Improving the efficiency of frozen soils excavation using high-frequency vibration

A V Ilyukhin, V I Marsov, E V Marsova, T A Syetina and K A Dzhabrailov*

The Moscow State Automobile & Road Technical University, Russia, 125319, Moscow, Leningradskiy Prospect, 64

* E-mail: hizarmuslim@mail.ru

Abstract. Loosening machines occupy a special place for mechanization of earth-moving. Despite rapid development of new methods for soils excavation and specialized machines, the mechanical method of their destruction by rippers in the near future will remain the most effective in most operating conditions. This is explained by relative simplicity of rippers design, wide scope and versatility of their applications, high productivity and low cost per unit of work performed. Rippers play a special role while excavating rocky and frozen soils, and in the latter case, the issue of loosening is particularly relevant, since the area occupied by permafrost is 58% of our country, and together with seasonally frozen soils it covers almost 90% of its territory. One of the most rational ways to intensify the processes of loosening are high-frequency oscillations of the ripper working body in the sonic range using resonant magnetostrictive vibrators. A new approach to the design of a loosening process control system is needed, which covers a range of issues related to development of new principles and methods of automation. Only in this way it will be possible to significantly improve the technical and economic indicators of loosening machines, to avoid influence on them of significant fluctuations in quantitative and qualitative characteristics of soil. Analysis of loosening processes showed that earthworks in heavy soils using traditional methods and mechanisms of loosening are not sufficiently effective first of all due to insufficient use of energy potential of loosening machine. Therefore, one of the most important tasks that needs to be solved when introducing the methods of vibro-loosening of frozen soils is to increase energy efficiency of these processes. Since traditional methods for excavation of frozen soils require substantial energy costs of 5–6 kW per m³, the introduction of the proposed system makes it possible to reduce these costs by 15–20%.

1. Introduction

The rapid growth in the volume of earthworks makes it urgent to create highly efficient equipment for excavation of frozen soils, which is one of the most labor-intensive and expensive processes in construction.

To increase the productivity of earthmoving equipment without increasing their traction characteristics, and, consequently, without increasing their mass and dimensions, allows one to create machines with so-called active working bodies. These machines use the principle of energy flow separation, when additional energy is supplied to the teeth or cutting edges of the working bodies, bypassing the drive (engine): mechanical (forced oscillations of teeth or cutting edge of the working body in shock or vibration modes); electric (when cutting zone is exposed to a strong electromagnetic field of high (HFC) or ultra-high (UHFC) frequency); thermal (when exposed to laser or low-
temperature plasma); gas-dynamic (when the explosion energy of solid, liquid or gaseous substances is supplied to the cutting zone) [1-3].

One of the established directions in the field of improving excavation of heavy soils is intensification of working processes and creation of a new technology based on high-frequency vibration using resonant magnetostrictive vibration exciters. The equipment is rather reliable, applicable in heavy operational and soil conditions; exciters are simple in design, do not have parts moving relative to each other, are not afraid of dust, moisture, or negative temperatures.

2. Problem statement
The mechanism of softening heavy soil when applying vibrations to the working body of loosening machine is the following: when energy is radiated into the mass, an elastic wave of displacements propagates in it, exposing it to compression-tension and shear deformations. The stresses arising in the soil can cause its destruction or significant softening, while it is not a separate impact which prevails in the soil mass, but it is a continuous oscillatory (wave) process, and the destruction effect depends on the intensity of the elastic wave and degree of its transmission to the mass.

Despite the large energy possibilities of oscillating working bodies, the transfer of energy into the soil is far from being a solved task. The ripper effectively works in the resonant mode, which allows one to obtain a relatively large displacement amplitude of loosening tooth for a relatively small power consumption. However, when interacting with the soil, the original resonant oscillatory system loses its resonant properties in the presence of the initial frequency of the driving force. The nodal sections of the system, to which the working body is attached, will shift, and the fasteners will begin to be subjected to vibration effects with simultaneous reduction of amplitude of the loosening tooth displacement and intensity of wave transmitted to the soil. At the same time, preservation of the resonant mode of oscillations when loading the ripper, maintains the parameters of the wave transmitted into the soil sufficiently close to the maximum value even with a significant inequality of resistances of oscillatory system and soil.

3. Problem solution
Thus, it is necessary to develop a set of measures aimed at establishing and maintaining the resonant mode of oscillatory system, by means of introduction of automated control of modes of vibration impact on the soil.

If high-speed loads (high-frequency oscillations) are applied to the working body of the loosening machine, then the soil mainly experiences elastic deformations, which reduces energy consumption for plastic deformations, and the soil collapses like a brittle body [4].

The elastic properties of soil promote distribution of vibrations excited in it by high-frequency vibrations of the working body at considerable distances. In most cases, the attenuation coefficient of high-frequency oscillations in the soil is less than 0.005. The scattering of oscillation energy at frequencies of 5-8 kHz remains small when the size of inclusions is up to 0.05 m [5] [6].

The front of the emitted wave at the point of contact of the loosening organ with the soil retains the shape of the radiating surface. Due to the fact that the length of sound waves is many times greater than the size of radiating surface of tips of the emitters (0.01-0.1 m), the radiation source can be considered as point-like, and the wave front transmitted into the soil mass is spherical (Figure 1).
Figure 1. Interaction between radiator and load.

The distance which denotes when the wave front turns into a sphere is:

\[ r = \frac{2d^2}{\lambda} \]  

(1)

where \( d \) is radiator diameter; \( \lambda \) is wavelength emitted into the soil.

The emitter forms an acoustic field in the soil, the main characteristic of which is distribution in space and time of velocity potential \( \Phi \), which is connected with force of soil reaction \( F \) and the oscillation speed \( V \) by the following relationships:

\[ F = \frac{\partial \Phi}{\partial t}; \]
\[ V = \frac{\partial \Phi}{\partial t}. \]

(2)

where \( r \) is medium density.

The wave equation of a spherical wave will be:

\[ \frac{\partial^2 \Phi}{\partial t^2} = C^2 \frac{\partial^2 \Phi}{\partial r^2} \]

(3)

where \( C \) is the speed of movement of elastic wave in the medium.

The solution of equation (3) for the emission of acoustic energy into the medium will be:

\[ \Phi = \frac{A}{r} e^{i(\omega r - kr)} \]

(4)

where \( A \) is oscillation amplitude, \( \omega \) is angular frequency; \( k \) is wavenumber, \( k = \frac{\omega}{c} = \frac{2\pi}{\lambda} \).

Substitution of (4) into expressions (2), (3) gives the medium reaction force \( F \) to the speed of oscillations \( V \):

\[ F = i\omega \rho \frac{A}{r} e^{i(\omega r - kr)} \]

(5)

\[ V = \left( \frac{A}{r^2} + i \frac{kA}{r} \right) e^{i(\omega r - kr)} \]

(6)
The ratio of $F$ to $V$ in the place of contact of the exciter with soil, is the medium resistance to radiation [7-10]:

$$Z_u = \frac{F}{V} = \frac{\imath \omega \rho_c r}{1 + \imath \omega kr} = \rho_c S \left( \frac{k^2 r^2}{1 + k^2 r^2} + i \frac{kr}{1 + k^2 r^2} \right)$$

(7)

where $\rho_c$ is wave medium resistance; $S$ is radiation area.

The expression (7) can be divided into active $R_n$ and reactive component $X_n$:

$$R_n = \rho_c S \frac{k^2 r^2}{1 + k^2 r^2}$$

(8)

$$X_n = \rho_c S \frac{\imath \cdot kr}{1 + k^2 r^2}$$

(9)

From the expressions (8), (9) it can be seen that both components of soil resistance to the acoustic wave are functions of radiation area $S$, wave soil resistance $\rho_c$ and wavelength $\lambda$.

Thus, the resistance of soil to high-frequency sound vibrations is complex, and increases with an increase in its strength due to an increase in the speed of sound wave propagation. It should be noted that the reactive component $X_n$ affects frequency of oscillatory system, and the active component $R_n$ generates a running wave in it [7]. The negative impact of $X_n$ on natural frequency of the system can be significantly reduced if the resonant mode of vibration exciter is kept stable.

The relationship between resonance frequency of the oscillatory system, which includes working body and the attached soil, and its wave resistance first shows an intense, and then with an increase in the wave resistance of the soil, a monotonic increase in the resonant frequency (Figure 2).

![Figure 2](image_url)

**Figure 2.** Relationship between resonance frequency $\omega$ of the system and soil resistance wavenumber $W$.

The dependence in Figure 2 shows that there exist conditions that determine efficiency of vibrating ripper, excited by the magnetostrictor, by maintaining vibration resonant frequency of the working body, which varies depending on the properties and volume of the attached soil.
Using the intensities, the measured power consumed by magnetostrictor from the power source, we obtained the relationship between power, consumed by magnetostrictor and frequency with a change of soil wave resistance (Figure 3).

The dependences presented in Figure 3 show that a change in wave resistance of soil leads to a sharp drop in radiation intensity with respect to the resonance state at a certain wave resistance of soil. This is due to a sharp drop in the amplitude of the working body oscillation, if the frequency of exciting oscillations does not correspond to the resonant frequency of the system “working body - attached soil”. All of the aforesaid proves once again that taking into account the frequency correction when loading the working body can improve the efficiency of soil excavation. Therefore, it is necessary to develop control devices for the vibration exciter in order to maintain the mode of resonant oscillations in it [9, 10].

The functional diagram of extremal system for control of vibratory shredding technological process for the loosening machine is presented in Figure 4.

![Functional diagram of extremal system for control of vibratory shredding technological process](image_url)

**Figure 3.** Relationship between power consumption of magnetostrictor and frequency for various wave resistances of soil.

**Figure 4.** The functional diagram of extremal system for control of vibratory shredding technological process.
PS is power source 1, MS is magnetostrictive vibration exciter with loosening tooth, CPG is power generator, voltage rectifier (VR) 4, VM, CM are voltage and current meters 6, F1, F2 are signal conditioners, MD is multiplying device, ER is extreme regulator, PD is programmable divider, CG is clock pulse generator. Random changes in soil resistance when loosening affect the change in current of the magnetostrictor winding. Structurally, this means turning on the feedback loop (Figure 4).

The power source of vibrating ripper 1 feeds a controlled generator 2, producing electrical voltage pulses U of a certain frequency, depending on current, determined by the force of soil loosening. Electric signals are sent through the former (F1) and (F2) to the multiplying device 7, and then to the input of the extreme regulator (ER) 8. The regulator realizes the process of searching for the extremum of static characteristics of the vibratory ripper by changing its frequency of vibrations before they get into resonance when power for soil loosening takes the minimum value.

The signal from ER output is fed to the input of divider 9. The signal from the generator 10 is fed to the other PD input.

Thus, the automatic adjustment of the system “magnetostrictive transducer - working organ - soil” into resonance is carried out.

4. Conclusions

The conducted analysis of processes of heavy soils loosening, allowed us to draw the following conclusions:

The parameters of wave passing into the soil reach a maximum value when resistance of the oscillating system of the working body becomes equal to that of the attached soil. This condition becomes possible only by maintaining the resonant mode of oscillation of the working body, i.e. matching them with load through the use of an automatic optimization system.

We developed the self-adjusting system of extreme regulation, which allows providing efficient loosening at the resonant frequency of the magnetostrictive working body with minimum energy consumption. The contour of the automatic optimization system with extreme regulator connects the power N applied to the magnetostrictive working body and the frequency of the control signal. Thus, the technical and economic effect of using sound methods of loosening the soil, expressed in increasing the efficiency of the loosening machine by an average of 20% and increasing the energy efficiency of these processes, reducing the energy consumption for excavation of frozen soils by 15-20%.

References
[1] Kirilov G V, Markov P I, Rannev P V and others 1994 Machines for earthworks 288.
[2] Antonov A 2015 Modern electronics 4 16-20.
[3] Dotsenko A I, Karasev G N, Kustarev G V, Shestopalov K K2012 Machines for excavation 688
[4] Karasev G N 2011 Research and improving the efficiency of soil excavation machines 174
[5] Vaschilov M F 1986 Optimization of parameters of a magnetostrictive two-tooth ripper for frozen soils. Thesis dis. Cand. tech. sciences 24
[6] Karpov V V 1975 Investigation of the process of vibro-sound destruction of frozen soil. New vibration equipment and technology of special construction works: Abstracts 89-92.
[7] Sapozhnikov A I 1984 Improving the efficiency of dynamic loosening of frozen soil: Thesis dis. Cand. those. Sciences 22
[8] Balovnev V I 1981 Road-building machines with working bodies of intensifying action 223
[9] Ilyukhin A V, Marsov V I, Dzhabrailov Kh A, Chantiev M E 2018 Bulletin of Eurasian science 10(2)
[10] Ilyukhin A V, Marsova E V, Dzhabrailov Kh A, Chantiev M E 2018 Transport facilities 5(2)