The paper was published in the proceedings of the 7th International Young Geotechnical Engineers Conference and was edited by Brendan Scott. The conference was held from April 29th to May 1st 2022 in Sydney, Australia.

Thermal resistivity of soils: A geotechnical investigation perspective to support renewable energy projects

La résistivité thermique des sols: une perspective d'investigation géotechnique pour soutenir les projets d'énergies renouvelables

Alex Lodenkemper
Geotechnical, SMEC, South Africa, alex.lodenkemper@smec.com

ABSTRACT: The thermal resistivity of on-site soils plays a significant role in the design of a renewable energy facilities' electrical cabling and if not fully quantified may lead to the erroneous de-rating of cables or the unnecessary importation of cable bedding to site. It is the geotechnical practitioner's role to quantify this parameter and recommend how best to utilize the on-site material in achieving its thermal resistivity potential. This paper presents a geotechnical investigation methodology aimed at obtaining the necessary data from soil samples in order to best understand their thermal resistivity potential. This methodology was implemented on 30 proposed renewable energy facilities in South Africa with data obtained for a variety of soil types. 120 samples were tested to obtain: 1) maximum dry density at optimum moisture content, 2) in-situ moisture content, and 3) thermal resistivity at varying moisture content and dry density. The results are analysed and corrected at different dry-out stages to produce a table of suggested thermal resistivity ranges for different soil types. The table can be used by design engineers for the preliminary selection of electrical cable de-rating values and by geotechnical practitioners to corroborate their field results and further guide detailed geotechnical investigations.

RÉSUMÉ : La résistivité thermique des sols sur site joue un rôle important dans la conception du câblage électrique d'une installation d'énergie renouvelable et, si elle n'est pas entièrement quantifiée, elle peut entraîner un déclassement erroné des câbles ou l'importation inutile de nappes de câbles sur le site. C'est le rôle du géotechnicien de quantifier ce paramètre et de recommander la meilleure façon d'utiliser le matériau sur site pour atteindre son potentiel de résistivité thermique. Cet article présente une méthodologie d'investigation géotechnique visant à obtenir les données nécessaires à partir d'échantillons de sol afin de mieux comprendre leur potentiel de résistivité thermique. Cette méthodologie a été mise en œuvre sur 30 installations d'énergie renouvelable proposées en Afrique du Sud avec des données obtenues pour une variété de types de sols. 120 échantillons ont été testés pour obtenir : 1) une densité sèche maximale à une teneur en humidité optimale, 2) une teneur en humidité in situ et 3) une résistivité thermique à différentes teneurs en humidité et densité sèche. Les résultats sont analysés et corrigés à différents stades d'assèchement pour produire un tableau des plages de résistivité thermique suggérées pour différents types de sol. Le tableau peut être utilisé par les ingénieurs de conception pour la sélection préliminaire des valeurs de déclassement des câbles électriques et par les praticiens de la géotechnique pour corroborer leurs résultats sur le terrain et orienter davantage les études géotechniques détaillées.

KEYWORDS: thermal resistivity, thermal conductivity, renewable energy, SANS 10198, ASTM D5334.

1 INTRODUCTION

In response to climate change there has been a global rise in the commissioning of renewable energy facilities. Since the formulation of the Renewable Energy Independent Power Producer Procurement (REIPPP) programme in 2011, South Africa has seen a tremendous increase in the commissioning of renewable energy facilities. REIPPP is the mechanism in which the South African Government aims to achieve its goal of 17 800 MW of renewable energy by 2030 as highlighted in the government's Integrated Resource Plan (IRP) of 2010.

For the successful financial close, engineered design and sustainable operations of an energy facility, geotechnical investigations are required to define the geotechnical zonations of the parcel of land to be developed. An often-over-looked aspect is the thermal resistivity of on-site soils and whether these may be utilized as electrical transmission cable bedding

The electrical capacity of a transmission cable is limited by the maximum permissible temperature of the cable as well as by its surrounding bedding. It is clear that electrical transmission cables that can carry more current are more economical to an energy producing facility which may have in excess of kilometers of underground cabling. To avoid the unnecessary de-rating, and subsequent current carrying capacity of transmission cables, the appointed design engineer must have confidence in the thermal resistivity of the bedding to be utilized for the project. The lower the thermal resistivity of the cable bedding, and importantly, the soils ability to retain this thermal resistivity at low moisture content, play a fundamental role in the design and cost of electrical transmission cabling for any electrical infrastructure project.

2 FACTORS AFFECTING THERMAL RESISTIVITY

The thermal resistivity of a soil is its ability to resist thermal energy transfer, hence the lower the thermal resistivity the more likely heat can transfer through the soil mass. The following factors, after Mitchell et al (1977), affect a soil's thermal resistivity.

2.1 *Soil Composition*

Some minerals can resist thermal energy transfer less than others, for instance quartz has a much lower thermal resistivity compared to mica. Other constituents to a soil include water, air and organic matter all of which have substantially higher thermal resistivity than mineral solids. It is clear than that a soil mass must have a higher ratio of mineral solids to water, air and organic content in order for it to obtain its most efficient thermal resistivity.

2.2 *Density*

Density is considered one of the most important factors affecting soil thermal resistivity. Simply put the greater the density of a soil mass the greater the number of soil particle/ mineral contacts and thus the greater the opportunity for thermal energy to be transferred. In essence the greater the density of a soil mass the lower the thermal resistivity.

2.3 *Water Content*

When water is introduced into a soil mass it coats individual soil particles. The water coating substantially increases the contact zones between soil particles and subsequently decreases the thermal resistivity. Only small quantities of water are required to facilitate lower thermal resistivity and is primarily dependent on the particle shape and size. Where excess water is added to fill the voids between soil particles, it does not facilitate further lowering of thermal resistivity as the thermal energy is more effectively transferred through solid particle contacts.

2.4 *Particle Shape and Size*

The aforementioned factors show a similar trend in the fact that the greater the contact area of soil/ mineral particles, the lower the thermal resistivity of the soil mass. Wiseman et al (1960) concluded that larger particle sizes and rounded particle shapes have lower thermal resistivity than compared to smaller particles and blocky shapes. Even more importantly the particle shape and size, as well as their distribution, affect the compacted density of a soil mass.

2.5 *Particle Size Distribution*

For a soil mass to achieve a high compacted density it requires a well-graded particle distribution so that small grains may fill the voids between lower grains. In essence well-graded soil masses can achieve higher soil density and thus have lower thermal resistivity than poorly graded soils.

2.6 *Temperature*

Higher soil temperatures result in faster loss of soil moisture resulting in a reduction of soil particle contacts and to a certain degree soil density resulting in an overall increase in thermal resistivity.

2.7 *Type of Compaction*

It is not the compactive effort per se that influences the thermal resistivity but more the water content used during compaction. Dry or relatively dry (low water content) compaction may result in the segregation of soil fines. Variable fines distribution may lead to higher thermal resistivity. Compaction at higher water content generally produces a soil mass with a lower thermal resistivity.

3 APPLICABLE STANDARDS

In South Africa there are primarily two standards that govern the selection and testing of soil for thermal resistivity.

3.1 *ASTM D5334*

The ASTM D5334 test method is the standard for the determination of thermal conductivity of soil and soft rock by thermal needle probe procedure (2014). This standard is implemented by accredited civil engineering soil and rock testing laboratories. For clarity, thermal conductivity is the inverse of thermal resistivity.

The standard specifies the test method for both in-situ and reconstituted samples. In most instances, unless a geotechnical practitioner owns their own probe, soil samples are taken from site and sent to the laboratory for testing following the methodology offered by the standard. A critical aspect to the methodology is that the sample must be compacted to a desired density and moisture content. The laboratory should request this information from the consultant and thus the consultant should have a predetermined idea of what density and moisture content they would like the thermal conductivity to be tested at.

3.2 *SANS 10198-5*

"The selection, handling and installation of electric power cables of a rating not exceeding 33 kV, Part 5: the determination of thermal and electrical resistivity of soil" (2004). A design standard that assists engineers in rating electrical transmission cables based on the thermal resistivity of cable bedding.

The standard indicates that an idealized thermal resistivity for bedding material is 1.2 K.m/W. Where the thermal resistivity increases beyond this value the electrical cables need to be de-rated accordingly to avoid run-off heating which may cause the malfunction of cables. The standard offers a testing methodology to determine the thermal resistivity of soil, however the procedure is found lacking crucial elements such as the need to determine the density and moisture content at which the samples are tested at.

4 TESTING METHODOLOGY

To adequately assist design engineers in quantifying soil thermal resistivity the geotechnical consultant must understand the standard used by the engineers (SANS 10198-5) and prescribe a soil testing schedule that will provide qualitative thermal resistivity data by correct testing procedures (ASTM D5334). The following testing methodology has been used on numerous energy facilities and is considered as providing the essential parameters required to understand the thermal resistivity potential of on-site soils.

4.1 *Material Selection*

One needs to remember the key factors (Chapter 2) determining a soil's thermal resistivity and actively pursue materials on site that are likely to offer the best results. Similarly, if a site does not offer material perceived to be of good cable bedding the thermal resistivity must nonetheless be determined so that boundary limits may be prescribed to the design engineer.

Depending on the type and rating of transmission cables, cable trenches are typically excavated within the upper 1.5 m of the ground profile. It is reasonable then to focus material sampling within this profile across the site, however one may also consider sampling material at greater depths where for instance large quantities are anticipated for removal during excavation and stockpiling. One should also sample greenfield and commercial material sources (borrow pits and quarries) within a reasonable haulage distance of the energy facility.

4.2 *Particle Size Distribution and Atterberg Limit Determination*

To quantify the index parameters of the soil and empirically define the class of soil, as per the Unified Soil Classification System, the samples must be subjected to the relevant test procedures (ASTM D6913 and ASTM D4318).

4.3 *Maximum Dry Density*

The maximum dry density at optimum moisture content must be determined per sample taken. The Modified Proctor compaction technique (ASTM D1557) is the most relevant testing method; however a standard proctor may suffice as well. From the test results the laboratory, or geotechnical practitioner, must produce the moisture density curve for the material. This will inform the density to moisture ratios the samples must undergo thermal resistivity testing.

4.4 *Natural Moisture Content*

The natural moisture content (ASTM D2216) of each sample must be determined. Furthermore, it should be noted whether the sample was taken during a dry period or wet period so the limits of how dry or wet the material may become during the operation of the facility may be approximated. The natural moisture content during the dry season will determine the likelihood of the compacted bedding maintaining a reasonable moisture content during operation or whether intervention is needed to prevent thermal run-off (progressive drying out of cable backfill).

4.5 *Thermal Resistivity*

Once the aforementioned parameters have been determined reasonable ranges of density and moisture content can be chosen for testing the thermal resistivity of the sample (ASTM D5334). It is advisable to test at least four (4no.) moisture contents and respective density ranges:

- 0% moisture content
- 2% moisture content
- Natural moisture content
- Optimum moisture content

Testing at 0% moisture content will provide the dried-out thermal resistivity of the soil and this will act as the boundary limit should the material ever experience thermal run-off. The remaining moisture contents and subsequent density ranges should produce a progressive decrease in thermal resistivity. Where the natural moisture content is close to one of the other defined moisture contents it is advised that a different moisture content and density be specified to offer additional data. It should be noted that the aforementioned ranges are dependent on the environment in which the energy facility will be located. In this regard the ranges provided are those typically used for a dry climate. Ranges will be higher in a wet climate.

5 RESULTS

The aforementioned testing methodology was implemented at 30 proposed renewable energy facilities and a total of 120 samples were tested. For clarity the facilities were all undergoing preliminary investigation some of which are located on extremely rocky terrain. As such the sample quantity defined herein should not form the basis for determining a testing schedule for geotechnical investigations which should rather be informed by the stage the investigation is at as well as the materials offered by the site.

The majority of the sites are located in the Northern Cape of South Africa with a desert or semi-desert environment. Some sites are located in the highlands of the Kingdom of Lesotho where heavy rainfall is experienced. Subsequently samples tested from the dry climates mainly comprised sands and gravelly sands whereas samples taken from the wet climates comprised mainly silts and clays. For ease of analysis samples were categorized according to their Unified Soil Classification. The soils tested include:

- SP: poorly graded sands, gravelly sands, little or no fines
- SM: silty sands, sand-silt mixtures
- SC: clayey sands, sand-clay mixtures
- CL: inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
- CH: inorganic clays of high plasticity, fat clays

Of the 120 samples tested 3% classified as SP, 65% as SM, 10% as SC, 19% as CL and 3% as CH. A summary of pertinent laboratory test results is provided in Table 1. For clarity SM samples were tested at two density ranges, below and above 1850 kg/m³, because of the large variety of densities achievable by this soil range. All samples tested showed a familiar trend of thermal resistivity lowering with increased moisture content and increased density. The decrease in thermal resistivity typically peaked at maximum dry density and optimum moisture content however did continue to decrease incrementally with an increase in water content. Figure 1 shows this trend graphically per soil type tested. For further analysis Table 2 indicates at what moisture content and density ranges the soil types start to meet the idealized thermal resistivity of 1.2 K.m/W (SANS 10198-5) for use as bedding for electrical transmission cables.

Table 1. Summary of maximum dry density (MDD) and optimum moisture content (OMC) results for various soil types tested. Standard deviation and coefficient of variance (COV) indicated.

Soil	Kg/m³	Std. D	COV	OMC	Std. D	COV
SP	1790	40	2%	12.5	0.4	3%
SM>1850*	2085	45	2%	9	1.6	18%
SM<1850*	1880	150	8%	10	3.5	34%
SC	1920	100	5%	11.5	2.5	22%
CL	1900	70	4%	15	3	20%
CH	1630	50	3%	20	3	15%

**Thermal resistivity tested at densities greater or lower than 1850 kg/m³*

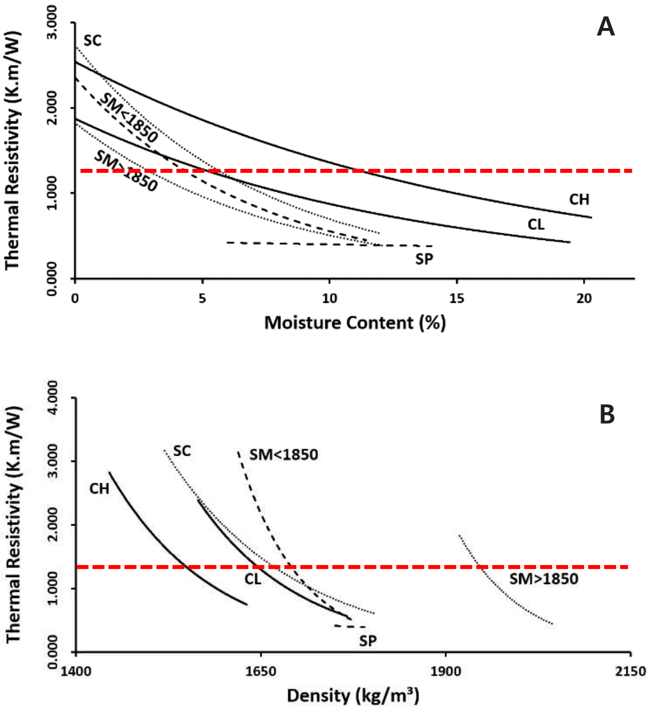

Figure 1. Exponential trend lines depicting the idealized decrease in thermal resistivity of different soil types as (a) moisture content increases, and (b) density increases. The idealized thermal resistivity (1.2 K.m/W) for cable bedding as per SANS 10198-5 (2004) is indicated.

6 ANALYSIS

A first observation is that the sandier soils (SP, SM and SC) reach the idealized thermal resistivity of 1.2 K.m/W quicker, and at lower water contents, than the clay-rich soils. This observation is expected due to the sandier soils having greater density potential but also that their particle shape and size increase contact for thermal transfer. Should one look at it in a hierarchical sense then it is further observed that SP soils have the lowest thermal resistivity properties at maximum dry density at optimum moisture content followed by high density (>1850 kg/m³) SM soils, low density (<1850 kg/m³) SM soils and then lastly by SC soils. When it comes to clay soils (CL and CH) the CL soils have more favorable thermal properties which is attributed to their ability to be compacted to higher density.

Table 2. Summary of minimum density and moisture contents to reach idealized thermal resistivity of 1.2 K.m/W.

Soil	Kg/m³	Std. D	COV	Moist.	Std. D	COV
SP	1750	0	0%	2	0	0%
SM>1850	1910	50	3%	2	0.6	30%
SM<1850	1680	70	4%	4	2.6	70%
SC	1650	110	6%	6	2.8	50%
CL	1610	100	6%	5	3.5	75%
CH	1530	30	2%	12	3.0	30%

A second observation is that all soil types reached the idealized thermal resistivity prior to reaching maximum dry density at optimum moisture content. One must however be cognizant that electrical cables will heat these soils and subsequent moisture loss will be experienced. The minimum density and moisture contents are thus not suitable ranges for long term functionality of cable bedding.

A third observation is that as density decreases a subsequent increase in moisture content is required to reach the idealized thermal resistivity. This observation is applicable to both low density soils and those with high fines content. Again one must take caution and pragmatically assess whether the high moisture content will be maintainable during the lifecycle of the cable bedding.

7 PROVISIONAL THERMAL RESISTIVITY RANGES

Based on available data Table 3 has been developed to provide provisional thermal resistivity ranges for the soil types tested. These have been evaluated further, using guidelines offered by SANS 10198-5, to provide dried-out thermal resistivity ranges for the soils. Table 3 is provisional, and its intention is to be used as a guideline for both design engineers and geotechnical practitioners. For design engineers the table can be used as a refined table guiding the de-rating, if necessary or not, of cables based on material chosen for cable bedding. For geotechnical practitioners the table can be used to corroborate their field results as well as guide them on detailed laboratory test scheduling.

8 DISCUSSION

The data is clear in showing that sandy soils have the lowest thermal resistivity ranges (Table 2 and 3). This is primarily due to their ability to reach higher density values at relatively low moisture contents. Pure sand (SP), although having the lowest thermal resistivity range at maximum dry density and optimum moisture content is however sensitive to moisture loss as observed with its comparatively higher dried-out thermal resistivity. The higher dried-out thermal resistivity for SP soils is due to its poorer particle size distribution and thus as moisture is lost there are more air voids and no smaller grains to take up the space as would be the case for mixed sands such as SM.

SM soils at the higher density range produce the most reliable results, in the sense that there is little reduction in their dried-out thermal resistivity. As the density range for SM soils decreases more variability is introduced to its thermal resistivity ranges. In all instances SM soils have the most favorable thermal resistivity ranges attributed to the good particle size distribution of these soils with subsequent high densities and retention of soil moisture. Splitting the SM soils into two separate classes was a necessary task as one can clearly see the dominant influence density plays in the thermal resistivity of these soils with the optimum moisture contents between the two of negligible difference.

SC soils, although with acceptable thermal resistivity ranges, perform the worst out of the sandy soils due to the introduction of clay. SC soils perform well where the moisture content can be maintained, and this is due to the clay assisting with compaction but also in retaining water for longer. SC soils at dried-out stage have a highly variable thermal resistivity range which is attributed to the clay drying up and sand crumbling resulting in the formation of cracks and subsequent introduction of air voids into the bedding.

Clay soils have low thermal resistivity at high moisture content. Out of the clay soils the CL type has the lowest and least variable thermal resistivity ranges. This is due to its ability to be compacted to higher density with less water content whereas CH soils have a very low density and require much more water to reach compaction. Subsequently CH soils perform the worst at dried-out thermal resistivity.

Although high moisture content decreases the thermal resistivity of a soil; it is important, for the long-term operation of the cable, that the dried-out thermal resistivity of cable bedding does not exceed, for long periods, the idealized thermal resistivity of 1.2 K.m/W. Soils requiring high moisture content to reach compaction are therefore at a disadvantage because the more moisture that is lost, the greater the difference between their functional and dried-out thermal resistivity ranges. This being said, cables can be covered by bedding with high thermal resistivity, however it is important for the design engineer to know these limits so that the cable may be de-rated accordingly.

As a general rule clay soils, although having low thermal resistivity, are unlikely to be used as cable bedding because when they dry-out they produce cracks in the bedding which introduce air – a poor transfer of thermal energy – and can also physically damage cables through heave and swell. Clay-rich soils, can however be utilized in environments where the moisture content is known not to vary considerably and a suitable bedding moisture content is maintainable.

Table 3. Provisional thermal resistivity (TR) and dried-out TR ranges for different soil types tested at maximum dry density (MDD) and optimum moisture content (OMC).

Soil	Kg/m³	OMC (%)	TR (K.m/W)	Dried-out TR (K.m/W)
SP	1790	12	0.4 - 0.5	1.2 - 1.5
SM>1850	2085	9	0.5 - 0.6	0.6 - 0.7
SM<1850	1880	10	0.7 - 1.0	0.9 - 1.2
SC	1920	12	0.6 - 0.8	1.1 - 1.5
CL	1900	15	0.6 - 0.7	1.0 - 1.2
CH	1630	20	0.7 - 0.8	1.3 - 1.4

9 LIMITATIONS

The following limitations should be considered prior to use of the suggested testing methodology and provisional thermal resistivity ranges:

- The majority of samples taken comprised variable quantities of gravel that no doubt contributed to the density ranges achievable. The thermal conductivity test procedure (ASTM D5334) limits the sample size to 50 mm in diameter and 300 mm in length (reconstituted). It is likely that the coarse fraction of the material is removed during this test procedure and thus thermal resistivity results are done at densities not truly reflective of the material. Furthermore, the data in this paper does not quantify the effect and extent that gravel contacts with cables may have on the overall performance of the cable bedding.

- SP and CH samples are of limited representation in the presented data pool. It is likely that the thermal resistivity ranges are subject to alteration as more data becomes available.
- This paper does not contain data for soil types GW, GP, GM, GC, SW, ML, OL and OH and thus no thermal resistivity ranges are yet forthcoming.
- Testing the thermal conductivity of in-situ soils using the thermal needle probe (ASTM D5334) will generally produce higher results than those achieved through sample reconstitution (as the in-situ density is typically greater than that achievable by compaction techniques). It is advisable then that on-site, soil likely to be used as cable bedding be tested using the reconstituted method as this will represent more readily the conditions achievable during construction.

10 CONCLUSIONS

Defining accurate soil thermal resistivity ranges for on-site soils can save drastically on cable bedding haulage to site where this is most likely unnecessary. The majority of on-site soils, at least those classified as SP, SM, SC, CL and CH, do have suitable thermal resistivity ranges and may act as electrical cable bedding to allow for adequate functioning of electrical cables (Figure 1). Moisture content, and thus the surrounding environment however, are limiting factors which will determine how reliably these soils will maintain their thermal resistivity ranges during heating of electrical cables as well as moisture loss during seasonal fluctuations.

It is established that all soil types have the lowest thermal resistivity values at maximum dry density at optimum moisture content. At these ranges the soil types have thermal resistivity ranges below the idealized 1.2 K.m/W, however some, for instance the clay soils, require much higher water contents to achieve suitable density and acceptable thermal resistivity ranges. Sandy soils are the most suited as cable bedding because they attain high density ranges at relatively low moisture contents. Out of the sandy soils those classified as SM with density ranges greater than 1850 kg/m³ have the most reliable thermal resistivity properties in the sense that the difference between functional (at MDD and at OMC) thermal resistivity and dried-out thermal resistivity is very low. SM soils with lower densities (<1850 kg/m³) have low functioning thermal resistivity's, however, have more variability at dried-out stage. SP soils have very low functioning thermal resistivity however are prone to rapid moisture loss resulting in high dried-out thermal resistivity ranges. SC soils have low functional thermal resistivity ranges, however at dry-out situations the clay and sand combination are prone to cracking allowing for air void formation and subsequently higher thermal resistivity values. Clay-rich soils, although having low functional thermal resistivity ranges, are subject to heave and shrinkage – and likely crack formation – at dried-out stage. Clay soils are only suitable for cable bedding in environments where the cable bedding soil moisture is guaranteed to stay at the high levels required to reach functional conditions (MDD at OMC).

A table of provisional thermal resistivity ranges for the different soil types tested has been produced as a guide to offer design engineers insight into the thermal resistivity achievable by different soil types at maximum dry density and at optimum moisture content to assist in the de-rating of electrical transmission cables. The same table may be used by geotechnical practitioners to guide detailed testing schedules and corroborate their laboratory test data.

It is concluded that the most suitable soil for use as thermal bedding for electrical cables, and generally the most available soil type – in a dry climate – are SM soils and in particular those with density ranges exceeding 1850 kg/m³. For optimum performance of electrical cable bedding, it is recommended that these soils be compacted to maximum dry density wet (2%) of optimum moisture content. Furthermore, to facilitate slower dried-out stages, it is recommended that cables be buried at depths no shallower than 1.2 m in dry climate regions. Alternatively, there are techniques, as studied by others, that assist in the retention of moisture content in cable bedding soils.

11 REFERENCES

ASTM D5334-14, Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure, ASTM International, West Conshohocken, PA, 2014.

ASTM D1557-12e1, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)), ASTM International, West Conshohocken, PA, 2012.

ASTM D2216-19, Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, ASTM International, West Conshohocken, PA, 2019.

ASTM D4318-17e1, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, West Conshohocken, PA, 2017.

ASTM D6913 / D6913M-17, Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, ASTM International, West Conshohocken, PA, 2017.

Mitchell J.K., Kao T-C. and Abdel-Hadi O.N. 1977. Backfill materials for underground power cables. Phase 1. Interim report: thermal resistivity measurement methods, backfill treatments heat and moisture flow analysis.

SANS 10198-5, The selection, handling and installation of electric power cables of rating not exceeding 33 kV. Part 5: Determination of thermal and electrical resistivity of soil, South African Bureau of Standards, Pretoria, Gauteng, 2004.

Wiseman R.J. and Burrel, R.W. 1960. Soil Thermal Characteristics in Relation to underground Power Cables. AIIE Committee Report, Transaction of AIEE, Vol. 79, pp. 792-856.