Experimental studies of stresses in soil affected by a vibratory roller

I S Tyuremnov, D V Furmanov

Yaroslavl State Technical University, Yaroslavl, Russia
E-mail: tyuremnovis@yandex.ru

Abstract Stresses in soil are a link between all parameters and operation modes of a vibratory roller and deformations at different depths of the soil. The paper presents a research technology and the results of measuring stress amplitudes in soil at depths of 0.15, 0.3, and 0.5 m at different dynamic moduli of soil deformation $E_{vd}$. It is established that in the surface layer (0.15 m deep) within a single loading cycle, the duration of stress buildup phase is 1.5—2 times lower than the duration of stress relief phase, and this ratio increases with compaction. Within one roller pass in the surface layer (0.15 m deep), the increase period of the amplitudes of separate stress cycles is 1.2—2 times longer than the decrease period of those, and this ratio also increases with compaction. It is established that the vibration impact of a roller, similarly to the impact loading of soil with a tamper, affects how the stresses change during the relief phase at each impact cycle. This change is the same as how the stresses change during the relief phase in a surface layer (0.15 m deep), which confirms that it is possible to apply the provisions of the dynamic theory of plasticity not only for impact, but also vibratory and vibro-impact soil compaction modes. The obtained results can be used to update and verify the existing and future mathematical models of soil compaction with vibratory rollers.

Keywords: soil, compaction, vibration, vibratory roller, stress, experimental research.

1. Introduction
Vibratory rollers are the most common means of soil compaction in road construction. However, despite the long production and operation period of vibratory rollers, most manufacturers still offer very limited recommendations on how to choose a model and what the operation modes are in the vibratory rollers produced by them, that are used for soil compaction in different technological and soil conditions. To solve this problem, it is necessary to develop a mathematical model for soil compaction with a vibratory roller. The model should account for the specific aspects of interaction between soil and the main elements of a vibratory roller (drum, drum frame, shock absorbers); for processes of stress development along the contact surface of the drum and soil and the stress distribution along the thickness of soil; for the processes of development and accumulation of soil deformation on the surface and along the thickness of soil layer. To develop a model that accounts for all the above processes, several different approaches can be used. As a good candidate to analyze the processes of change in the stress-strain state of soil under dynamic impact on its surface with a curved
tamper, there is an approach based on using the finite element method [2—4]. But this approach still causes difficulties to simultaneously account for all dynamic processes in the elements of a vibratory roller. A widely used method of rheological modeling [5—10] can be used to study the specific aspects of interaction between the main elements of a vibratory drum with the characteristics of the compacted soil accounted for. However, using the rheological modeling, it is not possible to analyze the processes of change of stress and strain at different depths in compacted soil. Therefore, it seems promising to use a combined method that would let us analyze the specific aspects of oscillatory processes of the vibratory roller elements with the properties of soil accounted for, as well as processes of stress distribution along the thickness of soil [12] and processes of deformation development in soil [13].

To verify the mathematical models, the calculation results of the modeling are compared with the results of the corresponding experimental studies.

Stresses at various soil depths during vibratory roller compaction are particularly important for the verification of the developed mathematical model. Stresses in soil are a link between all parameters and operation modes of a vibratory roller and deformations at different depths of the soil. The works of various authors [14—18] provide the measurement results of stresses in soil during compaction with a vibratory roller. However, the provided results do not encompass the whole range of possible combinations of parameters of a vibratory drum and soil properties. Also, it seems interesting to the authors to study more closely how the stresses of individual impact cycles change within one pass of a vibratory roller.

The stresses at various soil depths were studied at the same time as the oscillation values of the elements of a vibratory roller were recorded (mainly the drum and the roller frame) to study their connection and verify the mathematical model comprehensively. The results of the stress studies are presented in this paper.

2. Methods

Experimental studies of stresses in soil during compaction with a vibratory roller were conducted in the summer of 2018. The stresses were recorded at the same time as the oscillation values of the drum and the drum frame were recorded. The soil was compacted with 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).

The soil was 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, respectively, \( \rho_{dst}=1750 \text{ kg/m}^3 \) and \( W_{opt}=8.22\% \).

Vibratory roller operation mode: forward movement with the maximum driving force. It returned to the start of the passage through the adjacent plots.

The changes in soil properties during the studies were 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. After that, the results were averaged. Each series of \( E_{vd} \) was measured with an offset of the measurement area along the compaction strip, so each new sample was from a new soil patch that wasn't affected by the tamper of ZORN ZFG 3.0 previously.
The vertical stresses in the soil under the vibratory drum were measured with pressure cells with hydrotransducers (EPC sensors) Geokon 3500-1-1MPa produced by Geokon (USA). The diameter of the pressure cells – 100 mm, the thickness – 10 mm. Main specifications of the Geokon 3500-1-1MPa sensors: operating range – 0…1 MPa; linearity error – 0.06 %; accuracy – 0.25 %.

Before use, the pressure cells were calibrated in the soil in a special container with an inner diameter of 510 mm and a height of 510 mm. During calibration, the container was filled with the pre-loosened and pre-moistened soil (silty sand) not less than 200 mm thick and compacted manually. Then, a pressure cell was put leveled horizontally in two directions (Figure 1). The pressure cell was then covered with the 50 mm soil layer and compacted manually again. Then, a metal disc with a diameter of 400 mm and a thickness of 20 mm was put on top of it. A jack was mounted on the disc with the force of 160 kN to create stresses in the soil. The transmitted force was controlled with an electronic dynamometer ACD/2S-100/4I-2 (Figure 2) connected to the ZET 210 ADC DAC module. The readings of the dynamometer and the pressure cell were recorded as the jack was creating the load.

In the process of testing, we used the "XY-Plotter" tool from the ZETLAB software to plot a stress graph recorded by the pressure cell depending on the strain and to calculate the conversion rate for each pressure cell when measuring stresses in soil. Each pressure cell was loaded 5 times repeatedly.

As with the calibration, during the field experimental studies of soil compaction with the DM-617 vibratory drum, the readings of pressure cells were recorded with the ZET-210 ADC DAC module with the following parameters: inputs – 16 inphase or 8 differential; total frequency conversion by active channels – from 2 kHz up to 500 kHz; dynamic range – 84 dB; maximum FR unevenness in the range 10 Hz...200 kHz – 1 dB.

Three pressure cells were used during field experimental studies. All pressure cells were leveled horizontally. Pressure cell No. 1 was laid 0.15 m deep and 0.5 m to the left of the roller movement axis. Pressure cell No. 2 was laid 0.5 m deep along the intended roller movement axis. Pressure cell No. 3 was laid 0.3 m deep and 0.5 m to the right of the roller movement axis (Figure 3).

In the field, the ZET 210 ADC DAC module and the laptop were powered with a car battery (12V) through the power converter PSW-250 (250 W, pure sine wave) (Figure 4).
The readings from pressure cells were recorded when the vibrating roller approached them and stopped when it left them within a specific range (Figure 4).
No digital signal processing (filtering, correction etc.) was used during the recording of pressure cell readings.

![Figure 3. Pressure cells are laid into soil.](image1)

![Figure 4. Stress recording system during soil compaction with a vibratory roller.](image2)

Pressure cell readings were initially processed with the "ZSignalGallery" tool included in the ZETLAB software.

3. Results
The measurement results of change of stresses with time at a depth of 0.15 m (blue), 0.3 m (green), and 0.5 m (brown) are shown in (Figures 5—10). Stress waveforms (Figures 6—10) are shown with no preliminary processing (with no vertical offset to align to the same initial stress level and no offset along time axis).

At the end of the studies, when the pressure cells were extracted from soil, all cells were horizontal at depths of 0.115, 0.275, and 0.445 m respectively. The pressure cell closest to the surface (0.115 m deep) was displaced forward by 0.15 m along the movement direction of the vibratory roller.

The measurement results of stress amplitudes at different depths in soil during its compaction with the DM-617 vibratory roller are shown in (Figure 5).

Main view of the "ZSignalGallery" tool included in the ZETLAB software is shown in (Figure 6). Here it shows the measurement results of stresses at different depths during their processing. This tool can be used to view and zoom the signals on selected channels for analysis vertically (stresses) and horizontally (time).
Figure 5. The measurement results of stress amplitudes at different depths in soil during its compaction with the DM-617 vibratory roller.

Figure 6. Change in stresses with time at different depths in soil (0.15, 0.3, 0.5 m) during the 1st pass of the DM-617 vibratory roller ($E_{vd} \approx 14$ MPa).
Figure 7. Change in stresses with time at depths 0.15 m and 0.5 m during the 2nd pass of the DM-617 vibratory roller ($E_{vd} = 14$ MPa).

Figure 8. Change in stresses with time at depths 0.15 m and 0.5 m ($E_{vd} = 21$ MPa).

Figure 9. Change in stresses with time at depths 0.15 m and 0.5 m ($E_{vd} = 23$ MPa).
The analysis of measurement results of stresses during soil compaction with the DM-617 vibratory roller in the studied range of change of soil parameters showed the following:

- At depths of 0.3 and 0.5 m, the amplitudes of stresses in soil virtually stay the same with each roller pass and are in the range of 0.5…0.65 MPa at the depth of 0.3 m and 0.12…0.24 MPa at the depth of 0.5 m;
- Within one roller pass, during soil compaction, the ratio of stress buildup time of individual impact cycles ($T_1$ in Figure 7) and the stress relief time of individual cycles ($T_2$ in Figure 7) changes: first passes (specifically, the 2nd pass at $E_{vd} = 14$ MPa) $T_1/T_2 = 1.2$; at $E_{vd} = 21$ MPa, $T_1/T_2 = 1.36$; at $E_{vd} = 23.5$ MPa, $T_1/T_2 = 1.76$; at $E_{vd} = 25$ MPa, $T_1/T_2 = 2$;
- Within one impact cycle with the maximum amplitude within one roller pass, during soil compaction, the ratio of stress buildup time ($t_1$ in Figure 7) and stress relief time ($t_2$ in Figure 7) changes. The first passes (specifically, the 2nd pass at $E_{vd} = 14$ MPa) $t_1/t_2 = 0.64$; at $E_{vd} = 21$ MPa, $t_1/t_2 = 0.57$; at $E_{vd} = 23.5$ MPa, $t_1/t_2 = 0.49$; at $E_{vd} = 25$ MPa, $t_1/t_2 = 0.45$;
- Within each impact cycle, the nature of change in stresses during the relief phase at the depth of soil follows the nature of change in stresses during the discharge phase at the soil surface (0.15 m deep);

4. Discussion

For the top pressure cell (0.15 m deep), the difference between the stress buildup time during the loading phase ($t_1$) and the stress relief time during the discharge phase ($t_2$) within one impact cycle can be explained by the nonlinearity of soil properties during deformation. The change in the $t_1/t_2$ ratio from pass to pass can be explained by the change of the oscillation mode of the roller drum with the increase in soil density [19]. In this regard, it is reasonable to compare the study results for the change in stresses at the depth of 0.15 m with the change in the spectrum of vertical oscillations of the roller drum on the relevant passes.

How the ratio of stress buildup time of individual load cycles ($T_1$) and stress relief time of individual cycles ($T_2$) changes with the soil compaction requires further reflection.

The question why the nature of change in stresses during the discharge phase at the surface and deep within the soil is so similar can be answered with the dynamic theory of plasticity [20—22]. Since the dynamic effect disturbs a large mass of soil, which vastly exceeds the mass of source of disturbance, the soil discharge, which is elastic in nature, must be accompanied by a discharge spread from the soil surface inside the depth of stress waves, the speed of which will be determined by the soil properties regardless of the values of stresses in the wave front. This theory was previously confirmed experimentally during the experimental studies of how the stresses spread in soil after the
tamper impact [22—23]. The results of the experimental studies in this paper can be used to extend this theory to the soil compaction with vibratory rollers.

5. Conclusion
The obtained experimental data for the amplitudes and nature of change of stresses at different depths of soil during compaction with a vibratory roller can be used to extend the number of parameters for verification of various mathematical models of soil compaction with vibratory rollers. However, the recorded stresses at a depth of 0.15 m exceed the operating range of stress measurement in the Geokon 3500-1-1 MPa pressure cells. Therefore, the measured stresses exceeding 1 MPa should be treated as data with erratic error.

The asymmetric nature of changes of stresses in the loading and discharge phases within one impact cycle \( t_1/t_2 < 1 \) and the decrease of this ratio during soil compaction will have a significant effect on the duration of various stresses on the soil surface and the resulting stress distribution at depth. Future mathematical models must account for the asymmetric nature of stress change on the soil surface (within one oscillation cycle) when compacted with vibratory rollers.

The application range for the dynamic theory of plasticity [20—22] can be extended to the vibratory and vibro-impact soil compaction with the experimental confirmation that the speed with which the discharge stress waves spread in soil does not depend on the stress in the wave front.

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