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NUMERICAL MODELING OF RETAINING STRUCTURES MADE OF BLOCKS WITH SOIL INFILL

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Abstract: The relevance of the study is driven by the expanding use of numerical models in the design practice of retaining structures and the need for their verification. A promising design solution for retaining walls is a stepped structure, sequentially constructed from hollow-body box type blocks infilled with crushed stone. This solution has several features that require the adaptation of existing calculation methods.

A numerical model of a retaining structure made of thin-walled blocks infilled with soil has been developed based on the analysis of the interaction between the structure's components under load, taking into account the work of the foundation and surrounding soil. The SiO2D finite element modeling computer software was used as a modeling tool. The calculation results for the proposed numerical models are compared with corresponding results for analytical solutions. The parameter values of the main physico-mechanical properties of the numerical models were determined as a result of field and laboratory tests in accordance with standard methodologies considering the scale of the tests.

The features of the design solution and construction technology of retaining structures made of thin-walled reinforced concrete blocks infilled with crushed stone were examined. Numerical models of retaining structures made of soil-infilled blocks were constructed using the domestic software package SiO2D. Laboratory and field tests established the parameters of the numerical model of the retaining structure. The research demonstrates high values of the structural cohesion («interlocking») parameter c (up to 60 kPa), alongside a high internal friction angle value φ (up to 60°), ensuring high shear stability of the infilled blocks.

The study, using numerical models, proposes a calculation basis for retaining structures made of soil-infilled blocks forming a stepped construction, where the blocks are not rigidly connected but are held in their design position by the internal resistance forces of the soil against shear.

Keywords: retaining structures, new structures, calculation methods, numerical models, mechanical strength characteristics of crushed stone

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ПОДПОРНЫХ СООРУЖЕНИЙ ИЗ БЛОКОВ С ГРУНТОВЫМ НАПОЛНИТЕЛЕМ

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Аннотация: актуальность исследований обусловлена расширением области применения численных моделей в практике проектирования подпорных сооружений и необходимостью их верификации. Одним из перспективных конструктивных решений подпорных стен является ступенчатая конструкция, последовательно возводимая из пустотелых блоков-коробов с заполнением полостей щебнем. Решение обладает рядом особенностей, требующих адаптации существующих методов расчёта.

Численная модель подпорного сооружения из тонкостенных блоков, заполненных грунтом, разработана на основе анализа взаимодействия компонентов сооружения между собой под действием нагрузки с учетом работы основания и окружающего грунта. В качестве инструмента моделирования применена компьютерная программа конечно-элементного моделирования SiO2D. Результаты расчетов по предложенным численным моделям сопоставляются с соответствующими результатами аналитических решений. Значения параметров основных физико-механических характеристик численных моделей определены в результате полевых и лабораторных испытаний в соответствии с нормативными методиками с учётом масштаба испытаний.

Рассмотрены особенности конструктивного решения и технологии возведения подпорных сооружений, состоящих из тонкостенных железобетонных блоков, заполняемых щебнем. Построены численные модели подпорных сооружений из заполненных грунтом блоков с применением отечественного программного комплекса SiO2D. В результате лабораторных и полевых испытаний установлены параметры численной модели подпорного сооружения. Исследования демонстрируют высокие значения параметра структурного сцепления («зацепления») c (до 60 кПа), наряду с высоким значением угла внутреннего трения φ (до 60^0) обеспечивающего высокую устойчивость заполненных блоков на сдвиг.

В работе с применением численных моделей предложено расчетное обоснование подпорных сооружений, состоящих из заполненных грунтом блоков и составляющих ступенчатую конструкцию, в которой блоки не имеют между собой жёстких конструктивных связей, а удерживаются в проектном положении за счёт сил внутреннего сопротивления грунта сдвигу.

Ключевые слова: подпорные сооружения, новые конструкции, методы расчета, численные модели, прочностные характеристики щебня

INTRODUCTION

Numerical modeling of geotechnical systems is currently a relevant and routine task for design engineers [1, 2]. Modern finite element computer software packages, designed for mathematically describing system behavior, are typically verified by authoritative expert communities through a set of test solutions that possess a more rigorously established mathematical correctness [3, 4]. Such software packages serve largely as automated tools, allowing users to create models of system elements within the limits of their own ability, describe their interactions with each other and with the surrounding environment, based on their own understanding of the physical processes characteristic of the system. The methods for modeling system components in each program are implemented as a set of special user tools, enabling each component to be assigned a mathematical model that best corresponds to its actual performance [5, 6]. Therefore, despite the near-complete automation of calculations, system modeling remains a creative task, and the development of nearly any engineering model depends on the user's creative experience and preferences, rooted in their understanding of the actual behavior of the modeled system. As a result, research tasks aimed at justifying and developing methods for modeling complex engineering systems using mathematical tools, implemented as a set of tools in specific computer programs, remain highly relevant.

This is also true for systems that describe the interaction of retaining walls with surrounding soil and other components [7, 8]. Compared to analytical solutions, numerical models allow for more accurate reproduction of the configuration of the retaining structure within the computational model, the layering of soils, more precise positioning of applied loads, and the consideration of their distribution characteristics [9, 10]. The setup of the calculation allows for the description of the retaining structure's behavior, taking into account the stages of its construction and loading, as well as changes in loads over time and other factors.

Currently, combined solutions for retaining structures, where soil is used as a construction material, are becoming increasingly widespread [11]. This study investigates retaining walls composed of individual hollow-body box type blocks, stacked with an offset toward the slope and infilled with crushed stone (Fig. 1) [12, 13]. The use of retaining walls of this design began relatively recently in Japan [14], where initial studies on the stability of such structures under seismic loads were conducted [15].

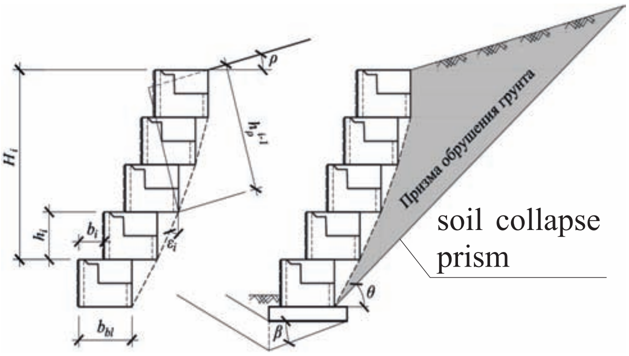


Figure 1. Cross-section of a retaining wall made of blocks infilled with crushed stone

The design offers several advantages, including high construction speed, cost-effectiveness, and aesthetic appeal. The main feature of the design, which affects its performance as part of a geotechnical system, is the absence of rigid structural connections between the blocks. The blocks are held in their design position by internal resistance to shear, generated by the weight of the infilled blocks and the shear resistance on the interfaces between the levels of the blocks.

The computational justification of this design and the potential expansion of its application scope require the substantiation of methods and techniques for numerical modeling. One of the criteria is the comparison of numerical modeling results with more mathematically rigorous analytical solutions, which should also be developed considering the design's specific features, including the perception of active soil pressure along the irregular profile of the retaining surface [16].

MATERIALS AND METHODS

The research is based on fundamental principles of structural mechanics, soil mechanics, elasticity and plasticity theory, as well as on methods of numerical modeling of spatial combined systems [17, 18]. When developing computational models of retaining walls made of soil-infilled blocks, the Coulomb-Mohr model was used by the authors to describe the properties of the granular medium [19].

In forming the computational models, modern achievements in applied mathematics and structural mechanics were utilized, particularly in the development of numerical methods for assessing the stress-strain state of calculated systems under static and dynamic loads. The SiO2D computational software was used as the primary modeling tool [20]. The main physical and mechanical properties of the computational models were determined through large-scale physical experiments and laboratory studies. The experiment planning adhered to the principles of similarity theory and dimensional analysis. The developed numerical models of retaining structures were verified by comparison with more rigorous mathematical solutions, feasible under specific computational conditions.

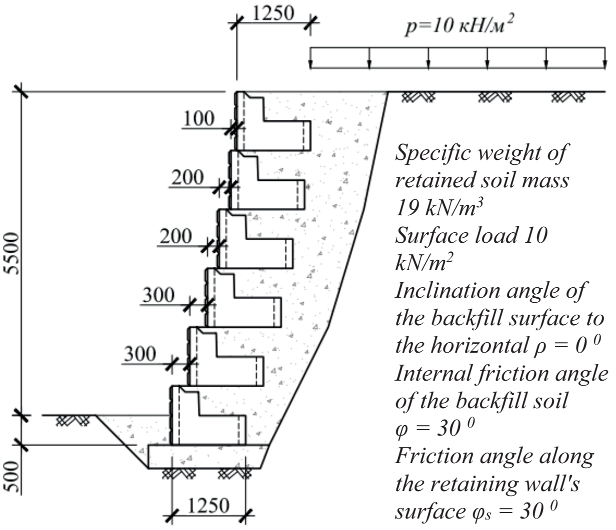
RESULTS OF THE RESEARCH

Provided below are the research results on the studied retaining structure, including the development of the computational model, results of numerical modeling, as well as the methodology and results of laboratory studies conducted to determine the parameters of the computational model.

Numerical Modeling in SiO2D

To enable a comparative analysis of the results from the analytical solution [16] with those obtained from numerical solutions, a calculation was performed for a retaining wall consisting of hollow-body reinforced concrete blocks infilled with soil. The profile of the retaining structure, along with the indication of the soil's physical and mechanical properties, is shown in Fig. 2. The blocks are numbered from top to bottom.

In general, the analytical and numerical approaches can be considered comparable, although there are differences that can lead to significantly different results. The main distinction lies in the determination of active pressure. Analytical calculations typically assume wall movement and therefore use active pressure, with a coefficient Ka of approximately 0.2÷0.4.



Specific weight of retained soil mass 19 kN/m^3
Surface load 10 kN/m^2
Inclination angle of the backfill surface to the horizontal $\rho = 0^0$
Internal friction angle of the backfill soil $\varphi = 30^0$
Friction angle along the retaining wall's surface $\varphi_s = 30^0$
Specific cohesion of retained soil $c = 0$ kN/m^2
Height of each block – 1 m;
Internal friction angle of the filler $\varphi = 30^0$
Specific cohesion of the filler $c = 0$ kN/m^2
Specific weight of the block with soil 20,15 kN/m^3
** The calculation is simplified by assuming that the bottom of the wall rests on a firm, non-deformable foundation.*

Figure 2. *Profile of the retaining wall*

Numerical modeling, through displacement calculations, allows for determining the degree of transition from at-rest pressure to active pressure. It should be noted that active pressure is lower than at-rest pressure (K0 is approximately 0.4÷0.6). A similar situation applies to passive pressure, where the transition from at-rest state to passive resistance must be determined, with the passive pressure coefficient being greater than the other two, being approximately 2÷6.

Another difference is the complexity of accounting for the existing slope with other strength characteristics. It is common to encounter situations where a retaining wall must be constructed in front of an existing slope. In this case, the slope, whether in its natural state or after partial cutting, must be stable, meaning that its contribution to active pressure follows different laws. The simplest way to account for such situations is to limit the volume of backfill when calculating active pressure. Sometimes, active pressure from backfill is combined with potential landslide pressure in the natural slope, but this is only possible if, given the specified safety factor, landslide pressure can take place.

Active Pressure) For comparing pressure values with analytical calculations, numerical modeling was performed using the finite element method in the SiO2D program. Figure 3a shows the results of horizontal displacements after the complete construction of the structure. The bottom block is fixed and has zero displacements, so maximum pressure is expected at this level not only due to the maximum soil height but also due to the use of the at-rest state lateral pressure coefficient K0. The top block has maximum displacement, and active pressure coefficient Ka is used in determining the pressure.

Initially, at-rest pressure was calculated by adding boundary conditions prohibiting displacements on the front face of each block. The pressure distributions are shown in Fig. 3b. The displacement constraints were then removed, and stress recalculation was performed. This resulted in the active pressure distributions shown in Fig. 3c.

In the studied scheme, the bottom block is assumed to be conditionally fixed, so its displacements can be considered zero. In this case, the pressure for this block will be calculated based on the at-rest lateral pressure coefficient (K0), and the pressure value will be significantly higher than the analytically calculated value based on the active pressure coefficient Ka. The average stress values on the vertical face of the block are presented in Table 1.

Table 1. Calculation results for block pressure according to FEM

Block №	Numerical pressure calculation		Analytical equivalent*, kPa
	by K0, kPa	by Ka, kPa	
1	13	5,5	12
2	36	19	20
3	52	20	25
4	65	22	34
5	68	19	35
6	66	66	43

**The analytical pressure equivalent is calculated for a rectangular pressure distribution*

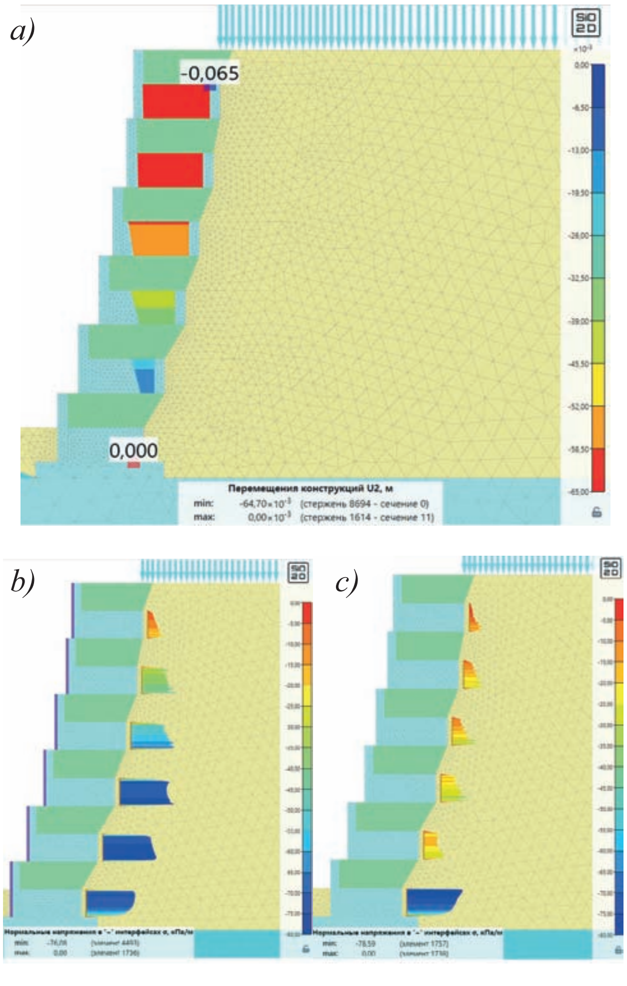


Figure 3. Stress distributions on the back face of the blocks: a – horizontal displacements of the blocks (min: -64,70×10^{-3} m (bar 8694 - section 0) max: 0,00×10^{-3} m (bar 1614 - section 11)); b – static pressure (normal stresses in '-' interfaces σ, kPa/m. min: -76,08 (element 4493) max: 0,00 (element 1736)); c – active pressure (normal stresses in '-' interfaces σ, kPa/m. min: -78,59 (element 1757) max: 0,00 (element 1736))

Conclusions: 1) The analytical calculation [16] takes into account the varying inclination of the back surface, considering each block level individually as a conditional monolith. Meanwhile, the numerical analysis can reveal several areas of shear deformations, forming local areas of active pressure within one global area;

2) In the analytical calculation, the distributed load is usually applied across the entire height of the wall, considering the coefficient of active lateral pressure. In the numerical calculation, the stresses are redistributed depending on the ultimate and pre-ultimate state of the finite element nodes;

3) The pressure distribution curve in the analytical calculation has a smooth shape, whereas in the numerical model, the shape depends on the mesh size of the finite elements;

4) In some cases, the uneven horizontal displacements of the front face of the modular retaining wall lead to different states of the soil behind it: part of the volume may be in a state of rest, part in a state of active pressure, and part in an intermediate state. This results in varying values of the lateral pressure coefficient depending on the state.

Determination of Numerical Model Parameters

A crucial task for successful numerical modeling was determining the actual values of the physico-mechanical properties of the soil material used to infill the blocks and voids between them – granite crushed stone with a particle size of 20-40 mm. Considering that the retaining walls are constructed using a unified technology, the parameters of the crushed stone had to be determined under conditions similar to those achieved in the field, corresponding to the desired compaction density. To achieve this, a series of tests on the soil material was conducted at the KorBet LLC testing site.

To ensure the crushed stone used met the supplier's declared specifications, a series of tests was conducted at the Petromodeling Lab LLC laboratory in accordance with GOST 8269.0-97 and GOST 8267-93 standards. The tests confirmed the compliance of the crushed stone with GOST 8267-93 and established its main physical characteristics.

The actual compaction density was determined by placing crushed stone in an air-dry state into the cavity of a KBP 100/200 block, positioned on a horizontal concrete foundation, with layer-by-layer compaction using a hand-operated vibrating tamper. After the cavity was filled, the horizontal alignment of the infill surface was checked, and excess crushed stone was removed. The crushed stone was then extracted from the cavity and weighed. This compaction and weighing process was repeated three times, resulting in obtaining the mass value of crushed stone filling the cavity of the KBP block with the selected compaction method. The cavity volume was measured by filling it with liquid and was determined to be 0.506±0.01 m³.

Based on the obtained crushed stone mass (M) and the known cavity volume (V), the average density of the crushed stone skeleton (ρ) was calculated as 1815±72.5 kg/m^3. This value was used as the target density for subsequent laboratory determination of shear resistance parameters.

The determination of shear resistance parameters was carried out in the Petromodeling Lab LLC laboratory using mobile shear units MSU-1 in accordance with GOST 20276.4-2020 and GOST 12248.1-2020 standards. The tests were conducted on disturbed structure samples with a diameter of 256 mm and a height of 195-200 mm [21]. The samples were formed directly in the shear carriage rings by filling them with compaction. The target density was specified as the previously obtained value of 1.82 g/cm^3. However, under laboratory conditions, this density could not be achieved, and the actual density range of the samples during testing was 1.48-1.66 g/cm^3.

The tests were conducted without water saturation, in a drained mode. The range of vertical stresses applied during the tests was 25-300 kPa, with a step of 25 kPa. The vertical stress was applied in one step and maintained until the displacement of the stamp stabilized to 0.1 mm/30 min. Then, a stepwise application of shear load was performed with holding until stabilization, in accordance with GOST 20276.4-2020 (0.1 mm/1 min). The shear load step was 5 kPa. A total of 12 tests were conducted. After completing the entire series of tests, some of the results were rejected based on the actual achieved density of the samples. The Coulomb-Mohr envelope constructed in the «σ – τ» coordinates is shown in Fig. 4.

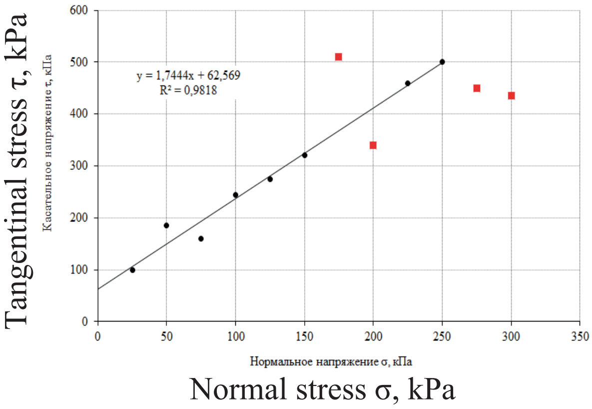


Figure 4. Coulomb-Mohr envelope constructed in «σ – τ» coordinates. Points excluded from consideration due to deviations in sample density are marked in red

As a result of processing in accordance with the requirements of Sections 7.6 – 7.12 of GOST 20522-2012, the normative and calculated values of shear resistance parameters were obtained. The average density of the samples was 1.6 g/cm^3, which is 12% below the target value. It is worth noting that within the investigated range of normal stresses, no deviations from linearity were observed in the Coulomb-Mohr envelope, allowing for the continued use of the Coulomb-Mohr strength theory in further modeling without switching to more complex nonlinear theories (such as the Hoek-Brown failure criterion).

It is also noteworthy that even at a density lower than that achieved in field conditions, this type of crushed stone exhibits significant interlocking (cohesion was 63 kPa). It is reasonable to assume that at the actual density in the mass, this crushed stone will have even higher cohesion values. The minimum pressure at the base from a single infilled block is 18 kPa, making lower normal pressure values in the retaining wall structure technically impossible. This allows us to disregard changes in cohesion in the low-stress region.

Considering the mono-fraction composition of the crushed stone used and the high compaction density, the dilatancy angle was determined to improve calculation accuracy. The determination was carried out during single-plane shear tests by additionally measuring vertical deformation. As a result, dependencies of vertical displacement of the stamp on the horizontal displacement of the shear carriage were obtained.

Table 2. Final table of physical and physico-mechanical properties of crushed stone

№	Parameter		Symbol	Unit	Value
1	Bulk density	norm.	ρ_{min}	g/cm^3	1,47
2	Density after compaction	norm.	ρ	g/cm^3	1,82± 0,07
3	Particle density	norm.	ρ_s	g/cm^3	2,69
4	Moisture content in air-dry state	norm.	W	%	0,1
5	Internal friction angle	norm.	$\varphi_н$	°	60,2
6		α = 0,95	φ_I		57,3
7		α = 0,85	φ_{II}		58,3
8	Specific cohesion	norm.	$c_н$	kPa	62,6
9		α = 0,95	c_I		55,9
10		α = 0,85	c_{II}		58,1
11	Dilatancy angle	norm.	ψ	°	7,9

The dilatancy angle was determined using the formula proposed by Bolton (1986) [22], based on the assumption of equality between the relative vertical deformation and the relative shear deformation. The range for determining the dilatancy angle was the section of maximum graph rise, which in most cases corresponded to the sample's hardening stage during shear. Table 2 presents the obtained values of the physico-mechanical properties sufficient for numerical modeling.

CONCLUSION

The main results obtained from the research are summarized by the authors in the following conclusions:

1) Stepped retaining structures made of box type blocks infilled with crushed stone are a promising design solution suitable for reinforcing soil slopes in civil, industrial, transportation, and hydrotechnical construction. However, due to the design’s structural features (primarily the absence of rigid connections between the blocks), this solution requires the development of traditional analytical calculation methods, as well as the justification for the creation of numerical calculation models;

2) For modular retaining walls, the use of numerical calculation methods is preferable due to the advantages of the finite element method. The "structure-soil" system is multiply statically indeterminate, and the soil's lateral pressure distribution under the same external load scheme will differ. Numerical calculations allow to identify a single stress state from a multitude of likely and permissible possibilities, determined by the set parameters of all system elements;

3) During a series of tests conducted in accordance with standard methodologies, the actual values of the physico-mechanical properties of the soil material used to fill the blocks and the spaces between them were determined. Normative and calculated shear resistance parameters were obtained. It was found that within the studied range of normal stresses, the Coulomb-Mohr envelope is linear. This allows the justified use of Coulomb-Mohr strength theory when model-

ing the considered retaining walls without resorting to more complex nonlinear theories, which require a larger number of parameters.

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