Design Validation of the Working Surface of a Sheep's Foot Roller for Compaction of Freshly Prepared Soil

D. Artemenko[1, a], V. Nastoyaschiy[1], V. Darienko[1]

1 – Central Ukrainian National Technical University, Kropivnitskiy, Ukraine

a – ingenerdu@gmail.com

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ABSTRACT. It is determined that the main factors which influence the process of soil compaction are the design of the roller working element and physical and mechanical characteristics of the soil. The process of interaction between the roller and the soil was studied with the help of math modelling. It was defined that the character of the contact pressure distribution under the roller surface corresponds to its design characteristics. A modified design of the roller drum and foot was introduced.

Introduction. Preparation of the construction site plays an important role in modern civil engineering work during the process of constructing buildings of agricultural purposes. One of the main stages is the preparatory compaction of the soil under the future foundation of the building and approach tracks. This technique allows avoiding such a negative phenomenon as surface subsidence and with time the building foundation and approach tracks ruining. A lot of construction equipment is used in this process and rollers of different types are the most popular machines (static [1], vibrating smooth wheeled rollers [2], vibrating pneumatic tired rollers [3]). Sheep's foot rollers, both of static and vibratory type, are considered to be the most effective as they are suitable for compaction of different types of soils. The main problem of construction rollers is unsatisfying compaction of the freshly prepared soil of the construction site for upcoming work. According to the specification documents [4-6] it is recommended to compact the soil of the site repeated layer by layer to make it ready for the construction work. It increases power consumption and prime cost of construction activity and also decreases general speed of work. For this reason it is important to increase operational efficiency of the roller for the preparatory compaction of the soil to the maximum depth and uniformity across the width.

Analysis of latest research. Static smooth wheeled rollers are the most popular rollers used for compaction of soil today. During his research Kushnarev A.S. [7] has found out that the smooth drum of the roller does not meet the requirements for the formation of the uniform compactness of the soil across the width and in depth.

Saveliev S.V. [8], while analyzing the work of smooth wheeled rollers, concludes that such a design does not provide the required state of the soil and it decreases their efficiency. This is the reason why this type of rollers is used in modern construction activity less and less. He thinks pneumatic tired rollers are more effective and their working surface has more opportunities for adjusting for compaction specifications. Usage of vibrating pneumatic tired rollers can essentially improve the soil compacting process and decrease its prime cost. The main disadvantage of such rollers is their low workability on non-cohesive soils. It greatly reduces their multipurposeness.

Improving the design of a construction roller, Dudkin M.V. [9] suggests changing its exterior outline in plane motion. He thinks it can greatly influence the uniformity of soil compaction.

In work [10] special attention is paid to the work of sheep's foot rollers and the peculiarities of their "feet". It was concluded that such rollers are better than smooth wheeled rollers for compacting the clayed soils.

Litvinenko T.V. [11] comes to a conclusion that sheep's foot rollers can be used for compaction lumpy soils. Feet crush lumps and make soil homogeneous over its thickness. It is useless to compact the upper layer of the earth fill with these rollers because the feet stir the soil. In this case it is better to use smooth wheeled rollers which make the surface smooth and even.

To be able to improve the design of construction rollers further we need clear understanding of how their working characteristics are formed. Experimental research [12, 13] proved the existence of stress fields and deformation of the inner soil body under the influence of compacting machines and because of this it is possible to say that their classification defines the main characteristic of the compacting process. So, designing the required working surface of a roller and its foot, one can substantially influence the quality of technical implementation of the process, especially providing uniform compaction of the soil across the width and in depth.

Work objective: improvement of uniform soil compaction across the width of the drum coverage and to the maximum depth through justification of a sheep's foot roller working surface design.

For achieving the objectives we solved the following problems:

to analyze the design of modern sheep's foot rollers to identify their advantages and disadvantages in the process of work;

to design an updated sheep's foot roller based on the detected disadvantages in the work of their drum and feet;

to prepare a mathematical model of the updated sheep's foot roller work and specify in general the character of contact pressure distribution under its working surface.

Statement of basic material.

The analysis of modern sheep's foot rollers work showed that both the design of the roller drum itself and the geometric form of the roller foot influence the quality of performance. The main disadvantages of the existing working elements are not uniform distribution of the soil compaction across the width and stirring of the soil by feet due to their design peculiarities. Thus it is necessary to continue further studies on validation of sheep's foot rollers working surfaces.

To avoid above mentioned disadvantages we introduced a roller [14], depicted in a two-level fig. 1; the first level (a roller drum) designed for the uniform compaction of the upper layer of the soil, the second level consists of the feet for the uniform compaction of the lower layer of the soil. The roller in question consists of side frames 1 with working arch curved surface 2, covered by overlapping barrel-shaped feet 3 placed on it on a spiral curve (further we consider that the drum and foot surface has an elliptical section).

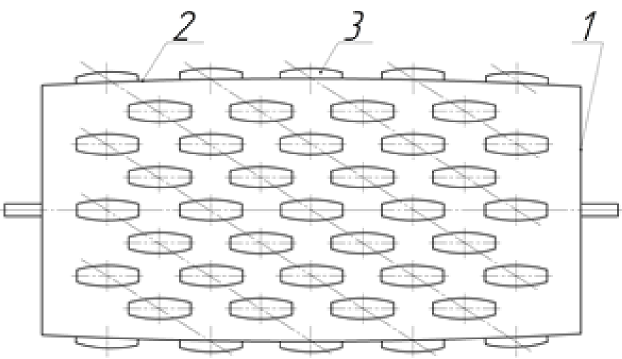

Fig. 1. A sheep's foot roller:

1 – side frames, 2 – working surface, 3 – feet

Work process of the suggested sheep's foot roller goes on in such a way: in the process the working surface 2 compact the upper layer of the soil uniformly and feet 3 placed on it on a spiral curve compact the lower layer of the soil uniformly providing uniform compaction of the soil across the width and in maximum depth.

The main factor with the help of which it is possible to define if the suggested design meets the requirements for the formation of the uniform compaction in the roller operating process is the character of the distribution of the load per surface unit across the width and to the depth.

It is possible to use methods of continuum mechanics [7, 12, 15] for creating a math modelling of the interaction process between a sheep's foot roller and soil in order to get the picture of the contact pressure distribution under it. Researches in continuum mechanics show that the hypothesis of continuity has a slight deviation from the results of the experimental research. That is why the soil can be regarded as a quasihomogeneous continuum the performance of which under pressure is defined by the balance of stress, deformation and their derivatives over time.

The interaction of the roller with the soil can be presented as the contact process of two objects which have different deformation moduli. A similar problem is considered in general in the theory of elasticity [16]. Due to symmetry a three-dimensional problem of the roller interaction with the soil can be narrowed down to a solution of a plain problem in which forms of the objects in contact are described with the help of functions: $y_1 = f_1(x)$ and $y_2 = f_2(x)$, where

$$y = y_1 + y_2 = f_1(x) + f_2(x) \tag{1}$$

On contact intervals $y = 0$:

$$f_1(x) + f_2(x) = 0 \tag{2}$$

As the result of compression the objects get axil motion along OY:

α_1 and α_2. Then $\Delta = \alpha_1 + \alpha_2$ is drawing of the compressed objects together.

Apart from the mentioned movement, spring-like movements are observed too U_1 and U_2 along axis OX. Final complete spring-like movement along axis OY equals:

$$\vartheta_1 + \vartheta_2 = \Delta - f_1(x - U_1) - f_2(x - U_2) \tag{3}$$

In case of slight displacement along axis OX there is:

$$f_1(x - U_1) \approx f_1(x) \text{ and } f_2(x + U_1) \approx f_2(x),$$

from which:

$$\vartheta_1 + \vartheta_2 = \Delta - f_1(x) - f_2(x) \tag{4}$$

Without taking into consideration the friction force we deal with the soil as a linear elastic environment to the border line of which standard pressure is applied $p(t)$. We use famous in the theory of elasticity Flamant problem (fig. 2).

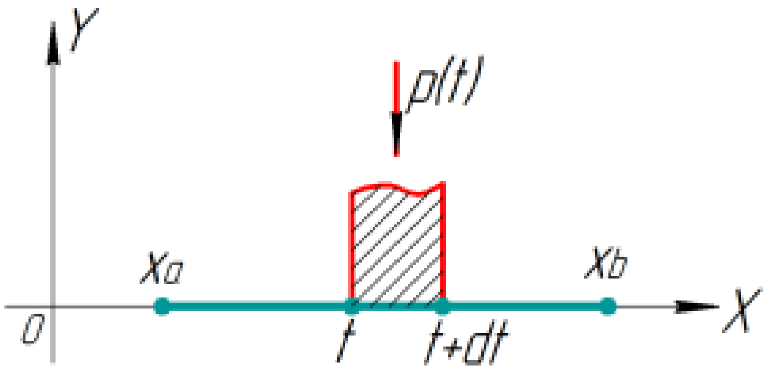

Fig. 2. The problem chart of standard force action on a spring half plane border.

Let us intercept a linear element on the contact line from point $x = t$ to $x = t + dt$, where the force $p(t)dt$ acts. Under the influence of concentrated force P the movement on the border of the contact line is:

$$\vartheta = -\theta p(t) \ln \frac{1}{|t - x|} + C, \tag{5}$$

where $C = const$ – a constant;

$|t - x|$ – distance between points of axis OX with abscissas x and t;

θ – elasticity composite index, which characterizes deformation properties of interacting materials:

$$\theta = \frac{2}{\pi E_d}\left(1 - \mu^2\right), \tag{6}$$

where E_d – deformation modulus (it has dimension Н/м2);

μ – poisson's ratio.

Force $p(t)dt$, applied to the border of half plane at the point $x = t$, causes in it elementary move in the direction of the force action:

$$d\vartheta = -\theta p(t) \ln \frac{1}{|t - x|} dt + C, \tag{7}$$

Movements ϑ_1 and ϑ_2 on the section of the contact line of the roller with the soil can be defined with the help of formulas:

$$\vartheta_1 = \theta_1 \int_L p(t) \ln \frac{1}{|t-x|} dt + C, \qquad (8)$$

$$\vartheta_2 = -\theta_2 \int_L p(t) \ln \frac{1}{|t-x|} dt + C, \qquad (9)$$

Taking into account total displacement and comparing right parts of the formulas (8), (9) and (4) we get an integral equation for pressure $p(x)$, which is the main one for solving plane contact problem of the theory of elasticity [16]:

$$(\theta_1 + \theta_2) \int_L p(t) \ln \frac{1}{|t-x|} dt = C - f_1(x) - f_2(x), \qquad (10)$$

where $\int_L p(t) \ln \frac{1}{|t-x|} dt = f(x)$ – is a function which depends on the form of pressing objects and their deformation properties;

L – contact line of the roller with the soil.

From equation (10), we have:

$$f(x) = \frac{C - f_1(x) - f_2(x)}{\theta_1 + \theta_2}, \qquad (11)$$

In equation (10) function $f(x)$ is considered to be given in the middle of the contact line border of the roller with the soil and defined from the statement of the problem.

Because the surface of the roller and the foot taken for the research has arch curved shape, we see its profile as a part of ellipse. In this case we can narrow down the problem to the definition of elliptically shaped deformer efficiency on the soil ground (fig. 3).

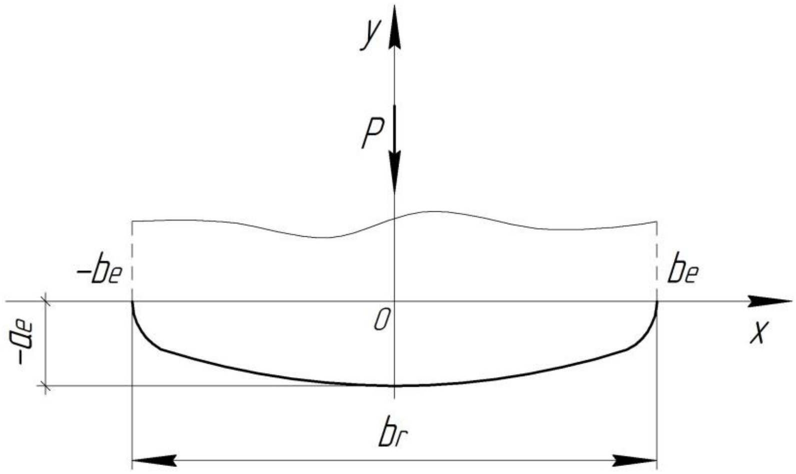

Fig. 3. Flow pattern for an elliptical deformer working on the soil ground.

In our case the sheep’s foot roller profile (fig. 3) is described in an equation:

$$f(x) = a_e - \frac{a_e}{b_e}\sqrt{b_e^{\,2} - x^2}\,, \tag{12}$$

where b_e – semimajor axis;

a_e – semiminor axis;

x – the coordinate.

In this situation the solving of the main contact problem equation of the elasticity theory makes it possible to get the pressure law under the working surface of the roller:

$$p(x) = \frac{C}{\pi b_r^{\,2}(\theta_1 + \theta_2)}\sqrt{b_e^{\,2} - x^2}\,, \tag{13}$$

where $b_r = 2b_e$ – the length of the contact area between the roller and the soil;

θ_1 – deformation constant of the roller material;

θ_2 – deformation constant of the soil.

As the real size of the deformer is unknown we will do the further research in relative units which depend on the roller surface material and physical and mechanical characteristics of the soil.

We reduce (13) to:

$$p(z) = K\sqrt{1 - z^2}\,, \tag{14}$$

where $K = \dfrac{C}{\pi b_r^{\,2}\left(\theta_1 + \theta_2\right)}$ - constant coefficient;

$$z = \frac{x}{b_e}.$$

Based on (14) we get the function characteristic curve in relative units (fig. 4).

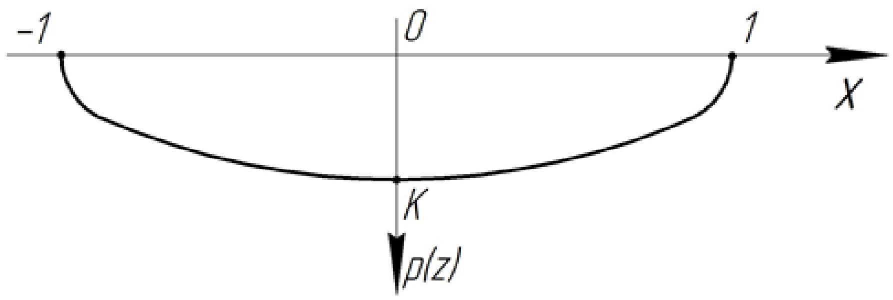

Fig. 4. General drawing of contact pressure on contact surface.

It is possible to see in fig. 4 that the character of the contact pressure distribution corresponds with the design peculiarities of the deformer. As the result, we can state that the geometry dimensions of the deformer are the main conditions which influence the final result – the formation of the necessary soil compaction on the whole contact area.

The math modelling under consideration makes it possible to take into account not only the characteristics of the roller working surface material, but its linear dimensions too while designing an updated sheep's foot roller. It is also possible to confirm that the coefficient *K*, which includes deformation properties of interacting materials θ_1 and θ_2, and the deformer linear dimensions (elliptic surface elements b_e and a_e), directly influence contact pressure level $p(x)$.

In general, if improved overlapping feet are placed on the drum surface we can state that the character of the contact pressure distribution across the width will look as in fig. 5.

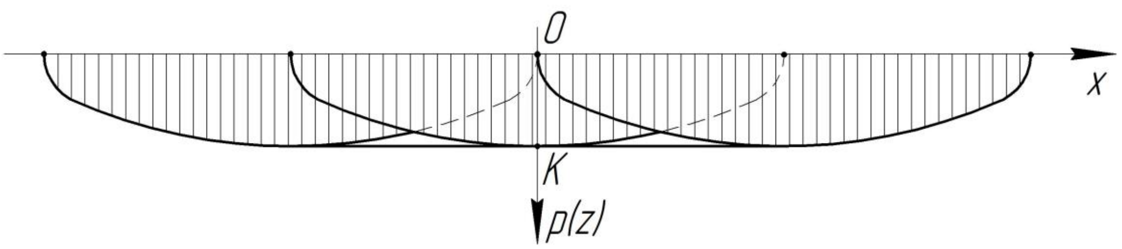

Fig. 5. Scheme of the contact pressure distribution after the pass of the sheep's foot part of the roller.

If to take into consideration that the drum surface also has an elliptical shape, which has much larger size than for the foot, we can say that the character of the contact pressure distribution on the contact surface will be the same with the above mentioned results.

The research results show that the character of pressure distribution under the suggested sheep's foot roller meets the requirements of the standardized documents as for the compaction of freshly prepared soil for the future construction site. But to define the rational value of the updated roller design parameters, additional experimental research with the help of simulation modelling and methods of planning an experiment is required.

Summary. 1. The analysis of the modern sheep's foot rollers operating allowed to define that their design does not meet all the requirements for getting maximum compaction of the soil across the width and to the depth per minimum passes and that is why we introduced a new design of a sheep's foot roller and formulated a math modelling of its work.

2. The suggested math modelling of the sheep's foot roller work allows defining the character of the contact pressure distribution depending on the design characteristics of the roller elements and physical and mechanical characteristics of the soil.

3. Modulus of deformation and coefficient of lateral expansion are its main characteristics which serve for the choosing technological and design factors of the sheep's foot roller.

4. Efficiency of the suggested compaction roller design is provided because thanks to the working surface and feet design it is possible to provide homogeneous compaction of the soil across the width and to the maximum depth and reduce the number of passes of the roller for the required compaction of the soil.

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