Automation of vibration modes of soil compaction machines

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Abstract. The relevance of high-quality compaction of soil foundations during the construction of embankments and foundations during the construction of engineering structures is given. An effective vibrodynamic method of compaction of gravel and sand materials for foundations of building structures for various purposes is substantiated and proposed. The method of continuous monitoring of the degree of compaction of the soil by measuring the magnitudes of the amplitudes and frequencies of harmonic oscillations of the compacted surface is determined. A schematic diagram of the automatic control system CAP of vibration modes of shock-absorbing soil compacting machines with a crank-oscillating exciter is proposed. The principle of regulating the operating modes of a vibrating machine using an automatic control pulse distributor is stated. A structural block diagram of the CAP elements is constructed and an analysis of the dynamic properties that determine the optimal control time is carried out. The main elements of the CAP are determined and their work in the control program is shown: the frequency of impact of the working mechanism on the soil surface being compacted, depending on the degree of compaction.

Key words: soil compaction degree, operating mechanism, amplitude and frequency of harmonic oscillations of the surface of the soil being compacted, vibro-shock machines with a crank-connecting rod exciter, automatic control system, control pulse distributor, process parameters sensors, on-board microprocessor controller.

1. Introduction
In modern construction, compaction of bulk soils is an important component of the technology of erection of engineering structures: foundations of buildings and structures for various purposes; embankments of hydraulic dams and dams; roads and railways; trenches of main pipelines, etc. [1]. This problem is especially urgent in connection with the rapid development in recent years of oil and gas production and transportation, since pipeline rupture due to subsidence due to poor compaction of bulk soil can lead to environmental disaster [1].

The bearing capacity, strength and durability of the erected structure depend on the quality of the compacted gravel-sand base. It has been established that up to 60% of damage occurs due to poor-quality compaction of bulk building materials [1].

During the construction of embankments, the following degree of compaction should be ensured: road-90-95%, railway-90-96%, hydraulic-98-100%, trenches of main pipelines-85-90% [2].

Poor soil compaction during the construction of road surfaces leads to the appearance of moisture from depth to surface due to uncompressed passages in the form of pores, voids, and friability [2].
Increasing the volume of construction work requires increasing the quality of production and controlling the degree of compaction of bulk soils on the basis of high-performance machines equipped with modern automation [2].

Hence the prerequisites for the need to automate the control of the technological process of compaction of bulk soils with the highest possible continuous output to the driver’s console objective estimates of the quality of the degree of control [2].

The disadvantage of domestic and foreign systems of automatic control and monitoring of the degree of compaction of the soil is that they are mainly informational (light panel) and do not have the ability to control the working mechanism (RM) of the soil compaction machine, depending on the optimal degree of compaction of the soil, taking into account external disturbing influences, $F_b$.

To solve the problem of creating an automatic control system (ACS) of a PM compacting machine, it is necessary to determine the technical means of an objective assessment of the degree of compaction and to develop a system of automatic optimization of the compaction process that provides signal conversion of vibroacoustic sensors, generation and generation of control signals for RM based on modern microprocessor computing tools techniques [3].

2. Research Methodology

Studies have shown that an effective method is compaction with the vibrodynamic effect of a PM machine on the surface of compacted sand and gravel substrates and therefore dynamic soil compaction methods using vibratory machines make up to 80% of the total number of compaction means [4].

Compaction in the dynamic method is provided by a combination of static pressure and vibration exposure to the soil.

When compaction of soils, the displacement and rapprochement of hard particles of sand and gravel, destruction, deformation and adhesion of brittle and viscous components occurs, increasing the density and strength of the soil base, displacing softening and weakening liquids and gases from it. According to experimental data, the bearing capacity of soils due to compaction increases by 40% [4].

In the process of compaction of the soil under the influence of vibrodynamic loads from the PM, harmonic vibrations of the surface of the soil bases are formed with a certain amplitude and frequency of harmonics depending on the degree of compaction.

Depending on the adjustable parameters of the PM, the maximum deformation of the soil varies in magnitude, which leads to different values of the amplitudes of harmonics $A_1$ and $A_2$ and, accordingly, the frequencies $S_1$ and $S_2$.

Oscillograms of harmonic oscillations obtained experimentally show that the $A_1$ harmonic practically does not change depending on the number of passes of the machine, but the amplitude harmonic of $A_2$ is significantly affected by the degree of compaction of the soil. If we determine the level of amplitudes of harmonics $A_1$ and $A_2$, then with great certainty we can get the main indicator, which is the current value of the degree of compaction of the soil.

A slightly compacted soil has the smallest deformation modulus characterizing the degree of elasticity of the soil and therefore the harmonics of vibrational vibrations have a very weak signal. As the degree of elasticity increases, the soil becomes more “rigid” and harmonics of the $A_1$ and $A_2$ vibrations appear.

Under the influence of the PM of a vibrating machine on the soil, a voltage appears in its near layer, the wave of which propagates in the medium being compacted in the form of harmonic surface vibrations. In this case, the amplitude and phase of these oscillations depends on the degree of compaction of the soil, which increase with increasing density. The signal from the accelerometer mounted on the PM vibrating plate enters the electronic analyzer, which selects the oscillation amplitudes of the first and second harmonics. As a result, the relationship between the number of passes of the machine along the compacted area and the actual density of the soil is determined based on the amplitude values of the accelerations $A_1$ and $A_2$. 
The frequency converter (automatic analyzer) is isolated from the input signal having a spectrum of harmonic frequencies, the fundamental frequency is the first harmonic and the second harmonic of the same frequency. After detecting these signals, the ratio of the second harmonic to the first is calculated, which characterizes the degree of compaction of the soil depending on the number of passes of the machine.

The input sine wave is determined by:

$$A(K) = \frac{1}{N} \sum_{n=0}^{N-1} A(n) (\cos \frac{2\pi}{N} mK - J_m \sin \frac{2\pi}{N} mk)$$

where $A$ is the amplitude of the input sinusoidal signal; $K = 1, 2$ - number of harmonics; $N$ - number of reports during the experiment; $m$ is the number of the interim report; $J_m$ - imaginary part of the complex plane.

From formula (1) we obtain the frequency of the 1st harmonic:

$$S_1(K) = \sqrt{[R_e A_1(K)]^2 - [J_m A_1(K)]^2}$$

where $R_e$ is the real part of the complex plane.

The frequency of the second harmonic is determined by a similar expression

$$S_2(K) = \sqrt{[R_e A_2(K)]^2 - [J_m A_2(K)]^2}$$

The operational experience of vibro-shock machines designed for soil compaction shows that the efficiency of these machines, in terms of improving the quality of compaction and reducing material costs, can be achieved only with the use of modern automation with the regulation of specified operating modes [5,7].

The operating mode of the control system should have a well-defined relationship between the resistance of the soil being compacted to the impact of PM and the machine parameters, corresponding to the optimal operating mode in each particular case, due to significant changes in the physicomechanical properties of soils with changes in their moisture content and granulometry [8].

The optimal mode of operation of a vibro-shock machine with a crank (eccentric) vibration exciter is achieved by maintaining the angular position of the eccentric shaft at the moment of impact of the PM against compacted soil $\alpha_{ud}$ (phase angle of impact) to its optimal value $\alpha_{op}$ (~ 90). It follows that the most effective system that ensures the optimal operation of the machine under varying external influences is a closed-loop automatic control system (ATS) that stabilizes the set value of the controlled variable — the phase angle of impact associated with the degree of compaction of the soil $\rho_0$ (Fig. 1).

ATS consists of an object of regulation; sensitive elements-sensors for monitoring the moment of impact; the angular position of the crank (eccentric) and the magnitude of the amplitude of harmonic oscillations of the compacted soil; microprocessor-based logic and amplification-conversion device.

To regulate vibro-shock machines with a crank oscillator, it is most advisable to adjust the angular rotation speed $\omega$ of the eccentric shafts. The microprocessor-based logic device compares the actual angular position of the crank (eccentric) at the moment of the start of the impact of the PO on the ground with the specified value based on the information perceived from the sensitive elements and generates a signal to control the operation mode to achieve the optimal value for the adjustable parameter — the degree of compaction of the soil $\rho_{opt}$. In this case, the principle of the main control signal control at the input of the control object is most effective, since in this case the minimum transient time is achieved and when the logic device supplies the corresponding control signal, the drive motor operates with a soft mechanical characteristic $\omega = f(M_{kr})$. 
Figure 1. The basic scheme of the system of automatic control of vibration modes of shock-absorbing soil compacting machines.

A1 is the harmonic amplitude $S_1$ of the surface of the compacted soil; $A_2$-amplitude of the harmonic $S_2$ of the thickness $H_0$ of bulk soil.

On the machine’s body 1 (Fig. 1), a distributor of signals (pulses) arriving from the PM 7 impact moment sensor 7 against compacted soil 5 is mounted. The pulse distributor consists of two insulated conductive rings mounted in a certain fixed position: solid 9, cut into isolated rings the other sectors A and B of the rings 8 and the sliding contact 2 sliding along them. The movable contact is mounted on the eccentric shaft so that it contacts the ring 8 cut into sectors in strict accordance with the position of the end an insulating portion of the crank 3. On continuous ring 9 and the sensor 7 on the crank angle position of the chain 1 is fed from the positive pole of the power supply unit PSU. The signals from sensors 6 and 7 are fed to the inputs “Vh$_1$, Vkh$_2$, Vkh$_3$” of the onboard microprocessor of the MCP, which performs the required switching in the control circuits of the windings W$_1$ or W$_{10}$ of the saturation inductor 10. The impact torque sensor 7 is connected between the solid contact ring 9 and Bx$_3$ of the MCP. A control sensor for 6 amplitudes of vibro-acoustic vibrations is connected through the “Vx” of the frequency converter with “Bx$_1$” and “Bx$_2$” of the microprocessor.

The pulse distributor is installed on the machine so that the axial line S-S passing through the middle of the deadband K is in the position of the set value of the phase angle of impact $\alpha_0$.

In those cases when the “Sector B” of the pulse distributor will be connected to the solid ring 9 through the rotating sliding contact 2 ($\alpha_{sp}<\alpha_{op}$) received from the shock moment sensor 7 to the “Vkh$_3$” MCP, then a signal is sent from the “Out$_1$” MCP to turn on the winding W$_1$ of the saturation inductor and thereby changing the voltage $U_3$ at the terminals of the stator winding C$_1$-C$_2$-C$_3$ of the power motor M, which leads to an increase in its speed. In the mode $\alpha_{sp}>\alpha_{op}$, the pulse from the impact moment sensor changes sign, because at the moments of impacts, “Sector A” of the pulse distributor will be connected with the solid ring 9. This will ensure the appearance of the control signal on the “Output2” of the MCP and the inclusion of the winding W$_2$, which leads to a decrease in voltage $U_3$ and a decrease in the frequency of rotation of the electric drive M.
3. Discussion

When adjusting the degree of compaction of the soil \( \rho_0 \), the speed of the drive M is changed in the same way with the “Output” of the MCP, only the control signal is fed to the “Output” and “Output” of the MCP from the IF frequency converter connected to the vibroacoustic sensor 6. Thus, In the manner of the ATS, by alternately turning on the power motor M to increase or decrease the speed depending on the sign of the deviation of the controlled variable (shock frequency), the optimum operation of the vibro-shock machine is ensured. This is due to the fact that the magnitude of the phase angle \( \alpha_{sp} \) is close to the specified value regardless of changes in soil conditions. Correction is made at the border between sectors A and B of the split ring of the pulse distributor when leaving the dead zone K. Using resistors \( R_1 \) and \( R_2 \), you can set the regulated voltage \( U_3 \) and the constant voltage \( U_4 \) incident on the motor windings, which determines the range of regulation of the engine speed.

![Figure 2. The structural block diagram of the elements of the system.](image)

1- microprocessor-based logic device for automatic regulation; 2- object regulation; \( W_1 \) amplifier; \( W_2 \)-induction motor; \( W_3 \)- crank mechanism; \( W_4 \)- vibrodynamic sensor.

The study of the regulatory object showed that in order to maintain the equality \( \alpha_{sp} = \alpha_{op} \) during operation, it is necessary, as the soil is compacted, \( \rho_{opt} \), to carry out a corresponding change in \( \omega \) from smaller values to large ones. (Fig. 2) Such regulation can be achieved by gradually increasing the output voltage \( U_3 \) from the minimum start of the seal to the optimal \( U_6 \) at the end of the seal. The rotation speed \( \omega \) is controlled by changing the duration of switching on and off the variable voltage component \( U_3 \). The constant component of the voltage \( U_4 \) is selected from the condition for ensuring \( \alpha_{sp} \) at the end of the compaction of the soil (with the voltage \( U_3 \) turned on) equal to or slightly lower than \( \alpha_0 \), that is, with \( U_4 = U_6 \). To achieve maximum system performance and ensure acceptable values of the amplitude of self-oscillations within the allowable error values \( \Delta u_0 \), it should be selected in the range of voltage values:

\[
\Delta u_0 = U_5 - U_4 \leq U_3 - U_{40P} - U_4,
\]

where \( U_{dop} \) is the maximum allowable voltage at the terminals of the stator winding \( C_1-C_2-C_3 \) of the electric motor.

In this case, the change in the rotation frequency \( \omega_t \) is a function of the voltage \( U_3 [\omega_{av} = f (U_3)] \), and the degree of compaction of the soil is a function

\[
\alpha_f [\rho_{av} = f (\omega_{av})].
\]

The vibroacoustic sensor 7, as the degree of compaction of the soil changes, gives signals to the “Vx” of the frequency converter, and from “Vy1” or “Vyk2” with the help of variable resistances \( R_1 \)
or R₂ changes the voltage U₃ in the range ω₁ - more, ω₂ - less and accordingly angular frequencies ω₁ and ω₂.

At the end of the soil compaction process with Ar “Exit 3”, the light alarm (lamp HL) and the sound signal (bell ON) are turned on, which is blocked by the toggle switch SA.

**Figure 3.** The dependence of the amplitude of the oscillations of the soil A₂ and the regulation time Tr from the frequency of rotation of the electric drive.

In the study of the proposed ATS (Fig. 2) with a self-oscillating steady state, it is necessary to obtain recommendations on choosing the operating mode of the system elements from the condition of obtaining the optimal value of the degree of compaction ρopt depending on the number of revolutions of the electric drive (Fig. 3). The optimum value of the degree of compaction ρopt is achieved with an increase in the rotational speed “n” of the electric rammer, since the amplitude of the second A₂ decreases, which characterizes the compaction process in that soil from a viscous mass at the beginning of the application of shock forces due to an increase in the frequency of vibration of the working body, turns into an elastic ground surface.

The time constant Tr, characterizing the inertia of the regulatory object, significantly affects the dynamics of the ATS. With an increase in Tp, the value of A₂ decreases to achieve ρopt, but at the same time, the system performance deteriorates. Thus, the moment of inertia of the rotating masses (flywheels) leads to a deterioration in the dynamic properties of the system, if at the same time the power of the drive motor is not increased. This allows us to conclude that, in principle, electric motors of any type can be used to drive vibro-shock machines, the mechanical characteristics of which are consistent with the load characteristics of rotating masses.

**4. Conclusions**

The proposed ATS with smooth control of two compaction parameters: the number of impacts Pm and the control of the degree of compaction of the soil has good dynamic properties and quality control, which allows to obtain a significant technical and economic effect when introducing vibro-shock action on automated machines.

Preliminary analysis shows that automation of the soil compaction process using the proposed ATS will increase the productivity of soil compaction work by at least 25% only by reducing the number of passes on one grapple and increasing the speed of the machine with small environmental impacts due to the created vibration load.
In addition, the automatic control system allows to improve the quality of soil compaction works, reduce the consumption of fuels and lubricants and, in some cases, completely abandon the traditional methods of controlling the degree of density by taking soil samples, which allows you to release workers performing these operations.

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