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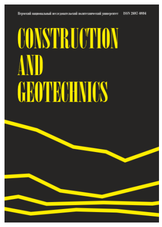

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NUMERICAL MODELING OF PIT EXCAVATION WITH ACCOUNT FOR REGIONAL PECULIARITIES OF MECHANICAL BEHAVIOR OF FOUNDATION SOILS

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ABSTRACT

The problems of undrained behavior of weak clayey soils of St. Petersburg are considered. The importance of taking into account the mechanism of shear hardening in calculations of excavations in weak clayey soils has been demonstrated. The problem of using undrained shear resistance as a strength parameter in full stress evaluation is shown. The modification of Y.I. Soloviev's theory of instantaneous strength has been presented with account for the formation of excess pore pressures under deviatoric loading in the plane formulation. With its help the calculated value of resistance to undrained shear through effective strength parameters for use in numerical modeling complexes is obtained. Numerical realization of the nonlinear model of soil with shear hardening in the software package implementing the finite element method has been performed. This model utilizes the proposed methodology for estimating undrained strength. Comparison of the calculation results of the proposed model and the Mohr-Coulomb model has been performed.

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ РАЗРАБОТКИ КОТЛОВАНА С УЧЕТОМ РЕГИОНАЛЬНЫХ ОСОБЕННОСТЕЙ МЕХАНИЧЕСКОГО ПОВЕДЕНИЯ ГРУНТОВ ОСНОВАНИЯ

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упрочнение, модель грунта, нелинейность, метод конечных элементов, численные методы, недренированное поведение, параметр Скемптона, сопротивление недренированному сдвигу, мгновенная прочность, котлован.

АННОТАЦИЯ

Рассматриваются проблемы недренированного поведения слабых глинистых грунтов Санкт-Петербурга. Продемонстрирована важность учета механизма сдвигового упрочнения при расчетах котлованов в условиях слабых глинистых грунтов. Показана проблема использования сопротивления недренированному сдвигу, как параметра прочности при оценке в полных напряжениях. Представлена модификация теории мгновенной прочности Ю.И. Соловьева с учетом образования избыточных поровых давлений при девиаторном нагружении в плоской постановке. С её помощью получено расчетное значение сопротивления недренированному сдвигу через эффективные параметры прочности для использования в комплексах численного моделирования. Выполнена численная реализация нелинейной модели грунта со сдвиговым упрочнением в программном комплексе, реализующем метод конечных элементов. В данной модели использована предложенная методика оценки недренированной прочности. Выполнено сравнение результатов расчета предложенной модели и модели Мора – Кулона.

Introduction

Expansion of the field of study of undrained behavior of soil foundation is associated with the practice of excavation pits calculation in the conditions of weak clayer soils. The study of properties of weak clayey soils is connected with their low mechanical characteristics with wide distribution in the active zone of the foundation during construction works.

This is especially relevant for St. Petersburg, where the thickness of weak soils reaches an average of 15 m. With respect to the active development of underground construction in the city it is necessary to provide special approaches to assess the bearing capacity of weak clayey soils in order to make safe and cost-efficient engineering solutions during works.

One of these approaches is the consideration of the weak clayey soils properties over time since they are characterized by low filtration coefficients. In this case, the possibility of formation and dispersion of excessive pore pressures is taken into account, what is important for impacts on the foundation in a limited period of time (for example, the construction of a pit).

Research in this area begins with the works of K. Terzaghi and is associated with the development of the theory of filtration consolidation. The influence of excessive pore pressures on soil strength was studied by A. Skempton [1–3], who introduced pore pressure coefficients and also conducted research for the examination of the clayer soils behavior. Significant research in the field of undrained behavior of soils was also carried out by A. Bishop, D. Henkel [4, 5], C. Ladd [6, 7] and others. Important studies in the field of undrained behavior were performed by the native scientists: A.G. Shashkin [8], V.M. Ulitsky [9], Y.I. Soloviev [10] and others.

In the world practice, with reference to the possibility of forming excessive pore pressures of the foundation soils two approaches have been formed for the analysis:

– analysis in effective stresses using effective strength parameters;

– analysis in total stresses using full strength parameters.

Evaluation of the bearing capacity of the foundation in total stresses is considered to be a more conservative approach. In the calculation it is used a well-known parameter – undrained shear resistance. Describing the shear resistance by only one parameter, it is impossible to take into account a number of dependencies strongly influencing its value:

– resistance to undrained shear depends on the degree of disruption of the sample structure which is confirmed by A. Skempton [3], P. Mayne [11], M. Jamiolkowski [7];

– type of stress-strain state of the sample during testing determines the value of undrained shear resistance which is confirmed by P. Mayne [11].

Also, the analysis in total stresses does not provide the ability to perform time calculations taking into account the filtration processes in the foundation [12].

During calculation in effective stresses, the angle of internal friction and cohesion are used as strength parameters. The use of effective strength parameters allows depending less on the quality of soil test specimens, what was proved by A. Skempton [3]. It also becomes possible to perform calculations in time. However, here an important role begins to play the laws of deformation embedded in the soil model.

The purpose of this study is to develop a method for assessing the undrained strength of weak clayey soils during calculation at effective stresses and its implementation in the numerical simulation software package.

To achieve this goal, the following tasks have been completed:

– modification of the theory of instantaneous strength by Y.I. Solovyov considering the parameter which takes into account the development of excess pore pressures during shear deformation;

– obtaining the calculated value of resistance to undrained shear Cu based on effective strength parameters and the undrained strength parameter Af;

– development and numerical implementation of a nonlinear model realizing shear hardening with account for the obtained value of resistance to undrained shear.

Experimental Methods and Theoretical Approaches

Mathematical modeling of undrained soil behavior

The special properties of clays play an important role in the study of undrained behavior of clayey soils. In the context of the pit excavation problem it is important to consider how these properties manifest themselves under shear deformation.

This can be shown graphically by means of effective soil stress trajectories, which describe the change in the stress state of the specimen under loading. The theoretical description of the dependence of the stress trajectory on the soil model in numerical modeling and the role of the A. Skempton parameter are presented in the previous article by the authors [13].

Thus, the main difficulty in using the analysis in effective stresses is the dependence of the ultimate strength realized in the calculation on the theoretical laws embedded in the soil model (see Fig. 1).

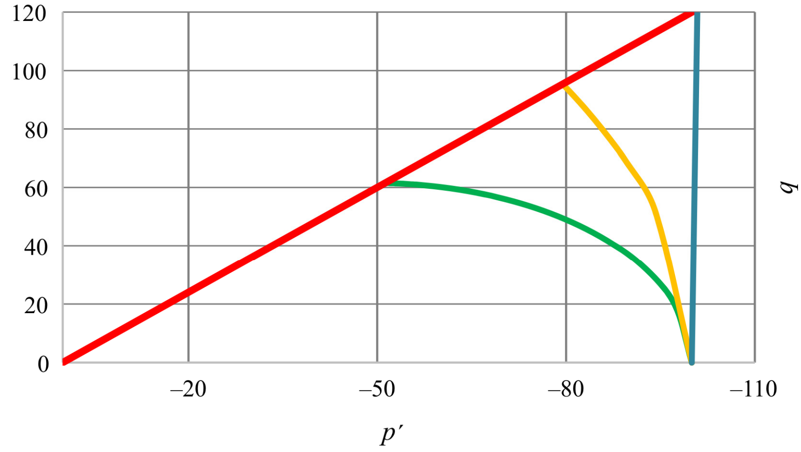


Fig. 1. Trajectories of effective stresses [13]
Рис. 1. Траектории эффективных напряжений [13]

Method for Estimating Undrained Strength by Effective Strength Parameters under Conditions of Plane Deformation

The parameter A_f can be used to obtain the value of undrained shear resistance C_u, which will take into account the peculiarities of deformation of weak foundation soils. However, determined under triaxial axisymmetric compression A_f it will not correspond to the plane stress state, to which the problem of the excavation can be referred.

For direct determination of excess pore pressure under shear deformation in plane deformation conditions it is possible to use the simple shear device (DSS), but in domestic practice it is found only in a limited number of scientific laboratories and testing on it is not encountered in the course of commercial engineering-geological surveys. This is facilitated by the lack of regulatory-technical base for testing in this device.

In conditions of simple shear, the Skempton parameter can be determined by the following formula:

$$\alpha = \frac{\Delta u - \Delta\sigma_3'}{\Delta\tau} = \frac{-2\Delta\sigma_3'}{\Delta\sigma_1' - \Delta\sigma_3'} \tag{1}$$

where α – Skempton parameter for flat SSS; u – pore pressure; $\Delta\tau$ – tangential stress change; σ_3' – lowest main effective pressure; σ_1' – the highest principal effective stress.

To obtain the resistance to undrained shear in the case of aflat setting we modify the law of A. Skempton [1]:

$$\Delta u = \beta(\alpha\Delta\tau + \Delta\sigma_3) \tag{2}$$

where $\beta = \dfrac{\Delta u}{\Delta\sigma}$ – Skempton Parameter for Flat SSS.

To calculate the value of resistance to undrained shear, we will use the theory of instantaneous strength of Yu.K. Solovyov [10]:

$$\tau = \sigma(1-\beta)\sin(\varphi') + \sigma_0\beta\sin(\varphi') + c'\cos(\varphi') \tag{3}$$

where $\sigma = \frac{\sigma_1 + \sigma_3}{2}$ – average stress in soil mass; $\tau = \frac{\sigma_1 - \sigma_3}{2}$ – shear stresses in a soil mass; c' – effective specific cohesion; φ' – effective angle of internal friction.

Numerical Implementation of a Nonlinear Model with Shear Hardening

To conduct numerical experiments according to the proposed methodology we realize a nonlinear model with shear hardening. To describe the stress-strain relationship under deviatoric loading, we adopt the expression proposed by R.L. Kondner [14]. A similar expression was previously proposed by A.I. Botkin [15].

Instead of the largest principal axial deformation as a variable, let us consider the parameter:

$$\gamma_s = \frac{\varepsilon_1 - \varepsilon_3}{2} \tag{4}$$

Then the expression for the relationship between stresses and strains under deviatoric loading will be as follows:

$$\mathrm{q} = \frac{\gamma_s}{a - b\cdot\gamma_s} \tag{5}$$

where a – the inverse of the tangent modulus; b – the inverse of the asymptotic stress deviator. Plastic component of deformation γ_s^p be found as:

$$\gamma_s^p = \gamma_s - \gamma_s^e \tag{6}$$

where γ_s^e – elastic component of deformation.

From the generalized law of R. Hooke we define γ_s^e:

$$\gamma_s^e = \frac{1+\nu}{2E}q \tag{7}$$

where ν – Poisson's ratio; E – modulus of elasticity.

Then substituting expressions (5) and (7) into (6) we obtain:

$$\gamma_s^p = \frac{q\cdot a}{1 - q\cdot b} - \frac{1+\nu}{E}q \tag{8}$$

Let us define the value as a value inverse to the modulus of elasticity and independent of stresses:

$$a = \frac{1+\nu}{2\cdot E} \tag{9}$$

The value *b* is calculated as:

$$b = \frac{1}{q_{ult}} = \frac{1}{\frac{q_f}{R_f}} = \frac{R_f}{q_f} \tag{10}$$

where q_{ult} – asymptotic value of the stress deviator; q_f – stress deviator limit value; R_f – fracture ratio.

Let us substitute the ratio of the stress deviator to the stress deviator at fracture:

$$\frac{q}{q_f} = \frac{C_u^{mob}}{C_u} \tag{11}$$

where C_u^{mob} – mobilized resistance to undrained shear.

Let's substitute expressions (9), (10) and (11) into (8) and determine the value of γ_s^p:

$$\gamma_s^p = \frac{1+\nu}{E} \cdot \frac{q}{\frac{c_u}{C_u^{mob} \cdot R_f} - 1} \tag{12}$$

As yield strength, we adopt Tresk's criterion to describe strength through undrained shear resistance:

$$f = q - 2 \cdot C_u^{mob} \tag{13}$$

Then C_u^{mob} is the hardening parameter. The law of plastic flow is assumed to be non-associated. As the plastic potential we take the Coulomb-Mohr law with the dilatancy angle $\psi = 0$:

$$g = q + (\sigma_1 + \sigma_3 - 2 \cdot c \cdot \cot(\varphi)) \cdot \sin(\psi) = q \tag{14}$$

The above relations are sufficient to realize the nonlinear solution. As an algorithm for nonlinear solution we adopt the method of initial stresses with step-by-step loading. The stiffness matrix is assumed to be variable depending on the achieved stress level. A detailed description of the algorithm realization is described in A.B. Fadeev [16] and V.N. Paramonova [17].

Results and discussion

The analytical solution obtained in the previous articles of the authors for calculating the parameter A_f [13] and analytical solution for finding the pressure on the enclosing structure [18] show the necessity of correct consideration of the shear component of pore pressure in undrained calculations of weak clayey soils. Also, it is noted in the works of C.P. Wroth [19], C. Surarak [20] and others.

To develop a method for estimating undrained shear resistance based on effective strength parameters and deformation features of foundation soils, we modify Soloviev's theory of instantaneous strength (3) using (2) to allow for shear deformation features. Here is a variant of the formula for the case of instantaneous loading of the soil mass, where $\beta = 1$:

$$C_u = \frac{\sigma'_0 (1 - (\alpha - 1)\dfrac{1 - K_0}{1 + K_0}) \sin(\varphi') + c' \cos(\varphi')}{1 + (\alpha - 1)\sin(\varphi')} \tag{15}$$

where σ'_0 – natural average effective stresses in the soil; K_0 – coefficient of lateral soil pressure.

By substituting the value, the solution of Y.I. Soloviev (3) can be obtained. This solution allows us to estimate the resistance to undrained shear with account for shear pore pressure, which develops significantly under deviatoric loading of weak clayey soils. To evaluate the influence of shear hardening and the development of shear pore pressure on the deformations of the soil mass, we perform a numerical calculation of the excavation in three formulations:

– undrained calculation in full stresses in the developed soil model with determination of strength parameters according to the proposed methodology (variant 1) – developed by PC;

– undrained calculation in effective stresses in the Mohr-Coulomb model (variant 2) – Plaxis 2D;

– drained calculation in effective stresses in Mohr-Coulomb model (variant 3) – developed by PC.

The realization is carried out in a program complex based on the finite element method, developed by the scientific team which includes the authors [21–23].

The calculation is performed in two stages: formation of the natural stress-strain state and pit digging. The general view of the calculation scheme is presented in Fig. 2.

As soils we will take two engineering-geological elements characteristic for the thickness of weak soils of St. Petersburg districts. Characteristics are presented in the Table.

As the resultsofthe calculation will present the isofields of displacements of the soil mass and the oints of plastic deformation in the developed software pachage in Fig. 3–5.

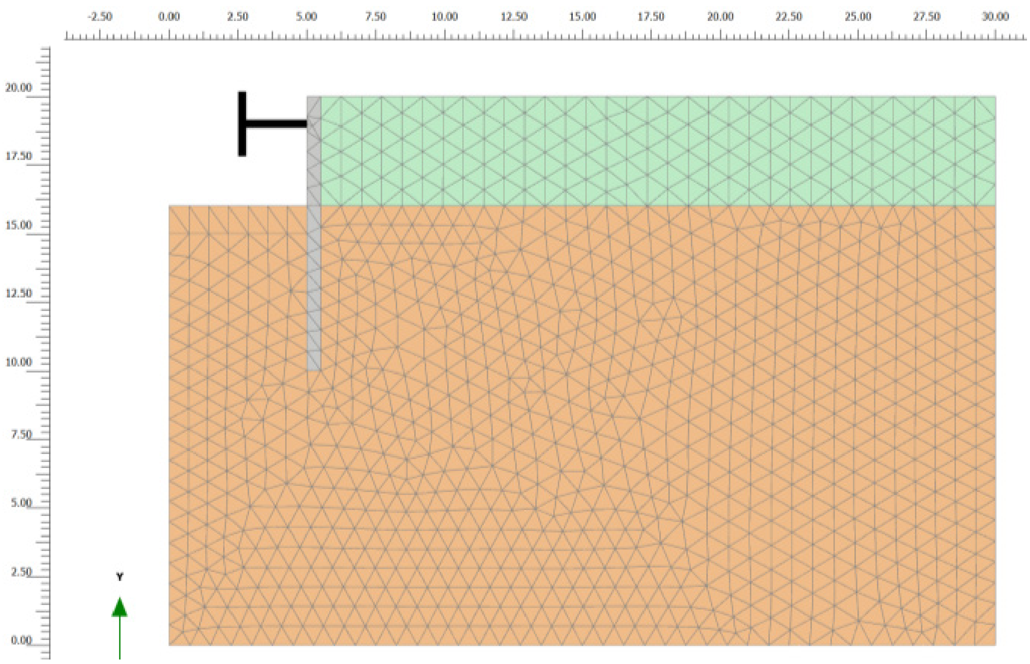
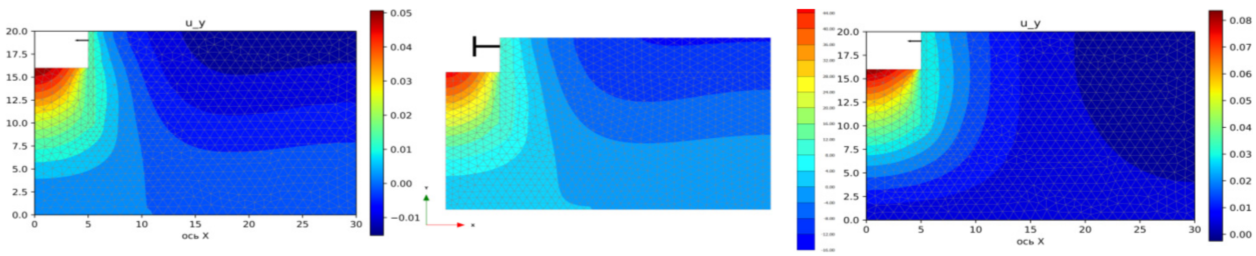


Fig. 2. General view of the calculation scheme in the last phase of the calculation
Рис. 2. Общий вид расчетной схемы на последней фазе расчета

Physical and mechanical characteristics of soils

Физико-механические характеристики грунтов

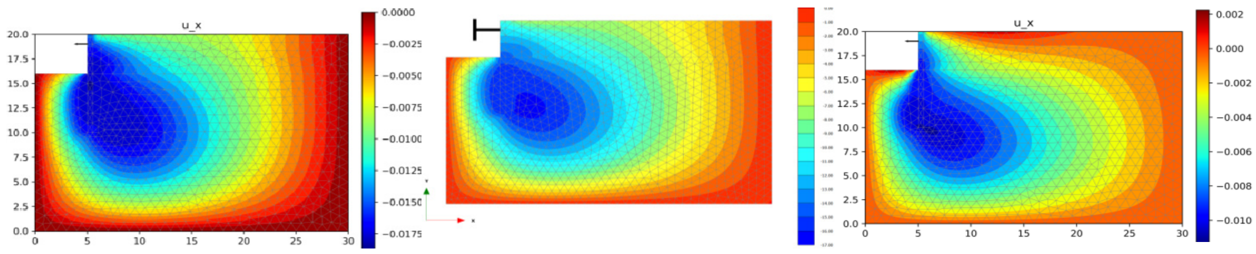
Characteristics	The proposed model and methodology	Mohr-Coulomb: Drained и Undrained A
Soil № 1 (top layer)		
Physical	$\gamma = 19\frac{kN}{m^3}$, $I_L = 1$	
Mechanical	$E_{ur} = 11{,}1$ MPa, $\nu_{ur} = 0.2$	$E_{ur} = 3.7$ MPa $\nu = 0.3$
	$C_u^{ref} = 3\,kPa, C_u^{inc} = 11\frac{\text{kPa}}{m}$, $R_f = 0.8$	$\varphi' = 23^{\circ}$, $c' = 5$ kPa
Soil № 2 (bottom layer)		
Physical	$\gamma = 18\frac{kN}{m^3}$, $I_L = 1.19$	
Mechanical	$E_{ur} = 24.3$ MPa, $\nu_{ur} = 0.2$	$E_{ur} = 8.1$ MPa, $\nu = 0.3$
	$C_u^{ref} = 47$ kPa, $C_u^{inc} = 10\frac{\text{kPa}}{\text{m}}$, $R_f = 0.75$	$\varphi' = 25^{\circ}$, $c' = 10$ kPa



1 2 3

Fig. 3. Isopoles of vertical deformations: variant 1 U_y = 51/15 mm, variant 2 U_y = 45/12 mm, variant 3 U_y = 83/2 mm

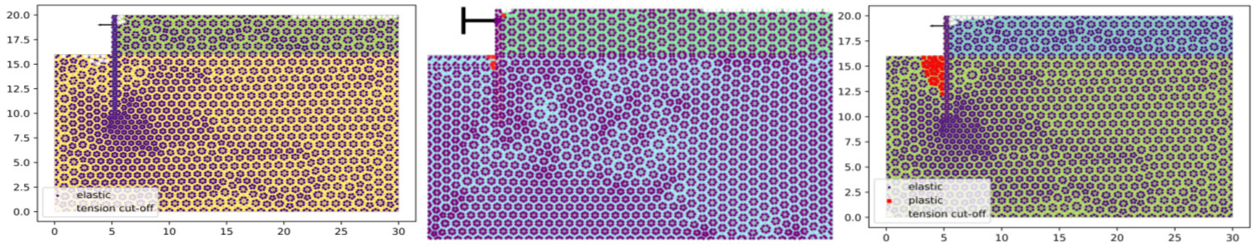
Рис. 3. Изополя вертикальных деформаций: вариант 1 U_y = 51/15 мм, вариант 2 U_y = 45/12 мм, вариант 3 U_y = 83/2 мм



1 2 3

Fig. 4. Isopoles of horizontal deformations: variant 1 U_x = 19/0 mm, variant 2 U_x = 16/0 mm, variant 3 U_x = 11/4 mm

Рис. 4. Изополя горизонтальных деформаций: вариант 1 U_x = 19/0 мм, вариант 2 U_x = 16/0 мм, вариант 3 U_x = 11/4 мм



1 2 3

Fig. 5. Plastic points: variant 1, variant 2, variant 3
Рис. 5. Пластические точки: вариант 1, вариант 2, вариант 3

The developed model shows larger displacements than the undrained calculation and smaller displacements than the drained one in the Mohr-Coulomb model. The drained calculation shows larger zones of plastic deformation development. Comparison of undrained calculations in the proposed model and in the Mohr-Coulomb model clearly illustrates the influence of plastic shear deformations on the calculation results.

Conclusion

The influence of the type of SSS and deformation features of weak clayey soils on shear pore pressure requires either an adequate estimation of the magnitude of the undrained shear resistance or model selection with respect to the regional characteristics of the soils.

It is convenient to estimate the magnitude of shear pore pressure using the Skempton parameter A_f. Determination of the parameter should be carried out in tests with pore pressure fixation with a calculation scheme realizing a SSS similar to reality.

Comparison of soil mass deformations in the Mohr-Coulomb model and the proposed model shows the importance of the shear component of deformation for this type of problems.

Финансирование. *Финансовая поддержка не оказывалась.*
Конфликт интересов. *Авторы заявляют об отсутствии конфликта интересов.*
Вклад авторов. *Все авторы сделали равный вклад в подготовку публикации.*

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