Modeling of segmental excavator working tool for soil compaction

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Abstract. The development of a methodology for physical modeling of the working process and a replaceable working tool of an excavator for soil compaction in the construction, maintenance, and repair of man-made engineering structures in confined spaces are considered in the article. This methodology is based on a rheological model of the soil compaction process containing Hooke and Newton's elements connected in parallel (the Voigt model is the method of integral analogs that have been used to obtain the main similarity criteria that adequately characterize the process of static compaction during elastoviscoplastic soil deformation). The formulas for the transition from the model parameters to the parameters of the full-scale process of soil compaction by a segmental working tool are obtained based on similarity criteria for modeling the option without changing soil properties.

1 Introduction

The SWT is designed for static compaction of backfill soils in hard-to-reach and confined spaces during construction. The working tool of this type can be used as replaceable working equipment for mobile hydraulic excavators and presents a rigid cylindrical segment with a horizontal axis. Soil compaction is conducted by the positional method due to static pressure from the own weight of the SWT and static vertical surcharge from the side of the base machine under repeated alternating rotation of the segment provided by the drive mechanism.

The soil compaction processes, the rationale for the design and technological parameters of wheel rollers, compacting working equipment to multi-purpose machines such as hydraulic excavators, and their choice based on operating conditions were studied by such scientists as V.F. Babkov [1], V.I. Balovnev [2-4], G.V. Kustarev [5], N.Ya. Kharkhuta [6], V.V. Mikheev [7], S. Masayuki [8], K.R. Massarsch [9], K.J.Rustamov [10,11,12].

These scientists successfully solved several theoretical problems in the mechanical foundations of compaction of elastic-viscous-plastic media; they studied the main patterns of interaction between the working bodies of compacting machines and a deformable medium within the framework of various model approximations. However, the issues related to the energy efficiency of the soil compaction process in confined and hard-to-reach spaces have not been sufficiently studied.

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The advantages of the SWT when compacting soils in confined spaces as compared to a smooth compacting roller are the possibility of realizing a small amount of plane-parallel movement (a stroke) of the axis of rotation of the cylindrical surface of the working tool and the uniformity of the coefficient of material compaction within the specified stroke (a smooth roller is characterized by a decrease in the compaction coefficient at the initial and end sections of the stroke, corresponding to the modes of reversing the roller motion). The metal consumption of a segmented working tool is at least two times less than that of a smooth roller.

The choice of rational design parameters and modes of operation of the SWT and the evaluation of its effectiveness were conducted using PM methods, which can significantly reduce the complexity and cost of research [13-18]. The use of largescale PMs for the compaction of the most representative soils (in particular, loamy soils) allows the simplest way to establish the productivity of the process of soil compaction to a state of standard density and rational energy costs corresponding to this productivity.

The working process of a segmental compactor is characterized by three main parameters: a linear parameter (determining the characteristic length l, equivalent to the radius of curvature of the generatrix of the cylindrical surface of the 2 segment), a kinematic parameter (the compaction speed, i.e., the derivative of the determining angular parameter - the angle of rotation φ of the segment concerning time t equal to the angular velocity of the segment, or the equivalent linear speed of the segment's translatory motion), and the static force parameter (the pressure force of the segment on the compacted soil, equal to the sum of the weight force of the SWT and the vertical static surcharge on the working tool from the side of the base machine). These parameters determine the active impact of the SWT on the compacted material. Vertical and horizontal responses of the compacted material, balancing the active effect of the working tool, are determined by the rheological properties of the compacted soil. The connecting parameter that determines the balance of active and reactive forces is the characteristic length of the interaction zone of the segmental working tool with soil; at a sufficiently large axial size of the cylindrical segment, which determines the plane compaction problem, the characteristic size of this zone is the length of the arc or chord of the curved cylindrical contact surface of the compacting segment with soil. Under other explicit conditions, this characteristic size is derived from the characterizing length of the working tool - the radius of curvature of the cylindrical surface of the segment. In turn, as shown below, the characteristic length of the interaction zone determines the depth and efficiency of compaction. Suppose a segmental working tool with a variable radius of curvature of the generatrix is used during compaction, which can reduce the likelihood of slippage of the surface of the cylindrical segment relative to the compacted soil (as an unconditionally negative factor). In that case, the determining linear parameter of the system under consideration is the minimum or average integral radius R of curvature of the cylindrical segment. However, the system of necessary, sufficient similarity criteria should be supplemented with criteria that include the derivative of the radius of curvature of this segment by the angle of rotation of its radius relative to the vertical axis of symmetry of the segmental working tool. The model of the cylindrical working tool closest to the process of static soil compaction is the rheological model of the system "rigid wheel mover - deformable soil", considered in detail by Prof. V.I. Balovnev [19]. This rheological model applied to the SWT is shown in Fig. 1.

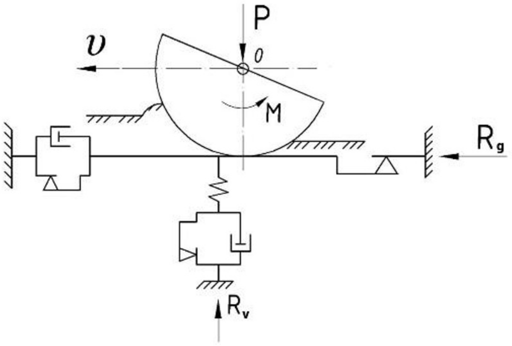

Fig. 1. Rheological model of process of soil compaction by rigid cylindrical segment.

The total horizontal soil response acting on the working tool is determined from the direction of the linear velocity vector ϑ of the plane-parallel movement of the rotary axis O of the segment by the resistance to viscous-plastic extrusion of soil in front of the working tool during compaction (the combined rheological Newton and Saint-Venant model); from the side opposite to vector ϑ, acts plastic resistance to soil shear under an active force of cohesion of the working tool to the soil, tangential concerning the cylindrical generatrix of the surface of the latter (Saint-Venant's rheological model) [27-33]. The vertical response of soil to the working tool is described by the elastic-viscous-plastic rheological Bingham model: the reversible elastic strain of soil, as the stress increases in the contact zone with cylindrical generatrix of the working tool surface, turns into the irreversible plastic strain of the soil compression, characterized by a decrease in the volume of the air phase inside the solid skeleton and is accompanied by viscous-plastic extrusion of soil from the zone of maximum stresses inside the compacted core along the path of least resistance into a bund formed in front of the cylindrical surface of the working tool from the side of the vector of the translatory motion of the working body, i.e., to the side of the day surface of the soil. A distinctive feature of this design scheme of the soil compaction process is the minimum length of the contact zone of the working tool with soil in the radial plane compared to the size of this zone, oriented along the rotary axis of the working tool, which determines a plane problem with minimal influence of edge effects of compaction by the side (end) surfaces of the working tool. On the contrary, the scheme of interaction of a rigid wheel with a deformable base is characterized by an excess of the length of the contact zone of the wheel with soil in the radial plane compared to the axial size of this zone. The fundamental significance of these distinctive features is explained by the fact that the minimum length of the contact zone of a cylindrical or another surface with the compacted soil determines the depth of formation of a compacted core and, thus, the depth of soil compaction to a given density value [18]. Therefore, for a rigid wheel, the width of which, as a rule, is less than the radius, the effect of soil compaction and its viscous-plastic flow, i.e., the passing ability of the wheel mover, is determined mainly by the width of the wheel, and for a smooth wheel roller or a cylindrical compacting segment, this effect is mainly determined by the radius of curvature of the cylindrical generatrix of the surface. At the same time, there are several similarities between the method of PM of the compacting SWT, discussed in detail below, to the method of modeling a wheel mover described by prof. V.I. Balovnev [19].

2 Materials and methods

Figure 2 shows the design scheme for determining the parameters and similarity criteria for the process of soil compaction by the SWT.

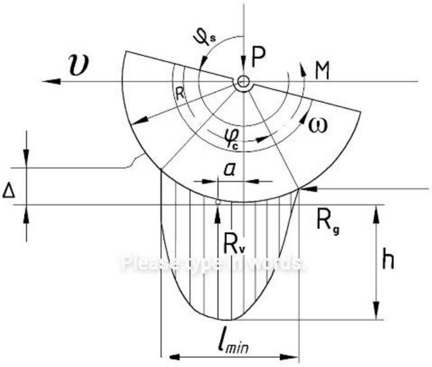

Fig. 2. Calculation scheme for determining parameters and similarity criteria for process of soil compaction by SWT.

When the working tool is rolled, the total absolute soil strain Δ is ensured, which is the sum of the reversible elastic strain $\varepsilon 1$ and the irreversible viscous-plastic strain ε.

$$\Delta = \varepsilon + \varepsilon_1 \qquad (1)$$

In turn, the viscous-plastic strain ε can be considered [6, 20, 21] as the sum of the plastic strain (shear) of soil and the strain appearing due to the viscous flow (the creep). Then the absolute strain can be represented as

$$\Delta = h\sigma\left[\frac{1}{E} + \frac{1}{G} + \frac{1}{\eta\chi}\ln(1+\chi t)\right] \qquad (2)$$

where h is the thickness of the compacted soil layer, m; G is the soil shear modulus, N/m^2; σ is the normal pressure of the SWT on soil, N/m^2; E is the modulus of elasticity, N/m^2; η is the coefficient of dynamic viscosity of soil, Ns/m^2; χ is the coefficient of variation in soil viscosity in time under the action of internal stresses, s-1; t is the characteristic time of the compaction process, s.

Following the rheological model of the soil compaction process (Fig. 1), the following main similarity criteria were obtained by the method of integral analogs, which adequately characterizes the process of static compaction with the elastic-viscous-plastic strain of soil:

$$\pi_1 = \frac{\sigma}{\gamma l};\ \pi_2 = \frac{\sigma}{E};\ \pi_3 = \frac{\sigma}{c};\ \pi_4 = \frac{\eta\vartheta}{\sigma l} \qquad (3)$$

where π_1 is the similarity criterion characterizing the ratio of the forces of normal pressure of the SWT on the soil to the forces of static pressure under the action of own weight of soil; $\pi 2$ is the similarity criterion characterizing the ratio of normal pressure forces to the forces of the elastic strain of soil; $\pi 3$ is the similarity criterion characterizing the ratio of normal pressure forces to the forces of internal cohesion of soil particles, which determine the plastic strain limit; $\pi 4$ is the similarity criterion that characterizes the ratio of normal pressure forces to viscous friction forces accompanying plastic extrusion of soil by the SWT from the zone of maximum static pressures (a compacted core) to the zone of minimum pressures - along the normal lines to the equivalent surfaces of the compacted core into the soil mass, which determines the viscous friction component of vertical response Rv , and towards the day surface of soil into a bunk formed in front of the working tool, which determines the component of the viscous friction of the horizontal response Rg; Γ is volumetric mass of soil, N/m3; l is the characteristic length of the modeled system; as shown above $l{\sim}R$, m; R is the radius of curvature of the cylindrical generatrix of the surface of the SWT, m; c is internal cohesion between particles of loose soil or fragments of a solid skeleton of cohesive soil; ϑ is the soil strain rate, identical to the speed of the translatory motion of the rotary axis of the SWT; in the absence of the working tool slippage on the soil surface

$$\vartheta = \omega R \qquad (4)$$

ω is the relative angular velocity of rotation of the SWT,

$$\omega = \varphi/t \qquad (5)$$

where φ is the current angle of the segment rotation; t is the characteristic time of the compaction process.

The strain (creep) of cohesive soil parabolically depends on the contact pressure σ applied to it and exponentially depends on the time t of strain development [22].

To describe the accumulation process of irreversible viscous-plastic strain ε during the creep of cohesive uncompacted soils, prof. N.Ya. Kharkhuta has proposed the following dependence [6]

$$\sigma = \eta(t)\frac{d\varepsilon}{dt} \qquad (6)$$

where the coefficient of dynamic viscosity η varies linearly as a function of time t of the strain process,

$$\eta = \eta_0(1+\chi t) \qquad (7)$$

η_0 is the initial coefficient of dynamic viscosity (viscous resistance); χ is the coefficient of variation in soil viscosity in time under internal stresses. At optimal moisture content, coefficient χ is a constant value; for heavy silty loam, it is $\chi = 2s^{-1}$ [6, 23].

When compacting cohesive soils, a change in the dynamic viscosity coefficient is identical to a change in the modulus of elasticity of soil [6].

Let us analyze the effect of the time-variable value of the dynamic viscosity coefficient η on the value of the similarity criterion $\pi 4$. Substituting expression (7) into criterion $\pi 4$, we obtain two similar criteria

$$\pi_4 = \frac{\eta_0(1+\chi t)\vartheta}{\sigma l}$$

$$\pi_5 = \frac{\eta_0\vartheta}{\sigma l}; \qquad \pi_6 = \frac{\eta_0\chi t\vartheta}{\sigma l}$$

Similarity criterion π_5 is completely similar to the original criterion $\pi 4$. Criterion $\pi 6$ is the product of two similarity criteria:

$$\pi_6 = \pi_5\pi_7$$

where $\pi_7 = \chi t = idem$

Similarity criterion π_7 determines the homochronism of the process of material compaction. From expressions (4) and (5), it follows that

$$t = \frac{\varphi}{\omega} = \frac{\varphi l}{\vartheta} \qquad (8)$$

Substituting dependence (8) into criterion $\pi 6$, we obtain

$$\pi_6 = \frac{\eta\chi\vartheta}{\sigma l} \cdot \frac{\varphi l}{\vartheta} = \frac{\eta_0\chi\varphi}{\sigma} = \pi_8 \cdot \pi_9$$
$$\pi_8 = \frac{\eta_0\chi}{\sigma}; \qquad \pi_9 = \varphi$$

where π_8 is the dynamic similarity criterion, similar to Newton's criterion π_5, considering the condition of homochronism, determined by the coefficient of variation of soil viscosity χ instead of the kinematic characteristic of the compaction process, determined by speed ϑ; π_9 is the simplex criterion that determines the geometric similarity of compaction processes. In this case, criterion π_9 characterizes not only the similarity of the angular displacements of the compacting working tool but also other characteristic angular parameters of the process, in particular, the central angle φc of the contact of the SWT with soil (Fig. 2).

Thus, the analysis conducted shows the consistency of the dynamic similarity criteria $\pi 5$ and $\pi 6$ ($\pi 5$ and $\pi 9$) and determines an additional simplex criterion of geometric similarity $\pi 9$.

The development of plastic strains in soil, as a whole, obeys the well-known Coulomb law [24, 25].

$$\tau = \sigma tg\rho_1 + c \qquad (9)$$

where τ are the tangential stresses in soil, characterizing its limiting equilibrium both during horizontal shear under the influence of a horizontal (tangential) force (Fig. 2) and during vertical subsidence of the compacted soil core under the working tool relative to the half-space of the soil surrounding this compacted core, which characterizes the irreversible vertical strain of soil under compaction; ρ_1 is the angle of internal friction of soil, which not only determines the linear dependence of shear stresses τ on normal stresses σ, but also characterizes the shape and volume of the compacted core.

Dividing both sides of expression (9) by the value of normal contact stresses σ, we obtain the following similarity criteria

$$\frac{\tau}{\sigma} = idem; \quad \rho_1 = idem; \quad \frac{c}{\sigma} = idem$$

The last similarity criterion has already been obtained by us earlier based on integral analogs, π_3. The simplex criterion $\pi_{10} = \rho_1$ determines the identity of the linear relationship between normal σ and tangential τ stresses in soil for different-scale compaction processes and the geometric similarity of the compacted core, which is formed in each case under the compacting working tool. When solving a plane problem, a compacted core can be characterized by two main geometric parameters: arc length $larc$ of the contact zone of a cylindrical compacting surface with soil,

$$l_{arc} = R\varphi_c \qquad (10)$$

and the depth of the compacted core h; the geometric similarity of the compaction processes is determined by the following criterion

$$\pi_{11} = \frac{l_{arc}}{h} = idem.$$

From geometric relationships, the length of the chord $l$ch that subtends the arc of contact of the compacting cylindrical surface with soil is given in Fig. 3.
Figure 3 shows the scheme for determining the minimum length of the contact zone of the SWT with soil.

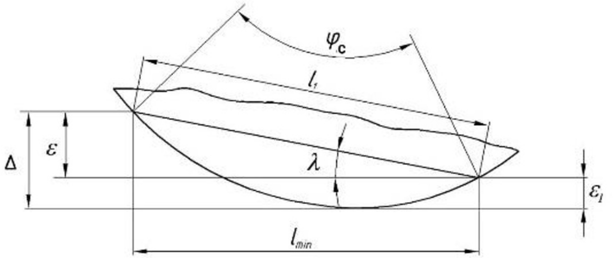

Fig. 3. Scheme for determining minimum length of contact zone of SWT with soil

From geometric relationships, the length of the chord $l$ch, which subtends the arc of contact of the compacted cylindrical surface with soil, is

$$l_{ch} = 2Rsin0{,}5\varphi_c \qquad (11)$$

Accordingly, the minimum length $lmin$ of the contact zone of the SWT with the compacted soil is

$$l_{min} = l_{ch}cos\lambda \qquad (12)$$

where λ is the angle of inclination of the chord lch relative to the horizon, which depends on the magnitude of the irreversible strain ε of soil,

$$\lambda = arcsin\frac{\varepsilon}{l_{ch}} \qquad (13)$$

ε is the absolute value of the irreversible plastic strain of soil. From expressions (11), (12), and (13), it follows that

$$l_{min} = 2Rsin0.5\varphi_c\sqrt{1 - (\frac{\varepsilon}{2Rsin0{,}5\varphi_c})^2} \qquad (14)$$

From expression (14) follows the relationship

$$\pi_{12} = \frac{l_{min}}{R}; \qquad \pi_{13} = \frac{\varepsilon}{R}$$

The similarity criteria π_{12} and π_{13} show that the absolute irreversible plastic strain ε of soil and the minimum length $lmin$ of the contact zone of the cylindrical working tool with soil change, all other conditions being the same, in the same way as the radius R of the curvature of the cylindrical surface, i.e., the change in these parameters, as well as the compaction depth h, taking into account simplex criterion ρ_1, is adequate to the change in the characterizing length in geometrically similar systems:

$$\varepsilon \sim l_{min} \sim h \sim R \sim l$$

This provision is a boundary condition for modeling and applies to SWTs and smooth wheel rollers. For SWTs with variable curvature of the cylindrical generatrix of the surface, the system of similarity criteria should be supplemented by a criterion characterizing the persistence of the current increment of the working tool surface curvature for similar polar, arc or Cartesian coordinates of the point of the determination of this curvature:

$$\pi_{14} = \frac{dR}{R\varphi d\varphi} = idem$$

where $R\varphi$ is the length of the characteristic arc of the working tool surface, reduced to a geometric similarity of a complex of linear and angular parameters characterizing the shape of the working tools. Similarity criterion $\pi 15$ = τ/σ obtained above from the Coulomb formula is an important basis for determining the energy similarity of compaction processes. The relationship between shear stresses and horizontal response Rg of soil is determined in the first approximation, for the total elastic-plastic strain of soil $\Delta \leq 10 \ldots 15R$, by the following dependence

$$\tau = \frac{R_g}{Bl_{min}} \tag{15}$$

where B is the width of the working tool. The validity of this assumption is explained by the small difference between the area of the curved cylindrical surface in contact with soil and the area of its projection onto the horizontal plane, as well as by the correction of the magnitude of stresses tangential to the cylindrical surface in their projection onto the horizontal line. At complete geometric similarity of the SWTs, the change in their width B correlates with the change in radius R of the generatrix curvature of the surface; therefore, B~l, and, as shown above, $lmin$~l. Then we can write

$$\pi_{15} = \frac{\tau}{\sigma} = \frac{R_g}{\sigma l^2}$$

3 Results and discussion

Thus, the geometric, kinematic, and dynamic similarity of soil compaction processes by the SWT is determined by the necessary and sufficient set of similarity criteria:

$$\pi_1 = \frac{\sigma}{\gamma l}; \; \pi_2 = \frac{\sigma}{E}; \; \pi_3 = \frac{\sigma}{c}; \; \pi_4 = \frac{\eta\vartheta}{\sigma l}$$

$$\pi_7 = \chi t \pi_5 = \frac{\eta_0\vartheta}{\sigma l}; \; \pi_6 = \frac{\eta_0\chi t\vartheta}{\sigma l} \; ;$$

$$\pi_8 = \frac{\eta_0\chi}{\sigma}; \;\; \pi_9 = \varphi, \pi_{10} = \rho_1 \;\; ; \pi_{11} = \frac{l_{arc}}{h} = idem.$$

$$\pi_{12} = \frac{l_{min}}{R}; \qquad \pi_{13} = \frac{\varepsilon}{R}$$

$$\pi_{14} = \frac{dR}{R\varphi d\varphi};$$

The necessary and sufficient similarity criteria equals the number of parameters included minus the number of dimensions used (mass, length, and two-time parameters of different scales). Based on a set of similarity criteria, formulas for the transition from the model parameters to the parameters of the natural process of soil compaction by the SWT were obtained to model the option without changing soil properties (see the table below).

Table 1. Formulas for the transition from model parameters to natural parameters of the soil compaction process by the SWT without changing soil properties

№	Parameters	Transition formulae
	Soil parameters	
1	Volumetric mass of soil	$\gamma_N = \gamma_M$
2	Elasticity modulus	$E_N = E_M$
3	Internal cohesion	$C_N = C_M$
4	Dynamic viscosity coefficient	$\eta_N = \eta_M$
5	Viscosity variation coefficient	$\chi_N = \chi_M$
6	Coefficient of internal friction	$\rho_{1N} = \rho_{1M}$
7	Coefficient of external friction	$\rho_{2N} = \rho_{2M}$
8	Shear modulus	$G_N = G_M$
9	Relative moisture content	$W_N = W_M$
	Working tool parameters	
10	Characteristic length	$l_N = l_M k_l$
11	Characteristic angular dimension	$\varphi_N = \varphi_M$
12	Compaction angular velocity	$\omega_N = \omega_M$
13	Design similarity coefficient	$A_N = A_M$
14	Vertical force	$P_N = P_M k_l^2$
15	Mass of the working tool	$m_N = m_M k_l^3$
	Compaction process parameters	
16	Static pressure on soil	$\sigma_N = \sigma_M k_l^2$
17	Shear stresses	$\tau_N = \tau_M k_l^2$
18	Soil strength	$\varepsilon_N = \varepsilon_M k_l$
19	The minimum length of the contact zone of the working tool with soil	$l_{min,N} = l_{min,M} k_l$
20	Compaction depth	$h_N = h_M k_l$
21	Moment of resistance to rotation of the working tool	$M_N = M_M k_l^3$
22	Capacity of the compaction process	$N_N = N_M k_l^3$

The limitation on the scale of modeling is such a decrease in the size of the SWT (compared to the natural dimensions), under which either the conditions that determine the plane problem of the compaction process are violated (especially with affine similarity with an intensive decrease in the width B of the SWT), or the characteristic dimensions of the working tool become comparable with the sizes of individual soil conglomerations. In these cases, the self-similarity is violated even if the parameters of the natural soil are maintained in the model processes and vice versa. The maximum linear scale for modeling similar processes is $k_l = 10 \div 15$.

4 Conclusion

1. It is appropriate to study SWTs for soil compaction using PM methods, which allow, at minimal material and labor costs, to assess the adequacy of the theoretical model of soil compaction by such working tools and confirm the reliability of the method for calculating rational design parameters and operating modes of SWTs and determine their effectiveness.
2. A characteristic feature of the scheme of the effect of a smooth cylindrical surface of compacting working tools on soil in comparison with the scheme of interaction of a rigid wheel mover with a deformable base is the location of the minimum size of the contact zone of the working tool with compacted soil in the radial plane; the minimum length of the contact zone and the depth of compaction of the material are determined by the segment of radius.

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