sciendo

Civil and Environmental Engineering
Vol. 20, Issue 2, 1055-1064, DOI: 10.2478/cee-2024-0076

ENERGY POTENTIAL OF THE BRATISLAVA NEOGENE

Juraj SLAVKOV[1,*], Dana TOMAJKOVÁ[1], Martin BRČEK[1], Lumír MIČA[2]

[1] Department of Geotechnics, Slovak University of Technology, Bratislava, Slovakia
[2] Institute of Geotechnics, Brno University of Technology, Brno, Czech Republic
[*] corresponding author: juraj.slavkov@stuba.sk

Abstract

The thermal conductivity of materials is characteristic extensively applied across various contemporary domains, ranging from civil engineering to agriculture. The capacity of a material to conduct heat underscores its significance primarily within civil engineering, particularly in energy-related applications. Notably, in the design of energy geostructures, the thermal conductivity of the soil assumes paramount importance. The principle of energy geostructures is to extract geothermal energy, where the base soil works as a heat source. As the thermal conductivity of the ground increases, the amount of extracted energy increases. It can be concluded that the exact determination of the thermal conductivity of the ground has a significant impact on the design of energy geostructures. This article is dedicated to the first detailed measurements of the thermal conductivity of the Bratislava Neogene in five selected localities on samples from depths of 7.1 m to 14.4 m.

Keywords:

Thermal conductivity;
Neogene subsoil;
Geothermal energy;
Energy piles.

1 Introduction

In current construction practices, a significant focus is on structural design that considers sustainability and carbon neutrality. Geotechnical engineering can support sustainable development by applying energy-efficient geotechnical structures in foundations and reusing waste to improve weak soils [1]. Reducing energy consumption and increasing the energy efficiency of apartment building renovations are also necessary [2].

Energy geotechnical structures are load-bearing structures that primarily transfer loads from the upper structure to the subsoil. The secondary purpose of these geotechnical structures is to harness the potential of geothermal energy, thus serving as geothermal heat exchangers. They are suitable for heating and cooling the upper structure, heating water, and thawing, and they serve as underground thermal energy storage. Geothermal energy is considered a renewable and inexhaustible energy source that does not negatively impact the environment. All geotechnical structures can incorporate heat exchangers to become energy geotechnical structures. These structures include energy slabs, piles, walls, and tunnels [3]. Besides energy piles (single piles), energy walls (diaphragm or bored pile walls) and energy bot-tom slabs are now increasingly used [4].

From an energy perspective, input parameters reflecting the properties of the rock environment are necessary for the proper design of these structures. These parameters include thermal conductivity, groundwater flow rate, and subsoil temperature. These input parameters are determined by laboratory or field tests [5]. The most crucial parameter is thermal conductivity, a key parameter characterising the geothermal potential of the subsoil [3].

Thermal conductivity (λ_{Soil}) [W/ (m. K)] is defined as the attribute indicating the amount of heat transmitted perpendicularly through the measured area in a given temperature gradient, thus representing the ability to conduct heat [6]. It depends on the mineral composition, bulk density in the dry state, water content, and grain size.

This attribute is important in the design of energy geotechnical structures as it defines how much heat can be extracted or injected from or into the subsoil, thereby determining the energy output of the geothermal system. A higher thermal conductivity value has a favourable effect and increases the energy output [7]. Thermal performance of energy piles could be improved using response surface methodology. The number of U-tubes, pile diameter, tube diameter, tube thickness, pile thermal conductivity, tube thermal conductivity, soil thermal conductivity, and velocity of circulated water in U-tubes affecting the thermal conductance of the energy piles are investigated to maximize the thermal performance of energy piles [8].

Thermal conductivity is encountered in construction practice during the energy evaluation of building materials. In this case, the lower a building material's thermal conductivity value, the better its insulation [9].

Thermal conductivity also plays a role in agriculture. Its higher value accelerates soil warming during spring months, significantly impacting crop growth and yield during harvest [10].

The thermal conductivity of the rock environment is determined in the field or the laboratory using special measuring instruments. Table 1 provides a comprehensive overview of methods for determining thermal conductivity with specifications. Generally, any method can be used for determining thermal conductivity in rock formations, while selecting methods for soils is more limited. The chosen methods for a particular rock environment influence the accuracy and reliability of the measured values.

Laboratory determination of thermal conductivity exhibits specific differences compared to field methods. Based on our results, measurements published in the past [11], and data from other authors [12], field-measured thermal conductivity values are 10 to 20% higher than those obtained in the laboratory. Deviations can primarily be attributed to the reduced water content of the samples in the laboratory compared to in-situ measurements.

Table 1: Methods for determining thermal conductivity λ_{Soil} [13].

Method	**Applicable to**		**Comment**
	Soil	**Rock**	
Multi-probe method	Yes	Yes	Transient field and laboratory method
Single-probe method (needle-probe)	Yes	Yes	Transient field and laboratory method
Divided-bar method		Yes	Stationary laboratory method
Transient plane source (TPS)	Yes	Yes	Transient laboratory method
Geothermal Response Test in a borehole (TRT)	Yes	Yes	Thermal response test in the field
Theoretical calculation	Yes	Yes	Calculation from rock and soil mineral content, porosity and water content

Table 2 shows the variation in thermal conductivity values of rock samples sourced from diverse regions of the Earth. This is caused by various physical and chemical factors influencing thermal conductivity, which are described below.

Table 2: Thermal conductivity λ_{Rock} of rocks.

Type	**λ_{Rock} [W/(m.K)] (Author´s data)**	**λ_{Rock} [W/(m.K)] (Özkarhraman [14])**	**λ_{Rock} [W/(m.K)] (Incropera [15])**	**λ_{Rock} W/(m.K)] (Rao [16])**	**λ_{Rock} [W/(m.K)] (Zhang [17])**
Andesite	1.68-1.71	0.64	-	2.11-2.87	-
Travertine	2.78	1.60	-	-	-
Sandstone	0.94	-	2.90	1.30-2.90	1.60-2.10
Limestone	1.83-25.8	0.80-2.70	2.15	-	1.26-1.33
Marble	2.68-2.98	-	2.90	-	2.80
Rhyolite	1.41	-	-	2.40-2.51	-

The mineral content in rock, such as quartz, which has a thermal conductivity of 8 W/(m.K), significantly impacts the overall thermal conductivity; therefore, the rock environment's chemical composition must be considered [17].

Granular characteristics representing porosity and particle arrangement significantly influence the thermal conductivity of rocks [18]. The bulk density of the rock is a crucial factor in heat transfer [19]. Reduction in the space between particles increases thermal conductivity [20]. This is because changes in the ratio of voids to solid particles affect the contact quality between particles. For example, the size and orientation of grains in clays and sands are significantly different, which has a pronounced effect on thermal conductivity, dependent on the mutual physical contact between individual grains.

Based on several experimental results, it can be stated that increasing the water content increases thermal conductivity [21], as water flow directly influences heat transfer [22]. Similarly, filling the air gaps in the rock with water creates a water film, which enhances the physical contact between individual grains and thus increases the thermal conductivity of the rock. Increasing the water content in the rock results in a reduction in thermal resistance [5]. Changes in thermal resistance are more significant in clays than sands due to particle size and orientation. Since the physical contact between particles is minimal in sands, even a tiny amount of water can improve it [23].

Temperature is another physical factor determining thermal conductivity, especially in unsaturated rocks. Thermal boundary conditions are an essential element of numerical modelling [24]. Temperature changes affect pore structure, degree of saturation, and heat transfer mechanisms [25]. From the conclusions of several measurements, it can be stated that thermal conductivity increases with increasing temperature [26]. Significant increases in thermal conductivity were observed, particularly at high temperatures during thermal conductivity measurements. Lu and Ren [27] confirmed that the thermal conductivity of a clay sample dramatically increased to two to four times its original value when the temperature rose to 81°C compared to its original temperature of 22°C. Similarly focused studies on thermal conductivity were conducted by Hiraiwa and Kasubuchi [28] and Liu et al. [29]. During measurements of sand in the temperature range from 30 to 70°C, it was observed that thermal conductivity significantly increased at temperatures above 50°C due to increased latent heat transfer in the rock [30].

Our research aimed to determine the thermal conductivity of Bratislava Neogene sediments and to investigate the dependence of thermal conductivity on temperature and water content. In the future, research will also focus on the energy potential of quaternary gravelly sediments.

2 Material

All samples originate from Bratislava and its surroundings. The locality is a geotectonic unit mainly formed by Neogene and Quaternary soils [31]. The measurements were carried out on samples from the Neogene formations found in Račianska (sample BA- NEO 1), and Tomášikova (sample BA-NEO 2), Mickiewiczova (sample BA- NEO 3) streets in Bratislava. Other measured locations were Bory (sample BA- NEO 4) and Triblavina (sample BA- NEO 5). The locations of the samples are presented in Figure 1. The choice of sample locations is made in areas where energy geotechnical constructions may be implemented shortly.

The Neogene (younger Tertiary - Miocene, Pliocene) substratum of Bratislava consists of rocks from two distinct lithostratigraphic units - the Vienna Basin and the Danube Basin, separated by the Little Carpathians Mountain range (Fig. 1). The uppermost layers of the Neogene sequence are represented by the Pannonian deposits, characterised by a lithological succession of colourful clays (most commonly green, blue, and grey), various sandy, calcareous clays, or silty clays with subordinate layers of sands and fine-grained gravels. As a result of weathering processes, the uppermost levels of clays are coloured brown, yellow-brown, and rust-brown.

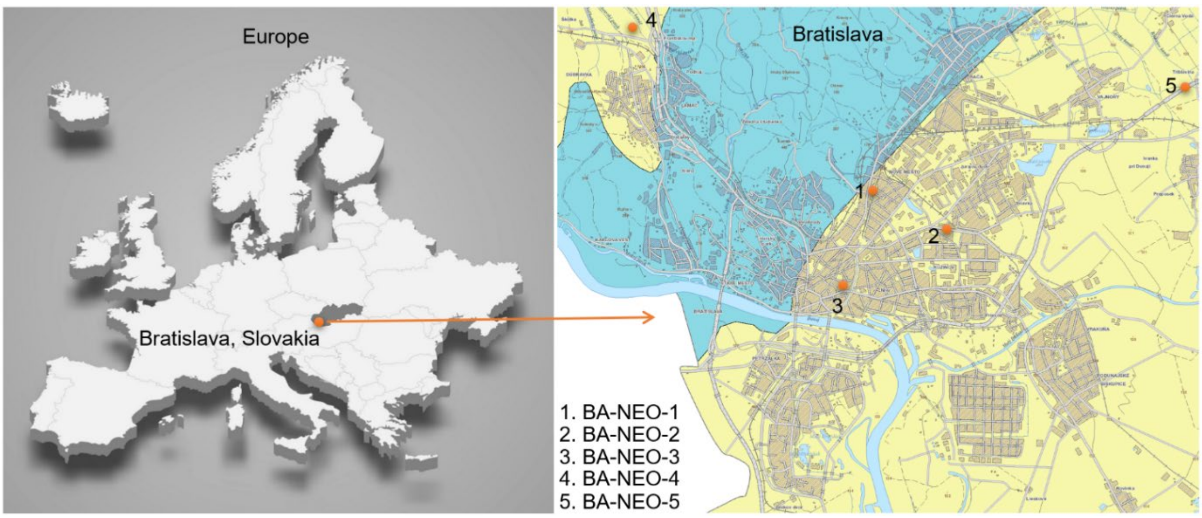

Fig 1: Location and Section from the map of the Regional Geological Division of the Slovak Republic scale 1: 500 000. Where: Blue colour: Little Carpathians; Yellow colour (northwest part): Vienna basin; Yellow colour (south-eastern part): Danube basin [32].

The samples were chosen from depths of 7 meters or more below ground level. This choice was made because standard high-rise buildings are typically designed with at least two underground floors. This depth is also significant because, beyond it, there are no significant temperature changes in the substrate due to seasonal variations. Thus, these changes will not adversely affect the thermal conductivity values throughout the year.

The selected samples come from depths ranging from 7.10 to 14.40 meters. Based on the grain size classification provided in Table3, the material could be classified as fine-grained soil with low and medium plasticity and course-grained soils (sand and gravel).

Table 3: Material classification.

Soil	Water content [%]	Depth [m]	Classification	
BA-NEO-1	16.9	12	CI	Inorganic clays of medium plasticity
	12.15	13.4	CI	Inorganic clays of medium plasticity
	13.79	14.4	CI	Inorganic clays of medium plasticity
BA-NEO-2	21.6	12.7	CL	Inorganic clays of low plasticity
	22.23	13.5	CH	Inorganic clays of high plasticity
	17.97	13.8	CL	Inorganic clays of low plasticity
BA-NEO-3	24.59	13.4	MS	Silty sands
BA-NEO-4	7.39	11.3	GC	Clayey gravels
BA-NEO-5	25.71	7.1	CH	Inorganic clays of high plasticity
	21.85	8.6	SC	Sandy clay
	24.96	10.9	MI	Inorganic silts

3 Methodology

The measurements aimed to determine the thermal conductivity in the given location while maintaining temperature and water content. Further measurements focused on monitoring the change in thermal conductivity due to variations in the water content and temperature of the measured sample.

The portable device Isomet 2104 was chosen (Fig. 2) to determine the thermal conductivity of selected samples in the laboratory (Tab. 1). The device is based on the transient plane source (TPS) method, which involves sending thermal flux pulses into the sample. It is a dynamic method that significantly reduces the measurement time compared to other measurement methods.

In addition to thermal conductivity (λ) [W/(m.K)], the device also measures the thermal diffusivity (α_d) [m²/s], specific heat capacity (c) [J/m³.K], and average sample temperature (T_M) [°C].

The measurement accuracy is highly sensitive to contact with the measured surface; hence, it is suitable for measuring rock formations and fine-grained soils with a levelled testing surface. According to the manufacturer's recommendation, the measured surface should have a diameter of at least 60 mm. The required thickness of the sample varies from 20 to 40 mm, depending on the type of measured sample.

Since the instrument technology is susceptible to the alignment of the measured surface, great emphasis was placed on ensuring alignment to avoid distortion of the measured values. The diameter and height of the sample complied with the manufacturer's recommendations (Fig. 2).

Fig. 2: Isomet 2104 device with surface probe and specimen of Neogene clay.

4. Results

240 individual measurements of the Bratislava Neogene thermal conductivity were conducted. The measured thermal conductivity ranged from 2.02 to 3.69 W/(m.K). Compared to Andujar Marquez et al. [33], which reports thermal conductivity values for fine-grained soils from Huelva, Spain, around 2.30 W/(m.K), these values are above average. Differences in the measured values compared to the literature are caused by factors that generally influence thermal conductivity, such as mineral composition, water content, and bulk density (Tab. 2). Values of thermal conductivity in the Bratislava region compared to the literature were also observed in previous measurements of thermal conductivity conducted in the framework of the previous series of measurements [11].

Fig. 3 depicts a graph illustrating the substrate's thermal conductivity values according to individual regions. The thermal conductivity values (Tab. 4) within a single geological area are approximately uniform, with a range of 2.02-2.99 (W/m.K). Except for the BA-NEO-5 location, it can be stated that the thermal conductivity within the Bratislava region did not significantly change. From this, it can be inferred that the chemical and physical properties of the soils exhibit similarity for each region. The differences in the measured values in the BA-NEO-5 area are due to the area being at the interface of two geological basin units (Gabčíkovo and Trnava-Dubnica basins units) with different origins.

Table 4: Statistic values for thermal conductivity values of the subsoil according to locality.

Variable	Sample	N	Mean	SE Mean	StDev	Variance	Minimum	Median	Maximum
λ	BA-NEO-1	58	2.7250	0.0194	0.1478	0.0219	2.3800	2.7600	2,9900
	BA-NEO-2	60	2.4117	0.0174	0.1349	0.0182	2.1000	2.3950	2,6500
	BA-NEO-3	20	2.8575	0.0200	0.0895	0.0080	2.6900	2.8900	2,9600
	BA-NEO-4	20	2.3180	0.0362	0.1620	0.0262	2.0600	2.3150	2,5700
	BA-NEO-5	60	2.5757	0.0582	0.4507	0.2031	2.0200	2.3500	3,6900

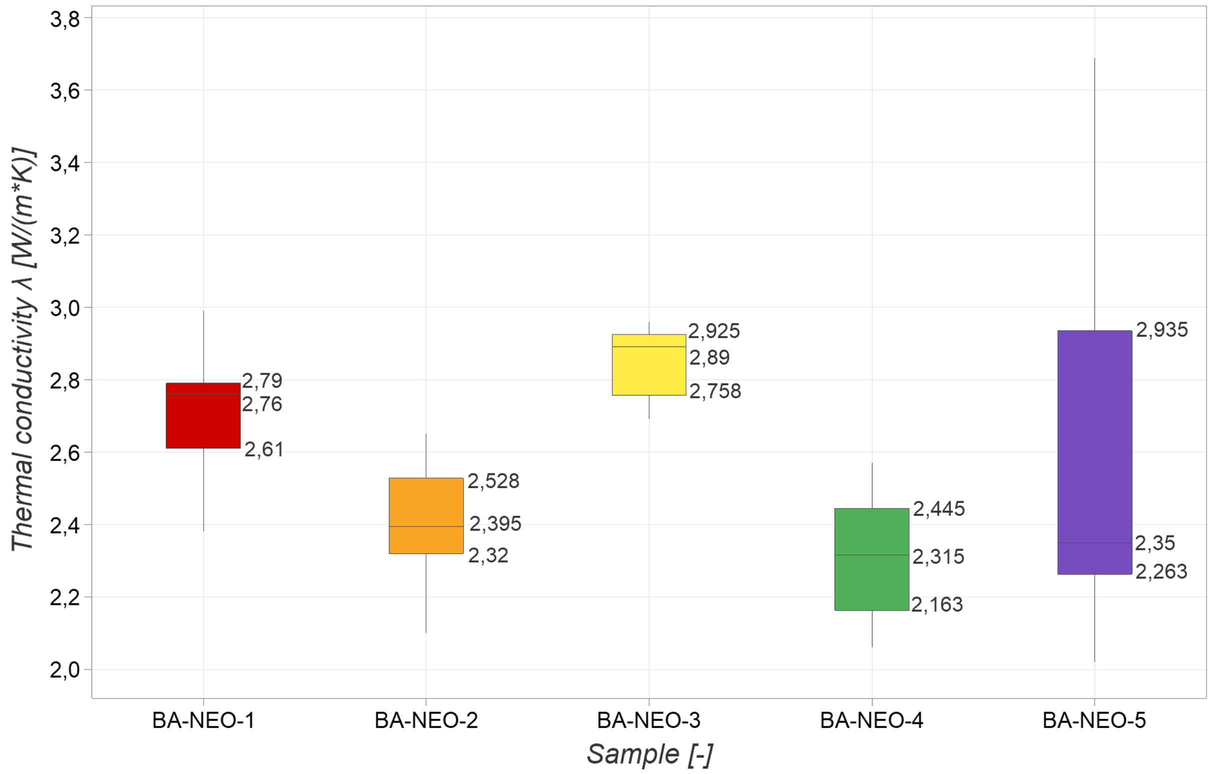

Fig. 3: Thermal conductivity of the subsoil according to locality.

Fig. 4 illustrates the values of thermal conductivity for individual soil types. The graph shows that the thermal conductivity value is approximately the same even when the values (Tab. 5) are classified based on grain size classification, regardless of the location. Fine-grained soils exhibited a roughly consistent thermal conductivity value throughout the area, ranging from 2.02 to 3.69 (W/m.K). Conversely, coarse-grained soils showed a more comprehensive range of measured values, spanning 2.06-2.96 (W/m.K).

Table 5: Statistic values for the subsoil's thermal conductivity values according to soil type.

Variable	N	Mean	SE Mean	StDev	Variance	Minimum	Median	Maximum
GC	20	2.3180	0.0362	0.1620	0.0262	2.0600	2.3150	2.5700
SC	20	3.1210	0.0779	0.3486	0.1215	2.6800	3.0500	3.6900
MS	20	2.8575	0.0200	0.0895	0.0080	2.6900	2.8900	2.9600
MI	20	2.3000	0.0428	0.1912	0.0366	2.0200	2.2500	2.6200
CI	98	2.5994	0.0215	0.2129	0.0453	2.1000	2.6100	2.9900
CL	40	2.3532	0.0141	0.0892	0.0080	2.1900	2.3300	2.5300

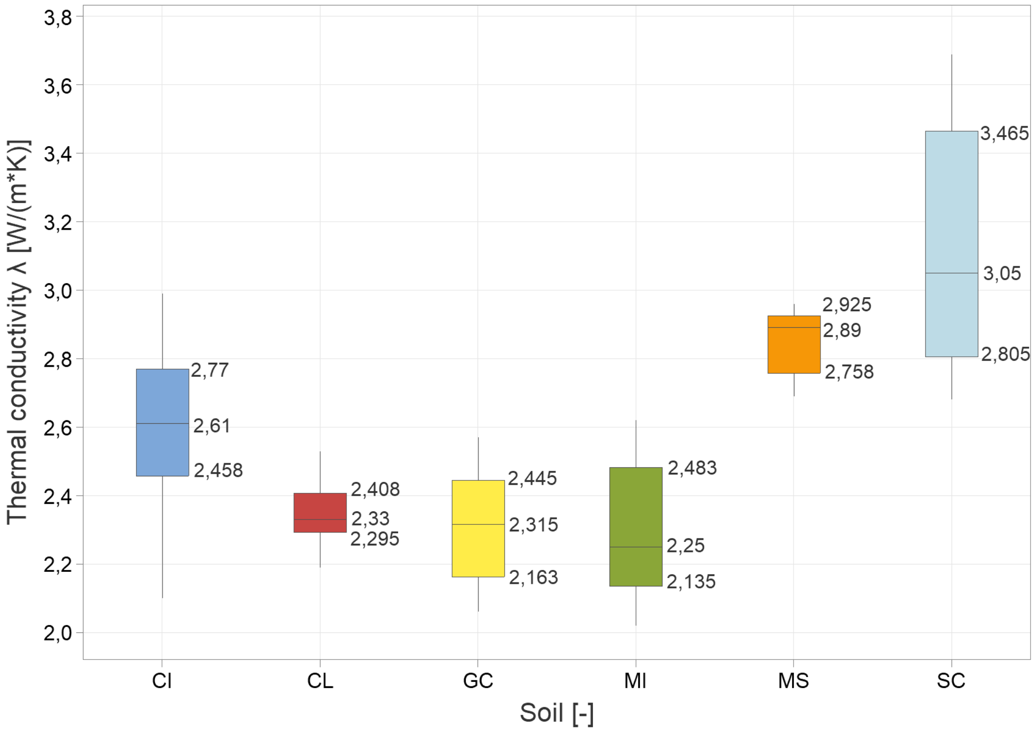

Fig. 4: Thermal conductivity according to soil type.

Experimental measurements aimed at determining the dependency of thermal conductivity on sample temperature were conducted on a sample of class CL (inorganic clays of low plasticity) from a BA-NEO-3 location at a depth of 13.80 m. In general, thermal conductivity increases with rising temperature. These temperature changes are not significant up to 30°C [26]. Our measurements confirmed these previous conclusions, even though compared to the Hiraiwa et al. [28], the thermal conductivity of the Bratislava Neogene sample increased more significantly (Fig. 5). The difference in the measured values of thermal conductivity at minimum and maximum temperatures (in the range from 20 to 30 °C) was 0.06 W/(m.K). This difference has a negligible impact on the operation of energy geotechnical structures.

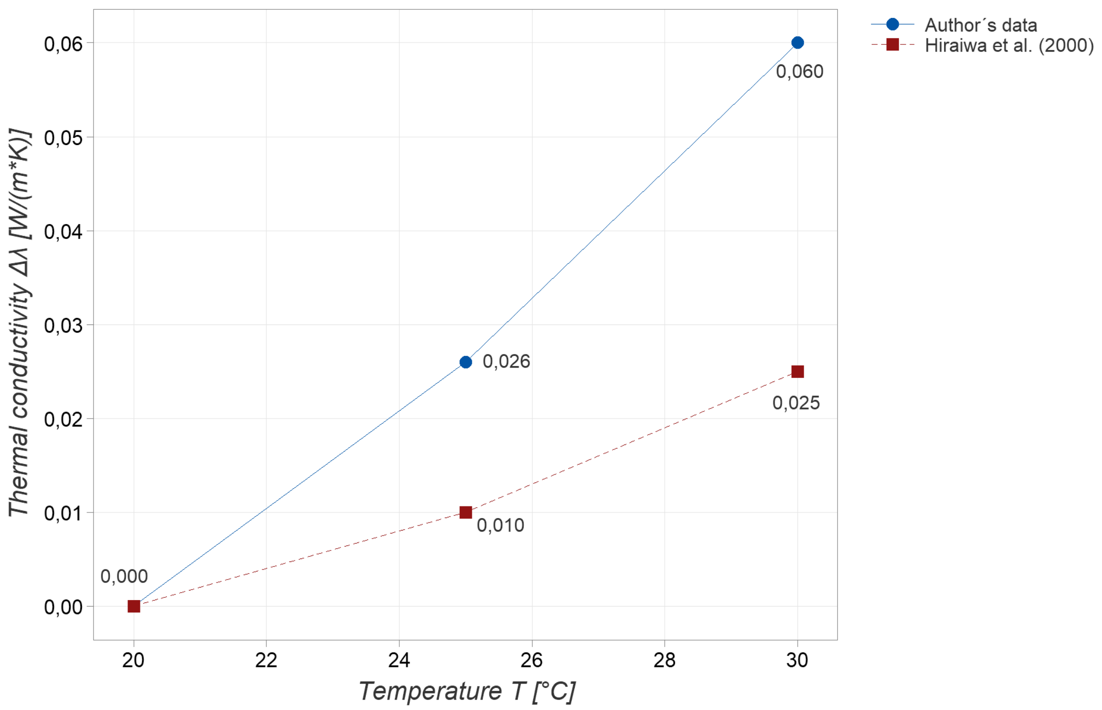

Fig. 5: Changes in thermal conductivity values depending on temperature.

The third series of measurements aimed to determine the relationship between thermal conductivity and water content. These measurements were carried out on a poorly graded sand sample from the location BA-NEO-2, taken from a depth of 7.20 m. The experiment involved testing a reconstituted sample with a gradual increase in water content while keeping the volume weight and sample temperature constant during repeated measurements. The results indicated a significant impact of water content on the sample's thermal conductivity (refer to Fig. 6). The red line in Fig. 6 represents the predicted thermal conductivity for water content values up to 25%, while the blue dashed lines show the 95% prediction range. The R-value is 0.7213. The average thermal conductivity of the dry soil at a water content of 0.26% was found to be 0.50 W/(m·K). As the water content increased to 22%, the thermal conductivity rose to 3.72 W/(m·K). Similar conclusions regarding the influence of water content on sand thermal conductivity were made by Chen [21], Zhang et al. [23], and Smits et al. [34]. The fitted line prediction plot for the quadratic model is described by equation (1).

$$y = 0{,}4087 + 0{,}1944 * x - 0{,}004706 * x^2 \quad (1)$$

Where:
y – is the thermal conductivity of the sample,
x – is the water content of the sample.

This suggests that the loss of water content from the sample during its transportation or storage could significantly impact the resulting value of thermal conductivity in the laboratory. This is also one of the reasons why in-situ thermal conductivity measurements are considered more reliable.

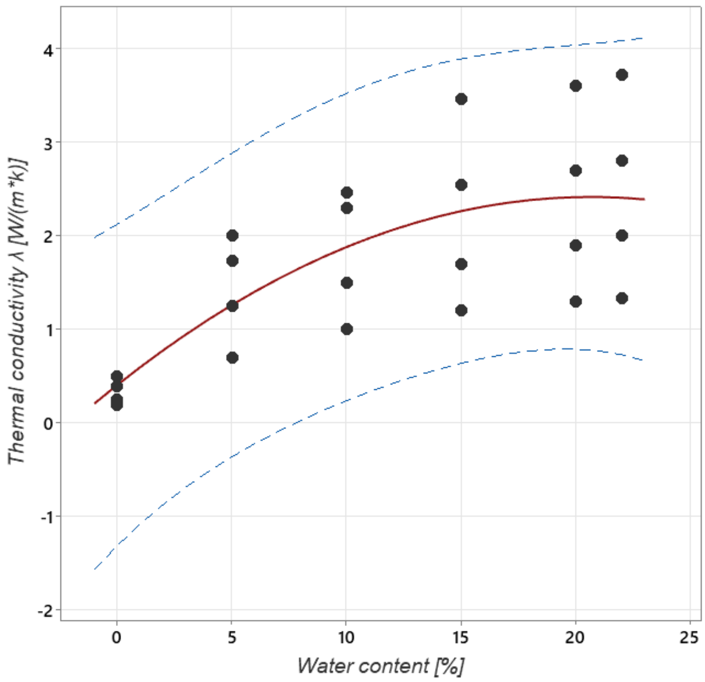

Fig. 6: Relation between thermal conductivity and water content.

5 Conclusion

In construction practice, the design of geotechnical structures concerning renewability and carbon neutrality is emphasised. With energy piles, we can reduce the consumption of CO2 emissions by 25-36% [33]. For the design of energy geostructures, the actual value of thermal conductivity is crucial as it determines the area's energy potential. Measurements have revealed that the nominal values [12] of thermal conductivity are more than 20% lower than measurements on Bratislava samples. Since a higher thermal conductivity value has a favourable impact on performance, it can be concluded that measurements in the construction area are more accurate than presumed values, which do not consider the actual water content and temperature of the sample.

Based on laboratory measurements on the Bratislava Neogene samples, the thermal conductivity values within a single geological area are approximately uniform, with a measured range of 2.02-2.99 (W/m.K). Fine-grained soils exhibited a roughly consistent thermal conductivity value throughout the area, ranging from 2.02 to 3.69 (W/m.K). Conversely, coarse-grained soils showed a more comprehensive range of measured values, spanning 2.06-2.96 (W/m.K).

Laboratory measurements have confirmed that the thermal conductivity increases with rising water content and temperature. At a water content of 0.26%, the average thermal conductivity of the rock was 0.50 W/(m.K). After increasing the water content to 22%, the thermal conductivity increased to 3.72 W/(m.K). The difference in the measured thermal conductivity values at the minimum and maximum temperatures (in the range from 20 to 30 °C) was 0.06 W/(m.K). The corelation between the thermal conductivity and water content was established for the range of occurring moisture in Bratislava Neogene. The conclusion drawn from the measurements is that the influence of water content on thermal conductivity is significant, while the influence of temperature within the measured range is less important.

Acknowledgement

The article was created with the support of the VEGA 1/0745/21 project of the scientific grant agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic and the Slovak Academy of Sciences, with the support of the Young Researcher grant 1611, and with the support of the Institute of Geotechnics, Faculty of Civil Engineering, Brno University of Technology.

References

[1] KADHIM, F. J. - ABED, M. S. - ALMUSAWI, J. K.: Feasibility of strengthening sandy soils using industry waste as geo-fiber, Civil and Environmental Engineering, Vol. 19, Issue 2, 649-661, DOI: 10.2478/cee-2023-0059.

[2] RÚHIG, R. - RÚHIGOVÁ, E.: Effect of glazed loggias on the energy efficiency of a T08b prefabricated dwelling – a case study, Slovak Journal of Civil Engineering, Vol. 29, 2021, No. 3, 41 – 50, DOI: 10.2478/sjce-2021-0020.

[3] LALOUI, L. - ROTTA LORIA, A. F.: Analysis and Design of Energy Geostructures. Academic Press, 2020, 1096 p., ISBN 978-0-12-820623-2.

[4] ADAM, D. - BRUNNER, A. - MARKIEWICZ, R. - PISTROL, J.: Long-term experience of the thermo-active ground source system at the metro station Taborstrasse in Vienna, Acta Polytechnica CTU Proceedings, Volume 45, 2023, 13 p.

[5] HOSEINIMIGHANI, H. - SZENDEFY, J.: Comparison of different methods for measuring thermal properties of soil: review on laboratory, in-situ and numerical modelling methods, Energy, 2021, Volume 27, 31 p.

[6] DURMEKOVÁ, T. - WAGNER, P. - FRANKOVSKÁ, J.: Properties of rocks and their determination in the laboratory. 1. Rocks. Comenius University in Bratislava (Vlastnosti hornín a ich stanovenie v laboratóriu. 1. Skalné horniny. Univerzita Komenského v Bratislave), 2013, 173 p., ISBN 978-80-223-3330-6.

[7] SIA D 0190: Use of geothermal energy with foundation piles and other concrete components in contact with the earth - Guide to planning, construction and operation, SIA Zurich. (Nutzung der Erdwärme mit Fundationspfählen und anderen erdberührenden Betonbauteilen - Leitfaden zu Planung, Bau und Betrieb, SIA Zurich.), 2005, 101 p.

[8] HARIDY, S. - ALNAGBI, K. - RADWAN, A. - ARAB, G. M.: Optimizing the thermal performance of energy piles using response surface methodology, Case Studies in Thermal Engineering, 2023, Volume 41, 102637.

[9] STN 73 0540-2+Z1+Z2: Thermal protection of buildings. Thermal technical properties of construction structures and buildings. Part 2: Functional requirements. Consolidated wording. (Tepelná ochrana budov. Tepelnotechnické vlastnosti stavebných konštrukcií a budov. Časť 2: Funkčné požiadavky. Konsolidované znenie.), 2019, 36 p.

[10] HANSEN, S. - JENSEN, H. E. - NIELSEN, N. E. - SVENDSEN, H.: Simulation of nitrogen dynamics and biomass production in winter wheat using the Danish simulation model DAISY, Fertilizer Research, 1991, Volume 27, pp. 245-259.

[11] SLAVKOV, J.: Thermal conductivity of soil in different climatic conditions. (Tepelná vodivosť horninového prostredia v rôznych klimatických podmienkach), Proceedings of the 15th Slovak Geotechnical Conference, Spektrum STU, 2023, pp. 370-378.

[12] BOUAZZA, A. - MANESSERO, M. - WANG, B. - DOMINIJANNI, A. - SINGH, R. M. - FORTI, S. - CEVRO, S. - MUSSO, G.: Soil effective thermal conductivity from energy pile thermal tests, Coupled Phenomena in Environmental Geotechnics: Proceedings of the International Symposium, Torino, Italy, 1–3 July 2013, Taylor & Francis, London, pp. 211–219.

[13] prEN 1997-2: Eurocode 7. Part 2. Geotechnical design - Ground properties, 2022, 148 p.

[14] ÖZKAHRAMAN, H. T. - SELVER, R. - IŞIK, E. C.: Determination of Thermal Conductivity of rock from P-wave velocity, International Journal of Rock Mechanics and Mining Sciences, 2004, Volume 41, pp. 703-708.

[15] INCROPERA, F. P. - DEWITT, D. P.: Fundamentals of Heat and Mass Transfer, 3rd Edition, Wiley, 1990, 992 pages.

[16] RAO, S. - HU, S. - ZHU, C. - TANG, X. - LI, W. - WANG, J.: The characteristics of heat flow and lithospheric thermal structure in Junggar Basin, northwest China, Chinese Journal of Geophysics, 2013, Volume 56, pp. 2760-2770.

[17] ZHANG, N. - WANG, Z.: Review of soil thermal conductivity and predictive models, International Journal of Thermal Sciences, 2017, Volume 117, pp. 172-183.

[18] TOAN, C. - KUMAR, S. - VAHEDIFARD, F. - AMIRLATIFI, A.: General Thermal Conductivity Function for Unsaturated Soils Considering Effects of Water Content, Temperature, and Confining Pressure, Journal of Geotechnical and Geoenvironmental Engineering, 2021, Volume 147, 18 p.

[19] BRANDON, T. L. - MITCHELL, J. K.: Factors influencing thermal resistivity of sands, Journal Geotechnical Engineering, 1989, Volume 115, No 12, pp. 1683–1698.

[20]YUN, T. S. - SANTAMARINA, J. C.: Fundamental study of thermal conduction in dry soils, Granular Matter, 2008, Volume 10, pp. 197-207.
[21]CHEN, S. X.: Thermal conductivity of sands, Heat Mass Transfer, 2008, Volume 44, pp. 1241–1246.
[22]VARGAS, W. L. - MCCARTHY, J. J.: Heat conduction in granular materials, American Institute of Chemical Engineers Journal, 2001, Volume 47, pp. 1052–1059.
[23]ZHANG, T. - CAI, G. - LIU, S. - PUPPALA, A. J.: Investigation on thermal characteristics and prediction models of soils, International Journal of Heat Mass Transfer, 2017, Volume 106, pp.1074–1086.
[24]MOHYLA, M. - HRUBESOVA, E. - MARTINKAUPPI, B. - MÄKIRANTA, A. - TUOMI, V.: Numerical simulation of the thermal response of seabed sediments to geothermal cycles in Suvilahti, Finland, Renewable Energy, 221, 119770, 2024.
[25]JOHANSEN, O.: Thermal conductivity of soils, Ph.D. dissertation, Defense Technical Information Center, Norwegian University of Science and Technology, 1977, 322 p.
[26]XU, Y. - SUN, D. - ZENG, Z. - LV, H.: Effect of temperature on thermal conductivity of lateritic clays over a wide temperature range, International Journal of Heat and Mass Transfer, 2019, Volume 138, pp. 562-570, ISSN 0017-9310.
[27]LU, S. - REN, T.: Model for predicting soil thermal conductivity at various temperatures, Nongye Gongcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering, 2009, Volume 25, pp. 13-18.
[28]HIRAIWA, Y. - KASUBUCHI, T.: Temperature dependence of soil thermal conductivity over a wide range of temperature (5–75°C), European Journal of Soil Science, 2000, Volume 51, pp. 211–218.
[29]LIU, C. H. - ZHOU, D. - WU, H.: Measurement and prediction of temperature effects of thermal conductivity of soils, Yantu Gongcheng Xuebao/Chinese Journal of Geotechnical Engineering, 2011, Volume 33, pp. 1877–1886.
[30]SMITS, K. M. - SAKAKI, T. - HOWINGTON, S. E. - PETERS, J. F. - ILLANGASEKARE, T. H.: Temperature dependence of thermal properties of sands across a wide range of temperatures (30–70 °C), Vadose Zone Journal, 2013, Volume 12, pp. 2256–2265.
[31]KUČOVÁ, E. - FRANKOVSKÁ, J.: The angle of the shear resistance of Danube gravel derived from the dynamic penetration test, Slovak Journal of Civil Engineering, 2023, 31. pp. 38-46.
[32]VASS, D. - BEGAN, A. - GROSS, P. - KAHAN, Š. - KÖHLER, E. - KRYSTEK, I. - LEXA, J. - NEMČOK, J.: Regional geological division of the Western Carpathians and the northern reaches of the Pannonian Basin on the territory of the Czechoslovak Socialist Republic (M 1:500 000), Geologický ústav Dionýza Štúra, Bratislava, 1988.
[33]ANDUJAR MARQUEZ, J. - BOHÓRQUEZ, M. A. - MELGAR, S.: Ground Thermal Diffusivity Calculation by Direct Soil Temperature Measurement. Application to very Low Enthalpy Geothermal Energy Systems, Sensors, 2016, 13 p.
[34]SMITS, K. M. - SAKAKI, T. - LIMSUWAT, A. - ILLANGASEKARE, H. T.: Thermal Conductivity of Sands under Varying Moisture and Porosity in Drainage–Wetting Cycles, Vadose Zone Journal, 2010, Volume 9, pp. 1–9.
[35]AYAZ, H. - FAIZAL, M. - BOUAZZA, A.: Energy, economic, and carbon emission analysis of a residential building with an energy pile system, Renewable Energy, 220, 119712, 2024.