{fr}}^{\text{out}}=\pi Dl_{\text{d}}q_{\text{c}}^{\text{av}}f, \quad (18)$$

where q_{c}^{av} is the average normal soil pressure on the outer cylindrical part of the drill.

This pressure is determined using the stress value σ_1 on the boundary of the elastic and plastic zones (the zone of destruction), which spreads from the axis of the ring-shaped drill at distance $D_{\text{p}}=2D$. The stresses on the boundary of the elastic and plastic zones create the force P_1 around the plastic (destroyed) zone with a diameter of D_p, which can be calculated as follows:

$$P_1=\sigma_1\pi D_p l_d. \quad (19)$$

This force is perceived by the outer lateral (cylindrical) surface of the drill:

$$q_{p\,d}^{\max}\pi Dl_d=\sigma_1\pi D_p l_d=2\sigma_1\pi Dl_d. \quad (20)$$

From which

$$q_c^{\max}=2\sigma_1,\ q_c^{av}=\sigma_1. \quad (21)$$

Then

$$P_{fr}^{out}=\pi D\sigma_1 fl_d. \quad (22)$$

The total force required for penetration of the annular drill with the external cone is determined as follows:

$$P_{\Sigma}=\pi E_s(1+fctg\beta)\times$$
$$\times\left[\frac{3\gamma^2-2\gamma-1}{16}-\frac{\gamma^2-2\gamma-1}{16\left[1-\left(\frac{\gamma+1}{2\gamma}\right)^2\right]}-\frac{\frac{(\gamma+1)^4}{\gamma^2}}{128\left[1-\left(\frac{\gamma+1}{2\gamma}\right)^2\right]}\right]\frac{D^2}{\gamma^2}+$$
$$+\frac{\pi D^2}{4\gamma^2}q_{\text{cr}}\left(1-\frac{1}{e^{\frac{4fql_{\text{d}}\gamma}{D}}}\right)+\pi D\sigma_1 fl_{\text{d}}. \quad (23)$$

The dependences of the total pressing force for different soils and ratios $\gamma=\frac{D}{d}$ are shown in Fig. 6, 7.

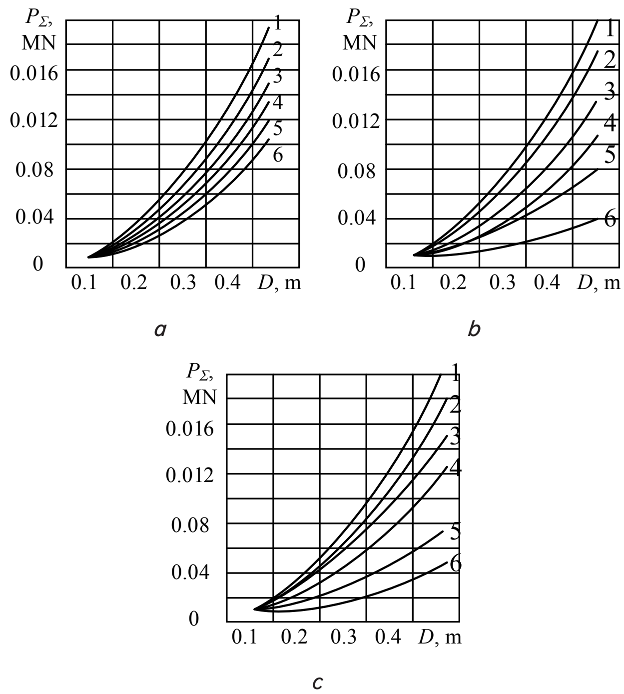

Fig. 6. Dependences of the total pressing force P_Σ with the ratio of γ: 1 – γ=1.2; 2 – γ=1.3; 3 – γ=1.4; 4 – γ=1.5; 5 – γ=1.6; 6 – γ=1.7 for different soils: *a* – for sandy clay; *b* – for semi-solid loam; *c* – for tough clay

According to the analysis of analytical models and the graphical representation, the total resistance force to penetration of the cylindrical drill differs depending on the type of soil. For instance, the difference for tough clay and sandy clay is 36–38 %.

Depending on the cylinder length in the range of 1.5 D-3.0 D, it can vary by up to 32 % for these soils. The dependence of soil resistance on the cylinder diameter is nonlinear in nature and it shows a significant rise with an increase of the diameter at the same path. For example, for tough clay with a cylinder length of 2 D and for γ=1.5 the resistance force increases from 0.03 MN to 0.067 MN when the diameter changes from 0.2 to 0.3 m. When the diameter changes from 0.4 m to 0.5 m, the force increases from 0.12 MN to 0.186 MN.

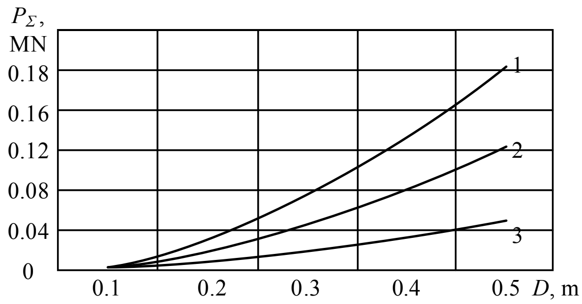

Fig. 7. Dependences of the total penetration force on the drill diameter when γ=1.4 and l_d/D=2 for different soils: 1 – semi-solid loam; 2 – sandy clay; 3 – tough clay

It should also be noted that the total soil resistance isn't essentially influenced by the ratio of cylinder diameters, and it even decreases in the tough clay. This can be explained by the fact that the friction force along the inner surface decreases with the decrease of the inner diameter, and the force of frontal resistance to core penetration increases.

6. Discussion of the results of investigating the pressing process of the cylindrical-tubular drill

This work is a part of the research that deals with the scientific foundations of the processes of creating boreholes in the soil by static pressing of the equipment. The efficiency of bore development by the pipe jacking method is determined by reducing the resistance to penetration of its working equipment in the form of a cylindrical-tubular drill into the soil.

The analytical method for determining the frontal resistance to penetration with the annular drill described in the work [15] is applied to in the formulas (1) and (2). It does not provide a general picture of the pressing process of the entire working body and does not allow the determination of its rational design parameters and the total soil resistance. In order to provide an objective basis for the pressing process, the law of normal stress distribution and soil friction force acting on the side walls of the inner cylinder along its length has been defined (6).

On the basis of the determined condition for the penetration of the soil core into the cylinder, the maximum length of soil movement has been obtained taking into account the internal diameter of the cylinder. The dependence of the maximum length of the drill on its internal diameter is shown in Fig. 2. Thanks to this, the analytical models for the inner surface of the cylindrical-tubular drill have been obtained. The dependence of frictional forces on the ratio of the drill diameters is shown in the graphs, Fig. 3–5.

Summing up all the components of soil resistance forces, the total force required for the penetration of the annular drill with the external cone has been determined (23); its graphical representation for different conditions is given in Fig. 6, 7.

The obtained dependences take into account the parameters of the annular drill as well as physical and mechanical properties of soils. This fact gives an opportunity to carry out an entire qualitative analysis of the influence of these factors. The scientific results obtained in the form of mathematical models (7), (9), (23) of the process of borehole formation by the method of soil punching are important from a theoretical point of view. These mathematical models are confirmed by the results of theoretical and experimental studies of other authors [5, 6, 17]. From a practical point of view, the identification of rational parameters of the drill for soil punching allows us to determine the conditions for its effective use in creating boreholes in different types of soils. The applied value of the obtained scientific results is the possibility of improving the working equipment for borehole formation by the pipe jacking method in the process of trenchless laying of underground communications.

7. Conclusions

1. The proposed theoretical dependences for determining the forces resisting the penetration of the annular drill of the equipment for trenchless laying of underground communications are based on the physics of the process of interaction between the drill and the soil and give an opportunity to obtain objective calculations of design parameters of the working equipment as well as to determine power characteristics of installations for the formation of boreholes by the pipe jacking method.

2. The calculated dependencies allow us to comprehensively evaluate the influence of all factors that are at the core of the borehole formation process and to determine the rational design parameters of the working body for soil punching. Namely, the maximum length of the annular drill for the conditions of soil movement (unplugged condition) has been determined, which, for example, with a cylinder diameter of 28 mm, is 0.87 m, 1.04 m and 1.16 m respectively for sandy clay, semi-solid loam and tough clay. It is now clear that a 2-fold increase in the internal diameter results is an increase in the core length by 1.75 times.

3. It has been determined that the two-cone drill does not facilitate passage of soil through itself and it causes soil plugging as well as formation of soil plugs on the frontal planes, which causes an increase in drag force. Therefore, to provide unplugged conditions during pipe jacking, the drill with a single external cone should be used.

4. It has been found that the total soil resistance isn't essentially influenced by the ratio of cylinder diameters, and it even decreases in the tough clay. It can be explained by the fact that the friction force along the inner surface decreases with the decrease of the inner diameter, and the force of frontal resistance to core penetration increases.

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