Complex approach to the optimal energy efficient work pattern for vibratory roller

V V Mikheyev¹ S V Saveliev² Permyakov V B²
¹Omsk State Technical University, 11, Mira ave., Omsk, 644050, Russia
²Siberian state road and highway university, 5/2, Mira ave., Omsk, 644080, Russia

e-mail: vvm125@mail.ru

Abstract. Soil compaction of fills performed by surface force is a process of key importance for road construction. Road rollers represent the most widespread type of compactors. Improvement of both quality of compaction and output of roller is technological problem of great interest. The key point for its solution is optimal choice of combination of parameters which determine the force causing plastic deformation of the soil layer. Theoretical consideration of the process is given in the framework of interaction between massive elastoviscoplastic region of soil layer and source of external surface force. It naturally produces resonance criterion for the energy effective compaction. Minimum value of mechanical resonance in respect to external force allows to find the combination of working regime parameters for the given type of roller. Results of experiments involving sandy loam and clay loam proved the results of numerical modeling and gave key for recommendations on combined speed-frequency energy effective regime of compaction for given types of soils by smooth drum vibratory roller.

1. Introduction

Optimization of work patterns for compactor machines from the point of energy efficiency nowadays is one of the leading directions for enhancement of their performance, output and quality of compaction. The main investigation technique here is combination of computer modelling of compactor-soil interaction along with experimental tests in order to check the adequacy of model assumption as well as prediction ability of the theory. Experiments may involve real rollers etc. Modelling keypoint is a choice of the approach to the description of the roller’s work tool motion even considering the motion of the frame [1]. Usually for that purpose method of lumped parameters when system is presented as a combination of massive, elastic and viscous elements. Motion of the soil mass may also be considered from the point of lumped parameters approach as well as from the point of FEM [2] even when compaction is parasite side effect. Nevertheless when the uniform description of motion for the frame and work tools and massive soil region is required then consideration from the point of lumped parameter approach is more reasonable. [3].

Further development of soil compaction technologies some researchers find in innovative systems of automatic control and regulation [4] which makes compaction a subject of functioning for intellectual systems [5]. But one fact is worth mentioning here. Numerous authors while considering vibratory compaction of soils with various level of cohesion [6,7,8] come up with the same interesting conclusions about perspectives of traditional approach for determination of regime parameters of compaction dynamic action. It was discovered that motion of soil mass possesses resonance properties which show up as relevant maximum of energy consumption for the soil being compacted.
2. Formulation of the problem

Energy efficiency of vibratory rollers performing vibration or tamping compaction can be increased even in case of restricted action parameters of rollers and lack of abilities for automatic control and regulation as well. The task of the article is to prove criteria for the choice of combination of speed-frequency parameters of work regimes for vibratory rollers which deliver energy efficient compaction for clay and sandy loams for a given roller. Method is based on results of theoretical consideration of properties of interaction between work tool and soil layer and experimental results on compaction process as well. Together with that we use the presumption that energy efficient compaction is delivered by the combination of parameters which include both set of parameters of surface action on the soil along with mechanical characteristics of the soil media which can not be considered constant for all stages of compaction.

3. Theory

The basic of theoretical approach to the solution of the problem of practical choice of optimal combination of frequency of periodic force and roller’s speed is consideration of dynamic soil-cylindrical drum interaction. We use here modified lumped parameters developed in [3] and taking into account close to real distribution of stresses in the depth of the soil layer. Experimental approach to the use of resonance frequencies of vibratory rollers for compaction of non-cohesive soils was proposed in [9,10].

Let’s consider the layer of the soil material being stressed by the action of periodic surface force with harmonic type of time dependence

\[ F(t) = F_0 \sin(\omega t) = F_0 \sin(2\pi ft) \]

(1)

Where \( F_0 \) is an amplitude value, \( \omega \) is cyclic frequency, \( f \) is linear frequency.

Linear approximation of the equation of motion for the elastoviscoplastic region of the soil media according to algorithm proposed in [3] gives the solution,

\[ \Delta z(t) = \frac{F_0 \sin(\omega t + \phi)}{m\sqrt{\left(\omega_0^2 - \omega^2\right)^2 + k^2\omega^2}}, \quad \phi = \arctan\left(\frac{-k\omega}{\omega_0^2 - \omega^2}\right) \]

(2)

here \( \omega_0 \) is natural frequency of the corresponding massive elastic element of mass \( m \) and damping coefficient \( k \). Amplitude value of these forced oscillations can be defined as

\[ \Delta z_{\text{max}} = \frac{F_0}{m\sqrt{((\omega_0(y, \Delta z))^2 - \omega^2)^2 + k(y, \Delta z)^2\omega^2}} \]

After i-th period of reloading the soil layer retains residual plastic deformation which can be expressed as

\[ \Delta z_{\text{res}}^{(i)} = \frac{\alpha^{(i)} F_0}{m\sqrt{((\omega_0(y, \Delta z))^2 - \omega^2)^2 + k(y, \Delta z)^2\omega^2}} \]

(3)

Natural oscillations of the soil can be neglected because of overwhelming viscous properties of the soil and fast damping. Coefficient \( \alpha^{(i)} \) describes recovery of the soil deformation. Here we take into account dependence of the stiffness and natural frequency as well and coefficient \( k \) on deformation and area of contact spot between drum and soil surface. This is parametrized with length \( y \).

Denominator

\[ Z = m\sqrt{((\omega_0(y, \Delta z))^2 - \omega^2)^2 + k(y, \Delta z)^2\omega^2} \]

represents mechanical impedance of corresponding oscillating system. It determines how effectively soil consumes the energy of surface dynamic action. Figures 1 and 2 represent graphical dependences of inverse impedance of soil layer during the vibratory compaction by smooth drum rollers of different mass at different stages of compaction.
a) 1 - non-compacted soil; 2 - medium compacted soil; 3 - strongly compacted soil

b) 1 - non-compacted soil; 2 - medium compacted soil; 3 - strongly compacted soil

c) 1 - non-compacted soil; 2 - medium compacted soil; 3 - strongly compacted soil

Figure 1. Amplitude-frequency characteristics for reverse impedance $1/Z$ of active zone of soil layer being compacted with a) heavy, b) midsize, c) lightweight roller

Figure 2. Amplitude-frequency characteristics for reverse impedance $1/Z$ of active zone of soil layer being compacted with a) heavy, b) midsize, c) lightweight roller
Since that all plastic residual deformation after \( i \)-th cycle of action is a sum

\[
\Delta \varepsilon_{\text{res}i}^{(i)} = \sum_{k=1}^{i} \Delta \varepsilon_{\text{res},k}
\]

The problem of soil compaction intensification comes down to the maximum value of \( (6) \) with minimal time of action. This can be achieved by adaptation of frequency and strength parameters of the action.

4. Results of numeric and real experiments

Assumptions about influence of resonance properties of soil media were proven in the work of several specialists. For instance, Massarsch [8] and Wersäll and Larsson et al [9,10] show the importance of use of alternating frequencies of periodic compaction force. This is considered necessary condition for efficient compaction in case of non-cohesive soils.

Numeric experiments on soil compaction at different combination of speed and frequency were performed along tests of real rollers at presumably energy-efficient regimes which can be achieved according to their parameters. Results of calculation had shown fairly good correspondence with experimental data.

As initial data for numeric modelling were chosen results of tests of compaction on working frequencies and layers of recommended depth for medium size vibratory roller Stavostroj STA VHS 102K (sandy loam) and light vibratory roller DU-107 (clay loam). Table 1

| Technical specification of DU-107 roller | Technical specification of Stavostroj STA VHS 102K roller |
|----------------------------------------|----------------------------------------------------------|
| Work mass, kg                          | Work mass, kg                                            |
| 1500                                   | 10276                                                    |
| Amplitude of periodic force, kN        | Amplitude of periodic force, kN                           |
| 6.2                                    | 2x50                                                     |
| Drum width, mm                         | Drum width, mm                                           |
| 700                                    | 1 800,00                                                 |
| Drum diameter, mm                      | Drum diameter, mm                                         |
| 550,00                                 | 1 200,00                                                 |
| Work frequency, min\(^{-1}\), (Hz)     | Work frequency, min\(^{-1}\), (Hz)                       |
| 3768 (60)                              | 2 520,00 (42)                                            |

Initial relative densities for both sandy and clay loams were in range 0.82-0.84, water content was 0.91-0.94 of optimal value. Depths of sandy loam layers were 65 and 45 cm, speeds of roller varied in 2-6.5 km/h. Depths of clay loam layers were 35 and 25 cm, speeds of roller varied in 2-6.5 km/h. Depth of layers and speeds were chosen to be in usual working ranges for both types of soils. Modelling method developed in [3] allowed to investigate frequency characteristics of plastic deformation for the soil layer in case of compaction by given rollers at different speeds (Fig. 3 and 4).

**Figure 3.** Sandy loam plastic deformation after one pass of a roller at different initial densities while compacted by Stavostroj STA VHS 102K at a speed of 0.9 m/s (3.24 km/h)

**Figure 4.** Clay loam plastic deformation after one pass of a roller at different initial densities while compacted by DU-107 at a speed of 1,1 m/s (3,96 km/h)
Further investigations of the complex speed-frequency work regime of the roller were performed at the same framework of numerical modelling for drum-soil interaction. For different initial densities and speeds of the roller were obtained graphic dependences of accumulated for one pass of the roller (Figures 5 and 6).

**Figure 5.** Sandy loam plastic deformation as a surface a) depending on the speed of the roller b) and initial relative density c) while compaction by roller STA VHS 102K

**Figure 6.** Power spent on sandy loam plastic deformation as a surface a) depending on the speed of the roller b) and initial relative density c) while compaction by roller STA VHS 102K

Energy efficiency was estimated by the part of power which was transmitted to the soil layer and was spent for plastic deformation (Fig.6 and 8). There is strong connection between plastic deformation of
the layer after one pass and combination of soil modulus, dynamic stiffness, yield stress and their
dependences on soil stiffness as one can see on the graphs. The same can be obtained for power spent
on plastic deformation. These results and their connection with impedance of the active zone of soil
layer gave the clue for optimization approach to the choice of parameters of energy efficient rollers
work regime in practical applications.

Figure 7. Sandy loam plastic deformation as a surface a) depending on the speed of the roller b)
and initial relative density c) while compaction by roller DU-107

Figure 8. Power spent on sandy loam plastic deformation as a surface a) depending on the speed
of the roller b) and initial relative density c) while compaction by roller DU-107
5. Discussion

Results of numeric modelling and experiments involving real rollers had shown significant difference in resonance properties exposed by clay lam and sandy loam. Reason for that is difference in behavior of moduli and dynamical viscosities of two types of soils along compactions process. Anyway this fact can’t be neglected and must be taken into account when one tries to use resonance properties of the soil in order to enhance performance of soil compactor. Numerical criteria for this may be presented by mechanical impedance. Following steps present:

1. Functional dependence of length $y$ and shape of contact spot of work tool on it’s characteristics is given.
2. Stiffness and viscosity of active zone are being calculated in the framework of lumped parameters model as well as natural frequency $\omega_0(y)$.
3. Frequency of the external force $\omega$ is being tuned in order to minimize impedance and maximize residual plastic deformation.
4. Steps 2–4 are being repeated for the new values of stiffness, viscosity and yield strength of the compacted soil after each step of the roller. Flow chart for the algorithm is given on Fig.9

\[ Z = m(y_0(y,z) - \omega_0^2) + k(y,\Delta z)\omega^2 \]

\[ \Delta_{z_{res}}^{(i)} = \sum_{k=1}^{\text{res}} \Delta z_{res,k} \]

\[ k_y(t) \geq k_{y_{mpsi}} \]

**Figure 9.** Flow chart of the method of realization of energy efficient compaction pattern for smooth drum vibratory roller based on use of resonant properties of the soil
6. Conclusion

Dependences of parameters for energy-effective work patterns of compaction in sandy loam and clay loam revealed strong connection between resonant (natural) frequency of active zone of the soil layer and maximum value of plastic deformation gained by the layer for one pass of the roller. Difference of frequency–speed combination that deliver optimal value of plastic deformation of the layer may me explained using the different stiffness and viscosity dependences on relative density for clay and sandy loams. The data obtained in the work allowed to reveal the combination of work parameters of vibratory rod roller which maximize the output of the roller. For this purpose were use both criteria of energy efficiency resonant properties of active zone in soil layer. The work was supported by Russian foundation for basic researches (RFBR) in cooperation with Government of Omsk region №18-48-550005 p.a.

References

[1] Shiping Li and Chunhua Hu 2018 IOP Conf. Ser.: Earth Environ. Sci. 113 012187
[2] Ungureanu et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 163 012001
[3] Mikheyev V V and Saveliev S V 2018 J. Phys.: Conf. Ser. 944 012079
[4] Tikhonov Anatoly Fedorovich and Anatoly Drozdov 2018 IOP Conf. Ser.: Mater. Sci. Eng. 317 012042
[5] Mooney M A Rinehart R V Facas N W Musimbi O M 2010 Intelligent Soil Compaction Systems NCHRP Report 676. (Washington D. C.)
[6] Wersäll C Nordfelt I Larsson S 2018 Transportation Geotechnics 14 Pages 93-97.
[7] Li HJ Liu SY Tong LY and Xu XC 2018 Engineering Geology 246
[8] Massarsch K R and Fellenius B H Proceedings of the Institution of Civil Engineers - Ground Improvement 170:3 149-158
[9] Wersäll C Larsson S Rydén N and Nordfelt I Geotechnical Testing Journal 38 2 198-207
[10] Wersäll C Nordfelt I Larsson S 2017 Geotechnique 67 (3) 272-278.