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Numerical modelling of vertical borehole heat exchangers performance under Lithuanian Quaternary conditions

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Abstract The vertical borehole heat exchangers were surrounded by the heterogeneous multilayered geological environment and groundwater flow that affected the performance of borehole plants. In this paper, the field investigation of vertical borehole ground heat exchangers in capital city Vilnius (Visoriai), Lithuania is presented. The numerical heat transfer model considering seven different geological strata was developed using the cylindrical heat sink model for vertical borehole inside by solving the soil mass and heat transfer equations with groundwater flow. The numerical multilayered ground vertical borehole heat transfer model was calculated and validated by *in-situ* thermal response test data. The numerical model results were also compared with the homogeneous finite difference model expressed by the temperature response functions (well known as "g-functions"). The practical realization of g-functions was designed in the Earth Energy Designer as a practical tool for geoengineers designing the vertical borehole plants. The temperature profiles at borehole wall at different heating times were presented and explored together with relative errors. The numerical model will be used as a practical tool for the Lithuanian Geological Survey under the Ministry of Environment to estimate the underground conditions for the consumption of shallow geothermal energy.

Keywords *• borehole ground heat exchanger* (*BHE*) *• in-situ experimental temperature response test* (*TRT*) *• multilayered ground • groundwater flow*

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INTRODUCTION

During the last decade, many numerical and analytical models of borehole heat exchanger (BHE) performance were studied under different ground stratigraphy and groundwater flow conditions. High-quality and accurate studies of heat transfer are essential for geologists and engineers dimensioning BHE plants seeking to optimize the installation costs of shallow geothermal plants (Blum *et al.* 2011). The most usable depth of a vertical borehole could vary between 40 and 150 m in the Baltic Sea countries. The performance of BHEs could be evaluated by many analytical or numerical models. It is well known that the thermal properties of geological underground differ depending on depth due to the geological formation and unsaturated, impervious, saturated layers of the geological stratum affected by groundwater flow. The BHEs may cross different layers along the depth with different hydro-geological and thermal properties for each layer. The long term performance of BHE array can exhaust the low conductive geological layers if the assumptions were made for the homogeneous ground in advance (Erol, François 2018).

Since 2012, there have been made many improvements developing new BHE analytical and numerical models incorporating the multilayered ground structure under dynamic hydrogeological conditions. Li *et al.* (2017) developed and presented a numerical multilayered model showing the performance of the BHE by various geological strata. The experimental thermal response test (TRT) data and finite length line source model results were analysed by the different geological characteristics validating the temperature profiles. The Borehole-to-Ground dynamic model was developed and validated by Cazorla-Marín *et al.* (2017) considering the heterogeneous borehole surrounding of different ground materials. The groundwater level changes should be taken into account in BHE's design study as stated by Luo *et al*. (2018). The experimental stratified geological environment was constructed by Li *et al.* (2018) to perform the transient heat transfer using a single BHE. The effect of temperature difference in the homogeneous and layered ground heat transfer models along the borehole axis was more than obvious. Some promising research studies developing the analytical multilayer models were made by Abdelaziz *et al.* (2014), and just a few of them included groundwater flow (Hu *et al.* 2017; Erol, François 2018). Many of researchers came to a conclusion that the heterogeneity of the subsurface layer has an effect on the performance of a BHE plant even when the groundwater flow is bigger than 1 m per day. Some field investigations and experiments were provided by Li *et al.* (2018) in the experimental sandbox, the multilayered ground TRT concept was provided by Sakata *et al.* (2018), and the *in-situ* TRT field tests were made by Li *et al.* (2017) with self-regenerations.

Our first research (Palaitis, Indriulionis 2012) was first done using TRT data from a BHE plant in Vilnius (Visoriai), Lithuania. The aim of the paper was to propose a numerical model for BHE plant performance simulation in the multilayered ground embedding the groundwater flow. In the test field, the general physical and hydrodynamic parameters of multilayered ground were measured. Then, a numerical multilayered BHE numerical model was developed including different types of soil: gravel, sand, clay, and loam. The numerical finite elements model incorporated the unsaturated and saturated zones in the ground with aquifer, impervious and dense layers at the bottom. First, the practical investigations were performed showing the *in-situ* TRT test performance under unified and multilayer geological conditions with groundwater flow. Second, the practical performance of the BHEs plant was imitated for the unified and multilayered geological subsurface. The numerical results were validated with the practical Earth Energy Designer application the output of which was used by geoengineers before practical BHE's installation. The average temperature on the borehole wall based on the numerical unified and multilayered BHE model under different performance conditions. Finally, the aim was to find out how different layered subsurface and groundwater affect the performance of BHE systems.

EXPERIMENTAL INVESTIGATION: *IN-SITU* TRT TEST

Many thermal response tests on vertical boreholes are performed under real *in-situ* geological conditions. For testing borehole heat transfer models, the quality of the reference data set should be very high, especially for the soil thermal properties and boundary temperature conditions. This geological section investigation was performed during the construction of the High-Tech Research Centre at Mokslininkų Street in Vilnius. The main point of geological investigation was to identify the geological layers and evaluate the hydrodynamic parameters of the whole geological strata. For this purpose, there was drilled a 150 meters-deep borehole with a ground heat exchanger (BGHE), performing the thermal response test (TRT) and geophysical investigations: gamma gamma log and electric log.

During the investigation, a number of parameters were obtained (Fig. 1) in order to collect a proper description of the geological layers of the BHE. The identification of the geological structure was performed by gathering the soil samples from the borehole during the drilling and logging data on the natural gamma and electrical resistivity of the soils. The borehole penetrated through all Quaternary layers to the Cretaceous rocks. There were 3 meters of Cretaceous aleurite in the lower part of the investigated borehole. Aleurite is covered by deposits of Dzūkija Stage of the Middle Pleistocene. The Dzūkija Stage is composed of 6 meters of fliuvioglacial (sand) and 5 meters of glacial (sandy loam) deposits. The deposits of this Stage are covered by 31 meters-thick deposits of the Dainava Stage. The 17 meters-thick Dainava Stage is represented by interlayering of fliuvioglacial sand and glacial (sandy loam) deposits. The thickness of sand interlayers varied from 3 to 4 meters. There are Žeimena Stage deposits on the top of the Dainava Stage in the investigated borehole. The total thickness of the Žeimena Stage is 62 meters. There can be distinguished the Žemaitija Substage in the lower part of the Žeimena Stage. The 56 meters-thick Žemaitija Substage is characterised by the layering of fliuvioglacial sand and glacial deposits (loam, sandy loam); sandy deposits prevail in the uppermost part, whereas glacial deposits in the lower part of this thickness.

There is distinguished the Medininkai Substage in the upper part of the Žeimena Stage. The lower part of the Medininkai Substage is composed by glacial deposits (loam and sandy loam) with an interbed of limnoglacial clay (up to 2 meters thick) – the total thickness of glacial deposits is 23 meters. The uppermost part of the Medininkai Substage is composed of fliuvioglacial sand whose thickness is 5 meters. The Nemunas Stage of the Upper Pleistocene was distinguished on the top of the investigated borehole. The deposits of this Stage belong for the Grūda Substage and are composed by layers of limnoglacial clay (7 meters) and fliuvioglacial gravel (8 meters). The deposits of lower and middle parts of the Nemunas Stage are absent in the studied borehole. Thus, the total thickness of Quaternary deposits is 150 meters. The stratigraphic subdivision of Quaternary thickness is shown in Fig. 1.

It was stated that hydraulic gradients for different borehole layers are various: about 0.011 in the second layer, 0.013 in the forth layer, 0.016 in the sixth

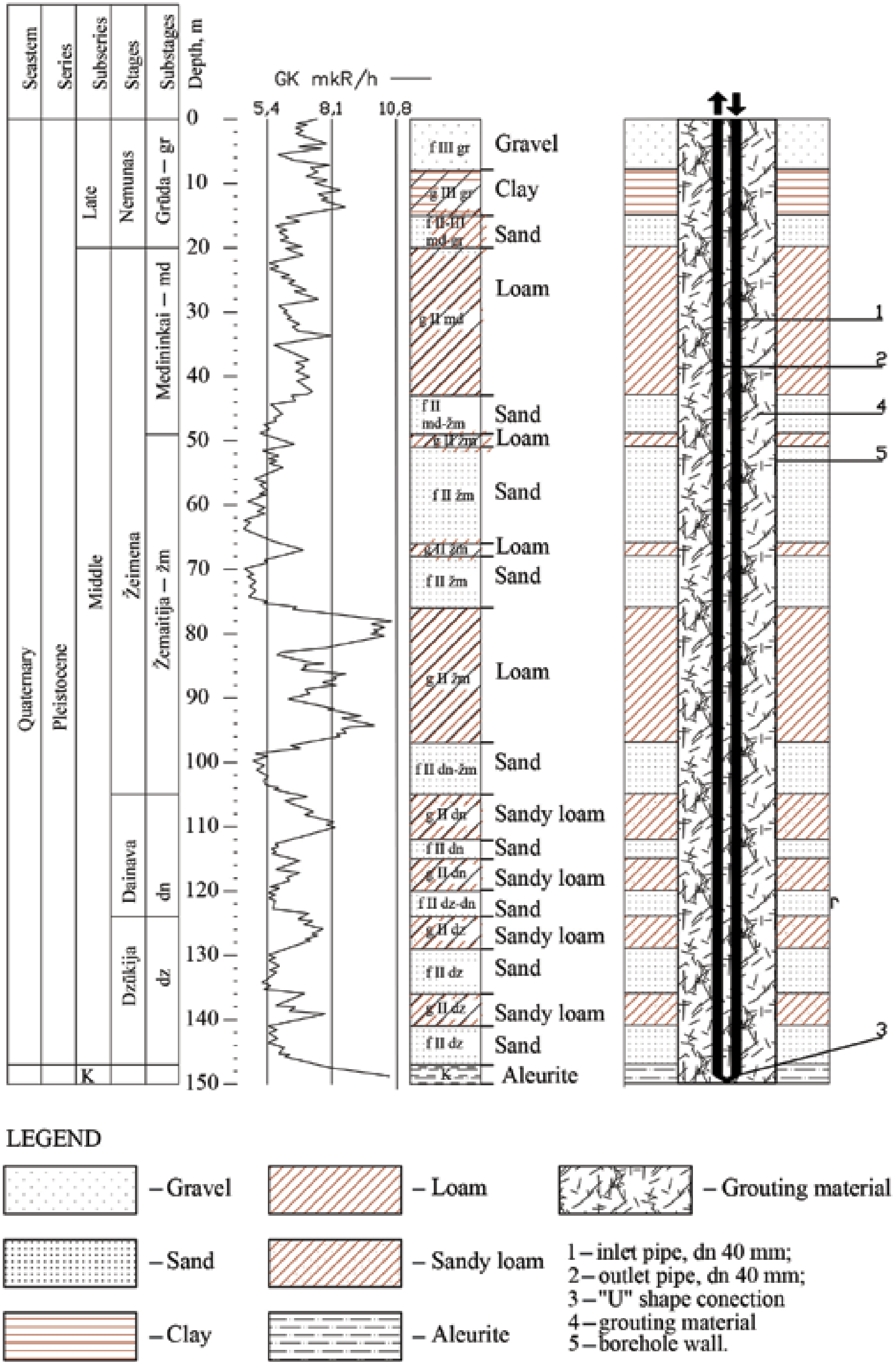

Fig. 1 Geological strata of a vertical borehole in Vilnius (Visoriai), Lithuania

Table 1 Hydrodynamic parameters of Quaternary deposits

Layer No	Hydrogeological index	Lithology and saturation	Groundwater filtration coefficient, (m/d)	Active porosity
1	g III gr	Unsaturated sand and gravel	30	0.35
2	f III gr	Saturated sand with groundwater flow	7	0.22
3	g II md	Impervious sandy loam	$8 \cdot 10^{-4}$	0.01
4	f II md-žm	Saturated sand with groundwater flow	3	0.15
5	g II žm	Impervious loam	$2 \cdot 10^{-4}$	0.009
6	f II žm-dn	Saturated sand with groundwater flow	5	0.2
7	g II dn	Impervious loam	$5 \cdot 10^{-4}$	0.01
8	f II dn	Saturated sand with groundwater flow	5	0.2
9	f II dn-dz	Saturated sand with groundwater flow	5	0.2
10	g II dz	Impervious loam	$5 \cdot 10^{-4}$	0.0095
11	K	Aleurite	0.0001	0.009

layer, etc. The groundwater flow rate is defined by filtration coefficient values in the experimental area by Bendoraitis *et al.* (2003, 2004). The multilayered soil hydrodynamic and active porosity parameters are defined in Table 1.

The authors assume that the practical experiment was performed following the ASHRAE (2007) procedures that all uncertainties of measured parameters are very small and don't have any relative impact on heat transfer results. The thermal response test was designed so that the heat input rate and the circulating fluid rate through the U-pipe are constant values and are controlled by geoengineers. In Fig. 2 you can see the *in-situ* TRT apparatus that was used for the practical experiment.

The U-pipe installed into the vertical borehole and the distance between U-pipe centres were fixed following the experiment practical procedures. The pipe and borehole physical parameters are shown in Table 2. More technical details are provided by Palaitis (2012) in the technical report.

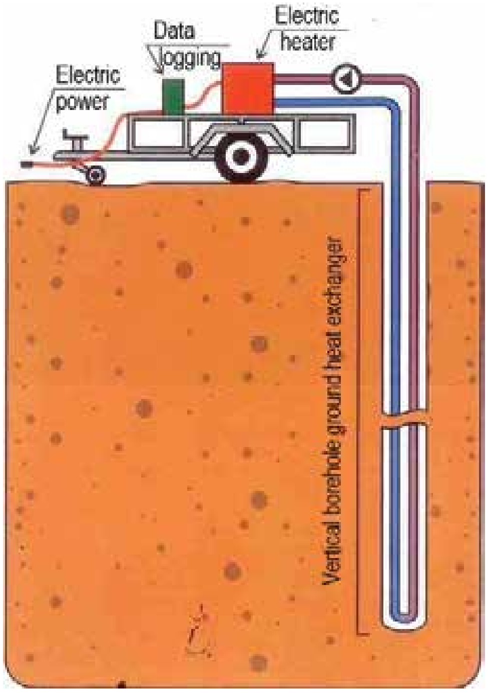

Fig. 2 TRT apparatus

The fluid circulating through the U-tube was started together with the electric heating elements which were providing a constant heat input rate to the fluid. Together, three electric heating elements supplied the heating power of approximately 6656 W to the circulating fluid with the flow rate of about 0.5 l/s. The voltage and current were recorded for each heater. The uncertainty of the measured flow rate and electric power to the heater was ±1%. A pump circulated the water through the U-pipe loop and a flow meter was used to measure the volume flow rate of circulating water. Temperature measurements with the thermistors had an uncertainty of ±0.03°C. All measurements about the fluid, air temperature, fluid flow rate, heat input rate were recorded by a computer once per 10 seconds. A 72.5-h thermal conductivity test was performed on the vertical borehole with different lithological composition Quaternary deposits. The *in-situ* practical test started at 7.1°C uniform temperature of soil surrounding the vertical borehole. The pump circulated the fluid, containing 37% antifreeze, through the U-tube. The electric heating elements were started at the same time with the fluid pump with the goal of providing constant values of already mentioned parameters. The circulating fluid temperatures were measured at the inlet and outlet at the supply and return locations of the U-tube.

Table 2 The technical parameters of the vertical borehole heat exchanger

Parameter	Vertical borehole	U-pipe
Material type	20% bentonite mixed with water, sand	Polyethylene
Spacing between U-pipe centres (m)		0.146
Length (m)	150	
Inner diameter (m)	0.185	0.0326
Outer diameter (m)	0.19	0.04

NUMERICAL MULTILAYERED BHE MODEL

The heat transfer of a BHE is greatly influenced by the saturated Quaternary subsurface and groundwater flow. According to experimental investigations, the multilayered subsurface will be conducted with seven geological layers. Let us specify the initial ground surface temperature, geothermal gradient and temperature variations along z-axis calculated as:

$$T_{0,m}(z,\tau) = T_0 - T_{grad} \times z,$$

where z is ground depth, τ is time, T_0 is the undisturbed ground temperature, T_{grad} is geothermal gradient. Before the numerical simulation, at the time moment $\tau = 0$, the temperature is equal to $T_{0,m}(z,\tau)$ in all surrounding ground, inside the borehole, as well as the fluid in the U-pipe. The Neuman boundary condition at borehole wall $r = r_b$ is defined by the formula below:

$$q(z,r_b,\tau) = \frac{T_b(z,\tau) - T_f(z,\tau)}{R_{effb}},$$

where R_{effb} is an effective borehole thermal resistance, T_b is the temperature at the borehole wall, and T_f is the mean temperature of the inlet and outlet fluid in the U-pipe under boundary conditions $z = 0$. The borehole thermal resistance (Hellstrom 1991):

$$R_p = \frac{1}{4\pi\lambda_p}\left(\ln\frac{r_{out}}{r_{in}} + \frac{\lambda_p}{h_f r_{in}}\right),$$

$$R_{effb} = \frac{1}{4\pi\lambda_g}\left(\ln\frac{r_b}{r_{in}} + \ln\frac{r_{bin}}{L_s} + \frac{\lambda_b - \lambda_s}{\lambda_b + \lambda_s}\ln\frac{s}{s-1}\right) + R_p,$$

where $s = (2 \times r_b / L_s)^4$; λ_g, λ_p are grout and the U-tube pipe thermal conductivities, accordingly; h_f is the convective heat transfer coefficient of fluid; r_b, r_{out} and r_{in} denote borehole radius, the outer and inner radius of the U-shaped pipe; and L_s is the spacing between the centre of legs of the U-pipe. At the upper layer, ground surface interacts with air temperature:

$$(\partial u) / \partial z = h_{air}\,(T_{z=0} - T_{air}),$$

where T_{air} is the ambient air temperature and h_{air} is the convective heat transfer coefficient between ground subsurface and air. The amount of heat injected from the borehole is calculated in order to get the heat balance at every time moment as defined in the equation below:

$$\frac{\Delta Q(\tau)}{C_f v_f A_f} = T_{fin}(\tau) - T_{fout}(\tau),$$

where C_f, v_f, A_f are the volumetric heat capacity of fluid, flow rate, and cross-sectional area of fluid, accordingly.

The heat transfer equation in formula (1) defines the unsaturated or low groundwater flow at the Quaternary subsurface:

$$C_s(z)\frac{\partial T(x,z,\tau)}{\partial \tau} = \frac{\partial}{\partial z}\left(\lambda_s(z)\frac{\partial T(x,z,\tau)}{\partial z}\right) + \\ + \frac{\partial}{\partial x}\left(\lambda_s(z)\frac{\partial T(x,z,\tau)}{\partial x}\right) \qquad (1)$$

where $T(x, z, \tau)$ is temperature distributed; $\lambda_s(z)$ and $C_s(z)$ are thermal conductivity and volumetric heat capacity in unsaturated or low groundwater flow in the Quaternary layer. The heat transfer with groundwater flow in saturated Quaternary layers could be written by equation (2):

$$C_m(z)\frac{\partial T(x,z,\tau)}{\partial \tau} = C_w(z)u_w(x)\frac{\partial T(x,z,\tau)}{\partial \tau} = \\ = \frac{\partial}{\partial z}\left(\lambda_m(z)\frac{\partial T(x,z,\tau)}{\partial z}\right) + \frac{\partial}{\partial x}\left(\lambda_m(z)\frac{\partial T(x,z,\tau)}{\partial x}\right), \qquad (2)$$

$$C_m(z) = (1 - \psi)C_s(z) + \psi C_w(z)$$

$$\lambda_m(z) = (1 - \psi)\lambda_s(z) + \psi\lambda_w(z),$$

where ψ, $\lambda_m(z)$, $C_m(z)$, $\lambda_w(z)$ and $C_w(z)$ are porosity, thermal conductivity and volumetric heat capacity in the Quaternary layer incorporating the groundwater flow. The porous Quaternary subsurface, soil and water material properties are denoted by indexes m, s and w, accordingly. In the formula (3) is shown the groundwater flow defined by Darcy law:

$$u_w(x) = k \times i, \qquad (3)$$

where k is hydraulic conductivity of isotropic medium, and the hydraulic gradient is defined as:

$$i = \mathrm{d}h / \mathrm{d}x$$

as hydraulic head change along x-axis.

NUMERICAL MULTILAYERED MODEL VALIDATION AND RESULTS

The aim of investigation was to get practical knowledge and experience seeking to account for the consumed shallow geothermal energy from the Quaternary multilayered ground with groundwater flow in BHE plants.

In Lithuania, there have been no attempts to perform a numerical multilayered borehole heat transfer model. The Comsol Multiphysics 5.4a version was used to develop a numerical vertical borehole heat exchange model. Two numerical simulations were performed for the estimation of the mean fluid temperature and temperature at borehole wall. First, the *in-situ* TRT data was used to evaluate the mean fluid temperature for a single U-pipe BHE. Second, the heat transfer simulation was performed under the periodic heat extraction conditions for the BHE array 9 × 13. All of the mentioned test case scenarios were investigated under unified, multilayered ground subsurface conditions with groundwater flow by comparing the results with the g-function approach. The U-pipe borehole geometry was approximated following Gu and O'Neal (1998) recommendations in order to get a less computationally expensive model avoiding the numerical fluid flow and heat transfer in the circulating U-pipe. The heat transfer with groundwater flow is present in multilayered ground for *in-situ* TRT reference data set and one-year heat extraction for a single U-pipe and BHE 9 × 13 plant under practical building heating/cooling conditions (see the building energy consumption profile in Palaitis 2012). The estimates of temperature at borehole wall are presented and compared with the g-function based method implemented in the Earth Energy Designer program. The real monthly energy values and the seasonal performance factor should be known in advance in order to get the real ground energy consumption values. The g-function method could be provided for 1-year single U-pipe installation for unified thermal parameters for the fixed and periodic heat extraction rate.

The homogenous geology numerical model was generated using the numerical multilayer model assuming that hydrodynamic properties of the ground are the same for all subsurface layers avoiding the groundwater flow. For both cases, TRT test data was compared with the TRT response data using Eskilson's (1989) g-function approach. The g-function configuration BHE array 9 × 13 was used for one year under the unified or homogenous subsurface. The numerical model results are analyzed in several aspects. First, the g-function approach results should be compared with the numerical model having a vertical borehole surrounding homogenous soil for short 72 hours and one-year simulation scenarios. Second, the numerical multilayered heat transfer model approach shows a different temperature response compared with the g-function approach. Third, the main insights should be provided due to unified geometry implemented in the numerical model and g-function approach. In Fig. 3, the temperature at borehole wall is the same after 60 hours for the homogeneous medium numerical model and g-function approach. The constant 1.2 °C temperature difference is between homogenous and multilayered medium numerical models for *in-situ* TRT data.

In figure 4 the developed and implemented cylinder source numerical model for the homogenous soil scenario changes faster under high heat extraction or injection rates. The temperature response of the mul-

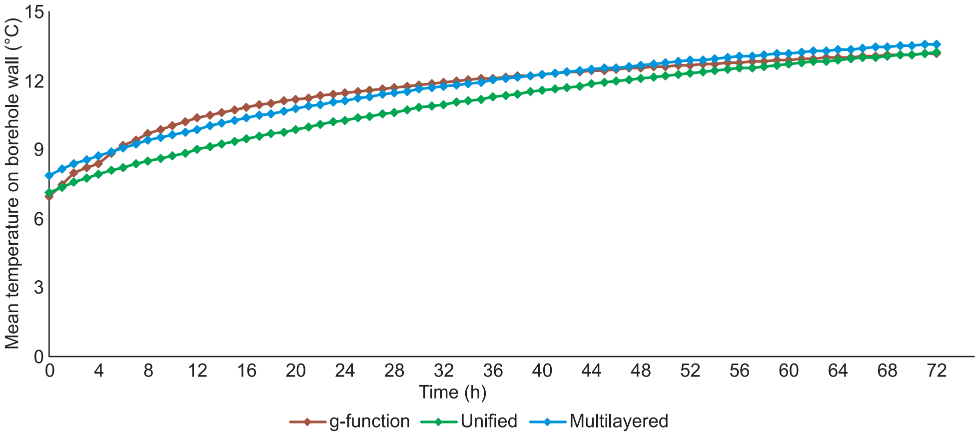

Fig. 3 Temperature profiles on borehole wall using *in-situ* TRT test data

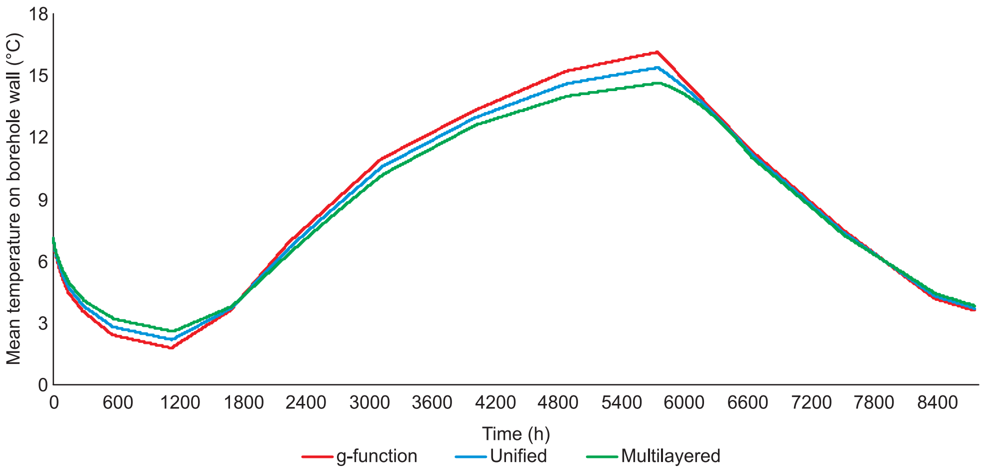

Fig. 4 Temperature at borehole wall for BHE's array using real heating/cooling consumption scenarios

tilayered numerical model is very close to the g-function method for one-year heat extraction simulation.

Table 3 The maximum relative errors of g-function, homogenous and multilayer numerical heat transfer approaches

Methods	Simulation time 72 hours	Simulation time 8760 hours
g-function vs. homogeneous	0.1	0.07
g-function vs. multilayered	0.05	0.08

The relative error analysis is provided to get the main insights about the vertical borehole heat transfer performance. It's obvious that cylinder borehole geometry and avoidance of internal heat transfer in the U-pipe generates high relative errors by comparing the g-function method with cylinder heat source homogenous numerical methods.

CONCLUSIONS

The numerical multilayered numerical model was presented and validated by fluid temperature response values. Different simulations were performed to show the methodological guidelines for the Lithuanian Geological Survey's geologists seeking to account for the Lithuanian shallow geothermal energy. The presented results show temperature response by using different research methods of extracting heat from the ground. The applicability of the numerical model could be extended to develop the Lithuanian shallow geothermal energy map from practical *in-situ* TRT data including laboratory experiments for the estimation of soil thermal parameters before designing the BHE plants. Further research steps of investigation should pay more attention to getting more precise estimates of soil thermal parameters, get the distributed TRT test data for the Quaternary ground and investigate the practical *in-situ* TRT tests from one plant under different heat extraction rates in order to develop the soil thermal parameters function dependent on soil saturation for different geological layers under Lithuanian Quaternary conditions. The practical TRT experiments could pave the way to the development of the Lithuanian regional shallow geothermal energy map extending the existing methodology of the proposed numerical model.

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NOMENCLATURE

T_0	undisturbed subsurface temperature (°C)
T_b	BHE temperature on borehole wall (°C)
T_f^{in}	inlet fluid temperature of BHE (°C)
T_f^{out}	outlet fluid temperature of BHE (°C)
H	BHE depth (m)
r_b	BHE radius (m)
r_{out}	outer pipe radius (m)
r_{in}	inner pipe radius (m)
q	heat transfer rate per unit area (W/m)
A_f	cross-sectional area of U-pipe (m^2)
λ	thermal conductivity (W/(m·K))
C	volumetric heat capacity (J/m^3·K)
ψ	active porosity of medium
L_s	shank spacing between U-pipe centres of legs (m)
R_{effb}	effective thermal resistance (m^2 K/W)
V_f	circulating flow velocity in U-pipe (m/s)
h_{ait}	convective heat transfer coefficient between subsurface and air (W/(m^2·K))
h_f	convective heat transfer coefficient of circulating fluid in U-pipe (W/(m^2·K))

SUBSCRIPTS

f – fluid in U-pipe
g – grout
p – pipe
m – porous Quaternary subsurface
s – soils subsurface
w – fluid in the aquifer or circulating fluid in U-pipe

ACRONYMS

BHE – borehole heat exchanger
EED – Earth Energy Designer
GHEPRO – ground heat exchanger design program
LGS – Lithuanian Geological Survey
MLM – multilayered model
TRT – thermal response test

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