

# DEPTH-DEPENDENT CHANGES IN SOIL THERMAL PROPERTIES: EVIDENCE FROM GOBUSTAN, AZERBAIJAN

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## Abstract

*This study investigates depth-dependent variations of soil thermal properties in the Gobustan region of Azerbaijan, an area characterized by a semi-arid climate and significant energy infrastructure development. Field measurements were conducted in trial pits excavated up to 3.0 m depth, using the thermal needle probe method in accordance with IEEE Std 442-1981 and ASTM D5334-00 standards. Soil thermal resistivity (R), thermal conductivity ( $\lambda$ ), temperature, and moisture content were measured at 0.5 m intervals to capture detailed depth-related trends. The results revealed a consistent depth-dependent pattern: with increasing depth, soil temperature decreased, while thermal conductivity increased and thermal resistivity correspondingly declined, indicating more efficient heat transfer in deeper layers. However, clear spatial variability was also observed across different soil types. In silty soils (Trial Pit-1) and clayey soils (Trial Pit-2), resistivity decreased sharply with depth due to greater compaction and moisture retention in lower horizons, accompanied by significant increases in conductivity. The argillite profile (Trial Pit-3) differed, showing the highest overall surface temperatures (up to 36.7 °C) and elevated resistivity values, though conductivity still increased gradually with depth. By contrast, the clay–argillite profile (Trial Pit-4) exhibited more stable and balanced results, with moderate increases in conductivity and only slight decreases in resistivity, reflecting a relatively homogeneous soil structure. Overall, the findings highlight both vertical and lateral variability in soil thermal properties across Gobustan, controlled by lithology, soil structure, and moisture content. From a practical standpoint, these results provide baseline data critical for the design and optimization of underground cable systems, geothermal energy projects, and other engineering applications under semi-arid conditions. From a scientific perspective, the study represents one of the first systematic applications of IEEE and ASTM international standards for assessing depth-dependent soil thermal properties in Azerbaijan, contributing valuable new insights and a reference framework for future research in the South Caucasus region.*

**Keywords:** Soil thermal resistivity, thermal conductivity, trial pits; Gobustan, Azerbaijan

## I. Introduction

Soil thermal properties, particularly thermal conductivity and thermal resistivity, play a crucial role in multiple engineering and environmental applications. They determine how efficiently heat is transferred through soil, directly affecting the design and performance of underground electrical cable systems, geothermal energy extraction, and building foundations [1]. These properties are fundamental physical parameters that regulate the processes of heat transfer and storage within soils [2,3]. Accurate knowledge of these properties is essential to prevent overheating in buried power cables, optimize geothermal heat exchange systems, and improve predictions of soil-atmosphere

energy fluxes [4]. Knowledge about soil thermal properties is also crucial for modeling soil thermal regimes and mass–energy exchange processes occurring in the soil–plant–atmosphere system [5].

Extensive research has been carried out worldwide to investigate soil thermal properties under various climatic and geological conditions. For instance, Ochsner et al. (2001) highlighted the influence of soil water content and bulk density on thermal conductivity[6]. Mengistu et al. (2017) investigated the effects of soil water content and temperature on the thermal properties of different soil types in South Africa under laboratory conditions [7]. Literature further indicates that soil thermal properties are significantly dependent on water content, with both linear and non-linear responses being observed [8,9,10]. Sun et al. (2020) examined the correlation between thermal conductivity and electrical resistivity of silty clay soil across temperatures from  $-20\text{ }^{\circ}\text{C}$  to  $+10\text{ }^{\circ}\text{C}$  under varying moisture conditions [11]. Al Nakshabandi and Kohnke (1965) investigated how soil thermal conductivity and diffusivity are influenced by moisture tension and other physical properties[12]. Studies have also shown that thermal conductivity and diffusivity generally increase with decreasing temperature and increasing water content, although responses vary with soil type and conditions [13,14]. These studies consistently confirm that soil thermal properties are depth-dependent and highly sensitive to environmental and physical soil conditions.

Despite the abundance of international studies, research on soil thermal properties in Azerbaijan remains limited. In particular, the Gobustan region characterized by semi-arid climate, diverse soil textures, and significant energy infrastructure development has not been systematically studied in terms of depth-dependent variations in soil thermal conductivity and resistivity. This knowledge gap restricts the optimization of underground cable installations and geothermal applications in the region.

Therefore, the objective of this study is to investigate the depth-dependent changes in soil thermal properties in Gobustan, Azerbaijan. Measurements were conducted in a 3-meter-deep trench at 0.5-meter intervals using the thermal needle probe method in accordance with IEEE Std 442-1981 and ASTM D5334-00 standards. The results provide new evidence on how soil thermal characteristics vary with depth under local conditions, offering both scientific insights and practical implications for engineering and energy applications in semi-arid environments.



**Figure 1:** Location Map of Gobustan Area on Google Earth

The field investigations were conducted approximately 30 km west of Baku city, in the elevated areas surrounding Chayly village of Gobustan district. The study sites are mainly located to the north and northeast of the village, with one section positioned toward the west. To the north of Chayly village, the Ilxidagh massif is observed, while in the western direction the Qara Islam and Balaga Aday mountain ranges dominate the landscape. These geological and geomorphological features significantly influence the soil conditions and the development of its thermal properties (Fig 1).

### Geological Setting

The study area is situated within upland zones where Upper Cretaceous rock complexes are widely distributed. Lithologically, these deposits are represented by clay, argillite, sandstone, and their interbedded sequences with sandy and marly layers.

Outcrops of clays along anticlinal structures are observed within the region. These strata occur in thin layers and beds, typically dipping at angles of 70–80°, with a general strike direction extending from southeast to northwest.

In addition, within the study sites, a thin soil–vegetation cover overlies the bedrock. Around the slopes, eluvial–deluvial deposits have formed as a result of the weathering and erosion of parent rocks, further influencing the soil composition and local geomorphology [15].

## II. Methods

### Soil Thermal Resistivity and Conductivity

One of the most critical factors affecting the reliable operation of underground cable systems is soil thermal resistivity. Thermal resistivity (measured in °C·m/W or K·m/W) expresses the resistance of a material to heat flow, while thermal conductivity (measured in W/m·K) represents its reciprocal property [1].

$$R = \frac{1}{\lambda}$$

Here,  $R$  denotes thermal resistivity, and  $\lambda$  denotes thermal conductivity.

### Experimental Setup

Trial pits up to 2.0 m deep were excavated, and measurements were conducted at 0.5 m intervals (0.25 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m). During the measurements, a constant heat flow was applied using the KD2 Pro Thermal Properties Meter, and the resulting temperature response of the soil was recorded. A minimum of 90 seconds was allowed for temperature stabilization, and each test lasted approximately 10–15 minutes. In parallel, undisturbed soil samples were collected to determine soil moisture content [16].

### Thermal Needle Probe Method

The thermal needle probe method was applied to determine the thermal properties of the soil. In this method, a heating wire embedded in the probe generates a constant heat flow, while a temperature sensor located within the same probe records the temperature change as a function of time. From the linear portion of the temperature–time curve, soil thermal conductivity ( $\lambda$ ) is determined, and subsequently, soil thermal resistivity ( $R$ ) is calculated [17].

### Standards Applied

The tests were conducted in accordance with international standards. For determining soil thermal resistivity, the IEEE Std 442-1981 – Guide for Soil Thermal Resistivity Measurements was applied, which is widely used in the design of underground electrical cables [17]. For determining the thermal conductivity of soils and soft rocks, the ASTM D5334-00 – Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure

was followed [16]. These standards define internationally accepted guidelines for applying the needle probe method, measurement conditions, and processing of results.

**Data Collection and Processing**

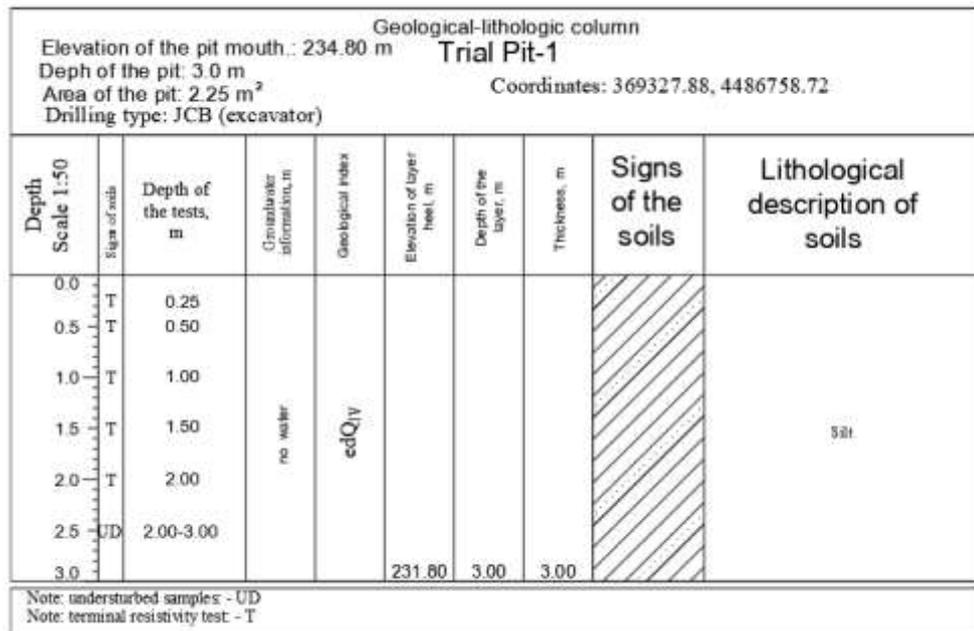
The following parameters were obtained from each measurement:

- Soil thermal resistivity (R)
- Soil thermal conductivity ( $\lambda$ )
- Temperature (T)
- Moisture content

The recorded temperature–time data were analyzed using computer software, and the average values of three repeated tests at each depth were calculated. The results were presented in the form of graphs and tables.

**IV. Results**

In Trial Pit-1, thermal resistivity tests were conducted at depths ranging from 0.25 m to 2.0 m in soils classified as silt according to the geological–lithological column (Fig. 2). The results show a clear depth-dependent trend in soil thermal properties. As depth increased, soil temperature decreased, while thermal conductivity increased, leading to a reduction in thermal resistivity. This indicates that deeper soil layers transfer heat more efficiently compared to near-surface layers. Detailed results are presented in Table 1 and Fig. 2–3 below.



**Figure 2:** Geological–lithological section of Trial Pit-1

**Table 1:** Thermal Resistivity test results (Trial Pit-1)

Depth (m)	Soil Temperature (°C)	Thermal Conductivity (W/m·K)	Thermal Resistivity (m·K/W)	Read Time (min)	Power Mode
0.25	27.7	0.396	2.415	5	HPM
0.5	25.1	0.452	2.215	5	HPM
1	23.38	0.603	1.658	5	HPM
1.5	20.79	0.624	1.603	5	HPM
2	18.96	0.756	1.322	5	HPM

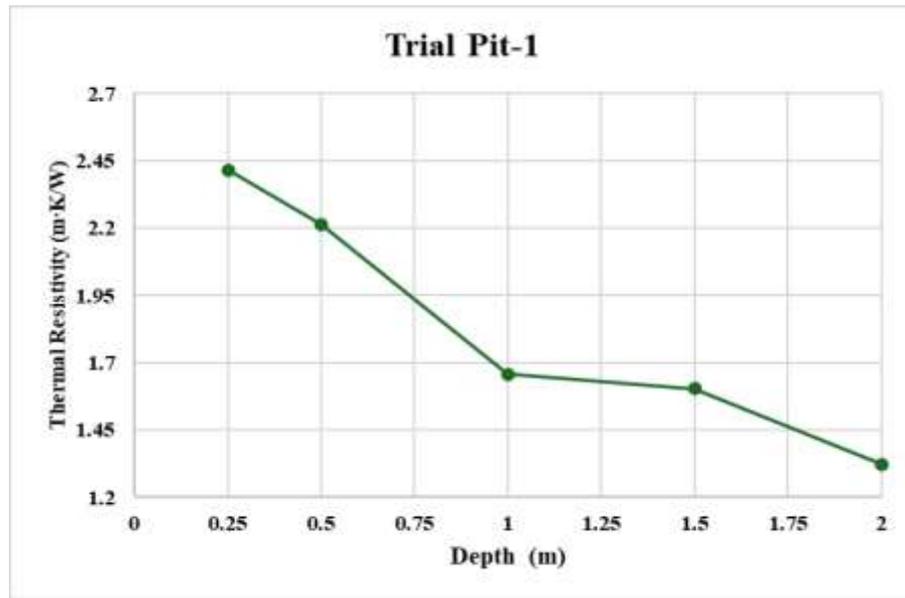


Figure 2: Variation of thermal resistivity with depth.

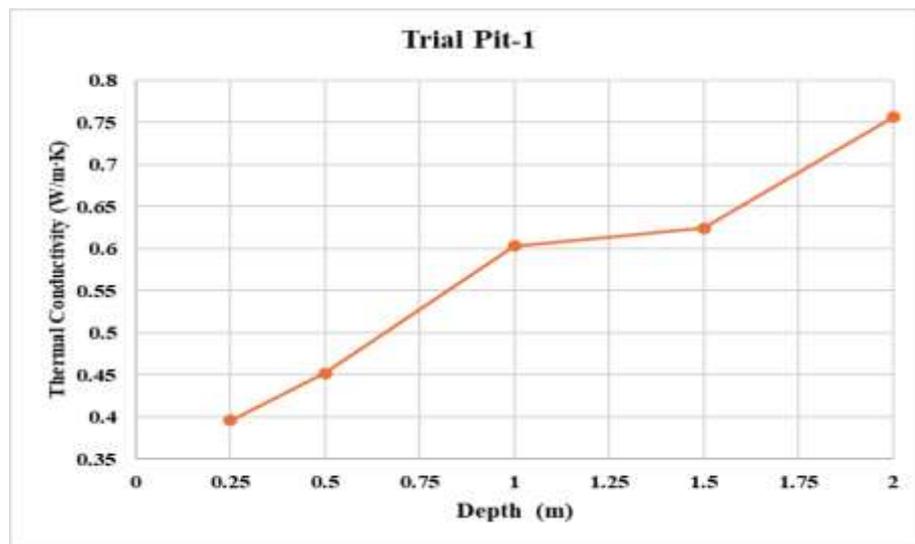


Figure 3: Variation of thermal conductivity with depth.

In Trial Pit-2, thermal resistivity tests were carried out at depths ranging from 0.25 m to 2.0 m in soils classified as clay according to the geological–lithological column (Fig. 4). The results demonstrate a depth-dependent variation in soil thermal properties similar to Trial Pit-1. With increasing depth, soil temperature decreased progressively, while thermal conductivity increased, resulting in a reduction in thermal resistivity. This pattern indicates that deeper layers exhibit better heat transfer capacity compared to shallow layers. The detailed outcomes are presented in Table 2 and Fig. 5–6 below.

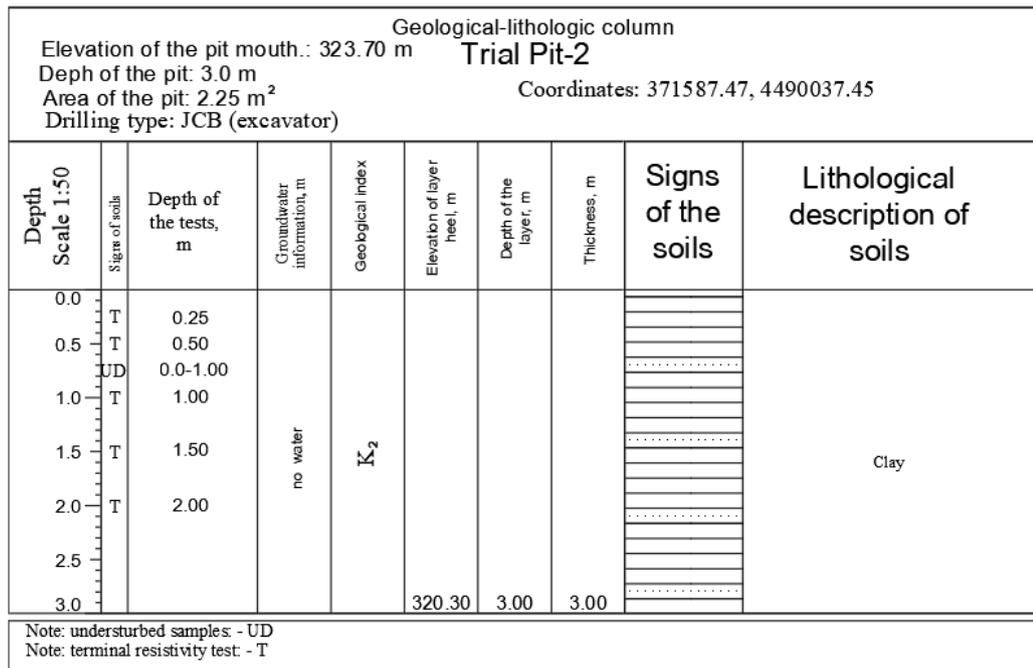


Figure 4: Geological-lithological section of Trial Pit-2

Table 2: Thermal Resistivity test results (Trial Pit-2)

Depth (m)	Soil Temperature (°C)	Thermal Conductivity (W/m·K)	Thermal Resistivity (m·K/W)	Read Time (min)	Power Mode
0.25	25.9	0.662	1.644	5	HPM
0.5	23.17	0.733	1.365	5	HPM
1	21.6	0.801	1.285	5	HPM
1.5	20.2	0.864	1.145	5	HPM
2	18.69	0.927	1.079	5	HPM

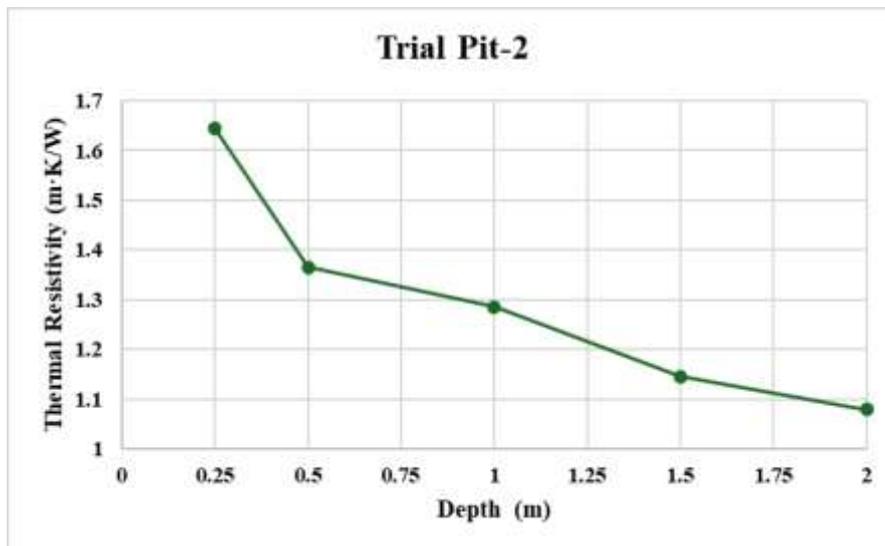


Figure 5: Variation of thermal resistivity with depth.

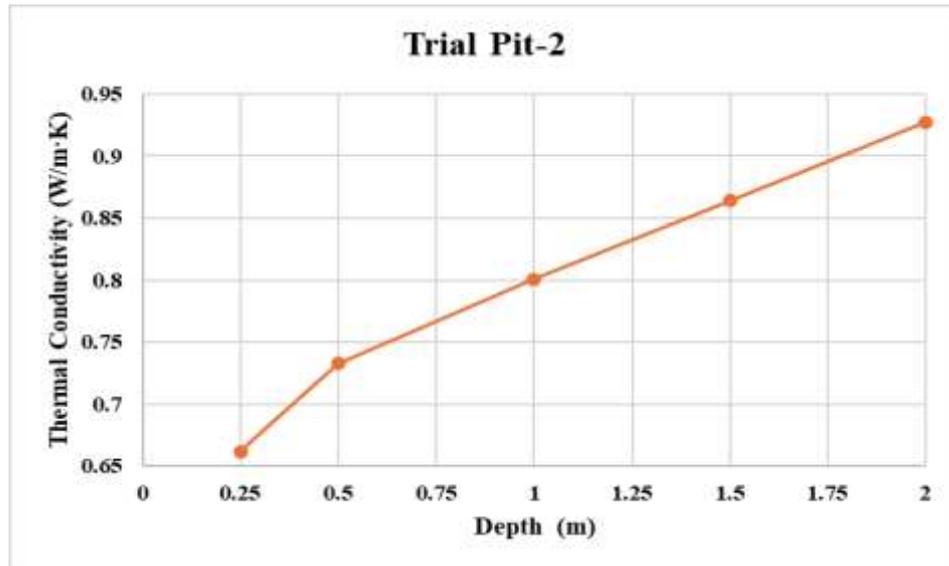


Figure 6: Variation of thermal conductivity with depth.

In Trial Pit-3, thermal resistivity tests were conducted between depths of 0.25 m and 2.0 m in soils classified as argillite according to the geological–lithological column (Fig. 7). The observed results differ from Trial Pits 1 and 2, showing significantly higher soil temperatures across all measured depths. Thermal conductivity increased gradually with depth, while thermal resistivity decreased correspondingly. This pattern suggests that despite the higher surface temperature, deeper soil layers exhibit improved heat transfer efficiency. The detailed results are summarized in Table 3 and Fig. 8–9 below.

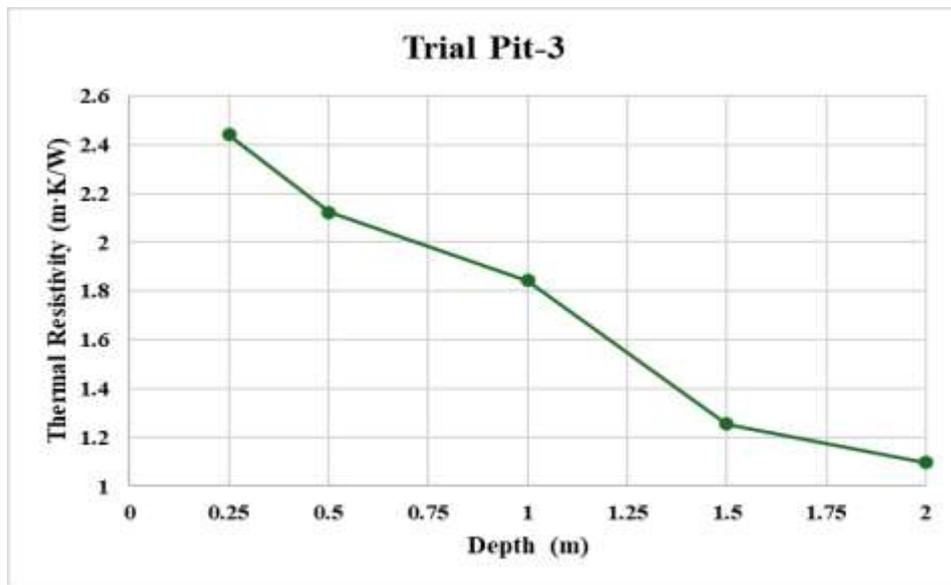
Geological-lithologic column									
Elevation of the pit mouth.: 199.50 m				Trial Pit-3					
Depth of the pit: 3.0 m				Coordinates: 374249.13, 4488224.89					
Area of the pit: 2.25 m <sup>2</sup>				Drilling type: JCB (excavator)					
Depth Scale 1:50	Signs of soils	Depth of the tests, m	Groundwater information, m	Geological index	Elevation of layer heel, m	Depth of the layer, m	Thickness, m	Signs of the soils	Lithological description of soils
0.0	UD	0.0-0.50	no water	K <sub>2</sub>	196.50	3.00	2.80		Argillite
	T	0.25							
0.5	T	0.50							
1.0	T	1.00							
1.5	T	1.50							
2.0	T	2.00							
2.5									
3.0									

Note: understurbed samples: - UD  
 Note: terminal resistivity test: - T

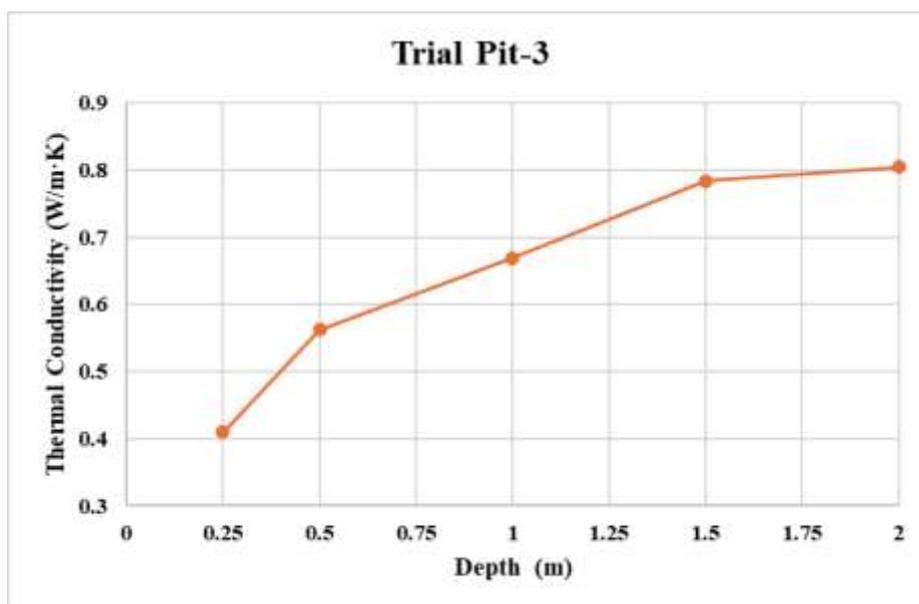
Figure 7: Geological–lithological section of Trial Pit-3

**Table 3:** Thermal Resistivity test results (Trial Pit-3)

Depth (m)	Soil Temperature (°C)	Thermal Conductivity (W/m·K)	Thermal Resistivity (m·K/W)	Read Time (min)	Power Mode
0.25	36.73	0.41	2.441	5	HPM
0.5	35.6	0.562	2.123	5	HPM
1	34.7	0.669	1.842	5	HPM
1.5	32.2	0.784	1.254	5	HPM
2	29.7	0.805	1.096	5	HPM



**Figure 8:** Variation of thermal resistivity with depth.



**Figure 9:** Variation of thermal conductivity with depth.

In Trial Pit-4, thermal resistivity tests were performed between depths of 0.25 m and 2.0 m. According to the geological–lithological column (Fig. 10), the soil profile consists of clay from the surface down to 1.0 m and argillite between 1.0 m and 3.0 m. The results show a relatively stable trend compared to other pits, with soil temperature gradually decreasing with depth. Thermal conductivity increased slightly with depth, while thermal resistivity remained relatively consistent, showing only minor decreases. This indicates that the soil profile in Trial Pit-4 maintains a more uniform heat transfer capacity across depths compared to other test sites. The detailed results are presented in Table 4 and Fig. 11–12 below.

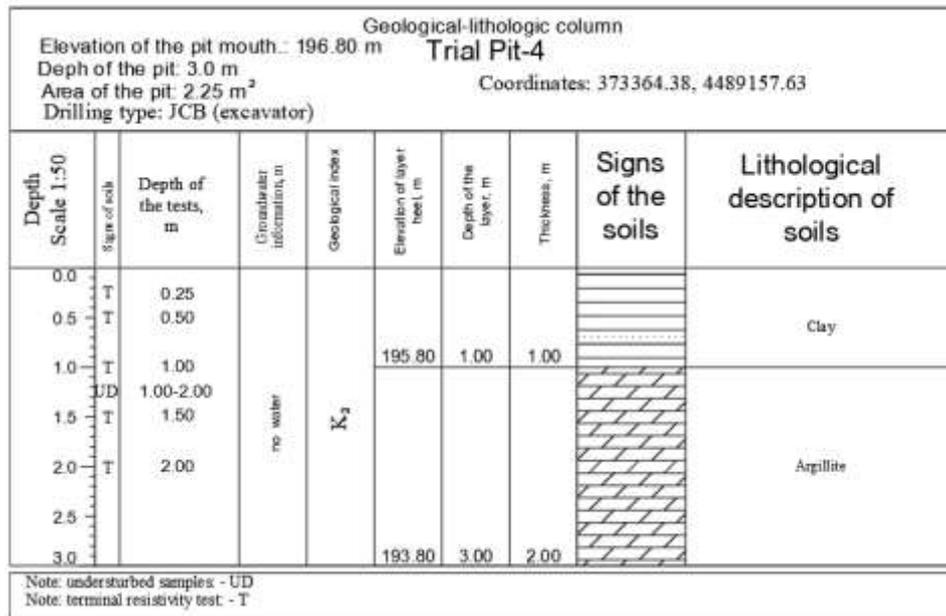


Figure 10: Geological–lithological section of Trial Pit-4

Table 4: Thermal Resistivity test results (Trial Pit-4)

Depth (m)	Soil Temperature (°C)	Thermal Conductivity (W/m·K)	Thermal Resistivity (m·K/W)	Read Time (min)	Power Mode
0.25	25.11	0.65	1.539	5	HPM
0.5	24.5	0.71	1.49	5	HPM
1	23.2	0.745	1.462	5	HPM
1.5	22.6	0.786	1.426	5	HPM
2	20.2	0.821	1.402	5	HPM

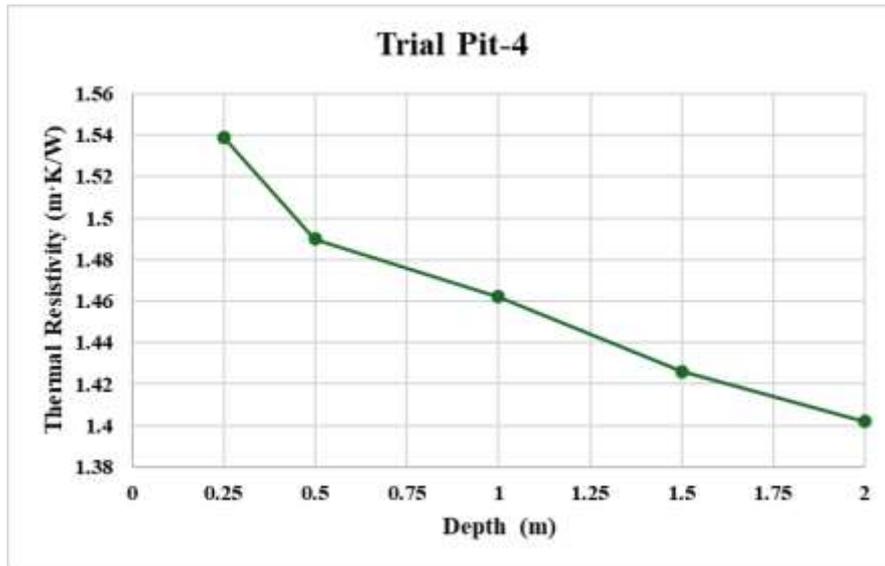


Figure 11: Variation of thermal resistivity with depth.

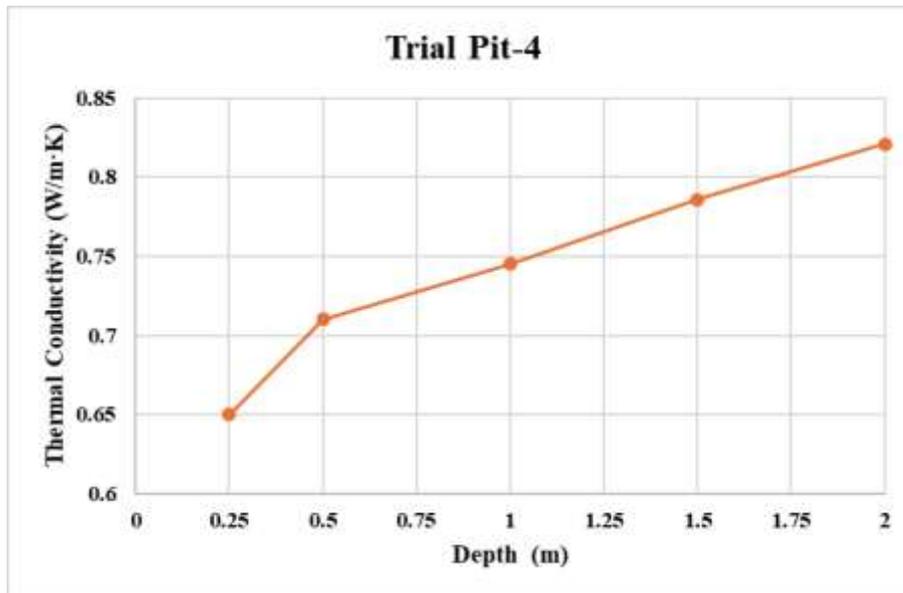


Figure 12: Variation of thermal conductivity with depth.

When comparing the results of all Trial Pits, it becomes evident that the thermal properties of the soil exhibit variability both with depth and spatially.

1. **Depth-Dependent Variation of Thermal Resistivity Depth ( $\rho$ ):** In all pits, soil thermal resistivity showed a decreasing trend with increasing depth. This behavior is attributed to higher density and moisture content in deeper layers, which enhance thermal conductivity. In Trial Pit-1 and Trial Pit-2, a sharp decrease was observed. In Trial Pit-3, resistivity values remained high with only a slight reduction, while Trial Pit-4 exhibited more stable results.
2. **Thermal Conductivity( $\lambda$ ):** Thermal conductivity increased with depth in all pits. The highest increase was recorded in Trial Pit-2 (from 0.662 W/m·K to 0.927 W/m·K). In Trial Pit-3 and Trial Pit-4, the increase was more gradual and consistent.

3. **Soil Temperature:** Surface layers showed higher temperatures (particularly in Trial Pit-3, reaching 36.7 °C), while deeper layers exhibited decreasing values. The lowest temperatures were recorded in the deeper sections of Trial Pit-2 and Trial Pit-4 (around 20 °C).
4. **Comparison Among Pits:**
  - Trial Pits 1 and 2 demonstrated significant variability.
  - Trial Pit-3 exhibited the highest temperatures and resistivity values.
  - Trial Pit-4 produced more stable and balanced results.

## IV. Conclusion

This study presented the results of soil thermal resistivity and conductivity measurements conducted in Gobustan, Azerbaijan, across four trial pits excavated to a depth of 3.0 m. Tests were carried out at 0.5 m intervals (starting from 0.25 m), allowing for detailed depth-dependent assessment of soil thermal behavior. The findings revealed a consistent pattern: as depth increased, soil temperature decreased, thermal conductivity increased, and thermal resistivity correspondingly decreased. This indicates that deeper soil layers provide more efficient pathways for heat transfer compared to near-surface horizons.

Comparison among the trial pits highlighted the influence of lithology. In silty soils (Trial Pit-1) and clayey soils (Trial Pit-2), sharp reductions in resistivity with depth were observed due to higher density and moisture retention in deeper layers. The argillite profile (Trial Pit-3) exhibited the highest surface temperatures (up to 36.7 °C) and resistivity values, although conductivity still increased gradually with depth. Trial Pit-4, consisting of clay in the upper 1.0 m and argillite below, showed more stable results with moderate increases in conductivity and only slight reductions in resistivity, reflecting a relatively homogeneous soil profile.

Overall, the study confirms both vertical and spatial variability of soil thermal properties in the Gobustan region, governed by lithology, soil structure, and moisture content. From a practical perspective, the results provide essential baseline data for the optimization of underground cable systems, geothermal energy applications, and infrastructure design under semi-arid conditions. From a scientific standpoint, this work represents one of the first systematic applications of IEEE Std 442-1981 and ASTM D5334-00 standards in Azerbaijan, contributing valuable new insights and a reference database for future studies on soil thermal regimes in the South Caucasus.

### CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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