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Research Article

In Situ Determination of Thermal Resistivity of Soil: Case Study of Olorunsogo Power Plant, Southwestern Nigeria

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This study measured in situ the thermal resistivity of soils at Olorunsogo Gas Turbine Power Station (335 MW Phase 1) which is located in Ogun State, Southwestern Nigeria. Ten pits, each of about 1.5 m below the ground surface, were established in and around the power plant in order to measure the thermal resistivity of soils in situ. A KD 2-Pro was used for the in situ measurement of thermal properties. Samples were also collected from the ten pits for laboratory determination of the physical parameters that influence thermal resistivity. The samples were subjected to grain size distribution analysis, compaction, specific gravity and porosity tests, moisture content determination, and XRD analysis. Also, thermal resistivity values were calculated by an algorithm using grain size distribution, dry density, and moisture content for comparison with the in situ values. The results show that thermal resistivity values range from 34.07 to 71.88°C-cm/W with an average of 56.43°C-cm/W which falls below the permissible value of 90°C-cm/W for geomaterials. Also, the physical parameters such as moisture content, porosity, degree of saturation, and dry density vary from 13.00 to 16.20%, 39.74 to 45.64%, 40.72 to 63.52%, and 1725.05 to 1930.00 Kg/m^3, respectively. The temperature ranges from 28.92 to 35.39°C with an average of 32.11°C in the study area. The calculated thermal resistivity from an algorithm was found to vary from 48.43 to 81.22°C-cm/W with an average of 65.56°C-cm/W which is close to the thermal resistivity values measured in situ. Good correlation exists between the in situ thermal resistivity and calculated thermal resistivity with $R = +0.85$ suggesting that both methods are reliable.

1. Introduction

The migration of heat in porous media has attracted attention of the research fraternity, since almost a century. Studies conducted in the past reveal that heat migration in a medium primarily depends on its thermal resistivity (ability of the material to resist heat flow in it), its specific heat (ability of the material to store heat), and thermal diffusivity (which combines the transmission and storage properties of the material and is indicative of the rate of change of temperature within the material).

For safe and proper execution of various civil and electrical engineering projects, determination of thermal resistivity of soils is quite essential. However, thermal properties of soils would play an important role for extremely environmental sensitive projects such as disposal of high-level radioactive waste in deep underground disposal sites or repositories [1, 2] and various engineering projects such as design and laying of high-voltage buried power cables, oil and gas pipe lines, and ground modification techniques employing heating and freezing. In addition to characterizing the soil's physical/hydraulic properties, knowledge of the soil's thermal properties is necessary for proper soil and water management in irrigated agriculture [3], determining the energy balance at the soil surface, soil water retention, and unsaturated hydraulic conductivity [4].

In this direction, attempts have been made wherein rock has been powdered to determine its thermal conductivity [5, 6] or its chips have been used [7]. However, these studies would not yield accurate results, mainly, due to the lack of representative matrix of the rock mass [8]. Attempts have also been made by earlier researchers to determine thermal properties of soils using divided bar method [9], the transient plane source, TPS method [10], and different probe methods [11, 12]. However, these methods are time consuming, expensive, and quite complicated in terms of instrumentation and insulation of the surfaces of the rock sample from the ambience.

Recently, Decagon Devices Inc. has developed the KD2-Pro meter logger and two specific sensors: the SH-1 thermal sensor, to measure the thermal properties employing the dual needle heat pulse (DNHP) method, and KS-1 thermal sensor that is a single needle employing an infinite line heat source (ILHS) method. In order to obtain reliable data, field and laboratory procedures to determine thermal properties with the KD2-Pro need to be normalized, according to existing standards and manufacturer's indications, since soil scientists, engineers, and other users are demanding these kind of data for different applications. The present work describes the step towards the development of a field procedure to obtain reliable, accurate, and rapid thermal properties dataset in soils, taking into account the current accepted standard [13].

Several researchers [14–21] have shown that the thermal properties of soil depend on numerous parameters such as mineralogical composition, grain size of soil, and physical properties like moisture content (w, %), porosity, dry density (ρ_d, g/cm^3), and saturation (S, %). Therefore, these factors have to be taken into account when performing measurements at laboratory and field scale.

1.1. Site Description. The study area is a 335 MW phase I, Olorunsogo Gas Turbine Power Station in Ogun state, Southwestern Nigeria. It is located within longitude 03° 18′ 45′′ to 03° 19′ 50′′ and latitude 06° 52′ 45′′ to 06° 53′ 00′′. The major road in the area runs from Papalanto in the Western part of the area to Ikereku in the eastern part. Another major road runs from Wasimi in the Northwestern part of the map to Isoku in the central North. There are so many minor paths in the area (Figure 1).

1.2. Drainage Pattern. The general drainage pattern is dendritic. The major river in the area is River Ewekoro that runs from the South to the North with several tributaries. Another major river that runs from Afowowa is the Afowowa river which runs in the Northern part of the area. The river that flows to the study area is River Ewekoro (Figure 2).

1.3. Geology of the Study Area. The study area falls within the alluvium, littoral and lagoonal deposits (Figure 3).

1.3.1. Littoral and Lagoonal Deposits. The sediments here consist of unconsolidated sands, clays, and muds with a varying proportion of vegetal matter. Occasional beds of sandstone with ferruginous cement were encountered during the drilling of test wells by Mobil Exploration Nigeria Incorporated. Correlation between one borehole and the next was usually very poor; the sediments were clearly deposited under littoral and lagoonal conditions and reflect continuously shifting lagoon and sea beach patterns and the varying sedimentation conditions within the lagoons.

1.3.2. Alluvial Deposits. The alluvial plain of the Ogun is 14 miles wide at one point, and smaller areas of alluvium follow the lower courses of the other major rivers. The borehole drilled penetrated clays and shales overlying alternating limestones and shales of the Ewekoro Formation.

2. Materials and Methods

The thermal resistivities of soils around Olorunsogo Power Plant were determined using KD2 Pro (Figure 16).

The KD2 Pro is a fully portable field and laboratory thermal properties analyzer. It uses the transient line heat source method to measure the thermal diffusivity, specific heat (heat capacity), thermal conductivity, and thermal resistivity. Sophisticated data analysis is based on over thirty years of research experience on heat and mass transfer in soils and other porous materials.

To determine the thermal resistivity, thermal sensor with one single needle (TR-1) (Figure 17) was employed. This kind of sensor uses the heat pulse methodology and yields reliable soil thermal resistivity (R) and the inverse thermal conductivity (λ) estimations by a nonlinear least squares procedure during both processes.

2.1. Field Procedure. The first step to develop a protocol to measure the thermal resistivity begins with the field sampling design.

2.1.1. In Situ Measurements. The measurements include establishments of ten pits of about 1.5 m below the ground and verification and preparation of the thermal sensor (calibration) using standard glycerol in order to check whether it was functioning properly [23–25]. The thermal sensor to be used was then selected (TR-1 was used). The ground was then scooped to allow firm positioning of the thermal sensor with the ground. The needle was positioned with respect to the pit established. Thermal resistivity was then measured by using the thermal sensor TR-1.

To take measurements with the KD2 Pro appropriate sensor was attached and the KD2 Pro was turned on; sensor was properly inserted into the material to be measured (for the dual needle sensor, the needles must remain parallel to each other during insertion); when the KD2 Pro turns on, one should be in the Main Menu and press enter to begin the measurement. The instrument was allowed to rest for about 25 minutes before taking the next reading.

2.2. Collection of Samples. Ten samples were collected at the established pits for laboratory analyses (Figure 4). The samples were kept in polythene bags and stored in a cool dry place before the necessary tests were carried out on them.

2.2.1. Analytical Laboratory Procedures. To characterize the soil of Olorunsogo Power Plant, the physical variables, particle size distribution, bulk density, dry density, specific gravity, degree of saturation, porosity, permeability, moisture content, and mineralogical composition were determined in the laboratory.

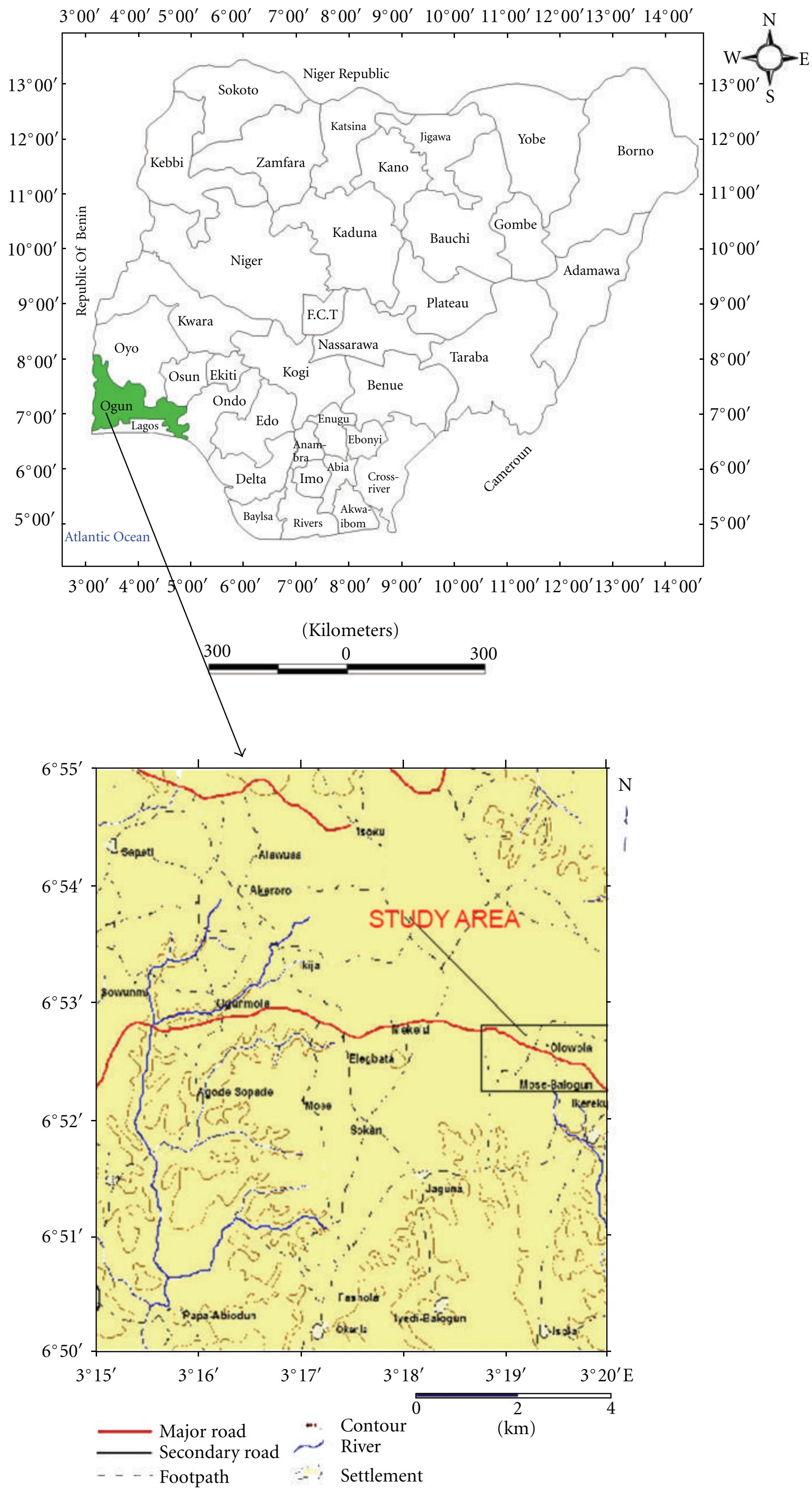


Figure 1: Topographical map of Papalanto area showing location of Olorunsogo Power Plant.

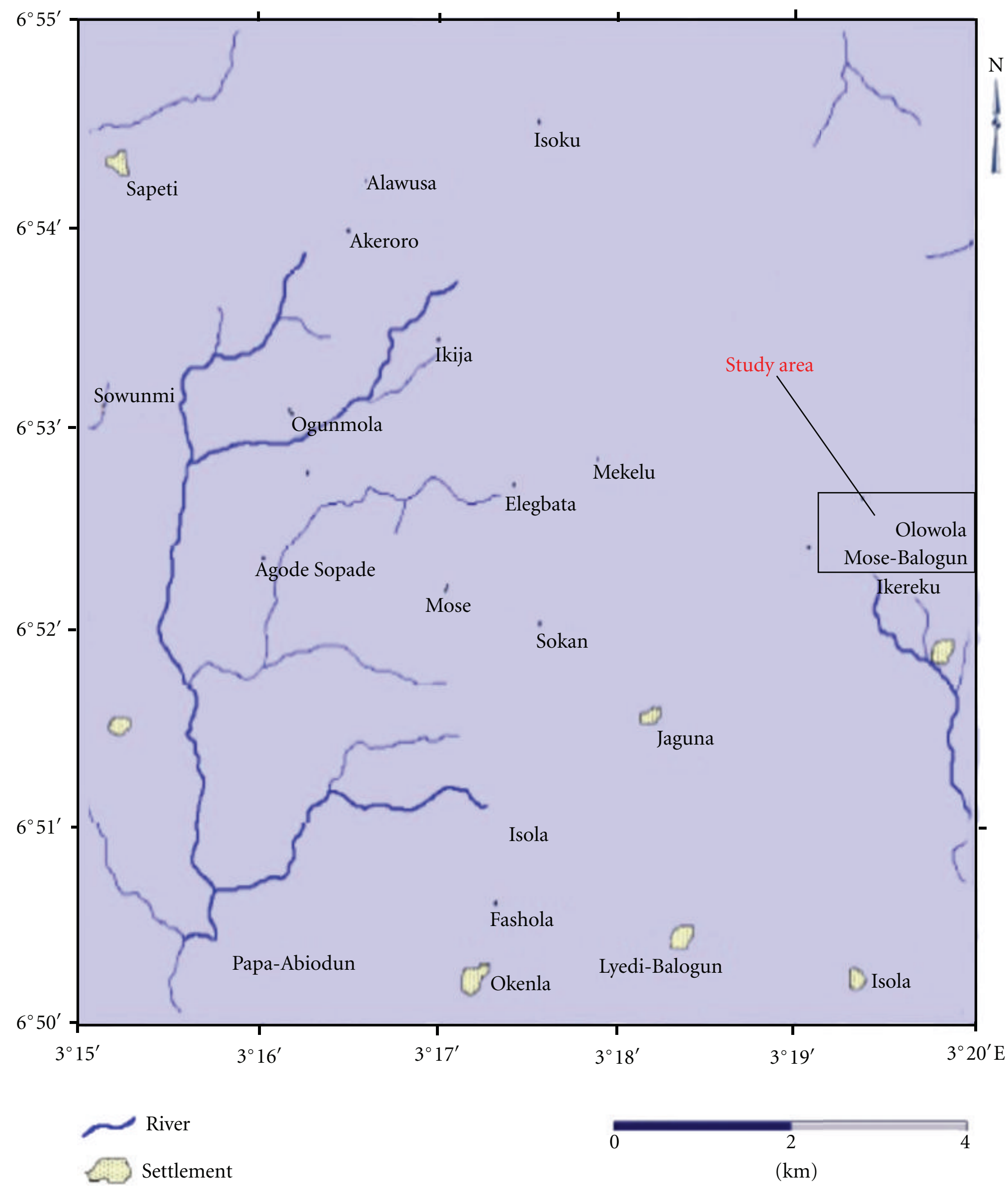


Figure 2: Drainage map of Olorunsogo Power Plant.

Due to the various fractions present in the soil, two stages are involved in the grain size distribution determination, as follows:

(a) mechanical or sieve analysis,

(b) hydrometer analysis.

Mechanical or sieve analysis was used for the coarse grained fraction (particle size >0.063 μm in diameter) while hydrometer analysis was used for the fine-grained fraction (particle size <0.063 μm in diameter).

Compaction tests were also carried out on the samples to determine the bulk density, optimum moisture content, and maximum dry density. Specific gravity, porosity, and permeability tests were carried out on the samples to determine specific gravity, porosity, and permeability, respectively. The degree of saturation was calculated from the formular: $Se = wG_s$, where S = degree of saturation, e = void ratio, w = moisture content, and G_s = specific gravity. XRD analysis was performed on two samples to determine its mineralogical composition.

3. Results and Discussion

The results of the thermal resistivities of soils measured are shown in Table 1.

3.1. Thermal Resistivity.

From Table 1, the thermal resistivity of soil in the study area ranges from 34.07 to 71.89°C-cm/W with a mean of 56.43°C-cm/W. Figure 5 shows that there is no much variation in the thermal resistivity values of the test

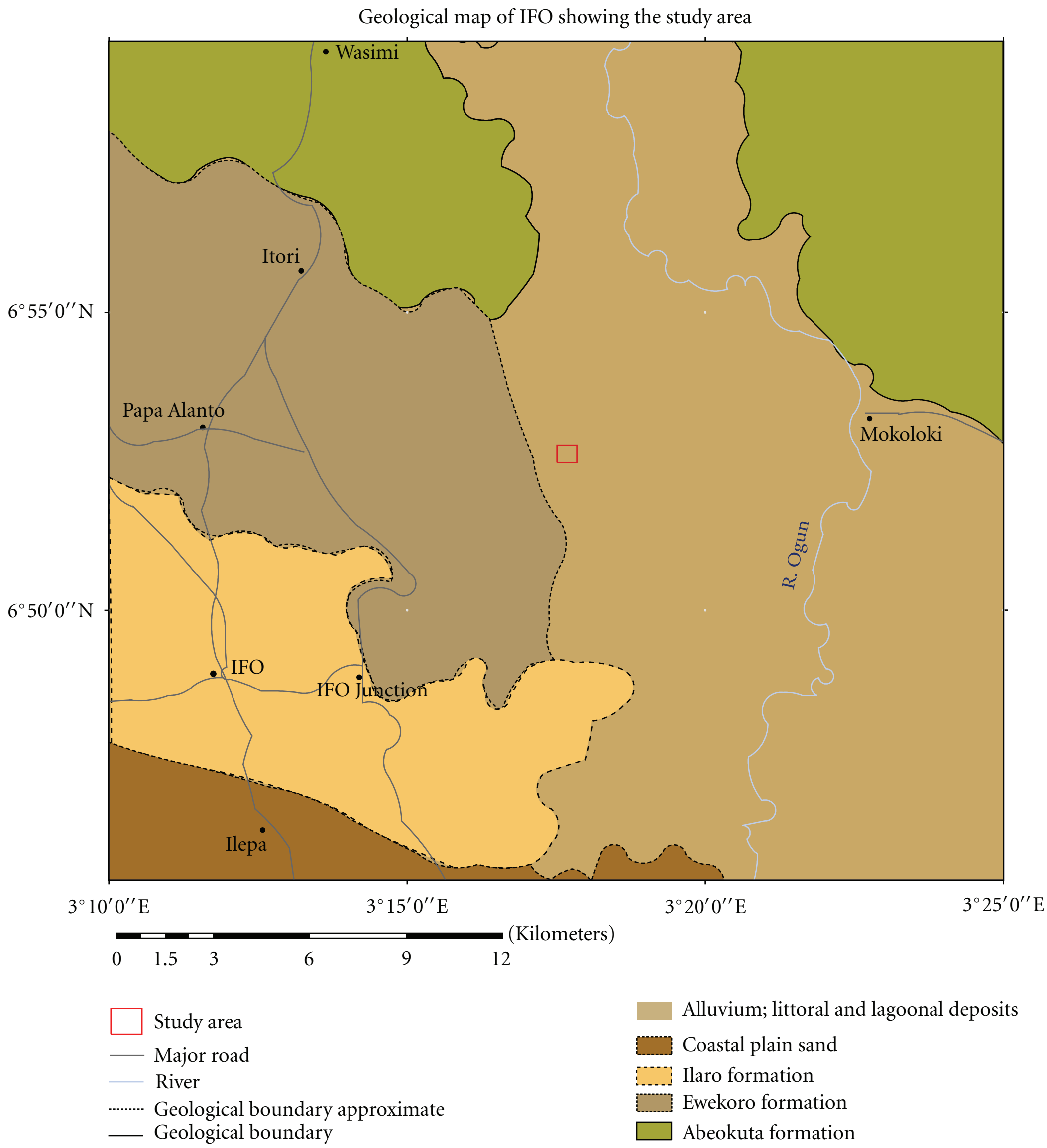


Figure 3: Geological Map of Ifo showing Olorunsogo Power Plant.

points except at location 4 where the value is relatively low (34.07°C-cm/W).

The use of soil thermal resistivity of 90°C-cm/W has become ingrained in cable engineering practices [26]. This means that the thermal resistivity values of soil in the study area fall below the safe value of 90°C-cm/W proposed by various workers [26, 27].

3.2. Variation of Thermal Resistivity with Physical Properties of Soil. The summary of the results of physical properties determined in the laboratory is presented in Table 2.

3.2.1. Moisture Content. The moisture contents of soil in the study area range from 13.0 to 16.2% with an average of 14.2%. The variation of thermal resistivity with moisture content is shown in Figure 6.

From Figure 6, it can be seen that a negative correlation exists between thermal resistivity and moisture content which means that as the thermal resistivity increases, the moisture content decreases and vice versa. This is in agreement with [17–19, 24, 28–32]. This may be as a result of one of the following.

(i) More heat is conducted through the individual soil grains because there are more of them to conduct heat.

(ii) More heat is conducted through the water alone because both the volume and the continuity of water increase.

(iii) More heat is conducted between the soil grains through the interstitial water because there is less air and more water between the particles.

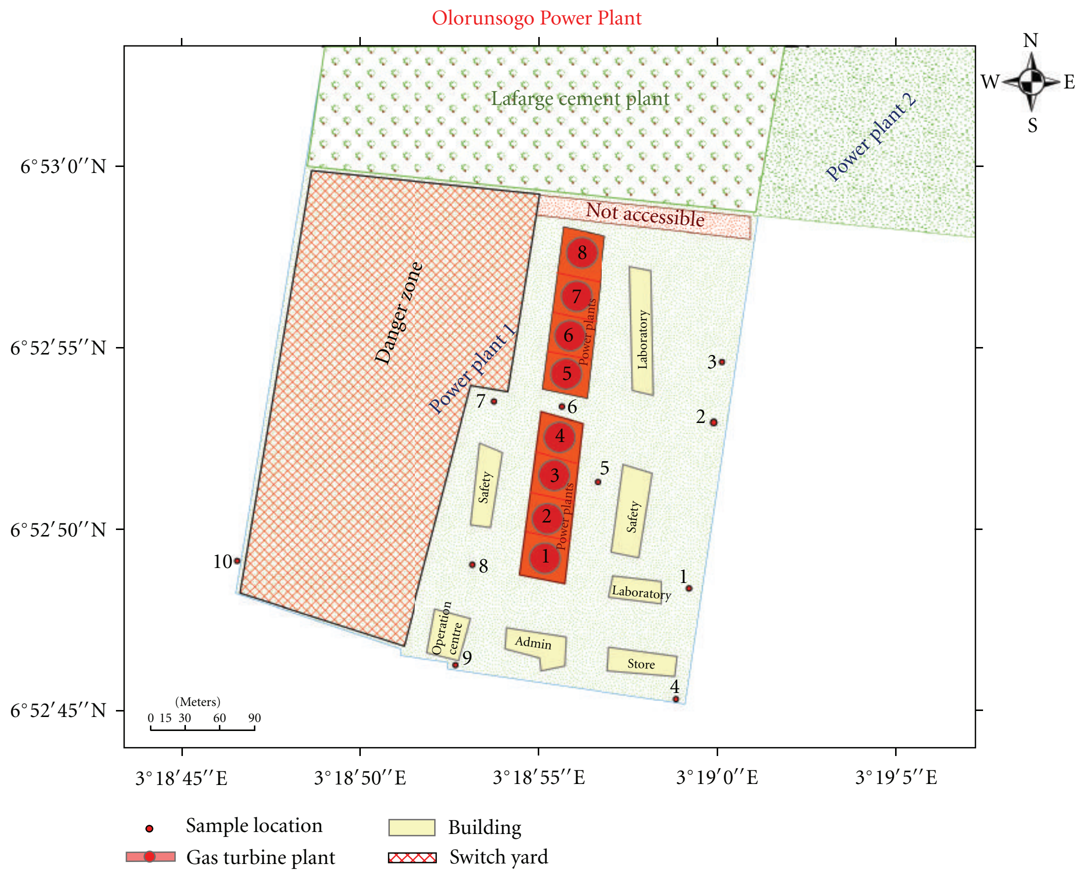


FIGURE 4: Map of the study area showing the test points.

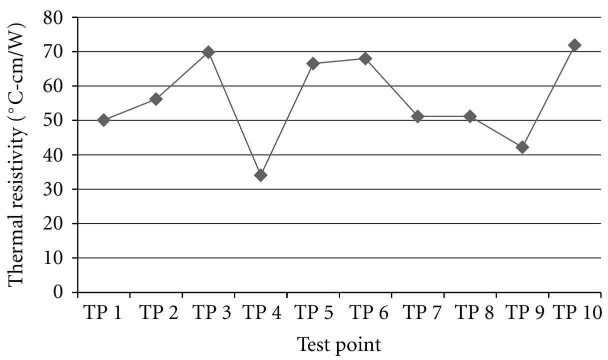


FIGURE 5: Variation of thermal resistivity of soil in the study area.

TABLE 1: Thermal resistivity of soils in Olorunsogo power plant.

Test point	Thermal resistivity (°C-cm/W)	Thermal conductivity (W/mK)	Temperature (°C)
1	50.10	1.996	31.13
2	56.20	1.779	32.21
3	69.84	1.432	35.39
4	34.07	2.935	28.72
5	66.54	1.503	33.04
6	67.99	1.471	33.81
7	51.15	1.955	32.66
8	54.27	1.954	32.41
9	42.21	2.369	31.98
10	71.88	1.391	34.20

(iv) As moisture is added to a soil, a thin water film develops which bridges the gaps between the soil particles. This "bridging" increases the effective contact area between the soil particles, which increases the heat flow and results in lower thermal resistivity [16, 18].

3.2.2. Dry Density. The dry density in the study area ranges from 1725.05 to 1930.00 Kg/m^3 with a mean of 1855.61 Kg/m^3 (Table 2).

It has long been recognised that an increase in the dry density of a soil results in a decrease in its thermal resistivity [17, 18, 30, 33, 34]. This effect is easily understandable considering the thermal resistivities of each of the constituents. With an increase in the dry density, air is replaced by the lower thermal resistivity minerals.

Figure 7 shows that as the dry density increases, the thermal resistivity decreases ($R = -0.25$). Since the percentage of minerals, as compared to air, increases with increasing dry

Table 2: Physical properties of soil samples in the study area.

Sample points	Optimum moisture content (%)	Porosity (%)	Degree of saturation (%)	Maximum dry density (Kg/m^3)	Permeability (cm/s)	Specific gravity
1	15.05	42.08	54.69	1850.10	0.0177	2.64
2	16.20	40.51	63.52	1920.25	0.0153	2.67
3	13.00	45.64	40.72	1800.25	0.0144	2.65
4	15.40	40.50	53.47	1840.25	0.0204	2.60
5	14.00	44.36	50.22	1725.05	0.0316	2.68
6	14.00	45.32	41.57	1930.00	0.0237	2.60
7	13.00	41.05	49.47	1880.20	0.0275	2.65
8	13.00	40.78	54.49	1810.00	0.0258	2.65
9	15.00	39.74	52.24	1890.02	0.0283	2.66
10	13.05	44.05	50.68	1910.02	0.0260	2.62

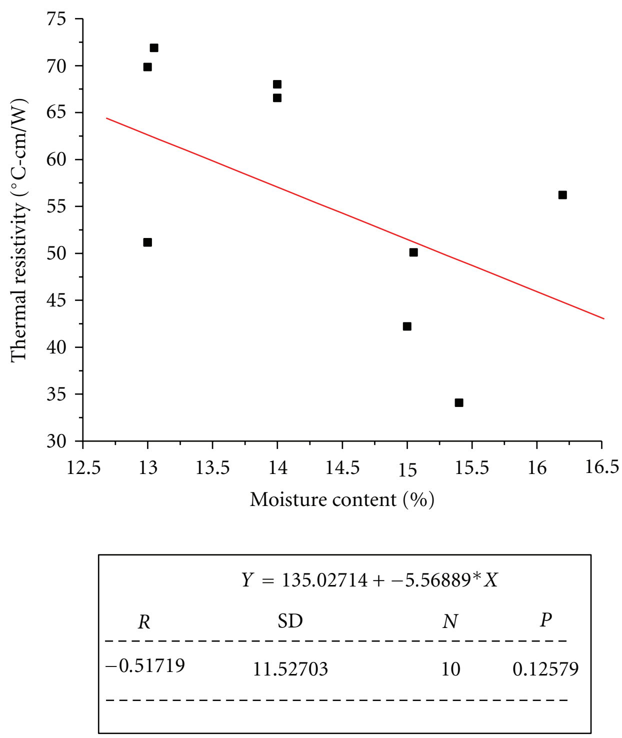


Figure 6: Variation of thermal resistivity with moisture content.

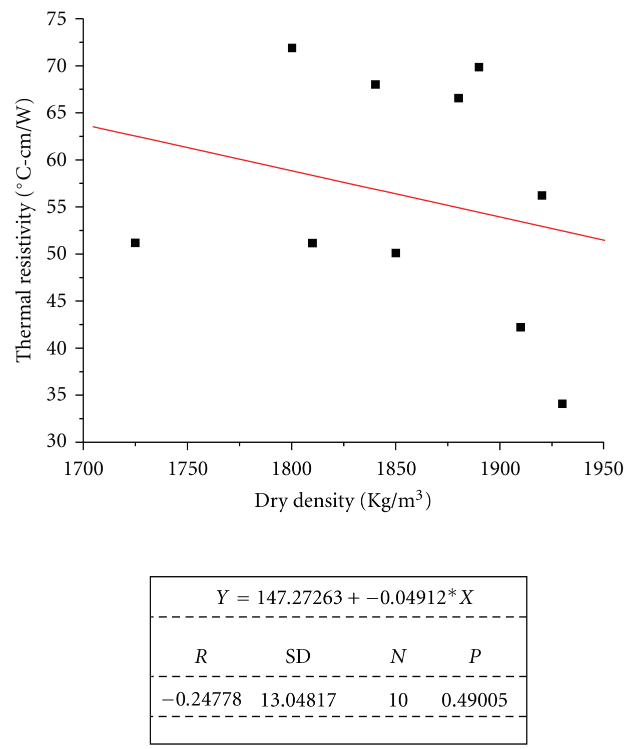


Figure 7: Influence of dry density on thermal resistivity of soil.

density, the greater the dry density of a soil, the lower the thermal resistivity [17–19, 30, 33–35]. This may be due to the improved contact between the soil grains that leads to better conduction of heat.

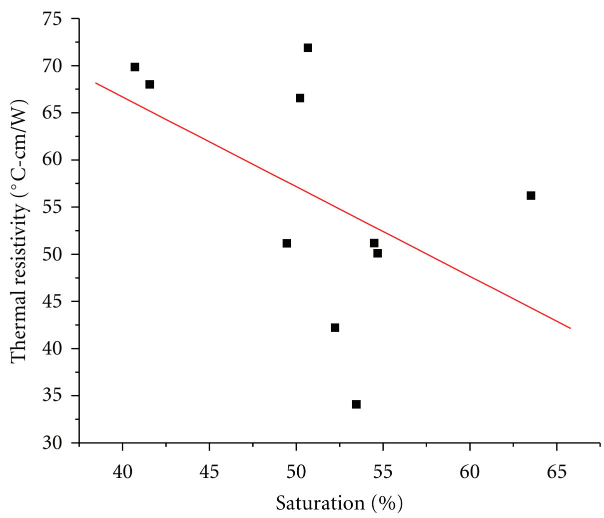
3.2.3. Degree of Saturation. The degree of saturation in the study area varies from 40.72% to 63.52% with an average of 51.11% (Table 2). This means that soil in the study area is partially saturated soil [36].

A soil's thermal property is significantly influenced by its saturation [37].

As shown in Figure 8, it was observed that an increase in the degree of saturation resulted in a decrease in its thermal resistivity ($R = -0.5$). This may be due to the improvement in contact between soil particles which leads to better conduction of heat. This agrees with previous works reported by literatures [26, 37–39].

3.2.4. Porosity. The data presented in Table 2 have been used to establish the influence of porosity of the soil on its thermal resistivity as depicted in Figure 9. Porosity of the soil samples varies from 39.74 % to 45.64 % with an average of 42.40 %.

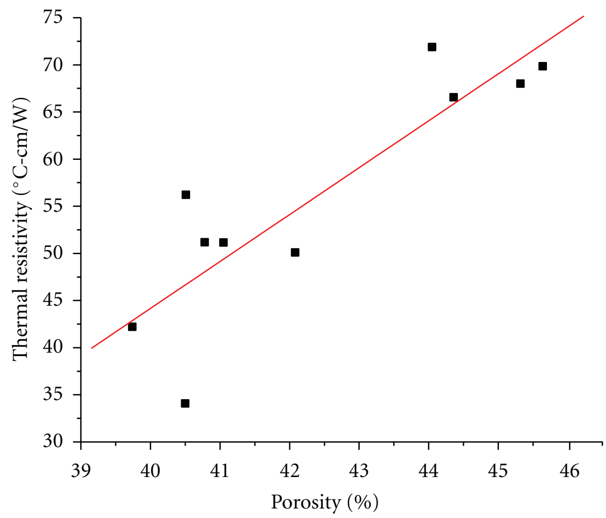
It can be noted that with increase in porosity, thermal resistivity increases ($R = 0.9$). Incidentally, variation of thermal resistivity with respect to porosity was noticed to be consistent with the trends reported in previous works



$Y = 104.71556 - 0.95094^* X$

R	SD	N	P
−0.49154	11.7288	10	0.14905

Figure 8: Variation of thermal resistivity with degree of saturation.



$Y = -154.89475 + 4.97632^* X$

R	SD	N	P
0.87041	6.63085	10	0.00105

Figure 9: Variation of thermal resistivity with porosity.

[5, 23, 40, 41]. Also the relationship between porosity and thermal diffusivity agrees with [40].

3.2.5. Temperature. The temperature of soils in the study area ranges from 28.72 to 35.0 8°C with a mean of 32.11°C. The variation of temperature in the area is shown in Figure 10 which shows that there is little variation in the temperature.

The influence of temperature on the thermal resistivity of soils in Olorunsogo (Figure 11) shows weakly positive correlation with $r = 0.1$.

As thermal expansions increase with temperature, but differently for all minerals, "thermal cracking" by differential expansion may create contact resistances between mineral grains thus contributing to the observed increase of resistivity with temperature. This is in agreement with previous works [30, 42–45].

However [16, 18] opined that temperature only has effect on the thermal resistivity of soils at the freezing point where the primary mode of heat transfer changes from convection to conduction and that in other temperature ranges, as in the study area, the variation of soil thermal resistivity with temperature is minimal.

However, [46] stated that for a soil in place, the temperature typically varies over a small enough range to have only a small effect on thermal properties (unless the soil freezes).

3.2.6. Mineralogical Composition. The results of XRD analysis are shown in Figures 12 and 13 while the interpretation

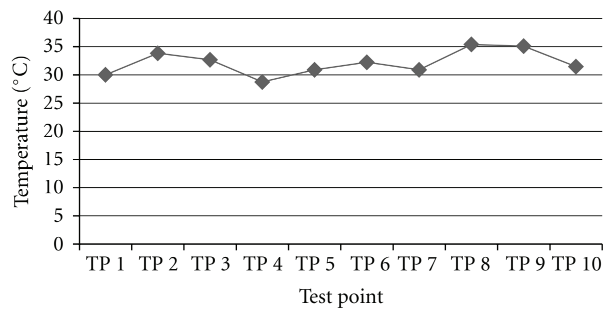


Figure 10: Variation of temperature of soil in Olorunsogo Power Plant.

Table 3: Mineralogical composition of two samples.

Sample point	Thermal resistivity (°C-cm/W)	Composition	
		Quartz (%)	Labradorite (%)
TP 5	66.54	74.72	25.28
TP 8	51.18	83.49	16.51

is shown in Table 3. From Table 3, the compositions of soils are quartz in abundance and minor portion of labradorite (feldspar).

In TP 5 with 74.72% quartz, the thermal resistivity is 66.54°C-cm/W while in TP 8 with 83.49% quartz has 51.18°C-cm/W thermal resistivity. This suggests that the soil with higher percentage of quartz will have a lower thermal resistivity [19]. In fact, soils with high quartz content generally have a lower thermal resistivity than soils with high contents of plagioclase feldspar and pyroxene [15].

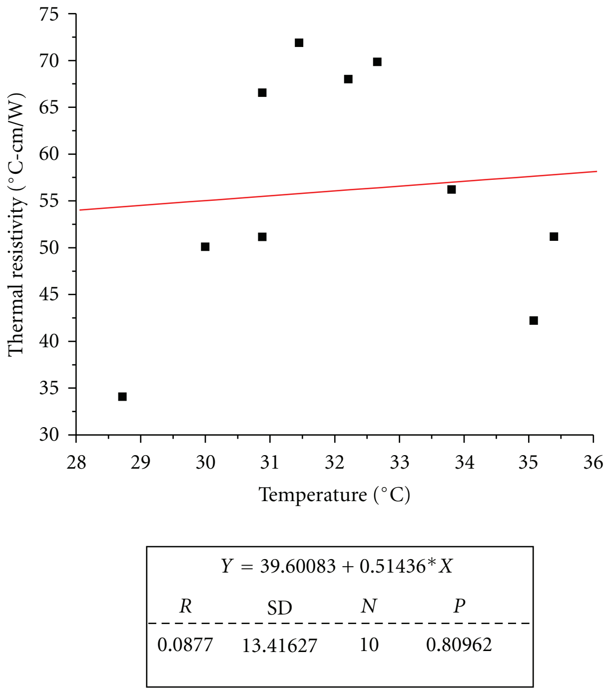


Figure 11: Variation of thermal resistivity with temperature.

Table 4: Thermal properties of soil materials (modified from [22]).

Material	Thermal resistivity (°C-cm/W)
Soil minerals	40
Granite	33
Quartz	11
Glass	100
Organic matter	400
Water	165@25°C
Ice	45@0°C
Air (101 kPa)	3880@25°C

The thermal resistivities of many of the minerals found in sands are also given in Table 4. Of these minerals, quartz has the lowest thermal resistivity of 11°C-cm/W. Quartz is also one of the most prevalent minerals in sand.

Also if a soil is to be used as insulation (i.e., oil pipeline applications or a backfill around a subsurface structure), then the sand should be poorly graded, mica-rich, and dry density and water content at compaction should be minimized. If heat transfer is to be maximized, the sand should be quartz-rich and well graded, and dry density and water content at compaction should be maximized [19]. Therefore it could be said that the soil in the study area will transfer heat well since it is composed mainly of quartz and was compacted at maximum dry density and optimum moisture content.

From the composition of the soil in the study area, it may therefore be said that heat will be well transferred since it is composed mainly of quartz, and maximum dry density and optimum water content were used.

3.2.7. Grain Size. The result of grain size analysis is given in Table 5 and Figure 14. It could be observed from the table that those with higher percentage of gravel and sand generally have low thermal resistivity. This may be explained by the fact that as the grain size decreases, more particles are necessary for the same porosity, which means more thermal resistance between particles [47].

The particle size and its distribution have an effect on the manner in which the moisture is held. With large-sized grains, the pore space available will be higher (due to the presence of air resulting in higher resistivity or lower conductance). Hence, dry soils have high resistivity values.

3.3. Calculated Thermal Resistivity. To demonstrate the utility and efficiency of the methods proposed by [35] termed *MDDTHERM* for predicting soil thermal resistivity, the measured results have been tested against the calculated results. The calculated thermal resistivity values are determined by the algorithm designed by [35] using the dry density, moisture content, and the particle size distribution.

The results are presented in Table 6. This table also presents the absolute percentage difference of the measured results with respect to the obtained results. From the table, it can be noticed that the proposed equations by Naidu and Singh gave thermal resistivity values which are close to the one measured in situ by KD 2 Pro.

It can also be observed from the table that the absolute percentage difference ranged from 0.018% to 35.24% and is less than 15–30%; for most of the sampled points some are even less than 1%.

Also, linear regression equation and correlation coefficient, R, between them were developed.

As shown in Figure 15, the value of $R = 0.85$ suggesting that there is fairly strong positive correlation between the measured thermal resistivity and the computed thermal resistivity.

4. Summary and Conclusion

4.1. Summary. The thermal resistivity of soil has been determined at Olorunsogo Power Plant. The results showed the values to range from 34.07–71.88°C-cm/W with an average of 56.43°C-cm/W. Also some factors have been found to influence the thermal properties of soils. As the moisture content increases, the thermal resistivity was found to be decreasing. Since the percentage of minerals as compared to air increases with increasing dry density, the greater the dry density of a soil, the lower the thermal resistivity. The degree of saturation was also found to influence the thermal resistivity of soil. Thermal resistivity increased with decreasing degree of saturation. As porosity and temperature increases, thermal resistivity also increased. Large-sized grains were found to have higher thermal resistivity while the small sized grains have lower thermal resistivity. Moreover, heat conduction through the minerals is an important mechanism of heat transfer in soil. Soils containing a high percentage of quartz will have a lower thermal resistivity

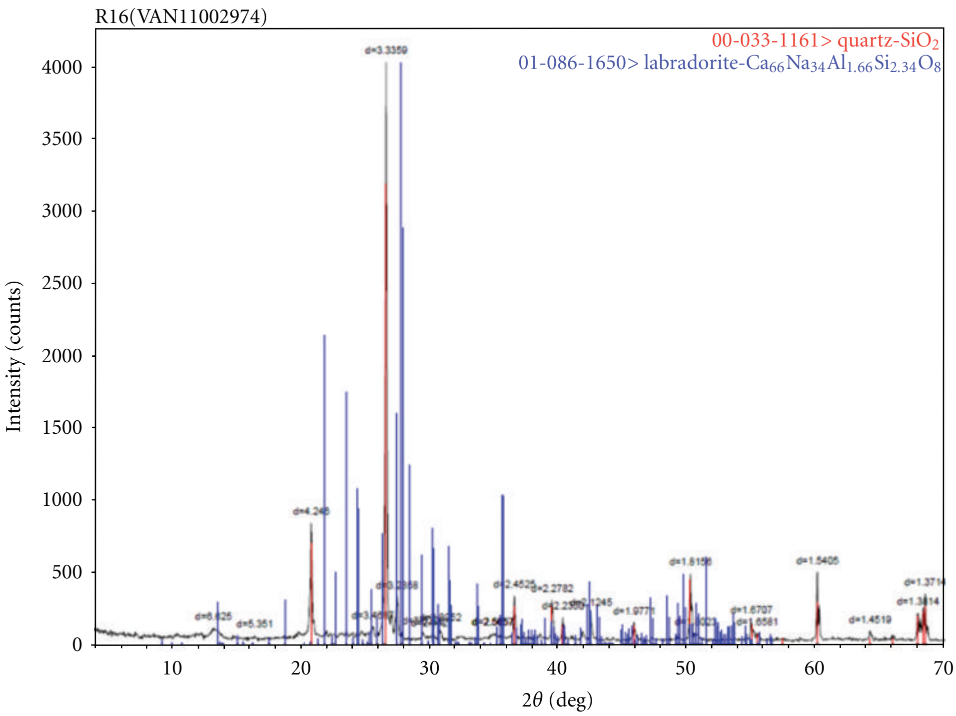


Figure 12: XRD result of Test Point (TP) 5.

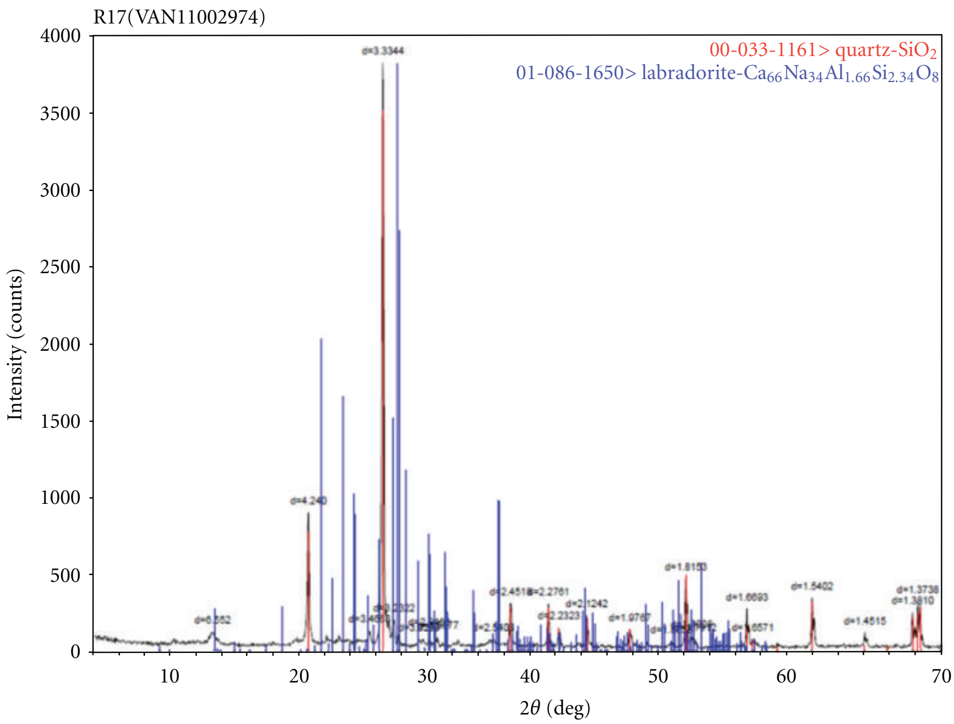


Figure 13: XRD result of test point (TP) 8.

than those containing a high percentage of mica, all other things being equal. The soil in study area was found to have high percentage of quartz which resulted in lower thermal resistivity.

Furthermore, the method proposed by [35] was used to calculate the thermal resistivity using the determined physical properties such as grain size, moisture content, and dry density. The result showed that there is a positive

Table 5: Grain size distribution of soils in Olorunsogo Power Plant.

Sample point	Gravel (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Silt (%)	Clay (%)
1	10.6	9.2	31.4	17.9	11.4	19.4
2	17.3	9.2	23.8	17.1	13.0	19.6
3	19.5	10.1	20.9	18.6	14.4	16.5
4	3.1	9.5	53.6	14.7	11.2	8.0
5	11.0	6.6	28.3	21.5	14.4	18.1
6	4.7	5.4	35.9	23.0	13.0	18.0
7	5.4	6.6	22.0	15.9	15.6	34.5
8	0	5.2	44.4	28.6	13.1	8.7
9	0	6.3	57.6	20.7	6.0	8.5
10	5.5	5.8	24.3	26.6	13.3	24.5

Table 6: Comparison of calculated and measured thermal resistivity.

Sample point (SP)	Dry density (g/cc)	OMC (%)	Measured thermal resistivity	Calculated thermal resistivity	% difference
1	1.85	15.0	50.10	63.99	21.71
2	1.92	16.2	56.20	56.21	0.018
3	1.80	13.0	69.84	73.33	4.76
4	1.84	15.4	34.07	52.61	35.24
5	1.73	14.0	66.54	81.22	18.07
6	1.93	14.0	67.99	75.81	10.32
7	1.88	13.0	51.15	67.44	24.15
8	1.81	13.0	51.18	64.43	20.56
9	1.89	15.0	42.21	48.43	12.84
10	1.91	13.0	71.88	72.13	0.35

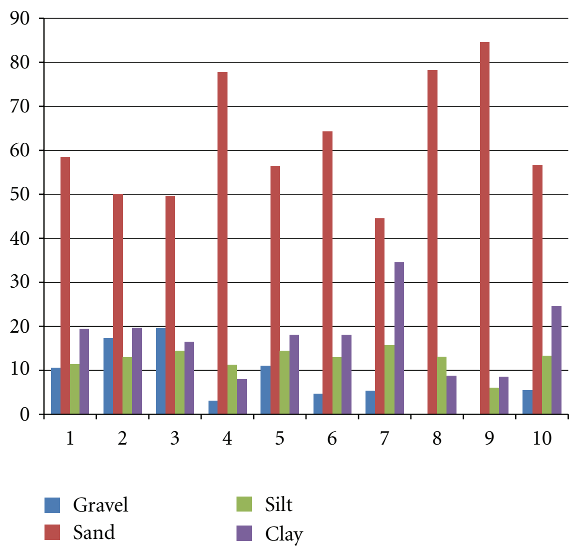


Figure 14: Bar graph showing grain size distribution of soils in Olorunsogo Power Plant.

correlation between the calculated thermal resistivity and the measured thermal resistivity.

4.2. Conclusion. It has been observed that the thermal resistivity of soil in the study area and their variation with moisture content, dry density, degree of saturation, porosity, temperature, grain size, and mineralogical composition agree with the results reported in the literature. From the thermal resistivity determined and the physical properties, it can be concluded that the soils in Olorunsogo Power Plant are good enough for laying of gas pipeline or buried cable in the area.

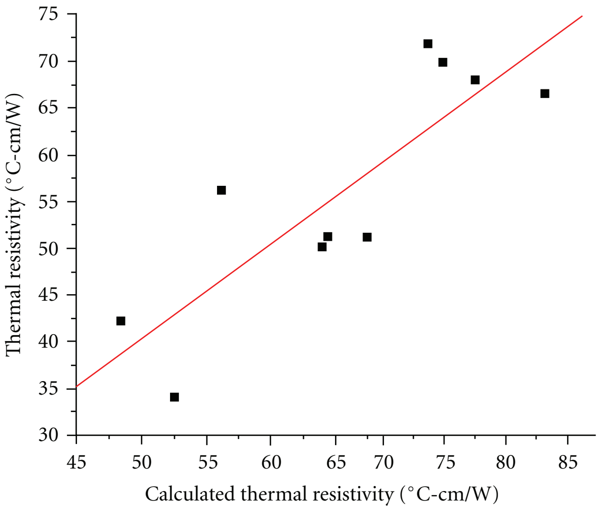
Table 7: Value of **a** for various soils.

Soil type	**a**
Clays Silts	0.219
Silty sand	0.385
Fine sand	0.340
Coarse sand	0.480
Gravel	0.21

Appendix

A. Proposed Generalized Relationships for Estimating Soil Thermal Resistivity

Naidu and Singh [35] developed generalized relationships for estimating the soil thermal resistivity using physical properties such as grain size, moisture content, and dry density. The relationships are described in the following.



$Y = -10.35864 + 1.01395B^*X$

R	SD	N	P
0.84577	7.18582	10	0.00205

Figure 15: Relationship between measured thermal resistivity and calculated thermal resistivity.

Figure 16: Photograph showing KD 2 Pro Meter.

A.1. Dry (Single Phase) Soils. For dry soils (single-phase) the following relationship to estimate soil thermal resistivity was proposed:

$$\frac{1}{R} = 0.01 \times \left[\mathbf{a} \cdot 10^{-3+0.06243\gamma\mathrm{dry}}\right]. \tag{A.1}$$

A.2. Moist (Single-Phase) Soils

(a) Clays and Silts. To obtain resistivity of moist clays and silts (single-phase), the following relationships are being proposed:

$$\frac{1}{R} = 0.01 \times \left[\mathbf{b} \cdot 10^{-3+0.06243\gamma\mathrm{dry}}\right], \tag{A.2}$$

$$\frac{1}{R} = 0.01 \times \left[1.07 \log(w) + \mathbf{c}\right] \times 10^{-3+0.06243\gamma\mathrm{dry}}, \tag{A.3}$$

Figure 17: TR-1 Needle.

Table 8: Value of **b** for clays and silts.

w (%)	Soil type	**b**
$4 > w \geq 2$	Clays	0.243
	Silts	0.254
$5 \geq w > 4$	Clays	0.276
	Silts	0.302

Table 9: Value of **c** for various soils.

Soil type	**c**	w (%)
Clays	−0.73	> 5
Silts (Fly ash)	−0.54	
Silty sand	0.12	≥ 1
Fine sand	0.70	
Coarse sand	0.73	
Gravel	0.8	

where R is the soil thermal resistivity (°C-cm/W), w is the moisture content (%), and γ_{dry} is the dry density of the soil (g/cc). Parameters **a, b**, and **c** depend on the type of the soil and its moisture content, and their values are presented in Tables 7, 8, and 9 respectively.

(b) Silts, Sands, and Gravel. Equation (A.3) can also be used to predict resistivity of silts and sands. In order to facilitate the computation of thermal resistivity of a multiphase system, generalized relationships were developed, assuming that soil consists of six-phase system (clays, silts, silty sand, fine sand, coarse sand, and gravel). For a naturally occurring soil, the resistivity of different phases is calculated by using (A.1)–(A.3). These resistivity values are multiplied by certain weights, which can be computed on the basis of their phase fraction. The weights assigned to different single-phase soils can be obtained as follows.

Weights

(a) For clay and silt phase:

$$\text{weight} = (\text{phase }\%), \quad \text{when } 5 \geq w\ (\%) \geq 2, \tag{A.4}$$

$$\text{weight} = \text{minimum of the (absolute } \mathbf{c} \text{ value or phase } \%), \quad \text{when } w\ (\%) > 5. \tag{A.5}$$

(b) silty sand, fine sand, coarse sand and gravel:

$$\text{weight} = (\text{phase}\ \% \times \mathbf{c} \text{ of the phase}) + \text{phase}\ \%, \quad \text{when } w\ (\%) > 1, \tag{A.6}$$

$$\text{weight} = \mathbf{a} \text{ of the phase}, \quad \text{when } w\ (\%) < 1\ (\text{dry soils}). \tag{A.7}$$

However, if a certain phase is absent, the weight for the phase is assigned zero. Sum of the resistivity values, so obtained, yields the thermal resistivity of the naturally occurring soil (or a mix soil).

Abbreviations

w: Moisture content
ρ_d: Dry density
S: Degree of saturation
MW: Mega Watts
G_s: Specific Gravity
e: Void ratio
TP: Test point
R: Coefficient of correlation
SD: Standard deviation
N: Number of samples
XRD: X-ray diffractometer
$\mathbf{a}, \mathbf{b}, \mathbf{c}$: Parameters having dependence on type of the soil.

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