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NATURE RESEARCH CENTRE

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The Borehole Heat Transfer Model Performance Analysis in the Multilayer Quaternary Sediments and Evaluation of Thermal Parameters Using Vertical Borehole Exchangers

Summary of doctoral dissertation

Nature science, Geology (N 005)

VILNIUS 2019

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VILNIAUS UNIVERSITETAS

GAMTOS TYRIMŲ CENTRAS

Audrius
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Įvairiasluoksnių kvartero nuogulų šilumos perdavimo modelis ir šilumos parametrų vertinimas vertikaliais šilumos kolektoriais

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Contents

Introduction

Relevance of work

During last decade in Scandinavian countries and USA are being made the huge efforts by scientists, business and technology companies to obtain new and more efficient heat transfer models and evaluation methods for determination of soil thermal parameters using vertical borehole heat exchangers (BHE). The quality of service was expanded cooperating technological and scientific experience and knowledge improving the performance of the thermal response tests (TRT). There is no practical knowledge and experience in simulating heat transfer using borehole heat exchangers in the multilayered Lithuanian Quaternary sediments. In Lithuania there are the big borehole heat exchanger's plants designed by foreign business companies and experts. In the Lithuanian Geological Survey there is no available practical TRT data and trained specialists with the practical experience of shallow geothermal energy. The Lithuanian country needs should be fulfilled providing the appropriate digital information for the regional, municipal and business economic needs. The shallow geothermal energy is one of the areas of renewable energy the potential of which is still unknown in Lithuania but only used by private business and households. At present, there are no scientific researchers, publications and more detailed practical studies related to shallow geothermal energy in Lithuania. This research could be able to expand a knowledge of heat transfer modeling using BHE under multilayered geological conditions. The efficient evaluation methods of thermal ground and grout parameters could increase the quality of BHE plant design.

The object and aim of the research

The efficient evaluation method of thermal parameters should be determined and applied using available TRT data simulating the heat transfer process by analytical temperature response functions. The performance analysis of heat transfer model was shown in the Quaternary sediments incorporating the effects of multilayered stratum and groundwater flow.

Tasks

1. review and investigate existing BHE heat transfer models and software;

2. select research objects, determine geological structures, hydro geological parameters;
3. to offer efficient thermal parameters (ground and grout) estimation methods;
4. under multilayered different geological and hydrogeological conditions to simulate the heat transfer using vertical borehole exchanger in order to determine the influential factors;
5. present the concept of the heat transfer model and implementation scheme of the thermal parameters evaluation algorithm as well the practical recommendations;

Originality of work

The first time in practice the particle swarm optimization algorithm has been applied to evaluate thermal ground and grout parameters. The sandbox laboratory TRT data was used to perform the analysis of linearity and sensitivity of thermal parameters. Also the estimates and errors of estimated thermal parameters are related with the duration and starting points of TRT data. The performance of multilayer heat transfer model were analyzed using different geological and hydrodynamic parameters and the heat flux rates investigating the influence of groundwater movements in the Lithuanian Quaternary sediments.

Defended highlights

1. TRT duration and start moments directly affect the accuracy of the estimated thermal parameters for different temperature response functions.
2. The thermal parameters of rocks can be reliably measured by the particle swarm optimization algorithm.
3. The changes of thermal conductivity values non-linearly affect the ground temperature response value in the multilayered geological structure.
4. The mean of temperature response changes shows relatively small the borehole heat transfer performance difference with or without the groundwater flow equation by Darcy low.

Practical use

The practical TRT data was designed to gain the determination of ground and grout thermal parameters and to convey practical recommendations to geologists who design the BHE. The practical recommendations for effective evolution algorithm was provided including the preconditions for the duration and starting moment of TRT test data. The practical analysis of heat transfer model in a multilayered geological environment have been performed. The applied methods and practical Matlab scripts could be used as an effective educational tool for the Lithuanian Geological Survey and the geology students during the practical training sessions at Vilnius University. The data obtained in the research can be used developing a map of shallow geothermal energy and the methodology for the assessment of shallow geothermal energy in Lithuania.

Approbation of results

The results of the research on the topic were presented at three international and four local scientific conferences. In total the 3 publications were published in the periodic scientific journals and two of them ISI Master Journal List and ISI Web of Science journals.

Structure of thesis

The thesis consists of the Introduction, Explanation of the therms, 4 chapters, Conclusion and the list of references. Overall 65 pages of the text, 17 figures, 13 tables. The structure of the dissertation according to the study objectives is presented in five chapters. This chapter covers the formulation and relevance of the problem and the aims, objectives and defended statements of the research, the novelty of the research work and its applicability in the assessment of Lithuanian shallow geothermal energy. The dissertation consists of the following sections:

1. The introduction introduces the part along with the above mentioned aspects.

2. Chapter 1 consists of an analysis of heat transfer models and practical applications used for vertical borehole heat exchangers.

3. Chapter 2 presents the research objects, their characteristics of geological

and hydrogeological environment with physical aspects.

4. Chapter 3 includes the methodology about practical application of particle swarm optimization algorithm for the determination of thermal parameters using the analytical temperature response functions.

5. Chapter 4 presents the results of multilayered heat transfer model under Lithuanian Quaternary conditions and estimates of thermal parameters.

6. Chapter 5 formulates the conclusions based on the results obtained during the research study.

1 Borehole heat transfer models and applications

The geologist engineers always have the goal to design an optimized plant of vertical borehole exchangers that the ground source heat pumps should perform in the most efficient way. This approach assures that the energy from the ground wouldn't wasted or exhausted during long time consumption of shallow geothermal energy. The main heat source is the ground surrounding vertical borehole. The heat exchange between the ground and a circulating fluid in U-type tube is an key topic of researchers. The U-shaped closed tube is installed in the vertical borehole called a vertical borehole heat exchanger (BHE). An appropriate design of BHE systems is particularly important for both short and long ground heat pump operations. BHE design is not always based on the extreme values of ground energy consumption but on a high quality dynamic heat transfer models incorporating BHE physical, geometric, grouting material and rock thermal parameters. There is no unified soil around the vertical borehole in geological stratum. In practice, the physical BHE parameters are known, as a U-type pipe diameter, wall thickness of pipe, U-pipe radius and thermal parameters of pipe, circulating liquid and filling material. The U-shaped tubes is made from the high quality polyethylene where the lifespan is not less than 50 years. The circulating U-tube fluid often a mixture of antifreeze and water (usually an effective antifreeze ratio in the circulating fluid is 37%), ethylene glycol, sometimes water just for TRT tests or experiments avoiding the freezing in wintertime's during the long-term operation. Also, an engineers select an effective liquid viscosity with the aim of improving heat transfer of the circulating fluid in the U-tube. The empty space in the vertical boreholes between the U-tube and the borehole are filled with materials with high thermal conductivity mixed with water. In both Lithuania and Scandinavian countries the vertical drilling diameter varies from 0.9 to 0.19 meters, and its length varies from 40 to 250 meters. The flow of the circulating fluid in the U-shaped tube and the fixed electric power is almost constant during TRT experiment. The heat is extracted from the rocks capturing the temperature of the circulating liquid takes time from 40 to 120 hours. The geological stratum surrounding the U-tube is used as a heat source to accumulate or extract heat depending on the technology of the ground heat pumps. The most commonly used types of BHE and their installations are shown in the figure 1. Typically BHE models are divided into three different categories that are based on analytical and semi-analytical

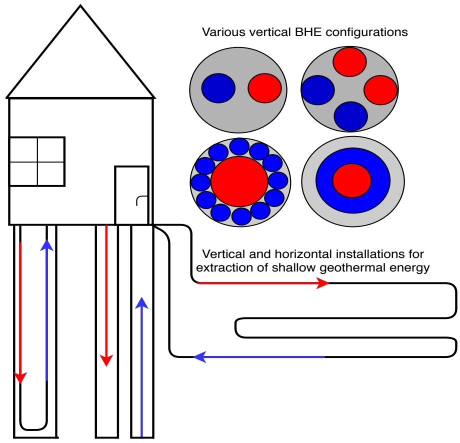


Figure 1 Various BHE configurations

solutions, temperature response functions or numerical models. Each category of heat transfer models will be reviewed separately with key wording and emphasis on application features. The advantages and limitations of the models that require additional experimental research will also be mentioned. The numerical expressions of temperature response functions ('g-functions') were obtained by solving the heat transfer equation using a two-dimensional finite difference method to determine the temperature response for each BHE configuration at a fixed heat flow rate. Such normalized temperature response solutions are commonly used by scientists, researchers and engineers. Eskilson and Claesson have received a long-term expressions of g-functions. Later Eskilson (1987) [13] has counted over 200 g-functions for different BHE array configurations and geometrical form e.g. in a single line, in a regular square or in a rectangle with different distances between BHE's. The complex BHE geometry was simplified that the installed U-tube is made as a finite-length cylinder with fixed diameter. The circulating fluid process in the U-tube and the borehole filling parameters are excluded from the heat transfer process. It is well known that numerical methods are more accurate for design and simulation of heat transfer of borehole ground heat exchangers despite the lower accuracy and computational costs the analytical methods are still popular for in-situ thermal response test analysis. The g-functions are divided into different time periods: the short time period g-function was developed by Yavuzturk [48], Zeng [53], Lamarche [30], the intermediate g-function (Carslaw and Jager [9]) and large time scales g-function Ingersol (1954) [24] and Eskilson [13]. The temperature response periods should conform with TRT duration which could vary from 40 to 240 hours. The following conditions should be satisfied for different terms: $t < t_b$ for short term period; $t_b \leq t \leq t_s$ for intermediate term; $t > t_s$ for long time. The stable times $t_b = \frac{5r_b^2}{\alpha_s}$ are $t_s = \frac{H^2}{9\alpha_s}$ defined and α_s, r_b and H are ground thermal diffusivity, borehole radius and active borehole length accordingly. The finite line source (FLS) models ([26]; [53]; [32]) are applicable and efficient for the borehole heat transfer modelling. The short therm g-functions developed by Li ([32], Claesson and Javed [26] are covering the time scales from minutes to decades. The various g-functions at the mid-point of borehole $z = \frac{H}{2}$ and the average temperature along z axis was proposed by Bandos [2] for intermediate and long time scales. Inaccurate TRT data cannot be used for testing, validating or simulating a heat transfer model. Some scientist Hu (2013) [40] stated that the heat transfer modelling results simply cannot be used due to uncertainties of TRT data. For this reason, laboratory experiments require the elimination of major uncertainties during TRT testing. The main advantages are that all the parameters of the TRT test are of high accuracy under the laboratory conditions and have a measured uncertainty of parameters. This makes possible to validate the mathematical model created using practical TRT data. Some of the most important advantages of this type of experiment are listed. First, to perform theoretical and practical validation of heat transfer models. Secondly, we have independently measured values of the rock parameters. Thirdly, it is possible to use these data to determine the thermal parameters values of rocks. Despite these advantages, only a few scientists Yu (2008) [52], Park (2012) [39] have provided practical research examples of this type of data together with validated heat transfer models and their errors. Reuss (1997) [43] conducted testing and validation of the heat transfer model for different rock types. Erol (2014) [12] together with colleagues carried out the short-term TRT tests by changing the BHE grouting material. Similar experiments were performed by scientists Shirazi (2014), [45] and Beier (2011) [4] that the vertical length of the vertical borehole is close to the actual dimensions of BHE. The sandbox laboratory TRT data was used by the author of this research.

1.1 Evaluation methods of soil and backfilling thermal parameters

The high quality in-situ TRT experiments could be performed in the sandbox data. It's possible to obtain the thermal parameters of the rocks by solving the inverse heat transfer but having the temperature response in space and time. Some researchers Rainieri et al. [41], Raymond et al. [42] used some methods to obtain the BHE backfilling thermal conductivity parameters. Most researchers use the analytical techniques that are simple to apply but with larger method errors and less reliable. Some scientists Roth [44], Fuji [14], Li [31] provided reliable results for steady-state process using long term TRT data. Shonder [46], Bozzoli [8] obtained reliable estimates for the thermal capacity of the vertical borehole filler using the numerical heat transfer modelling techniques. It' important to note that the researcher Javed (2012) [26] has evaluated the uncertainties of TRT data that directly effect on accuracy of the borehole heat transfer model or estimates of ground thermal parameters. In Box [7] publication is suggested that the uncertainty value of parameter must be mandatory in all thermal parameter evaluation procedures. It's obvious that inaccurate or pure quality TRT data cannot be used for testing, validating or simulating a heat transfer model. Hu (2013) [40] performed some BHE modelling attempts and came to conclusion that the obtained results simply cannot be used due to uncertainties of TRT data. For this reason, the laboratory experiments should eliminate the uncertainties during TRT. The key advantage of experiment is that the parameters are precisely measured with known the uncertainties that makes possible to validate the mathematical model created using practical TRT data. Some of the most important advantage of this type of experiment is to perform theoretical and practical validation of thermal rock parameters. Despite these advantages, only a few scientists Yu (2008) [52], Park (2012) [39] have provided the practical research together with validated heat transfer models results and their errors. Reuss (1997) [43] conducted testing and validation of the heat transfer model for different rock types. Scientists Shirazi (2014) [45], Beier (2011) [4] and Erol (2014) [12] together with colleagues carried out short-term TRT experiments changing the BHE grouting material.

1.2 Software for BHE desing and analysis

These already developed BHE design applications are used for different purposes:

- TRT data analysis;
- optimal BHE plant design; distances between BHE's, their number, geometric distribution by length and direction etc.

- analysing the BHE performance with the ground source heat pump for specified the heating and cooling consumption scenarios.

The USA Department of Energy calculated around 400 software tools that are available today to assess the energy efficiency, renewable energy and building sustainability. The five most popular applications DOE-2.2, eQUEST, EnergyPlus, TRNSYS and EnergyGauge perform the geothermal heat pump analysis together with the vertical borehole heat exchanger system according the building energy needs. Liu and Hellström (2006) [33] reported that DOE-2.2 has integrated the ground source heat pump performance with building energy needs. In eQUEST, EnergyPlus, TRNSYS [29] and EnergyGauge, this functionality was introduced earlier. eQUEST and DOE-2.2 uses the temperature response g-functions offered by Eskilson (1987) [13] for measuring the average circulating fluid temperature. In these programs Yavuzturk and Spitler [51] made some mathematical changes incorporating the short-term 'g-functions'. EnergyPlus program was developed by Jin and Spitler that is used to simulate an annual energy demand for a building along with a vertical borehole heat exchanger using the water-to-water heat pump operation. Similarly, the TRNSYS program was based by Hellström [18] heat transfer model together with Thornton's [50] was also technically realized. Other softwares includes common BHE design aspects together with ground source heat pumps are using analytical linear and cylindrical heat source techniques. Yang [34] provided several design tools that are based on cylindrical heat source models. Linear heat source applications are implemented in EED, GLHEPRO [47] and GeoStar applications and GchpCalc is a cylindrical heat source method. The EED program developed by Lund University in Sweden which is based on the long-term g-functions for different configurations of more than 200 BHE systems which are widely used in Lithuania. The programs provide the results in a minute for a periodic annual heat and cold consumption of a 20-25 years where the effective heat pump operating coefficient is not less than 4.5. GLHEPRO program [47] can simulate hourly heat or cold loads for commercial and private buildings based on of BHE systems. The effective depth of BHE and the distances between them also the average heat extraction rate are evaluated in advance. In China build GeoStar application includes heat transfer modelling for inside and outside the vertical borehole. The GchpCalc program is mostly used by geologists engineers seeking to define an optimised BHE plant.

2 Research objects

It is important to use the appropriate hydrogeological, geology engineering and thermal parameters of the rock layers in the heat transfer model which may differ significantly from the location, depth and conditions of sedimentation. Ignoring the values of the rock thermal parameters is a big obstacle in the borehole heat transfer modelling. In practice the whole multi-layered column is evaluated as uniform from the TRT data. The practical recommendations of ASHRAE (2011) [1] refers to suggestions on how to use in-situ TRT data. In-situ TRT tests require special testing equipment, the qualitative performance of TRT experiment and the reference data sets can be obtained. The specific sandbox laboratories are qualitatively equipped and prepared to perform TRT test under the best conditions.

2.1 in-situ TRT experiment in the multilayered Quaternary sediments

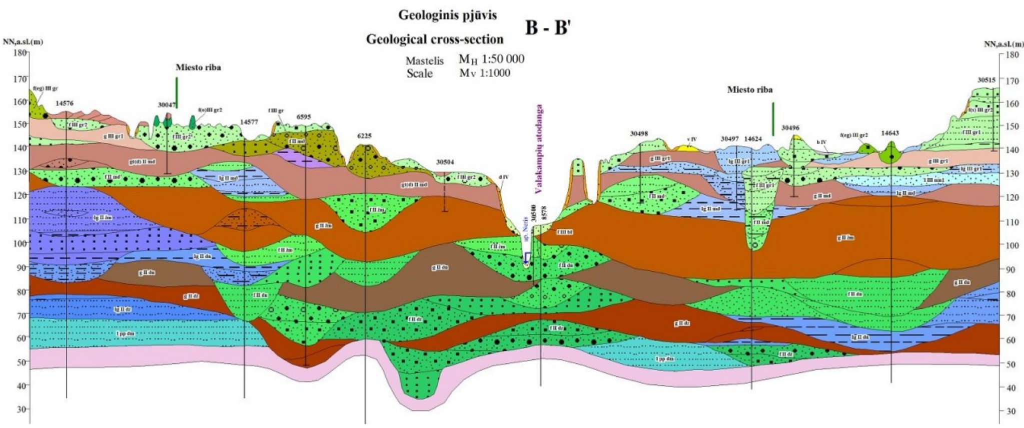


Figure 2 Vilnius capital city geological map Stankevičiūtė (2012)[49]

The study object is located in the Visoriai district of Vilnius city (Fig. 2) in the area of the Dzūkija marginal moraine highland, the area of Sudervė morainic hills. It is a Vilnius city part located on the right side of the Neris River valley in the area of the marginal formations of the Last Glaciation. The neighbouring districts Pagubė, Žalieji Ežerai, Gulbinai, Ežerėliai, Visoriai, Pašilaičiai, and Gudeliai are distinguished by different geomorphology and Quaternary geological structure. The highest surface elevations are characteristic of Visoriai and Pašilaičiai districts as a marginal formation relic of older Medininkai glaciation. Here the geological and geomorphological environment of the study object located in the area of Visoriai district is characterized. The glaciofluvial sediments of the Grūda stage (f III gr) of Last Glaciation are widespread throughout almost the entire territory of Vilnius city, except for its south-eastern part. The thickness of the sediments in places is up to 16.8 m. The marginal glaciofluvial sediments are mostly spread in the northern part of Vilnius, and their thickness varies from 0.2 to 11 meters. These sediments are composed of silty, clayey and gravelly sand, as well as sand and gravel. The glacial sediments of the Grūda stage (g III gr) are spread in a limited area of the eastern part of Vilnius. The thickness of the sediments in some places reaches up to 25.9 meters, and the sediments of the marginal formations, consisting of morainic sandy and silty clay, is spread in the northern, north-western and north-eastern parts of Vilnius city territory. Their thickness varies from 0.2 to 13.8 meters. The sediment sequence of the Middle Pleistocene include Medininkai Suite's glaciolacustrine (Ig II md), glaciolacustrine marginal (lgt II md), glaciofluvial (f II md), glaciofluvial marginal (ft II md), glacial of basal till (g II md) and glacial marginal (gt II md) sediments, as well as glaciolacustrine and glacial sediments of basal till of Žematija Suite. The glaciolacustrine (Ig II md) and glaciolacustrine marginal (lgt II md) subsurface sediments of Medininkai Suite are spread only on the southern part, consisting of clay and silty clay up to 0.9 meters thick. The thickness varies in the marginal formations, which are widespread in western parts of south-eastern and southern parts of Vilnius. Gaciofluvial (f II md) and gaciofluvial marginal (ft II md) sediments of Medininkai Suit are very limited in the western part, with a thickness varying from 0.2 to 16.3 meters. Gaciofluvial marginal sediments are widespread in the eastern and southern parts, with a thickness of 0.2 to 17.8 m. and rarely found in the north-western part of the area. It consists of silty, clayey, gravelly sand, medium sand, and gravel in places up to 14.4 meters thick. The glacial sediments of basal till of Medininkai Suite are spread in a small area in the western and northern parts, where their thickness reaches up to 28 meters. Glacial marginal (gt II md) sediments spread predominantly in the eastern, southern, and somewhat rarer in the western parts of Vilnius. The sediments consist of glaciomorainic silty loam and sandy loam. Glacigenic sediments of Žemaitija Suite: glaciolacustrine (Ig II žm), glacial of basal till (g II žm), glacial marginal (gt II žm) form in very small areas spread only in the central parts of Vilnius city territory. Glaciolacustrine sediments consist of silt and silty sand. Glacial and glaciomarginal sediments are formed of morainic silty loam and sandy loam. Their thickness varies from 0.2 to 6.8 m. In some places in the area, the pre-Quaternary rock blocks of the Cretaceous chalk are found. The glaciolacustrine, gaciofluvial and glacial sediments of Dainava and Dzūkija Suites of Middle Pleistocene, as well as glaciolacustrine and glacial sediments of the Lower Pleistocene and the Pre-Pleistocene lacustrine sediments, are not described due to an information absence on their occurrence and physical-mechanical properties by Stankevičiūtė (2012)[49]. 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 log and electric log. During the investigation, a number of parameters were obtained in figure 3 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. Thus, the total thickness of Quaternary deposits is 150 meters. The stratigraphic subdivision of Quaternary thickness is shown in figure 3. It was stated that hydraulic gradients for different borehole layers are various: about 0.011 , 0.013 , 0.016, 0.018, etc. The groundwater flow rate is defined by filtration coefficient values in the experimental area by Bendoraitis et al. [5, 6]. In the multilayered Quaternary sediments the following hydrodynamic and active porosity parameters are defined in Table 1. It was assumed that the practical experiment was performed following the ASHRAE (2011) [1] 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 controlled by geologist engineers. The U-pipe installed into the vertical borehole and the distance between U-pipe centres were fixed following the practical procedures. The pipe 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

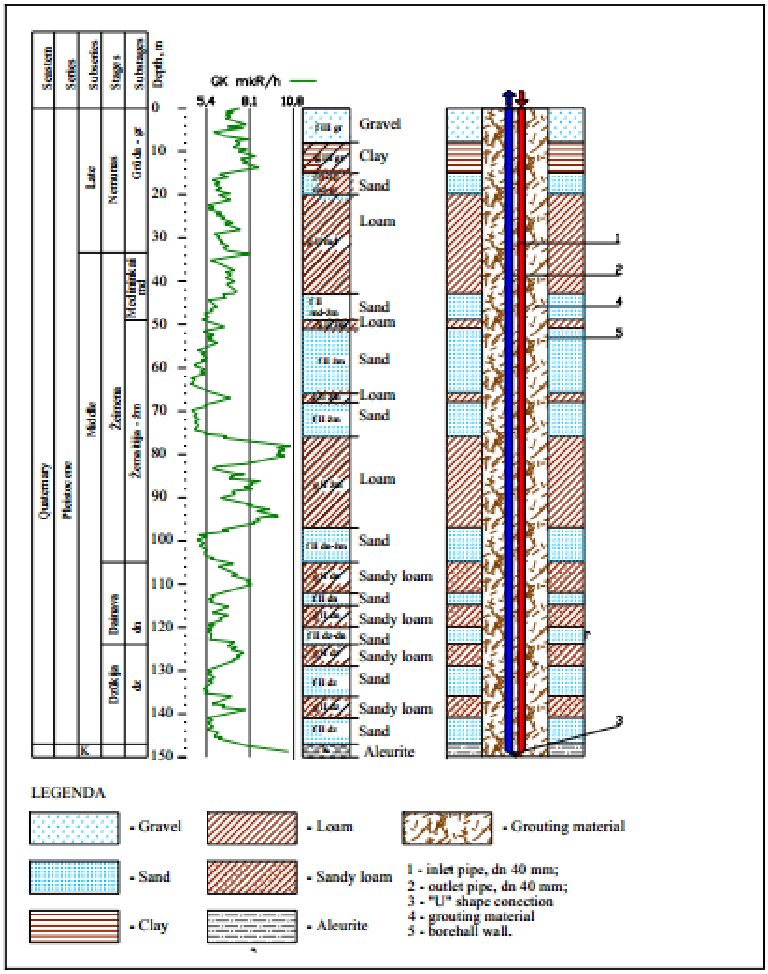


Figure 3 Vertical borehole heat exchanger in the Quaternary sediments [22]

for each heater. The uncertainty of circulating fluid flow rate and electric power to the heater was $\pm 1\%$. 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 $\pm 0.03°C$. All measurements about the fluid, air temperature, fluid flow rate, heat input rate were recorded by a computer once per 10 seconds. A 71.5 hours TRT test was performed on the test vertical borehole with Quaternary deposits. The uniform temperature of soil surrounding the vertical borehole is $7.1°C$. 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 constant values. The circulating fluid temperatures were measured at the inlet and out-

Layer Nr.	Hydrogeological index	Lithology and saturation	Hydraulic conductivity (m/d)	Active porosity	Depth range (m)	Thickness (m)	Hydraulic gradient(m/m)
1	f III gr	saturated sand	30	0.35	0-8	8	0.011
2	g III gr	unsaturated sand and gravel	$7 \cdot 10^{-4}$	0.01	8-15	7	
3	f III md-gr	saturated sand	7	0.22	15-20	5	0.011
4	g II md	impervious sandy loam	$8 \cdot 10^{-4}$	0.01	20-43	23	
5	f II žm-md	saturated sand	3	0.15	43-49	6	0.013
6	g II žm	impervious loam	$2 \cdot 10^{-4}$	0.009	49-51	3	
7	f II žm	saturated sand	5	0.2	51-65	14	0.013
8	g II žm	impervious loam	$2 \cdot 10^{-4}$	0.009	65-68	3	
9	f II dn-žm	saturated sand	5	0.2	68-76	8	0.016
10	g II žm	impervious loam	$2 \cdot 10^{-4}$	0.009	76-97	19	
11	f II dn-žm	saturated sand	5	0.2	97-105	8	0.016
12	g II dn	impervious loam	$5 \cdot 10^{-4}$	0.01	105-112	7	
13	f II dn	saturated sand	5	0.2	112-115	3	0.016
14	g II dn	impervious loam	$5 \cdot 10^{-4}$	0.01	115-120	7	
15	f II dz-dn	saturated sand	5	0.2	120-123	3	0.018
16	g II dz	impervious loam	$5 \cdot 10^{-4}$	0.01	123-129	6	
17	f II dz	saturated sand	5	0.2	129-135	6	0.018
18	g II dz	impervious loam	$5 \cdot 10^{-4}$	0.01	135-141	6	
19	f II dz	saturated sand	5	0.2	141-148	7	0.018
20	K	aleurite	0.0001	0.009	148-150	2	

Table 1 Hydrodynamic parameters of the multilayered Quaternary deposits

let at the supply and return locations of the U-tube. More technical details are provided by Palaitis (2012) [37].

2.2 Sandbox laboratory thermal response test

Many thermal response tests are performed on real in-situ geological conditions. From a large laboratory sandbox the reference data set was used for testing and validation heat transfer models while the quality of data set is very high. The sandbox was constructed from wooden frame. The form of sandbox is a rectangle with sides of 1.83 m and 18.32 m. The borehole was settled horizontally along the length (18.32 m) of sandbox. Plastic liner separates the sand from wooden frame in order to keep water. The sand was saturated from the local utility water line by the five perforated parallel lines uniformly spaced on the bottom of the wooden box. The whole external parts of the wooden sandbox were thermally insulated to minimize effect from changing weather conditions. The parameters of installed borehole into the sandbox are shown in the Table 2. Beier [4] described the

Experiment parameter	Values
Borehole length (H)	18.32 m
Borehole outer radius(r_{bout})	0.065 m
Borehole inner radius (r_{bin})	0.063 m
U-pipe inner radius (r_{out})	0.0137 m
U-pipe outer radius (r_{in})	0.0167 m
Spacing between centers of U-pipe (L_s)	0.053 m
Fluid flow rate (m_f)	0.197 kg/s
Heat injection rate (q)	57.7 W/m
Undisturbed soil temperature (T_0)	22 $°C$

Table 2 Sandbox experiment details [23]

measurement procedures determining grout and ground thermal conductivities by using a non-steady-state thermal probe invented by Hooper and Lepper [21]. The estimated uncertainty was ±5% for grout and ground thermal conductivities. The same TRT reference data set was used by Javed [25] for analysis and validation of borehole heat transfer model. A testing unit for in situ thermal response tests is connected to the U-tube in the sandbox. Together two electric heating elements supply approximately 1056 W to the circulating fluid during TRT test. The pipe material, grout and thermal properties are known in the Table 3. The TRT test was designed that the heat input rate and the fluid flow rate are close the

Thermal parameters	Values
U-pipe thermal conductivity (λ_p)	0.39 W/mK
Borehole effective thermal resistance (R_b)	0.173 mK/W
Soil thermal conductivity (λ_s)	2.82 W/mK
Soil thermal diffusivity (α_s)	1.47e-6 m^2/s
Grout thermal conductivity (λ_g)	0.73 W/mK
Grout thermal diffusivity (α_g)	1.9e-7 m^2/s

Table 3 Experimental values of thermal parameters [23]

constant value which circulates through closed U-pipe. In the U-pipe installed into horizontal borehole from aluminum pipe and the distance between U-pipe centers were fixed following the high quality of TRT test procedures. In the Table 3 you can see the experimental TRT apparatus technical parameters that were used for TRT test. The reference data set from the 24 thermistors that provide temperature measurements at the borehole wall and at specific locations in the surrounding soil, inlet (21) and outlet (20) of fluid. Measurements are recorded every minute on a computer data acquisition system for heat transfer model. The location schema of thermistors is shown on Figure4. The grouting material having

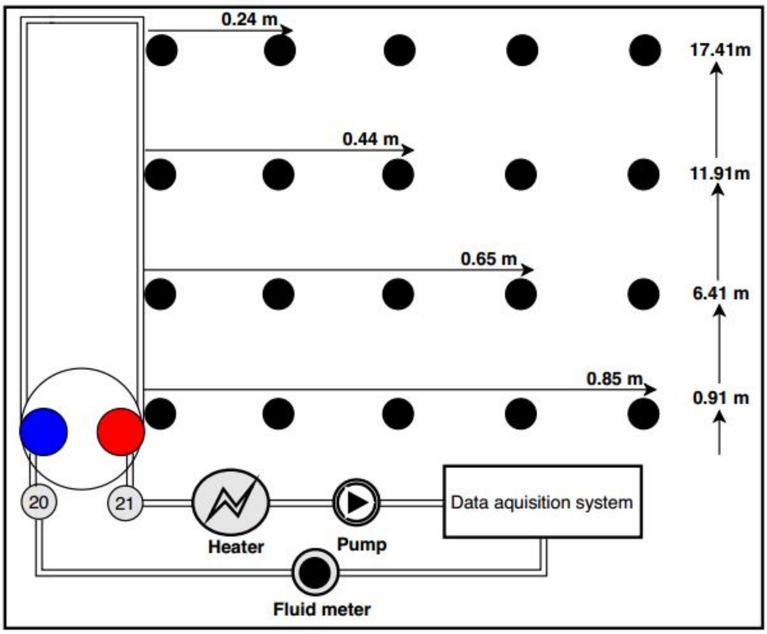


Figure 4 Measurement points schema in one part of the sandbox [23]

20% solids was mixed with water in order to make the borehole filling. Before each TRT test starts the uniform temperature of air, fluid and ground should be measured. The fluid circulating through U-tube should start together with the electric heating elements which are providing a constant heat input rate to the water. All measurements about the temperature at the thermistors locations, fluid flow rate and heat input were connected and recorded to a data acquisition system once per minute. Approximately 52 hours TRT test has been conducted within the saturated sandbox and serves as a reference data set for heat transfer modelling and simulation.

2.3 Lithuanian TRT experimental prototype

In this section is presented the project of the heat response experimental prototype produced in Lithuania without disclosing the technical details because the confidentiality agreement. Lithuania's closed joint-stock company 'Hidro Geo Consulting' (HGC-LTU) in cooperation with the Baltic Institute of Advanced Technology (BPTI) submitted (VP2-1.3-UM-05-K 'Inočekiai LT') project to get financial support from the Lithuanian Science Technology Agency (MITA). In October 2014 the funding was approved for the project. I was the project team member for evaluation experimental equipment and experimental data analysis. After the existing solution analysis the project team decided to get the experience and knowledge from the University College Dublin (UCD) Ireland. The constructed a low budget TRT device was tested with other certified commercial TRT equipment under the same geological environment conditions [20]. The goal of project was to construct commercially more attractive and reliable TRT equipment. The budget for this project was only 4.900 euros and the price was almost ten times lower while the sales price from a commercial supplier is almost 48.400 euros. It was very important that the UCD team leaders provided all technical elements that could be purchased for the construction of the TRT. This solution was approved due to the low budget and the use of simple technical details in TRT experimental equipment. The UCD-designed TRT apparatus is operating in the Norfolk UK as shown in the figure 5. In the publication Hemmingway (2012) [19] has provided the intervals and accuracy of the technical details of the TRT hardware and the design calculations and assumptions was mentioned the accuracy of technical details. UCD designers have developed a wireless data transfer capability through a data router to periodically transfer data to a remote server. In

Figure 5 UCD TRT rig Hemingway (2012) [19]

this way, the data can be recorded from any location during the experiment, and data analysis can only be performed after the temperature response test. If there is no problem with the operation of the TRT hardware, then the data analyst can analyze the data in the office and not go to the location of the experiment. In addition, they will separate the selection of the circulation pump and mention several aspects of the circulation in the U-tube in the vertical collector and in the TRT internal system. The UCD has been designed to be used for vertical depths of different depths and U-shaped tubes of different diameters. In the articles by Mike Long and Phil Hemmingway (2012) [19, 20], you can find a more detailed flow chart of the fluid flow rate by the distribution of fluid velocity and tube length diameters want to measure the drop in fluid pressure. Internal water heaters for UCD TRT have been selected to enable quick installation and good heat transfer to the liquid from the electric field. According to the recommendations of the American Heating, Conditioning and Ventilation ASHRAE (2009) Atlanta2009 TRT tests have a heat pumping rate of 50 to 80 W/m depending on the vertical depth of the collector and the potential heat or cold demand of the building. After a technical analysis the common requirements were agreed for Lithuanian TRT prototype:

- must be easily transported by car and all parts should be accessible and replaceable of the TRT rig;
- with designed a reliable frame insulated from outside to protect against external temperature changes;
- with installed the temperature measurement equipment: for circulating fluid

in U-tube, outside the TRT apparatus;

- at least once per 1 minute the temperature data must be recorded;
- circulating fluid meter could gather the fluid rate during the TRT test;
- the three 3 kW power heaters should be installed and connected in parallel;
- fluid pressure monometer and valves to assure the quality of circulating fluid speed;
- circulation pump would be sufficient to perform the reliable TRT operation.

The technical details are confidential and internal schemes of the Lithuanian TRT experimental prototype will not presented in this research. On the figure 6 is

Figure 6 HGC-LTU TRT prototype Palaitis (2015) [38]

presented the HGC-TRT experimental prototype which is connected to the vertical borehole heat exchanger by a flexible connection.

The following recommendations for HGC-TRT riq:

- the circulation pump must operate in both directions (inverse, reverse modes);
- the additional gas separators should be installed for the removing the unwanted air from the borehole heat exchanger;
- it's important to determine the influence of the circulation pump on operating mode to the fluid temperature at the start of the TRT test;

- to extend the ability to transfer TRT data over the 4G network and the TRT reference data set could be analysed in 'online' mode.

The HGC-TRT experimental apparatus has been significantly upgraded and improved during last years. This successful solution inspires the necessary TRT studies with the aim of developing the potential of shallow geothermal energy in Lithuania.

3 Methodology

Li [32] proposed analytical BHE transfer model by for unit-step heat load q

$$T_f(t) - T_0 = q \cdot G_{LS} + q \cdot R_b^{eff}, \quad 0 \leq t \leq (10 \sim 20)t_b, \tag{1}$$

and T_f the mean temperature of circulating fluid, T_0 undisturbed test field temperature, R_b^{eff} the effective borehole thermal resistance, $G_{LS}\,(t)$ temperature response function of the line source model. Hellström [18] defined the effective borehole thermal resistance by formula

$$R_{effb} = \frac{1}{4\pi\lambda_g}\left[\ln\frac{r_{bin}}{r_{in}} + \ln\frac{r_{bin}}{L_s} + \sigma\ln\frac{s}{s-1}\right] + R_p \tag{2}$$

and

$$R_p = \frac{1}{4\pi\lambda_p}\left(\ln\frac{r_{out}}{r_{in}} + \frac{\lambda_p}{h_f r_{in}}\right) \tag{3}$$

here $s = (\frac{2r_{bin}}{L_s})^4$, λ_g, λ_p are thermal conductivities of grout and the plastic pipe accordingly; h_f is the convective heat transfer coefficient of fluid; r_{bin}, r_{out} and r_{in} denote borehole inner, outer and inner radius of the U-shaped pipe; L_s is the half distance between the center of legs of U-type tube. The different temperature response g-functions will be described below developing the analytical BHE models.

3.1 Infinite line source model: ILS

The mean temperature on borehole wall presented and devloped by Carslaw and Jager [9] for analytical BGHE approach. This heat transfer equation for the effective ground thermal conductivity estimation are used having $in-situ$ thermal response test data. The temperature response function $G_{ILS}(t)$ with the constant q heat injection load is derived below

$$G_{ILS}(t) = \frac{1}{4\pi\lambda_s}\int_{\frac{r_b^2}{4\alpha_s t}}^{\infty}\frac{\exp^{-u}}{u}du \tag{4}$$

where α_s thermal diffusivity of surrounding ground, λ_s thermal conductivity of surrounding ground, t time and u the integral variable. The $G_{ILS}\,(t)$ has a great impact of ground surface temperature variation in thermal process more than 5 time period.

3.2 Infinite cylinder source model: ICS

The infinitive length line heat source model could be approximated as 'equivalent diameter' cylinder with the constant heat rate for BGHE approximation where U-pipe. The temperature response function is defined by Ingersoll [24]

$$G_{ICS}(z,p) = \frac{1}{\pi^2}\int_0^{\infty} f(\beta)\, d\beta \tag{5}$$

$$f(\beta) = \left(e^{-\beta^2 z} - 1\right) \cdot \frac{\left[J_0(p\beta)\, Y_1(\beta) - Y_0(p\beta)\, J_1(\beta)\right]}{\beta^2\left[J_1^2(\beta) - Y_1^2\ (\beta)\right]}$$

where J_0, Y_0, J_1, Y_1 are Bessel functions of first and second kind, and $z = \frac{\alpha_s t}{r_b}$, $p = \frac{r}{r_b}$ are the G function parameters. Carslaw and Jaeger [10], other authors (Kavanaugh and Rafferty [27]) were developed and applied more analytical solutions for the design of BGHE's.

3.3 Finite line source model: FLS

Claesson and Javed [26] are presented the mean temperature at a distance r of a finite length line heat source (FLS) extending from $z = D$ to $z = D + H$. At the surface $z = 0$ the temperature is equal $T = 0$. The FLS g-function at the distance $r = r_b$ of borehole at time t has an expression

$$\begin{aligned} G_{FLS}(t) &= \frac{1}{4\pi\lambda_s}\int_{\sqrt{4\alpha_s t}}^{\infty} \frac{e^{-(r_b s)^2} I(h,d)}{H s^2} ds, \\ I(h,d) &= 2ierf(h) + 2ierf(h+2d) - ierf(2h+2d) - ierf(2d), \\ ierf(X) &= Xerf(X) - \frac{1}{\sqrt{\pi}}(1 - e^{-(X)^2}), \quad h = Hs, \quad d = Ds \end{aligned} \tag{6}$$

where $erf(X)$ denotes exponential complementary function and $G_{FLS}(t)$ is the average temperature response function on the borehole wall. The transient thermal process between the ground surrounding borehole and backfilling material in the borehole couldn't be accounted for 6 equation. The estimates of g-functions should meet the following time criterion $t_b \geq \frac{5r_b^2}{\alpha_s}$ than maximum of error not exceed 10%. Gehlin (2002) showed that the maximum error could be less than 2.5% if that $t_b \geq \frac{20r_b^2}{\alpha_s}$ condition is met. The estimates of average fluid temperature are calculated as shown in formula below

$$T_f(t) = T_0 + q \cdot G(t) + q \cdot R_{effb} \tag{7}$$

where $G(t)$ could be one of the g-function definitions $G_{ILS}(t)$ (4), $G_{ICS}(t)$ (5), $G_{FLS}(t)$ (6).

3.4 Particle Swarm Optimization

The particle swarm optimization (PSO) proposed by Kennedy and Eberhart [28] was first introduced by stochastic algorithms imitated the social behavior of a particles. The population of particles is called the swarm that consists from M moving particles in a N-dimensional search space. Each particle is defined as a potential solution, there the position of the i^{th} particle is represented as $X_i^n = (x_{i1}, x_{i2,}, \ldots, x_{iN})$. The new position of particle is calculated by adding a displacement to the current position and for every generation could be calculated by equation 8

$$X_i^{n+1} = X_i^n + V_i^{n+1} \tag{8}$$

where the current and previous positions of particle i are represented by X_i^n and X_i^{n+1}, and V_i^{n+1} is the current velocity of particle i is represented as $V_i^n = (v_{i1}, v_{i2}, \ldots, v_{iN})$. The velocity of each particle i is updated by following formula

$$V_i^{n+1} = w\ V_i^n + \varphi_P c r_1 \left(X_{Pbest,i}^n - x_i^n\right) + \varphi_G c r_2 \left(X_{Gbest}^n - x_i^n\right) \tag{9}$$

where V_i^n and V_i^{n+1} are the current and previous velocities of each particle i, and inertial weight was changed for every iteration as $w = w_{max} - \frac{iter*(w_{max}-w_{min})}{max(iter)}$, w_{max} and w_{min} inertial maximum and minimum values, respectively. The previous best position of each particle could be defined $X_{Pbest,i}$ giving the best fitness function value. The global best position $X_{G_{best}} = (x_{gbest,1}, x_{gbest,2}, \ldots, x_{gbest,N})$ is described among all particles in the swarm, here $G_{best} = \min_{1 \leq i \leq n} f\left(X_{Pbest,i}\right)$ and the fitness function f is described as a root mean square error (RMSE) below

$$f_{RMSE} = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(T_{f,k}^{actual} - T_{f,k}^{estimated}\right)^2} \tag{10}$$

here $T_{f,k}^{actual}$ is the the average fluid temperature during experiment, $T_{f,k}^{predicted}$ is the estimates of fluid temperature enabling heat transfer simulation, N is the number of TRT test data points. The equation 9 consists of three parts: the first one is called the momentum part that defines the previous velocity; the second part is called the cognition part that represents the best position of individual particle; the third part is called the social component that represents the collaboration among particles in the swarm. The cognitive learning coefficient φ_P and social learning coefficient φ_G and cr_1, cr_2 are two random numbers generated by the uniform distribution within interval $[0, 1]$. The relative sizes of these components determine their contribution to the new particle velocity. It's well known that the standard PSO algorithm could be balanced between global and local minimum because of proper selection the inertial weight parameter. Clerc's suggested [11] how to assure the convergence of the algorithm for the determination of heat transfer coefficients. The aim of analysis is the iteratively estimate the unknown heat transfer coefficients using the PSO procedure which results a negligible difference between temperature measurements taken at the given locations and temperatures computed from the numerical simulation. The numerical simulation temperatures were calculated on the borehole wall using above mentioned thermal response functions. The fitness function RMSE value of each particle at the n^{th} iteration is given by the difference between the measured and calculated temperature curves, at the position X_i^n. The short description of PSO algorithm is given in Figure 7.

3.5 Multilayred borehole heat transfer model

The vertical borehole heat exchanger is directly influenced by the thermal properties of the multi-layered sedimentary rocks and the groundwater movements. Numerical 3D model of multilayered heat transfer model consists of 20 different hydrogeological layers. A detailed description of lithology is provided in the section 2. The heat transfer equation specified by formula 11 for unsaturated or low groundwater flow at the Quaternary sedimentary subsurface

$$C_s(z)\rho_s(z)\frac{\partial T(x,z,\tau)}{\partial \tau} = \frac{\partial}{\partial z}\left(\lambda_s(z)\frac{\partial T(x,z,\tau)}{\partial z}\right) + \frac{\partial}{\partial x}\left(\lambda_s(z)\frac{\partial T(x,z,\tau)}{\partial x}\right) \tag{11}$$

o $T(x, z, \tau)$ temperature in the Quaternary sediments, o $\lambda_s(z)$, $C_s(z)$ - ground thermal conductivity and volumetric heat capacity by z axis. The water saturated

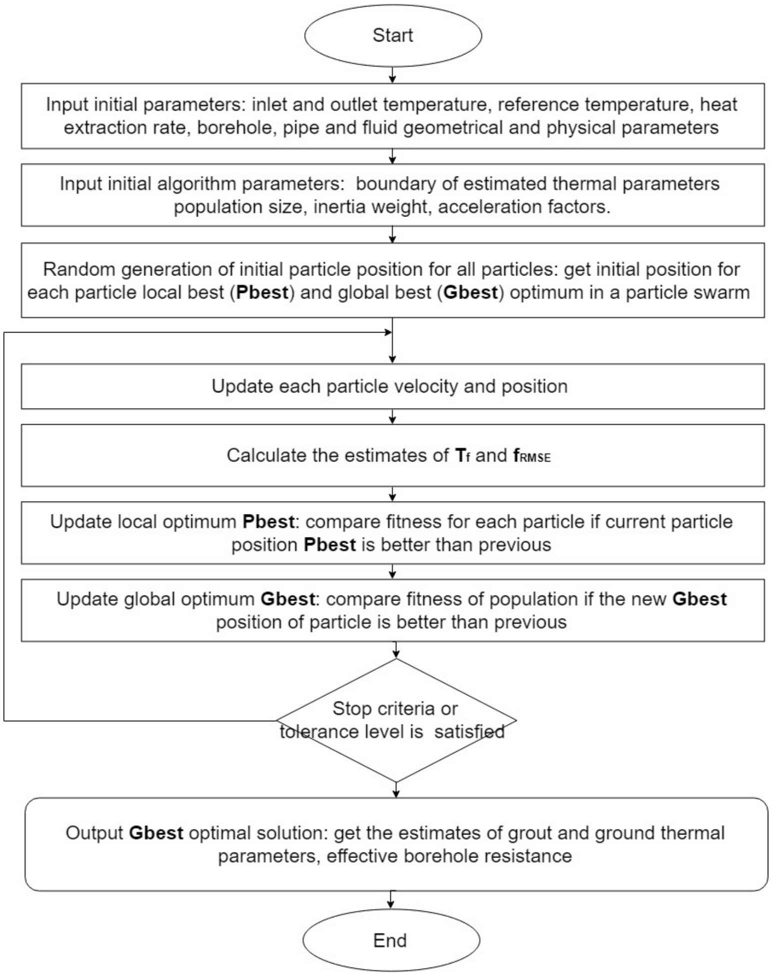


Figure 7 The thermal parameters estimation procedure Indriulionis (2019)[23]

geological layer with groundwater flow are defined by the heat transfer equation 12

$$
\begin{aligned}
C_{sg}(z)(z)\frac{\partial T\left(x,z,\tau\right)}{\partial \tau} + C_w(z)u_w(x)\frac{\partial T(x,z,\tau)}{\partial \tau} &= \frac{\partial}{\partial z}\left(\lambda_{sg}(z)\frac{\partial T(x,z,\tau)}{\partial z}\right) \\
&+ \frac{\partial}{\partial x}\left(\lambda_{sg}(z)\frac{\partial T\left(x,z,\tau\right)}{\partial x}\right)
\end{aligned}
\tag{12}
$$

here the saturated ground thermal parameters are related by formula

$$C_{sg}\left(z\right) = \left(1-\theta\right)C_s\left(z\right) + \theta C_w\left(z\right) \tag{13}$$

and θ, $\lambda_{sg}\left(z\right)$, $C_{sg}\left(z\right)$, $\lambda_w\left(z\right)$ porosity, thermal conductivity, volumetric heat capacity in porious saturated geological layer. Saturated ground with groundwater flow , ground and water are defined by indexes sg, s ir w accordingly. The formula

14 shows the groundwater flow defined by Darcy low

$$u_w = k \cdot i \tag{14}$$

that k hydraulic conductivity and hydraulic gradient i. Here i is defined by equation $i = \frac{dh}{dx}$ as hydraulic head difference by x axis. The temperature at the top of ground is calculated by the difference of the undisturbed temperature and geothermal gradient along z axis. The equation 15 could be find below

$$T_{top}(z,\tau) = T_0 - T_{grad}(z,\tau) \tag{15}$$

here τ time, o T_0 undisturbed ground temperature, $T_{grad}(z,\tau)$ geothermal gradient along z axis. At the moment $\tau = 0$ the temperature in the ground is equal to $T_0 = T_s(z,\tau)$. The temperatures of circulating fluid in the U-pipe are the same before the heat transfer starts in the vertical borehole heat echanger. The extracted heat rate from the Quaternary sediments at the borehole wall $r = r_b$ is specified by Neuman boundary condition:

$$q(z, r_b, \tau) = \frac{T_b(z,\tau) - T_f(z,\tau)}{R_{effb}} \tag{16}$$

here R_{effb} effective borehole thermal resistance, T_b the temperature on borehole wall. The effective borehole thermal resistance could be find after TRT analysis or could be used Hellström's [18] formula 2 as shown above. The mean temperature T_f of circulating fluid in the U-pipe where $z = 0$. The temperature at the top of soil is affected by daily air temperature fluctations

$$\frac{\partial T}{\partial z} = h_{air}(T_{top} - T_{air}) \tag{17}$$

T_{air} air temperature, h_{air} air convection coefficient. The ground layers are related by formula 18

$$\lambda_{sg(j)} \cdot \frac{\partial T}{\partial z}|_{z=z_{j-0}} = \lambda_{sg(j+1)} \cdot \frac{\partial T}{\partial z}|_{z=z_{j+0}}. \tag{18}$$

The energy balance condition should be satisfied by equation 19 during the heat energy extraction from the ground

$$\frac{\triangle Q(\tau)}{C_f v_f} = T_{fin}(\tau) - T_{fout}(\tau) \tag{19}$$

here C_f the volumetric thermal capacity of fluid and v_f fluid flow rate in the U-pipe.

4 Results

4.1 Evaluation of thermal parameters using evolution algorithm

The standard PSO algorithm was applied on TRT data set of single-objective minimization problem in two-dimensional search space because of the ground and grout thermal parameters. The number of optimization problems was equal to the different temperature response functions $G_{ILS}(t)$, $G_{ICS}(t)$, $G_{FLS}(t)$ which were used in the heat transfer simulation. These all benchmark functions incorporating with objective RMSE function were performed in Matlab 2016 programming language. The numerical simulation was performed using these parameters as following: the number of particles $N = 200$, inertia weight $\omega \in (0.2; 1.2)$, ϕ_P, $\phi_G = 2$ are the particle and swarm best weights accordingly. The maximum number of generations and simulation runs were equal to 20. The mean values of surrounding air temperature and heat flux per unit of borehole length were used for the performance of heat transfer simulation. Before data analysis starts the grout and ground thermal conductivity values in the two-dimensional search space could vary in the interval [0;5]. Some practical investigations were done to define the inertia weighting function, particle and swarm weights parameter values in advance. First, Bansal [3] showed an efficiency of linear decreasing inertia weight formula which was used in PSO algorithm. Second, the trial and error method were used to select the particle and swarm weights which give good results but not always the rule of thumb. The authors carried out the linear independency analysis of thermal parameters, U-pipe shank spacing value impact on the effective borehole thermal resistance and calculated errors of thermal parameters under various TRT durations. Before the thermal parameter estimation starts the linear dependency analysis should performed and analysed. The first derivatives of fluid temperature with respect to thermal parameters are defined in order to get the relative sensitivity coefficients (RSC) which are defined in formula 20

$$RSC_i = \frac{\partial T_f(p)}{\partial p} p, \qquad p = [\alpha_s, \lambda_s, \lambda_g] \tag{20}$$

The Matlab 2016a Symbolic toolbox was used to calculate the RSC's. Ozisik (2018) [36] stated that the relatively large value of the determinant $\det|RSC^T RSC|$ assure the linear independence in estimating the thermal parameters. The RSC values for heat transfer models using different G-functions $G_{ILS}(t)$, $G_{ICS}(t)$ and

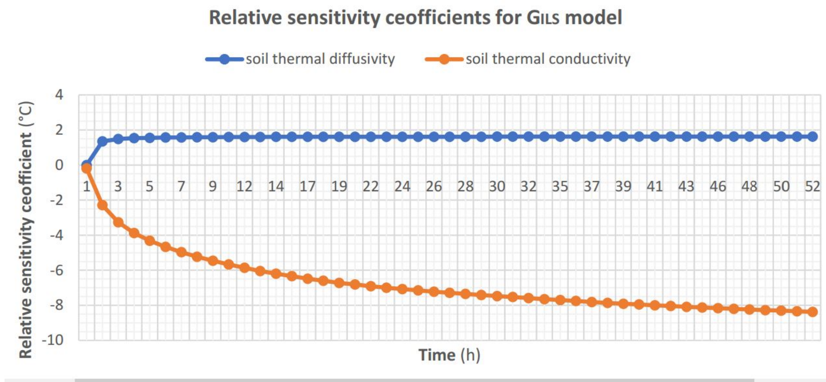
$G_{FLS}(t)$ were calculated and presented in figure 8 following Zhang (2018) [54] publication. The high det$|RSC^T RSC|$ values assures the linear independency between the thermal parameters and the PSO algorithm could be performed selecting they simultaneously (see Figure 9). The exact RSC values of grout thermal conductivity and U-pipe shank spacing are -7.261 and -7.735 accordingly. The TRT reference datasets durations were divided selecting different starting points 1 h, 2 h, 7 h, etc. excluding first 2 hours from analysis. The TRT duration for infinite line source model should be not less than 50 hours and first few hours are excluded from analysis by Gehlin (2002) [15] recommendation. The TRT duration condition $t_b \geq \frac{5r_b^2}{\alpha_g}$ was disclosed by Zhang [54] that directly effects the stability of thermal parameter estimates. The relative errors are less than 3% for the mean value of identified thermal parameters if the TRT duration is not less than 28 hours. The thermal parameters estimates for different TRT starting points and durations are illustrated in figure 10. The analysis was performed to get necessary knowledge about the borehole thermal resistance due to the uncertainty of installed U-pipe location. The U-pipe shank spacing was identified using Hellström's formula [17] in order to propose the suitable L_s value that eliminates the uncertainty of the fluid temperature prediction. The designed U-pipe spacing between centers L_s (0.053 m) value was changed to 0.0688 m that are shown in publication [23]. The relative errors of estimates are compared with Beier [4] and Zhang [54] results in Table 4. It's important to state that the RMSE mean values are close the temperature measurement uncertainty 0.03. The calculated estimates of thermal parameters were presented by Beier [4], Zhang [54] presented the applicability of genetic algorithms despite the high relative errors.

Parameters	Error (%)			Zhang(%)	Beier(%)
	G_{ILS}	G_{ICS}	G_{FLS}		
λ_s	3.7	0.5	0.7	14.4	0.7
λ_g	4.2	11.4	4.9	6.6	
R_b	12	6.9	11.5	10	8.1
RMSE	0.036	0.033	0.033		

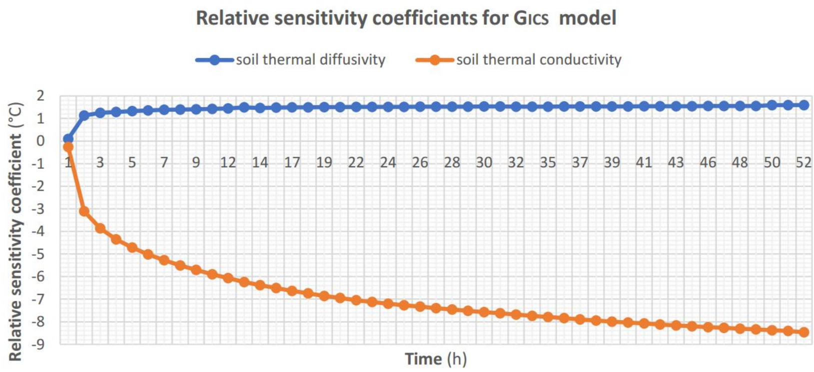
Table 4 Relative errors of identified thermal parameters

4.2 Uncertainty effects on the thermal parameter estimates

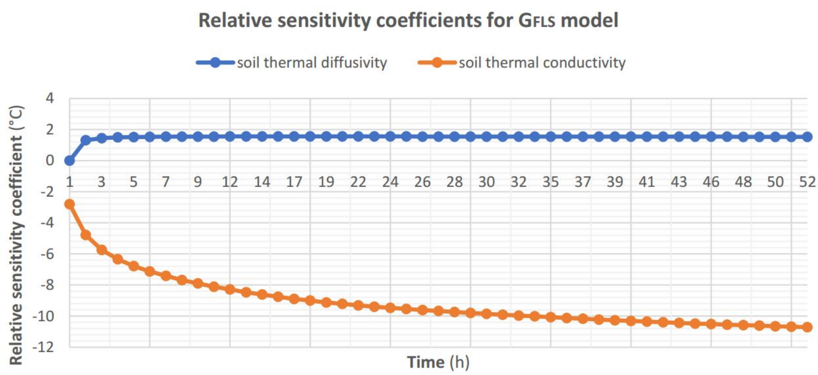
This subsection is dedicated for the analysis of uncertainties with the aim to provide practical implications using the PSO algorithm. It is assumed there is



(a) G_{ILS} function [23]



(b) G_{ICS} function [23]



(c) G_{FLS} function [23]

Figure 8 Relative sensitivity coefficient of thermal parameters [23]

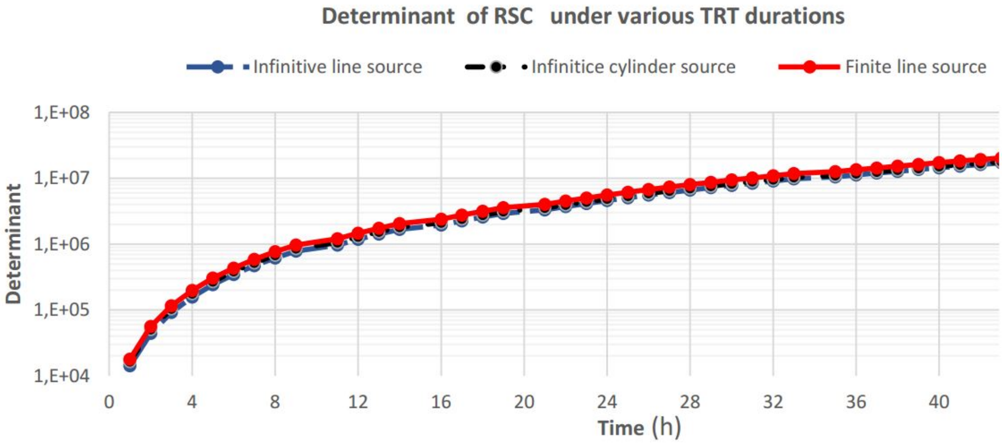


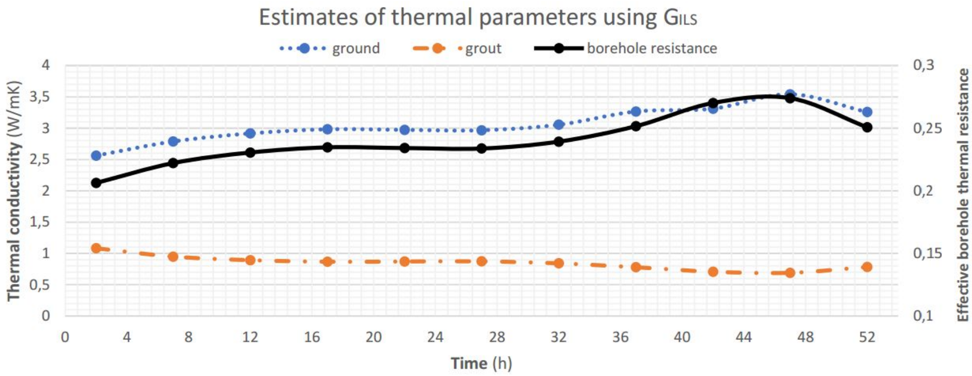
Figure 9 Determinant of relative sensitivity coefficients for G_{ILS}, G_{ICS} and G_{FLS} functions)[23]

no valuable difference in between the relative errors of the thermal parameters for different g-functions. The G_{FLS} 6 was used for the borehole heat transfer process. The results of the analysis clearly shows the asymmetric influence of the uncertainties on the estimates of thermal heat parameters. It should also be emphasized that the analysis was performed by different percentage deviations from the known value of the parameter e.g. -5% and $+5\%$.

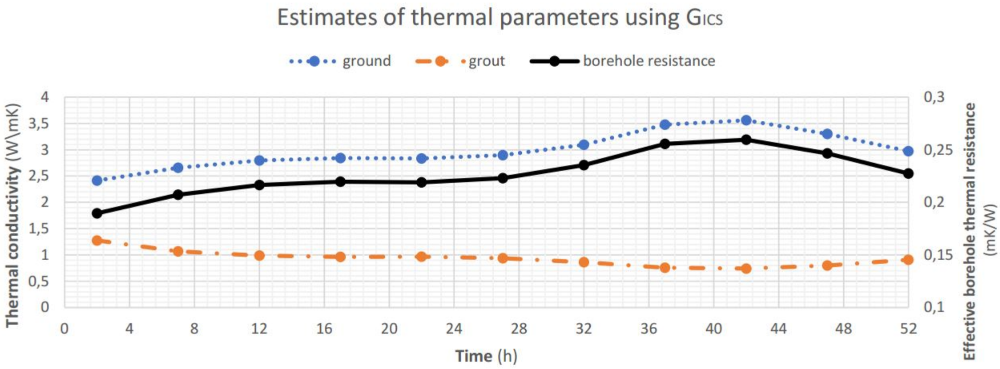
Parameter	$r_{b(+5\%)}$	$r_{b(-5\%)}$	$T_{0(+5\%)}$	$T_{0(-5\%)}$	$q_{(+5\%)}$	$q_{(-5\%)}$
λ_s	4.4%	4.9%	4.8%	5.0%	9.9%	0.2%
λ_g	22.0%	3.7%	33.8%	3.3%	21.1%	4.0%
R_b	28.2%	25.1%	34.0%	18.8%	29.8%	22.7%

Table 5 Relative errors of thermal parameters for G_{FLS} function

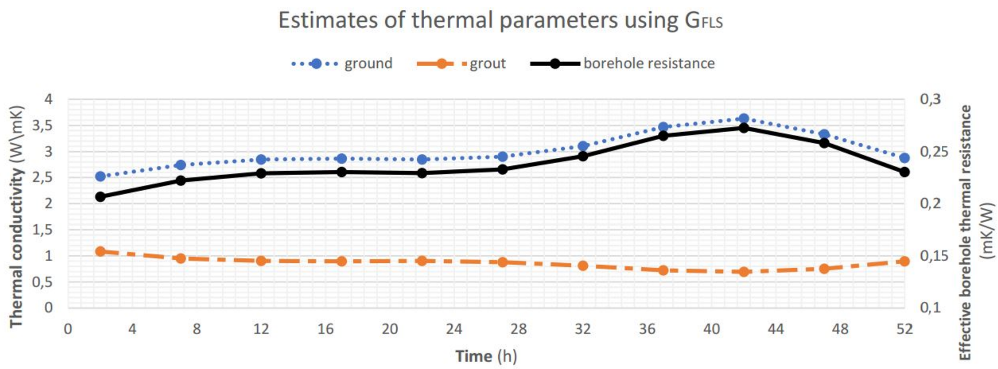
In Table 5 the relative errors of thermal parameters are not affected having the -5% uncertainty value for r_b, T_0, q accordingly. The $+5\%$ uncertainty value has the valuable impact on the estimates of thermal parameters λ_g and R_b. The relative error values of λ_g are more than 6 times greater than for -5% uncertainty value. The more detailed numerical sensitivity analysis should be performed to emphasize the asymmetry effect of the grout thermal conductivity to uncertainty values of TRT experiment parameters.



(a) G_{ILS} function



(b) G_{ICS} function



(c) G_{FLS} function

Figure 10 Estimates of thermal parameters under various TRT durations and starting points [23]

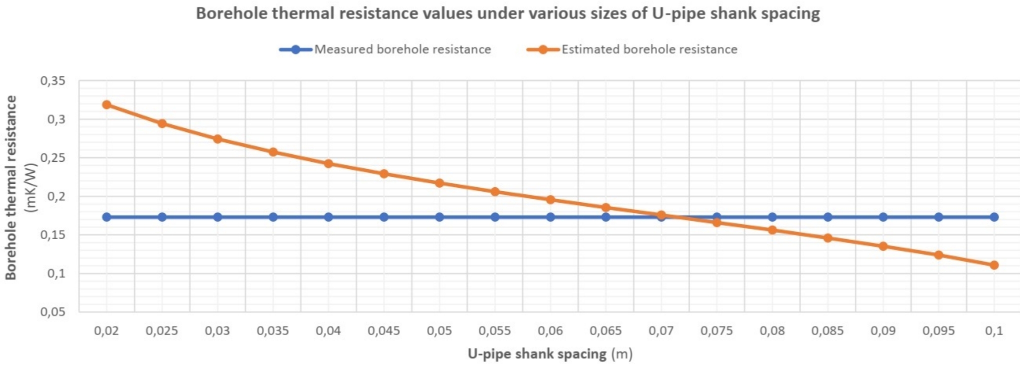


Figure 11 The U-pipe shank spacing value effects on R_b Indriulionis (2019)[23]

4.3 Multilayered heat transfer model validation

Before the multilayered borehole heat transfer analysis starts the numerical model was developed. The quality of cylinder source heat transfer model was presented together with maximum relative errors in publication [22]. The U-pipe geometry was approximated as one pipe by Gu and O'Neal (1998) [16] recommendations. The fluid flow was modeled keeping the heat balance equation 19. This approach is computationally not expensive. The two test cases were performed in order to get the response temperature from ground for 72 and 8670 hours duration. First simulations were made using the in-situ TRT data for single BHE for the BHE array $9x13$ using periodic heat extraction conditions. From TRT test data the effective ground thermal conductivity and borehole thermal resistance values were used for borehole heat transfer analysis. The borehole heat transfer analysis was performed using g-function approach [18], unified and multi-layered ground subsurface conditions with groundwater flow. The temperature response results were compared with the g-function approach which is implemented in Earth Energy Designer program. The difference of the maximum relative errors between g-function and unified solution shows the performance quality of borehole heat transfer model under the unified geological conditions. The practical heating and cooling loads for building was used from Palaitis (2012) [37] technical report. Maximum relative errors of response temperatures are shown in figure 6 for 72 hours and 8670 hours periodic heat extraction case scenarios. The difference of errors is sufficient to perform the following analysis. These estimates are required to determine the temperature response of the multilayer Quaternary sediments with and without groundwater movements changing the values of the estimated

Method	72 hours	8760 h
g-function vs. unified	0.1	0.07
g-function vs.multilayered	0.05	0.08

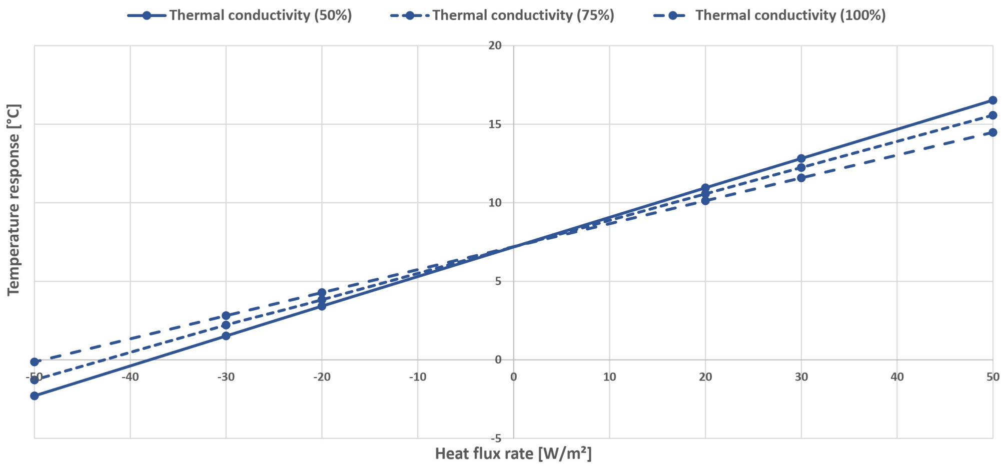
Table 6 Maximum relative errors benchmark

effective ground thermal conductivity 50%, 75%, 100% accordingly. It's known that the ground thermal conductivity value is affected by degree of saturation, dry soil thermal conductivity, active porosity is stated by Ould-Lahoucine (2002) [35]. There wasn't evaluated in the laboratory following parameters: degree of saturation, dry soil thermal conductivity that have the huge impact on the real ground thermal conductivity value. For this reason, three scenarios were selected then the effective thermal conductivity remains the same, reduced to 75% and 50% of initial effective heat conductivity value. In practice, in case of dry rock, moist and saturated rock water, the thermal conductivity values differ from 30% - 50%. In the Figure 12 is shown the temperature response graph between thermal conductivity and heat flux rate due to existence of groundwater flow.

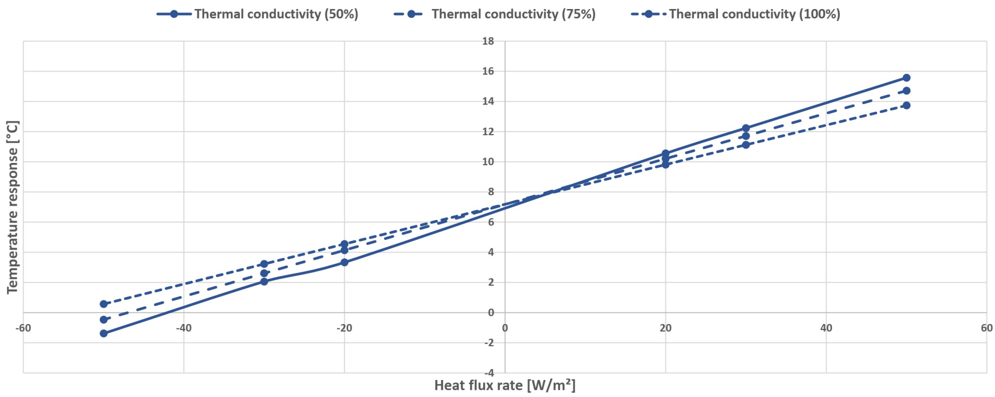
The temperature response at the vertical borehole heat exchanger varies linearly for with groundwater and without groundwater flow. The temperature response percentage changes are presented by the different heat flux rates in the Table 7. These calculations are valuable for geologists engineers that have an aim to properly design the vertical borehole exchangers under specified geological conditions and take into account the temperature response of the medium for extreme heat flux values. The temperature response values enables the engineers to evaluate the costs of ground heat source pump performance for extra discharge 2-3 weeks.

Heat flux rate (W/m^2)	without groundwater flow			with groundwater flow		
	(50% vs 100%)	(75% vs 100%)	Change (%)	(50% vs 100%)	(75% vs 100%)	Change (%)
50	14.1%	7.5%	87.6%	13.4%	7.1%	88.0%
30	10.7%	5.7%	87.5%	10.0%	5.3%	88.3%
20	8.1%	4.3%	87.7%	7.5%	4.0%	88.6%
-20	-20.1%	-10.6%	89.1%	-26.7%	-9.0%	196.2%
-30	-46.0%	-21.2%	117.4%	-36.1%	-19.1%	89.2%
-50	1585.2%	840.6%	88.6%	-344.0%	-181.7%	89.3%

Table 7 Relative error of temperature response



(a) Without groundwater flow



(b) With groundwater flow

Figure 12 Temperature response after 500 hours

5 Conclusions

1. The duration of the TRT experiment should be at least $t_b \geq \frac{5r_b^2}{\alpha_g}$ for determining stable estimates of thermal parameters using particle swarm optimization algorithm and the all G_{ILS}, G_{ICS}, G_{FLS} analytical functions provide the stable estimates of thermal parameters.

2. Particle swarm optimization algorithm provided the smaller relative errors for thermal parameters than genetic algorithm (Zhang, 2018) or standard numerical method (Beier, 2011).

3. The 50% change of thermal conductivity values can decrease about 89% the ground temperature response value.

4. With or without the groundwater movements the mean of temperature response changes are almost the same $93,9\%$ ir 93% after the borehole heat transfer performance.

Thermal response test data

Thermal response test data for multi-layered Quaternary sediments

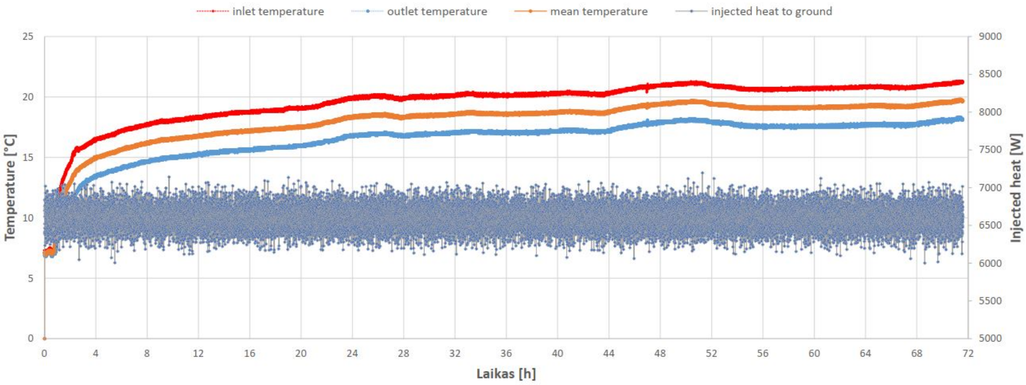


Figure 13 Temperature dynamics of inlet, outlet fluid and injected heat energy

Parameter	Uncertainty value
Fluid flow rate	$\pm 1\%$
Injected heat energy	$\pm 2\%$
Ground and fluid temperature	$\pm 0.03K$

Table 8 Uncertainty values of in-situ multi-layered TRT experiment

Sandbox TRT reference data

Parameter	Uncertainty value
Electric power	$\pm 1\%$
Fluid flow rate	$\pm 0.05\%$
Injected heat energy	$\pm 0.05\%$
Temperature	$\pm 0.03K$
Ground thermal conductivity	$\pm 5\%K$
Grout thermal conductivity	$\pm 5\%K$
Borehole thermal resistance	$\pm 5\%K$

Table 9 Uncertainty values of sandbox TRT experiment

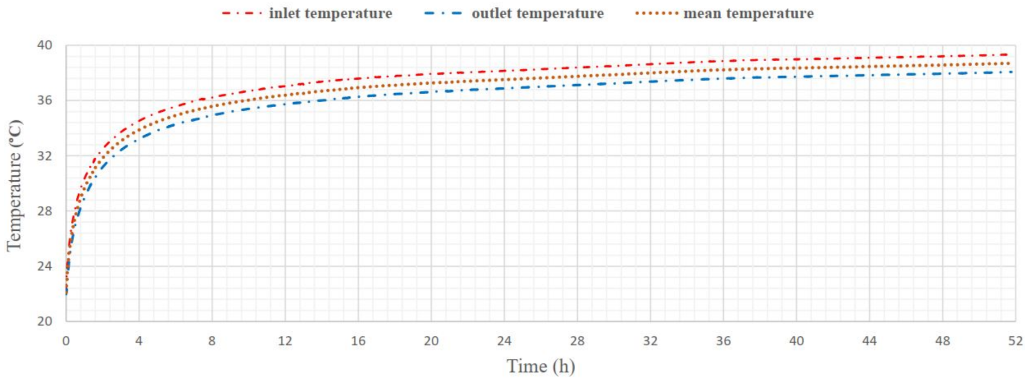


Figure 14 Fluid temperature dynamics

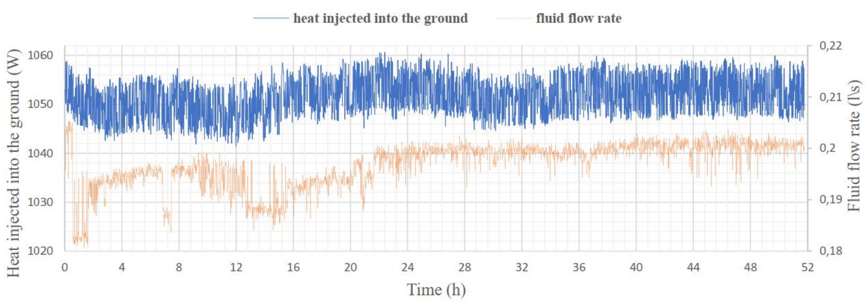


Figure 15 Fluid flow rate and injected heat energy

Matlab code for calculation of relative sensitivity coefficients

```
%Analysis of linearity dependency and relative sensitivity coeficients
% Programmer: Audrius Indriulionis
% Created date: Oct 28, 2017
% Update date: Sep 10,  2018
tic
clearvars all

load  RefSet_TRT52.mat;

start = 1;
ends = 2830;
time = RefDataSet(start(k):ends(k),1)*60; time(1,1)=1;% avoid 0 value
Tf_ref = RefDataSet(start(k):ends(k),2);
T0 = 22;% mean((RefSet(start(k):ends(k),4))) ;
q =  57.7;%mean(RefSet(start(k):ends(k),5));
%%
%syms Tf Rb G_2
syms as ks kb t z x D real
% one hour = 3600 seconds
hr = 3600;
% Euler's number
eu = 0.5772;
% thermal conductivity k, diffusivity a, and initial temperature of the ground
%ground = struct('k',{2.82},'a',{1.47e-6},'T0',{22.0});
ground = struct('ks',{2.82},'as', {1.47e-6},'T0',{22.0});
% radius of borehole rb, depth H
borehole = struct('rb',{6.3e-2},'H',{18.32});
% thermal conductivity k, diffusivity a of the backfilling material
grout = struct('kb',{0.73},'ab',{1.901e-7});              % kb, ab
% thermal conductivity k, diffusivity a, inner radius ri and outer radius ro of the U-pipe
Utube = struct('k',{0.39},...
            'ri',{1.3655e-2},'ro',{1.67e-2});
% definition of the fluid
```

```
fluid = struct('hf',{750});
% definition of the borehole ground heat exchanger
boreGHE = struct('bore',{borehole},'grout',{grout},...
                 'Upipe',{Utube},'D',{6.88e-2});

Rp = 1/(4*pi*Utube.k)*(log(Utube.ro/Utube.ri)+ Utube.k/(fluid.hf*Utube.ri));
s = (boreGHE.bore.rb./(D/2)).^4;sigma = (kb - ks)./(kb + ks);
Rb(kb,ks,D) = 1/(4*pi*kb)*(log(boreGHE.bore.rb/(boreGHE.Upipe.ro))
                  + log(boreGHE.bore.rb/(D)) + sigma*log(s/(s-1))) + Rp;
gamma = 0.577216;

G_1(as,ks,t,z)  = G_syms(boreGHE,1);
Tf = T0 + q*G_1(as,ks,t,z) + q*Rb(kb,ks,D);
assume(Tf,'real')

SenCoefMatrix = [diff(Tf,as),diff(Tf,ks), diff(Tf,kb) diff(Tf,D)];
\color{mgrey}as = ground.as;ks = ground.ks; kb = boreGHE.grout.kb;  D = boreGHE.Ls;
JMatrix = subs(SenCoefMatrix);% substitute the values of thermal parameters

JMatrix_t = subs(JMatrix,t,time); %substitute the values of time
Params = [ ground.as ground.ks boreGHE.grout.kb boreGHE.Ls]';
RSC = [JMatrix_t(:,1)*Params(1) JMatrix_t(:,2)*Params(2)
 JMatrix_t(:,3)*Params(3) JMatrix_t(:,4)*Params(4)];
\color{mgrey}
RSC_params  = [];
detJ_params = [];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for i= start:1:ends/60; %by hours
    detJ_params = [ detJ_params;
(abs(JMatrix_tt(i:60*i,:)*Params)'*abs(JMatrix_tt(i:60*i,:))*Params)];
end
%accumulated sum of detJ_params should be calculated
```

The particle swarm optimization algorithm for ground and grout thermal parameters evaluation

```
%Analysis of linearity dependency and relative sensitivity coeficients
% Programmer: Mahamad Nabab Alam
% Codes in MATLAB for Particle Swarm Optimization
% Programmer: Audrius Indriulionis
% Created date: Oct 28, 2017
% Update date: Sep 10,  2018
tic
clc
clearvars all
close all
rng default
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
global Tf T0 q t boreGHE ground  Rp;
%Load TRT data from sandbox reference set%
load RefSet_TRT52.mat;
%%
% one hour = 3600 seconds
hr = 3600;
% Euler's number
eu = 0.5772;
% thermal conductivity k, diffusivity a, and initial temperature of the ground
ground = struct('k',{2.82},'a', {1.47e-6},'c',{1918000});
% radius of borehole rb, depth H
borehole = struct('rb',{6.3e-2},'H',{18.32});
% thermal conductivity k, diffusivity a of the backfilling material
grout = struct('k',{0.73},'a',{1.92e-7},'c',{3840000});              % kb, ab
% thermal conductivity k, diffusivity a, inner radius ri and outer radius ro of the U-pipe
Utube = struct('k',{0.39},...
              'ri',{1.3655e-2},'ro',{1.67e-2});
% definition of the fluid
fluid = struct('hf',{750});
% definition of the borehole ground heat exchanger
```

```
boreGHE = struct('bore',{borehole},'grout',{grout},...
                'Upipe',{Utube},'D',{6.88e-2});
%%
Rp = 1/(4*pi*Utube.k)*(log(Utube.ro/Utube.ri)+ Utube.k/(fluid.hf*Utube.ri));
s = (boreGHE.bore.rb./(boreGHE.D/2)).^4;
sigma = (boreGHE.grout.k - ground.k)./(boreGHE.grout.k + ground.k);
Rb = 1/(4*pi*boreGHE.grout.k)*(log(boreGHE.bore.rb/(boreGHE.Upipe.ro))
 + log(boreGHE.bore.rb/(boreGHE.D)) + sigma*log(s./(s-1))) + Rp;
%
LB = [0 0]; %lower bounds of variables
UB = [5 5]; %upper bounds of variables
% pso parameters values
m = 2; % number of variables
n = 50; % population size
wmax = 1.2; % inertia weight
wmin = 0.2; % inertia weight
c1 = 2; % acceleration factor
c2 = 2; % acceleration factor
% pso main program----------------------------------------------------start
maxite = 50; % set maximum number of iteration
maxrun = 20; % set maximum number of runs need to be
start = 1; ends = 2830;step = 60;
best_variables = []; statistics =[]; rgbest = [];
for k = start:step:ends

    t = RefDataSet(k:ends,1)*60;
    Tf = RefDataSet(k:ends,2);
    T0 = 22; % undisturbed temperature of the soil
    q = 57.7;% average of heat inhection   rate;
    for run = 1:maxrun
    % pso initialization----------------------------------------------start
     for i = 1:n
        for j = 1:m
            x0(i,j) = round(LB(j)+rand()*(UB(j)-LB(j)));
        end
```

```
end
x = x0; % initial population
v = 0.01*x0; % initial velocity
for i = 1:n
   f0(i,1) = fun(x0(i,:));
end
[fmin0,index0] = min(f0);
pbest = x0; % initial pbest
gbest = x0(index0,:); % initial gbest
% pso initialization----------------------------------------------end

% pso algorithm---------------------------------------------------start
ite = 1;
tolerance = 1;
while ite <= maxite && tolerance > 10^-4
w = wmax-(wmax-wmin)*ite/maxite; % update inertial weight
% pso velocity updates
for i = 1:n
   for j = 1:m
       v(i,j) = w*v(i,j) + c1*rand()*(pbest(i,j)-x(i,j))...
           + c2*rand()*(gbest(1,j) - x(i,j));
   end
end
% pso position update
for i = 1:n
    for j = 1:m
       x(i,j) = x(i,j)+v(i,j);
    end
end
% handling boundary violations
for i = 1:n
   for j = 1:m
       if x(i,j) < LB(j)
           x(i,j) = LB(j);
       elseif x(i,j) > UB(j)
```

```
            x(i,j) = UB(j);
        end
    end
end
% evaluating fitness
for i = 1:n
    f(i,1) = fun(x(i,:));
end
% updating pbest and fitness
for i = 1:n
    if f(i,1) < f0(i,1)
        pbest(i,:) = x(i,:);
        f0(i,1) = f(i,1);
    end
end
[fmin,index] = min(f0); % finding out the best particle
ffmin(ite,run) = fmin; % storing best fitness
ffite(run) = ite; % storing iteration count
% updating gbest and best fitness
if fmin < fmin0
    gbest = pbest(index,:);
    fmin0 = fmin;
end
% calculating tolerance
if ite > 100;
    tolerance = abs(ffmin(ite-100,run)-fmin0);
end
% displaying iterative results
if ite == 1
    disp(sprintf('Iteration Best Particle Objective Fun'));
end
%disp(sprintf('%8g %8g %8.4f',ite,index,fmin0));
    ite = ite + 1;
end
% pso algorithm-----------------------------------------------------end
```

```
    ground.k = gbest(1);      % thermal conductivity of the ground
    boreGHE.grout.k = gbest(2) ;   % thermal conductivity of the grout
    %boreGHE.grout.a = gbest(4)*1e-7; % thermal diffusivity of grout
    %ground.a = gbest(3)*1e-6;      % thermal diffusivity of the ground
    s = (boreGHE.bore.rb./(boreGHE.D/2)).^4;
    sigma = (boreGHE.grout.k -  ground.k)./(boreGHE.grout.k + ground.k);
    Rb = 1/(4*pi*boreGHE.grout.k)*(log(boreGHE.bore.rb/(boreGHE.Upipe.ro))
        + log(boreGHE.bore.rb/(boreGHE.D)) + sigma*log(s/(s-1))) + Rp;%% --- G functic
%%% --- infinite composite-medium line-source model ---
   %G_1 = GfunU1(t,boreGHE,ground);
   %% --- infinite line-source model ---
   % G_2 = G(t,boreGHE,ground,1);
   %% --- finite line-source model ---
    G_5 = G(t,boreGHE,ground,5);
   %% --- infinite cylinder-source model ---
   % G_4 = G(t,boreGHE,ground,4);
   %% --- composite full-scale G function ---
    %G_c = G_1 + G_5' - G_2;
   % Gc =  G(t,boreGHE,ground,5);

    fvalue =  sqrt(mean((Tf - T0 - q.*G_5 - q.*Rb).^2)); %RMSE as the objective function
    fff(run) = fvalue;
    rgbest(run,:) = gbest;
    %disp(sprintf('----------------------------------------'));
   end
%%
   % pso main program------------------------------------------------------end
   disp(sprintf('\n'));
   disp(sprintf('*********************************************************'));
   disp(sprintf('Final Results-----------------------------'));
   [bestofun,bestrun] = min(fff);
   best_variables = [ best_variables; [rgbest(bestrun,:) bestofun round(t(1)/3600)]];
   disp(sprintf('*********************************************************'));
   avg = mean(rgbest);
   stDev = std(rgbest);
```

```
    MinVal = min(rgbest);
    MaxVal = max(rgbest);
    statistics = [statistics ;[avg stDev MinVal MaxVal]];

    toc
end
```

References

[1] ASHRAE (2011). HVAC applications handbook. SI Edition.

[2] Bandos, T. V., Montero, Á., Fernández, E., Santander, J. L. G., Isidro, J. M., Pérez, J., de Córdoba, P. J. F., and Urchueguía, J. F. (2009). Finite line-source model for borehole heat exchangers: effect of vertical temperature variations. Geothermics, 38(2):263–270.

[3] Bansal, J., Singh, P., Saraswat, M., Verma, A., Jadon, S., and Abraham, A. (2011). Inertia weight strategies in particle swarm optimization. In Nature and Biologically Inspired Computing (NaBIC), 2011 Third World Congress on, pages 633–640. IEEE.

[4] Beier, R. A., Smith, M. D., and Spitler, J. D. (2011). Reference data sets for vertical borehole ground heat exchanger models and thermal response test analysis. Geothermics, 40(1):79–85.

[5] Bendoraitis, A., Gregorauskas, M., Klimas, A., and Mališauskas, A. (2007). Vilniaus miesto Sereikiškių, Tupatiškių, Pūčkonių, Pavilnio, Naujosios Vilnios, Mickūnų, Trinapolio, Verkių, Turniškių, Smėlynės, Pečiukų, Virių, Karveliškių ir Nemenčinės vandenviečių sanitarinių apsaugos zonų nustatymo projektas. Technical report, UAB „Vilniaus hidrogeologija“.

[6] Bendoraitis, A., Gregorauskas, M., Klimas, A., and Plankis, M. (2003). Simulation of sanitary protection zones of Vilnius wellfields. Scientific Proceedings of Riga Technical University in Series „Computer Science“ (Boundary Field Problems and Computer Simulation), (2):11–15.

[7] Box, G., J.S.Hunter, and Hunter, W. (2005). Statistics for experimenters: design, innovation and discovery. Hoboken:John Wiley& Sons, 2 edition.

[8] Bozzoli, F., Pagliarini, G., Rainieri, S., and Schiavi, L. (2011). Estimation of soil and grout thermal properties through a TSPEP applied to TRT data. Energy, 36(2):843–846.

[9] Carslaw, H. and Jager, J. C. (1947). Heat conduction in solids. Oxford: Claremore Press ,1’st ed.

[10] Carslaw, H. S. and Jaeger, J. C. (1986). Conduction of Heat in Solids.

[11] Clerc, M. (1999). The swarm and the queen: towards a deterministic and adaptive particle swarm optimization. In Evolutionary Computation, 1999. CEC 99. Proceedings of the 1999 Congress on, volume 3, pages 1951–1957. IEEE.

[12] Erol, S. and Franҫois, B. (2014). Efficiency of various grouting materials for

borehole heat exchangers. Applied Thermal Engineering, 70(788-799).
[13] Eskilson, P. (1987). Thermal analysis of heat extraction boreholes. PhD thesis, Ph.D. thesis, University of Lund, Sweden.
[14] Fujii, H., Okubo, H., Nishi, K., Itoi, R., Ohyama, K., and Shibata, K. (2009). An improved thermal response test for U-bube ground heat exchanger based on optical fiber thermometers. Geothermics, (38):399–409.
[15] Gehlin, S. and Hellström, G. (2003). Influence on thermal response test by groundwater flow in vertical fractures in hard rock. Renewable energy, 28(14):2221–2238.
[16] Gu, Y., O'Neal, and L., D. (1998). Development of an equivalent diameter expression for vertical u-tubes used in ground-coupled heat pumps. ASHRAE transactions, 104:347.
[17] Hellström, G. (1989). Duct ground heat storage model. Manual for Computer Code.
[18] Hellström, G. (1991). Thermal analysis of duct storage system. PhD thesis, Department of Mathematical Physics,University of Lund.
[19] Hemmingway, P. and Long, M. (2012a). Design and development of a low-cost thermal response rig. Proceedings of the Institution of Civil Engineers-Energy, 165(3):137–148.
[20] Hemmingway, P. and Long, M. (2012b). Thermal response testing of compromised borehole heat exchangers. International Journal of Low-Carbon Technologies, 8(3):180–187.
[21] Hooper, F., Lepper, F., et al. (1950). Transient heat flow apparatus for the determination of thermal conductivities. National Emergency Training Center.
[22] Indriulionis, A., Palaitis, Ž., Šinkūnas, P., and Mokrik, R. (2018). Numerical modelling of vertical borehole heat exchangers performance under lithuanian quaternary conditions. BALTICA, 31(2):146—-153.
[23] Indriulionis, A., Palaitis, Ž., Šinkūnas, P., and Mokrik, R. (2019). Estimation of the vertical borehole thermal parameters based on the evolution algorithm using temperature response functions. Estonian Journal of Earth Sciences, 68(1):15–25.
[24] Ingersoll, L. R., Zobel, A. C., and Ingersoll, A. C. (1954). Heat conduction with engineering, geological and other applications. New York: McGaw-Hill.
[25] Javed, S. (2012). Thermal modelling and evaluation of borehole heat transfer. Doctoral thesis, Lund University, Sweden.

[26] Javed, S. and Claesson, J. (2011). New analytical and numerical solutions for the short-term analysis of vertical ground heat exchangers. ASHRAE Transactions, 117(1):3.

[27] Kavanaugh, S. and Rafferty, K. (1997). Ground-Source Heat Pumps: Design of Geothermal Systems for Commercial and Institutional Buildings. American Society of Heatingm Refrigerating and Air-Conditioning Engineers, Inc.

[28] Kennedy, J. and Eberhart, R. (1995). Particle swarm optimization. In Proceedings of IEEE International Conference on Neural Networks IV, pages, volume 1000.

[29] Klein, S. A. and Beckman, W. A. (2007). Trnsys 16: A transient system simulation program: mathematical reference. 5:389–396.

[30] Lamarche, L. and Beauchamp, B. (2007). New solutions for the short-time analysis of geothermal vertical boreholes. International Journal of Heat and Mass Transfer, 50(7):1408 – 1419.

[31] Li, M. and Lai, A. (2012). Parameter estimation of in-situ thermal response tests for borehole ground heat exchangers. Journal of Heat Mass Transfer, (55):2615–2624.

[32] Li, M., Li, P., Chan, V., and Lai, C. (2014). Full-scale temperature response function (g-function) for heat transfer by borehole ground heat exchangers (ghes) from sub-hour to decades. Applied Energy, 136:197 – 205.

[33] Liu, X. and Hellström, G. (2006). Enhancements of an integrated simulation tool for ground-source heat pump system design and energy analysis. In Proceedings of Ecostock 2006. The Richard Stockton College of New Jersey.

[34] Man, Y., Yang, H., and Wang, J. (2010). Study on hybrid ground-coupled heat pump system for air-conditioning in hot-weather areas like hong kong. Applied Energy, 87(9):2826–2833.

[35] Ould-Lahoucine, C., Sakashita, H., and Kumada, T. (2002). Measurement of thermal conductivity of buffer materials and evaluation of existing correlations predicting it. Nuclear Engineering and Design, 216(1-3):1–11.

[36] Ozisik, M. N. (2018). Inverse Heat Transfer: Fundamentals and Applications. Routledge.

[37] Palaitis, Ž. (2012). Ground research in high technology park at mokslininkų str. 6, Vilnius. Technical report, Lithuanian Geological Survey.

[38] Palaitis, Ž. and Indriulionis, A. (2015). Geologinių sluoksnių šilumos charakteristikų tyrimas ir jų naudojimo galimybės Lietuvoje. Geologijos akiračiai,

16(45):16–26.

[39] Park, H., Lee, S., Yoon, S., Shin, H., and Lee, D. (2012). Case study of heat transfer behaviour of helical ground heat exchanger. Energy Buildings, (53):137–144.

[40] P.Hu, Yu, Z., Zhu, N., Lei, F., and Yuan, X. (2013). Performance study of a ground heat exchanger based on the multipole theory heat transfer model. Energy Builings, (65):231–241.

[41] Rainieri, S., Bozzoli, F., and Pagliarini, G. (2011). Modeling approaches applied to the thermal response test: a critical review of the literature. HVAC&R Resolution, 17(6):966–990.

[42] Raymond, J., Therrien, R., L.Gosselin, and Lefebvre, R. (2011). A review of thermal response test analysis using pumping test concepts. Ground Water, 49(6):932–945.

[43] Reuss, M., Beck, M., and Müller, J. (1997). Design of a seasonal thermal energy storage in the ground. Solar Energy, 59(4):247–257.

[44] Roth, P., Georgiev, A., and Barraze, E. (2004). First in situ determination of ground and borehole thermal proeprties in Latin America. Renewable Energy.

[45] Shirazi, A. and Bernier, M. (2014). A small-scale experimental apparatus to study heat transfer in the vicinity of geothermal boreholes. HVAC§R, 20(7):819–827.

[46] Shonder, J. and Beck, J. (2000). Field test of a new method for determining soil formation thermal conductivity and borehole resistance. ASHRAE Transactions, 106(1):643–850.

[47] Spitler, J. D. (2000). GLHEPRO - a design tool for commercial building ground loop heat exchangers. In Proceedings of the fourth international heat pumps in cold climates conference, pages 17–18.

[48] Spitler, J. D., Yavuzturk, C., and Rees, S. J. (2000). In situ measurement of ground thermal properties. volume 1, pages 167–170.

[49] Stankevičiūtė, S. and Guobytė, R. (2012). Vilniaus miesto inžinerinių geologinių duomenų bazės sukūrimas. Technical report, Lietuvos geologijos tarnyba.

[50] Thornton, J., McDowell, P., et al. (1997). Residential vertical geothermal heat pump system models: calibration to data. ASHRAE Transactions, 103:660–674.

[51] Yavuzturk, C. and Spitler, J. D. (1999). A short time step response factor model for vertical ground loop heat exchangers. ASHRAE Trans., 105(2):475–485.

[52] Yu, Y., Ma, Z., and Li, X. (2008). A new integrated system with cooling storage in soil and ground-coupled heat pump. Applied Thermal Engineering, 28(11):1450–1462.

[53] Zeng, H. Y., Diao, N. R., and Fang, Z. H. (2002). A finite line-source model for boreholes in geothermal heat exchangers. Heat Transfer—Asian Research, 31(7):558–567.

[54] Zhang, L., Zhang, L., Chen, J., Wang, J., and Huang, G. (2018). Estimation of soil and grout thermal properties for ground-coupled heat pump systems: Development and application. Applied Thermal Engineering, 143:112–122.

List of publications

1. Palaitis Ž., Indriulionis A., 2015. Geologinių sluoksnių šilumos charakteristikų tyrimas ir jų naudojimo galimybės Lietuvoje. Geologijos akiračiai. Nr.2, 11-15. ISSN 1392-0006.

2. Indriulionis, A., Palaitis, Ž., Šinkūnas, P., Mokrik, R., 2018. Numerical modelling of vertical borehole heat transfer performance under Lithuanian Quaternary conditions. BALTICA, Vol. 31, No. 2, 146–153, https://doi.org/10.5200/baltica.2018.31.14.

3. Indriulionis A., Šinkūnas P., Mokrik R., 2019. Estimation of the vertical borehole thermal parameters based on the evolution algorithm using temperature response functions. Estonian Journal of Earth Sciences, Vol. 68, No. 1, https://doi.org/10.3176/earth.2019.02.

List of Scientific Conferences

1. Palaitis Ž., Indriulionis A., Satkūnas J., Šinkūnas P. 2014. Ground thermal properties evaluation of quaternary section: by example of High-Tech research center, the 9^{th} Baltic Stratigraphic Conference. Vilnius Lithuania.

2. Palaitis Ž., Indriulionis A., Satkūnas J., 2015. The influence of geological conditions for geothermal parameters using TRT data from Alytus city (Lithuania). 6th European Geothermal PhD Day 2015. Delft, The Netherlands.

3. Indriulionis A., Bielskus J. and Vaitkus P. 2016. New radial basis function method modelling borehole heat transfer: a theoretical survey.XXI international master and PhD students conference 'Information Society and University Studies', ISSN 2029-4824.

4. Indriulionis A., Vaitkus P., 2015. Evaluation of ground thermal conductivity parameters 'employing' evolution algorithms. 56th Conference of Lithuanian mathematical society.

Notes

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