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Determination of Critical Stresses in Frozen Soils Under Wave Acoustic Loading

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Abstract

The issues related to the development of permafrost and seasonally frozen soils without their preliminary loosening by various earthmoving machines with active working bodies, magnetostrictive vibrators, that soften dense and frozen soils using acoustic elastic waves, are considered. The analytical studies allowed us to establish the regularities of the process of destruction of frozen soil by active teeth of bucket working bodies, according to which, the formulas for calculating the critical tensile stress and shear resistance were obtained. The research results allow us to determine the main parameters of wave loading for both a single radiation source and a group of "n" in-phase radiation sources. The intensity of the acoustic field from the group of "n" emitters increases in proportion to the number of vibration exciter.

Keywords: Frozen soil, Magnetostrictive vibration exciter, Excavator bucket, Acoustic energy, Critical stress

1. Introduction

One of the main interests of economic and social development of the Russian Federation is to increase the productive areas of the regions of the Far East, Siberia, and the Far North, where permafrost and seasonally frozen soils are widespread. The increased interest in the Arctic is due in part to the presence of large reserves of various minerals. The development of the mineral resource based on the Arctic is crucial to the infrastructure development of the Northern territories [1]. In the construction of highways and roads, one of the main activities is earthworks. This activity has an economic and environmental impact that cannot be overlooked [2,3]. The effective construction production of earthworks on these soils requires the development of innovative technological processes, based on the results of advanced scientific research in the field of fracture mechanics, and the creation of new structures of earthmoving machines [4,5].

It is also necessary to improve existing machines by increasing their unit power and energy capacity, combining them into complexes or intensifying their working bodies. An example is the creation of machines with so-called active working bodies, which are based on other physical principles. For example, softening of dense and frozen soils with the help of acoustic elastic waves [6], which significantly intensifies the process of their destruction.

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The activation of working bodies by magnetostrictive vibration exciters makes it possible to develop frozen soils without their preliminary loosening by various machines, in particular, single-bucket excavators [7].

However, despite these advantages, the industrial development of such working bodies is being delayed. This is due to the complexity of studying the physical process of frozen soil destruction and establishing the most effective method of force action on the soil. Difficulties also arise with the definition the rational parameters of this process that ensure the optimal mode of operation in terms of minimum energy consumption and maximum productivity.

2. Methods

Frozen soil as a four-phase natural formation (solid mineral particles, ice-cement, unfrozen and strongly bound water, and gaseous components in the pores and voids of the soil) has the properties of inhomogeneous materials. The presence of pores (voids) is typical for many building materials. The low strength of ice-cement bonds between mineral particles in soils porosity essentially determines the physical state of frozen soils [8,9] as well as compaction, shear resistance and gap under external influences. The problem of developing frozen soils has now become one of the most important tasks. In most parts of Russia, where winter lasts from 4 up to 7 months, the soil freezes to a depth of 0.8-2.5 meters. More than 40% of the territory of Russia is occupied by perennially frozen soils and permanently frozen soils.

The strength and deformation properties of frozen soils depend on its porosity negative temperature, total content, and location of ice-cement bonds (ice content) [8, 10, 11]. Frozen soil has anisotropic properties and is destroyed in stretched zones as a brittle material, and in compressed zones - as plastic. The reason for this phenomenon is the structure of frozen soil, detailed above. Many voids of various shapes and sizes in the frozen soils are the zones of stress concentration. According to Zelenin, the process of processing frozen soils should be carried out with the help of certain working devices and technologies, at which frozen soil rupture deformations (stretching deformation, tensile deformation) will prevail [12]. This is due to the fact that the resistance of the soil at rupture is 9 times less than the resistance of frozen soil during cutting and 21 times less than static pressure.

Some scientific research works [13, 14, 15] were devoted to the identification of patterns of mechanical destruction of frozen soils. The results of these studies encourage us to search for progressive ways to develop frozen soils, to justify the choice of parameters of some types of machines and to create new devices with magnetostrictive vibration exciters.

Currently, the existing development methods of frozen soils of seasonal frost penetration are carried out according to two schemes: 1) the direct development of the frozen soil with earthmoving machines with operating implements created for this purpose; 2) the preparation of the frozen soil layer for the excavation by conventional earthmoving machines.

The main advantage of the machines with operating implements consists in almost unlimited perturbing forces due to high-rate vibrations, shocks or force cutting. Under other equal conditions of capacity, weight, dimensions and performance, such rippers allow us to develop 2-3 times firmer soils than static ones. Considerable attention is given to the creation of such machines.

The research on activating the earthmoving machines implemented with magnetostrictive vibration exciters was performed at Leningrad Civil Engineering Institute (at present – Saint Petersburg State University of Architecture and Civil Engineering) [4,5]. As a result of the

studies, the range of the resonant frequencies of earthmoving machines implements was estimated at 0.5-15 kHz. The method for calculating magnetostrictive vibration exciters of sound frequency and the power system for these vibration exciters was developed.

The formation of cracks, that are 0.5-0.8 m ahead of the operating implements, proves that elastic waves of high intensity propagate in the soil. These waves ensure softening or destruction of the frozen soil [16].

When using a group emitter, a quasi-plane wave occurs, which is the most suitable to irradiate firm soils for softening purposes from the energy point of view. The destruction is conditioned by the engineering data of the group dipole radiator (vibrator emitter), the technology of its application, the parameters of the soil. Moreover, the destruction has a fatigue or instantaneous nature.

3. Results and Discussion

The study of achievements in the field of technology for developing frozen soils using acoustic energy has shown that the efficiency of the earthmoving machines depends on the operative matching of the characteristics of the vibration exciter with the properties of the developed soil. Therefore, present studies are aimed at identifying the optimal parameters for transmitting acoustic energy to the soil mass.

Sound waves and their use for the destruction of solid materials have long attracted the attention of specialists. The first examples of using sound waves for these purposes have deep historical roots. The Bible tells about the destruction of the walls of Jericho by means of sound. In the Egyptian sources [17], there is a report that with the help of sound the Egyptians could make stones (and other materials) levitate (rising above the ground), and, if necessary, destroy them.

To establish methods for effective development of frozen soils for various types of tunneling and earthworks, it is particularly important to study the parameters of wave loading/stresses.

When interacting with the frozen soil, the implement of the earthmoving machine, activated by high-frequency vibrations, is a rigid oscillating sphere. This radiation source, interacting with the frozen soil, emits not only a longitudinal wave, but also a transverse one [16, 18]; each of them has its own directional characteristic and propagation velocity.

To obtain the energy characteristic of an acoustic field, it is necessary to determine the value of energy in a given place and its movement speed, which are generalized in a single concept – the intensity of the sound wave. It is determined by the amount of acoustic energy passing through a unit area per unit time, normal to the direction of propagation. In other words, the intensity J is equal to the acoustic power per unit of the wave front surface [19]: $J = \frac{N_a}{S_\phi}$, where N_a is acoustic power (radiant power); S_ϕ – wave front surface.

In the contact zone of the active tooth with the soil, the wave front coincides with the radiating surface in shape, but at a certain distance the wave form is transformed. If the size of the emitter is small compared to the wavelength, i.e. it can be considered to be a point source of vibrations, spherical waves propagate from it. For a flat radiating surface, the distance, at which the wave front becomes spherical, is as follows: $L = \frac{2D^2}{\lambda_b}$ [19, 20], where D – acoustic radiator size; λ_b – wavelength, spreading in the environment.

The surface S_ϕ is defined as the area of the hemisphere of radius r : $S_\phi = 2\pi r^2$.

Radiation power is determined by the formula [19, 20], $N_a = \frac{\omega^2}{24\pi} \left[2 \left(\frac{F}{\mu} \right)^2 \rho C_t + \left(\frac{F}{\lambda + 2\mu} \right)^2 \rho C_l \right]$.

Here F is the force of the radiator, work member operating on the environment [19, 20]:

$$F = \frac{12\rho\omega^2 A\pi r^3}{3k_t^2 r^2 + k_l^2 r^2} \quad (1)$$

Where: A – displacement amplitude; r – source radius; k_l , k_t – wave numbers of longitudinal and transverse wave, respectively,

$$k_l = \frac{\omega}{C_l}; \quad k_t = \frac{\omega}{C_t} \quad (2)$$

The velocity of propagation of longitudinal C_l and transverse C_t waves are determined as in Lamé problem [19, 20]:

$$C_l = \sqrt{\frac{E(1-\nu)}{\rho(1-2\nu)(1+\nu)}}, \quad C_t = \sqrt{\frac{E}{2\rho(1+\nu)}}, \quad (3)$$

μ , λ – coefficients, characterizing elastic properties of the frozen soil, E – elastic modulus, ρ – soil density, ν – Poisson's ratio [19, 20],

$$\mu = \frac{E}{2(1+\nu)}; \quad \lambda + 2\mu = \frac{E(1-\nu)}{(1-2\nu)(1+\nu)}, \quad (4)$$

Substituting (2), (3) in formula (1), after simple transformations we get :

$$F = \frac{12\rho r A E (1-\nu)}{7-\nu-8\nu^2}, \quad (5)$$

Then, taking into account (4) and (5), the acoustic power N_a can be represented as a summation of the propagation energy of the longitudinal and transverse waves

$$N_a = \frac{6A^2\omega^2 r \pi}{(7-\nu-8\nu^2)^2} (1+\nu)^2 \left[8(1-\nu)^2 \sqrt{\frac{E\rho}{2(1+\nu)}} + (1-2\nu)^2 \sqrt{\frac{E\rho(1-\nu)}{(1+\nu)(1-2\nu)}} \right], \quad (6)$$

The first and second terms in brackets define the power radiated by transverse (shear) and longitudinal waves respectively.

Expression (6) allows us to calculate the radiation power of a single source. Since several active teeth can be installed on the working bodies of earthmoving machines, it is necessary to take into account their joint work. The active teeth located in the same plane can be considered as a linear group of « n » radiation sources, performing in-phase oscillations with a single vibrational speed.

Consider a field of several simultaneously operating emitters: it is known that the intensity of the acoustic field from a group of « n » emitters can be « n^2 » times greater than the intensity corresponding to the total power of the group (the law of quadratic equivalence) and is expressed by the formula [20]:

$$J_m = \frac{n^2 N_a}{S_\phi}, \quad (7)$$

Where: J_m – the resulting intensity; n – number of radiation sources.

This pattern is explained by the mutual influence of sources, which is determined by the distance d between them. At a certain value of d the sources will interact the most.

Research has shown that at the distance $d = \lambda_b$ the total displacement amplitude is equal to double the displacement amplitude from each source. Taking the wavelength as $\lambda_b = \frac{C_l}{f}$, where f is the cyclic frequency of vibrations, the optimal distance between the teeth can be represented as:

$$d = \frac{1^2}{f} \sqrt{\frac{E(1-\nu)}{\rho(1-2\nu)(1+\nu)}} \quad (8)$$

It can be seen from Eq. (8) that when choosing the optimal distance between the teeth activated by high-frequency vibrations, it is necessary to take into account the elastic properties of the soil and the frequency of the teeth vibrations. At this distance between the radiation sources the intensity of the resulting field is determined by Eq. (7).

Substituting the value of N_a (the power of one source) from Equation (6) into Equation (7), we get:

$$J_m = \frac{6A^2\omega^2r^2n^2\pi(1+\nu)^2}{S_\phi(7-\nu-8\nu^2)^2} \left[8(1-\nu)^2 \sqrt{\frac{E\rho}{2(1+\nu)}} + (1-2\nu)^2 \sqrt{\frac{E\rho(1-\nu)}{(1-2\nu)(1+\nu)}} \right] \quad (9)$$

Consequently, the radiation power of a group of « n » emitters will increase by « n^2 » times. Knowing such values as the optimal distance between vibration exciters and the width of the working body, the number of active teeth can be calculated.

By finding the radiation intensity of spherical wave sources, the sound pressure generated by them can be determined [19] as

$$J = \frac{P^2}{\rho C_1}, \quad (10)$$

where C_1 - speed of wave propagation in the soil.

Expression (10) is valid for a liquid medium. In a solid body, such as the frozen soil, the pressure P is equivalent to the separation stress σ directed along the wave propagation and the shear stress τ in the transverse direction [19, 20].

Similarly, to Eq. (6), the first and second terms in brackets of Eq. (9) correspond to the intensity of shear and longitudinal wave radiation.

Therefore,

$$J_m = J_t + J_l = \frac{\tau^2}{\rho C_t} + \frac{\sigma^2}{\rho C_l}, \quad (11)$$

where J_t - the intensity of shear wave radiation; J_l - the intensity of radiation of longitudinal waves.

Using Eq. (9) and (11), the stresses σ , τ in the resulting acoustic field between the teeth at $r = d/2$ can be determined:

$$\sigma = \frac{A\omega nr(1-2\nu)(1+\nu)}{d(7-\nu-8\nu^2)} \sqrt{\frac{3E\rho(1-\nu)}{(1-2\nu)(1+\nu)}}; \quad \tau = \frac{A\omega nr(1-\nu)(1+\nu)}{d(7-\nu-8\nu^2)} \sqrt{\frac{12E\rho}{(1+\nu)}}.$$

4. Conclusion

The analytical studies have allowed us to establish the regularities of the process of breaking frozen soil with the active teeth of bucket working bodies, in accordance with which the formulas for calculating critical recall stresses and shear resistance were obtained. In this case, geometric and kinematic parameters of the working process, physical and mechanical characteristics of frozen soils should be the initial data. The results of the research allow us to determine the main parameters of wave loading both for a single radiation source and for a group of « n » in-phase radiation sources. The intensity of the acoustic field from the group of "n" emitters increases in proportion to the number of vibration exciters. Therefore, the use of a group emitter is the most advantageous solution, from an energy point of view, for irradiating strong soils in order to soften them.

Conflict of Interest: The authors declare that they have no conflicts of interest.

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