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The definition of necessary axial force for extension of initial borehole for soft soil compaction process design

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Abstract. The article provides an analytical solution of the soil pile and surrounding soil cylinder interaction problem, with the possibility of extension of the pile shaft in its construction. Presents a closed solution for determination of radial and tangential stresses in the process of expansion of the pile shaft, as well as the minimum vertical force sufficient for the crushing of the pile material and move it in radial direction to the specified value. The problem is most actual for compacted soil bases with use of piles-drains of sand and sand-gravel mixture.

1 Introduction

During construction on weak water-saturated clay soils, as a rule, use bored piles of finite stiffness, as well as jet-grouting piles or made of soil (sand, gravel) [1]. The last is used also as a drain on the preliminary stage of weak water-saturated soils compaction, and as a bearing element for subsequent loading of a compacted soil composed of the foundation [2]. Thus, soil pile – drain plays role of a filter and bearing element in the composition of the compacted weak soil layer. Major supporting part consisting of compacted weak layer is a clay cylinder, containing the pile – drain. Such a "cell" or "system" has the same properties as the surrounding cells of the converted layer. The dimensions of such cells are determined by the distance between their centers in a staggered arrangement of piles – drains. The diameter of piles – drains depends on the technology of their production during deep compaction, i.e. on the expansion of the initial borehole and fill it with sand – gravel mixture.

Thus, as the estimated model is considered a bearing massif consisting of a soil thick-walled cylinder enclosing a pile – drain and serves as the drain and as a supporting element in this column (fig. 1). Under the pressure of the foundation plate in this layer is formed a complex heterogeneous stress-strain state, which is in the process of loading can be transformed as a result of redistribution of load between the pile – drains and the surrounding soil up to the buckling pile – drains. It depends on numerous factors, including:

• diameter and length of piles-drains and the distance between them, i.e. the diameter of the bearing massif;

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• physical and mechanical properties of pile – drains, compacted surrounding and underlying soils;
• boundary conditions under the pile-drains and on the level of contact with the plate, and in contact with the surrounding soil and at the outer edge of the bearing massif.

2 The interaction between soil pile of finite stiffness and surrounding soil with a view to expanding its diameter

Define stress-strain state of the soil around the pile, including the contact between pile and soil. In the first stage is to determine the radial σ_r and tangential σ_θ stresses at the contact of the pile with the ground when you increase the diameter of the initial borehole by a given value u. Thus, by setting the value of the borehole extension u, we determine the stress in the surrounding soil massif.

Formulation and solution of the problems are considered in polar coordinates in terms of plane stress state, i.e. when σ_z=0. Consider stress-strain state a soil pile and surrounding soil separately, assuming that the contact between pile and soil radial displacement and stress are equal, i.e. when r=r_c.

$$u_{rc} = u_{rs}\,,\ \sigma_{rc} = \sigma_{r2} \tag{1}$$

From the condition of equal deformation the settlement of foundation plate, piles and surrounding soil are equal:

$$S_p = S_c = S \tag{2}$$

On the outer boundary of the soil cylinder there is a condition of the lack of radial movement, i.e. u_{r2}=0.

Additionally, there is an equilibrium condition between the load of the slab and stresses in the pile and the surrounding soil , i.e. have:

$$p = \sigma_{z1} \cdot \omega + \sigma_{z2} \cdot (1-\omega)\,, \tag{3}$$

where $\omega = r_1^{\ 2} / r_2^{\ 2}$, r1 and r2 – initial radius of the pile and radius of the cell respectively.

The original equations to solve this problem in cylindrical coordinates are [7]:

geometric equations:

$$\varepsilon_r = \frac{du}{dr}, \varepsilon_\theta = \frac{u}{r}, \varepsilon_z = \frac{dw}{dz}\,, \tag{4}$$

physical equations :

$$\sigma_r = 2G\left(\frac{du}{dr} + \frac{\nu}{1-2\nu} \cdot \varepsilon_V\right),\ \sigma_\theta = 2G\left(\frac{u}{r} + \frac{\nu}{1-2\nu} \cdot \varepsilon_V\right),$$
$$\sigma_z = 2G\left(\frac{dw}{dz} + \frac{\nu}{1-2\nu} \cdot \varepsilon_V\right), \tag{5}$$

where ε_V - volumetric deformation, is defined as follows , G – shear modulus, ν – Poisson's ratio.

$$\varepsilon_V = \varepsilon_r + \varepsilon_\theta + \varepsilon_z = \frac{du}{dr} + \frac{u}{r} + \frac{dw}{dz} \ . \tag{6}$$

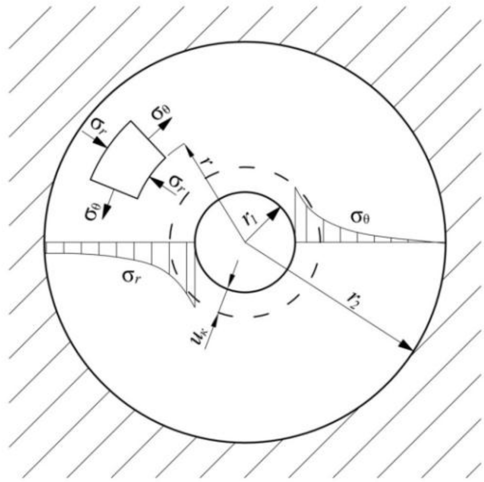

Fig.1. The scheme of increasing the diameter of the initial borehole in the process of pile construction

On the basis of joint consideration of geometric (4) , physical (5) equations and the equilibrium equations (3), the problem of stress-strain state of the soil cylinder can be reduced to the solution of the differential equation in displacements [8]:

$$\frac{d^2u}{dr^2} + \frac{1}{r} \cdot \frac{du}{dr} = \frac{u}{r^2} \tag{7}$$

The solution of this equation is known and has the following form:

$$u = A \cdot r + \frac{B}{r}, \tag{8}$$

where A and B – the constants of integration, that are determined from boundary conditions : when $r=r_1$ $u=u_1$, when $r=r_2$, $u=0$.

Substituting these values in (8) we get:

$$A = \frac{u_1 \cdot r_1}{r_1^2 - r_2^2} \ , B = -\frac{u_1 \cdot r_1 \cdot r_2^2}{r_1^2 - r_2^2} \ , \tag{9}$$

and finally :

$$u = \frac{u_1 \cdot r_1}{(r_1^2 - r_2^2)} \cdot (r - \frac{r_2^2}{r}) \tag{10}$$

Given that $\sigma_z = const$, the first two equations (5) can be represented as:

$$\sigma_r = \frac{E}{(1+\nu)(1-2\nu)} \cdot \left[\frac{du}{dr} + \left(\frac{\nu}{1-\nu} \right) \left(\frac{u}{r} + \frac{dw}{dz} \right) \right],$$

$$\sigma_\theta = \frac{E}{(1+\nu)(1-2\nu)} \cdot \left[\frac{u}{r} + \left(\frac{\nu}{1-\nu} \right) \left(\frac{du}{dr} + \frac{dw}{dz} \right) \right] \tag{11}$$

Values $\frac{u}{r}$ and $\frac{du}{dr}$ can be determinated from (8) with (9). Then we have :

$$\varepsilon_r = \frac{du}{dr} = A\left(1 + \frac{r_2^2}{r^2}\right), \ \varepsilon_\theta = \frac{u}{r} = A\left(1 - \frac{r_2^2}{r^2}\right). \tag{12}$$

Then we get expressions for the radial and tangential stresses in final form:

$$\sigma_r(r) = \frac{E}{1-\nu^2} \cdot \frac{u_1 \cdot r_1}{r_1^2 - r_2^2} \left[1 + \nu + \frac{r_2^2}{r^2}(1-\nu) \right] \tag{13}$$

$$\sigma_\theta(r) = \frac{E}{1-\nu^2} \cdot \frac{u_1 \cdot r_1}{r_1^2 - r_2^2} \left[1 + \nu - \frac{r_2^2}{r^2}(1-\nu) \right]. \tag{14}$$

It follows that:

$$\sigma_r + \sigma_\theta = \frac{2E}{1-\nu} \cdot \frac{u_1 \cdot r_1}{r_1^2 - r_2^2}. \tag{15}$$

Then at $r=r_1$ (maximum value) and $r=r_2$ (minimum value):

$$\sigma_{r1} = \frac{E}{1-\nu^2} \cdot \frac{u_1 \cdot r_1}{r_1^2 - r_2^2} \left[1 + \nu + \frac{r_2^2}{r_1^2}(1-\nu) \right], \ \sigma_{r2} = \frac{2E}{1-\nu^2} \cdot \frac{u_1 \cdot r_1}{r_1^2 - r_2^2}. \tag{16}$$

To find the necessary vertical load that needs to be passed through ramming equipment to the soil massif, we have to use the equation of limit equilibrium, where the principal stresses will be present by vertical and radial stresses. The vertical stress must be limit to tamp the layer of material has exhausted its strength, it collapsed and took its proper position in the already enlarged borehole.

The limit equilibrium equation can be written as:

$$\frac{\sigma_z^* - \sigma_r}{\sigma_z^* + \sigma_r + 2c \cdot ctg\varphi} = \sin\varphi. \tag{17}$$

Then we can express the value of the vertical stress:

$$\sigma_z^* = \frac{\sigma_r(1+\sin\varphi) + 2c \cdot \cos\varphi}{(1-\sin\varphi)} \tag{18}$$

Then a necessary load that needs to be applied through the compression equipment to the soil massif, is determined by the formula:

$$N^* = \pi \cdot r_1^2 \cdot \sigma_z^*, \tag{19}$$

where σ_z^* can be found from (18).

Thus, for the design process of material compression into the borehole it is necessary to determine the design diameter of the reinforcing pile-drains and its pitch. Next, we can determine radial stress in the soil in process of extension of the initial borehole to design value and determine necessary compression force for selection the equipment at the construction site.

For example, consider the stress state masiva soil with the following initial data:

r1=0.2 m, *u*=0.1 m, *E*=15 MPa, *v*=0.3 r2=1 m, *c*=1 kPa, $\varphi = 30^\circ$.

Then, we have values of $\sigma_r = 6456$ kPa and $\sigma_\theta = 19360$ kPa.

And, finally, *N**=2433 kN=243.3 t.

3 Conclusions

1. The stress state of soil around an expanding initial borehole can be determined on the basis of geometrical and physical input equations of the classical theory of elasticity.
2. Using the limit equilibrium equation it is possible to determine the maximum value of vertical stress for compacted column of soil required for crushing on a certain design value.

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