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The Impact of Freezing-thawing Process on Slope Stability of Earth Structure in Cold Climate

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Abstract

The paper deals with assessment of impact of freezing-thawing process on slope stability. Numerical simulation with using coupled thermal–hydraulic–mechanical analysis (software “Geostudio 2012”, Canada) was implemented to make accurate time-dependent forecast of safety factor and defined probable slope failure mechanism of earth structures in cold climate. Results of modelling showed safety factor value was decreased from 2.15 to 1.13 when earth structure’s slope is thawing. Significant increase of hydraulic gradient (from 0.1 to 14) was observed in the toe of dam.

Keywords: Safety factor, cold climate, slope stability, numerical simulation, coupled convective thermal model, Morgenstern-Price method.

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1 Introduction

Transport and hydrotechnical engineering in cold climate is challenge for geotechnical engineers, primarily which is associated with need for dams’ and roads’ safety in time related to processes of freezing or thawing of soils as well as frost heaving on frost-susceptible soils.

The main task for geotechnical engineers is to ensure the safety of transport and hydrotechnical structures in cold climate. First, it can be achieved by maintaining of appropriate thermal mode of soils to predict possible slope failure when soil is going melting. The second, it can be ensured by keeping of estimated water level into earth structure. Freezing of slopes will lead to freezing water in the downstream slope what is reason for rising of depression curve in place of output flow. Melting of soils can lead to dramatically increase hydraulic gradients (higher than critical values), soil strength reduction and finally to getting of slope failure (Andersland, 2004).

In order to make forecast of earth structure behavior in cold climate and assess of probability of failure time-dependent safety analysis should be implemented and is to be based on coupled thermal–hydraulic–mechanical model. For this purpose we analyzed the behavior of earth structure – tailings

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dam placed in northern part of Arkhangelsk region. The cross-section of the dam is shown on Figure 1.

Tailings dam is constructed from overburden rocks obtained as a result of mining and waste materials (tailings) which are washed on face of each dam's tier as a result of kimberlite ore dressing. The dam (on the 3rd tier) has a length of 2450 m, a height is about 20 m. Width of tailings beach is 40-70 m The slope of upstream face varies from 1:.. 5 to 1: 8. The slope of downstream - 1: 2 to 1: 2.5.

Quaternary deposits are bedded below first tier of the dam and are represented by semi-decayed peat, medium density silty sands, clays in a stiff and very stiff state with gravel content up to 10 %. The bedding is non-homogeneous, there are lenses, layers and interlayers of different thickness, thinning at some places. The tailings of kimberlite ore dressing are used for forming the bedding of the 2-nd and 3-rd tiers of the dam.

The geotechnical monitoring indicates that tailings are represented by coarse sands, medium sands, fine sands and silty sands with the content of clay particles up to 20%. The main component of clay is saponite (montmorillonite).

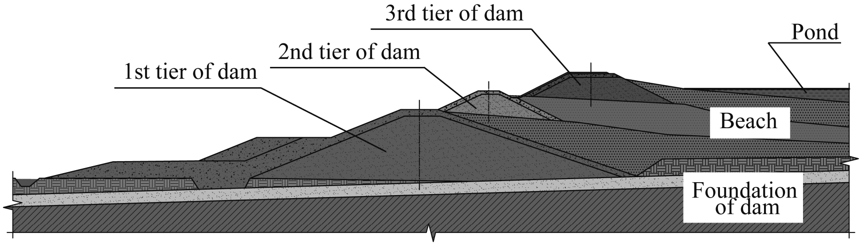


Figure 1: Cross-section of tailings dam

2 Numerical Simulation

Numerical simulation of freezing earth structures was carried out in GeoStudio 2012 (Canada) with using following finite element modules TEMP/W, SEEP/W and SLOPE/W (Figure 2). The first two modules are applied to simulate the effect of water transport on heat transfer and it cannot deal with physical coupling between soil/water and ice during heaving. Thus finite element model doesn't consider ice lens formation. The third module is used for slope stability analysis with limit equilibrium methods (e.g. Morgenstern-Price).

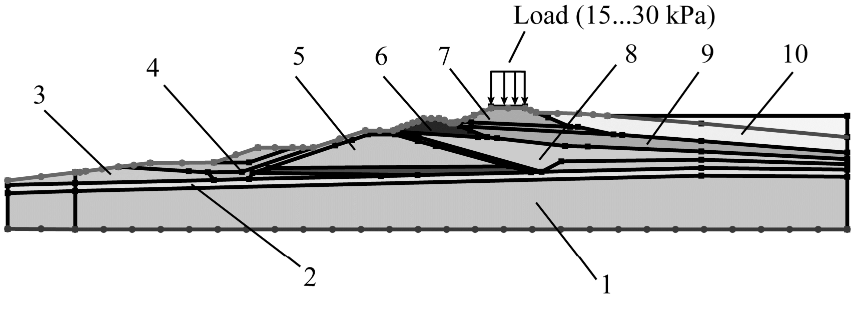


Figure 2: Numerical model of dam:
1-clay (CL); 2 – Sand; 3 – Peat; 4 – Crashed rock; 5,6,7 –soils of 1, 2, 3 tiers of dam respectively;
8, 9, 10 – tailings of 1, 2, 3 tiers of dam respectively.

To simulate freezing/thawing of soils Full Thermal model (TEMP/W) was applied. The water content in the model is changed during the analysis.

The governing differential equation used in formulation of coupled convective analysis in TEMP/W and SEEP/W is:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial T}{\partial y}\right)+c_w\frac{\partial\left(q_w T\right)}{\partial y}+Q=\left(c+Lw\frac{\partial W_u}{\partial T}\right)\frac{\partial T}{\partial t} \tag{1}$$

where T = temperature; K_x, K_y = thermal conductivity in the x- and y-directions respectively; c_w = volumetric heat capacity of water; q_w = the specific discharge of water; Q = applied boundary flux; c = volumetric heat capacity of soil; L = latent heat of water; w = the volumetric water content; W_u = the total unfrozen volumetric water content; t = time.

The key functions of the model are:

1. Thermal conductivity vs. temperature (Figure 3);
2. Unfrozen water content vs. temperature (Figure 4);
3. Volumetric heat capacity of unfrozen and frozen soils;
4. In-situ initial water content.

Thermal parameters of unfrozen and frozen soils were determined by M. Kersten equations (Table 1) and are presented in Table 2.

Thermal conductivity	
Frozen soils:	Unfrozen soils:
$K_f = 0{,}011 \cdot 10^{0{,}81\rho_d} + 0{,}46 \cdot W_{tot} \cdot 10^{0{,}91\rho_d}$	$K_{th} = \left[0{,}1 \cdot \lg\left(100W\right) + 0{,}06\right] \cdot 10^{0{,}62\rho_d}$
where ρ_d – dry density, g/cm^3; W_{tot} – total water content, m^3/m^3.	where W – water content, m^3/m^3.
Volumetric heat capacity	
Frozen soils:	Unfrozen soils:
$C_{vf} = \rho_d \cdot \left[C_s + C_w W_w + C_i\left(W_{tot} - W_w\right)\right]$	$C_{vth} = \rho_d \cdot \left[C_s + C_w W\right]$
where C_s – volumetric heat capacity of solid particles, kJ/(kg·°C), C_s=0.71 kJ/(kg·°C); C_w – volumetric heat capacity of water, kJ/(kg·°C), C_w=4.2 kJ/(kg·°C); C_i – volumetric heat capacity of ice, kJ/(kg·°C), C_i=2.1 kJ/(kg·°C); W_w – unfrozen water content, m^3/m^3;	where W – water content, m^3/m^3.

Table 1: M. Kersten equations

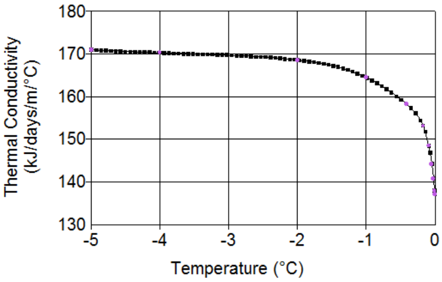


Figure 3: Thermal conductivity vs temperature

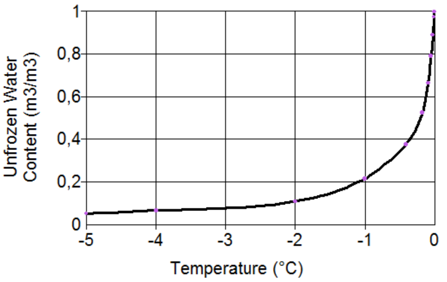


Figure 4: Unfrozen water content vs. temperature

№	Soil type	W	ρ_d, g/cm^3	λ_f, kJ/(m·°C)	λ_{th}, kJ/(m·°C)	C_{vf}, kJ/(m^3·°C)	C_{vth}, kJ/(m^3·°C)
1	Clay (CL)	0.18	1.72	170.8	136.9	1872	2540
2	Sand	0.29	1.44	251.0	139.2	1891	2775
3	Peat	2.23	0.33	344.5	37.9	1749	3271
4	Crashed rock	0.12	1.60	153.5	142.0	1518	1917
5	Soils (1 tier)	0.16	1.80	294.8	201.3	1846	2435
6	Soils (2 tier)	0.22	1.56	248.8	155.6	1818	2545
7	Soils (3 tier)	0.24	1.51	238.4	146.8	1808	2562
8	Tailings (1 tier)	0.25	1.45	222.6	136.5	1781	2550
9	Tailings (2 tier)	0.24	1.45	214.1	135.5	1749	2484
10	Tailings (3 tier)	0.25	1.48	238.8	142.8	1824	2614

Table 2: Thermal properties of soils

To simulate water flow into soils Saturated/Unsaturated model (SEEP/W) was applied. The model allows making seepage analysis in fully saturated and unsaturated soils. The main parameters of model are: type of soil, initial water content, water conductivity vs matrix suction (Figure 5), water content vs matrix suction (Figure 6).

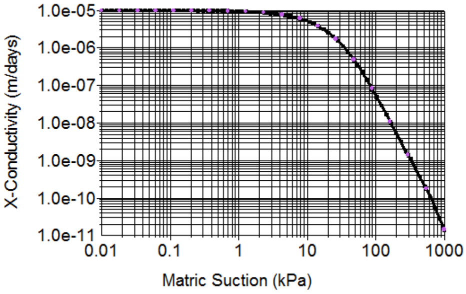


Figure 5: Water conductivity vs matrix suction

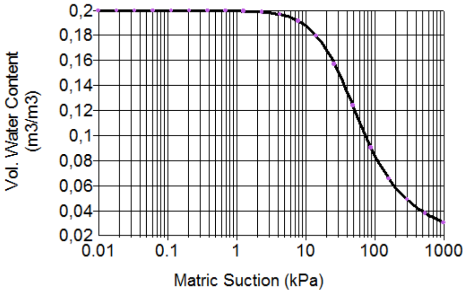


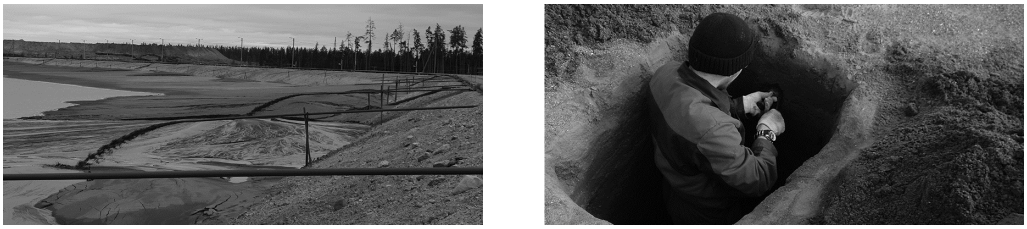
Figure 6: Water content vs matrix suction

To simulate thermal boundary conditions we used time-dependent function based on climate conditions of Arkhangelsk region (Table 3)

Month	January	February	March	April	May	June
Temperature, °C	-13.8	-12.7	-8.0	0.0	+7.1	+12.4
Month	July	August	September	October	November	December
Temperature, °C	+15.7	+12.4	+7.9	+1.5	-3.7	-8.7

Table 3: Average monthly temperature

To make slope stability analysis Mohr-Coulomb model (SLOPE/W) was applied. The main parameters of model (unit weight, friction angle, cohesion) were obtained as a result of geotechnical monitoring during erection of tiers and washing of tailings (Figure 7a, 7b). SLOPE/W is formulated in terms of moment and force equilibrium factor of safety equations (e.g. Morgenstern-Price). Properties of soils are presented in Table 4.



a) b)

Figure 7: Tailings washing on dam's beach (a) and sampling of soils (b)

№	Soil type	Parameters of Saturated/Unsaturated model		Parameters of Mohr-Coulomb model in SLOPE/W		
		Material model	Hydraulic conductivity, m/day	Friction angle, ^{o}	Cohesion, kPa	Unit weight, kN/m^3
1	Clay (CL)	Clay	10^{-5}	27.1	27.5	20.4
2	Sand	Sand	0.50	25.0	1.0	18.6
3	Peat	-	0.01	10.0	10.0	10.5
4	Crashed rock	Gravel	1.00	40.0	1.0	17.9
5	Soils (1 tier)	Sand	0.28	35.4	4.0	20.8
6	Soils (2 tier)	Sand	0.27	36.6	3.0	19.1
7	Soils (3 tier)	Sand	0.11	26.1	10.0	18.6
8	Tailings (1 tier)	Sand	0.08	28.5	10.2	18.1
9	Tailings (2 tier)	Sand	0.28	29.1	8.1	18.0
10	Tailings (3 tier)	Sand	0.12	32.9	9.7	18.5

Table 4: Permeability and strength parameters

3 Results

Numerical simulation was implemented in two stages: steady-state and transient thermal- hydraulic – mechanical analysis. On the first stage thermal and hydraulic analysis was carried out in order to determine the initial distribution of temperatures into the dam and to get water flow net with depression curve. The results of numerical simulation are presented on Figures 8 and 9 respectively.

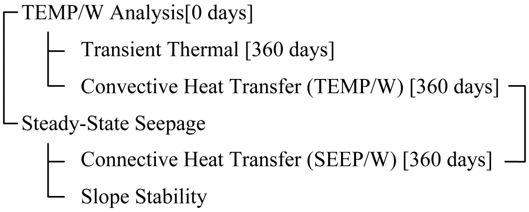


Figure 7: Stages of simulation in GeoStudio

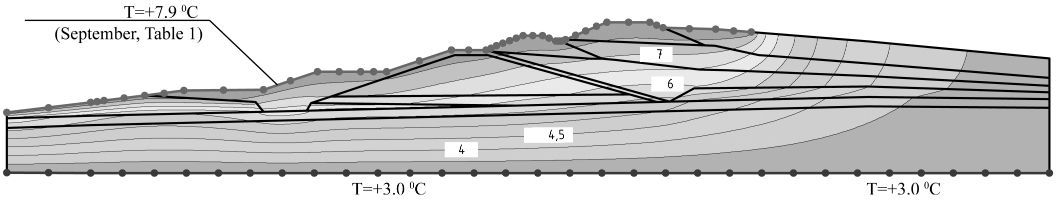


Figure 8: Initial distribution of temperatures

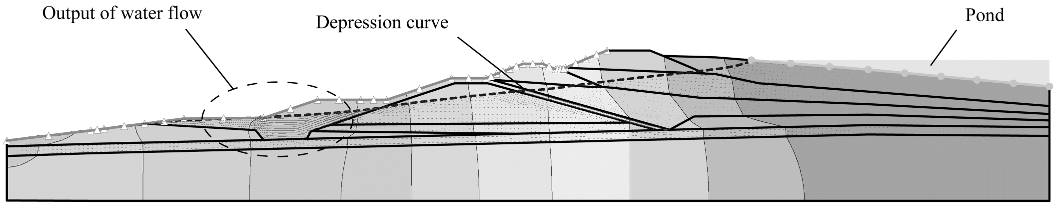


Figure 9: Initial water flow

On the second stage coupled transient thermal and hydraulic analysis was carried out and every 30 days to the end of the year slope stability analysis was implemented. So distribution of temperatures and water flow were determined for each month of year. Results of numerical simulation showed maximum frost penetration is 2.0…2.1 m in March. Active melting would lead to significant increasing of hydraulic gradient (from 0.1 to 14) in the places where output of water flow was observed before slope freezing (Figure 10). This can be explained by the transfer of heat with water from pond and respectively more rapid thawing of the soils at the output of water flow.

Numerical simulation showed that the level of depression curve into dam was raised on 1-1.5 m after slope of downstream was frozen to 2.0…2.1 m. This fact should be taken into account in the process of designing earth structures and correction of its exploitation.

Slope stability analysis with transport loads which is varied from 15 to 30 kPa and subject to results of coupled transient thermal and hydraulic analysis demonstrated that minimum safety factor is 1.129. Result of Morgenstern-Price analysis of dam is presented on Figure 11.

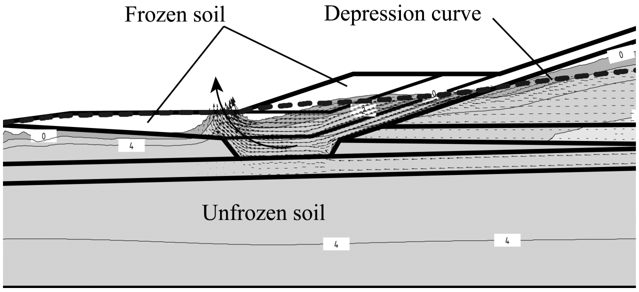


Figure 10: Density of Hydraulic gradient in April

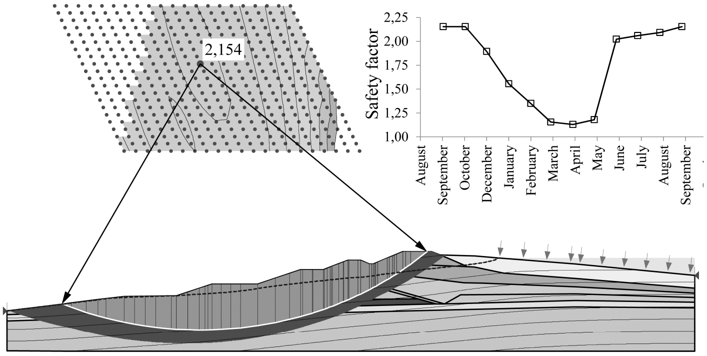


Figure 11: Result of Morgenstern-Price analysis of dam (September)

4 Conclusions

Results of numerical simulation of earth structure in cold climate showed significant influence of climate boundary conditions on level of depression curve into tailings dam. Level of depression curve is raised on 1-1.5 m after slope of downstream was frozen. Maximum frost penetration depth is 2.0…2.1 m in March.

Safety factor of tailings dam varies from 1.129 to 2.154 with the lowest value in April when active melting is observed. The main reason of decreasing of safety factor is high level of depression curve into dam at the end of winter and active melting which is accompanied by increasing of hydraulic gradient (from 0.1 to 14). These facts should be taken into account in the process of designing and exploitation of earth structures.

Numerical simulation of behavior of earth structures in cold climate can identify potential areas which will have lower values of safety factors and to take preventive measures to ensure the reliability of structures.

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