

Interaction of the Bored Sand and Gravel Drain Pile with the Surrounding Compacted Loam Soil and Foundation Raft Taking into Account Rheological Properties of the Loam Soil and Non-Linear Properties of the Drain Pile

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Abstract. The task of the interaction of the sand and gravel drain pile with the surrounding loam soil after its preliminary deep compaction and formation of the composite ground cylinder from the drain pile and surrounding compacted loam soil (cells) is considered in the article. It is seen that the subsidence and carrying capacity of such cell considerably depends on physical and mechanical properties of the compacted drain piles and surrounding loam soil as well as their diameter and intercellular distance. The strain-stress state of the cell is considered not taking into account its component elements, but taking into account linear and elastic-plastic properties of the drain pile and creep flow of the surrounding loam soil. It is stated that depending on these properties the distribution and redistribution of the load on a cell takes place from the foundation raft between the drain pile and surrounding soil. Based on the results of task solving the formulas and charts are given demonstrating the ratio of the load between the drain pile and surrounding loam soil in time.

1. Introduction

When performing construction on the soft loam soil of limited thickness the bored sand and gravel piles are frequently used which during the preliminary depth (radial) compaction serve as drains and subsequently together with the compacted surrounding loam soil as the bearing element inside a separate cell as a part of the combined piled-raft foundation.

The diameter of the cell and sand a gravel pile and the distance between the cells are taken according to the load on the raft (plate) and physical and mechanical properties of the cell soil after their preliminary compaction. Experimental research of the compacted soil and sand and gravel drain pile demonstrate that the drain pile is compacted and strengthened due to the colmatation (injection) of a part of the surrounding loam soil. And deformation module of the colmataged drain pile increases and reaches up to 100 MPa [1]. Together with that the deformation module of the compacted weak (5-10 MPa) loam soil rises up to 20 MPa, where the reduced deformation module of the cell as a whole rises up to 30-40 MPa. The load distribution process between the drain pile and surrounding soil starts under the load action on the cell through the raft (plate). A complicated, non-homogeneous strain-stress state occurs, which depends on the physical and mechanical properties of the drain pile and surrounding soil taking into account their compaction and strengthening as well as the drain pile and surrounding soil diameter ratio ($\omega = a^2 / b^2$). The necessity of providing the qualitative assessment of



the cell strain-stress state occurs, including the distribution of the general load between the drain pile and surrounding soil, and the general settlement of the cell over time [2].

The distribution of the general load on the foundation raft between the drain pile and surrounding compacted soil takes place provided that the pile foundation raft and surrounding soil settlement is equal, i.e. ($S_p = S_c = S_s$), where the equilibrium condition between the constant load on the foundation raft p and the sum of $\sigma_c(t)$ and $\sigma_r(t)$ variables is realized, so we have the following:

$$p = \omega \sigma_c(t) + (1 - \omega) \sigma_s \quad (1)$$

The present article considers the strain-stress state of the cell resting on a rather rigid basis ($G_{\text{nod}} \gg \overline{G}_{\text{яч}}$) taking into account different physical and mechanical properties of the drain pile and surrounding loam soil. It is taken, as the first approximation, that the cross impact on the contact pile - surrounding soil surface is absent, i.e. they get deformed under the compression conditions [3]. The formulation and solution of a number of tasks on evaluating the strain-stress state of the cell taking into account various properties of the drain pile and surrounding soil in the framework of the pile-stand analytical model is given below, assuming that $E_{\text{nod}} \gg E_{\text{яч}}$. (Figure 1)

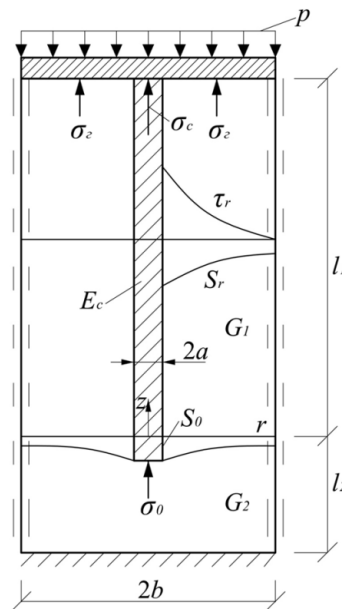


Figure 1. Design scheme of the pile with the surrounding soil (1 cell).

2. Strain-Stress State of the Cell in the Linear Position

In this case it is more convenient to use the relative compressibility coefficient m , i.e. when $m = E \cdot \beta(\gamma)$, where E is the linear deformation module, $\beta(\gamma) \approx 0,8$. Since in conditions of the compressive constriction of the "pile-surrounding soil" system the tangential stress doesn't occur, the task can be considered with the help of the linear deformation, i.e. $\varepsilon_{\text{яч}} = \varepsilon_c = \varepsilon_s = S/l$ where S is the raft settlement, l is the cell length. In this case we get that $\varepsilon = \overline{m} \cdot p$, $\varepsilon_c = m_c \cdot \sigma_c$, $\varepsilon_s = m_s \sigma_s$, where \overline{m} is the reduced relative compressibility coefficient of the cell as a whole [4]. Taking into account these dependencies and the equilibrium equation (1), we get the following:

$$\sigma_c = p \frac{m_r}{m_s \omega + m_c (1 - \omega)}; \quad \sigma_s = p \frac{m_c}{m_s \omega + m_c (1 - \omega)} \quad (2)$$

$$\bar{m} = \frac{m_c m_e}{m_e \omega + m_c (1 - \omega)}; \text{ or } \bar{E} = E_c \omega + E_e (1 - \omega) \quad (3)$$

From here it follows that the raft settlement as a whole is equal to

$$S_p = p \bar{m} l \quad (4)$$

3. Strain-Stress State of the Cell Taking into Account Creeping of the Loam Soil and Linear Deformation of the Drain Pile

In the course of distribution over time the conditions of equality of the deformation speed ($\dot{\varepsilon} = \dot{\varepsilon}_c = \dot{\varepsilon}_r$) will be in effect, and the equilibrium condition (1) with regard to $p = \text{const}$ takes the following form:

$$\dot{\sigma}_c \omega + \sigma_r (1 - \omega) = 0 \quad (5)$$

Let's take the modified rheological Maxwell's equations as the design equation for describing the creep flow of the surrounding soil with regard to the soil, i.e.

$$\varepsilon_e = \frac{\sigma_e(t)}{\eta_e(t)} + \dot{\sigma}_e m_e \quad (6)$$

where $\eta_e(t)$ is the loam soil viscosity coefficient under the compressive constriction.

In such case the deformation speed of the drain pile will take the following form:

$$\dot{\varepsilon}_c = \dot{\sigma}_c \cdot m_c \quad (7)$$

where m_c is the relative compressibility coefficient of the drain pile. Comparing (6) and (7) and taking into account (5) we get the following:

$$-\dot{\sigma}_r \frac{(1 - \omega)}{\omega} m_c = \frac{\sigma_r(t)}{\eta(t)} + \dot{\sigma}_r \cdot m_r \quad (8)$$

After several transformations of (8) we get the following:

$$\dot{\sigma}_r(t) + \sigma_r \frac{\omega}{\omega m_r + (1 - \omega) m_c} \cdot \frac{1}{\eta(t)} = 0 \quad (9)$$

with

$$\frac{\omega}{\omega m_r + (1 - \omega) m_c} = Q$$

Solution of this homogeneous differential equation can be given as follows:

$$\ln \sigma_r(t) = - \int \frac{Q dt}{\eta(t)} + C \quad (10)$$

with

C is the constant integration defined at $t = t_1 \cong 0$.

3.1. Let $\eta(t)$ Proportionally Increases over Time $\eta(t) = \lambda_1 \cdot t$

In this case we get the following:

$$\ln \sigma_r(t) = - \frac{Q}{\lambda_1} \ln(\lambda_1 t) + C \quad (11)$$

where C is determined from the initial condition:

$$\ln \sigma_z(t_1) = -\frac{Q}{\lambda_1} \ln(\lambda_1 t_1) + C$$

Substituting here from (2) the value $\sigma_z(t_1)$, finally we get the following

$$\ln \sigma_z(t/t_1) = -\frac{Q}{\lambda_1} \ln(t/t_1) \quad (12)$$

Taking into account that $\sigma_z(t_1)$ can be determined based on (2) from (12) we get the following

$$\sigma_z(t) = p \frac{m_c}{m_c \omega + m_c (1 - \omega)} \cdot \exp \left\{ -\frac{Q}{\lambda_1} \ln(t/t_1) \right\} \quad (13)$$

From here it follows that with $t = t_1$, $\sigma_z(t) = \sigma_z(t_1)$ over time $\sigma_z(t) \rightarrow 0$ and, hence $\sigma_c(t) \rightarrow p$. It is necessary to check the long bearing capacity of the pile, that is $\sigma_c(t) \leq p_c^*$. However, the fact that the soil compaction process depends on the $\lambda \ll 1$ coefficient, it should be expected that the load redistribution process on the foundation raft will last for a long period of time. Let's consider the fast strengthening process.

3.2. *With Fast Viscosity Increase We can Put down the Following* $\eta(t) = \eta_0 \cdot e^{\lambda_2 t}$
It follows from (10) that

$$\ln \sigma_r(t) = Q \frac{\lambda_2 e^{-\lambda_2 t}}{\eta_0} + c \quad (14)$$

From the initial condition $t = t_1 = 0$ we will determine the c . We get the following:

$$\ln[\sigma_z(t)/\sigma_z(t_1)] = -\frac{Q}{\eta_0 \lambda_2} (1 - e^{-\lambda_2 t}) \quad (15)$$

and finally

$$\sigma_z(t) = \sigma_z(t_1) \cdot \exp \left\{ -\frac{Q}{\eta_0 \lambda_2} (1 - e^{-\lambda_2 t}) \right\} \quad (16)$$

It is evident that with $t = 0$ $\sigma_z(t) = \sigma_z(t_1)$, and with $t \rightarrow \infty$

$$\sigma_z(\infty) = \sigma_z(t_1) \cdot \exp \left\{ -\frac{Q}{\eta_0 \lambda_2} \right\} \quad (17)$$

It follows hence from that under fast hardening of the loam soil $\sigma_z(t)$ doesn't tend to zero under $t \rightarrow \infty$ but to the constant value, i.e. $\sigma_r(t = \infty) = const$. Hence, the load distribution process on the foundation raft between the drain pile and surrounding loam soil can be stabilized over time [5]. In this case it is necessary to check the long bearing capacity of the pile, that is $\sigma_c(t) \leq p_c^*$.

4. Strain-Stress State of the Cell Taking into Account Elastic-Plastic Properties of the Drain Pile from the Sand and Gravel Mix (Sgm)

To determine the settlement of the drain pile under the action of the axial stress σ_c we will take the triaxial compression conditions in which the drain pile is located. In such case it is more convenient to use the Hencky's equation, so we have the following:

$$\varepsilon_c = \frac{\sigma_c - \sigma_m}{2\bar{G}_c} + \frac{\sigma_m}{\bar{K}_c} \quad (18)$$

where \bar{K}_c and \bar{G}_c are non-linear modules of the volume and shear deformation;

$\varepsilon_m = (\varepsilon_c + 2\varepsilon_3)/3$, $\sigma_m = (\sigma_c + 2\sigma_3)$, where ε_3 is the radial deformation equal to zero; σ_3 is the unknown lateral stress. With $\bar{G}_c \rightarrow G_c^e = const$, $\bar{K}_c \rightarrow K_c^e \rightarrow const$ the equation (18) coincides with the Hooke's equation. Let's take the following constitutive equations as a rated value to define the shear and volume deformations of the soil column:

$$\gamma_i = \frac{\tau_i}{G_c^e} \cdot \frac{\tau_i^*}{\tau_i^* - \tau_i}; \quad \varepsilon_c = \sigma_c m_c \quad (19)$$

where τ_i and τ_i^* are the intensity of effective and ultimate tangential stresses, accordingly, where

$$\tau_i = \sigma_m \cdot t_y \varphi_i + c_i \quad (20)$$

where φ_i and c_i are parameters of the ultimate line of the sand and gravel mix in the coordinates $\sigma_i - \sigma_m$,

where
$$\tau_i = \frac{\sigma_1 - \sigma_3}{\sqrt{3}}; \quad \sigma_m = \frac{\sigma_1 + 2\sigma_3}{3} \quad (21)$$

It follows from the equation (19) that

$$\bar{G}_c = G_c^e \frac{\tau_i^* - \tau_i}{\tau_i^*}; \quad \bar{K} = \frac{1}{m_c} \quad (22)$$

To determine the unknown radial stress σ_3 in the point of pile contact with the surrounding soil, let's take the condition $\varepsilon_3 = 0$, i.e. we get the following:

$$\varepsilon_3 = \frac{\sigma_3 - \sigma_m}{\bar{G}_c} + \frac{\sigma_m}{\bar{K}_c} = 0 \quad (23)$$

Substituting here the value \bar{G}_c and K_c from (22) and σ_m from (18) we will obtain the transcendental equation on σ_3 depending on σ_c . The solution of this equation, obtained by means of the Mathcad, as a dependency $\sigma_3 = f(\sigma_c)$ is given on Figure 2.

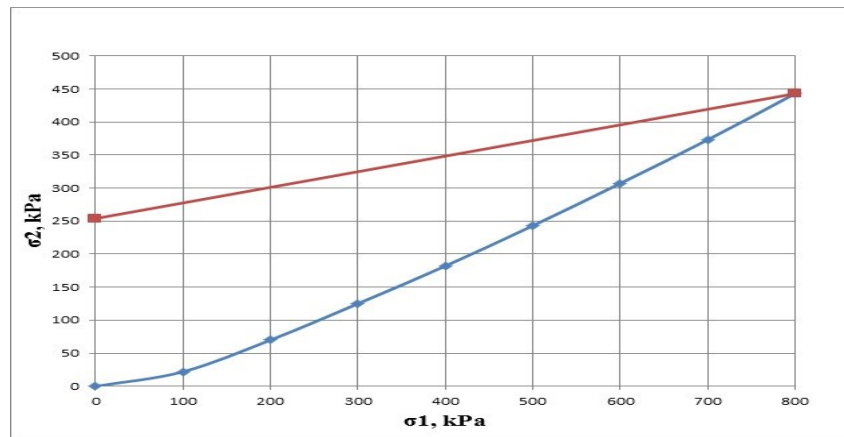


Figure 2. Dependency $\sigma_3 = f(\sigma_2)$ built based on (23) with the load (blue curve) and unloading (red curve).

Substituting the value $\sigma_3(\sigma_c)$ from the formula (19) and (22) we will determine the ε_c or ε_z . From the condition of equality $\varepsilon_c = \varepsilon_z$ we will get the dependency of the following form

$$\frac{\sigma_c - \sigma_m}{2\bar{G}_c} + \frac{\sigma_m}{\bar{K}_c} = \frac{\sigma_z}{E_z} \beta(v_z) \quad (24)$$

Substituting here the value σ_z from the equilibrium condition of the form (1) we will get the final dependency σ_c from the load p [6]. It allows determining the pile and foundation raft settlement in the following form:

$$S_p = S_c = \frac{\sigma_c - \sigma_m}{\bar{G}_c} + \frac{\sigma_m}{\bar{K}_c} \quad (25)$$

The dependence $S_p - p$ is given on Figure 3.

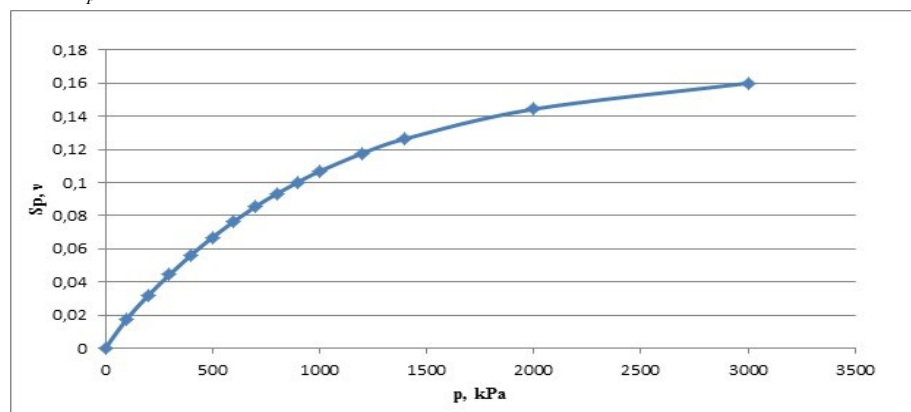


Figure 3. Dependence of the foundation raft settlement S_p from the distributed load p on the foundation raft.

5. Main Conclusions

A complicated and non-homogeneous strain-stress state occurs under the action of the distributed load on the foundation raft in the composite ground cylinder from the sand and gravel drain pile and surrounding compacted loam soil. The distribution and redistribution of stresses on the foundation raft

between the drain pile and surrounding loam soil takes place in space and over time. With the linear dependency of deformation properties and surrounding soil the distribution of stresses from the foundation raft takes place proportionally to their rigidity (2) and according to the equilibrium condition (1).

The interest ratio of total stress distribution on the foundation raft between the pile and surrounding loam soil depends substantially on physical and mechanical properties of the soil, pile and surrounding soil.

In case of the creep flow of the loam soil the stress on the foundation raft is redistributed over time and is transferred to the drain pile or partially depending on the speed of the loam soil strengthening.

In case of elastic-plastic properties of the drain pile and linear deformation of the surrounding soil the load from the foundation raft is distributed between the pile and surrounding soil inversely proportional to their rigidities, i.e. the pile \overline{G}_c and the surrounding soil \overline{G}_s provided the equilibrium condition of (1) is met, where the foundation raft settlement S_p non-linearly depends on the distributed load p .

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6. References

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