Increasing the efficiency of trenchless laying machines using vibrating knives

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Abstract. Modern requirements for the laying of underground communications consist of a combination of high construction rates with low energy consumption. The highest rate of laying linear objects is ensured by knife-type cable and pipe-layers, which are designed for their trenchless burial - this is when a narrow slot is cut in the soil, through which a cable or pipeline is launched. A feature of this process is the need to use large traction forces, which are determined by the resistance forces of the soil when cutting it. Accordingly, the cutting resistance of the soil depends on the dimensions of the width and depth of the gap and the physical and mechanical properties of the soil. Finding ways to reduce forces for deep cutting of soils is an important problem.

One of the ways to improve the efficiency of trenchless laying machines is to equip them with vibrating knives. It is known that when the knife oscillates in the vertical direction, it leads, depending on the soil and the speed of movement, to a 30…60% decrease in traction resistance. But the use of more complex vibration movements of the knives allows reducing the traction resistance during deep cutting of soils by 70…90%. It is well-known that various designs of mechanical drive are used to implement the process of vibration of knives. These are complex devices that, together with the entire machine, require calculations. Therefore, studying the forced vibration of the knives of pipe deepeners is an urgent task, which is aimed at reducing the energy consumption of the process of soil deep cutting and improving the overall performance of knife machines for trenchless laying of underground utilities.

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To achieve the goal, the paper considered possible variants of the vibration oscillation of the knives and provided calculation dependencies for determining the resistance of soil cutting by active knives; also the dependence for determining the maximum average drive power of a centralized unbalanced vibrator was given. At the same time, the dimensions of the gap obtained, the physical and mechanical properties of the soil and the technical characteristics of the vibrator were taken into account.The obtained recommendations can be used when designing trenchless laying machines using vibrating knives.

Keywords: deep cutting of the soil, soil resistance, trenchless laying machines, vibrating knives, engineering communications, laying of underground networks

INTRODUCTION

One of the ways to improve the efficiency of trenchless laying machines is equipping them with vibrating knives. This makes it possible to reduce traction resistance during deep soil cutting by 30...60% to 70...90%, depending on the direction of oscillating movements, the speed of the machine and the type of soil being developed. Studying the process of forced vibration of pipe deepener knives is an urgent task, which is aimed at reducing the energy consumption of the process of deep cutting of the soil and improving the overall performance of knife machines for trenchless laying of underground utilities. The work provides calculated dependencies for determining the resistance of soil cutting by active knives and a dependency for determining the maximum average drive power of a centralized unbalanced vibrator required when designing trenchless laying machines which use vibrating knives.

ANALYSIS OF PUBLICATIONS

During the construction of linear and pulling sections of engineering communications, such as pipelines, communication lines, and others, an important issue is the choice of construction technology, which significantly affects the cost of the work. It is admitted that the most time-consuming and material-intensive stage of construction of pipelines and communication lines is excavation work [1]. Its costs make up more than half of the total estimate of construction works. They are especially large in operations related to the reclamation of fertile soils, excavation of a trench and its backfilling after laying of a pipeline. The rate at which these works are executed is extremely low and requires the involvement of a large number of construction equipment: excavators, bulldozers, pipe-layers and recultivators [2].

In the last decade, trenchless technologies based on the methods of pulling or deepening pipelines and other engineering communications have gained popularity in this field of construction [3].

When laying pipelines by the method of deepening or pulling, basic machines use large tractive forces, which in some cases do not reach their limit value determined by the hitching weight of the tractor. As a result of this, there is a certain surplus of power, which can be implemented by creating new working organs of active action [4].

It is known that soil cutting resistance can be significantly reduced by intensification of the process when using a number of physical phenomena aimed at soil destruction, its transportation on the surfaces of the working bodies of earthmoving machines. One of these directions is the use of the vibration effect to reduce the resistance of digging soils during deep cutting of the soil, which is typical for the processes of deepening and pulling pipelines, cables of communication lines and other engineering communications in the soil. In particular, the machines of such companies as: Lancier, Vermeer, etc., have recently been widely used when laying communication lines. [5, 6].

Vibrating cable-layers have a knife that is set in an oscillating motion in vertical and horizontal directions or in a circular motion along a complex trajectory. From the analysis of technical sources [7], it was established that the greatest effect, namely a reduction in traction resistance by 70...90%, is achieved with plane-parallel circulation (orbital) movement of the knife along elliptical, circular or oval trajectories when the speed of the working stroke is less than the amplitude value speed of oscillations.

Cable laying machines with oscillating knife movement in the vertical plane have become the most widely used due to the simplicity of the design and reliability in operation.

The rational use of vibrating cable-layers is ensured in loose soils (clogged with stones, construction debris, on pebbles). The vibrating knife is well cleaned of plant residues.

Non-directional and directional vibrators, cam and crank mechanisms are used as drive mechanisms of the knife. The frequency of oscillations excited by drive mechanisms (vibro exciters) is 15…46 Hz in the completed designs; the amplitude of oscillations varies from 15 to 93 mm [8].

However, the review of the technical literature showed neither the studies of the physics of the interaction process between the vibrating knife working body and the soil nor the calculation dependencies that would allow, on the basis of the established laws of soil cutting, obtaining recommendations for the creation of machines and mechanisms that realize the conditions for the maximum effect of laying underground communications. There are also no known cases of using a flow of high-pressure hydraulic fluid from the hydraulic drive system of the base machine as a generator of oscillations on the knife working body.

GOAL AND PROBLEM STATEMENT

The purpose of the research is to establish the possibility of increasing the efficiency of the processes of soil deep cutting by knife trenchless laying machines, in order to solve the following issues:

- justify the approaches to the use of vibrating knives for trenchless machines and establish the regularities and features of their action;
- decide on the calculation models for determining the resistance of soil cutting with active knives and the dependence for calculating the maximum average drive power of a centralized unbalanced vibrator.

USE OF VIBRATING KNIVES FOR TRENCHLESS MACHINES AND ESTABLISHMENT OF REGULATIONS AND FEATURES OF THEIR ACTION

To increase the efficiency of trenchless cable layers by reducing their traction resistance, modern cable layers are equipped with vertically vibrating knives (Fig.1, a). In this case, the knife oscillates in the vertical direction, which, depending on the soil and the speed of movement, leads to a decrease in traction resistance by 30…60%.

The use of longitudinal vibrations (Fig.1, b) or vibrations arising due to angular oscillations of the knife around the transverse axis is more effective in reducing traction resistance (Fig.1, c).

The greatest effect, which reduces traction resistance by 70…90%, is obtained when the knife makes plane-parallel circulation (orbital) movement along elliptical, circular, oval and other closed trajectories (Fig.1, d).

There are designs of cable layers in which the knife oscillates along an arc of a circle with a radius of ***r*** (Fig.1, e) and at the same time vertically with an amplitude equal to *h/2*. The movement of the knife in this case is called circulation.

Cable laying machines with vertically vibrating knives are characterized by relative simplicity of design and reliability compared to cable laying machines in which the knives make longitudinal or circular oscillations, and therefore are increasingly used.

Cable laying machines with vibrating knives work particularly effectively in soils contaminated by rocks, in bulk soils containing construction debris, on gravel pits. In these cases, the reduction in traction resistance compared to passive cutting can be 2…3 times.

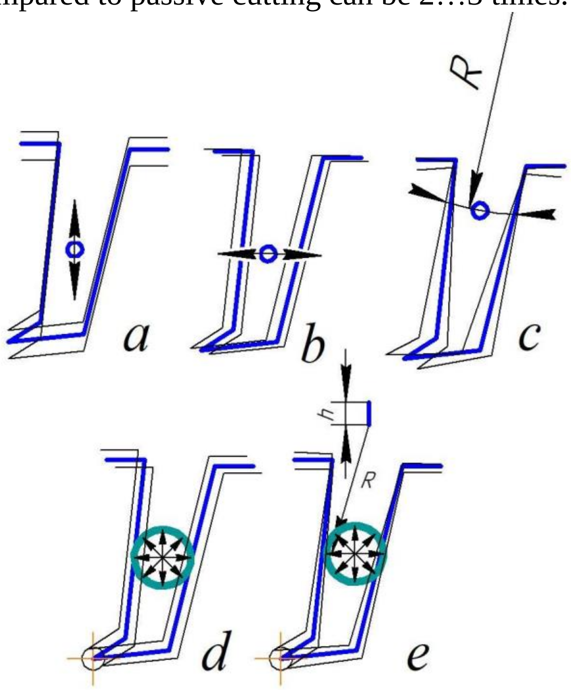

Fig. 1. Schemes of vibrating knives of cable-layers

Vibrating cable-layers have a fairly high degree of the knife self-cleaning, they stably withstand the depth of the move, do not destroy the top layer of the soil to the same extent as passive cable-layers. The gap formed by the vibrating cable layer disappears faster than when working with passive knives, and in the presence of supporting pneumatic trampling rollers, it is completely covered, which excludes the use of a backfill trench. These qualities stimulate the development and production of vibrating cable layers.

CALCULATION MODELS FOR DETERMINING RESISTANCE OF SOIL CUTTING WITH ACTIVE KNIVES AND THE DRIVE POWER OF A DECENTRATED UNBALANCED VIBRATOR

Vibrating cable-layers have a knife that is set in an oscillating motion in the vertical and horizontal planes or in a circular motion along a complex trajectory [1]. The greatest vibration effect (decrease of traction resistance by 70...90%) occurs during plane-parallel circulation (orbital) movement of the knife along elliptical, circular or oval trajectories when the speed of the working stroke is less than the amplitude value of the oscillation speed.

Cable layers with oscillating knife movement in the vertical plane have become the most widespread due to the simplicity of the design and reliability in operation.

The most effective use of vibrating cable-layers is on non-cohesive soils (contaminated by rocks, construction debris, on pebbles). The vibrating knife is well cleaned of plant residues.

The drive mechanisms of the knife are vibrators of non-directed and directed action, cam and crank-rod mechanisms. The frequency of oscillations generated by drive mechanisms (vibrators) is 15...46 Hz in the completed structures; the amplitude of oscillation varies from 15 to 93 mm.

We will consider the design of vibrating cable layers on the example of the Lancier company models (Germany), Table 1. The difference of the KR cable layer attachment is that it uses two sequentially installed hinged parallelograms, the front 2 of which is connected to a vertical rotary column located in the supports, rigidly connected to the frame of the basic tractor, and the rear 3 – to the vertical link of the front parallelogram 2, and carries the vibrator 4 and knife 8 with the cassette 7 (Fig.2). This form of attachment reduces the transmission of vibrations to the base tractor.

Table 1. Technical characteristics of Lancier vibrating cable layers (Germany)

Indicator	KV1	KV2	KV15	KR
Cable drum				
Diameter, mm	1400	1800	3000	3000
Width, mm	710	1300	1960	2×1760
Weight, kg	–	2700	5000	2×5000
Puncture depth, m	0.63	1.0	1.0	1.2
Engine power of the basic tractor, kW	20…30	58	100	300
The minimum radius of the curvature of the track, m	4.0	8.0	8.0	12.0
Dimensions, m:				
length	–	7.7	10.0	12.5
width	–	1.8	2.4	3.25
height	–	3.5	3.5	3.8
Weight, kg	–	8000	18,000	40,000

For vibrating cable-layers the wheeled tractors are mainly used to ensure that cable-layers can move to the work site without the use of trailers.

The working movement of a tractor equipped with the vibrating cable-laying device must go on at a low speed, therefore, basic tractors are aggregated with speed reducers or hydraulic transmissions of the hydrovolume type with stepless adjustment of the speed of movement. The most advanced is hydraulic transmission, adjusted for a certain tangential traction force.

Trailed vibrating cable-layers are less common than mounted ones, because the cable-laying unit, consisting of a trailed cable-layer

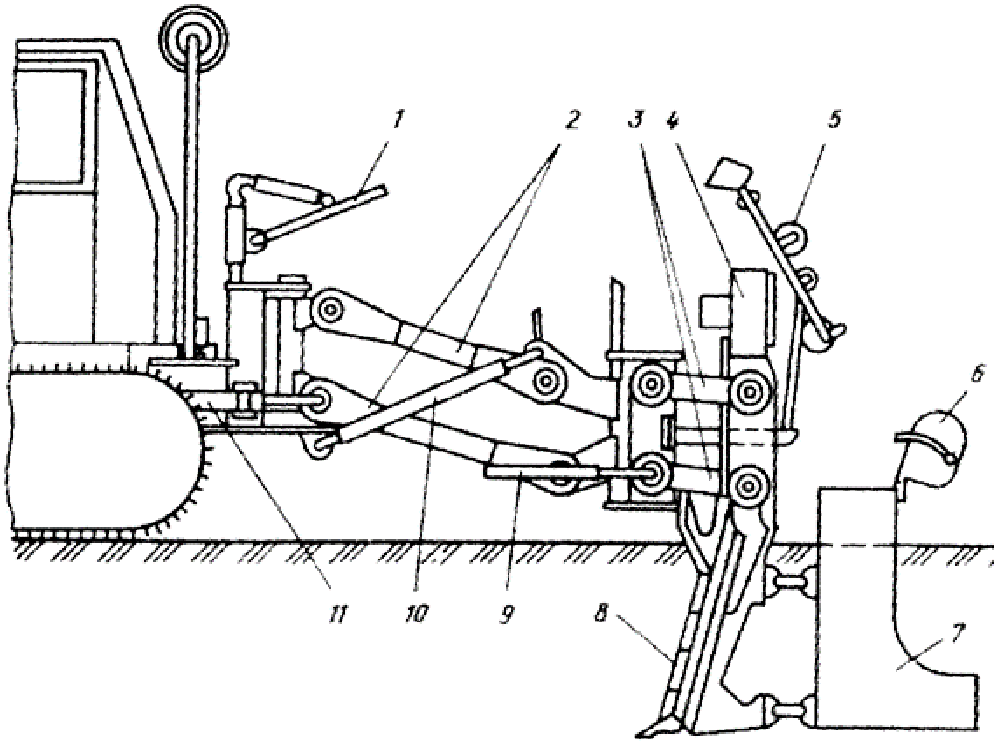

Fig.2. Vibrating cable layer. 1 – the bracket with lightning protection wire; 2 and 3 – the links of the front and back parallelograms; 4 – the vibrator; 5 – the roller clip; 6 – the signal tape coil housing; 7 – the cable cassette; 8 – the knife; 9, 10, 11 – the hydraulic cylinders

and a tractor towing it, loses one of the main advantages of a mounted vibrating cable-layer – maneuverability. In addition, such a unit requires more service personnel.

Trailed vibrating cable-layers have two support wheels. The vibrator is driven by the power take-off shaft of the tractor or by the hydraulic motor. An autonomous internal combustion engine installed on the cable laying frame is also used.

Cutting resistance for active knives is determined by dependence

$$W_{\partial} = \frac{Uk_{\partial}bH\left(f - f\sin^2\frac{\alpha}{2} - \sin\frac{\alpha}{2}\cos\frac{\alpha}{2}\right)}{\upsilon k_{\beta}\cdot\cos\beta\sin^2\frac{\alpha}{2}\cos\frac{\alpha}{2}}, \quad (1)$$

where U is the rate of deformations propagation in the soil; k_{∂} is the specific resistance to dynamic destruction, which depends on the speed of load application, soil properties and the type of dynamic compression diagram.

$$\sigma_{\partial} = f\left(\varepsilon_{\partial}\right), \quad (2)$$

where b, H are the width and depth of cutting; υ is the speed of soil loading; k_{β} is a coefficient that depends on the angle of the knife sharpening in the plan; β, f is the friction coefficient of the soil on the steel; α is the angle of inclination of the knife rack to the horizon.

$$U = \sqrt{\frac{E_{\partial}(1-\mu)}{\rho_0\left(1-\mu-2\mu^2\right)}}, \quad (3)$$

where E_{∂} is the modulus of soil deformation; μ is the coefficient of transverse deformation (Poisson's ratio); ρ_0 is the natural density of the soil.

In the theory of vibration technology, it is determined that the maximum average power per drive of a centrifugal unbalanced vibrator is equal to

$$N_{cp} = \frac{m_0^2 r^2 \omega^5}{4\left(m_1 + m_0\right)\left(\omega_0^2 - \omega^2\right)}, \qquad (4)$$

where m_0 is the mass of the unbalanced vibrator; r is the radius of rotation of imbalance; ω is the vibration frequency (angular speed of the vibrator); m_1 is the mass of the vibrator with a knife; ω_0 is the natural angular frequency.

$$\omega_0 = \sqrt{\frac{g}{x_{cm}}}, \qquad (5)$$

where $g = 9{,}81$ m/s^2; x_{cm} is the static deformation of pneumatic tires under the force of gravity of the system.

Vibrating cable-layers lay the cable in various soils (except frozen and rocky) with a working speed of up to 1000 m/h. Most of the vibrating cable-layers lay the cable at a speed of 180...360 m/h, which is 5 ÷ 10 times less than the speed of cable-layers with passive working bodies.

One of the directions for further research related to the vibration method of increasing the efficiency of knife pipelayers is the use of other energy sources for the implementation of oscillating movements of the machine working equipment. For example, it can be the energy of liquid cavitation, which is supplied under pressure through a throttle device. It is known to have a significant destructive power, and can be used to solve the goal set in the work. The review of the technical literature showed that the possibility of practical implementation of this oscillation method was not scientifically estimated.

CONCLUSION

1. It was determined that excavation work is the most time-consuming and material-intensive stage of constructing pipelines and communication lines. Their costs make up more than half of the total estimate of construction works.

2. To increase the efficiency of trenchless cable layers by reducing their traction resistance, modern cable layers are equipped with vertically vibrating knives (Fig.1, a). In this case, the knife oscillates in the vertical direction, which, depending on the soil and the speed of movement, causes a 30…60% decrease in traction resistance.

3. The performed calculations showed that the majority of vibrating cable layers lay the cable at a speed of 180…360 m/h, which is 5…10 times less than the speed of laying by cable layers with passive working bodies.

One of the directions for further research related to the vibration method of increasing the efficiency of knife pipelayers can be the search for other sources of energy to implement oscillating movements of the working equipment of the machine. For example, from a scientific point of view, it is interesting to determine the possibility of using the effect of cavitation of liquid, formed when flowing under pressure through a throttle device, which can be rigidly mounted in a knife.

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Повышение эффективности бестраншейных составителей использованием вибрирующих ножей

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Аннотация. Современные требования к прокладке подземных коммуникаций состоят в сочетании высоких темпов строительства с низкими затратами энергии. Наибольший темп прокладки линейно-протяженных объектов обеспечивается ножевыми кабеле- и трубоукладчиками, которые предназначены для их бестраншейного углубления - когда в грунте нарезается узкая щель, через которую запускается кабель или трубопровод. Особенностью этого процесса является необходимость использования больших тяговых усилий, определяемых силами сопротивления грунту при его резке. Соответственно сопротивление резки грунта зависит от размеров ширины и глубины щели и физико-механических свойств грунтов. Поиск путей снижения сил для глубокой резки грунтов является важной проблемой.

Одним из направлений повышения эффективности работы бестраншейных составителей является их оборудование вибрирующими ножами. Известно, что, когда нож совершает колебания в вертикальном направлении, это приводит в зависимости от грунта и скорости движения к снижению тягового сопротивления на 30…60%. А применением более сложных вибрационных движений ножей позволяет снизить тяговое сопротивление при глубокой резке грунтов на 70…90%. Известно, что для реализации процесса вибрации ножей используют разные конструкции механического привода. Это сложные устройства, которые вместе со всей машиной нуждаются в проведении расчетов. Поэтому исследование принудительной вибрации ножей трубоуглубителей является актуальной задачей, направленной на снижение энергозатрат процесса глубокой резки грунта и повышение в целом работы ножевых машин для бестраншейной прокладки подземных коммуникаций. Для достижения поставленной цели в работе были рассмотрены возможные варианты вибрационного колебания ножей и предоставлены расчетные зависимости для определения сопротивления резания грунта активными ножами. Приведена зависимость для определения максимальной средней мощности привода отцентрированного дебалансного вибратора. При этом учтены были размеры получаемой щели, физико-механические свойства грунтов и технические характеристики вибратора. Полученные рекомендации могут быть использованы при создании бестраншейных составителей с использованием вибрирующих ножей.

Ключевые слова: глубокая резка грунта, сопротивление грунта, машины для бестраншейной прокладки, виброножи, инженерные коммуникации, прокладка подземных сетей.