Modelling of dredging process with vibrating digging bucket under subzero temperatures

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Abstract. A mathematical model of ground motion on the vibrating surface of the digging bucket under subzero temperature is suggested. High-frequency oscillations influence on the ground sliding resistance force on the surface under subzero temperature is analyzed. This analysis proves that shear strength is defined by the pressure magnitude of ultrasonic waves affecting the ground from the sliding surface and significantly depends on acoustic properties of the ground. The ground sliding resistance force is stated to decrease under the exposure of ultrasonic oscillations mainly due to a decrease of cohesive forces and ground friction on the metal.

1. Introduction
The research objective is to define the ground shear strength along the sliding surface under the exposure of ultrasonic oscillations and subzero temperature. The presented model of ground motion on the sliding surface, which emits high-frequency fluctuations, is designed using the approximate physical modelling method with the linear scales distributed to reference axes [1-5].

The approximate physical modelling method with the linear scales distributed to reference axes allows one to carry out the research without modifying environment conditions. The main requirement is creating the conditions for the propagation of oscillatory waves in the model which are identical to real-life conditions.

To define the propagation process of ultrasonic and audio-frequency range oscillations, we use the general equation of elastic waves propagation in a medium [1]:

$$\frac{d}{dt} \left[ (\lambda + 2G) \frac{d^2u}{dx^2} \right] = \frac{\gamma_r d^3u}{gd t^3} + \frac{\gamma_r d^2u}{gt_2 dt^2} + \frac{k d^2u}{gt_2 dx^2}$$

(1)

where: $\lambda$, $G$ – Lame constants; $u$ – path; $\gamma_r$ – medium bulk density; $k$ – volume compression modulus; $t_2$ – relaxation time (for the given process $t_2 = G/\eta'$); $\eta'$ – medium viscosity under the exposure of high-frequency oscillations.

2. Formulation of the problem and method of solution
Let us consider the digging process. The problem of reducing the digging strength while reducing the friction on the inner bucket surface can be considered under the following assumption: let us presume that at the final stage of filling the bucket with ground, while the chip is moving along the front wall and the bottom, it also surmounts the inner and outer friction forces. The friction between chips and...
bucket walls is ignorable. The mathematic expression of the cut bank motion for the given case is arrange in accordance to the calculation model presented in figure 1.

The forces applied to the bank are given in figure 2. The ground inside the bank is assumed to be incompressible.

The cut volume of the ground moves along the curved surface of the work tool. The ground is affected by ultrasonic exposure from the sliding surface at the same time. Ground particles under the exposure of the ultrasonic wave are oscillating around their equilibrium point. The impact of high-frequency oscillations (with frequencies from the audio and ultrasonic range) results in changing the viscous friction forces, which causes thixotropy effect under some conditions.

The cut elementary volume of ground is affected by the following forces: weight force \( d_g \), inertial force \( d_{P_{IN}} \), tangential component, \( d_{N_{C}} \), normal component, pressure forces \( d_{F_{1,2}} \), friction forces \( d_{N_{BEND}} \), resisting force caused by bending of the bank, ultrasonic pressure force \( d_{P_{US}} \) applied normally to the ground sliding surface and friction force \( d_{F_{US}} \).

Force \( P_R \) is applied to the ground elementary volume to conform to the D’Alembert principle. Therefore, the sum of force projections in the radial direction is defined as follows:

\[
dP_2 + (P_0 + dP_0) \sin \frac{d\phi}{2} + P_R \sin \frac{d\phi}{2} - dN_C - dP_1 - dN_{BEND} + dG \left( \frac{\phi - \psi}{2} \right) + dP_{US} = 0
\]

where \( \phi \) – the angle defining the element position on the surface; \( \psi \) – the central angle of the sliding surface.

\[\text{Figure 1.} \hspace{1cm} \text{The plan of the ground chip motion on the curved surface of the work tool (bucket) emitting high-frequency oscillations: } P_0 \text{ – the force preventing bank movement; } H \text{ – the altitude of the ground ascending on the sliding surface; } \sigma \text{ - direct stress on the considered surface; } a \text{ – soil layer thickness; } B \text{ – bucket width.} \]

Bearing in mind that \( dP_1 \approx dP_2 \); \( \sin \frac{d\phi}{2} \approx \frac{d\phi}{2} \); \( dP_R \frac{d\phi}{2} \to 0 \) we have:

\[
dN_C + dN_{BEND} + dP_{US} = P_R d\phi + dG \left( \frac{\phi - \psi}{2} \right)
\]
Figure 2. The force diagram for the element of the ground bank.

The sum of force projections on the normal to the radius is given by:

\[ dF_1 + dF_2 + dF_{\text{BEND}} + dF_C + P_R \cos \frac{d\varphi}{2} + dP_{\text{IN}} + dg \cos \left( \varphi - \frac{\nu}{2} \right) - (P_R + dP_C)\cos \frac{d\varphi}{2} + dF_{US} = 0 \]  

(4)

The weight of an elementary ground volume is:

\[ dg = \gamma, aRd\varphi dz \]  

(5)

where \( R \) – sliding surface curve radius; \( a \) – chip thickness.

The tangential component of the inertial forces is:

\[ dP_{\text{IN}} = \frac{\gamma'\nu}{g} dxdydz \frac{dv_x}{dt} \]  

(6)

where \( \nu \) – ground chip movement velocity on the sliding surface.

Since \( \cos \frac{d\varphi}{2} \approx 1 \), we take the friction forces to be \( dF_1 \approx dF_2 \approx dF_t \) as first approximation.

\( dF_t \) can be defined as the function of tangential stresses:

\[ dF_t = \tau_n Rd\varphi dz \]  

(7)

where \( \tau_n \) - tangential stress in the plane of sliding.

Taking into account that [6, 7]

\[ \tau_n = \frac{fP + f_1p_{AD}S}{S} = f_{SFF} \frac{P}{S} \]  

(8)

where \( S \) – area of contact; \( f_{SFF} \) – superficial friction factor; \( p_{AD} \) – specific adhesion force; \( P \) – resultant of contact normal pressure force; \( f \) – coefficient of proportionality for the deformation component of friction; \( f_1 \) – coefficient of proportionality for the adhesion component of friction.

Therefore,
\[ dF_c = f_{SSF} \frac{dPRd\varphi}{dx} \]  

Centrifugal inertial force \( dN_C \), bank bending force \( dN_{BEND} \) and ultrasonic pressure force \( dP_{US} \) cause the tangential friction forces, respectively \( dF_C, dF_{BEND}, dF_{US} \).

The sum of these forces is:

\[ dF_c + dF_{BEND} + dF_{US} = \tan \delta' \left( dN_C + dN_{BEND} + dP_{US} \right) \]  

where \( \delta' \) - angle of wall friction along the sliding surface under the ultrasonic exposure.

The pressure force of the ultrasonic wave can be defined as the product of wave pressure and the area [7]:

\[ dP_{US} = dP_{US} Rd\varphi dz = 2\pi f_{US} dA_{US} C \frac{\varphi}{g} Rd\varphi dz \]  

where \( f_{US} \) – oscillations frequency; \( A_{US} \) – oscillations amplitude; \( C \) – velocity of wave propagation in the ground.

With reference to (3), we have:

\[ dF_c = dF_{BEND} + dF_{US} = P_k \tan \delta' d\varphi + \tan \delta' \sin \left( \varphi - \frac{\psi}{2} \right) \]  

Having implemented in (4) the corresponding substitutes, we get:

\[ dP_k - P_k \tan \delta' d\varphi = 2f_{SSF} \frac{dP_k d\varphi}{dx} + \gamma_c \tan \delta' \sin \left( \varphi - \frac{\psi}{2} \right) Rd\varphi dz \]  

\[ + \gamma_c \cos \left( \varphi - \frac{\psi}{2} \right) + Rd\varphi dy dz + \frac{\gamma_c dy}{g dt} dxdy dz \]  

As known [1], the influence of the curve radius on changing formation resistivity can be neglected if \( R/H \geq 9 \). For the case of formation movement on a flat surface along the X axis, equation (13) takes the form:

\[ dP_k = 2f_{SSF} dP + \frac{\gamma_c dy}{g dt} dxdy dz \]  

where \( P_k \) – resisting force to ground movement in the bucket surface.

Taking into account the charts available from experiments, ground motion resistance [7] in the bucket surface can be defined:

\[ dP_k = \frac{4.42 + 0.15P + 0.07W}{0.01PW} - 0.07T + 330.5D - 24DT + 59Dt + \frac{0.01PW - 0.01PT - 0.03WT - 19 \cdot 10^4 D^2 - 0.01P^2 - 0.02W^2 - 0.01T^2}{dxdy dz + \frac{\gamma_c dy}{g dt} dxdy dz} \]  

where \( P \) – ground pressure, kPa; \( T \) – zone area temperature, °C; \( W \) – ground relative wetness, %; \( t \) – contact time, sec.; \( D \) – ground dispersion, mm.

The continuity equation for moving ground bank with elastic wave propagation is:

\[ \frac{d\gamma_c}{dt} + \gamma_c \left( \frac{dv_x}{dx} + \frac{dv_y}{dy} \right) + v_x \frac{d\gamma_c}{dx} + v_y \frac{d\gamma_c}{dy} = 0 \]  

where \( v_x, v_y \) – ground motion velocity projections.

Boundary conditions on the surface of chip sliding on the ground and metal take the form:
for $\varphi = 0$, $P_R = P_0$; for $\varphi = \varphi'$, $P_R = P_{R_{\text{max}}}$;

for $t = 0$, adhesion coefficient $C_w' = C_w'$, internal friction angle $p' = p$, wall friction angle $\delta' = \delta$;
for $t = t_0$, $C_w' = C_{w_{US}}$, $p' = p_{US}$, $\delta' = \delta_{US}$.

According to the boundary conditions, ultrasonic exposure on the ground starts when $t \neq 0$.

Therefore, expression (15) defines the mathematical model of ground moving on vibrating surface of the work tool for calculating ground motion resisting force under the influence of ultrasonic oscillations.

3. Results and Discussion

Analysis of high-frequency oscillations effect on ground motion resistance forces on a sliding surface under subzero temperatures proves that bank motion resistance is defined by the pressure of ultrasonic waves, affecting the ground from the sliding surface, and to a great extent depends on acoustic properties of the ground. Resisting force to ground bank motion on a sliding surface under ultrasonic oscillations can be reduced essentially by means of reducing adhesion forces and friction forces on metal. Quantitative assessment of the effect under investigation will be calculated through experiments.

The conditions of approximate physical modelling for the ground movement process on a surface that emits the audio range and ultrasonic oscillations are defined by basic similarity criteria [1]. The approximate physical modelling for the ground movement process on a surface that emits the audio range and ultrasonic oscillations is reasonable to conduct with scale division to the coordinate axis. This allows one to carry out the research without modifying conditions of the medium and parameters of intensifying equipment. Methods of multi factor planning were used for experiments.

The effect was assessed through the magnitude of the conditionally momentary freezing distribution coefficient, which is approved to be shear stress $U$. It conforms to the start of ground element motion against the working surface which is defined as follows:

$$U = \frac{P_R}{S},$$

where $P_R$ – load required for the metal surface to move against the ground, $H$; $S$ – working area of the iced ground element, $m^2$. Shear force $U$ was calculated without external influence ($U_{wi}$), but with ultrasonic exposure ($U_{US}$).

To carry out an active experiment, the rotatable central composite design was chosen for the five-factor model with plan linear kernel on $2^k+1$ half-replicate and the total number of points $N = 32$. The plan has start points with the axial distance of $\alpha = \pm 2$. Planning the matrix and the results of the multifactor experiment with the ultrasonic effect of the PMS-6M emitter are outlined in [7].

Parameters of ultrasonic equipment (rational values) were not modified during the experiment: frequency is 21.8 kHz, amplitude is 0.005 mm, exposure time is 10 sec, emitting surface temperature is $25 ^\circ C$.

Experimental research [7] processing using the computer program ‘MNKLUX’ resulted in the regression equation that approximates experimental data:

- under ultrasonic exposure in coded representation:

$$Y_{T,A,B} = 7.72 + 1.61X_2 + 0.49X_3 + 1.96X_4 + 0.38X_5 - 0.48X_1X_4 - 1.18X_1X_5 + 0.72X_2X_3 + 1.09X_2X_4 + 1.26X_3X_4 - 0.76X_1^2 - 1.01X_2^2 - 0.55X_3^2 - 0.45X_5^2$$

- in natural representation:

$$\tau_{T,A,B} = 4.42 + 0.15p_{UB} + 0.2W + 0.58T - 0.07t + 330.5D - 24DT + 59Dt + 0.001p_{UB}W - 0.01p_{UB}T - 0.03WT - 19 \cdot 10^4D^2 - 0.01p_{UB}^2 - 0.02W^2 - 0.01t^2$$
4. Conclusion

The equation (17) analysis for optimum showed that this point is located in the negative area of response. All factors within the investigated range mainly facilitate an increase in adfreezing strength. In ascending order of adhesion, they make up a series: $D, t, W, P, T$.

The increase of pressure impact under the ultrasonic exposure can be explained by fading cementing links of ice under the influence of thermal energy (melting) and the transition of its water into an open-grained and free condition.

The experiments proved the 25-time reduction of adfreezing strength of the ground and the metal surface under ultrasonic exposure in average.

References

[1] Balovnev V I 1981 Modelling of road-building machines work tools interacting processes with the medium (Moscow: Vysshaya shkola) p 335
[2] Sharma V K, Drew L O, Nelson L 1977 Transactions of the ASAE 20 46-51
[3] Tong J 1993 Study on reducing adhesion and resistance of soil to soil engaging components of machinery for land locomotion by bionics. A Ph.D. Dissertation, Jilin University of Technology, Changchun, China (in Chinese)
[4] Tong J, Ren L, Yan J, Ma Y and Chen B 1999 Int. Agricultural Eng. J. 8 pp 1-22
[5] Wang X L, Ito N, Kito K and Garcia P P 1998 J. of Terramech. 35 pp 87-101
[6] Zenkov S A, Ignatyev K A, Filonov A S and Lkh anag D 2013 Materials of the 8th Int. Forum on Strategic Technology (MUST 2013 vol 1) pp 729-731
[7] Zenkov S A 2009 Systems Methods Technologies 1 59-64