Formation of the soil foundation for the open storage areas

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Abstract. Precompaction of soil and construction materials used as the open storage areas foundations makes it possible to increase their bearing capacity. It ensures the stability of the material assets stacks of the foundation soil and their safety during the standard storage period. The research objective is to select and provide a theoretical basis to the technology of constructing the material assets open storage areas foundations. The design of the open storage area foundation and the operating element of its construction are proposed. Theoretical dependences describing the influence of the operating element design parameters on the characteristics of the soil foundation compaction are obtained. The analysis of the obtained dependencies makes it possible to define the operating element design parameters rational values for the particular soil conditions of the material assets open storage area.

Key-words: soil, compaction, open storage area, technology, attachments

1. Introduction

Currently, material assets are kept in the open storage areas not only in Russia and Kazakhstan, but also in a number of neighbouring countries, due to the limited capacity of the special storage areas. This leads to the degradation of the technical characteristics and operational properties of the stored objects over the years. During the long-term storage period in harsh environments of keeping the material assets, the problems related to ensuring the safekeeping and safe qualitative condition began to emerge [1, 2]. The analysis of the material assets state in the open storage areas showed that the main factors having influenced their safety are: changes in the physical and mechanical properties of the foundation soils, decomposition and destruction of the backing material (figure 1).

(a) is the structural failure of the wooden supports; (b) is sinking the wooden support into the soil
Figure 1. Instability of the material assets stacking in the open storage areas.

For preventing the emergencies due to instability of stacks in the storage areas, it is necessary to move the material assets packing cases every year. In addition, practical experience of the open storage areas operation shows that when restoring the foundations, the works are performed without the appropriate regulations and techniques [2].

2. Problem statement

Addressing the challenge of ensuring the material assets stacks stability concerning the foundation soil and their safekeeping in the open storage areas during the standard storage period is to improve the technology of their soil bases compaction under the force action of the specialized operating element (OE).

3. Processing

The need to increase the soil foundations bearing capacity of the material assets storage areas actualizes the search for the advanced soil foundations formation technologies and design improvement of the existing soil compacting equipment. The problem of ensuring the material assets stacks foundation soil stability in the open storage areas in different climatic zones and stochastic nature of soil deposits is solved by the preliminary preparation, namely, grading the existing soil foundation. The proposed processing sequence of constructing the open storage area soil base (1) includes step-by-step realization of the following technological operations: removing the topsoil, vegetation cover, roots, impurities and grading the pit by a bulldozer (2); the pits compaction by a tamping roller (3); unloading the local soil for filling the pit (4); grading the backfilled soil by a bulldozer (5); compacting the bulldozed soil by the tamping roller (6); the second unloading the local soil to form the mound in the area foundation (7); the second grading of the mound soil by a bulldozer (8); recompaction of the mound soil by a tamping roller (9) (figure 2) [3-5]. After forming the dispersed non-cohesive soil filling by applying the specialized OE, the compacted trapezium-shaped pits are formed (10 and 11) with following installation of the reinforced concrete supports for the material assets (12). At the final stage, there is filling the gravel (sandy gravel) of the compacted soil mound of the area with concrete supports and grading (13), then there are placing the material assets packages and forming the stacks in the open storage area (14 and 15).
Figure 2. Processing sequence of constructing the open storage area foundation for placing the material assets stacks.

The implementation of the above mentioned technological order of constructing the soil foundation makes it possible to increase the structure reliability of the open storage area and improve its bearing capacity. Therefore it will ensure the stability of the material assets stack for a long storage period. For carrying out timely engineering and technology measures, both to strengthen the existing soil foundations of the open storage areas and to construct new ones, the following is required:

- conducting the laboratory tests and field studies of soils deformation properties;
- setting the rational parameters of the OE structural elements to construct the foundation.

In the construction industry, a wide range of specialized soil compacting machines and mechanisms is actively used when constructing the roads and airfields [6]. However, the specifics of their application for constructing the material assets open storage areas require the additional study. For implementing the proposed technology of the open storage areas soil foundations construction, the attachable equipment design to form the compacted pits for the reinforced concrete supports, on which the material assets packages are installed, was developed. The attachable soil compaction equipment consists of the metal smooth roller 1 with a radius of $R_{RI}$ connected to the frame 2 by the front pin. The frame 2 with the roller 1 is rigidly connected to the pushing frame 3, which is pivotally connected to the base machine 5 by means of the fork pins 6. The attachable equipment with a specialized OE is lifted and lowered by the hydraulic cylinder 4 which is connected to the roller frame with the bracket 7. After compacting the soil with a smooth roller, a banding ring of $R_{BR}$ radius with a trapezoidal surface 9 is installed to form the pits (figure 3 a, b) [3].
Bandng rings made in the form of half-rings are bolted 10 to the roller on the special threaded holes, after removing the bolts of the plugs 8. The distances between the banding rings are set depending on the size of the material assets packaging of the formed stack in the open storage area.

The banding ring cross section is an isosceles trapezoid with a smaller base equal to $a$ and with a slope angle $\gamma$ of the cone-shaped side surface of the band to the plane perpendicular to the rotation axis of the specialized OE (figure 4).

It is obvious that the dynamics of the OE will be influenced by both the physical and mechanical properties of the foundation soil and geometric characteristics of the OE. This should be taken into account in structural and parametric connecting the base machine with the proposed attachments.

4. Theory

In the course of analytical studies, it is proposed to clarify the nature of the force interaction between the OE and the soil foundation in the process of forming a profiled compacted pits for the reinforced concrete supports. In the future, the analysis of the regularities describing the processes occurring in the «operating element-soil foundation» system will make it possible to define the OE design parameters rational values as well as the processing conditions [7-9]. In the process of the analytical studies, it is proposed to specify the nature of the force interaction between the OE and soil foundation when forming the graded compacted pit for the reinforced concrete support. Earlier studies have shown that the dependence between the applied stresses and resulting soil deformations is nonlinear [10-13]. Moreover, in sinking the operating element into the soil, the soil deformations development process is described by the complex system of differential equations [7]. The existing analytical and empirical dependencies generally take into consideration the stochastic nature of soil deposits on the construction sites and represent various rheological models [7, 14]. When conducting the analytical studies of the force interaction between the OE and soil foundation in the process of forming the graded compacted pit for the reinforced concrete support, the following assumptions are required to be introduced:

- the tractive effort of the base machine $P_{TE}$ and the soil loading force by the OE $P_C$ are constant;
- the soil filling compacted layer of thickness $h$ is prepared on the completely rigid bed;
a dispersive non-cohesive soil is an isotropic, compressible medium moistened to the optimal value and having the internal friction;

- soil is compacted in the direction perpendicular to the daylight soil surface under the action of the vertical compressive stress $\sigma_z$ caused by the OE weight action and its pressing force of the base machine hydraulic cylinders;

- soil compaction is caused entirely by the plastic deformations, there are no elastic deformations;

- the operating element consists of the cylindrical roller, on which $n$ identical sealing elements are installed, including two banding half-rings with two conical side surfaces (figure 3);

- the resistance to the rectilinear movement and to the operating element pressing into the soil caused only by the soil reaction force action.

In accordance with the accepted assumptions, complex shaped pits are formed under the impact of the operating element weight and its pressing force of the base machine hydraulic cylinders. The system «operating element-soil foundation» is in the equilibrium condition described by the following equation:

$$\sum F_z = 0$$

(1)

According to the accepted assumptions and calculation scheme shown in figure 4, equation (1) can be recorded in the following form:

$$P_C + Q - n \left( R_{BRC, z} + 2 \cdot R_{BRS, z} + R_{RL, z} \right) = 0$$

(2)

Where $P_C$ is the pressing force of the OE; $Q$ is the weight of the OE; $n$ is the number of the OE similar sealing sections; $R_{BRC, z}$ is the resultant force of the projections into the $OZ$ axis of the soil response to the load transmitted by the cylindrical part of the OE band; $R_{BRS, z}$ is the resultant force of the projections into the axis $OZ$ of the soil response to the load transmitted by one of the OE band sides; $R_{RL, z}$ is the resultant force of the projections onto the axis $OZ$ of the soil response to the load transmitted by the OE cylindrical roller.

In forming the compacted pit bottom with a width of $a$ from the banding ring cylindrical part, the $R_{BRC}$ reaction occurs in the soil. Let us mark the infinitesimal area, the center of which is defined by the angular coordinate $\alpha$ and the distance from the symmetry plane $XOZ$ of the operating element sealing section $y$ on the cylindrical section of the soil and OE banding ring contact zone (figure 4, 5).
Figure 5. Calculation scheme for determining the reaction on the cylindrical surface of the OE band.

Thus, the area $ds$ of the selected elementary area will be equal to:

$$ ds = dl \cdot dy $$ (3)

The projection on the axis $OZ$ of the soil response to the load transmitted by the OE band cylindrical part and influencing the elementary area is described by the equation:

$$ dR_{BR-C,z} = \sigma_z \cdot ds \cdot \cos \alpha $$ (4)

Taking into account equation (3), equation (4) can be recorded in the following form:

$$ dR_{BR-C,z} = \sigma_z \cdot \cos \alpha \cdot dl \cdot dy $$ (5)

where the value $dl$ is defined according to the formula:

$$ dl = r_{BR} \cdot d\alpha $$ (6)

When conducting the analytical studies of the OE and soil interaction, the empirical model establishing the dependence between the vertical compressive stress $\sigma_z$ which occurs in the soil when the OE is pressed into the soil and the resulting soil vertical relative deformation $\varepsilon_z$ [10] is proposed to be used:

$$ \varepsilon_z = k_1 \left(1 - e^{-k_2 \cdot \sigma_z}\right)^{k_3} $$ (7)

where $\sigma_z$ is the vertical compressive stress in the soil layer caused by the external loading action, MPa; $k_1$, $k_2$, $k_3$ are positive coefficients (>0) depending on the soil physical and mechanical properties and specified by the compression tests results.

The value of the soil layer relative vertical deformation $\varepsilon_z$ is calculated by the famous equation:

$$ \varepsilon_z = \frac{\Delta h_z}{h_0} $$ (8)

where $\Delta h_z$ is the soil layer vertical deformation resulting from the external load action;

$h_0$ is the initial thickness of the compacted soil layer.

Taking into account equation (8), let us solve equation (7) relative to the vertical compressive stress $\sigma_z$:

$$ \sigma_z = -k_4 \ln\left(1 - k_5 \cdot \Delta h_z^{k_6}\right) $$ (9)

where $k_4$, $k_5$, $k_6$ are positive coefficients (>0) depending on the coefficients $k_1$, $k_2$, $k_3$ calculated using the following formulas:
Whereas, the vertical deformation of the soil layer $\Delta h$ due to the external forces action is described by the following equation:

$$\Delta h = r_{BR} \cdot \cos \alpha - r_{BR} \cdot \cos \alpha_c = r_{BR} \cdot (\cos \alpha - \cos \alpha_c)$$

Therefore, taking into consideration equations (5), (9) and (11), the resultant force $R_{BRC,z}$ of the projections on the axis $OZ$ of the soil reaction to the load transmitted by the OE band cylindrical part, is calculated using the formula:

$$R_{BRC,z} = \int_{-a/2}^{a/2} \int_0^\alpha \left[ k_4 \ln\left(1 - k_5 \cdot (r_{BR} \cdot (\cos \alpha - \cos \alpha_c))^k\right) \right] \cos \alpha \cdot r_{BR} \cdot d\alpha \cdot dy$$

After transformations, equation (12) will have the following form:

$$R_{BRC,z} = -k_4 \cdot a \cdot r_{BR} \cdot \int_0^\alpha \left[ \ln\left(1 - k_5 \cdot (r_{BR} \cdot (\cos \alpha - \cos \alpha_c))^k\right) \right] \cos \alpha \cdot d\alpha$$

By analogy with equation (13) for the resultant force $R_{BRC,z}$ of the projections on the axis $OZ$ of the soil reaction to the load transmitted by the OE cylindrical roller, the following equation can be derived:

$$R_{RL,z} = -k_4 \cdot b \cdot r_{RL} \cdot \int_0^\beta \left[ \ln\left(1 - k_5 \cdot (r_{RL} \cdot (\cos \beta - \cos \beta_c))^k\right) \right] \cos \beta \cdot d\beta$$

To determine the soil response $R_{BRS}$ to the load transmitted by the side surface of the OE cone-shaped band, let us mark the infinitesimal area, the center of which is defined by the angular coordinate $\beta$ and the distance $r$ from the OE rotation axis on the lateral surface of the cone-shaped band contacting with soil (figure 6).

**Figure 6.** Calculation scheme for determining the reaction on the side surface of the cone-shaped band.

Thus, the area $ds$ of the selected elementary area on the side surface of the cone-shaped band is equal to:
\[ ds = \frac{dl \cdot dr}{\cos \gamma} = \frac{r}{\cos \gamma} \cdot dr \cdot d\beta \]  \hspace{1cm} (15)

where the value \( dl \) is defined according to the formula:
\[ dl = r \cdot d\beta \]  \hspace{1cm} (16)

The projection on the axis \( OZ \) of the soil response to the load transmitted by the side surface of the OE cone-shaped band and influencing the elementary area is described by the following equation:
\[ dR_{BRS,z} = \frac{\sigma_z \cdot \cos \beta}{\sin \gamma} \cdot ds \]  \hspace{1cm} (17)

Taking into account equation (15), equation (17) will have the following form:
\[ dR_{BRS,z} = \frac{\sigma_z \cdot r \cdot \cos \beta}{\sin \gamma \cdot \cos \gamma} \cdot dr \cdot d\beta = \frac{2 \cdot \sigma_z \cdot r \cdot \cos \beta}{\sin 2\gamma} \cdot dr \cdot d\beta \]  \hspace{1cm} (18)

The resultant force \( R_{BRS,z} \) of the projections on the axis \( OZ \) of the soil reaction to the load transmitted by one of the OE band sides, is proposed to be defined as the sum of two resultant forces \( R_{I,z} \) and \( R_{II,z} \) of the projections on the axis \( OZ \) of the soil reaction to the load on sections \( I \) and \( II \), correspondingly (figure 6):
\[ R_{BRS,z} = R_{I,z} + R_{II,z} \]  \hspace{1cm} (19)

The resultant force \( R_{I,z} \) of the projections on the axis \( OZ \) of the soil reaction to the load transmitted by the section \( I \) of the side surface of the OE cone-shaped band is calculated using the formula:
\[ R_{I,z} = \int_{\beta_1}^{\beta_2} \frac{2 \cdot \sigma_z \cdot r \cdot \cos \beta}{\sin 2\gamma} \cdot dr \cdot d\beta \]  \hspace{1cm} (20)

The soil layer deformation \( \Delta h_z \) caused by the external load impact of the side surface of the OE cone-shaped band is described by the equation of the following form (figure 6):
\[ \Delta h_z = r \cdot \cos \beta - r_{go} \cdot \cos \beta_c \]  \hspace{1cm} (21)

Thus, taking into account equations (9) and (21), equation (20) will have the following form:
\[ R_{I,z} = -\frac{2 \cdot k_4}{\sin 2\gamma} \int_{\beta_1}^{\beta_2} \ln\left[-k_5 \cdot (r \cdot \cos \beta - r_{go} \cdot \cos \beta_c)^\psi \right] \cdot r \cdot \cos \beta \cdot dr \cdot d\beta \]  \hspace{1cm} (22)

The resultant force \( R_{II,z} \) of the projections on the axis \( OZ \) of the soil reaction to the load transmitted by the section \( II \) of the side surface of the OE cone-shaped band is calculated according to the formula:
\[ R_{II,z} = \int_{\beta_2}^{\beta_f} \frac{2 \cdot \sigma_z \cdot r \cdot \cos \beta}{\sin 2\gamma} \cdot dr \cdot d\beta \]  \hspace{1cm} (23)

where the function \( f(\beta) \) is defined by the equation:
\[ f(\beta) = r_{go} + \frac{(r_{go} - r_{go}) \cdot (\beta - \beta_c)}{\alpha_c - \beta_c} \]  \hspace{1cm} (24)

Consequently, taking into consideration equations (9) and (21), equation (23) will have the following form:
\[ R_{II,z} = -\frac{2 \cdot k_4}{\sin 2\gamma} \int_{\beta_2}^{\beta_f} \ln\left[-k_5 \cdot (r \cdot \cos \beta - r_{go} \cdot \cos \beta_c)^\psi \right] \cdot r \cdot \cos \beta \cdot dr \cdot d\beta \]  \hspace{1cm} (25)

5. Results discussion
During the analytical studies, the equations (2), (13), (14), (19), (22) and (25) describing the interaction between the operating element and soil in the process of compaction were obtained. The preliminary analysis of the equations revealed that their analytical solution is not possible. The equations (2), (13), (14), (19), (22) and (25) are suggested to be solved by using the numerical method. The initial data for the numerical solution of the equations are:

- the deformation characteristics of soil;
• the design parameters of the OE attachments for compacting the soil by pressing.

The equations numerical solution results make it possible to define the OE rational parameters for the specific soil conditions of the open storage area. At the same time, it is obvious that the total value of the loading force of the soil by the hydraulic cylinders of the base machine $P_C$ and its weight $Q$ should not be less than the operating load value. The similar loads are required to be provided when conducting the compression tests of the compacted soil samples in the laboratory conditions and when conducting the experimental studies by using the OE models.

6. Conclusions
Accumulated material assets do not reduce the significance of the safety ensuring objective when placing in the open storage areas. The proposed technological solution to the problem is expected to reduce the risks of emergencies associated with the foundations soil instability of the material assets stacks. The suggested design of the OE will make it possible to implement the developed technology of the soil compaction for the reinforced-concrete supports. Determining the modes of the interaction between the OE soil compacting machines and mechanisms and the compacted soil space is the fundamental step when choosing the rational parameters and designing the similar technology systems. Therefore, the numerical solution of the obtained equations describing the foundation soil reaction to the compacting action of the specialized OE will make it possible to choose the OE rational parameters for the specific soil conditions of the material assets open storage area.

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