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THEORETICAL SUBSTANTIATION OF THE MECHANISM PATTERNS OF THE MANMADE BASE “STRUCTURAL GEOTECHNICAL SOLID”

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Abstract. When building on weak water-saturated soils, manmade base in the form of a "structural geotechnical solid" are increasingly used. The article provides a theoretical substantiation for the use of a model of a transversally isotropic material with the given deformation characteristics for the design of such structures. The problem of determining the radius of a rigid cylindrical element during its formation in an elastic-plastic porous medium under normal pressure of jet-grouting of soil is considered. A method is proposed for determining the effective modulus of deformation of a "structural geotechnical solid" with the allocation of a representative volume – a periodicity cell, within which the geometric averaging of deformation characteristics is performed depending on the volume contribution of its components. Analysis of the results of modeling the joint operation of the base-building system using the proposed base model showed the effectiveness of its application.

Keywords: weak water-saturated soil; structural geotechnical solid; jet-grouting

ТЕОРЕТИЧЕСКОЕ ОБОСНОВАНИЕ ЗАКОНОМЕРНОСТЕЙ ПОВЕДЕНИЯ ИСКУССТВЕННОГО ОСНОВАНИЯ «СТРУКТУРНЫЙ ГЕОТЕХНИЧЕСКИЙ МАССИВ»

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Аннотация. При строительстве на слабых водонасыщенных грунтах возрастающее применение находят искусственные основания в виде «структурного геотехнического массива». В статье приводятся теоретическое обоснование использования для проектирования таких конструкций модели транверсально-изотропной среды с приведенными деформационными характеристиками. Рассматривается задача определения радиуса жесткого цилиндрического элемента при формировании его в упруго-пластической пористой среде под нормальным давлением струйной цементации грунта. Предлагается методика определения эффективного модуля деформации «структурного геотехнического массива» с выделением представительного объема – ячейки периодичности, в пределах которого выполняется геометрическое усреднение деформационных характеристик в зависимости от объемного вклада его составляющих. Анализ результатов моделирования совместной работы системы основание-здание с использованием предлагаемой модели основания показал эффективность ее применения.

Ключевые слова: слабый водонасыщенный грунт; структурный геотехнический массив

INTRODUCTION

Artificial bases are used in cases where compliance with regulatory requirements for limiting the difference in the settlement of foundations of buildings and structures is not ensured, or this is technically difficult and economically ineffective [1–4]. In weak water-saturated soils, artificial bases are increasingly used in the form of a structural geotechnical solid [5, 6]. The study of the state of the art has shown that the choice of design methods and the technology of artificially improved bases in most cases is carried out experimentally on the construction site and the obtained solution was not always optimal [7]. In this regard, the development, on the basis of experimental and theoretical studies, of the calculation and design methodology for one of the types of artificial bases with specified physical and mechanical characteristics – "structural geotechnical solid" is an urgent problem.

The structure of the structural geotechnical solid (Fig. 1) consists of a weak initial soil (2), rigid reinforcing soil-concrete elements (1) and a flexible distribution grillage (3) [8].

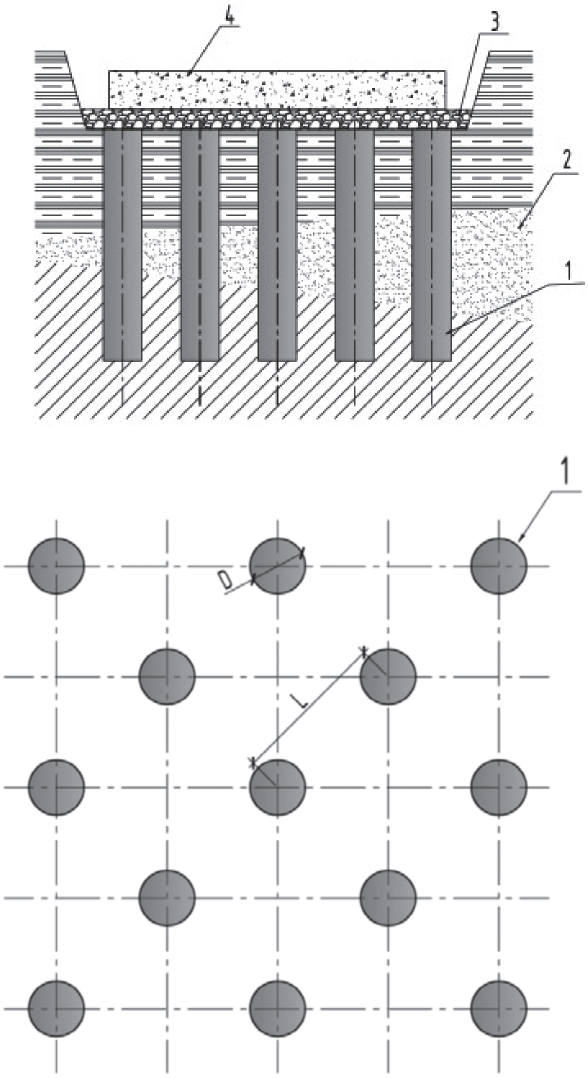

Figure 1. Construction of an artificial foundation "structural geotechnical solid"

In the course of modeling the joint operation of the building-foundation-base system, the required diameter (D) and the spacing of the reinforcing elements (L) are determined.

In this paper, an artificial base is considered, reinforced with vertical rigid cylindrical elements, performed using the technology of jet grouting of the soil [9.10].

1. MODEL OF VERTICALLY REINFORCED SOIL BASE - STRUCTURAL GEOTECHNICAL SOLID

The base model should be adequate for the accuracy of the initial data and the required accuracy of the final results of the calculation of the "building-foundation-base" system [11]. Due to the large variety of types of base soils, conditions for the addition of solids, etc., none of the existing models is universal and is used only for certain specific types of soils.

To construct a mechanical model of "structural geotechnical solid", we apply the approach used in geomechanics to describe the behavior of a rigid body with a structure [12].

“Structural geotechnical solid” is represented as an ideal continuous medium, the deformations of which are linear with respect to external forces, if only the internal stresses in the soil do not exceed the limiting values. At the same time, in a solid body, heterogeneities (soil-concrete reinforcing elements) are evenly scattered over the volume, and the distance between them is much larger than their own size. These inhomogeneities are responsible for irreversible deformations: stresses are concentrated on them and they relax in time. Let us accept this mechanism of energy dissipation as the only one.

Taking into account that inhomogeneities occupy a small fraction of the volume, the deformations of the structural geotechnical solid have been characterized only by the values averaged over space. The uneven distribution of stresses within the geotechnical solid qualitatively distinguishes the proposed model: they consist of two components – general stresses caused by a change in volume or distortion of the shape and local stresses on inhomogeneities.

At high rates of deformation, stresses on inhomogeneities lead to an increase in the rigidity of the structural geotechnical solid, and under dynamic influences, to an increase in effective strength ("dynamic strength"). The proposed mechanical model of "structural geotechnical solid" allows us to consider classical problems of determining stresses and deformations arising under the influence of external forces, but not limited to finding equilibrium parameters, since after the application of a load in the soil mass, irreversible deformations and stress relaxation on inhomogeneities continue.

In this case, to describe the behavior of the "structural geotechnical solid", one can use the models of the linear theory of elasticity and the creep model, and also consider the process of attenuation of elastic seismic waves.

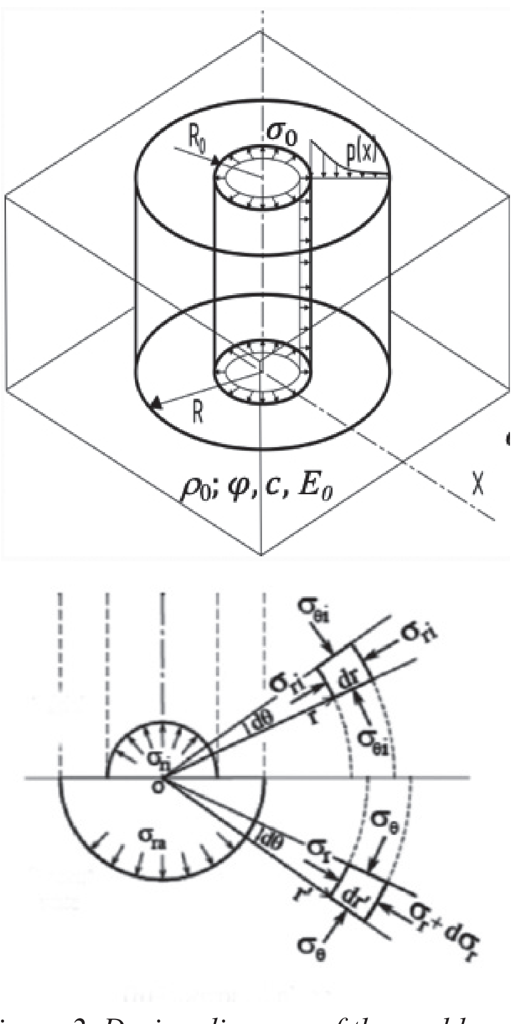

Figure 2. Design diagram of the problem of forming a cylindrical element

2. CYLINDRICAL ELEMENT SIZE IN ELASTIC MEDIUM

One of the main theoretical problems is to determine the required radius of a soil-concrete element in an elastic-plastic porous medium under the action of normal pressure of jet cementation (σ_0). In the papers [13, 14], analytical solutions to the problem of the development of a cylindrical well are given taking into account the elasticity and plasticity of materials. The problem was considered when a hard core penetrated into a soil environment. Let us apply the development of these solutions to the problem of the formation of a soil-concrete element in a soil environment during jet grouting. Let us determine the size of the expansion zone taking into account the final deformations and the dependence of the yield point on pressure.

Figure 2 shows the calculation scheme of the problem. The soil medium is characterized by an initial density – ρ_0; internal friction angle – φ; specific adhesion – with and modulus of deformation E_0.

In order to find the boundary between the area of plastic yield and the area of elastic compression of the porous medium under the action of jet grouting pressure, the motion of a material particle of a cement solution in a soil medium is considered, described by the following equation:

$$\rho_0 r \frac{\partial v}{\partial t} = x \frac{\partial \sigma_r}{\partial r} + (\sigma_r - \sigma_\theta) \frac{\partial x}{\partial r} \qquad (1)$$

Joint solution of the system of physical equations of state of the medium:

- for an elastic area

$$\frac{\partial S_i}{\partial t} = 2G \left(\frac{\partial \varepsilon_i}{\partial t} + \frac{1}{3\rho} \cdot \frac{\partial \rho}{\partial t} \right) \qquad (2)$$

- for a plastic area

$$\sigma_r - \sigma_\theta = -\tau_0 + \mu(\sigma_r + \sigma_\theta);$$
$$\tau_0 = 2c \cdot cos\varphi; \;\; \mu = sin\varphi. \qquad (3)$$

and the closing equation of the soil medium:

$$p = 3K\varepsilon_p \frac{\ln \rho_0 - \ln \rho}{\ln \rho_0 - \ln \rho - 3\varepsilon_p} = K\left(\frac{\rho_0}{1-\rho}\right) \quad (4)$$

allows you to obtain the equation of the separation boundary of the plastic and elastic zones from the relation

$$\frac{\partial x}{\partial r} = \frac{r}{x}\left[1 + \frac{3\varepsilon_p p(x)}{p(x)+3K\varepsilon_p}\right] \quad (5)$$

By integrating the equation over a unit volume, we obtain the dependence of the radius on the volumetric modulus of deformation and the reduced strength of the original soil:

$$R = \frac{C}{\sqrt{K}}\text{; where: } C = 1{,}497\ \tau_0^{-0{,}113} \quad (6)$$

Analysis of the solution shows that with an increase in the volumetric modulus of deformation, the size of the expanded cavity decreases (Fig. 3).

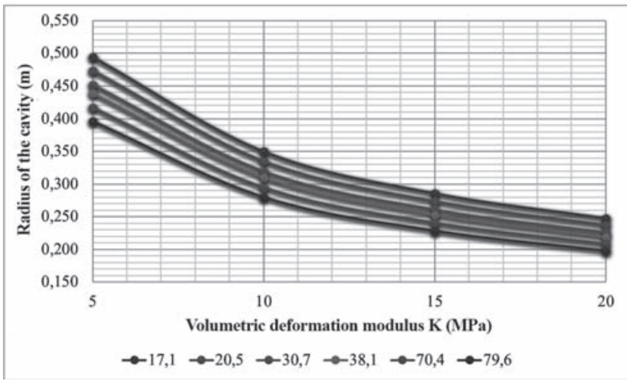

Figure 3. Graph of the change in the radius of the expandable cavity depending on the volumetric deformation modulus (K) and the reduced resistivity (τ_0)

This behavior can be explained by different values of soil porosity; in more porous soil, the expansion of the cavity occurs due to the elimination of pores in the plastic region, which leads to a rapid drop in the effective pressure with an increase in the cavity radius and the formation of a small zone of plastic deformation.

The obtained solution to the problem of static expansion of a cylindrical cavity in an elastoplastic compressible medium, taking into account the nonlinear compressibility, makes it possible to calculate the theoretical diameter of a soil-concrete element depending on the physical and mechanical properties of soils.

3. DETERMINATION OF EFFECTIVE DEFORMATION CHARACTERISTICS OF A STRUCTURAL GEOTECHNICAL MASSIVE

The base, reinforced with vertical elements at axial distances of no more than three diameters, is a composite system consisting of a soft and pliable matrix (soil) and rigid reinforcing (soil-concrete) elements. In this case, most of the external load is absorbed by the soil matrix. To describe the behavior, a continuum hypothesis is introduced, which includes the averaging procedure, through which the structure and state of the material are idealized in such a way that the material is considered homogeneous, for which the characteristic properties inherent in a homogeneous medium are the same at all points. The main task is to use the averaging procedure to predict the effective properties of an idealized homogeneous medium in terms of phase properties and geometric characteristics. We consider the "structural geotechnical solid" as a two-dimensional periodic medium – a fibrous unidirectional composite, which is a periodic system of parallel cylindrical fibers immersed in a homogeneous matrix, the characteristics of the physical and mechanical characteristics of which are different from the characteristics of the fibers (Fig. 4). Based on the structure of a unidirectional composite with hexagonal fiber packing and according to the continuum hypothesis, the material can be considered a homogeneous medium with an axis of elastic symmetry coinciding with the direction of the fibers, i.e., is a transversely isotropic material [15].

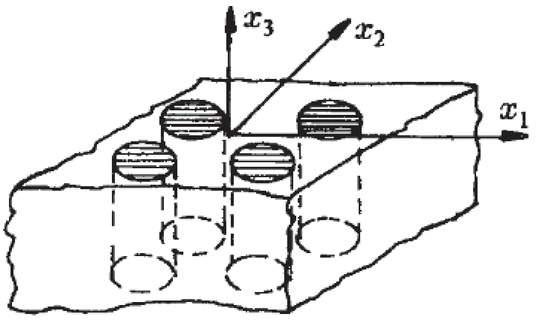

Figure 4. Two-dimensional periodic medium – fibrous unidirectional composite

Thus, the elastic behavior of the composite is characterized by five independent constants: elastic moduli E_1 and E_2 corresponding to the directions along and across the fibers, Poisson's ratios v_{12} and v_{23}, and the operator shear modulus G_{12}.

We select a periodicity cell in it – a representative volume with a characteristic size of inhomogeneity, within which the properties can be averaged. The scale of the representative volume should be much larger than the characteristic size of the inhomogeneity and small in comparison with the characteristic size of the body (Fig. 5). Under these conditions, a heterogeneous material can be idealized, considering it as equivalent to a homogeneous material with properties averaged over a representative volume [16]. Within the boundaries of the periodicity cell, the gradient of external influences (pressure) changes insignificantly.

The condition for the correct selection of the effective characteristics of the structural geotechnical solid is the equality of the average deformations of the selected heterogeneity cell when simulating it with individual elements and a single array.

We introduce two specific parameters

– the coefficient of reinforcement, characterizing the volume fraction of reinforcing elements in the soil mass:

$$\propto = V_r / V_s \qquad (7)$$

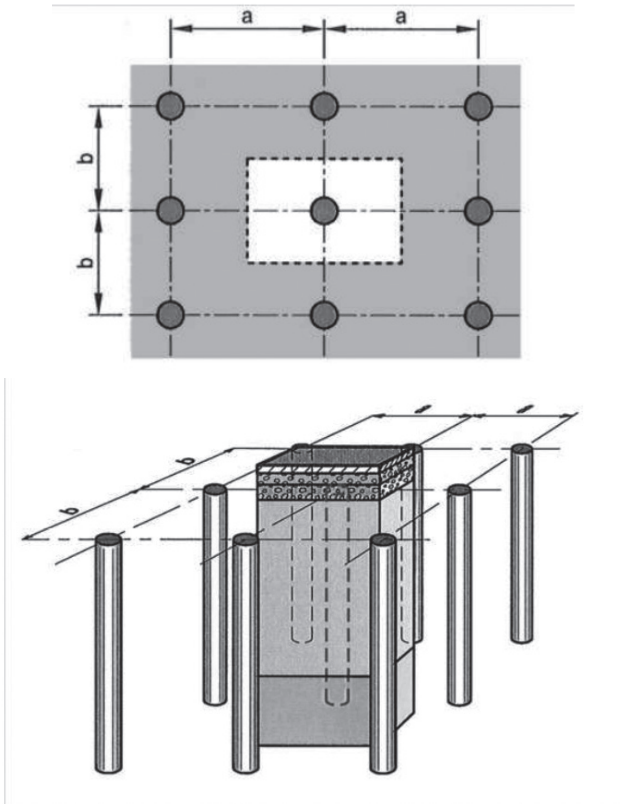

Figure 5. Allocation of the periodicity cell in the structure of the structural geotechnical solid

where V_S is volume of soil reinforced; V_r is volume of reinforcing elements and ratio of deformation moduli:

$$\eta = E_s / E_r. \qquad (8)$$

where E_s, E_r are calculated values of the modulus of elasticity of reinforcing elements and the modulus of soil deformation.

The reinforcement coefficient is a function of the diameter of the soil-concrete elements (D) (variation range 1.0 ... 1.2 m) and the distance (L) between the element axes (variation range 2 ... 3 D).

The ratio of the deformation moduli is determined for the most widely used initial range of the deformation modulus of the fixed soil (5.0 ... 20.0 MPa).

In this case, the effective modulus of deformation of the structural geotechnical solid (E_{sgs}) along the axis coinciding with the direction of reinforcement can be determined by geometric averaging according to Voigt [17]:

$$E_{sgs} = \propto E_r + (1-\propto)E_s \qquad (9)$$

CONCLUSIONS

The fundamental difference of the proposed model lies in the use of a homogeneous medium with effective characteristics, which replaces the field of elements with interelement soil mass and significantly reduces the time required for calculating the mechanical behavior of a large number of variants of foundation structures. Comparative analysis of patterns of distribution of vertical displacements of the base, determined by this model, shows that the average absolute values differ within 5 ... 10 percent from the model with selected reinforcing elements, and are within the accuracy of engineering calculations. Consequently, the application of the “structural geotechnical solid” model, taking into account the reduced stiffness of the underground part of the building, is quite sufficient to determine the final stabilized settlement of the building and will be further considered as the main design scheme.

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