Experimental research of vertical movements and accelerations of the drum vibrations of the DM-617 vibratory roller during soil compaction

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Abstract Rheological modeling of how the elements of a vibratory roller during soil compaction interact with each other allows the optimization of parameters of the roller and soil compaction modes based on the study of the obtained model, as well as the improvement of the soil compaction continuous control system, and the solution of other practically important tasks. To verify the models, it is required to compare the calculation results for the models with experimental data. The paper includes the results of experimental studies of the acceleration range for the vibratory drum of the DM-617 vibratory roller during soil compaction in the steady vibration mode, when the vibration is turned on, and when it is turned off. It is established that during the compaction of the soil in question in the range E<sub>vd</sub> = 14...25 MPa, the range of vertical movements and accelerations of the vibratory drum in the steady vibration mode does not depend on the soil density. When the vibration is turned on, the vertical movements and accelerations of the drum is 1.5...2 times higher than those of the steady mode. When the vibration is turned off, the vertical movements are increased by 1.5...2 times when passing the resonance zone, and the drum accelerations do not exceed the range of those in the steady vibration mode. The obtained results allow the mathematical models of vibratory rollers during soil compaction to be verified not only in the steady vibration modes, but also in transient modes, including passing the resonance areas when switching the vibration on and off.

Keywords: soil, compaction, vibration, vibratory roller, rheological model, experimental research, drum movement, drum acceleration, resonance.

1. Introduction

Vibratory rollers are the most widely used machines in soil compaction for road construction. To optimize the design and operation modes of the vibratory rollers, they are modeled mathematically. One of the most widely used methods of mathematical modeling of how the vibratory rollers operate is the rheological modeling. With this method, for the oscillating masses (drum frame, vibratory drum, soil etc.), the differential equations of their movement are formulated and studied. These masses are interconnected by the elements that describe the idealized elastic, viscous, and plastic components of the resistances against the movement of the interacting elements. Various authors proposed different
rheological models to analyze the interaction between the vibratory drum and soil. These models include single-mass with elastic [1], elastic-viscous [2], and elastic-viscous-plastic [3, 4] bonds; dual-mass with elastic-viscous [5, 6, 7], and elastic-viscous-plastic [8] bonds; three-mass [9, 10] and more. The simulated results heavily depend on the elastic and viscous resistance factors of the shock absorbers; the elastic, viscous, and plastic soil resistance factors and relative position of these resistances; the weight of the apparent mass [11], and other characteristics of elements of the rheological model. The rheological model needs to be verified in order to study the dynamics of elements of the vibratory roller, justify the amount and characteristics of shock absorbers of the vibratory drum [12], ensure safe vibration, improve the soil compaction continuous control systems [13] and more. The verification procedure consists of comparing the calculation results as per the rheological model with the corresponding experimental data. The best combination of taking the specific aspects into account and a low complexity is embodied in a three-mass rheological model with elastic-viscous bonds [9, 11]. It is possible to verify the three-mass rheological model with elastic-viscous bonds with the following parameters: the amplitude and nature of vibratory drum oscillations; the amplitude values of vertical accelerations of the drum and its frame; the spectrum of vertical accelerations of the drum and its frame. The results of the tests mentioned above are not included in the known results of experimental studies of vibrations of the elements of vibratory rollers during soil compaction [9-10, 14-16]. These do not affect the transients when the vibration is turned on and off, or passing the resonance zones of the vibratory drum's shock absorbers, and are only limited to recording the vertical accelerations of the drum and the spectrum of vertical accelerations of the drum in the steady vibration mode. It hinders the comprehensive verification of the rheological model and restricts the range of possible applications of the modeling results. Thus, the problem of experimental studies is yet to be solved. These studies are needed to obtain more complete data on the specific aspects of vibration of the vibratory drum and its frame depending on the changing properties of soil during compaction, and turning the vibration on and off. This paper presents some results of experimental studies that were conducted. They reflect the obtained data on the range of vertical movements and accelerations of vibrations of the vibratory drum in a roller.

2. Methods
Experimental studies of soil compaction with a vibratory drum were conducted in the summer of 2018. For this research, we used a DM-617 vibratory drum produced by "Road Machinery Factory" (Rybinsk, Russia) with the following parameters: structural mass of the roller (operational) – 15.5 (16.0) T; axle mass distribution (front/rear axle) – 55% / 45%; drum diameter – 1550 mm; drum width – 2000 mm; linear static axle load – 43.5 kg/cm; engine Cummins 6BTA5.9-C175 (rated power – 128 kW; rated engine speed – 2100 rpm; operating engine speed – 1800 rpm); drum vibration frequency – 30/30 Hz; rated drum vibration amplitude – 1.15/1.6 mm; centrifugal force of the vibration generator – 170/230 kN; shock absorbers in the drum – GMT 58200715 (20 pcs).

Compacted soil parameters: natural sand-gravel mixture, gravel grains sized more than 5 mm – 40.5%, medium sand (FM=2.24) – 59.5%, and the largest sized gravel grains – 70 mm. Paved layer thickness – 0.5 m. Standard particle specific gravity and optimum moisture are defined in GOST 22733-2016 "Soils. Laboratory method for determining of maximum density" and were equal $p_{o}^{3}=1750$ kg/m$^3$ and $W_{opt}=8.22\%$.

During the research, the vibratory roller moved around the plot (Figure 1) only forward with the maximum driving force. It returned to the start of the passage through the adjacent plots.

During soil compaction, the vertical movements of the vibratory drum of the DM-617 roller were measured with the BAUMER OADM 13U6480/S35A laser sensor with the following parameter: measurement range – 50...550 mm; resolution 0.01…1.1 mm; linear error ±0.08…±3.5 mm; response time <0.9 ms. During measurement, the sensor was manually held 100 mm above the highest point of the drum sheet to minimize measurement errors (Figure 1). The soil sticking to the drum was scraped off to ensure that it had no effect on how the laser sensor recorded the drum movement.
Figure 1. Plot for the research of soil compaction with a vibratory roller.

To measure the vertical accelerations of the vibratory drum, a high-sensitivity piezoelectric accelerometer with integrated electronics AP2099-100 made by LLC Globaltest (Sarov, Russia) with the following parameters: operating frequency range 0.5...10000 Hz; maximum amplitude of the measured acceleration ±50 g; adjustment resonance frequency in axial direction >24 kHz; noise level, RMS <5·10⁻⁵ m/s². The accelerometer was attached to a bracket and mounted on the vibratory drum vertical to the longitudinal rotation axis of the drum (Figure 2).

Figure 2. Installation location of the accelerometer of the vibratory drum.

When the measurement results were processed, the real accelerometer conversion factor was set based on the issued calibration certificate.
The accelerometer and laser movement sensor readings were recorded with the ZET 017-U8 spectrum analyzer made by ZETLAB. Sensor polling rate was 5000 Hz. The measurement results of the drum movements and accelerations were displayed in real time on the laptop screen (Figure 3) and recorded to its hard disk drive for further processing. The spectrum analyzer and the laptop were powered through the voltage converter Ritmix RPI-6100С (12/220V, 600W, pure sine wave) connected to the battery of the vibratory roller.

Soil compaction result was evaluated through the dynamic modulus of deformation $E_{vd}$, which was measured with the dynamic weight load ZORN ZFG 3.0. The dynamic modulus of soil deformation was measured every two passes of the vibratory roller in 3 points across the movement direction: at the right edge, in the middle, and at the left edge of the compaction strip (Figure 4). After that, the results were averaged. Each series of $E_{vd}$ was measured with an offset of the sampling area along the compaction strip, so each new sample was from a new soil patch that wasn't affected by the tamper previously.

![Figure 3. Recording of vibration parameters during compaction.](image1)

![Figure 4. Measurement of soil deformation dynamic modulus $E_{vd}$.](image2)

The studies were repeated 3 times with the best possible reproduction of the original process conditions.

The accelerometer and laser movement sensor readings were processed with the "ZSignalGallery" tool included in the software package of the ZET 017-U8 spectrum analyzer. The characteristic oscillogram of the roller accelerations is shown in (Figure 5).

![Figure 5. The characteristic oscillogram of acceleration of the drum.](image3)
3. Results
The measurement results of vertical movements of the vibratory drum of the DM-617 roller during soil compaction while moving with the steady vibration are shown in (Figure 6).

![Figure 6](image_url)

**Figure 6.** The measurement results of vertical movements of the vibratory drum of the DM-617 roller during soil compaction while moving with the steady vibration.

The measurement results of vertical movements of the vibratory drum of the DM-617 roller during soil compaction (attempt No. 1) while moving with vibration are shown in (Figure 7), while the vibration generator was starting up are shown in (Figure 8), while the vibration generator was turned off (stopped) are shown in (Figure 9).

The acceleration waveform contains harmonics not only at the base frequency (30 Hz), but also at other frequencies that make the signal noisy. However, before determining the sources of high-frequency vibrations of the vibrator, the analysis of its accelerations was carried out without the use of digital signal filtering technologies.

![Figure 7](image_url)

**Figure 7.** The measurement results of vertical movements of the vibratory drum during soil compaction while moving with the steady vibration (attempt No. 1, forward movement with maximum vibration).
Figure 8. The measurement results of vertical movements of the vibratory drum during soil compaction (attempt No. 1, starting the vibration generator).

Figure 9. The measurement results of vertical movements of the vibratory drum during soil compaction (attempt No. 1, stopping the vibration generator).

Processing (including all 3 attempts) the measurement results of changes in vertical movements of the vibratory drum during soil compaction while moving with the steady vibration showed the following:

- In the researched range of variation of soil parameters, the amplitude of oscillations of the vibratory drum with the maximum operating driving force (230 kN) and forward movement in
the steady vibration mode is 4...4.5 mm and virtually does not depend on the dynamic modulus of soil deformation $E_{vd}$;

- When the driving force is at maximum, and the vibration generator starts or stops (the vibrations are turned on or off), the range of vertical movements of the vibratory drum is, on average, 1.5-2 times higher than the range of vertical movements of the steady vibration mode of the drum;

- In the researched range of dynamic moduli of soil deformation 14...25 MPa, when the driving force is at maximum, the amplitudes of vertical accelerations of the vibratory drum are, on average, from +60...+85 to -55...-75 m/s$^2$. At the same time, there is no correlation between the $E_{vd}$ value and the amplitude values of vertical accelerations of the drum;

- In the researched range of dynamic moduli of soil deformation, when the driving force is at maximum, the vertical accelerations of the vibratory drum are, on average, from +110...+120 to -100...-110 m/s$^2$, which is 1.5-2 times higher than the vertical accelerations of the steady vibration mode of the drum and virtually does not depend on the dynamic modulus of soil deformation $E_{vd}$. When the vibration generator is stopped, the vertical accelerations of the vibratory drum are, on average, from +35...+45 to -35...-45 m/s$^2$, which does not exceed the vertical accelerations of the steady vibration mode of the vibratory drum.

4. Discussion

From the one hand, the lack of correlation between the amplitudes of movements and accelerations of vibrations of the vibratory drum and soil density (measured as $E_{vd}$) is not consistent with the intuition that the accumulation of soil density leads to the increase of the amplitude of vibrations of the vibratory drum and the range of amplitudes of accelerations. However, this correlates with the results of the previously conducted experimental studies with the DM-614 vibratory roller [11]. Those studies also showed the independence of amplitudes of movements and accelerations of vibrations of the vibratory drum from soil density in the range $E_{vd} = 6.8...15.1$ MPa. The accuracy of the obtained result is confirmed not only because it can be reproduced with 3 tests, but also because the soil compaction continuous control systems, which are widely used nowadays in the vibratory rollers, do not use the range of oscillations or amplitudes of accelerations of the vibratory drum as a criterion, which would be quite logical and expected, but instead they use other indicators based on drum acceleration spectrum, for example [17].

When the vibrations are turned on and off, the oscillations of the drum pass through the resonant frequencies zone of the shock absorber in the drum. This is accompanied by a short increase in the range of movements and accelerations of the vibrations of the drum. When the vibration is turned on and it passes the resonance zone, the movement and acceleration values of the drum become 1.5...2 times higher. When the vibration is turned off and it passes the resonant frequencies zone, the acceleration values do not seem to increase when the vibration generator is stopped, but the range of oscillations of the drum shortly increases by a factor of 1.5...2. This result requires further reflection and comparison with experimental results of measurements of drum frame accelerations when the vibration is turned on and off.

5. Conclusion

The obtained experimental data on oscillation amplitudes and amplitudes of accelerations of vertical oscillations of the vibratory drum during roller operation in various modes (steady vibration, turning the vibration on and off) can be used to verify different mathematical models (including three-mass rheological model with elastic-viscous bonds [11]) that describe dynamic processes of interaction between the elements of the vibratory roller and soil during compaction. In this regard, the obtained results extend the range of conditions, for which experimental data were obtained by using vibratory rollers produced by "Road Machinery Factory" (Rybinsk, Russia), and can be used to verify the developed [11] rheological model in a wider range of soil conditions.
To improve the rheological model verification quality, it is reasonable to compare the calculated results with experimental values not just for movements and accelerations of vibrations of the vibratory drum, but also the movements and accelerations of vibrations of the drum frame in the steady vibration mode, as well as when the vibration is turned on and off, taking into account the changes in soil density from pass to pass. These data (except measurements of drum frame oscillation amplitudes) were also measured and are planned to be published.

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