FEFU
FAR EASTERN FEDERAL UNIVERSITY

School of Engineering

Department Offshore and Structural Mechanics

Master's Thesis

«The Modeling of Influence of Frost Heaving on Retaining Structures»

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Introduction

Relevance of the research:

- There are no comprehensive methods for assessing the effect of frost heaving on hydraulic structures;
- There is a need for an assessment, because the radical methods currently used are expensive and time consuming.

State-of-art developments in the field of research:

- There are a number of narrowly specialized models of frozen soils behavior abroad, which can be used for solving problems of interaction of soils with structures

Introduction

The main goal of the study:

- Create a model of an idealized retaining hydraulic structure interacting with frozen soil.

To achieve this goal, it is necessary to solve a number of tasks:

- To review the theory of frost heaving of soils, to give a description of the applied constitutive model of frozen soil;
- Create a computer model of the "retaining wall – frozen soil" system, taking into account the influence of the frozen soil, and estimate relevance of model;
- Conduct laboratory tests of the chosen soil to clarify its specific parameters;
- Carry out the refined modeling of the "retaining wall – frozen soil" system and estimate the difference in the final results of the initial and refined models.
- To give recommendations on further improvement of the modeling methodology.

Introduction

The scientific novelty:

- A model of interaction between frozen soil and a retaining hydraulic structure was created using computer simulations based on the constitutive model of frozen soil (UDSM "Frozen and Unfrozen Soil Model").
- Laboratory tests were carried out, in the result the specified specific characteristics of the soil were obtained, which is necessary for a more accurate simulation of this interaction.

Theoretical and practical significance of the research:

- The obtained model and the results can be used in further development to assess the value of frost heave influence on the retaining structures, which will confirm or deny the necessity of applying such radical methods as complete soil replacement, and rethink the possibility of using previously considered insufficiently reliable approaches.

Introduction

Provisions to be protected:

- ❖ The variant of the "retaining wall - frozen ground" model in PLAXIS 2D.
- ❖ Technique for obtaining specific soil characteristics based on laboratory tests.

The reliability of the results is confirmed by laboratory tests of the chosen soil type, based on the results of which computer simulation was carried out.

The author's personal contribution is in conducted laboratory tests aimed at obtaining specific characteristics of the chosen soil and the description of the methodology for obtaining these characteristics.

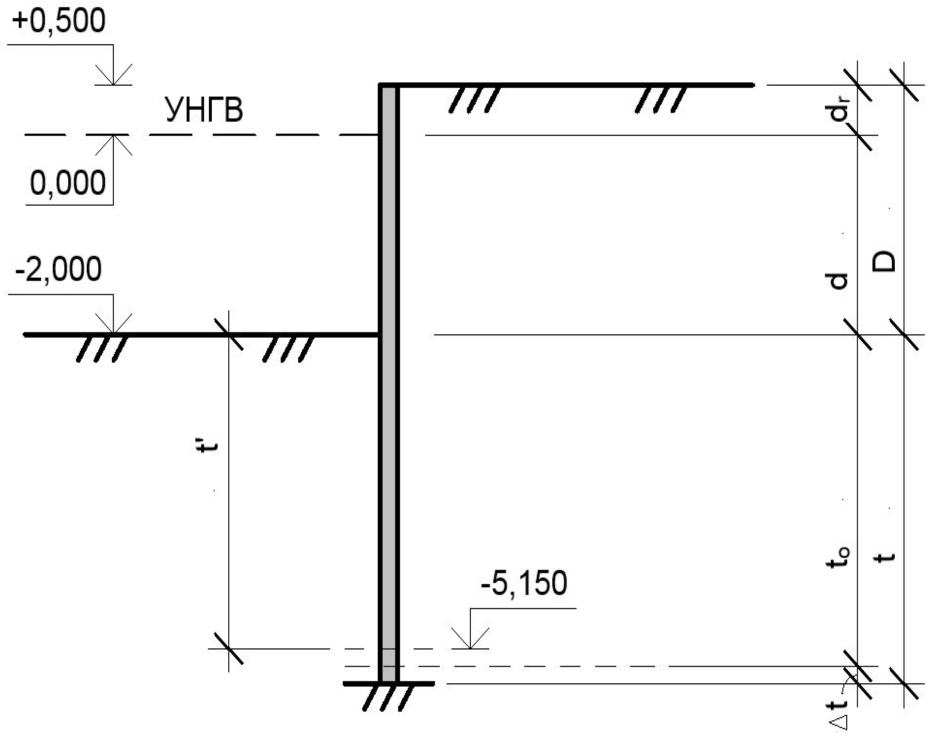
Chapter 1:
Review of the theory of frost heave of soils

This chapter gives an overview of the features of seasonally frozen soils, and also describes the processes that arise in these soils under the influence of internal and external factors. If tells short, it answers on the following question:

- ❖ What the frozen soil is?
- ❖ From what it consists?
- ❖ Why occurs migration of moisture occurs during soil freezing?
- ❖ What phenomenas occurs because of this migration?
- ❖ What is the frozen heaving?
- ❖ How it acts on the structures?
- ❖ How can this phenomena be modeled?

Chapter 2:
Calculation of the parameters of the sheet-pile wall

This chapter shows a technique for chosen the type of sheet-pile wall and the depth of its drive into the soil, which will be necessary for computer modeling.



Preliminary parameters of the sheet-pile wall and its driving into the soil can be seen on the picture.

Soil is accepted in accordance with the conditions:

I) The condition of the heaving – the soil must be clearly prone to seasonal frost heaving.

II) The condition of subsequent applicability – the soil must have a sufficient set of specific characteristics necessary for subsequent computer modeling.

Chapter 2:
Calculation of the parameters of the sheet-pile wall

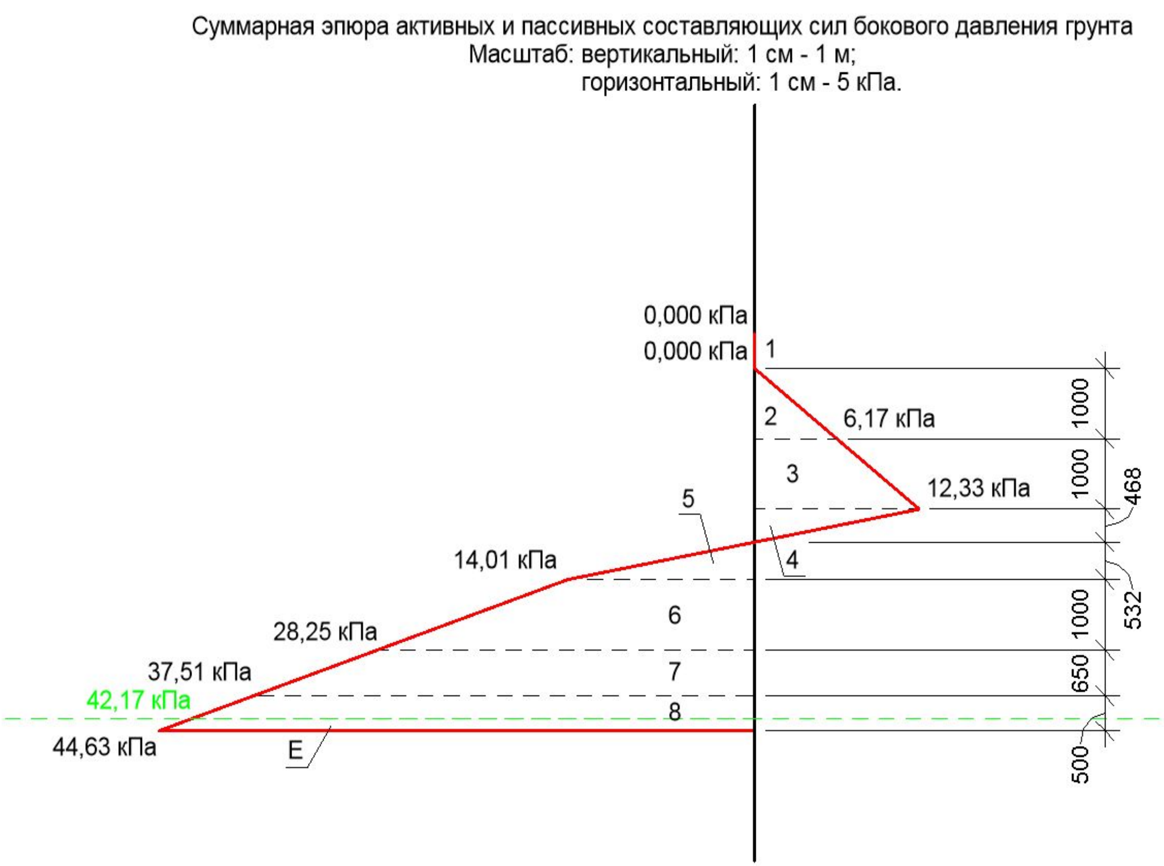
Chosen soil type: soft clay.

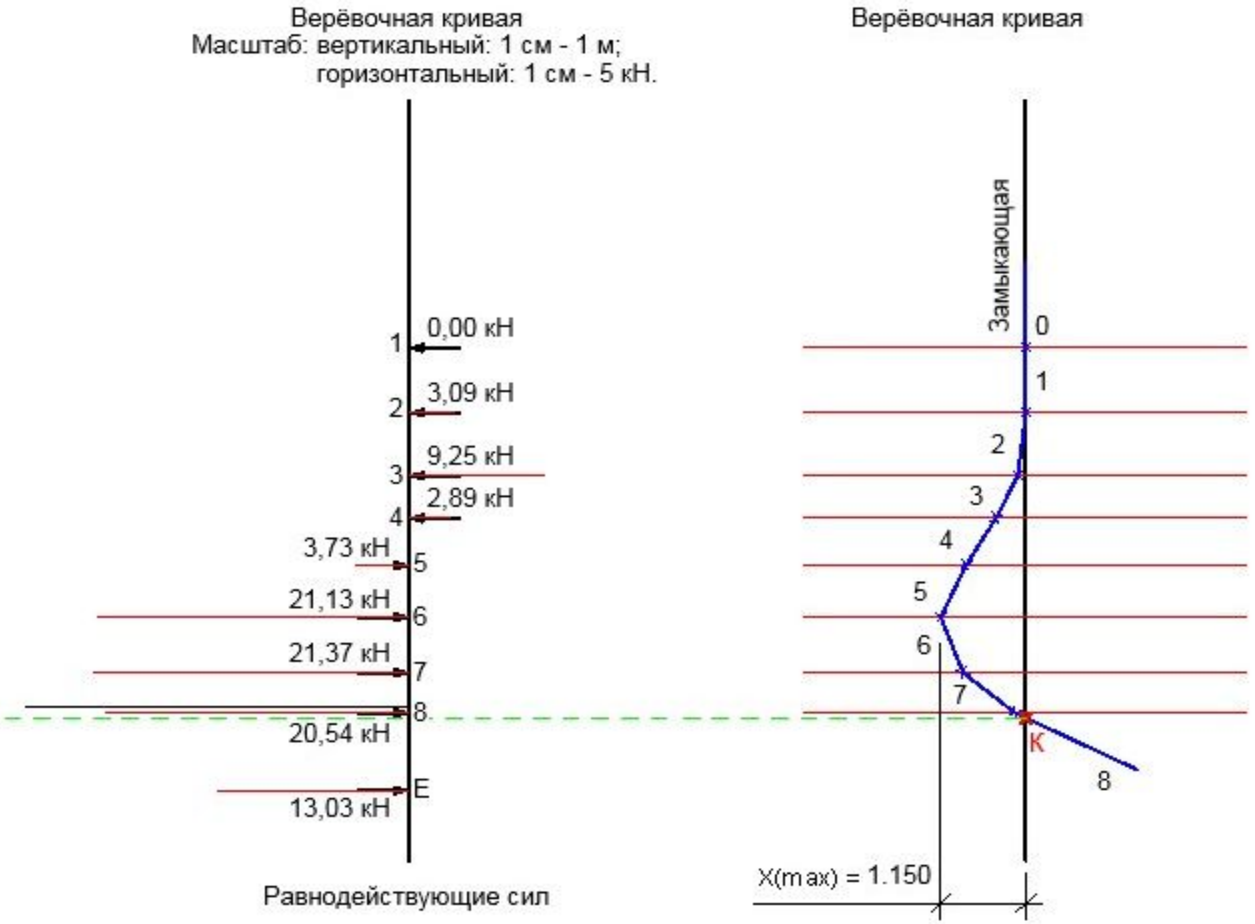
The presence of organic impurities in the composition is neglected.

In this section, only loads from the soil are considered.

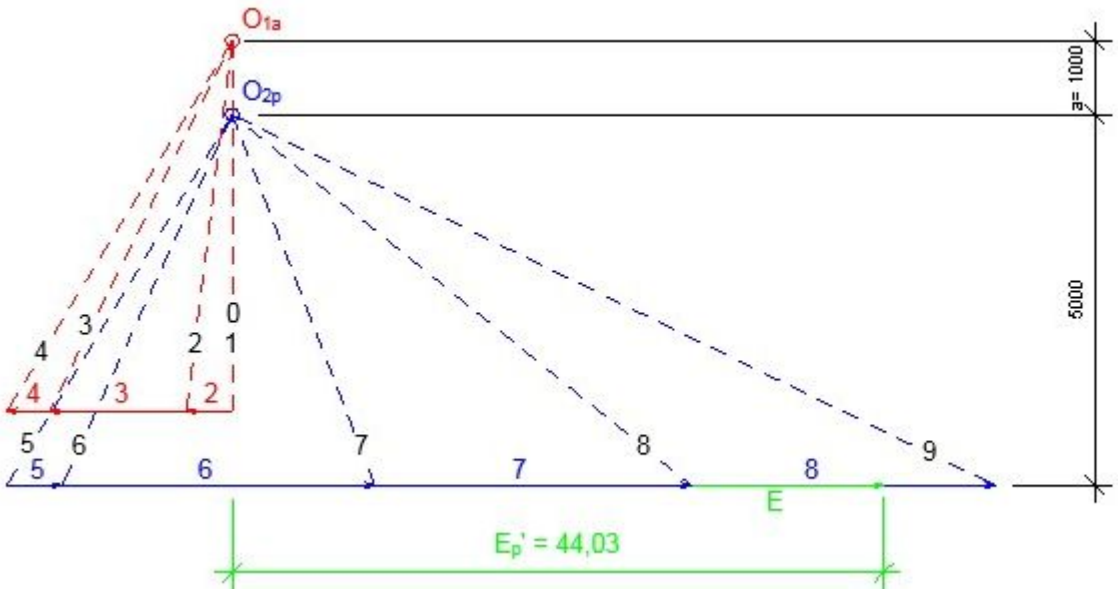
The calculation was carried out based on a manual for the design of marine berthing facilities РД 31.31.27-81.

Chapter 2:
Calculation of the parameters of the sheet-pile wall





Chapter 2:
Calculation of the parameters of the sheet-pile wall



As a **result** of calculations of the ordinates of diagrams of the active and passive soil pressure, the construction of the total soil pressure diagram, the polygon of forces and the rope curve, the value of **the total depth of the driving** was calculated as **t ≈ 5.7 m** and the **maximum bending moment** in the wall equal to **M(max) = 28.75kN·m**.

After checking the strength of the section of the previously adopted type of **Larsen L5-UM** sheet pile on the action of the bending moment, the preliminary type is approved as the main design type.

Chapter 3:
Modeling of the «thin wall – frozen soil» system

This chapter describes the chosen constitutive model of frozen soil and its features, the selection of input parameters, the algorithm for creating the model and the obtained results.

Modeling is performed in the **PLAXIS 2D** software with the help of the **user-define "Frozen and Unfrozen Soil Model"**, capable of describing the behavior of frozen soils, depending on the temperature and groundwater filtration. The developed **model is based on the idea of the relationship between freezing and thawing of pore fluid in soils with complex thermal, moisture and mechanical processes**. Combined numerical thermo-hydro-mechanical (TGM) modeling allows solving the problems of multiphase processes, which simultaneously consider the temperature and its changes, pressure and fluid motion, as well as mechanical deformations.

Chapter 3:
Modeling of the «thin wall – frozen soil» system

- The model takes into account the real features of the freezing process of pore water in the soil in dependence from water content, pressure, salinity, latent heat capacity;

- In this model it is assumed that the soil is a completely saturated, isotropic and elastic composition of the particles.

- It is assumed that each component of the soil is incompressible.

- To take into account the local thermal equilibrium in the model, the temperature of soil particles, pore water and ice is the same at each point of the soil.

Chapter 3:
Modeling of the «thin wall – frozen soil» system

To carry out the first model a set of parameters for clay soils from the PLAXIS manual "Frozen and Unfrozen Soil Model" was used.

- In the study considered a period of 5 months of the cold period of the year, during which the soil passes from the unfrozen to the frozen state.
- Temperatures of the bottom of the shallow water zone and the ground surface were taken in accordance with the actual temperatures of the Chukchi region and were set up using linear functions.

Chapter 3:
Modeling of the «thin wall – frozen soil» system

	Температура, ⁰С											
Месяц	1	2	3	4	5	6	7	8	9	10	11	12
Период	Холодный период				Теплый период				Холодный период			
Температура дна в мелководной зоне	-2,0	-3,0	-2,0	-1,0	0	+5,0	+7,0	7,5	+5,0	+3,0	0	-1,0
Температура поверхности грунта	-14,7	-14,3	-12,5	-8,3	-1	+6,3	+11,6	+10,1	+4,6	-3,0	-8,6	-12,5

Table 1 – Monthly averages of bottom temperatures in the shallow water zone and on the ground surface

Фаза	Начальные фазовые значения температур, К		Изменение температуры в течении фазы, ΔК/мес.		Продолжительность фазы	
	Дна	Поверхности	Дна	Поверхности	мес.	с.
Initial phase	278.16	277.76	0	0	-	-
Phase 1	278.16	277.76	-2.0	-7.6	1	2.592.000
Phase 2	276.16	270.16	-3.0	-5.6	1	2.592.000
Phase 3	273.16	264.56	-1.0	-3.9	1	2.592.000
Phase 4	272.16	260.66	-1.0	-2.2	1	2.592.000
	271.16	258.46				

Table 2 – Temperature and time parameters of the design phases

Chapter 3:
Modeling of the «thin wall – frozen soil» system

Table 3 – Data for functions describing the character of time dependent temperature boundary conditions

№	Function type	Environment	Parameter	Phase 1	Phase 2	Phase 3	Phase 4
1	Linear	Air	Time, s	2.592.000	2.592.000	2.592.000	2.592.000
			Δt°, K	-7.6	-5.6	-3.9	-2.2
2	Linear	Air	Time, s	2.592.000	2.592.000	2.592.000	2.592.000
			Δt°, K	-7.6	-5.6	-3.9	-2.2
3	Linear	Water	Time, s	2.592.000	2.592.000	2.592.000	2.592.000
			Δt°, K	-2.0	-3.0	-1.0	-1.0
4	Linear	Water	Time, s	2.592.000	2.592.000	2.592.000	2.592.000
			Δt°, K	-2.0	-3.0	-1.0	-1.0

Chapter 3:
Modeling of the «thin wall – frozen soil» system

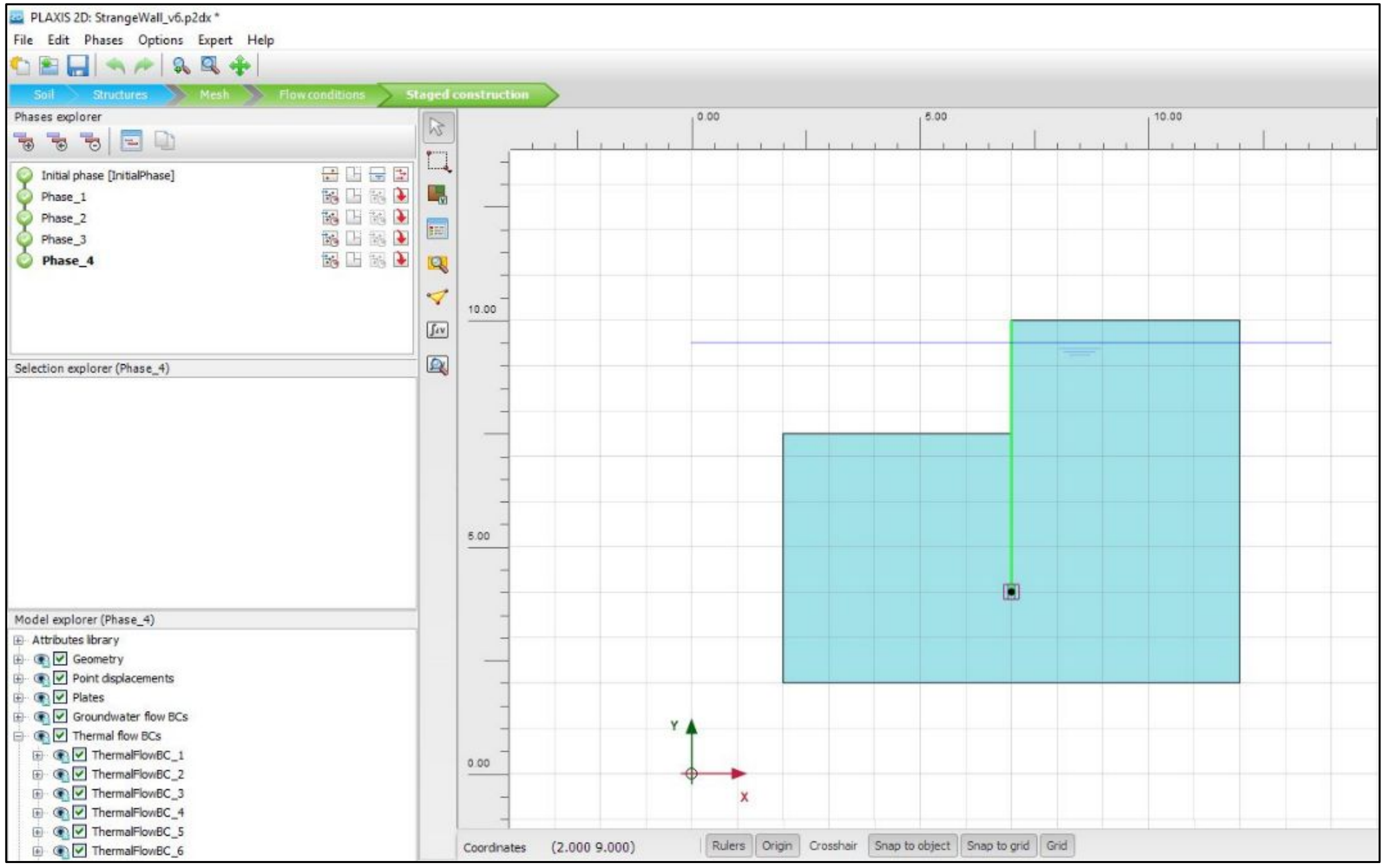
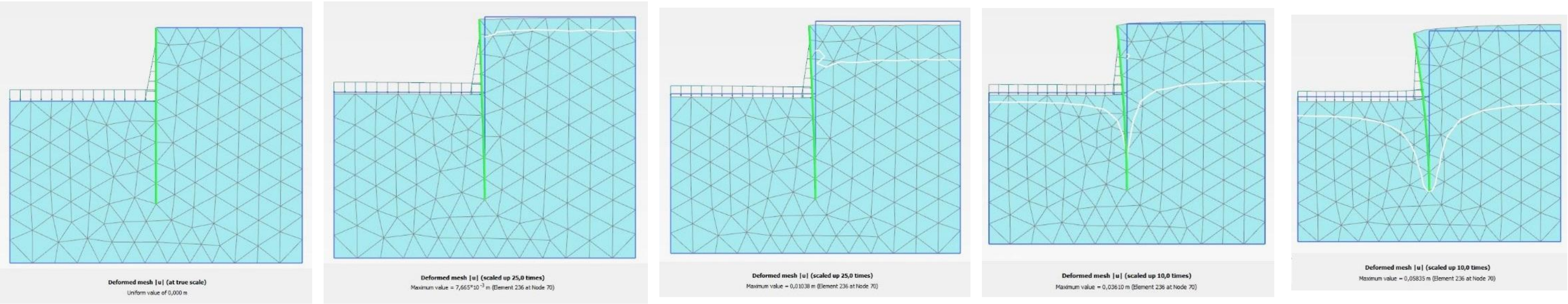


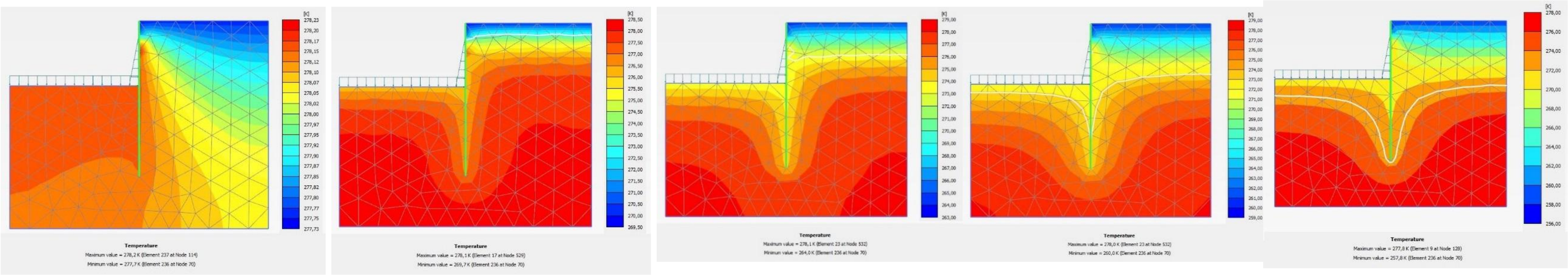
Figure 4 - General view of the model before calculation

The results of the calculations made it possible to evaluate the influence of frost heave on the shit-pile wall, as well as to see the deformations of the soil, the change in the temperature regime depending on the phase, and the direction of groundwater filtration. In addition, it be-comes possible to draw a conclusion about the reliability of the model.

Chapter 3:
Modeling of the «thin wall – frozen soil» system

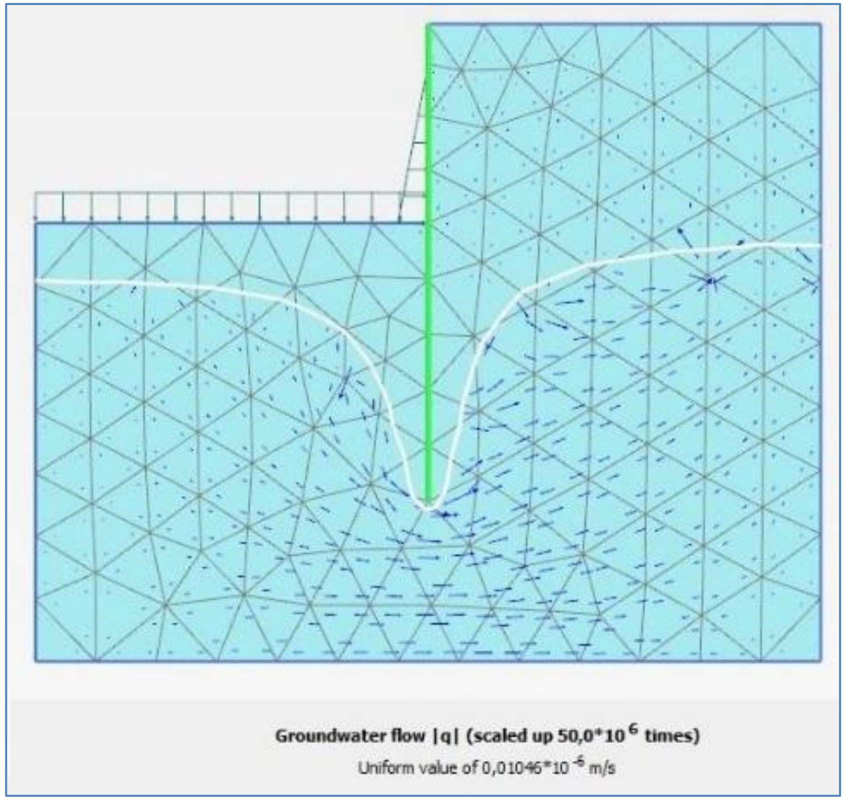


Deformed meshes of finite elements from Initial phase till Phase 4



Temperature distributions from Initial phase till Phase 4

Chapter 3:
Modeling of the «thin wall – frozen soil» system



Ground water filtration (Phase 4)

Table 4 – Forces in the sheet-pile wall

Parameter	Units	Value	Phase				
			Initial	Phase 1	Phase 2	Phase 3	Phase 4
M	N·m	min	0	$-9.86 \cdot 10^3$	$0.12 \cdot 10^{-12}$	$1.82 \cdot 10^{-12}$	$7.73 \cdot 10^{-12}$
		max	0	$196.7 \cdot 10^3$	$203.1 \cdot 10^3$	$527.6 \cdot 10^3$	$804.8 \cdot 10^3$
Q	N	min	0	$-10.4 \cdot 10^3$	$-8.29 \cdot 10^3$	$44.3 \cdot 10^3$	$79.13 \cdot 10^3$
		max	0	$108.3 \cdot 10^3$	$104.5 \cdot 10^3$	$209.3 \cdot 10^3$	$279.1 \cdot 10^3$
N	N	min	0	$-4.49 \cdot 10^3$	$-21.6 \cdot 10^3$	$-70.5 \cdot 10^3$	$-54.1 \cdot 10^3$
		max	0	$1.030 \cdot 10^3$	$69.31 \cdot 10^3$	$168.8 \cdot 10^3$	$229.7 \cdot 10^3$

Chapter 3:
Modeling of the «thin wall – frozen soil» system

Estimating the obtained results, we can say the following:

- ❖ Temperature distributions and the behaviour of their changes over time, depending on the external conditions and properties of the sheet pile wall material, appear to be reliable. This is clearly seen from the displacement of the zero-isotherm line. The effect of the steel wall on cooling the ground is also clearly visible.
- ❖ The nature of migration of soil moisture up to phase 4 is not reliable. But in phase 4, when the sheet-pill wall is completely surrounded by frozen soil, migration of moisture becomes reliable – it exists in the unfrozen ground below the freezing front and is absent in the frozen zone, remaining in it only in the form of pellicular moisture.
- ❖ The nature and magnitude of the frost heave, as well as its influence on the sheet pile wall, depends directly on a number of specific characteristics of the soil. As it was noted earlier, the used characteristics are not exact values for the chosen type of soft clay, so talk of complete reliability of the results, despite the similarity of the result obtained with the proposed (some settlement that can be seen in the model are also exists in nature during the initial period of clay freezing), – is incorrect.

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Chapter 4:
Choosing of the specific characteristics for laboratory tests

Parameter	Units	Definition
e_0	-	Initial void ratio
	Н/м^2	
	Н/м^2	Soil adhesion
	°	Angle of internal friction
ψ	°	Angle of dilatancy
k_x	м/с	Hydraulic conductivity in «x» directions
k_y	м/с	Hydraulic conductivity in «y» directions
α_x	1/K	Thermal expansion coefficient in «x» directions
α_y	1/K	Thermal expansion coefficient in «y» directions
α_z	1/K	Thermal expansion coefficient in «z» directions
$E_{f,ref}$	Н/м^2	Frozen Soil Young's Modulus at a reference temperature
$E_{f,inc}$	Н/м^2·K	Rate of change in Young's modulus with temperature
υ_f	-	Frozen Soil Poisson's ratio
G_0	Н/м^2	Unfrozen soil shear modulus
$\kappa 0$ (-)	-	Unfrozen soil elastic compressibility coefficient
λ_0 (-)	-	Elasto-plastic compressibility coefficient for unfrozen state
M (-)	-	Slope of the critical state line
p_{ref}	Н/м^2	Parameter for the pressure dependency of ice thawing t°
	Н/м^2	Initial segregation threshold

Due to the absence for now of any wide a bit database of specific characteristics for various types of soils, it was decided to conduct a series of laboratory tests of the chosen type of soft clay in order to refine some specific characteristics necessary to obtain more correct results.

Describes the characteristics chosen for refining, their impact on the behavior of the model and how to determine them.

Chosen characteristics can be seen in the table.

Chapter 5:
Modeling of the «thin wall – frozen soil» system with refine specific characteristics

This chapter presents refined modeling results, taking into account the specific soil characteristics obtained experimentally in Chapter 4, and also compares it with the results of the modeling from Chapter 3.

Conclusions

1. To evaluate the influence of frost heaving on retaining structures, **it makes sense to use existing software and constitutive models of frozen soils**, which will confirm or deny the necessity of using such radical methods to reduce the influence of frost heaving, as a complete replacement of soil.

2. The **constitutive model of frozen soil** used in this work **critically depends on the accuracy of the input parameters**, and therefore for each investigated soil **they must be taken from the results of laboratory tests**.

3. The performed **tests showed differences in the values of number of parameters** of the accepted soft clay from the parameters adopted in the preliminary modeling on the basis of available sources.

Conclusions

4. **The refined modeling showed a sufficient reliability** of the behavior of frozen soil **at** a relatively short time **interval of 4 months.** However, **simulation of longer periods and/or multiple freeze-thaw cycles** due to program code imperfection currently **can not be performed**. Changes in the **temperature distribution**, the behaviour of the **groundwater migration**, **deformation** of the soil and shit-pile wall **look reliable**.

5. **To use this model of frozen soil for practical purposes, it is critically important to test the most common types of soils and**, on the basis of test data, **create** a simple and understandable **database** that will reduce the dependence of users from experimental work. **Work on the composition of such a database is recommended by the author as one of the most important steps in the development of modeling frost heaving of soils and assessing their impact on structures. Further researching in this direction has commercial potential.**

Thanks for your attention!