Automatic control of soil puncture

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Received 04.08.2022, accepted 25.10.2022
https://doi.org/10.32347/uwt.2022.12.1501

Abstract. Among the existing methods of making horizontally directed wells for trenchless laying of utilities, the method of static soil puncture is the most popular. The main disadvantage of this method is poor accuracy of the piercing head movement in the soil. This drawback requires constant adjustment of the trajectory of this movement. The movement of the head is controlled by using a head with an asymmetric tip and the action of translational and translational-rotational motion on it. The transmission of these movements from the power plant is accomplished by means of a set of fixed pushing rods. If you know how the process of off and on deviation of the head happens, you can make it possible to automatically control the puncture of the soil by timely changing the direction of the head tip shift.

To achieve this goal, the following issues have been resolved. It is determined that for automated control of the soil puncture process by static method it is necessary to use a puncture head with an asymmetric tip. Changing its position in the soil space can be controlled by rotating the tip and orienting it according to the direction of deviation.

The obtained mathematical model of correcting the trajectory of the head with a truncated cylindrical tip makes it possible to predict the process of soil puncture in time depending on different soil conditions and to get a solution to the problem of deviation from the specified design trajectory of the tip head which has a recognized angle of the frontal plane cut to the horizon with successive build-up of rods.

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Changing the orientation in the space of the cut front surface of the cylindrical tip, taking into account the obtained mathematical model of correcting the trajectory of the head in the soil, allows to increase the span length to 100 m due to the proposed automated principle of correcting its movement.

Keywords: soil puncture, soil resistance, asymmetric tip, static puncture installations, puncture control, types of soils, trenchless laying of communications, well.

INTRODUCTION

Among the present methods of forming horizontally directed wells for trenchless laying of utilities, the method of static soil puncture is the most popular. The main disadvantage of this method is the lack of accuracy of the piercing head movement in the soil. This flaw requires constant adjustment of the trajectory of its movement. The movement of the head is controlled by using a head with an asymmetric tip and the action of translational and translational-rotational motion on it. The transmission of these movements from the power plant is accomplished by means of a set of fixed pushing rods. If you know how the process of periodical deviation of the head happens, you can make it possible to automatically control the puncture of the soil by timely changing the direction of the tip head shift.

ANALYSIS OF PUBLICATIONS

Today the requirements for building engineering networks in large cities impose certain restrictions on their construction [1]. These limitations are particularly relevant to trenching technologies, which involve digging trenches, entailing significant financial costs and additional problems, such as the complexity of freight and passenger transportation. An alternative to them are trenchless methods of laying underground communications. For example, laying large diameter pipelines can be performed by micro-tunneling [2]. One of the ways to increase the efficiency of laying distribution networks of small diameter up to 350 mm is to use the control system of the trajectory of the working body in the ground, which allows bypassing obstacles in the form of cables and pipelines [3]. Effective laying of underground communications by trenchless methods is provided by correctly selected technologies for building horizontally oriented wells, which are considered in [4]. The main disadvantage of these technologies is their cost, which is caused by the high cost of drilling equipment and work. Of the various methods to obtain technological cavities in the soil available on the market, the simplest and cheapest is static soil puncture [5]. But this statement can be true only for small sections of the route up to 25 ... 30 m, which often does not meet the real requirements. Over long distances, pipelines can be laid by using the method of controlled puncture in making a leading well, which is proposed in [6]. But the nature of the tip and the way how its parameters influence the control process are not considered by the authors.

General patterns of soil puncture processes and formation of horizontally directed wells are described in [7]. The process of interaction of the soil-piercing working body with the soil is considered in [8]. However, the research conducted by the author of this work is aimed only at improving the efficiency of the process of penetrating the soil by the working body with a symmetrical conical tip, and does not provide an answer to the problem of increasing the accuracy of penetration or changing the trajectory of the working body in the soil.

The review of the technical literature showed that the issues of soil puncture are considered in many studies [9 − 14] and practical recommendations are given in works [15 − 17, 21, 22]. In these works, it is stated that the tip of the soil piercing head for controlled soil puncture should have an asymmetrical shape, for example in the form of a beveled cylinder or a cone with an offset top. However, the calculated dependences presented in the works are empirical in nature and have significant assumptions, which causes meaningful differences with the real values that arise in specific soil conditions.

In [18], an analytical model is given for determining the resistance forces of the soil to the puncture by the head with an asymmetric tip, including the deflecting force acting on it. The studies in [19] propose a process control model. However, the use of these calculated models of the movement of the working body with an asymmetric tip in the soil is not considered for automatic control of the puncture. Therefore, solving the problem of automatic control of soil puncture with a soil-piercing head with an asymmetric tip can be regarded an urgent task. These issues may also be interesting for the improvement of underwater technologies of laying communication networks [20].

GOAL AND PROBLEM STATEMENT

The aim of the research is to establish the possibility of automated control of the process of soil puncture with an asymmetrically tipped head, for which it is necessary to address the following issues:

- to substantiate the approaches to automated control of soil puncture process;
- to develop a mathematical model of correcting the trajectory of the head with a truncated cylindrical tip.

PRINCIPLE OF AUTOMATED CONTROL OF SOIL PUNCTURE PROCESS

It is proposed to automate the process of soil puncture in order to prevent significant deviations of the head from the specified direction. Since the process of soil puncture is discrete-continuous due to the suspension of the process for building new rods, in order to automate the puncture, it is necessary to measure the coordinates of the head in three-dimensional space after each section of the puncture starting from the first rod.

If any significant deviation from the specified direction is detected, the beveled surface of the tip must be rotated so that there is a force in the opposite direction from the deviation relative to the axis of movement. This process must be carried out at each site of the puncture where deviations from the specified direction of the puncture are detected.

We introduce the Cartesian coordinate system with the origin at the point of the head entry into the soil with the *OX* axis in the direction of the puncture (Fig. 1).

The movement of the head under the action of force P will be created in the plane passing through the points of *O* (0; 0; 0), *A* (x_1; y_1; z_1), *B*(x_1; 0; 0).

The equation of such a plane has the following form

$$z_1 y - y_1 z = 0 \quad (1)$$

It should be noted that the segment of line *MN*, which is the diameter of the cylindrical surface of the head also lies in this plane. The presence of this fact enables to automate the control of soil puncture. To do this it is necessary to calibrate the base of the piercing head, which is shown on the computer display.

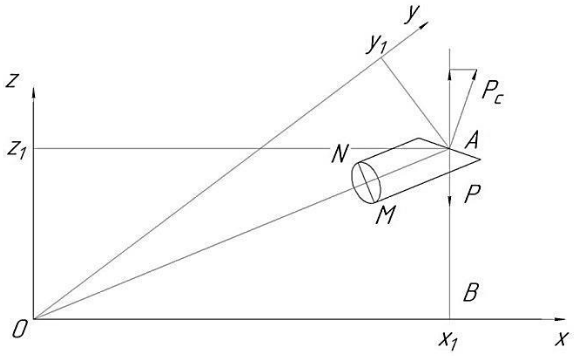

Fig.1. Diagram of the location of the head and forces in space

The equation of the plane where the deflecting force acts will have the following form:

$$P\text{-}P_c \geq 0; \quad \alpha = \mathrm{arctg}\frac{z_1}{y_1}. \quad (2)$$

when y=0, we obtain:

$$\alpha = \pm\mathrm{arctg}\infty = \pm\frac{\pi}{2}$$

The deflecting force acts along the Y axis up or down depending on the sign of Z_1 (Fig.2, *a*). When Z_1=0, we obtain

$$\alpha = \mathrm{arctg}0 = 0.$$

The deflecting force acts along the Y axis to the right or left depending on the sign of Y_1 (Fig.2, b).

Figure 2, *c* shows the case when Y_1 and Z_1 are equal to each other and have the same signs, the deviation force will act normally to the *MN* segment. In Fig. 2 *d*, Y_1 and Z_1 are the same size, but have different signs. The deflecting force will act normally to the *MN* segment.

The other location of the *MN* segment is determined by the ratio

$$\alpha = \mathrm{arctg}\frac{z_1}{y_1}. \quad (3)$$

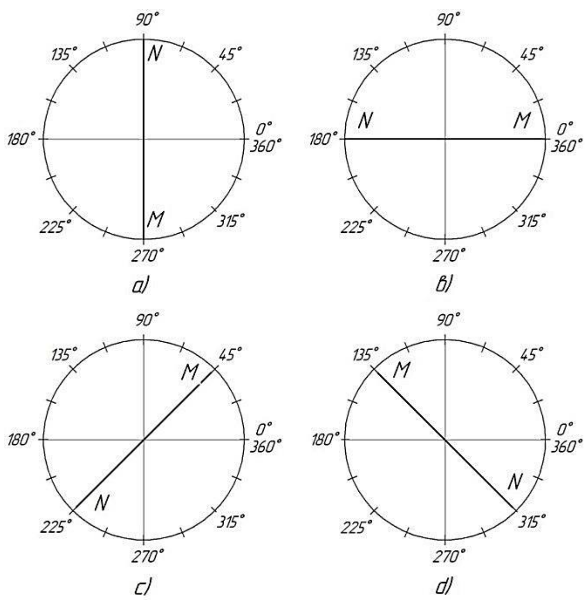

Fig.2. Diagram of controlling the direction of the deflecting force of the soil puncture

The magnitude of the deviation force can be adjusted by selecting the angle of the bevel of the front surface of the head tip. Theoretical aspects of the process of piercing by the head with an asymmetric tip on the example of its shape in the form of a truncated cylinder are discussed below.

MATHEMATICAL MODEL OF CORRECTING THE MOVEMENT TRAJECTORY OF THE HEAD WITH TRUNCATED CYLINDRICAL TIP

The process of soil puncture by piercing devices is discretely continuous. It is stipulated by the need to suspend the puncture process in order to build-up additional rods for further movement of the tip head. At each of the continuous sections of the path the movement of the tip head occurs in two mutually perpendicular directions due to the axial force. One is in the direction of the axis of the puncture, and the other – in the direction perpendicular to the axis due to the asymmetric force on the head of the truncated cylindrical tip.

In [11] the force dependences of soil resistance on its physical and mechanical properties and the geometry of the tip head are established. These forces are determined both in the direction of the puncture and in the direction perpendicular to the axis. We apply Newton's second law to the workflow. In addition, we take into account the fact that the active force of the tip movement and the force of resistance to this movement are proportional through the coefficient of proportionality. Then Newton's second law can be written in the form of a differential equation at each section of the displacement

$$m\frac{d^2x}{dt^2} = P - P_c, \tag{4}$$

where m is the weight of the tip together with the rod;

x is the current value of the coordinate of movement in the direction perpendicular to the axis of the puncture;

t is the time of movement of the piercing head (tip);

P is an active force of movement of the tip in the direction perpendicular to the axis;

P_c is resistance to the movement of the tip in the same direction.

Moving will be possible if $P - P_c > 0$. Given this condition, equation (5) will be rewritten as

$$m\frac{d^2x}{dt^2} = P(1-\lambda), \tag{5}$$

where λ is the coefficient of proportionality.

As a result of integrating equation (2.132) under initial conditions

$x|_{t=0} = 0$ і $\frac{dx}{dt}|_{t=0} = 0$ we obtain

$$x = \frac{P(1-\lambda)}{2m}t^2. \tag{6}$$

When moving the nozzle head in the direction perpendicular to the value of S for time t_1, taking into account the relationship between the values of horizontal L and vertical displacement of S relative to dependence (7) and specific dependencies given in Table. 1, we can write

$$S = \frac{1 - f\,\text{tg}\beta}{N}L, \tag{7}$$

where f is the coefficient of external friction of the soil;

β is the angle of inclination of the cylinder truncated plane to the horizon (see Fig. 1);

N is numerical coefficients that depend on the physical and mechanical properties of the soil and the geometric parameters of the nozzle (see Table 2.4 for sand N = 21.3; for loam N = 33.16; for clay N = 46.88). Equating (6) and (7), we determine the coefficient of proportionality

$$\lambda = 1 - \frac{2mL(1 - f \cdot \mathrm{tg}\beta)}{PNt_1^2}. \tag{8}$$

After substituting (8) in (5) we obtain:

$$\frac{d^2x}{dt^2} = \frac{2L(1 - f \cdot \mathrm{tg}\beta)}{Nt_1^2}. \tag{9}$$

Whence

$$x = \frac{(1 - f \cdot \mathrm{tg}\beta)}{Nt_1^2} L \cdot t^2 , \tag{10}$$

where t_1 is the time of movement of one rod of the piercing device.

Formula (10) allows us to calculate the value of the deviation of the puncture trajectory as a function of time. For a piercing installation with rods 0.5 m long and a travel speed of 0.033 m/s, the following deviations of 0.5 m are obtained, which are given in Table 1.

Table 1. The maximum deviation of the head of a rod on the length of 0,5 m

Type of soil	Deviation of the head (cm) at the inclination angles of cutting sites (deg)		
	25°	40°	55°
Solid sand	1.62	1.10	0.18
Semi-hard loam	1.16	0.87	0.41
Refractory clay	0.85	0.72	0.47

Fig. 3 shows the results of calculations of the deviation of y from the axis of the puncture depending on the angle of inclination of the truncated plane of the cylindrical tip to the horizon for different types of soils. Given that the maximum deviations (at a cutting angle of 25 °) are insignificant, which, depending on the type of soil are within 20…40 cm in the area of 10 m, correcting the process in these conditions will require an area of more than 15-20 m. Thus, we can assume that in the area of puncture up to 100 m long about 3-4 of such areas of correction can occur.

In the process of puncture there is a change in the orientation of the frontal cut plane of the tip relative to the axis of the puncture as a result of the deviation of the tip head from the design axis. Fig. 4 shows that in the process of deviation of the tip head from the design trajectory of the puncture the axial and normal components of the puncture resistance change, and therefore so does the deviation force.

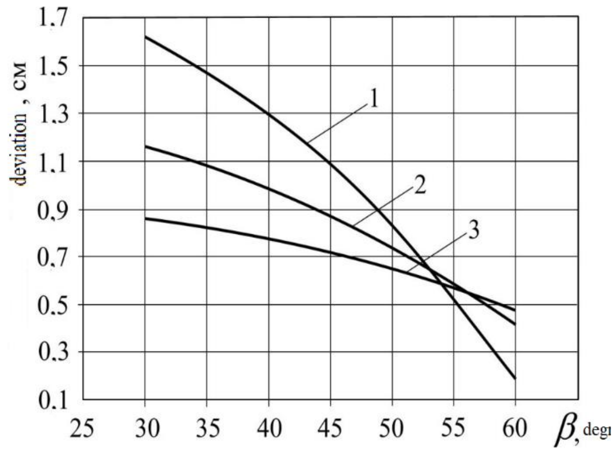

Fig. 3. Dependence of the deviation of the head on the length of the rod moving step on the angle of inclination of the cut site: 1 – solid sand; 2 – semi-hard loam, 3 – refractory clay

In the mathematical model (10) considered above, this factor is not taken into account on the assumption of its insignificance. To determine the influence of this factor, the mathematical model (10) needs to be specified through the angle of deviation of rod α relative to the design axis (see Fig. 4).

The specified mathematical model has the following form:

$$m\frac{d^2x}{dt^2}=P(1-\lambda)\cos\alpha. \quad (11)$$

In our case

$$\sin\alpha=\frac{x}{L},\quad \cos\alpha=\sqrt{1-\left(\frac{x}{L}\right)^2}. \quad (12)$$

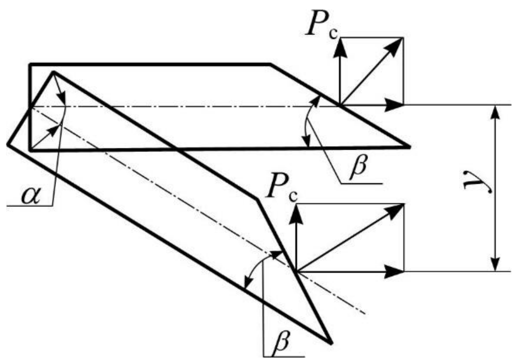

Fig. 4. Diagram for calculating the effect of deviation of the tip head from the design axis

Then equation (11) will be rewritten as

$$m\frac{d^2x}{dt^2}=P(1-\lambda)\sqrt{1-\left(\frac{x}{L}\right)^2}. \quad (13)$$

Equation (13) is a nonlinear differential equation; its approximate solution showed a very slight change in the calculation results compared to model (10). The error was not more than 1.5% downwards. This confirms the sufficient reliability of the use of a linear mathematical model (11).

Mathematical model (11) enables to predict the process of soil puncture in time depending on different soil conditions. Thus, we have to get an answer to the question of what will be the deviation from the specified design trajectory of the tip head having an angle β of the frontal plane cut to the horizon with successive extension of the rods. To do this, it is necessary to consistently consider the solution of such problems. At the first stage for one rod

$$x_1=\frac{(1-f\cdot\mathrm{tg}\beta)}{N}L_1, \quad (14)$$

where L_1 is the length of the first rod.

After that, to determine the deviation of the two rods, we consider the equation

$$m\frac{d^2x}{dt^2}=\frac{2L_{1+2}(1-f\cdot\mathrm{tg}\beta_2)}{Nt_2^2} \quad (15)$$

under initial conditions:

$$x|_{t=0}=0 \quad \text{i} \quad \frac{dx}{dt}|_{t=0}=0 \quad (16)$$

where L_{1+2} is the length of the first plus the second rod; t_2 is the time of passage of the second rod.

The solution of task (15) under condition (16) gives the following result

$$x_2=\frac{L_{1+2}(1-f\cdot\mathrm{tg}\beta_2)}{N}. \quad (17)$$

The total deviation in the *i*-th section of the rod will be determined by the expression

$$x_i=\frac{(1-f\cdot\mathrm{tg}\beta_i)}{N}L_{1+i}, \quad (18)$$

where β_1, β_2, β_i are the angles of inclination of the frontal plane of the tip to the horizon in each section.

The calculations according to formula (18) allow us to adjust the deviation of the tip head in any radial direction (relative to the design axis of the puncture) in order to reduce or increase it. This is achieved both by changing angle β_i and by rotating the head of the asymmetric tip around its axis.

Thus, changing orientation in the space of the cut frontal surface of the cylindrical tip makes possible to increase the length of the span with an established accuracy of 100 m by correcting the movement of its head.

CONCLUSION

1. It is determined that for automated control of the soil puncture process by static method it is necessary to use a puncture head with an asymmetric tip. Changing its position in the soil space can be controlled by rotating the tip and orienting it according to the direction of deviation.

2. The obtained mathematical model of correcting the trajectory of the head with a truncated cylindrical tip makes it possible to predict the process of soil puncture in time depending on different soil conditions and to get a solution to the problem of deviation from the specified design trajectory of the head which has a recognized angle of the frontal plane cut to the horizon with successive build-up of rods.

3. Changing the orientation in the space of the cut frontal surface of the cylindrical tip, taking into account the obtained mathematical model of correcting the trajectory of the head in the soil, allows increasing the span length to 100 m due to the proposed automated principle of correcting its movement.

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Автоматическое управление проколом грунта

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Аннотация. Среди существующих методов формирования горизонтально направленных скважин для бестраншейной прокладки инженерных коммуникаций наиболее популярным является метод статического прокола почвы. Главным недостатком такого метода является недостаточная точность движения прокалывающей головки в массиве грунта. Это требует постоянной корректировки траектории ее движения. Управление движением головки осуществляется путем использования головки с асимметричным наконечником и действия на нее поступательного и поступательно-вращательного движения. Передача этих движений от силовой установки происходит с помощью наборных фиксированных между собой толкающих штанг. Если знать, как происходит процесс отклонения головки от времени, то путем своевременного изменения положения направления смещения наконечника головки можно получить возможность автоматического управления проколом грунта. Для достижения поставленной цели в работе решены следующие вопросы. Определено, что для автоматизированного управления процессом прокола грунта статическим методом необходимо использовать прокалывающую головку с асимметричным наконечником. Изменением ее положения в грунтовом пространстве можно управлять путем вращения наконечника и его ориентировки в соответствии с направлением отклонения.

Полученная математическая модель коррекции траектории движения головки со срезанным цилиндрическим наконечником позволяет спрогнозировать процесс прокола грунта во времени в зависимости от различных грунтовых условий и получить ответ на вопрос, каким будет отклонение от заданной проектной траектории движения головки наконечника, имеющего принятый угол. среза лобной плоскости до горизонта при последовательном наращивании штанг. Изменение ориентации в пространстве срезанной лобовой поверхности цилиндрического наконечника с учетом полученной математической модели коррекции траектории движения головки в почве позволяет за счет предложенного автоматизированного принципа коррекции ее движения повысить длину пролета с установленной точностью до 100 м.

Ключевые слова: прокол грунта, сопротивление грунта, асимметричный наконечник, установки статического прокола, управление проколом, типы грунтов, бестраншейная прокладка коммуникаций, скважина.