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Original Research Article

THE INTERACTION FEATURES OF THE MULTI-LEVEL RETAINING WALLS WITH SOIL MASS

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Abstract

The interaction features of multi-level retaining walls with soil base were researched by changing their geometric parameters and locality at the plan. During excavation of deep foundation pits it is important to choose the type of constructions which influences on the horizontal displacements. The distance between the levels of retaining walls should be based on the results of numerical modelling. The objective of this paper is to present a comparison between the data of numerical simulations and the results of the in-situ lateral tests of couple piles. The problems have been solved by using the following soil models: Coulomb-Mohr model; model, which is based on the dilatation theory; elastic-plastic model with variable stiffness parameters.

Keywords: multi-level retaining wall, elastic-plastic model, in-situ lateral tests, geodetic monitoring

1. INTRODUCTION

In the modern city development conditions, few horizontal grounds for buildings have remained. Therefore, there is a need to plan the slopes in order to increase the horizontal land for the construction of buildings. The terrace configurations slopes – is a costly part of the construction, so the important task is not only to develop the complex activities for preventing landslides but to make it reliable. It is important to find the most rational solutions. One of these solutions is using of multi-level retaining walls.[1]

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In this paper a few tasks are described, which are important in the design of retaining walls. One of the most important factors in numerical simulation of the interaction between retaining structures and soil base is the right choice of soil model. Furthermore, the influencing of the position of the retaining walls levels on the horizontal displacement and taking in to account the impact of the additional stiffness of the retaining walls from the plane during numerical modelling are researched in the paper.

2. SELECTION OF SOIL MODEL

The in-situ lateral tests of couple piles were conducted, for evaluation of the work structures at the horizontal loads.
Three soil models were chosen for comparison the assessment of interactions the restraints structures with soil [8,10].

2.1. Description of selected models

Coulomb-Mohr model consists of two components: Hooke's law and Coulomb friction law. Hooke's law is linear relationship between elastic deformations and stresses $\sigma = \varepsilon \times E$. Coulomb friction law: $\tau = C + \sigma \cdot tg\ \varphi$, where C is a cohesion, the parameter corresponding to the strength of the soil at zero normal stresses at the platform of displacement; σ is an effective normal stress, at the cut platform; φ is a friction angle; τ is a shear stresses.
This model considers the elastic work of the soil at the small deformation condition, the low stiffness of the material and the elastic unloading.
The yield surface of Coulomb-Mohr model is fixed in principal stress space. For this model, deformation modules and Poisson's ratio are constant. Often, the Coulomb-Mohr models is used for calculation of stability of slopes, structures of retaining walls. Numerical modelling of retaining walls must include the history of the loading. Full strain increment consists of the elastic and plastic strains. This strain in differential form is shown as following:

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} \tag{2.1}$$

The yield function is given by equation:

$$f = (\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3) \cdot sin\varphi - 2c \cdot cos\varphi . \tag{2.2}$$

The plastic potential function is given by equation:

$$g = (\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3) sin\psi . \tag{2.3}$$

The yield surface is considered as a potential surface ($g = f$), using the associated rule of the plastic flow.

The next model soil is elastic-plastic model with variable deformation characteristics. This model includes as failure surfaces – the definition of Coulomb-Mohr. Duncan-Chang hyperbolic model with interchangeable modules are used for the definition of the elastic region of stress-strain state. In this model is being used the varied model for trajectory of initial loading and of unloading-reloading [8]. In contrast to the elastic perfectly-plastic model, the yield surface of this model is not fixed in principal stress space, but it can be expanded due to the plastic straining. This model simulates the soil behavior during the excavation of deep pits too. To describe nonlinear elastic region, the hyperbolic relationship between stresses and deformations in primary triaxial loading is used, which was proposed by R.L. Kondner and J.S. Zelasko in 1963, and supplemented by J.M. Duncan and C.-Y. Chang in 1970 [4]. The yield curve can be described by following equation:

$$\varepsilon_1 = \frac{1}{2 \cdot E_{50}} \cdot \frac{q}{1 - q / q_a} \qquad \text{for} \quad q < q_f \tag{2.4}$$

where q_a is the asymptotic value of the shear strenght. The ultimate deviatoric stress q_f and the parameter q_a are defined as $q_a = q_f / R_f$. The ratio R_f varies within 0,75…1.

$$q_f = (c \cdot ctg\varphi + \sigma_3) \cdot \frac{2 \cdot sin\varphi}{1 - sin\varphi} \cdot \tag{2.5}$$

The yield function for deviatoric loading f describes plastic shear strains and given by the equation:

$$f = \overline{f} - \gamma^p , \tag{2.6}$$

where $\overline{f}$ is a function of stress and γ^p is a function of plastic strains:

$$\overline{f} = \frac{1}{E_{50}} \cdot \frac{q}{1 - q / q_a} - \frac{2q}{E_{ur}} , \;\; \gamma^p = -(2\varepsilon_1^p - \varepsilon_v^p) \approx -2\varepsilon_1^p . \tag{2.7}$$

Plastic potential function for deviatoric loading is given by equation:

$$g = (\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3) sin\psi , \tag{2.3}$$

where ψ is mobilized dilatancy angle.

The last chosen model for the research is Mises-Huber model, which is modified by professor Boyko. This model of physically nonlinear elastic-plastic soil environment is based on the theory of dilatation. Mises-Huber's evaluative criteria [2,3] is used as a condition of plastic flow f to increase the convergence of simulation results with experimental data in a wide range of loads. The ultimate limit state becomes by achieve conditions $f = 0$, where f takes the form:

$$f = \begin{vmatrix} T + \sigma_m \cdot tg\psi - \tau_s = 0 \quad ,if \quad \sigma_m \geq P_0 \\ T + \sigma_m \cdot tg\psi - \tau_s = 0 \quad ,if \quad \sigma_m < P_0 \end{vmatrix}, \tag{2.8}$$

where T is the intensity of tangential stresses; σ_m is the hydrostatic pressure; τ_s is limiting intensity value of tangential stresses in the absence of hydrostatic pressure; P_0 - the level of hydrostatic pressure, which determines the transition from conical to cylindrical surface. For non-associated law [1] of plastic flow $F \neq f$, where f is a function, that determines the condition of plasticity $(f = 0)$. Plastic flow is given by equation:

$$F = T^2 - \Lambda \cdot tg\psi \cdot (\sigma_m + H)^2, \tag{2.9}$$

were Λ is the coefficient of dilatancy; $H = \tau_s/\text{tg}\ \varphi$ is the ultimate resistance to volumetric extention.

For the solutions of tasks with nonlinear deformation of soil the dilatation condition by prof. Nikolaevsky [7] are used:

$$d\varepsilon^p = \Lambda(\chi, \sigma_m)d\gamma^p, \tag{2.10}$$

where $d\varepsilon^p$ is increase of the volumetric plastic strains; χ is the strengthening parameter; $d\gamma^p$ is the increase of the intensity of plastic shear strains.

2.2. Description of full-scale test piles

The results of in-situ lateral test of couple piles, which combined by grillage used for soil models choosing.

This test was used to verify numerical simulation data, because the same construction of retaining walls were adopted in the project of the real construction. In real project was applied double row pile of retaining wall.

Numerical simulation of the interaction of these piles with soil mass was conducted in volumetric setting. Solving the task in such setting allows to consider not only the stiffness of piles in compression and bending, but the impact of the side surfaces and the soles of piles on the stress-strain condition of the system "soil mass – retaining construction" [11].

The test was conducted at the experimental platform with following design: two bored piles with the diameter of 1020 mm and a length of 19 m, which were located at the distance of 3 meters from each other and these piles was united by using of monolithic raft. Height of monolithic raft was 2 m. The connection between piles and raft was rigid.

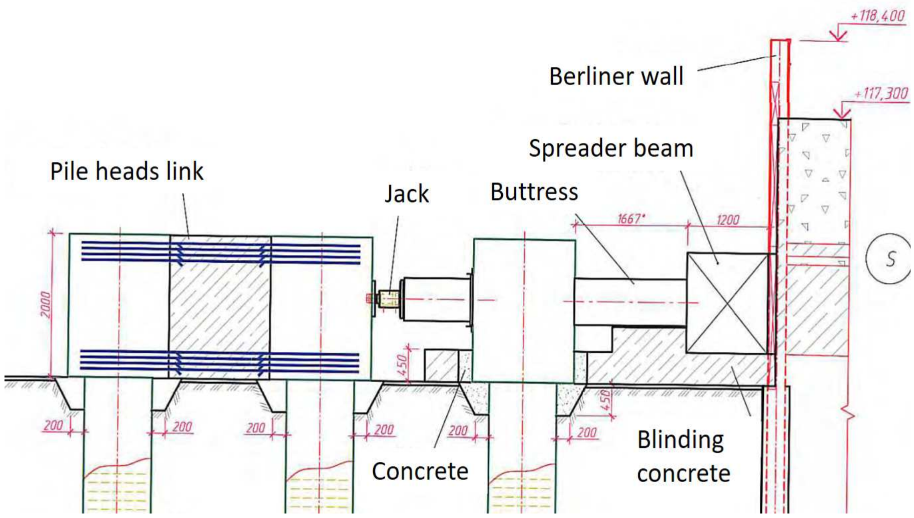

Fig. 1. Circuit of in-situ lateral tests of couple piles

The results of numerical simulation are shown on Figure 2 in the form of graphs.

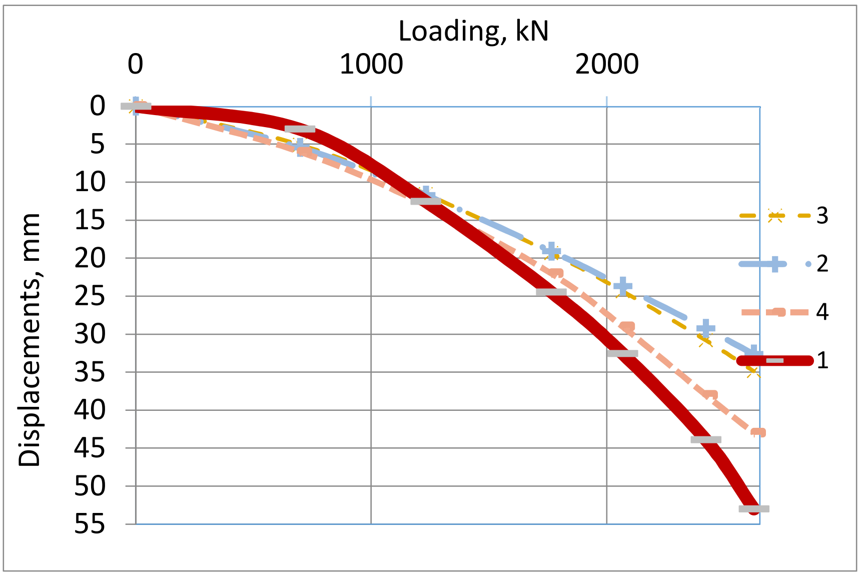

Fig. 2. The results of numerical simulation of in-situ lateral tests of couple piles: 1 - the results of in-situ tests, 2 - Coulomb-Mohr model, 3 - elastic-plastic model with interchangeable deformation characteristics, 4 - Mises-Huber modified model

The graphs show that at low loads, each of selected soil models overestimates the displacements and continues to work at the same condition, but with increasing loading the errors also increase. The error reaches almost 60% at the last load stage of Coulomb-Mohr model. Elastic-plastic model with interchangeable deformation characteristics shows the error of 54% and the nature of the deformation is similar to the Coulomb-Mohr model.

The model with Mises-Huber modified strength criteria shows a fairly high reproducibility (below 30%) even in the last stages of loadings. Within loadings from 0 to 1700 kN all proposed models show a high convergence results and error not exceeds 18%. The closest to the results of in-situ lateral test is the graph of the dependence between displacements and loadings, obtained by using of Mises-Huber nonlinear modified model.

3. RESEARCHING THE INFLUENCE OF DESIGN FEATURES LAYERS OF RETAINING WALLS TO THE STRESS-STRAIN CONDITION OF SYSTEM "RETAINING WALL – SOIL MASS"

The interaction between the retaining walls and the soil mass, and the peculiarities of their numerical simulation are discussed in papers by such scholars as R. Kathenbach [5], H.Popa [6], N.K. Kim [9] et al.

Researches were conducted during the development of the real project complex of retaining walls in Kyiv. It was necessary to design a retaining wall that would have been retained the slope with height nearly 27 meters. Combined scheme, namely the complex of retaining walls, which included three levels was accepted to ensure reliablity and effective operation of retaining structures.

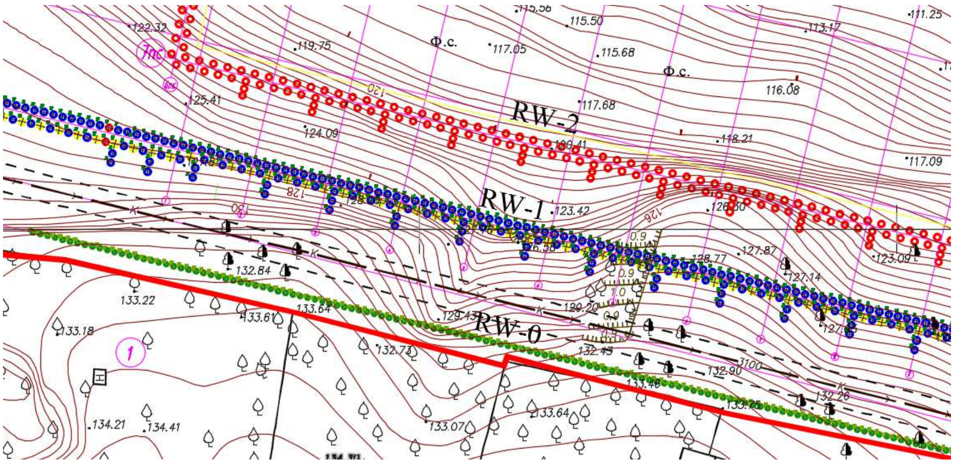

Fig. 3. Location of retaining walls at the topographic map

The upper level of retaining walls made of bored piles. Diameter of piles is 420mm length is 16 m, step piles in a row is 600 mm (RW-0). Middle level consists of two rows of piles with a diameter of 620 mm and a length of 24 m and 20 m. The distance between the rows of piles is 1000 mm (RW-1). The lowest level consists of two rows of piles with a diameter of 620 mm and a length of 16 m. Step of piles in a row is 1000 mm (RW-2). The location of retaining walls on the general plan is shown on Figure 3.

There are the counterforts in the structures of the two lower levels of retaining walls, which were provided for increasing the rigidity of the retaining walls from the plane. Counterfort piles are situated from the side of the ground; this location of pile evidently reduces the horizontal displacement. Two tasks were solved to consider the impact counterfort piles on the interaction between soil mass and retaining structures. The tasks were solved in the flat setting.

The solution of the task considers the structural nonlinearity, that takes into account all stages of the constructing of retaining walls and technological sequence of construction. Thus, the calculation consist of 16 stages.

At the first stage, we calculate the stress-strain state of own weight of soil mass. The second stage of calculation is adding (constructing) of retaining wall RW-0. The third and fourth stages are excavation of ground near RW-0. We plan a slope from the fifth to eighth stages of the calculation. Ninth stage is construction of the retaining wall RW-1. We model the excavation of ground near RW-1 from tenth to twelfth stages of calculation. Thirteenth stage is construction of the retaining wall RW-2. We model the excavation of ground near RW-2 from fourteenth to sixteenth stages of calculation.

The scheme of cross-section of the slope is shown below. There are stages of calculating the position of retaining walls and soil profile of the site on the scheme.

The soil mass was modeled by 4-node physically nonlinear flat finite elements. Each soil finite element has 17 integration points. The size of the finite element is 1×1 m. The finite-element mesh is concentrated in the zone of retaining walls placement. The size of the final elements in the concentration zone 0,5×0,5 m. Dimensions of the finite-element model are 115×60 m. The total number of finite elements is 12045. Boundary conditions are standard for flat setting tasks.

Numerical simulation is performed taking into account the stages of soil excavation. Initial stresses in the soil mass are also taken into account.

Due to the results of calculation of two options of retaining walls, the installation of additional buttress piles reduces the horizontal displacement of retaining walls. Displacement of RW-2 decreased by 23%, displacement of RW-1 decreased by 21%, and for RW-0 displacement decreased by 7%. That is, the installation of additional buttress piles reduces horizontal displacements not only of retaining walls in which they install, but general displacements of all soil mass. Therefore, the position of pile, that is shown on Figure 3 was accepted in the project.

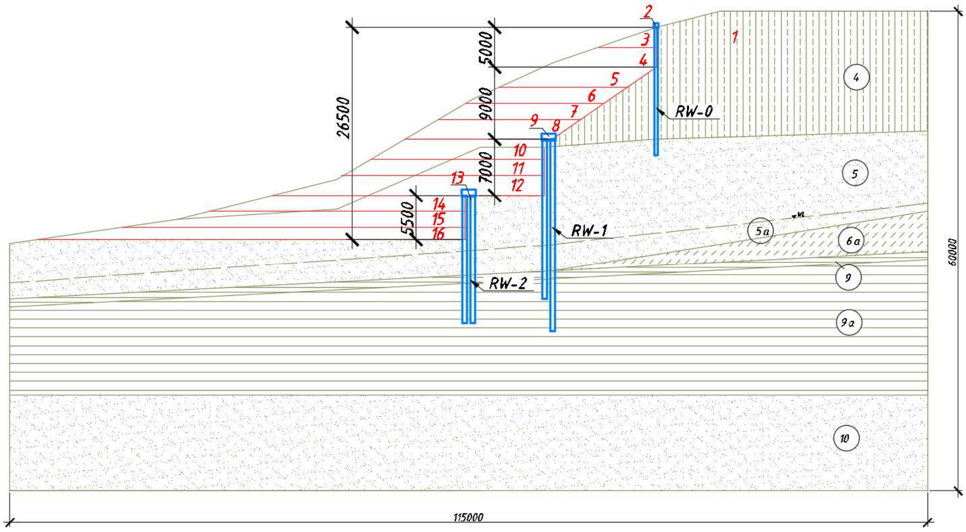

Fig. 4. Scheme of location of retaining walls and stages of excavation pit

Table 1. Physical and mechanical properties of engineering geological units

Number IGU	Name IGU	Specific weight, *γ, kN/m*	Poisson ratio, ν	Cohesion, *C, кPa*	Friction angle, *ϕ*	Deformation modulus, *E, MPa*
4	Stiff loessial sandy loam	17,26	0,32	30	23	14
5	Fine solid sand	16,7	0,3	2	36	30
5a	Fine solid sand, watersaturated	19,1	0,3	2	30	30
6a	Sandy loam plastic	17.3	0,33	4	15	51
9	Slightly plastic clay	18.4	0,42	42	19	22
9a	Semisolid clay	19.5	0,42	92	15	41
10	Fine solid sand	19,8	0,3	3	32	30

4. RESEARCHING THE INFLUENCE OF LEVEL POSITION OF RETAINING WALLS IN PLAN ON THE HORIZONTAL DISPLACEMENTS

The feature of this multi-level retaining wall is that the top layer of soil is not horizontal, but designed at an angle because of the limited land area. This, in its turn, reduces the passive soil pressure near the upper level of retaining wall (RW-0) and additionally loads middle level (RW-1) as shown on Figure 4. So, the next task was to assess the impact of position of retaining wall level in plan on the horizontal displacements. Another two tasks were solved for this. Task 1: retaining wall RW-1 is located closer to RW-2 than 3 meters, and the position and elevation of all other layers leave unchanged. Task 2: retaining wall RW-1 is located closer to RW-2 at 5.5 meters. We analyzed the displacement of all retaining walls on the last stage of the calculation, were we used the results of numerical simulation. In calculations that evaluated the effect of changing the position of retaining walls on their horizontal displacement were considered buttresses piles of the retaining walls RW-1 and RW-2.

According to the results it was found that changing the position of RW-1 leads to the reduction of displacement of retaining walls RW-1 by 14% and RW-0 by 32%, simultaneously increase the displacement of RW-2 by 27%. Change the position of RW-1 leads to decrease the angle of planning soil near the RW-0, that, in its turn, increases the passive soil pressure near the RW-0 and reduces the additional load on RW-1. The change of position of RW-1 in the direction to RW-2 has reduced the passive soil pressure near the RW-1, so the changing position of RW-1 is not significantly affected by the own work compared with work of RW-0.

The results of the calculations showed that imposition of additional structural elements in retaining walls significantly impacts on the increasing of their stability. Changing the position of the middle level of retaining wall reduces to displacement of the upper level by 24% and displacement of the lower level increased by 16%, while own displacement of RW-1 decreased by 9% only.

Geodetic monitoring of retaining walls was conducted at the construction after the building of retaining walls and after extraction of soil. Methods for observing landslide-prone slopes are described вy I. Skrzypczak [12].

The results of geodetic monitoring are given for comparing the results of numerical simulation and the actual displacements of the retaining walls. Only the maximum values of displacements, which obtained by the results of observations, were analyzed and compared. The changing displacements in time was not investigated in the calculations.

Research the influence of retaining walls position on the overall stability of the slope was conducted after the construction of retaining structures was finished, because the middle level was used for the passage and the distance between the

RW-2 and RW-1 had to be at least 6 m according to the project specifications. Therefore, we will compare the results of geodetic monitoring with basic level provision of retaining walls, which is shown on Figures 3 and 4.
The results of monitoring the retaining wall RW- 1 are shown below.

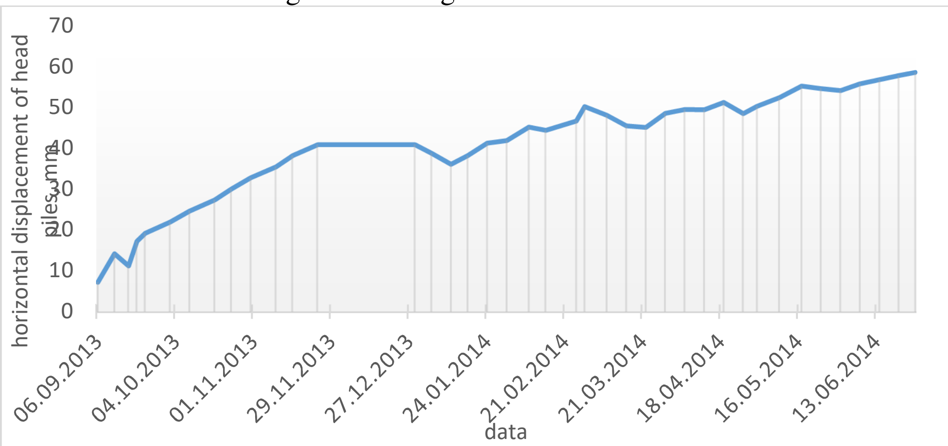

Fig. 5. The results of monitoring the retaining wall RW-1

The maximum displacement of retaining wall on the results of observations on the PS-1 was 59 mm. The maximum displacement of heads of the piles of RW-1 was 53 mm. So the calculation error was just a 10%. But if account the buttresses piles in the flat statement of the task, the displacement of RW-1 is 42 mm, in this case, the error of calculations is 29%. So, accounting of buttresses piles in the calculation makes it possible for the engineer to experience how these structures will improve the work of retaining walls. Determination of places for layers of retaining wall is an important task that influences the additional load from one level to the other.

5. CONCLUSIONS

It is established that the comparison of the numerical simulation results and results of in-situ lateral tests of couple piles showed reproducibility in limits of loads up to 1700 kN. A modified model of Mises-Huber showed convergence of results in the last stage loads about 30%, which is 2 times less than the errors in other models.
It is shown that in case of installation of additional buttresses piles in the lower retaining walls the corresponding horizontal displacement reduced for RW-2 by 23%, for RW-1 by 21% and for RW-0 by 7%.
Features of interaction of multilevel retaining walls with soil mass was detected. So, changing the place of the retaining wall RW-1 resulted in a reduction of their

displacement by 14%, and for RW-0 by 32%. At the same time the displacement of the lower level increased by 27%. This method allows to substantiate the location of each level.

The introduction of additional structural elements influences the reduction of displacement for each of them. Change the position of RW-1 most affects the horizontal displacement in RW-0 by 24% but less than RW-1 by to 9% and RW-2, up to 16%.

Datas of geodetic monitoring are consistent with the results of numerical simulation, and error does not exceed 29%, which confirms the correctness of solving tasks.

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ANALIZA WŁAŚCIWOŚCI INTERAKCJI POMIĘDZY WIELOPOZIOMOWYMI MURAMI OPOROWYMI A GRUNTEM

Streszczenie

W pracy są analizowane właściwości interakcji pomiędzy wielopoziomowymi murami oporowymi, a gruntem. Analiza polega na sterowaniu parametrami geometrycznymi i lokalizacją ścian oporowych. Przy głębokich wykopach ważny jest wybór odpowiedniego rodzaju konstrukcji zabezpieczającej przed wpływem sił poziomych tj. ścian oporowych. Odległość między poziomami ścian oporowych powinna opierać się na wynikach analiz numerycznych. Celem pracy jest porównanie wyników symulacji numerycznych z wynikami badań polowych. Problem rozwiązano numerycznie z zastosowaniem trzech modeli sprężysto-plastycznych gruntu.

Słowa kluczower: wielopoziomowa ściana oporowa, model sprężysto-plastyczny, testy boczne in-situ, geodezyjne monitorowanie

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