Vibrodynamic mechanism control automation in soil compacting machine

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Abstract. Article investigates relevance of high-quality compaction of soil bases during construction of different buildings. Influence of oscillation frequency on to values of disturbing force, total applied load and vertical travel range of the drum is substantiated. Improvement in performance of vibratory roller compactors during operation is provided by resonating frequency, which is optimal during soil-vibratory drum system interaction. Article presents schematic diagram and description of the operation concept for automatic controller with microprocessor, which performs continuous analysis of the interaction between soil and drum, which allows to set optimal frequency of vibratory drum vibrations, to achieve required degree of soil compaction, compensating for disturbing force.

1. Introduction
Compaction of filled soil is an important technological operation during construction of building foundations, hydrotechnical dykes and dams, road and railroad embankments. Especially relevant today this task is in connection with the construction of large volumes of trunk pipelines for the extraction and transportation of oil and gas. It is known that damage to pipelines due to subsidence of soil because of poor compaction leads to large unexpected costs and environmental catastrophe [1].

Bearing capacity, strength and durability of the foundations of constructed buildings and structures depends on the quality of compacted soil. It has been established that up to 60% of damage occurs due to poor-quality compaction of bulk building materials. Domestic and foreign experience (Dynapac, Sweden; Bomag, Germany and others) of construction of filled up building foundations shown that solution to high-quality soil compaction, reduction of material and labour costs is largely determined by automated control of operating mechanism of soil compacting machine with continuous control for soil compaction level during construction works [2].

The durability of building bulk structures is determined by an indicator of the degree of soil compaction, which depends on the actual density of the material and is the main technological indicator of the quality of construction of foundations for foundations and road surfaces. Due to changes in various external unauthorized parameters (changes in the properties of building materials, the height of the compacted layer, soil moisture, terrain, etc.), it is practically impossible to determine the exact value of the degree of compaction of the soil. And this, in turn, leads to a decrease in the productivity of the soil compacting machine due to unnecessary unauthorized passes on one grab, and reducing the passes can lead to a weakening of the construction grounds and, as a consequence, to emergency situations. Excessive compaction time leads to waste of fuels and lubricants and wear of the equipment of the machine. In addition, as a result of over-compaction, the soil is again loosened.
and the quality of such an important construction operation as compaction of bulk construction soil decreases [2].

These circumstances determine the need for continuous determination of the degree of compaction of the soil in the process of production, taking into account the input unauthorized impacts and controlled parameters to compensate for external disturbances. Since the above effects affect differently the degree of soil compaction, the solution to this problem is possible only on the basis of an automated control system using modern computer technology.

A rough estimate of the degree of compaction of the soil is based on data from mobile laboratories, the content of which requires unjustified material and labour costs [2].

The lack of domestic (TsNIOMTP Gosstroi RF) and foreign (firm Deepapak, Sweden; Bomag, Germany and others) control systems for the degree of soil compaction that they are informational (light display) and do not have the ability to control the working mechanism (WM) to maintain a given value soil density in compensation of external disturbing influences [3].

To external disturbing influences include: M - moisture compacted soil; Н0 - height (thickness) of the layer; ψm - granulometry and chemical composition of the material to be compacted; Zn - conditions of the construction site, for example, the relief associated with height differences, grooves, ruts and lowlands; Егр - the degree of elasticity of the soil, associated with the property of loose rock and variable strength, depending on the degree of compaction [4].

Changes in various external unauthorized impacts of FB significantly affect the optimal value of the degree of compaction of the soil. On the basis of this, it is necessary to develop and introduce a regulated RM and an automated control system (ACS) for its operation modes as part of sealing units. An important step is to determine the methodology for obtaining continuous information on the degree of soil compaction during the operation of the machine.

To solve the problem of creating and implementing the ACS of the WM soil-compacting machine, it is necessary to determine the compaction method, develop the structure for building the ACS, substantiate the technical means of the system and propose a method for converting vibroacoustic signals that determine the optimal degree of compaction of the soil, as described in this material.

2. Research technique

Experience has shown that vibrodynamic soil compaction methods take an increasing role in construction and in some counties, dynamic action machines account for more than 80% of the total number of compacting means [4].

The use of vibrodynamic soil compacting machines ensures uniform pressure distribution on the surface of the soil being compacted, which reduces the number of passes on a single “seizure” and allows for compaction of any soil with different uniformity in grain size distribution: gravel, sand, clay [5].

To create vibrations of the rollers on the vibratory machines, unbalances are set, which rotate in the same direction and their phases are mixed by 180°. As a result of the centrifugal force, one unbalance (vibrator roller) acts upwards, while the other - downwards on the sealing soil [6].

Dynamic compaction is achieved by a combination of static pressure (figure 1; Fс) and vibration (figure 1; FV). Usage of vibration compaction methods is associated with the optimal combination of speed and movement of the machine, loading and vibration of the operating mechanism, ensuring the best quality compaction in minimum time.

The performance of the vibration machine (hourly performance at a given degree of compaction) depends on the operating parameters: movement speed of the machine, number of passes, regulated oscillation frequency of the drum and variable mass moment of inertia for eccentrics [6].

Automatic control system for vibrodynamic mechanism (VDM) of soil compacting machine should regulate operational characteristics by changing parameters and should have a possibility for operator to quickly input required characteristics from the control panel. Rotational frequency of the eccentric vibrator, which creates frequency of its oscillations determines the value of disturbing force of pressure on the soil (figure 1):
\[ F_C = m_0 V_M \omega^2, \]

where \( m_0 \) - eccentric weight of the vibratory drum; \( R_e \) - eccentricity; \( V_M \) - the speed of movement of the machine; \( \omega = 2\pi f_v \) - angular oscillation frequency of vibrating mass.

**Figure 1.** The change in disturbing force is \( F_C \), the amplitude of the vertical displacements of the drum: \( A_{v2} \) is at the depth of the compacted layer, \( A_{v1} \) is at the compaction surface and the total applied load is \( F_v \) depending on the oscillation frequency of the vibrodynamic mechanism.

Total value of disturbing force \( F_v \) (figure 1), transmitted onto the soil is an algebraic sum of mass and dynamic force, which changes not only from eccentric mass of vibrator and oscillation frequency \( f_v \) but also from parameters, determined by external disturbing influences \( F_v \).

Compaction (irreversible movement of soil particles as volume changes) depends not only on the total value of the disturbing force applied onto soil, but also from ground vibration amplitudes \( A_{v1} \) and \( A_{v2} \) (figure 1).

The higher the value of this amplitude, the easier is relative movement of soil particles.

If the disturbing resistance force \( F_C \) increases with an increase in the oscillation frequency \( f_v \), oscillation frequency \( A_{v1} \) and \( A_{v2} \) increases only in a certain range of excited frequencies. The amplitude of the vertical displacements of the drum increases with increasing frequency of oscillations and reaches maximum values \( A_v \) (max) at a frequency called resonating frequency (T.A.), and after reaches its asymptotic value \( A_{v10} \) and \( A_{v20} \) (figure 1).

The dependence \( F_v = f \left( f_b \right) \) (figure 2, a) makes it possible to determine, in addition to \( \rho_0 = f \left( f_b \right) \) (figure 2, b), another regulating effect on the degree of compaction of the soil \( \rho_0 \) by changing the frequency of striking WM's gain \( F_v \) on the ground surface at an adjustable point in time.

In the process of compaction of the soil under the influence of vibrodynamic loads from the WM, harmonic oscillations of the surface of the soil bases with a certain amplitude and frequency depending on the degree of compaction are formed. Under the influence of the controlled parameters \( F_p \) WM, the limiting deformation of the soil \( \rho_0 \) changes in magnitude, which leads to different values of the amplitudes \( A_{v1} \) and \( A_{v2} \) (figure 1) and, accordingly, harmonics \( S_1 \) and \( S_2 \).
The dependence of the degree of compaction of the soil from regulatory actions of the WM:

a) \( \rho_0 = f(F) \); b) \( \rho_0 = f(f) \).

The vibrodynamic analyzer (figure 3) filters the main frequencies from the spectrum of harmonic oscillations, which determine the actual degree of soil compaction taking into account external disturbing influences and adjustable parameters of the WM of the vibrating machine.

The automatic analyzer extracts from the input signal having a spectrum of harmonic frequencies, the fundamental frequency is the first harmonic and the second harmonic of this frequency. After detecting these signals, the ratio of the second harmonic to the first is calculated, which characterizes the degree of soil compaction depending on the number of passes of the machine.

Input sine wave is determined by:

\[
A(K) = \frac{1}{N} \sum_{n=0}^{N-1} A(n) \left( \cos \frac{2\pi mK}{N} - J_m \sin \frac{2\pi mK}{N} \right)
\]

where \( A \) is the amplitude of the input sinusoidal signal; \( K = 1,2 \) - harmonic number; \( N \) - the number of reports during the experiment; \( m \) is the number of the intermediate current report; \( J_m \) is the imaginary part of the complex plane.

From the formula (2) we obtain the frequency of the 1st harmonic:

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

where \( R_e \) is the real part of the complex plane.

The frequency of the 2nd harmonic is determined by a similar expression:

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

The actual degree of compaction of the soil is determined by:

\[
\rho_f = \frac{S_2(K)}{S_1(K)} < \frac{g}{cm^3}
\]

In figure 3 we marked: \( W_1 \) - device for setting the required degree of soil compaction: keypad of the key switch for changing the microprocessor’s program when compacting soils with different grain size and elastic moduli; \( W_2 \) is a comparison element: a bridge measurement circuit that determines the voltage unbalance \( \Delta U \) (control signal) when the specified vibration frequency of the WM and the
speed of rotation of the shaft $W_8$ deviates, regulating $\rho_0$ in the specified values; $W_3$ - on-board world processor; $W_4$ - display: indicator of control of measurement of regulatory parameters and the degree of compaction of the soil; $W_5$ - program corrector: produces a program change on the technological requirements associated with a variety of compacted soils; $W_6$ - the relay control unit communicates (booster) the low-power signal $W_5$ with VDM drives; $W_7$, $W_8$, $W_9$, $W_{10}$ - structural mechanisms of the vibrodynamic drive, which regulate the speed of rotation of the sealing roller and its vibration frequency; $W_{11}$ - tachogenerator (control of roller rotation speed $V_0$); $W_{12}$ - drum vibration frequency control sensor - $f_v$; $W_{13}$ is a frequency converter that, using pulse-width modulation, extracts harmonics $S_1$ with amplitude $A_{1}$ and $S_2$ with amplitude $A_{2}$, connected directly with the degree of compaction $\rho_0$ and converts into an electrical signal; $F_p$ - adjustable operator exposure at the setter $W_1$ to change $\rho_0$ according to technological requirements; $M_{cr}$ - torque roll; $F_v$ - external disturbing effect; VDM - vibrodynamic mechanism.

**Figure 3.** The automated control system for the vibrodynamic mechanism of a soil compacting machine.

### 3. Discussion

Practice has shown that the highest hourly performance of vibratory roller compactors is achieved at a resonant frequency [7]. Consequently, optimization of the frequency parameter is related to provision of the resonant frequency in the soil – drum pair. Resonating oscillation frequency of vibratory roller compactor is not constant and depends on $F_v$. Therefore, maintaining values of this frequency with compensation for $F_v$ (humidity, degree of elasticity, granulometry, surface relief etc.) can be provided only by ACS with regulation of rotational speed $V_0$ and vibration frequency $f_v$ of the drum depending on required compaction level $\rho_0$. (figure 1). In this case, change in these regulatory physical parameters, converted into electrical values in form of voltages $U_2$ and $U_3$ will go on until offset of voltages $\Delta U = U_1 - (U_2 + U_3)$ will become 0. This state of ACS corresponds to the steady-state control, with $\rho_0 = \rho_{opt}$ meaning given compaction level equals to actual one.

It should be noted that mechanical properties of the roller-frame bond of existing vibratory roller compactors provides a frequency of oscillation within $f_v = 15-50$Hz. This frequency range creates comfort for the operator and increases the reliability of the equipment, due to low $f_v$ values [8].
When developing an ACS to control optimum oscillation frequency during roller drum displacement, following physical properties should be considered: eccentric torque, oscillation amplitude without load, natural oscillation frequency and decay coefficient.

Additionally, ACS should continuously make an assessment of the parameters $F_v$ and promptly correct control mode of vibrodynamic mechanism in soil compacting machine.

Drum movement speed $V_v$ and eccentric movement frequency $f_e$ are determined using primary transducers $W_{11}$ and $W_{13}$, attached to the frame of the machine. Two values of voltages $U_2$ and $U_3$ are fed to the frequency converter $W_{13}$, and then to the comparison element $W_5$, which determines oscillation frequency, amplitude of displacements and the displacement of the drum relative to the eccentric (figure 3).

Microprocessor $W_5$ sends commands to the control unit $W_6$, which controls VDM, that consists of servo valve $W_7$, hydraulic pump $W_8$, hydraulic motor $W_9$ and drum itself $W_{10}$.

At a length of about 50 m, the vibratory roller compactor is moved back and forth along the loosened material. During each pass, system provides an increase in the oscillation frequency and determines amount of displacement in accordance with resonating frequency. Data on the parameters of ACS operating mode are entered into the display unit $W_4$. Correction of the microprocessor program after changes in technological standards for compaction of bulk soils is carried out from block $W_5$.

4. Conclusions

The stated theoretical rationales are an integral part of the technical specifications for the development of the project of ACS modes of operation of the WM of the vibration machine and are accepted for implementation.

A preliminary analysis shows that the automation of the control process will increase the productivity of soil compaction by at least 25% only by reducing the number of passes on one pick-up and increasing the speed of the machine moving at low environmental impacts due to the generated vibration load.

In addition, the automatic control system allows improving the quality of soil compacting work, reducing the consumption of fuel and lubricants and, in some cases, completely abandons traditional methods of controlling the degree of density by sampling the soil and freeing workers who perform these operations.

References

[1] Shilkov V A, 1992, *Automation of machinery vibro-impact actions for compaction and piling*. M. Stroyizdat 365
[2] Tikhonov A F and Kashechev A A 2005, *Engineer fur – 2005, Moscow*, MGSU 36-8
[3] Anashkin Z T and Balakirev V Y 1994, *Construction and road machines* 6 95
[4] Barkan D D and Shekhter O. Ya 2002 *Gosstroizdat* 91 89
[5] Vas'kovskiy A M and Vorobyov V 1998 *Izvestiya vuzov* 5 36-8
[6] Bykhovsky I I and Baumann V A 1996 *stroizdat* 286
[7] *Note technique complementaire au guide pour le controle du compactage des couches de Routes et autoroutes, laboratoire Central des Ponts et Chausses* 1995 c. 1-17
[8] *Mikrorechnep – destutzte kontrole der Bodenvezdichtung bei vibrationg – verdichtungwalzen. Verdichtungstechnik* 1989 943-7