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ИНЖЕНЕРНО-ГЕОЛОГИЧЕСКОЕ ОБОСНОВАНИЕ ПАРАМЕТРОВ КУЧНОГО ВЫЩЕЛАЧИВАНИЯ ЗОЛОТА ИЗ БЕДНЫХ ПЕСЧАНО-ГЛИНИСТЫХ РУД

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Аннотация: На сегодняшний день наиболее экономически целесообразной технологией для извлечения ценных компонентов из низкосортных руд является технология кучного выщелачивания. Основной принцип технологии кучного выщелачивания заключается в миграции раствора выщелачивания через неподвижный объем руды, таким образом, по пути движения раствора происходит окисление металлов за счет их взаимодействия с химическими реагентами, в результате чего металлы преобразуются в легкорастворимые соединения, из которых легко извлечь полезный компонент. В процессе кучного выщелачивания в зависимости от режима эксплуатации происходит изменение инженерно-геологических параметров, таких как физико-механические свойства слагающих грунтов, уровень водонасыщения, уплотнение под действием вышележащих пород, что непосредственно влияет на устойчивость массива грунтов и развитие деформационных процессов. С целью получения более достоверного прогноза геомеханической и инженерно-геологической обстановки на площадке кучного выщелачивания было произведено численное моделирование напряженно-деформированного состояния горных пород в соответствии с расчетной схемой, учитывающей изменение физико-механических свойств горных пород в результате уплотнения, насыщения массива растворами цианида и осадками. В результате чего разработана методика обоснования оптимальных геотехнических параметров и фильтрационного режима эксплуатации штабелей кучного выщелачивания (КВ) и управления их устойчивостью, учитывающая специфику функционирования сложных инженерно-геологических сооружений техногенного происхождения, подверженных процессу выщелачивания.

Ключевые слова: кучное выщелачивание, окомкованная руда, обеспечение устойчивости штабеля, коэффициент фильтрации, численное моделирование, напряженно-деформированное состояние, геомеханические процессы, инженерно-геологический прогноз, оценка устойчивости.

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Engineering and geological parameters for heap leaching of gold from low-grade sandy clay ores: a feasibility study

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Abstract: The most economically feasible technology for extracting valuable components from low-grade ores is the heap leaching technology. The main principle of heap leaching technology is the migration of the leaching solution through a stationary volume of ore, so that along the way of the solution movement the oxidation of metals occurs due to their interaction with chemical reagents, as a result of which metals are transformed into easily soluble compounds from which a useful component is easily extracted. In the process of heap leaching, depending on the operating mode, engineering and geological parameters such as physical and mechanical properties of the constituent soils, water saturation level, compaction under the action of overlying rocks change, which directly affects the stability of the soil mass and the development of deformation processes. In order to obtain a more reliable forecast of the geomechanical and engineering-geological situation at the heap leaching site, the numerical simulation of the stress-strain state of rocks was carried out in accordance with the calculation scheme which takes into account changes in the physical and mechanical properties of rocks resulting from compaction, saturation of the massif with cyanide solutions and precipitation. As a result, a methodology for substantiating optimal geotechnical parameters and filtration regime of heap leach piles operation and management of their stability, taking into account the specifics of functioning of complex engineering and geological structures of man-made origin, subject to the leaching process, was developed.

Key words: heap leaching, pelletized ore, stack stability, permeability coefficient, numerical modeling, stress-strain analysis, geomechanical processes, geotechnical forecasting, stability assessment.

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Introduction

Due to the reduction in the reserves of high-grade gold ores and the annual increase in the volume of mining waste, there is a growing need to process low-grade gold ores [1, 2]. However, traditional processing technologies are not always economically viable for such materials, making it essential to explore efficient and cost-effective methods for producing gold [3—6]. Among them, the heap leaching (HL) method is the most effective as it can process poor ores with gold content as low as 0.5 g/t [7—11].

The effective and safe operation of HL stacks is influenced by various engineering, geological, and geomechanical processes that determine the stability of man-made structures [12—14], and there are several limitations to the application of this method. These include the deterioration of the physical and mechanical properties of the soils in the HL stack [15, 16], the uneven distribution of clays in the run-of-mine ore, which reduces the permeability performance of the HL stack rock [17, 18], oversaturation of the HL stack with cyanide solutions and precipitation, which alters the permeability characteristics of soils, and a decrease in the stability factor with an increase in stack height, among others [19—22].

The factors mentioned above can cause various negative dynamic processes such as displacement, changes in the design dimensions of the HL stack, sloughing, and accidental failure. Therefore, evaluating the stability of HL stacks is of great scientific, technical, and technological importance.

In the design and construction of man-made structures such as dumps, dams, waste heaps, and tailings ponds, basic calculation algorithms are used to ensure their stability and safety. This is acceptable for small-scale structures with low capital investments. However, they become inadequate for larger-scale projects covering several hectares of land. The use of such algorithms may result in significant financial [23, 24] and production safety and environmental [25, 26] risks for mining operations. The experience of creating man-made structures for other purposes cannot be fully adapted to the case of heap leach stacks, which require individual design considerations.

When designing multilevel heap leach stack structures, it is crucial to consider mining and geological conditions, as well as the factors that can affect the physical and mechanical properties of the constituent soils [27]. This is necessary to ensure effective and safe operation, as it directly impacts the stability, maximum overall slope, and height of the heap leach stack. Ignoring factors such as compaction and consolidation can result in the loss of useful stack height, and in the worst case, lead to structural integrity issues, instability, increased water cut, lower metal extraction, and longer leaching times.

Therefore, during the design phase, it is reasonable to adopt an approach that guarantees the stack's dependable and secure operation. To achieve this goal, this study utilizes the outcomes of modeling the stress-strain behavior of an engineering structure, considering variations in the physical and mechanical properties of the stack’s soils prior to and after leaching. Additionally, it accounts for the fact that such structures are constructed in several stages.

Methods

Methods based on the finite element method (FEM) are widely used to solve applied problems is geotechnology, engineering geology, and geomechanics, with the aim of improving the reliability of numerical calculations and predictive assessments [28].

The FEM-based calculation of the stress-strain behavior of a man-made rock structure satisfies the condition of static equilibrium for the chosen geomechanical model of the medium. This approach enables for making assessments that take into account the spatial variability of both the structure as a whole and its individual elements, as well as the heterogeneity of the medium.

In order to ensure the stability of the HL stack, it is essential to justify the choice of its technological and design parameters by utilizing adequate soil deformation models. These models must take into account various physical and mechanical properties of the soil.

The necessary condition for obtaining reliable numerical modeling results is factoring in stack construction stages in order to reproduce the real character of the changes in the stress-strain behavior of the rock mass and its saturation with leaching solutions. Stack stability assessment should be performed for a given case at the construction stage, representing the stress parameters of the heap during its formation, and at the operation stage to reproduce changes in the stress-strain behavior in the rock mass directly during leaching. When analyzing the stress-strain behavior, it is necessary to take into account scenarios both with and without transport load for each of the cases being modeled.

The Plaxis software package is widely used to perform stability calculations by means of numerical modeling in the frame-

Table 1

Key parameters of a heap leach toe (in the transverse direction)
Основные параметры конструкции основания откоса кучного выщелачивания в поперечном направлении

№	Layer	Layer thickness, mm	Material
1	Drainage layer	1,000	Crushed stone (20 – 70 mm)
2	Protective layer	300	Sand
3	Geomembrane	2	LLDPE polyethylene
4	Drainage layer	500	Crushed stone (5 – 20 mm)
5	Geocomposite	–	–
6	Loamy soil	200	Loam
7	Engineered liner	–	Loam

work of planar deformation. It is capable of determining the strength and stability of various geotechnical objects, including waterlogged ground masses [29, 30].

In the planar deformation formulation of the problem, the longitudinal deformations equal zero ($\varepsilon_y = 0$) along the whole extended part of the system under study, while the main normal stresses σ_1, σ_2 and σ_3 can differ from zero. Such a formulation reduces the dimensionality of the problem considered while maintaining satisfactory accuracy of the numerical results, and it represents a traditional approach to analyzing the stress-strain behavior of rock masses. However, the spatial formulation of such a problem has significant limitations due to the lack of reasonable recommendations for developing adequate geomechanical models of the medium.

For the numerical modeling of the HL stack, we used the parameters presented in Tables 1 to 2.

The HL stack with pelletized ore consists of four layers, with each divided into panels, which are separated from each other by two-meter dams. The ore is transported to the stack by means of conveyors.

The stability of the HL stack was evaluated by adopting the Mohr-Coulomb model [31] as a computational model of media deformation.

The condition of plasticity for solids (Coulomb's law of friction) is expressed as:

Table 2

Parameters of the ore stack adopted for the calculation
Параметры рудного штабеля, принятые для расчета

Parameters	Data
Bench height, m	10
Inter-tier berm width, m	30
Material size, mm	–125+0
Bulk density of agglomerated material, t/m^3	1,3
Angle of natural slope, deg.	42,5
Irrigation density, l per day per m^2	300
Underlying slope in the transverse direction	30
Under lying slope in the longitudinal direction	10

$$f = \tau - c - \sigma_n \mathrm{tg}\varphi, \quad (1)$$

where τ is shear strength, MPa; c is adhesion, MPa; φ is the angle of internal friction in degrees, σ_n is normal stress, MPa.

The generalized Mohr-Coulomb fluidity condition can also be specified by means of six fluidity functions [32] represented as functions of the principal normal stresses, e.g. f_{1a} in the form:

$$f_{1a} = \frac{1}{2}(\sigma_2 - \sigma_3) + \frac{1}{2}(\sigma_2 + \sigma_3)\sin\varphi - c\cos\varphi, \quad (2)$$

where σ_2 and σ_3 are main normal stresses, MPa; c is cohesion, MPa; φ is the angle of internal friction indegrees.

This plastic flow model is suitable for solving problems related to estimating the carrying capacity of the man-made structures under consideration.

The physical and mechanical parameters of soils in the foundation and the structure itself are presented in Table 3.

The hardening soil model was used to describe the mechanical behavior of pelletized ore [33]. It is based on the nonlinear elastic Duncan-Chang model [34], which is characterized by a hyperbolic relationship between vertical relative deformations ε_1 and the deviatoric component of the stress tensor q_a. In drained triaxial tests under the condition $q_a < q_f$, the soil behavior is described by the equation:

$$\varepsilon_1 = \frac{q_a}{2E_{50}} \frac{\sigma_1 - \sigma_3}{q_a - (\sigma_1 - \sigma_3)}, \quad (3)$$

where σ_1 is the main normal maximum stress, MPa; σ_3 is the main normal minimum stress, MPa; q_f is limit value of the deviatoric component; E_{50} is the soil deformation modulus.

The surface of the plastic flow for the hardening soil model can be expressed as:

$$f_{12} = \frac{q_a}{E_{50}} \frac{\sigma_1 - \sigma_2}{q_a - (\sigma_1 - \sigma_2)} - \frac{2(\sigma_1 - \sigma_2)}{E_{ur}} - \gamma^p;$$
$$f_{13} = \frac{q_a}{E_{50}} \frac{\sigma_1 - \sigma_3}{q_a - (\sigma_1 - \sigma_3)} - \frac{2(\sigma_1 - \sigma_3)}{E_{ur}} - \gamma^p, \quad (4)$$

where γ^p is volumetric plastic deformation; E_{ur} is the independent modulus of elasticity of soil, which is determined empirically.

The double hardening soil model is used when it is necessary to consider the shear and compressive behavior of the ground, with the possibility of independent shear and compressive hardening.

Table 3

Mohr-Coulomb model data
Данные модели Кулона-Мора

Soil	γ_{unsat}, unit weight of soil at natural humidity, kN/m^3	γ_{sat}, unit weight of soil at full water saturation, kN/m^3	*e*, porosity coefficient	E_0, deformation modulus, MPa	ν_0, shear strain coefficient	*c*, cohesion, kPa	φ, effective angle of internal friction, deg.
Foundation							
High-plasticity gravelly loam with an admixture of peat	15.6	18.4	0.73	10.0	0.35	18	20
Structure							
Body	21.0	22.0	0.32	40.0	0.40	10	35
Impervious element	17.5	20.5	0.05	15.0	0.40	5	15
Protective layer of crushed stone	22.0	24.0	0.73	40.0	0.40	5	40

Table 4

Hardening soil model data for pelletized ore

Данные модели Hardening soil для окомкованной руды

γ_{unsat}, unit weight of soil at natural humidity, kN/m^3	γ_{sat}, unit weight of soil at full water saturation, kN/m^3	*e*, porosity coefficient	E_{50}, elastoplastic modulus, MPa	E_{oed}, oedometric modulus, MPa	E_{ur}, young's modulus, MPa	*m*, parameter factoring in the influence of the average stress on the deformation properties of the soil	*c*, cohesion, kPa	φ, effective angle of internal friction, deg	ψ, dilatancy angle, deg.
15.6	17.3	–	10.0	6.5	30	0.6	40	31	0

Table 5

Parameters of the van Genuchten–Mualem permeability model

Параметры фильтрационной модели Van Genuchten–Mualem

Material	Permeability coefficient of a fully saturated porous environment k_{sat}, m/day	Model parameters					
		S_{res}	S_{sat}	g_a, 1/м	g_n	g_c	g_l
Pelletized ore	2.35	0.139	1.0	12.4	2.28	−0.56	0.5
Gravel	7.0	0.105	1.0	14.5	2.68	−0.62	0.5
Sand	3.5	0.105	1.0	14.5	2.68	−0.62	0.5

The physical and mechanical parameters of pelletized ore which were adopted based on the results of laboratory tests are presented in Table 4.

Permeability characteristics of the porous medium of the HL stack are calculated based on the van Genuchten–Mualem model [35, 36]. The parameters of this model for pelletized ore were determined through laboratory tests, which included determining the particle size distribution and the permeability coefficient in a completely water-saturated state. The parameters for the crushed rock and sand layers underlying the pelletized ore are presented in Table 5.

To determine the optimal height of the stack bench, we considered the problem

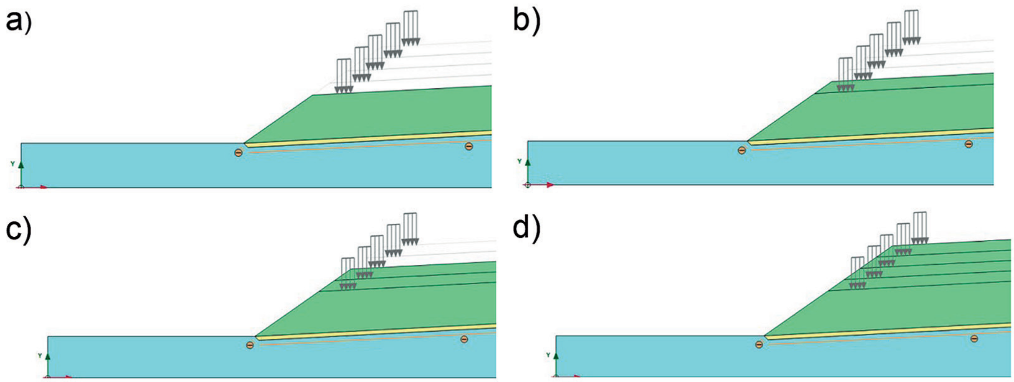

Fig. 1. Diagrams for evaluating the slope stability of the heap leach stack at different level heights: 10 m (a); 20 m (b); 30 m (c); 40 m (d)

Рис. 1. Схема оценки устойчивости откоса штабеля кучного выщелачивания при разной высоте яруса: 10 м (а); 20 м (б); 30 м (в); 40 м (г)

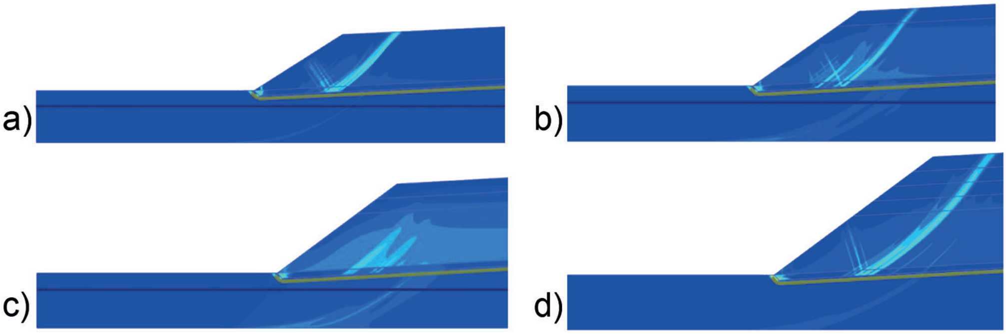

Fig. 2. Dry heap leach stack at different bench heights with geomembrane present: 10 m (a); 20 m (b); 30 m (c); 40 m (d)
Рис. 2. Сухой массив, пленка присутствует: 10 м (а); 20 м (б); 30 м (в); 40 м (г)

of assessing the stability of the heap leach stack made of one bench, whose height ranges from 10 to 20 m with a step of 2.5 m. The height of the bench is taken as its final height after compaction. The angle of slope of the stack is assumed to be 35°.

Different water cuts were considered for the stack, ranging from completely dry to fully watered. Intermediate values were also considered, with values of 1, 2, 3, and 9 m relative to the foundation.

Results

Schematic diagrams of the design models used for assessing the slope stability of the HL stack are presented in Fig. 1. The position of loads from transport equipment is indicated, with a value of 133 kPa adopted.

Table 6

Slope stability factors of a heap leach stack
Коэффициенты запаса по устойчивости откоса штабеля кучного выщелачивания

№	Loading conditions	Slope stability factors for different bench heights (m)				
		10.0	**12.5**	**15.0**	**17.5**	**20.0**
	No load from transport equipment					
1	Dry stack, no geomembrane	2.40	2.17	2.00	1.86	1.77
2	Dry stack, geomembrane present	2.12	1.85	1.71	1.59	1.47
3	Water-saturated stack, geomembrane present, water cut of 1.0 m	1.98	1.80	1.65	1.55	1.46
4	Water-saturated stack, geomembrane present, water cut of 2.0 m	1.95	1.77	1.62	1.50	1.42
5	Water-saturated stack, geomembrane present, water cut of 3.0 m	1.89	1.73	1.60	1.47	1.35
6	Water-saturated stack, geomembrane present, water cut of 9.0 m	1.38	1.30	1.24	1.21	–
7	Full water saturation	1.36	1.16	1.03	<1.00	<1.00
	With load from transport equipment					
8	Dry stack, no geomembrane	1.91	1.82	1.73	1.67	1.62
9	Dry stack, geomembrane present	1.57	1.51	1.43	1.39	1.35

Table 7

Local stability assessment during the construction phase

Оценка местной устойчивости отвала на стадии строительства

Design cross-section	Stability factor							
	Bench I		Bench II		Bench III		Bench IV	
No load from transport equipment								
I	2.16	1.72*	2.12	1.72*	1.98	1.72*	1.98	1.72*
II	2.18	1.87*	2.16	1.87*	2.13	1.87*	2.01	1.87*
With load from transport equipment								
I	1.57	1.44*	1.76	1.73*	1.97	1.82*	1.90	1.82*
II	1.80	1.53*	1.95	1.84*	1.99	1.85*	1.93	1.80*

Stack slope stability calculations were performed for both saturated conditions at different water cuts and dry conditions under loads from transport equipment (Fig. 2).

The results of slope stability calculations for the heap leach stack are shown in Table 6.

The calculations performed demonstrate that the accepted physical and mechanical parameters of the stack and foundation materials provide sufficient stability, with a minimum permissible stability factor of 1.22. However, exceptions are observed in cases where the HL stack is fully saturated with water at a bench height greater than 10 m or when the water cut is 9 m or more at a bench height greater than 15 m. It should be noted that such water cut values do not correspond to normal operation modes [37].

Stability assessment results obtained by means of the adopted calculation algorithm are presented in Tables 7 and 8.

Where I is the transverse design cross-section, II is the longitudinal design cross-section; the asterisk means that the calculation was performed by the method of limiting equilibrium without regard to compaction.

Where I is the transverse design cross-section, II is the longitudinal design cross-section.

Stability assessment results at the operation stage are shown in Table 9.

Stability loss cases for the longitudinal cross-section at the operation stage are shown in Figures 3 (with load from transport equipment) and 4 (without load from transport equipment).

Numerical models were used to evaluate the effectiveness of the drainage layer in allowing solution to filter through the stack. The height of the stack was assumed to be 20 m, with an irrigation intensity of 300 liters per day per m^2. The permeability coefficient was considered variable in

Table 8

Overall slope stability

Общая устойчивость откоса

Design cross-section	Stability factor at different operation stages				
	construction	normal operation	operation at full water saturation of the first bench	operation at full water saturation of all benches taking into account the dams between the benches	operation at water saturation of all benches
I	1.83	1.61	1.36	1.21	0.76
II	1.94	1.88	1.52	1.42	0.91

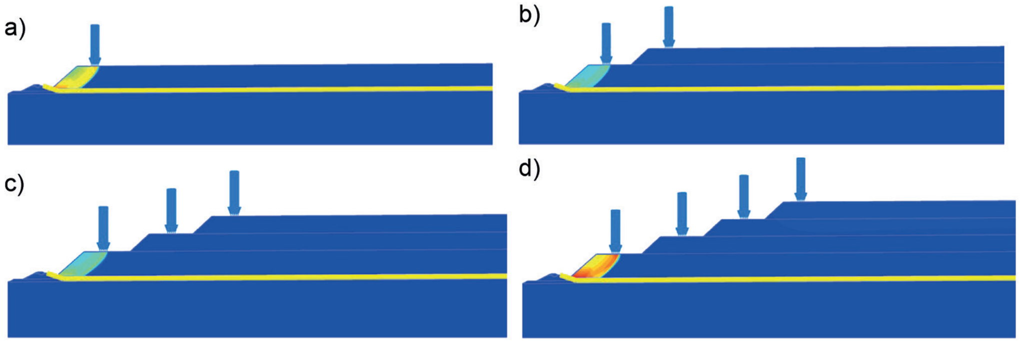

Fig. 3. Heap leach stack stability simulation at the operation stage with load from transport equipment (longitudinal cross-section): 10 m (a); 20 m (b); 30 m (c); 40 m (d)

Рис. 3. Моделирование устойчивости штабеля КВ на стадии эксплуатации с учетом нагрузки от транспорта (продольное сечение): 10 м (а); 20 м (б); 30 м (в); 40 м (г)

Table 9

Heap leach stack stability at the operation stage (permeability analysis)
Устойчивость штабеля КВ на стадии эксплуатации (фильтрационный расчет)

Designcross-section	Stability factor			
	Bench I	Bench II	Bench III	Bench IV
No load from transport equipment				
Crosssection I	1.54	1.55	1.56	1.69
Longitudinal section II	1.71	1.71	1.80	1.83
With load from transport equipment				
Cross section I	1.26	1.27	1.26	1.36
Longitudinal section II	1.52	1.53	1.53	1.54

depth, and the distribution of the permeability coefficient by depth was analyzed for two grain sizes: 20 mm and 125 mm. The results obtained for the value of 20 mm indicate that if the HL stack consisted only of such ore, complete water saturation zones would form in the stack.

Based on the numerical calculations, it was found that for pelletized ore with permeability characteristics corresponding to the 120 mm size, the degree of water saturation varied from 0.54 to 0.91 as the height of the stack increased. It should be noted that pelletized ore experiences a sig-

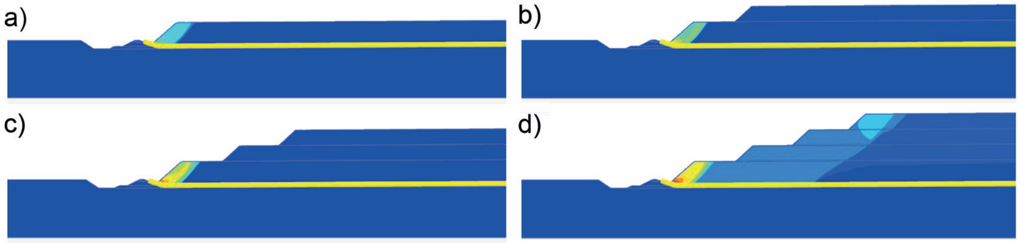

Fig. 4. Heap leach stack stability simulationat the operation stage without load from transport equipment (longitudinal cross-section): 10 m (a); 20 m (b); 30 m (c); 40 m (d)

Рис. 4. Моделирование устойчивости штабеля КВ на стадии эксплуатации без учета нагрузки от транспорта (продольное сечение): 10 м (а); 20 м (б); 30 м (в); 40 м (г)

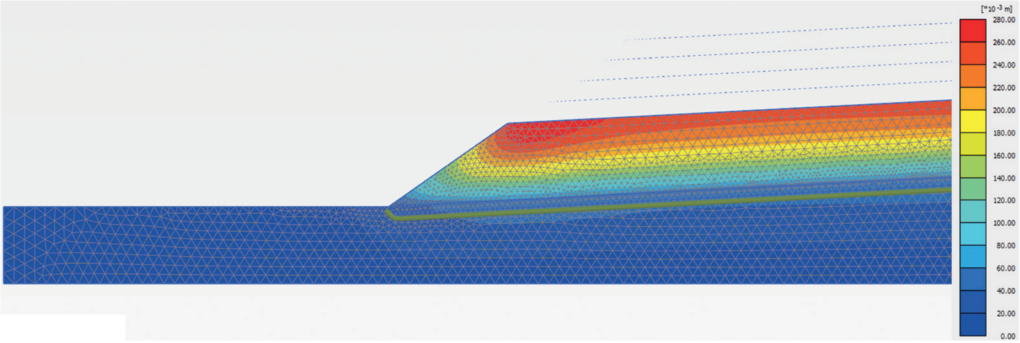

Fig. 5. Distribution of the resulting absolute deformations (m) in the stack during the formation of the first bench (a height of 10 m)

Рис. 5. Распределение результирующих абсолютных деформаций (м) штабеля при формировании первого яруса (высота 10 м)

nificant change in its physical condition at values ranging from 0.85 to 0.9, meaning that it can be conditionally considered fully saturated. Thus, the results indicate that at a stack height of 17 m and above, the degree of water saturation of the pelletized ore reaches limiting values.

The numerical simulation analyzed the mechanical deformation of the HL stack during its formation using the hardening soil model as the medium model. This model accounts for the deformation of pelletized ore due to changes in the stress-strain behavior of the stack (such as backfilling and water saturation), but does not consider compaction resulting from changes in its physical state. As an example, a stack bench 10 m in height was analyzed.

The results of the study show that the degree of surface subsidence due to ore compaction is dependent on its initial void ratio, with values ranging from 0.3 to 0.5 m (as shown in Fig. 5). When accounting for the additional deformation caused by saturation of the pellets with solution, an additional subsidence of 0.6 to 0.7 m is expected. Therefore, the total amount of subsidence is estimated to be between 0.9 and 1.2 m.

Discussion

The hydrogeological factor that determines the stable operation of the structure is the permeability coefficient, which depends on various factors such as the quality of leaching solutions, the degree of soil compaction, and the presence of fine soil particles that can lead to pore clogging.

The stability of an HL stack is strongly influenced by the filtration mode adopted. It is important to note that if the leaching solution migrates through the stationary volume of ore in an improper filtration mode, it can lead to a decrease in the weight of the rock within the sliding surface, which can result in a decrease in retention forces and small particles being removed due to suffosion. In such cases, slope failure and landslide processes are highly likely. When the sliding surface passes through the near-slope zone composed of fine material, excessive pore pressure can weaken the internal retention forces [33, 34]. If containment dams are used to secure water-saturated foundation sand the soils are under too much pressure, there is a risk of extrusion landslides.

The permeability calculations have established that under the given heap leaching stack conditions, the bench height should not exceed 18 m at an irrigation density of 300 liters per day per m^2. However, decreasing the irrigation density would allow for the formation of an HL stack with a height of up to 20 m.

When modeling the stability and deformations in an HL stack, it is crucial to ensure that its design model accurately reflects the conditions of its construction and subsequent operation. The modeling results revealed that the sliding surface remains within one bench and is confined to it, without spreading to the entire stack. This finding indicates a high stability factor.

An exception is observed in cases where a bench with a height exceeding 10 m is fully saturated, or at a water cut of 9 m for a bench height of more than 15 m.

Based on the stability assessment results, it can be concluded that increasing the number of stack benches does not significantly affect the stability factor. In the considered calculation scenarios, deformations are localized within the first bench, provided that complete water saturation does not occur. It is important to note that displacements from the design dimensions are possible within the first bench. Therefore, it is necessary to implement additional measures to monitor and maintain the stability of the HL stack.

Conclusion

A heap leach stack is a complex engineering structure with dynamic properties, and its stability is influenced by various engineering and geological parameters. These include the physical and mechanical properties of the constituent soils, the height of the water cut, compaction under the pressure of overlying rocks, temperature, and operating conditions. These parameters directly impact the stability factor and may trigger deformation processes.

Deformation processes can occur on the slopes of an HL stack when the rock mass is highly saturated with water, leading to a decrease in the strength properties of pelletized soils. This can be further aggravated by mechanical destruction of pellets and physical and chemical transformations resulting from the use of a chemical solution of sodium cyanide.

To improve the accuracy of geomechanical and geological predictions at an HL site, we recommend to implement numerical simulations that consider the changes in physical and mechanical properties of the rocks caused by compaction, cyanide solution saturation, sedimentation, and the subsequent formation of a rock mass with altered mechanical properties. Monitoring of physical and mechanical parameters at various stages of the HL stack operation is also crucial for applying reliable engineering and technological solutions to ensure its stability.

Slope stability management necessitates regular monitoring of the slopes, which involves taking periodic measurements of vertical and horizontal displacements along reference lines located along the slopes. Particular attention should be paid to areas with a foundation angle that coincides with the slope angle. This will make it possible to calibrate the numerical model, specify deformation process indicators, and make more accurate forecasts of mining and geomechanical conditions at a heap leaching site.

Implementing hydrogeological monitoring of the solution distribution within the HL stack can help prevent excess moistening and changes to soil properties, over-saturation with leaching solutions, and consequently, rock mass sliding and other processes resulting in the loss of compacted soils.

СПИСОК ЛИТЕРАТУРЫ

1. *Трубецкой К. Н., Каплунов Д. Р., Рыльникова М. В.* Принципы обоснования параметров устойчивого и экологически сбалансированного освоения месторождений твердых полезных ископаемых // Горный информационно аналитический бюллетень. — 2014. — № 2. — С. 3—10.

2. *Чантурия В. А., Вайсберг Л. А., Козлов А. П.* Приоритетные направления исследований в области переработки минерального сырья // Обогащение руд. — 2014. — № 2. — С. 3—9. DOI: 10.17580/or.2014.02.01

3. *Шумилова Л. В., Хатькова А. Н., Черкасов В. Г.* Альтернативные варианты подготовки техногенных отходов к выщелачиванию металлов // Горный информационно-аналитический бюллетень. — 2021. — № 3-2. — С. 173—181. DOI: 10.25018/0236_1493_2021_32_0_173.

4. *Иваник С. А., Илюхин Д. А.* Флотационное выделение элементарной серы из золотосодержащих кеков // Записки Горного института. — 2020. — Т. 242. — С. 202—208. DOI: 10.31897/PMI.2020.2.202.

5. *Alexandrova T., Nikolaeva N., Afanasova A., Romashev A., Aburova V., Prokhorova E.* Extraction of low-dimensional structures of noble and rare metals from carbonaceous ores using low-temperature and energy impacts at succeeding stages of raw material transformation // Minerals. 2023, vol. 13, no. 1, pp. 84—112. DOI: 10.3390/min13010084.

6. *Соколов И. В., Антипин Ю. Г., Рожков А. А., Соломеин Ю. М.* Экогеотехнология добычи бедных руд с созданием условий для попутной утилизации отходов горного производства // Записки Горного института. — 2023. — Т. 260. — С. 289—296. DOI: 10.31897/PMI.2023.21.

7. *Ларичкин Ф. Д., Войтеховский Ю. Л., Воробьев А. Г., Гончарова Л. И.* Особенности обоснования параметров кондиций рентабельного извлечения ценных редкоземельных составляющих многокомпонентного минерального сырья // Горный журнал. — 2016. — № 1. — С. 49—53. DOI: 10.17580/gzh.2016.01.10.

8. Подземное и кучное выщелачивание урана, золота и других металлов: в 2 т. / Под ред. М. И. Фазлуллина. Т. 1: Уран. — М.: ИД «Руда и Металлы», 2005. — 407 с.

9. *Санакулов К. С.* Эффективное использование техногенных отходов при кучном выщелачивании золота. — Навои: Типография НГМК, 2021. — 379 с.

10. *Голик В. И., Разоренов Ю. И., Бригида В. С., Бурдзиева О. Г.* Механохимическая технология добычи металлов из хвостов обогащения // Известия Томского политехнического университета. Инжиниринг георесурсов. — 2020. — Т. 331. — № 6. — С. 175—183. DOI: 10.18799/24131830/2020/6/2687.

11. *McBride D., Gebhardt J., Croft N., Cross M.* Heap leaching: Modeling and forecasting using CFD technology // Minerals. 2018, vol. 8, no. 1, article 9. DOI: 10.3390/MIN8010009.

12. *Кутепов Ю. И., Кутепова Н. А.* Методология инженерно-геологического изучения гидрогеомеханических процессов в техногенно-нарушенных массивах при разработке МПИ // Горный информационно аналитический бюллетень. — 2014. — № 8. — С. 123—131.

13. *Petersen J.* Heap leaching as a key technology for recovery of values from low-grade ores. A brief overview // Hydrometallurgy. 2016, vol. 165, pp. 206—212. DOI: 10.1016/j.hydromet.2015.09.001.

14. *Глазунов В. В., Бурлуцкий С. Б., Шувалова Р. А., Жданов С. В.* Повышение достоверности 3D-моделирования оползневого склона на основе учета данных инженерной геофизики // Записки Горного института — 2022 — Т. 257 — С. 771—782. DOI: 10.31897/PMI.2022.86.

15. *Лушников Я. В., Багазеев В. К.* Определение физико-механических свойств окатышей при формировании штабеля кучного выщелачивания // Известия вузов. Горный журнал. — 2013. — № 8. — С. 124—127.

16. *Татауров С. Б.* Экспериментально-теоретические исследования и обоснование геотехнологии формирования штабеля из окомкованных золотосодержащих руд для улучшения его фильтрационных свойств // Записки Горного института. — Т. 189. — С. 168—174.

17. *Toro N., Ghorbani Y., Turan M. D., Robles P., Gálvez E.* Gangues and clays minerals as rate-limiting factors in copper heap leaching: a review // Metals. 2021, vol. 11, pp. 1539—1554. DOI: 10.3390/met11101539.

18. *Дементьев В. Е., Татаринов А. П., Гудков С. С.* Основные аспекты технологии кучного выщелачивания золотосодержащего сырья // Горный журнал. — 2001. — № 5. — С. 53—55.

19. *Robertson S. W., van Staden P. J., Cherkaev A., Petersen J.* Properties governing the flow of solution through crushed ore for heap leaching // Hydrometallurgy. 2022, vol. 208, pp. 1 — 17. DOI: 10.10165/j.hydromet.2021.105811.

20. *Argimbaev K. R.* Investigations of the deposit geological structure impact on the technogenic accident risk at the mining plant // Journal of Engineering and Applied Sciences. 2018, vol. 13, no. 7, pp. 1713 — 1717.

21. *Reyes A., Garma P., Parra D.* 3D slope stability analysis of heap leach pads using the limit equilibrium method. Peru, 2014, pp. 257 — 271.

22. *Wei L., Zhang Y., Zhao Z., Zhong X., Liu S.* Analysis of mining waste dump site stability based on multiple remote sensing technologies // Remote Sensing. 2018, vol. 10, no. 12, pp. 2025 — 2045. DOI: 10.3390/rs10122025.

23. *Ponomarenko T., Nevskaya M., Marinina O.* An assessment of the applicability of sustainability measurement tools to resource-based economies of the commonwealth of independent states // Sustainability. 2020, vol. 12, no. 14, pp. 5582 — 5589. DOI:10.3390/su12145582.

24. *Smith M., Parra D., Asociados A.* Leach pad cost benchmarking / Proceedings of Heap Leach Solutions. Peru, 2014, 9 p.

25. *Пашкевич М. А., Алексеенко А. В., Нуреев Р. Р.* Формирование экологического ущерба при складировании сульфидсодержащих отходов обогащения полезных ископаемых // Записки Горного института. — 2023. — Т. 260. — С. 155 — 167. DOI: 10.31897/PMI.2023.32.

26. *Petrova T. A.*, Rudzisha E, *Alekseenko A. V.*, Bech J., *Pashkevich M. A.* Rehabilitation of disturbed lands with industrial wastewater sludge // Minerals. 2022, vol. 12, no. 3, pp. 1 — 19. DOI: 10.3390/MIN12030376.

27. *Господариков А. П., Ефимов Д. А.* Технико-технологические аспекты использования валков с профилем в форме треугольника Рело в дробящих агрегатах на рудоподготовительном переделе // Горный информационно-аналитический бюллетень. — 2022. — № 10-2. — С. 117 — 126. DOI: 10.25018/0236-1493-2022-102-0-117.

28. *Mostaghimi P., Tollit B. S., Neethling S. J., Gorman G. J., Pain C. C.* A control volume finite element method for adaptive mesh simulation of flow in heap leaching // Journal of Engineering Mathematics. 2014, vol. 87, no. 1, pp. 111 — 121. DOI: 10.1007/S10665-013-9672-3.

29. *Miao X., Narsilio G. A., Wu A., Yang B.* 3D dual pore-system leaching model. Part 1: Study on fluid flow // Hydrometallurgy. 2017, vol. 167, pp. 173 — 182. DOI: 10.1016/j.hydromet.2016.11.015.

30. *Brinkgreve R. B.* J. PLAXIS 3D 2017. Material Models Manual, Netherlands, 2018. 212 p.

31. *Протосеня А. Г., Алексеев А. В., Вербило П. Э.* Прогноз напряженно-деформированного состояния и устойчивости лба забоя тоннеля при пересечении нарушенных зон грунтового массива // Записки Горного института. — 2022. — Т. 254. — С. 252 — 260. DOI: 10.31897/PMI.2022.26.

32. *Smith I. M., Griffith D. V.* Programming the finite element method. John Wiley & Sons, Chisester, U.K, 2nd edition, 1982. 351 p.

33. *Schanz T., Vermeer P. A., Bonnier P. G.* The Hardening Soil Model: Formulation and verification / Beyond 2000 in Computational Geotechnics. 1999, pp. 281 — 290.

34. *Деменков П. А., Трушко О. В., Комолов В. В.* Прогноз оседания поверхности земли при сооружении котлована вблизи застройки // Известия Тульского государственного университета. Науки о Земле. — 2019. — № 2. — С. 300 — 309.

35. *Schaap M. G., Van Genuchten M. Th.* A modified mualem-van genuchten formulation for improved description of the hydraulic conductivity near saturation // Vadose Zone Journal. 2006, vol. 5, pp. 27 — 34. DOI: 10.2136/vzj2005.0005.

36. *Mostaghimi P., Tollit B. S., Neethling S. J., Gorman G. J., Pain C.* A control volume finite element method for adaptive mesh simulation of flow in heap leaching // Journal of Engineering Mathematics. 2014, vol. 87, pp. 111 — 121. DOI: 10.1007/S10665-013-9672-3.

37. *Thenepalli T., Chilakala R., Habte L., Tuan L., Kim C. S.* A Brief note on the heap leaching technologies for the recovery of valuable metals // Sustainability. 2019, vol. 11, no. 12. article 3347. DOI: 10.390/SU1112334730.

REFERENCES

1. Trubetskoy K. N., Kaplunov D. R., Rylnikova M. V. The principles of parametes justification of sustainable and ecologically balanced exploration of solid mineral resources. *MIAB. Mining Inf. Anal. Bull.* 2014, no. 2, pp. 3—10. [In Russ].

2. Chanturiya V. A., Vaysberg L. A., Kozlov A. P. Promising trends in investigations aimed at all-round utilization of mineral raw materials. *Obogashchenie Rud.* 2014, no. 2, pp. 3—9. [In Russ]. DOI: 10.17580/or.2014.02.01

3. Shumilova L. V., Khatkova A. N., Cherkasov V. G. Alternative preparation of mining waste for metal leaching. *MIAB. Mining Inf. Anal. Bull.* 2021, no. 3-2, pp. 173—181. [In Russ]. DOI: 10.25018/0236_1493_2021_32_0_173.

4. Ivanik S. A., Ilyukhin D. A. Flotation extraction of elemental sulfur from gold-bearing cakes. *Journal of Mining Institute.* 2020, vol. 242, pp. 202—208. [In Russ]. DOI: 10.31897/PMI.2020.2.202.

5. Alexandrova T., Nikolaeva N., Afanasova A., Romashev A., Aburova V., Prokhorova E. Extraction of low-dimensional structures of noble and rare metals from carbonaceous ores using low-temperature and energy impacts at succeeding stages of raw material transformation. *Minerals.* 2023, vol. 13, no. 1, pp. 84—112. DOI: 10.3390/min13010084.

6. Sokolov I. V., Antipin Yu. G., Rozhkov A. A., Solomein Yu. M. Environmental geotechnology for low-grade ore mining with the creation of conditions for the concurrent disposal of mining waste. *Journal of Mining Institute.* 2023, vol. 260, pp. 289—296. [In Russ]. DOI: 10.31897/PMI.2023.21.

7. Larichkin F. D., Voitekhovsky Yu. L., Vorobyov A. G., Goncharova L. I. Peculiarities of substantiating the parameters of the conditions for cost-effective extraction of valuable rare-earth components of multicomponent mineral raw materials. *Gornyi Zhurnal.* 2016, no. 1, pp. 49—53. [In Russ]. DOI: 10.17580/gzh.2016.01.10.

8. *Podzemnoe i kuchnoe vyshchelachivanie urana, zolota i drugikh metallov*: v 2 t. Pod red. M. I. Fazlullina, t. 1: Uran [Underground and heap leaching of uranium, gold and other metals: in 2 vol., Fazlullin M. I. (Ed.)], Moscow, ID «Ruda i Metally», 2005, 407 p.

9. Sanakulov K. S. *Effektivnoe ispol'zovanie tekhnogennykh otkhodov pri kuchnom vyshchelachivanii zolota* [Effective use of anthropogenic waste in the heap leaching of gold], Navoi, Tipografiya NGMK, 2021, 379 p.

10. Golik V. I., Razorenov Yu. I., Brigida V. S., Burdzieva O. G. Mechanochemical technology of metal mining from enriching tails. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering.* 2020, vol. 331, no. 6, pp. 175—183. [In Russ]. DOI: 10.18799/24131830/2020/6/2687.

11. McBride D., Gebhardt J., Croft N., Cross M. Heap leaching: Modeling and forecasting using CFD technology. *Minerals.* 2018, vol. 8, no. 1, article 9. DOI: 10.3390/MIN8010009.

12. Kutepov Yu. I., Kutepova N. A. Methodology of engineering-geological study of hydrogeomechanical processes in technogenic-disturbed massifs during mining MPI. *MIAB. Mining Inf. Anal. Bull.* 2014, no. 8, pp. 123—131. [In Russ].

13. Petersen J. Heap leaching as a key technology for recovery of values from low-grade ores. A brief overview. *Hydrometallurgy.* 2016, vol. 165, pp. 206—212. DOI: 10.1016/j.hydromet.2015.09.001.

14. Glazunov V. V., Burlutsky S. B., Shuvalova R. A., Zhdanov S. V. Increasing the reliability of 3D modeling of a landslide slope based on accounting for engineering geophysics data. *Journal of Mining Institute.* 2022, vol. 257, pp. 771—782. [In Russ]. DOI: 10.31897/PMI.2022.86.

15. Lushnikov Ya. V., Bagazeev V. K. Definition of physical and mechanical properties of ore pellets when forming a stack of heap leaching. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal.* 2013, no. 8, pp. 124—127. [In Russ].

16. Tataurov S. B. Experimental and theoretical studies and justification of geotechnology of stock pile formation from pelletized gold-bearing ores in order to enhance its filtration properties. *Journal of Mining Institute*, vol. 189, pp. 168—174. [In Russ].

17. Toro N., Ghorbani Y., Turan M. D., Robles P., Gálvez E. Gangues and clays minerals as rate-limiting factors in copper heap leaching: a review. *Metals*. 2021, vol. 11, pp. 1539—1554. DOI: 10.3390/met11101539.

18. Dementev V. E., Tatarinov A. P., Gudkov S. S. Main aspects of heap leaching technology for gold-bearing raw materials. *Gornyi Zhurnal*. 2001, no. 5, pp. 53—55. [In Russ].

19. Robertson S. W., van Staden P. J., Cherkaev A., Petersen J. Properties governing the flow of solution through crushed ore for heap leaching. *Hydrometallurgy*. 2022, vol. 208, pp. 1—17. DOI: 10.10165/j.hydromet.2021.105811.

20. Argimbaev K. R. Investigations of the deposit geological structure impact on the technogenic accident risk at the mining plant. *Journal of Engineering and Applied Sciences*. 2018, vol. 13, no. 7, pp. 1713—1717.

21. Reyes A., Garma P., Parra D. *3D slope stability analysis of heap leach pads using the limit equilibrium method*. Peru, 2014, pp. 257—271.

22. Wei L., Zhang Y., Zhao Z., Zhong X., Liu S. Analysis of mining waste dump site stability based on multiple remote sensing technologies. *Remote Sensing*. 2018, vol. 10, no. 12, pp. 2025—2045. DOI: 10.3390/rs10122025.

23. Ponomarenko T., Nevskaya M., Marinina O. An assessment of the applicability of sustainability measurement tools to resource-based economies of the commonwealth of independent states. *Sustainability*. 2020, vol. 12, no. 14, pp. 5582—5589. DOI:10.3390/su12145582.

24. Smith M., Parra D., Asociados A. Leach pad cost benchmarking. *Proceedings of Heap Leach Solutions*. Peru, 2014, 9 p.

25. Pashkevich M. A., Alekseenko A. V., Nureev R. R. Environmental damage from the storage of sulfide ore tailings. *Journal of Mining Institute*. 2023, vol. 260, pp. 155—167. [In Russ]. DOI: 10.31897/PMI.2023.32.

26. Petrova T. A., Rudzisha E, Alekseenko A. V., Bech J., Pashkevich M. A. Rehabilitation of disturbed lands with industrial wastewater sludge. *Minerals*. 2022, vol. 12, no. 3, pp. 1—19. DOI: 10.3390/MIN12030376.

27. Gospodarikov A. P., Efimov D. A. Technical and technological aspects of the use of Reuleaux triangular profile rolls in crushing units in the ore processing plant. *MIAB. Mining Inf. Anal. Bull.* 2022, no. 10-2, pp. 117—126. [In Russ]. DOI: 10.25018/0236-1493-2022-102-0-117.

28. Mostaghimi P., Tollit B. S., Neethling S. J., Gorman G. J., Pain C. C. A control volume finite element method for adaptive mesh simulation of flow in heap leaching. *Journal of Engineering Mathematics*. 2014, vol. 87, no. 1, pp. 111—121. DOI: 10.1007/S10665-013-9672-3.

29. Miao X., Narsilio G. A., Wu A., Yang B. 3D dual pore-system leaching model. Part 1: Study on fluid flow. *Hydrometallurgy*. 2017, vol. 167, pp. 173—182. DOI: 10.1016/j.hydromet.2016.11.015.

30. Brinkgreve R. B. J. PLAXIS 3D 2017. Material Models Manual, Netherlands, 2018. 212 p.

31. Protosenya A. G., Alekseev A. V., Verbilo P. E. Prediction of the stress-strain state and stability of the front of tunnel face at the intersection of disturbed zones of the soil mass. *Journal of Mining Institute*. 2022, vol. 254, pp. 252—260. [In Russ]. DOI: 10.31897/PMI.2022.26.

32. Smith I. M., Griffith D. V. *Programming the finite element method*. John Wiley & Sons, Chisester, U.K, 2nd edition, 1982. 351 p.

33. Schanz T., Vermeer P. A., Bonnier P. G. The hardening soil model: Formulation and verification. *Beyond 2000 in Computational Geotechnics*. 1999, pp. 281—290.

34. Demenkov P. A., Trushko O. V., Komolov V. V. The forecast of earth surface subsidence at the excavator of the pit near the building. *News of the Tula state university. Sciences of Earth*. 2019, no. 2, pp. 300—309. [In Russ].

35. Schaap M. G., Van Genuchten M. Th. A modified mualem-van genuchten formulation for improved description of the hydraulic conductivity near saturation. *Vadose Zone Journal*. 2006, vol. 5, pp. 27—34. DOI: 10.2136/vzj2005.0005.

36. Mostaghimi P., Tollit B. S., Neethling S. J., Gorman G. J., Pain C. A control volume finite element method for adaptive mesh simulation of flow in heap leaching. *Journal of Engineering Mathematics*. 2014, vol. 87, pp. 111—121. DOI: 10.1007/S10665-013-9672-3

37. Thenepalli T., Chilakala R., Habte L., Tuan L., Kim C. S. A Brief note on the heap leaching technologies for the recovery of valuable metals. *Sustainability*. 2019, vol. 11, no. 12. article 3347. DOI: 10.390/SU1112334730.

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