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4D modeling of concentrating mill tailings dam protecting dike soil consolidation

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Abstract

Introduction. *The research aims to study concentrating mill tailings dam protecting dike soil consolidation on the example of a mining enterprise of the Kola Peninsula.*

Research methodology. *The research is based on 4D modeling (taking into account a time factor) using PLAXIS software solution. The computer hydro-geomechanical 3D model of the concentrating mill tailings dam fragment has been developed allowing to investigate both geomechanical and filtration processes, and their collateral influence on protecting dike and alluvial beach soil consolidation. The following options of tailings dam hydro-geomechanical condition development are considered: a reference state at the current parameters of operation, increase in the level of water-saturated tail deposits and the subsequent consolidation of bulk and alluvial soils within 1, 2, 3, 5, 10, 15, 20, 30, 50 and 80 days.*

Research results and analysis. *The received results have been analyzed on the dynamics of the tailings dam hydro-geomechanical condition therefore revealing its behavior in time. It has been established that the nature of bulk and alluvial soils consolidation is identical, however, differs significantly in terms of quantity.*

Conclusions. *Dependences of bulk and alluvial soils consolidation of the tailings dam hydraulic engineering construction on consolidation time are established providing a scientific and technical basis for its mechanical state and stability assessment, and for engineering recommendations about the terms of the following stage of dams building.*

Key words: *tailings storage; hydro-geomechanical 3D model; 4D modeling; soil; consolidation; sustainability.*

Introduction. As a rule, concentrating mill tailings dams of Kola enterprises were constructed on relatively soft ground in ravines or river basins [1, 2]. As concequence, the hydrogeological conditions of tailings dams operation due to both high natural groundwater level and regular storage of water-saturated pulp tailings from concentrating mills, conditions increased pore water pressure in soils of all hydrotechnical structures of the tailings dam. As a result, effective stress in soils turns out to be low requiring the adopted time periods for intermediate soil compaction due to consolidation in order to ensure reliable operation of a tailing storage and dam stability [3–5]. Due to soil consolidation, excess pore water pressure disperses and reduces, and soil can acquire "skeletal" rigidity providing shearing strength required for dam operation [6, 7]. Therefore, the research aims to study concentrating mill tailings dam protecting dike soil consolidation on the example of a mining enterprise of the Kola Peninsula.

Research methodology. The research is based on 4D modeling (taking into account a time factor) using PLAXIS software solution [8]. To assess soil consolidation degree and determine the dependences in their consolidation due to excess pore pressure dispersion in water-saturated soil of a tailing storage as a function of time (automatic

time discretization), computer modeling of deformation-filtration processes has been carried out (soil consolidation) by the example of the concentrating mill tailings dam of a mining enterprise on the Kola Peninsula.

For PLAXIS environment, a hydro-geomechanical 3D model for a tailings dam fragment located at the subjacent geological base has been created including the protecting dike and alluvial tail deposits; the model is equivalent to geometric dimensions from fig. 1. The parameters of physicomechanical characteristics of dam soils, alluvial deposits and basement rocks of the geological basis used for calculations, are shown in table 1.

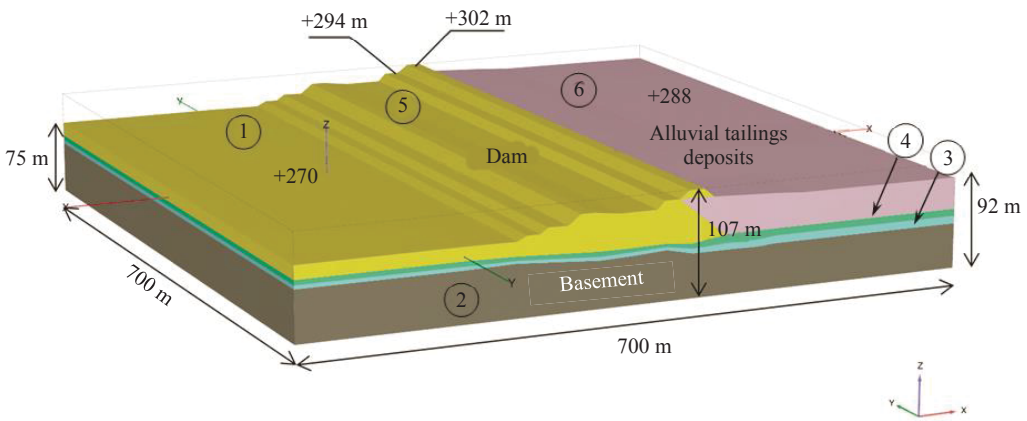

Fig. 1. Hydro-geomechanical 3D model of the tailings dam fragment (the 1–6th – types of soils and rock according to table 1)

Рис. 1. Гидрогеомеханическая 3D-модель фрагмента хвостохранилища (1–6 – типы грунтов и пород согласно табл. 1)

Consolidation processes were modeled with PLAXIS software units, which make it possible to simulate the realistic process by means of introducing various boundary conditions for stresses and pore pressure, and by setting an extra parameter of time interval [8–10], so, 4D modeling of soil consolidation was in fact carried out. The regularities in hydro-geomechanical state change were studied of a hydrotechnical system of the tailing dam in time, within the periods from 1 to 80 days. In total, 12 variants of tailings dam hydro-geomechanical state were modeled: a reference state at the current parameters of operation (1), increase in the level of water-saturated tail deposits (2), and the subsequent consolidation of soil within a day (3), 2 days (4), 3 days (5), 5 days (6), 10 days (7), 15 days (8), 20 days (9), 30 days (10), 50 days (11) and 80 days (12).

While modeling it is assumed that in the process of soil consolidation, the filtration ratio remains constant.

Research results and analysis. As a result of modeling, the patterns of soil movement and hydro-geomechanical state of the tailings dam have been obtained making it possible to trace the dynamics of their change in time. Fig. 2 shows the most contrasting patterns of soil consolidation in the model illustrating the trends of tailings dam hydro-geomechanical state variation. Within the first day, soil consolidates in practically whole bulk part of the protecting dike with gradual attenuation until the 10th and further until the 50th day. However, general increments of soil movements are related to alluvial tailing deposits to a greater extent, which are highly water-saturated. Soil consolidation here is intensive within 10 days with further stabilization.

Based on the results of the variants of filtration-deformation computer simulation, the dependences between tailings dam soil movement and consolidation time have been determined [10–12]. It has been stated that the most active soil consolidation takes place in the first day, the values of movements may increase by 1.5–2 times. After that within subsequent 8–10 days, deformational processes attenuate gradually and the hydro-geomechanical situation stabilizes.

Table 1. The parameters of physicomechanical characteristics of dam soils, alluvial deposits and basement rocks of the geological basis used for calculations

Таблица 1. Параметры физико-механических характеристик грунтов дамбы, намывных отложений и подстилающих пород геологического основания, используемые для расчетов

Parameter	Rock, soil*					
	Moraine**	Gneissoid granite***	Strong gneissoid granite ***	Gravel-cobble soil***	Gravelly sand**	Tailings deposits**
γ_{unsat} (specific weight of soil), kN/m^3	18.7	25.3	25.8	22.5	19.8	18.0
γ_{sat} (specific weight of saturated soil), kN/m^3	19.2	25.5	26.7	23.5	20.0	19.0
k_x (*X*-direction filtration ratio), m/day	10	0.01	0.05	5	1	20
k_y (*Y*-direction filtration ratio), m/day	10	0.01	0.05	5	1	20
k_z (*Z*-direction filtration ratio), m/day	10	0.01	0.05	5	1	20
E (modulus of deformation), kN/m^2	25 000	40 000	500 000	30 000	30 000	56 000
ν (Poisson's ratio)	0.3	0.25	0.2	0.3	0.3	0.4
c_{ref} (cohesion), kN/m^2	2	6	37	4.4	2	5
φ (angle of shear resistance), degrees	25	34	37	26	30	38.5
ψ (dilatancy angle), degrees	0	4	7	0	0	3.5

* Model type – Mohr Coulomb; ** soil behavior type – drained; *** soil behavior type – undrained.

Note that the expected values of the absolute movements of the tailings dam alluvial part make up 0.10–0.15 m; it is actually a proper vertical shrinkage which may reach 0.08–0.12 m. For the alluvial part (crest and the downstream slope) of the protecting dike, total soil movements make up 0.27–0.32 m, soil compaction up to 5 cm may be vertical, and horizontal up to 2 cm. Such consolidation processes distribution is explained by the fact that water is "displaced" more intensely out of the alluvial soils reducing pore pressure and soil particles consolidate more actively in a vertical direction, while the alluvial part of the protecting dam is under the subhorizontal pressure from the alluvial tailing deposits [13].

Taking into account the compression speed being an important feature of soil consolidation, the calculations have been made; the results are presented in fig. 3.

Based on the analysis it has been determined that the speed of consolidation of the protecting dam crest, alluvial beach, and the downstream slope of the protecting dam have practically identical character with higher intensity in the crest and the alluvial part of the dam. Soil consolidation speed in the downstream slope of the protecting dam where the compression was initially lower, is significantly lower. According to the results of the three simulation variants and the curves in fig. 3, it can be stated that the basic consolidation of soil will take place within first 10 days with further general attenuation to the 80th day. The revealed regularities lay groundwork for some practical recommendations on the time of further stage of dikes' build-up. The next level of the dike is to be built up not earlier than 80 days after the alluviation (pulp flush) of tailings deposits.

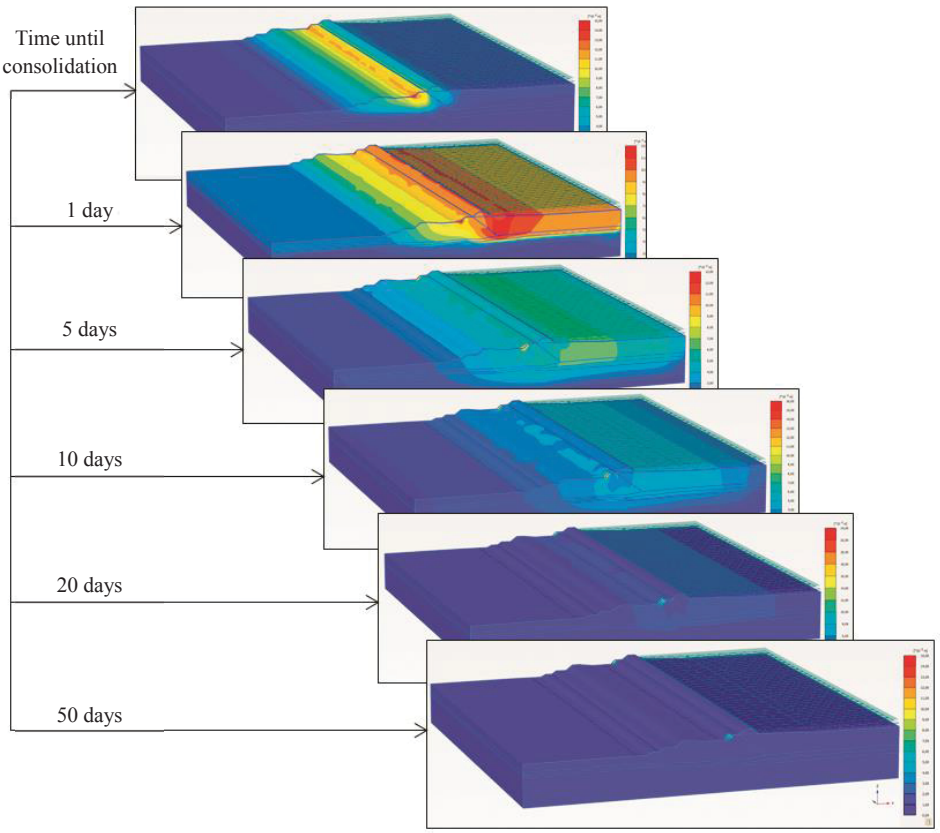

Fig. 2. Trends in the overall increments of soil movements over time due to their consolidation
Рис. 2. Тенденции изменения общих приращений перемещений грунтов с течением времени вследствие их консолидации

Conclusions. A computer hydro-geomechanical 3D model of a fragment of mining enterprise concentrating mill tailings dam protecting dike has been developed which makes it possible to study both geomechanical and filtration processes and their joint effect on the state of bulk soil and alluvial tailings deposits. Based on the computer 4D modelling (with the account of the time factor) the dependences have been determined between the filtration-deformation processes in the tailings dam hydrotechnical system and soil consolidation time, representing the deterministic basis for the assessment of protecting dikes stability and the reliability of the hydraulic engineering structures of a

tailings dam as a complex water-saturated natural-technical system. It has been revealed that the main compression of soil takes place within the first 1–5 days when compression speed of structural particles falls from 3–6 to 1 cm/day with further attenuation of

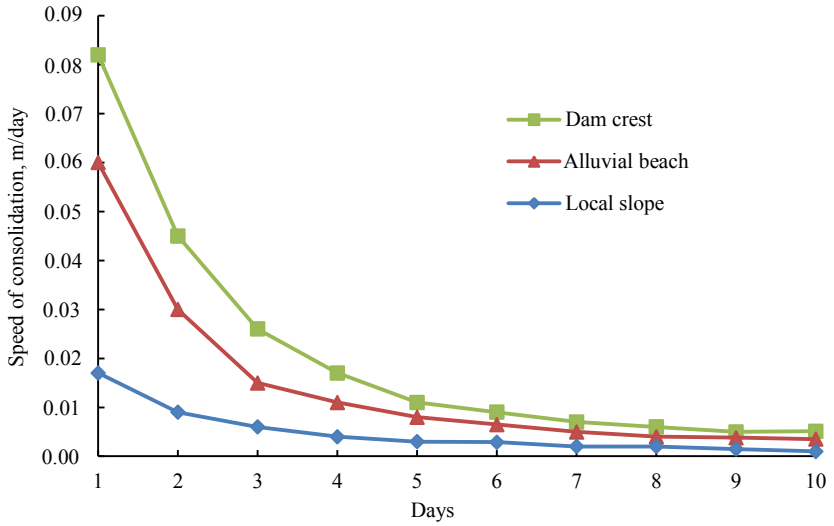

Fig. 3. Dependences of soils consolidation speed on time
Рис. 3. Зависимости скорости консолидации грунтов от времени

filtration processes. It has been determined that filtration and deformation totally attenuate up to 80 days predetermining the basis for engineering recommendations about the terms of the following stage of dams building.

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4D-моделирование консолидации грунтов ограждающей дамбы хвостохранилища обогатительной фабрики

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Реферат

Введение. *Целью работы являлось исследование процессов консолидации грунтов ограждающей дамбы хвостохранилища обогатительной фабрики на примере одного из горнорудных предприятий Кольского полуострова.*

Методология исследований. *Исследования выполнены на основе 4D-моделирования (с учетом фактора времени) с использованием программного комплекса PLAXIS. Разработана компьютерная гидрогеомеханическая 3D-модель фрагмента хвостохранилища обогатительной фабрики, позволяющая исследовать как геомеханические, так и фильтрационные процессы, а также их совместное влияние на состояние грунтов насыпной ограждающей дамбы и намывного пляжа отстойника. Рассмотрены следующие варианты развития гидрогеомеханического состояния хвостохранилища: исходное состояние при текущих параметрах эксплуатации, повышение уровня водонасыщенных хвостовых отложений и последующая консолидация насыпных и намывных грунтов в течение 1, 2, 3, 5, 10, 15, 20, 30, 50 и 80 дней.*

Результаты исследований и их анализ. *Полученные результаты проанализированы по динамике гидрогеомеханического состояния хвостохранилища, в результате чего выявлены тенденции его изменения во времени. Установлено, что характер консолидации насыпных и намывных грунтов идентичен, но количественно существенно различается.*

Выводы. *Установлены зависимости уплотнения насыпных и намывных грунтов гидротехнического сооружения хвостохранилища от времени консолидации, что предоставляет научно-техническую основу для оценки его механического состояния и устойчивости, и для инженерных рекомендаций по срокам следующего этапа наращивания дамб.*

Ключевые слова: *хвостохранилище; гидрогеомеханическая 3D-модель; 4D-моделирование; грунты; консолидация; устойчивость.*

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