Evaluation of thermal transfer processes and back-fill material around buried high voltage power cables

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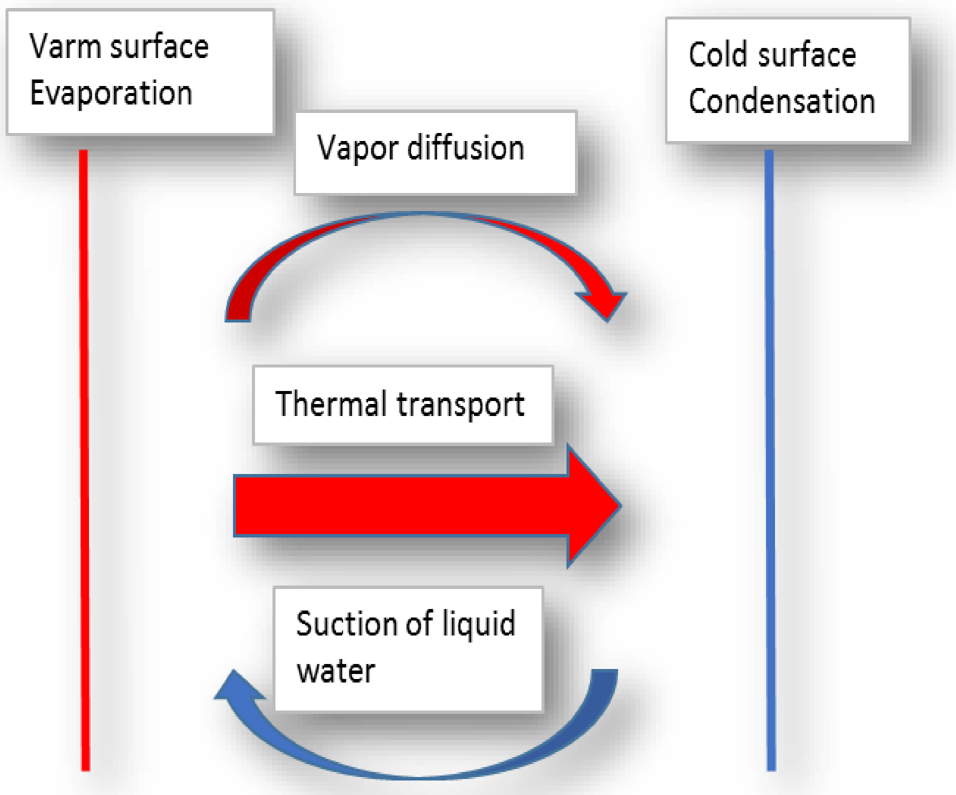

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Content

Glossary and definitions

Thermal transport

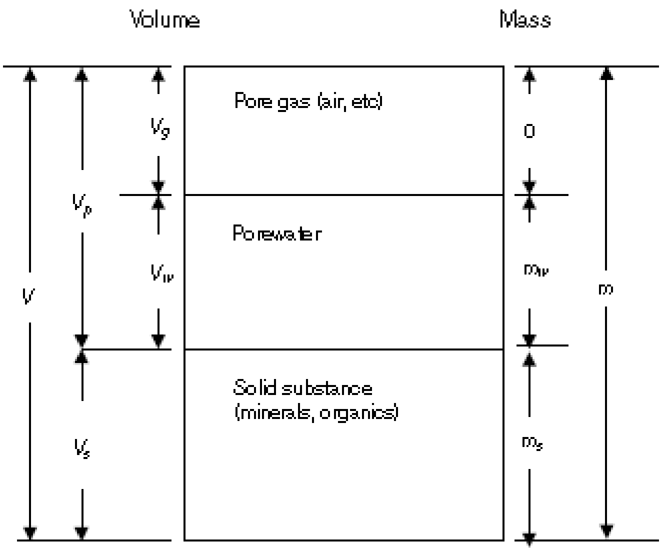
- Thermal resistivity, Rho ((m·K)/W): a material´s resistance to transport thermal energy. The thermal resistivity is the inverse of the thermal conductivity R=1/λ.
- Thermal conductivity, λ (W/(m·K)): the ability for a material to transport thermal energy
- (Volumetric) Heat capacity, C (J/(m^3·K)): a materials ability to store thermal energy C=ρ·c, ρ=density (kg/m^3), c=specific heat capacity (J/(kg·K))
- Thermal diffusivity, κ (m^2/s): the ability of a material to level temperature differences

The thermal properties are related to each other as follows:

$$\kappa = \lambda/(\rho\cdot c) = \lambda/C = 1/(Rho\cdot C)$$

Structure of porous media

The principal structure of soils, or other porous media, can be expressed by the figure below. It consists of solid soil particles (V_s) and pore volume (V_p) and related masses (m). The pore volume is in nature filled with partly water and air above the ground water table. Below the ground water table the pores are completely filled with water. A well compacted soil has a lower pore volume (higher density) compared to a non-compacted soil. The relationship between the pore volume and the total volume is the porosity (V_p/V). The degree of water saturation (S_r) is a measure of how large part of the pore volume that is filled with water ($S_r=V_w/V_p$). In the figure below the porosity is about 60% and about 2/3 of the pore volume is filled with water (S_r≈65%). See also Figure 2.



The density can relate to different mass-volume relationships, e.g. the dry density is the relation between the dry solid mass (m_s) and the total volume (V). The water content can be expressed in several common way meaning quite different things. It is therefore necessary to define the water content in a proper way. Normally the water content relates to the mass of water (m_w) and the total mass (m) but in geotechnical papers it is common to relate to the dry mass (m_s) instead of the total mass which can be confusing if it is not clearly expressed (the latter definitions implies a possible water content exceeding 100%). A third possibility is a definition per volume. Some definitions are clarified below:

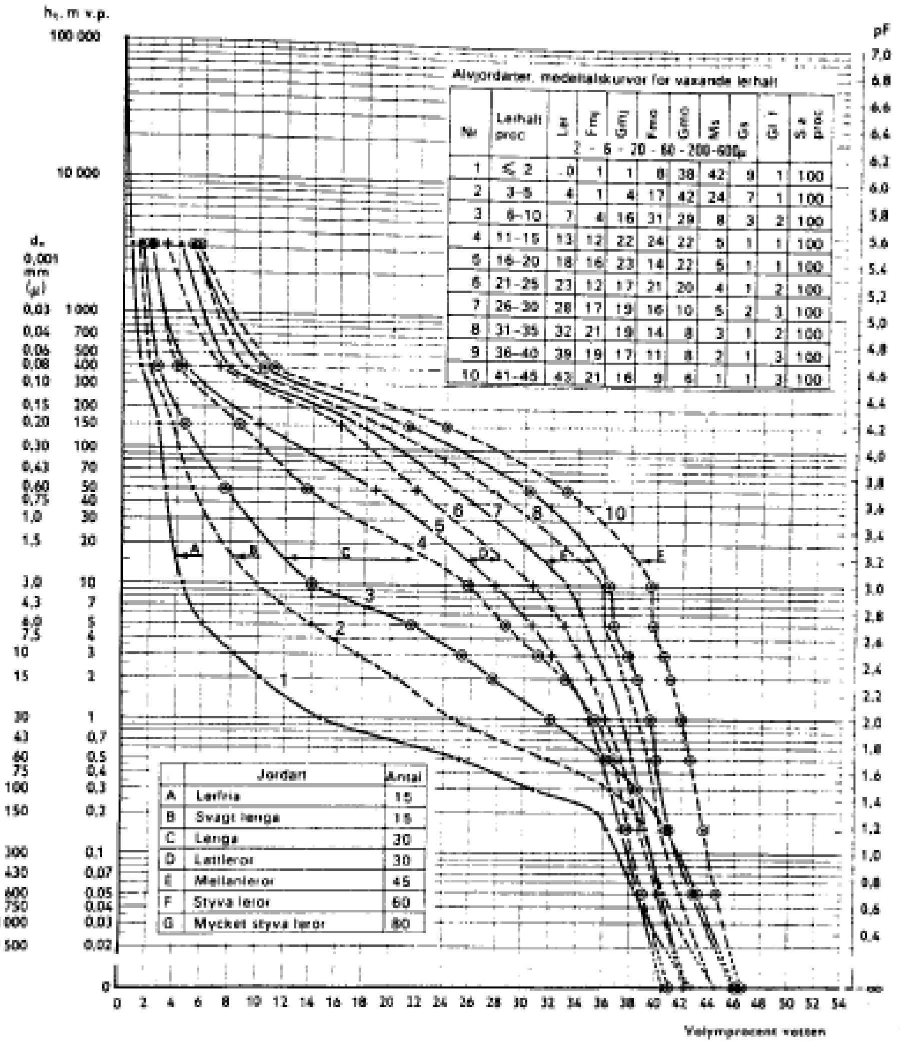
Density of solid particles, ρ_s (kg/m3)	$\rho_s = m_s/V_s$
Bulk density, ρ (kg/m3)	$\rho = m/V = \rho_d \cdot (1+w)$
Dry density, ρd (kg/m3)	$\rho_d = m_s/V = \rho \cdot (1/(1+w))$
Water content, w_h (%)	$w_h = m_w/m$
Water ratio, w (%) (or water content)	$w = m_w/m_s$
Volumetric water content, Θ (%)	$\Theta = V_w/V = (\rho_d/\rho_w) \cdot w = n \cdot S_r$
Porosity, n (%)	$n = V_p/V = 1- \rho_d/\rho_s$
Degree of water saturation, S_r (%)	$S_r = V_w/V_p$

Water retention

Below the ground water table the pore system is saturated with water. Above the ground water table the water content is lower. The water retention capacity influence the water content in relation to the suction head (distance above ground water table) under steady state conditions.

In the Figure below water retention curves (or pF curves) are illustrated for different soils from sand to clay. The groundwater table can be assumed to be at pF=0 on the vertical scale (in reality it corresponds 1 cm above the ground water table). The pF scale (left vertical scale) is linear and corresponds to a logarithmic scale with the negative pressure (or suction head) expressed as cm water table (right scale): e.g. pF=2 corresponds to 100 cm since $\log^{10}(100)=2$. The curves are sorted on clay content. The lowest curve (1) is a clean sand and the uppermost curve has the highest clay content.

The horizontal scale express the water content, commonly expressed as volumetric water content. This is quite convenient since it also gives information about the porosity of the soil since porosity is equal to volumetric water content at full water saturation (pF=0).



The water retention capacity (or pF curves) for different soil types, from a sand to a clay, sorted by the clay content; 1: low, 10: high (Andersson & Wiklert, 1972).

Hydraulic transport

The hydraulic conductivity describes the ability for a material to transport water in a saturated pore system. The unsaturated hydraulic conductivity corresponds to unsaturated conditions and is much lower the saturated ditto for a specified soil type.

1 Introduction and objectives

1.1 General

The thermal processes around buried power cables control the temperature of the cable and the size of the possible electric power transmission. At low temperature and stationary conditions the heat transport is controlled mainly by the thermal resistivity of the backfill and the surrounding soil. At high temperature the thermal processes are much more complicated and includes vapor diffusion in the direction of the thermal gradient and a balanced suction of water in the opposite direction.

If the suction of water cannot balance the vapor diffusion, the soil around the cable is drying out and the thermal resistivity is significantly increased. The temperature rise may damage the cable or, in extreme cases, destroy the cable.

This report is focused on the state of knowledge of the thermal processes around power cables and cable back-fill material.

In Appendix 5 there is a literature review with focus on the thermal processes around cables.

Some definitions (SI units) on thermal properties:

- Thermal conductivity, λ (W/(m·K)): the ability for a material to transport thermal energy
- Thermal resistivity, Rho ((m·K)/W): a material´s resistance to transport thermal energy. The thermal resistivity is the inverse of the thermal conductivity $R=1/\lambda$.
- (Volumetric) Heat capacity, C (J/(m^3·K)): a materials ability to store thermal energy $C=\rho\cdot c$, ρ=density (kg/m^3), c=specific heat capacity (J/(kg·K))
- Thermal diffusivity, κ (m^2/s): the ability of a material to level temperature differences

The thermal properties are related to each other as follows:

$\kappa = \lambda/(\rho\cdot c) = \lambda/C = 1/(Rho\cdot C)$

Other glossary and definitions are described in the section “Glossary and definitions”.

1.2 Factors affecting the thermal design

The cable's temperature is affected by the following factors:
1. Thermal properties of natural soil
2. Natural undisturbed temperature and temperature variation in the ground
3. A cable's thermal properties at different temperatures
4. Type of cable, wire size and number of cables
5. Laying depth for cable
6. Distance between cables
7. Dimensioning Electric power and its duration

Paragraph 2, but mainly paragraph 1, naturally varies by route. The variations are in a comparatively small scale. Paragraph 3-7, can often be controlled and off-suited so that the temperature of the cable is adjusted.

The cables are generally in the cable trench at least 1.2 m deep, see Principle in Figure 1. Drilled installation also occurs, primarily in peat.

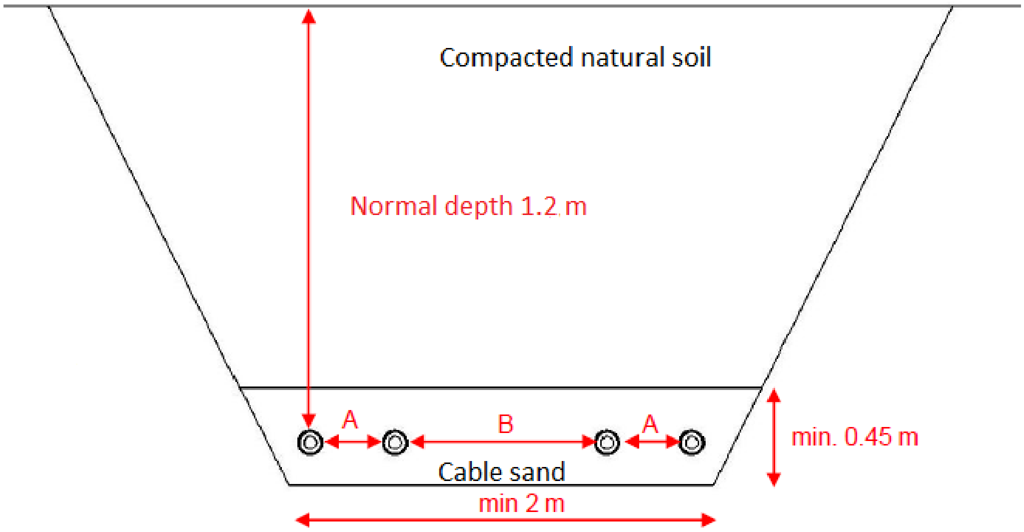


Figure 1 Principle of the cable trench in soil with 4 cables at the Southwest Link.

Soil thermal properties under paragraph 1 vary in both space and time. The thermal properties at normal temperature depends mainly on the density, water content and the mineral distribution. The thermal property variation in time depends on variation in the water content due to infiltration of water (consequence of rainfall, surface runoff and evaporation), soil type and ground water level.

The natural mean ground temperature (2) is usually estimated from the annual mean air temperature. However, the mean soil temperature is influenced by snow cover and the freezing process and is therefore expected to be a bit higher than the mean air temperature in the northern part of Sweden. Continuous measurements of natural soil temperature outside roads etc. are rare.

Cable Sands (3) protects the cable and have a thermal surface enlarging influence and thus lowers the surface temperature of the cable. Quality, extent and geometry of the cable sand can significantly affect the cable temperature and counter the influence of high thermal resistivity of the natural ground.

Type and dimension of the cable (4) affect its temperature. The total thermal resistance is smaller if the cable installation is shallow (5) However, protection of the cable demands a minimum depth. The cable depth is governed by the terrain and other considerations (eg. road crossings). Increasing the distance between the cables (6) to reduce temperature is a simple action but results in increased area consumption, larger trenches and increased amount of cable sand. The cable design effect is often a prerequisite (7).

1.3 Objectives

The objectives is to give

- a brief description of the thermal processes in the soil around buried power cables and critical conditions in the nature
- a state of knowledge of the above mentioned processes
- a review of different back-fill materials

2 Thermal transport in soil

2.1 Thermal transport mechanisms

Thermal energy can be transported in earth material by conduction, radiation, convection and by diffusion of vapor and water, see Figure 2. Above the ground water level and at natural ambient temperature (in Scandinavia), thermal conduction is the entirely dominant transport mechanism. High water content, density and quartz content are the most important factors to obtain a low thermal resistivity. At higher temperatures and intermediate degrees of saturation, vapor diffusion becomes an important transport mechanism and contributes significantly to the effective thermal resistivity.

Radiation can have influence on the thermal transport in coarse material at rather dry conditions and high temperatures. Natural convection have influence mainly at fully saturation and substantial temperature differences. Forced convection can have significant contribution to the thermal transport below the ground water level.

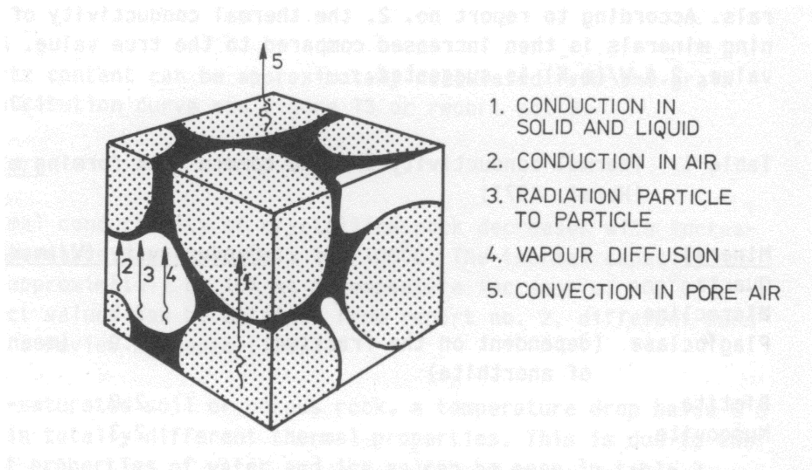


Figure 2 Thermal transport mechanisms in porous medium (In Sundberg, 1988 after Johansen 1975).

The thermal resistivity of a soil depends mainly on the moisture content, density and grain conductivity. High thermal resistivity is obtained at low water content, low density and high thermal resistivity of the grains. The water content may vary over the year due to changes in groundwater level and evaporation conditions, etc. The water retention capacity of the soil is important. A fine-grained soil (clay or silt) above the groundwater table has significantly less variability over time compared to a more permeable soil like gravel or sand. Soils with high organic content generally have high thermal resistivity. A soil type for a specific site can be expected to have a lower thermal resistivity if the distance down to the water table is short.

2.2 Influence of various characteristics

2.2.1 Mineral content

Different mineral distribution influences the thermal resistivity of a material. The mineral content has a higher influence if the density is high. Consequently the mineral distribution has a higher influence on crystalline rock compared to a porous medium as soil. The most important rock forming mineral is quartz that have a 3-4 times lower thermal resistivity compared to other common minerals (Table 1).

Table 1 Thermal properties of some common rock forming minerals (Horai, 1971)

Mineral	**Thermal resistivity m·K/W**	**Thermal conductivity W/(m·K)**	**Comment**
Quartz	0.13	7.7	
Microcline	0.4	2.5	
Plagioclase	0.53 (0,43-0.68)	1.9 (1.46 – 2.34)	Mean, depends on the anorthite content
Biotite	0,5	2.0	
Muscovite	0.43	2.3	

In soil the knowledge of the mineral content is far lower compared to rock. In Figure 3 the variation in quartz content with grain size is summarized for different soils. The results seem to confirm the theory that the resistible quartz mineral would accumulate in certain grain size interval. The results for a specific grain size are different depending on the origin of the soil.

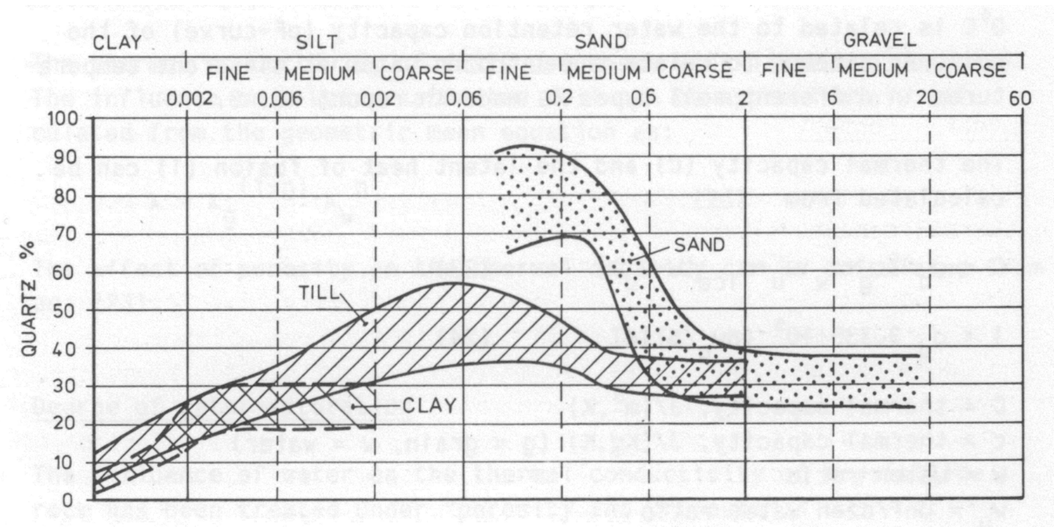


Figure 3 Quartz content versus grain size for different soil types (Sundberg 1988).

2.2.2 Porosity and water content

Increasing porosity (decreasing density) leads to increasing thermal resistivity. The trend is logical since the higher conductive grains (see Figure 2) are coming closer to each other at the expense of the lower conductive pore space, air/water. The influence of porosity on a **water saturated** soil can be approximately calculated from the geometric mean equation:

$Rho = 1/(1/Rho_g)^{(1-n)} \cdot (1/Rho_w)^n)$

Where Rho_g and Rho_w are the thermal resistivity for grain and water respectively, and n is the porosity.

The porosity can be calculated from the dry density (ρ_d) and the grain density (ρ_s) as follows:

$n = 1 - \rho_d / \rho_s$ (ρ_s is approximately 2650 kg/m^3 for normal crystalline rock)

The water content is essential for the thermal resistivity since it controls the size of the contact resistance between the grains. If it is water in the grain contact (see Figure 2, black colour, $\lambda_w = 0.57$ W/(m·K))) the contact resistance is much lower compared to a situation with air ($\lambda_a = 0.024$ W/(m·K)) in the contact zone. The dependence of the water content is in principle illustrated in Figure 5 for the low temperature curves.

In Figure 4 measured thermal *conductivities* of natural soils are illustrated along the cable trench "South west link". The grain conductivity, density and water content varies and causes different thermal conductivity for the different soils. The lowest conductivities (highest thermal resistivities) are found in sandy till and sand (at low water content) and soils with high organic content and high porosity.

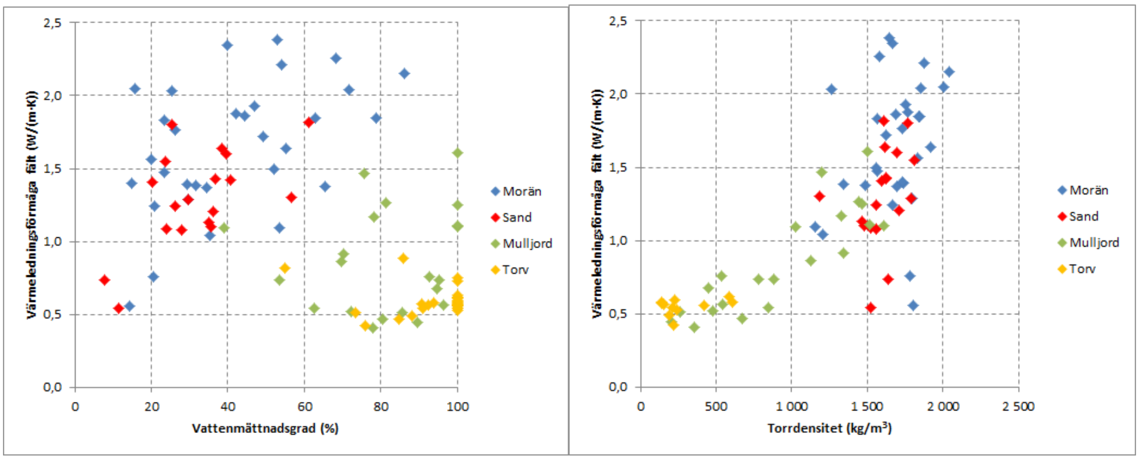


Figure 4 Thermal conductivity (the inverse of thermal resistivity) for different groups of natural soil at different water content, mainly above the ground water table (exception for some organic samples). Left: Thermal conductivity vs degree of water saturation. Right: Thermal conductivity vs dry density. Blue: till, Red: sand, green: organic soil, yellow: peat. (Sundberg et al, 2011).

Different soils have different ability to retain water above the ground water table. Below the ground water table, the pore system is saturated with water. Above the ground water table the water content is lower and the water content depends on soil type. The water retention capacity influence the water content in relation to the suction head (distance above ground water table) under steady state conditions. Coarse soils types as gravel and sand has a much less ability to retain water above the ground water table. The water retention curve (or pF-curve) for a specific soil controls the water content at a specified distance above the ground water table. See more in “Glossary and definitions” and in section 4.3.

2.2.3 Temperature

At experimental determination of thermal resistivity, it is more accurate to talk about the measurement of the effective thermal resistivity. This consists of the thermal resistivity and other heat transporting mechanisms that cannot be distinguished. In particular this is relevant in the field where both vapor diffusion and convection can occur. In the laboratory, it is mainly vapor diffusion that can give a contribution to the thermal resistivity. This is small at low temperature, but gives at higher temperatures a very significant contribution.

The effective thermal resistivity at higher temperatures have been explored in a number of studies, see Appendix 5 for a comprehensive description. One of the best documented and most recent studies have been made of Nikolaev et al, 2013. In Figure 5 and Figure 6 results from this study is shown for two different soils, one quartz sand and one sandy loam. The soils have quite different mineral content and grain size distribution. Consequently they have large differences in compaction properties which can be seen in the figures.

The influence of vapor diffusion is obvious at temperatures higher than approximately 30°C. At dry and water saturated conditions the there is no influence of vapor diffusion since vapor cannot be formed. The temperature dependence in thermal resistivity at full saturation is partly and artefact (Nikolaev et al, 2013) and exceeds the combined effect of the positive temperature dependency of water and the slightly negative dependency of quartz.

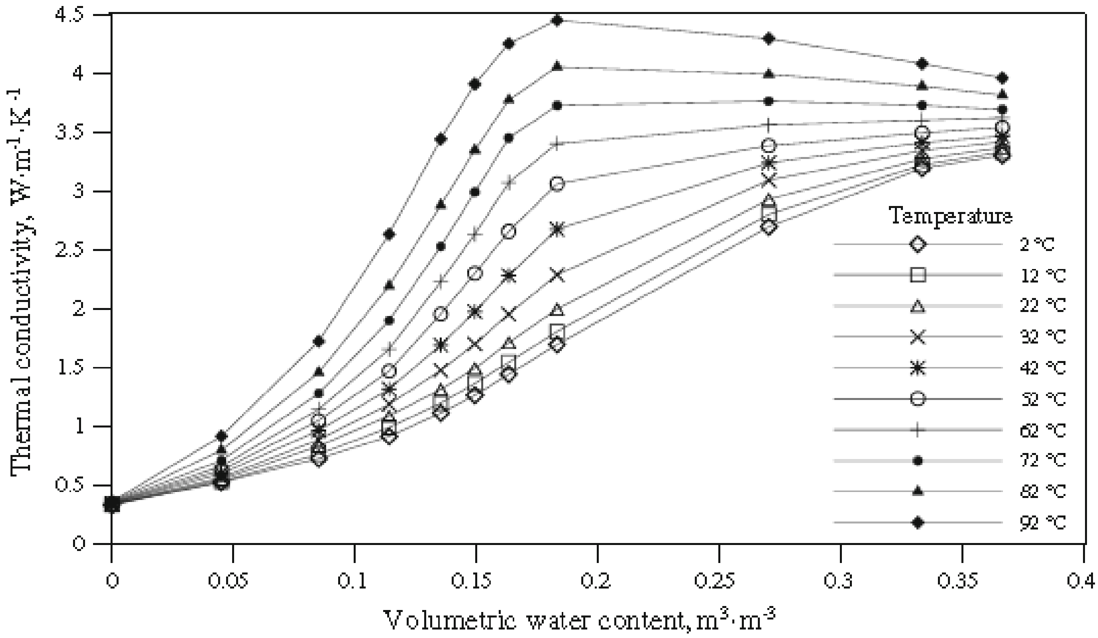


Figure 5 Thermal conductivity (the inverse of thermal resistivity) of Ottawa sand with volumetric water content and temperature. The sand is fully saturated at volumetric water content 0.366 (also equal to the porosity). The dry density is 1680 kg/m3 at well compacted conditions and the quartz content is 99 %. The grain size distribution is between 0.59 mm to 0.84 mm. Nikolaev et al, 2013.

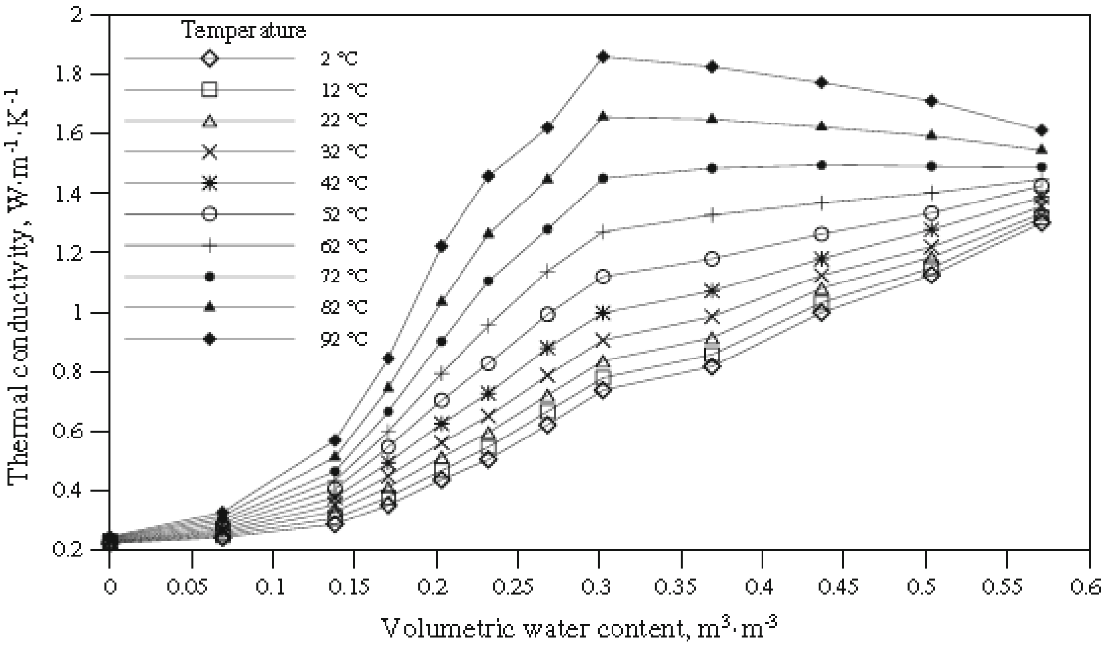


Figure 6 Thermal conductivity (the inverse of thermal resistivity) of Richmond Hill fine sandy loam with volumetric water content and temperature. The loam is fully saturated at volumetric water content 0.571 (also equal to the porosity). The dry density is 1137 kg/m3 at well compacted conditions and the quartz content is 33 %. The grain size distribution is between clay and sand with the following mass fractions; sand 0.523, silt 0.322, clay 0.155. Nikolaev et al, 2013.

2.2.4 Anisotropy

A medium is isotropic if it has the same properties in all directions. The mean thermal conductivity (inverse of resistivity) in an anisotropic two dimensional medium is $(\lambda_x \cdot \lambda_y)^{0.5}$ where λ_x and λ_y are the conductivities in the principal directions. Anisotropy in soil is not well investigated. However, some anisotropy can be expected in all layered soils e.g. sand and clay, with lower thermal resistivity parallel to the layering (normally sub horizontal). The bounds for the thermal resistivity in the principal directions in a two dimensional material can be calculated from the arithmetical and harmonic means.

2.3 Determination of thermal properties

2.3.1 Experimental methods

The most common method for determination of thermal properties of soil is the probe method. The method is also used for solid materials, such as rock. The method was first described in the literature by the two swedes Stålhane and Pyk (1931) and has been used extensively throughout the world from the 50th century onwards (eg. Blackwell (1954), Saare and Wenner (1957), Sundberg (1988)). Today essentially the same technique is used but have been further developed and automatized. A number of commercial equipment’s are on the market.

The measurement technique is simple. A heat generating probe is inserted in the ground (or soil sample) with a temperature sensor at half the probe length. A constant electric power is turned on and the temperature rise with time is registered. After a sufficient time, depending on probe size and soil material, the power is turned off and the thermal resistivity is evaluated from the heating period and eventually also from the cooling curve.

The method have many similarities to evaluation of aquifers in the hydrogeological area. Some reasons for the probe methods popularity is the short time of measurement, easy insertion in soft material and the simple theory with possible graphically evaluation.

For evaluation, the infinite line source theory is normally used:

$$T = \frac{q}{4\pi\lambda} \cdot E_1\left(\frac{r^2}{4\kappa t}\right)$$

Where
T = temperature increase, °C
q = heating power, W/m
λ = thermal conductivity, W/(m·K) (inverse of thermal resistivity)
r = probe radius, m, or distance between probe centre and temperature sensor
κ = thermal diffusivity, m^2/s
t = time, s
E_1 = exponential integral

For sufficient long time the equation can be simplified and the evaluation can be made graphically from the slope of the temperature – logarithm time curve. “Sufficient” long time is very short if the probe radius is small, approximately 1-2 mm. In theory, also diffusivity can be determined. However, for practical purposes the uncertainty is far too high and a better approach is to calculate the heat capacity in a theoretically way.

A variant of the probe method is the multi-probe method. One or more temperature sensors are placed at a distance from the heat generating probe. The method was developed at the department of geology at Chalmers and first describe by Landström et al, 1978, and further developed by Sundberg (1979). It has been used in several projects in different scales, mainly meter scale (eg. Mossmark and Sundberg, 2007). It can also be used for anisotropy evaluation (Sundberg et al, 2008).

The same theory as above can be used. However, the solution cannot be simplified for reasonable measurement times. Instead the exponential logarithm can be developed using Taylor expansion. For multi-probe measurements it is possible to evaluate the thermal diffusivity. A normal measurement time is 2-4 hours for a measurement scale in approximately 0.5 m scale, depending on the distance between the heating probe and the temperature sensors and the thermal properties of the material investigated.

When the measurement technique becomes automatized and the results are delivered from a “black box” it is important to become aware of the potential errors that are related to the method. The most important demands one the method are:

- Steady and constant initial temperature in the soil/sample or knowledge of a *constant* temperature drift
- The heating power is adapted to the size of the thermal resistivity which otherwise might result in too small/high temperature rise
- The heating power is constant
- Control of the contact resistance (influences the measurement time and the part of the temperature-time curve that is possible to evaluate). The measurement time may need to be increased.
- The demands on the infinite line source theory is fulfilled

These demands have to be fulfilled in order to have control of potential errors.

There are a number of other methods to determine the thermal properties of soil. For example different types of steady state techniques (e.g. method used by Nikolaev et al (2013)) and other types of transient methods, (eg. TPS-method: Gustafsson (1991)).

The steady state method used by Nikolaev et al (2013) at elevated and high temperatures is showed in Figure 7.

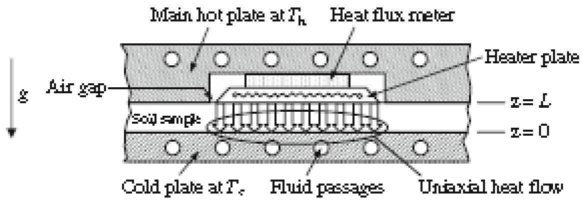


Figure 7 View of the apparatus used by Nikolaev et al (2013). The gradient is given as 170 K/m and ΔT between the plates are 4°C which together gives a thickness of the sample somewhere between 2 and 2.5 cm. The calculated heat flow varies between 38 – 765 W/m^2.

2.3.2 Theoretical methods

There are a number of methods to calculate the thermal resistivity from the porosity, mineral distribution and the water content and other related properties. Some of these are further described in Appendix 5. Some methods also take into account the effect of elevated temperature and the contribution of vapor diffusion to the effective thermal resistivity. A detailed description of these methods are found in Appendix 5.

3 Thermal processes around buried power cables

3.1 Ampacity of buried cables

DC power cable generates heat due to the electrical resistance in the cable. The electrical resistance increases with elevated temperature. The current-carrying capacity (the ampacity) of a cable system is influenced by the capacity of the installation to extract the heat from the cable and dissipate it into the surrounding medium.

The cable is designed for an ampacity that generates a certain maximum temperature, related to the thermal resistivity of the soil. If the design temperature is exceeded it may influence the guarantee from the manufacture and the functionality and lifetime of the cable.

The temperature of a buried cable is controlled by:

- the initial soil temperature at the actual depth and its variation
- the power distribution by time in the cable and the effective total thermal resistance of the surrounding media.

The thermal resistance is mainly depending on the buried depth and thermal resistivity for the backfill and the natural soil. The cable temperature is also influenced by the number of buried cables and possible adjacent heat sources.

It may be difficult to make prognosis of the power distribution of a cable in advance. However, a good assumption may be a high and steady power if alternative exists since HVDC cables have a smaller resistance compared to other distribution forms.

3.2 Thermal resistivity around buried cables

The thermal resistivity at natural soil temperature at buried depth (approximately 5-15°C) varies for different soil types. Below the water table (e.g. buried submarine cables or cable below the ground water table) the main factors that influence the thermal resistivity is porosity, mineral distribution (especially the amount of high conducting quartz) and organic content. These conditions are barely variable in time (in the perspective of human lifetime).

However, for cables above the ground water table the amount of water in the pore system becomes an important components. A soil with low degree of water saturation (low water content) have a significant higher thermal resistivity at normal natural ground temperature, see Figure 4.

At elevated temperature there are minor changes in thermal resistivity if the soil pore system is saturated with water. If the water content is lower and the pore system is unsaturated, vapor diffusion is initiated at elevated temperature and significantly influence the thermal resistivity, see Figure 5.

3.3 Coupled thermal and moisture transport

3.3.1 Overview

Near the cable surface evaporation of water take place and moisture is transported in direction of the heat flow, see Figure 8. This moisture migration induce a lower water content near the cable (and a higher at larger distance) which in turn induce a water flow in the opposite direction.

If the moisture migration, due to temperature gradient, in the long term is in balance with the return flow of liquid water, the thermal resistivity decreases at elevated temperature. However, if the return flow of liquid water for some reason cannot balance the vapor flow, the water content decreases and the thermal resistivity increases.

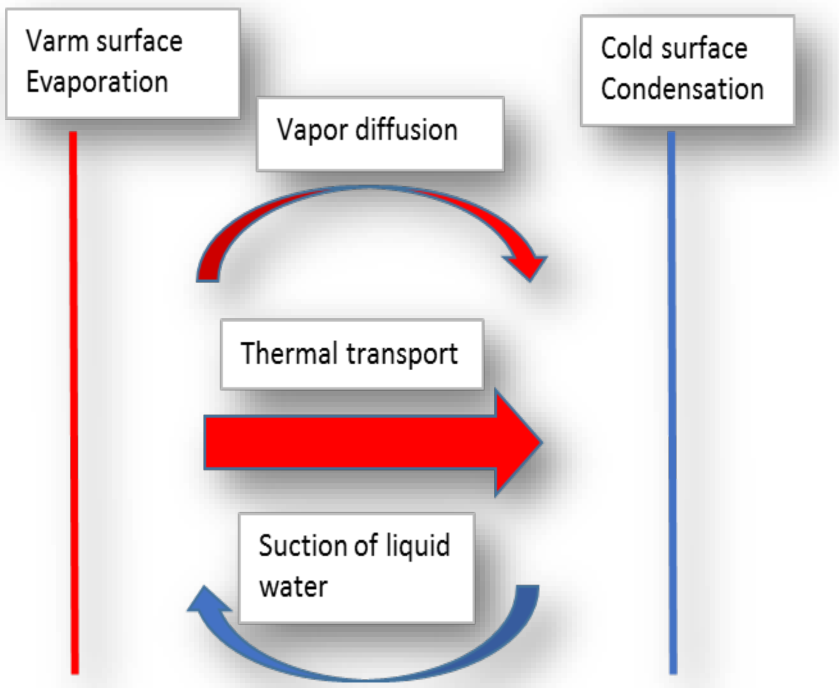


Figure 8 Simplified sketch of coupled heat and moisture transport.

The theory for the combined transport due to temperature gradient and the transport related to moisture gradient are described in section 3.2 in Appendix 5.

Both a continuity equation for the total moisture transfer and a continuity equation for total heat transfer are described, in both vapor and liquid phase, and it is obvious that these transient equations and processes are interdependent.

3.3.2 Important parameters

There are a number of parameters that influence the possible dry out around buried cables. The main important factors that influence the moisture movement are:

1. The rate of *heat flow* generated by the cable. The heat flow is the driving force for moisture movement and vapor diffusion under temperature gradient.

2. The *temperature* level. Influences the moisture movement, the effective thermal resistivity and water retention capacity (among others).

3. The effective *thermal resistivity* of the backfill and soil. Influences the temperature and the thermal gradient that induce temperature dependent moisture movement

4. The *water retention capacity* (pF) and *ground water level*. It influence the water content in relation to the suction head (distance above ground water table) under steady state conditions and prevents/counteracts the backfill from drying out.

5. Unsaturated *hydraulic conductivity*. Influenced by temperature and water content and control how much liquid water that may be transported in relation to a specified suction head.

6. Boundary conditions. Lower: ground water level, upper: climate conditions

The heat flow (1) is the main driving force inducing all other mechanisms. A low cable temperature (2) gives less influence on the vapor diffusion and on all temperature dependent parameters. A low thermal resistivity (3) gives lower temperature and thermal gradient under steady state conditions and less ability for the soil to dry out. The thermal resistivity is mainly dependent on the density, grain conductivity and water content.

Bullet 4, the water retention capacity, control the water content in the soil in general and close to the cable in particular. A soil with high water retention capacity have less ability to dry out. High temperature gives lower water retention capacity. A fine grained soils has a higher water retention capacity compared to a coarse grained soil. If there is a hysteresis in the water retention curve it could influence the ability to retrieve the water after a temporary lowering of the ground water table.

Saturated hydraulic conductivity is dependent of the grain size distribution and coarse grained soils have much higher conductivity compared to fine grained soils, up to 10^{10} times. It is also dependent on the temperature. The unsaturated hydraulic conductivity (5) is in addition highly dependent on the water content and tends to zero when the water content approaches zero.

So to summarize; all parameters are affected of other parameters. A genuine coupled problem. The problem is possible to model. However, the significant temperature and water content dependence on the sometimes well-known parameters are less well known. Therefore any modelling approach must be supported by experimental data.

3.3.3 Experimental laboratory studies

Different experimental studies have been made on the potential drying out phenomena around buried power cables (see the literature study in Appendix 5). The studies have been performed both in the laboratory and as field experiments. Examples on good studies are by Snijders and Vermeer, (1981) and by Gouda et al, (1997, 2010, 2011). Goudas work seems to be inspired of Snijders and Vermeer, (1981) and e.g. similar laboratory equipment are used, se Figure 9. In Snijders and Vermeer, (1981) also theoretical modelling were done based on Philip and de Vries theory (1957).

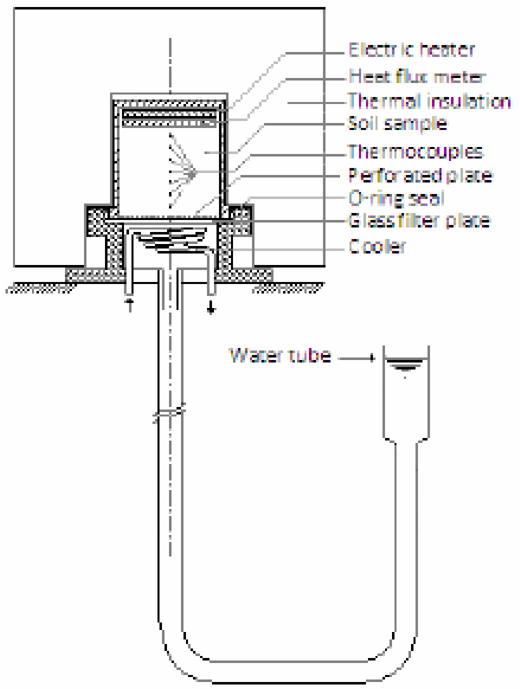


Figure 9 Laboratory equipment to study the dry-out process on soil samples (from Gouda et al 2010). Top: heater and heat flux meter; bottom: cooler and porous plate coupled to a suction head.

The equipment allows a soil sample under a specified suction head (pF) to be exposed to a constant 1D heat flow of variable size. Sensors within the soil sample measures the temperature at specified distances from the top. The thermal resistivity can be calculated from the heat flux and the temperature differences.

Results of the experiments with three different types of sand is summarized in Figure 11-Figure 10 in different ways. In Figure 11 the principle critical conditions are described in the water retention diagram for the different soils. Figure 12 displays critical conditions for pF vs heat flow at different temperatures. The critical conditions for drying out was defined as when the thermal resistivity of the top layer exceeds the previous steady state thermal resistivity with 50%.

These figures shows the following:

- Higher temperature gives critical conditions at lower pF (higher water content)
- Higher heat flow gives critical conditions at lower pF
- Higher water retention capacity (“higher” pF curve) gives critical conditions at higher pF

According to Snijders and Vermeer (1981) it takes long time before the drying out are complete and become obvious, approximately 40-50 days according to Figure 10. This is dependent on the temperature and the suction rate. However, according to Gouda it takes approximately 15 days (Gouda et al, 1997) or 25 hours (Gouda et al, 2010), probably depending on suction rate.

For the different sands tested Snijders and Vermeer (1981) concluded that the critical conditions for the performance of a drying out zone, around the cable, was very sensitive to:

- The water retention capacity of the soil (and its hysteresis) and the applied suction tension
- The temperature

They also concluded that that introduction of hysteresis in the pF curve in the theoretical model gave a much better consistency with experimental results. Some measuring results are summarized in Figure 11.

They recommended the use of sands with a relatively high loam content (good water retention capacity) and optimized packing (lower thermal resistivity and water retention capacity) of the back fill. For their most examined sand, critical conditions could appear at temperatures between 40 to 55°C (Snijders and Vermeer, 1981).

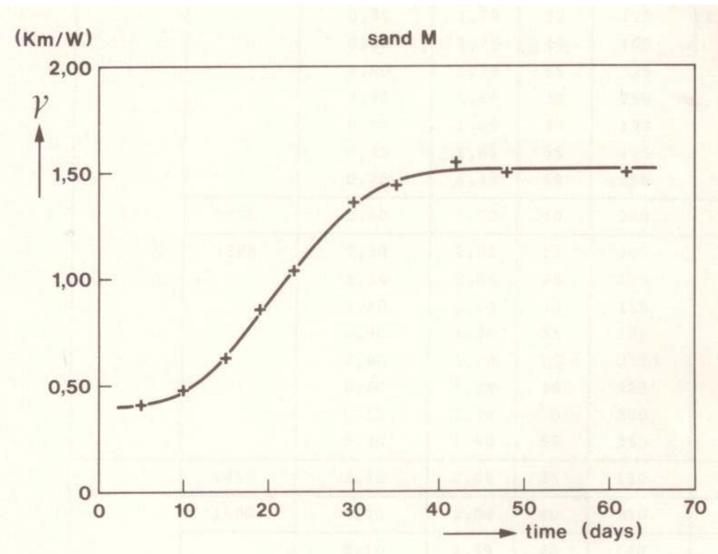


Figure 10 Increase of thermal resistivity in time (Snijders and Vermeer, 1981).

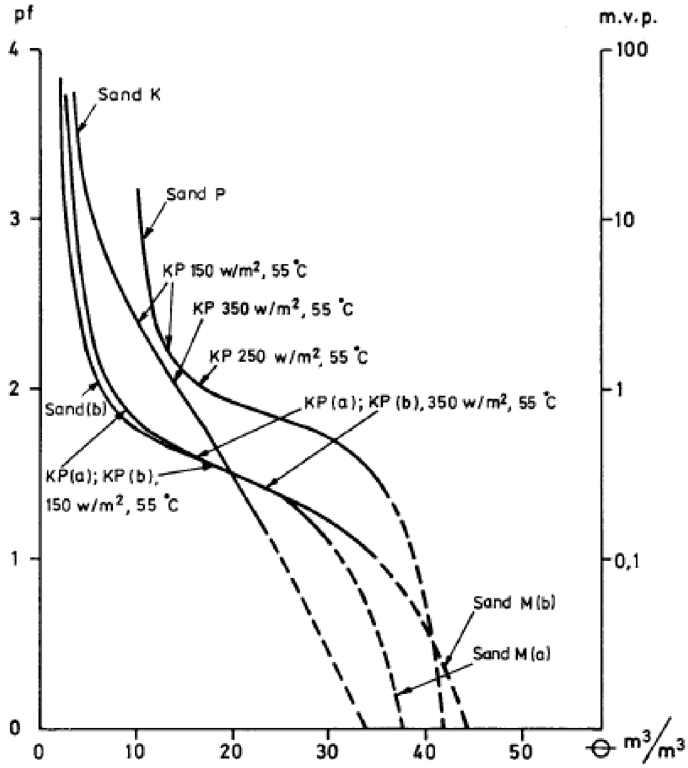


Figure 11 Critical point for drying out (KP) for three different sands (Sundberg, 1988). The figure is constructed from the results from Snijders and Vermeer (1981) together with the pF curves for the different material and summarize the results with respect to temperature, heat flow, water content, water retention capacity and negative pressure. The figure gives a principal view. For exact results see Figure 12. pF can also be expressed as meter water pressure, see the scale to the right (pF=log10(water pressure in cm)).See "Glossary and definitions for more info.

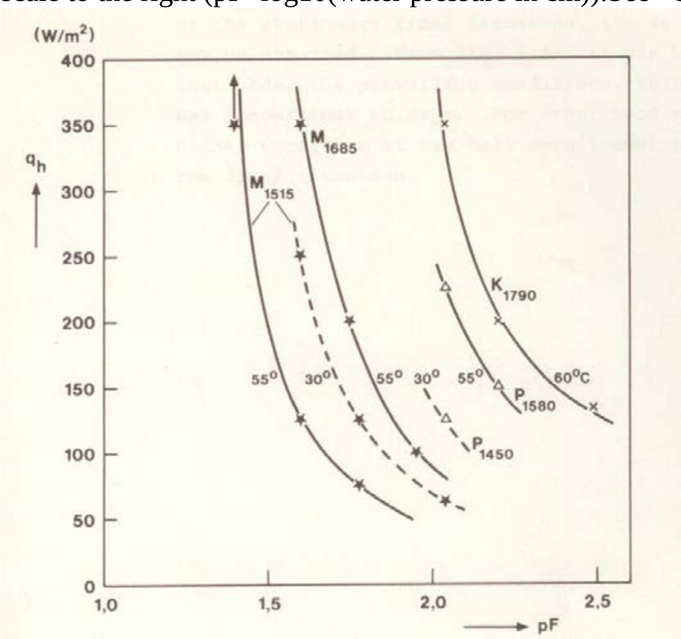


Figure 12 Comparison of critical conditions for the three sand types investigated (Snijders and Vermeer, 1981).

Gouda (1997) tested three different sands and found different critical conditions due to water retention capacity, see Figure 13. He also concluded that the drying out process started at 55°C.

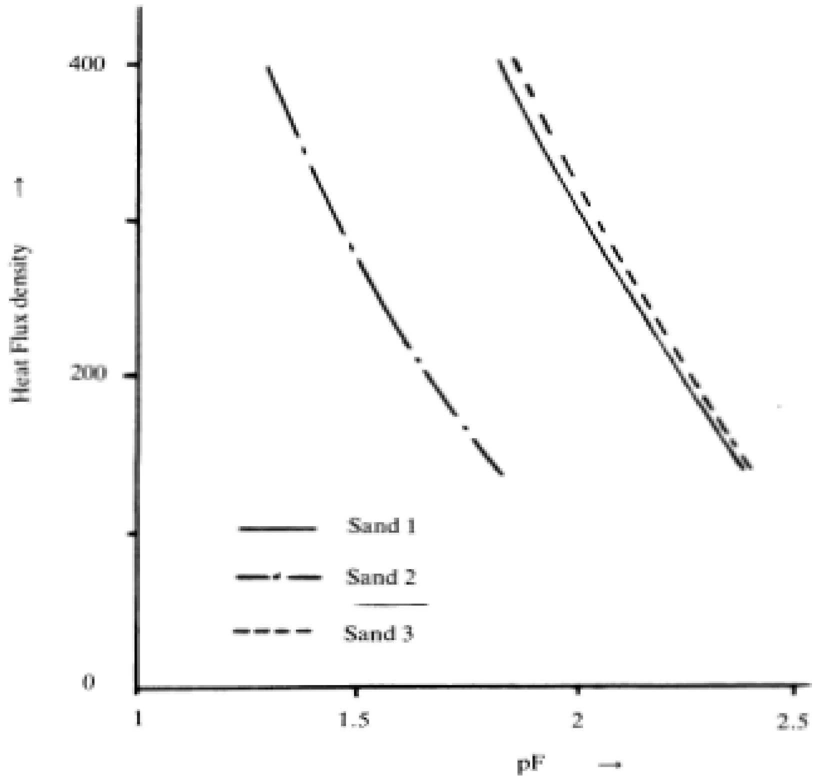


Figure 13 Critical condition for drying out at increasing heat flux (W/m^2) in the different sands at different water retention capacity (pF) tested by Gouda et al, 1997. Sand 2 with largest ability to dry out is also the sand with the lowest water retention capacity, see Appendix 1. Sand 3 has the highest water retention capacity.

In a study on different mixtures of materials the results are summarized in Table 2.

Table 2 Thermal resistivity for different soils and different pF (Gouda et al, 2010).

Soil Type	Thermal Resistivities	pf		
		∞	2	1
Lime	ρ_{dry}	2.35	1.8	1.7
	ρ_{wet}	0.941	0.85	0.76
25% Lime+75% Sand	ρ_{dry}	1.304	1.22	1.02
	ρ_{wet}	0.522	0.50	0.48
Clay	ρ_{dry}	1.586	1.53	1.51
	ρ_{wet}	0.627	0.61	0.61
Sand	ρ_{dry}	2.03	1.7	1.46
	ρ_{wet}	0.968	0.75	0.75
Clay + Silt + sand	ρ_{dry}	1.65	1.6	1.469
	ρ_{wet}	0.83	0.756	0.705
Silt + Sand	ρ_{dry}	1.9	1.68	1.5
	ρ_{wet}	0.756	0.66	0.67

In another study (Gouda et al, 2011), with some material with high loam content under constant high water suction, Pf= ∞ (assumed to be approximately pF =3, and low water content). He concluded that the drying out phenomena started at different temperatures and with different velocities (less than 1 hour up to 48 hours) depending on the proportion of silt in the samples. The critical temperature for wet soils under testing was closer to 60 °C rather than 50 °C and all soils dried out.

Table 3 Thermal resistivity for different soils, pF and other conditions (Gouda et al, 2011).

Type of Soil	Q_h W/m²	p_f	Time in hours	ρ_{dry} °Cm/W	ρ_{wet} °Cm/W	Rate of the formation of the dry zone cm/hrs
Sand1	728	∞	1	0.137	0.137	0.45 between 1 to 3 hours
			3	1.136	0.471	
			5	1.2	0.543	0.1 between 5 to 9 hours
			24	1.67	0.766	0.00416 between 24 to 48 hours
			48	1.64	0.749	
Sand2	728	∞	1	0.188	0.188	0.36 between 1 to 3 hours
			3.5	1.089	0.484	
			6	1.244	0.6	0.016 between 6 to 24 hours
			24	1.648	0.763	0.0041 between 24 to 48 hours
			48	1.737	0.686	
Sand3	728	∞	2	0.549	0.374	0.25 between 2 to 4 hours
			4	0.869	0.549	
			6	1.010	0.597	0.2 between 4 to 6 hours
			24	1.751	0.789	0.033 between 6 to 24 hours
			48	1.537	0.795	0.0085 between 24 to 48 hours
Sand4	728	∞	1	0.477	0.12	0.6 between 1 to 3 hours
			5	0.986	0.670	
			24	1.770	0.784	0.2 between 3 to 5 hours
			48	1.654	0.534	0.0041 between 24 to 48 hours
Silt + Sand	728	∞	1	0.223	0.223	1.66 between 1 to 4 hours
			4	1.098	0.4995	
			6	1.226	0.554	0.15 between 4 to 6 hours
			24	1.590	0.883	0.055 between 6 to 24 hours
			48	1.609	0.732	0.012 between 24 to 48 hours
Clay + Silt + Sand	728	∞	3	0.565	0.283	0.2 between 3 to 6 hours
			6	0.8360	0.481	
			24	1.694	0.824	0.38 between 6 to 24 hours
			48	1.648	0.549	0.01 between 24 to 48 hours

3.3.4 Experimental field studies

Both Gouda et al 1997 and Snijders and Vermeer 1981, performed field studies. They could observe a drying out process for investigated sands. However, in the studies not all parameters were known, for example the ground water level that's control the water content together with the pF-curve, and therefore the field experiments are more problematic to evaluate. It may also be a combination of different effects that influence the measurable parameter. In the laboratory it is possible to study them one by one.

The results from Gouda´s field experiment are summarized in graphs in Appendix 2. A previous constructed 66 KV cable installation in Cairo was instrumented with temperature sensors at different vertical distance from the central cable (of 3), see Figure 14. The cables were at 1 m depth. Diameter 0.06 m each and cc distance 0.12 m. The distance between the periphery cables outer radius can be calculated to 0.30 m. The cables were surrounded by a silty sand, see grain size distribution and proctor curve in Appendix 1. The temperature sensors were at various distances from the central cable, from 0 to 13 cm, in the upwards direction. The upper soil surface temperature was also measured and the rainfall during the summer period was zero.

The conclusions from the Cairo field study was that drying out had occurred during July – August 1991. The evidence presented for a dry zone was the discontinuity in the temperature gradient in surrounding soil and the measured water content.

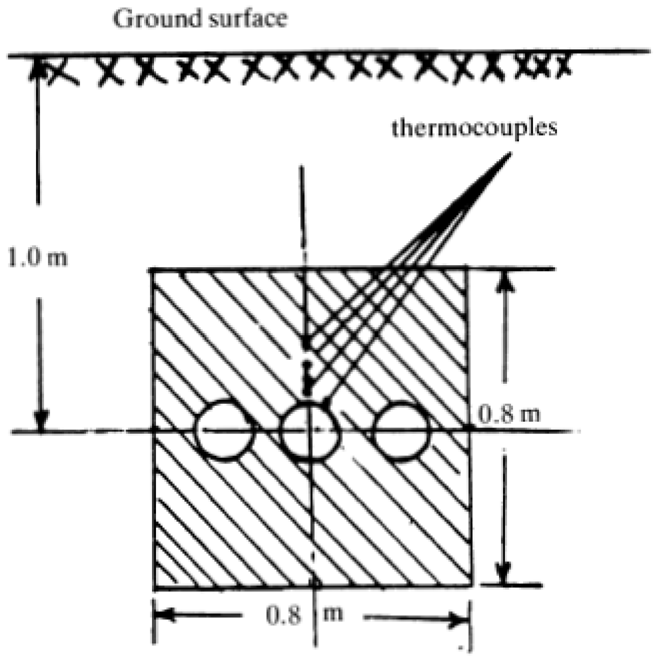


Figure 14 Sketch of field experiment. Please note the cable size in the sketch is far too large, see text. Gouda et al, 1997

4 Critical conditions in the nature

Unfavourable conditions for the temperature of a buried cable is dependent of high soil temperature and high thermal resistance in the surrounding soil at a constant load and resistance on the cable. In the following a broad description of the critical conditions in the nature is made. However, regarding the natural ground temperature a more comprehensive compilation and discussion is made.

4.1 Ground temperatures in Sweden

4.1.1 General

The mean temperature in the ground is often assumed to coincide with the mean air temperature. The soil temperature varies during the year. The variations are damped depending on the period length, depth and thermal ground properties. Normally the highest temperature is during the end of summer, slightly out of phase compared to the air temperature. The mean ground temperature is normally slightly higher compared to the air temperature due to processes close to the ground surface such as vegetation, snow cover and freezing process. The soil temperature is not commonly monitored on undisturbed ground. The road surface temperature are monitored on many locations by the Swedish road administration but the measured temperature cannot be translated to undisturbed ground temperature for a number of reason (no snow cover, no vegetation, different albedo, heat from traffic etc). However, SLU (Swedish university of Agriculture science) has during many decades been monitoring the soil temperatures at seven special experimental test sites. For two of them, Asa and Jädraås, have SLU kindly given us access to the temperature at 0.2 m depth and the air temperature (SLU, 2014), see Appendix 3 for location and description.

4.1.2 Results

In Figure 15 - Figure 18 the temperatures at 0.2 m depth and the air temperatures are showed for the period 2001-2010. The monthly maximum temperature at 0.2 m depth are 16-17 °C. The highest mean ground temperature at 0.2 m for the period 2001-2011 is approximately 15°C. The corresponding highest mean air temperature is almost the same for Jädraås but 3°C higher for the more southern Asa. The mean ground temperatures are 0.3°C and 1.3°C higher compared to the mean air temperatures for Asa respective Jädraås, see Table 4.

Table 4 Mean air temperature and ground temperature at Asa and Jädraås, 2001-2010 (SLU, 2014).

	Mean air	Mean ground 0.2 m depth	
	2001-2010	2001-2010	Difference
Asa	6.37	6.66	-0.29
Jädraås	4.27	5.54	-1.27

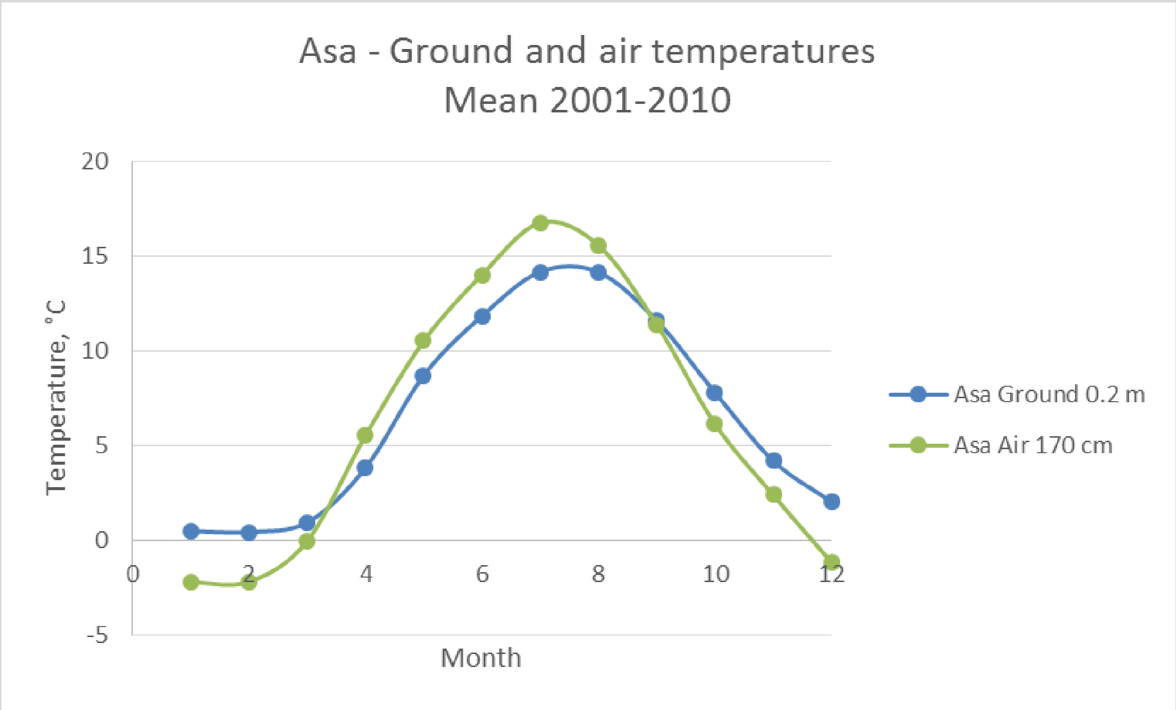


Figure 15 Ground temperature at 0.2 m depth and air temperature at Asa. Mean 2001-2010.

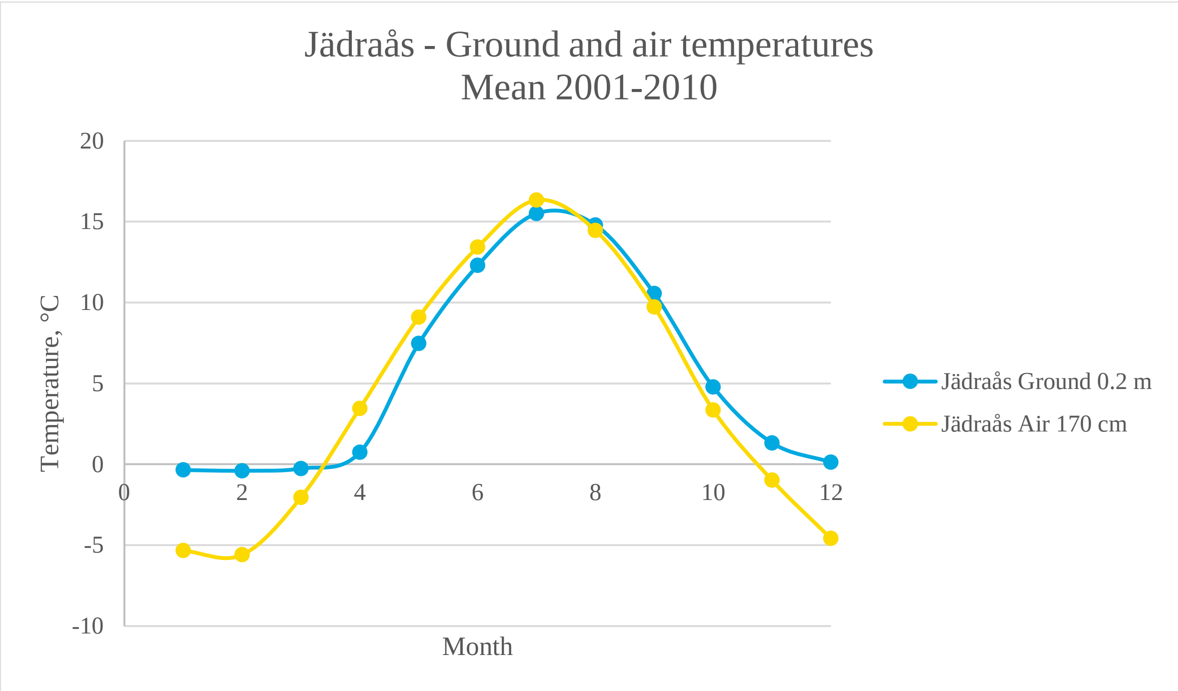


Figure 16 Ground temperature at 0.2 m depth and air temperature at Jädraås. Mean 2001-2010.

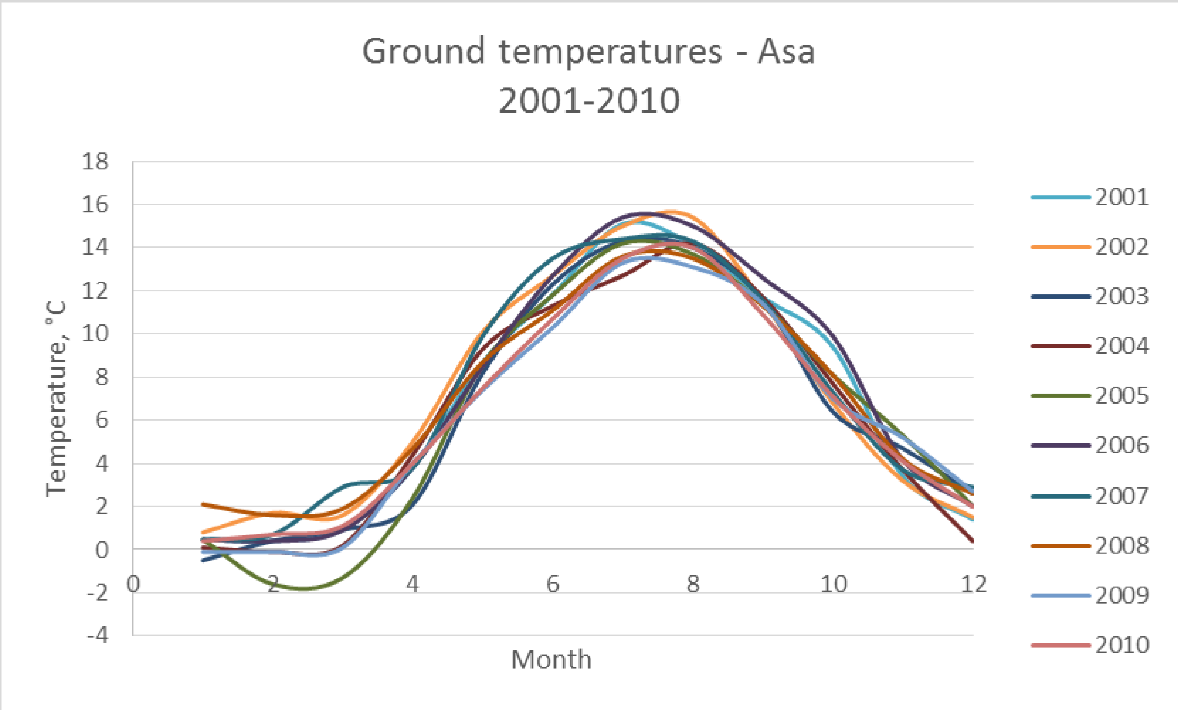


Figure 17 Ground temperature at 0.2 m depth at Asa. 2001-2010.

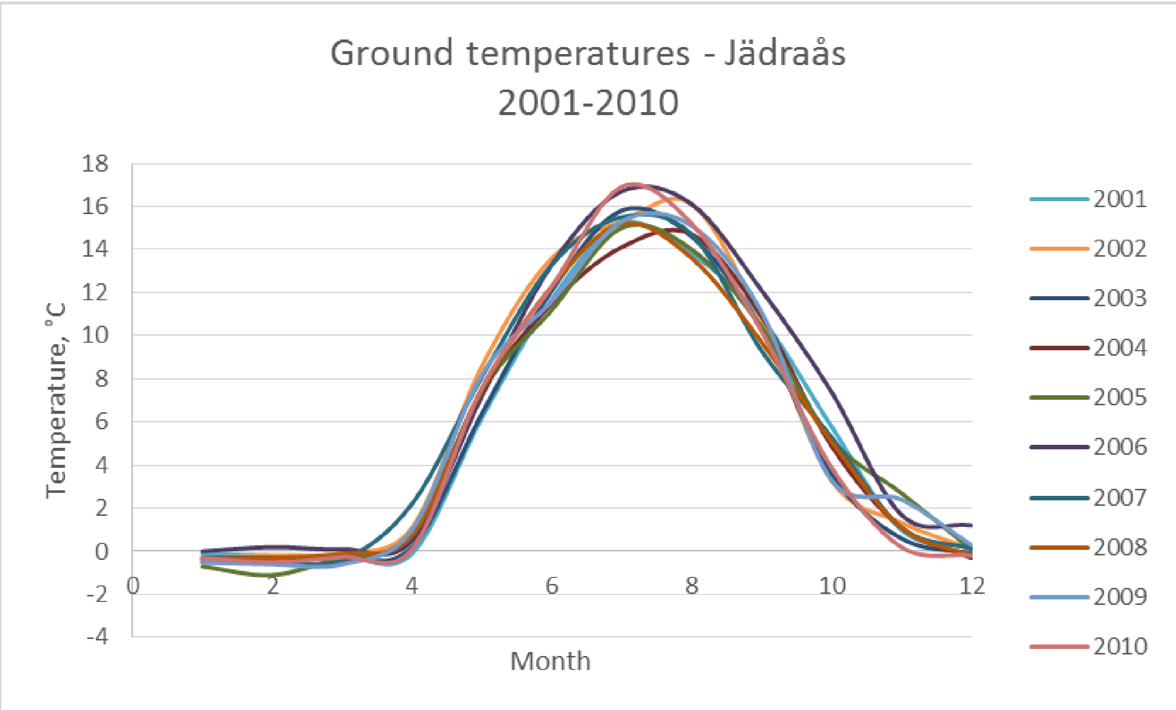


Figure 18 Ground temperature at 0.2 m depth at Jädraås. 2001-2010.

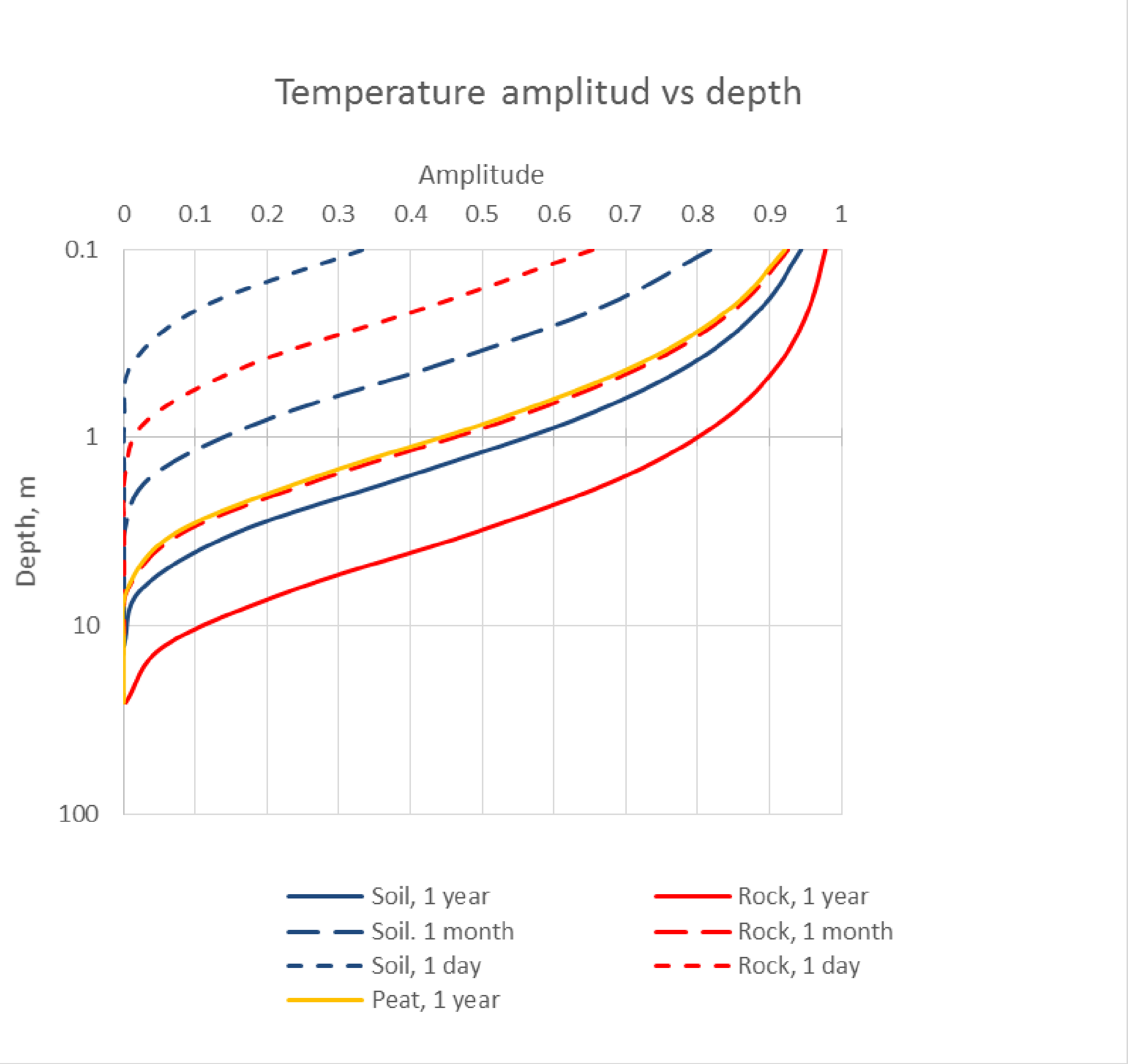


Figure 19 Calculated ground temperature amplitude versus depth in typical rock (κ=$2 \cdot 10^{-6}$ m^2/s) and soil (κ=$3 \cdot 10^{-7}$ m^2/s) at different length (period) of the temperature wave (year, month, day). In addition the annual wave in water saturated peat is included. The amplitude at ground surface is 1°C. Example: if the temperature at ground surface has an amplitude of 20°C during a year, the amplitude at 1 m depth in soil is 55 %, approximately 11°C. The mean ground temperature at Asa and Jädraås are 5.5°C and 6.7°C respectively during 2001-2010.

In Figure 19 the temperature amplitudes are calculated versus depth for different frequency of a temperature wave at the ground surface, 1 day to 1 year. The figure illustrates how deep a daily, monthly or annual wave penetrates.

4.2 Soil types

Soil types can be classified in various ways. Common ways are in organic and inorganic soil and after genesis. The inorganic soils or mineral soils can be sorted or unsorted. A sorted soil has usually been transported by water (or wind) and different grain sizes have been deposit at different locations. A type of unsorted soil has been directly deposit by the ice and is moraine or till and normally consist of all grain fractions. However, because of various reasons the grain size distribution in moraines can be quite different, see Figure 20.

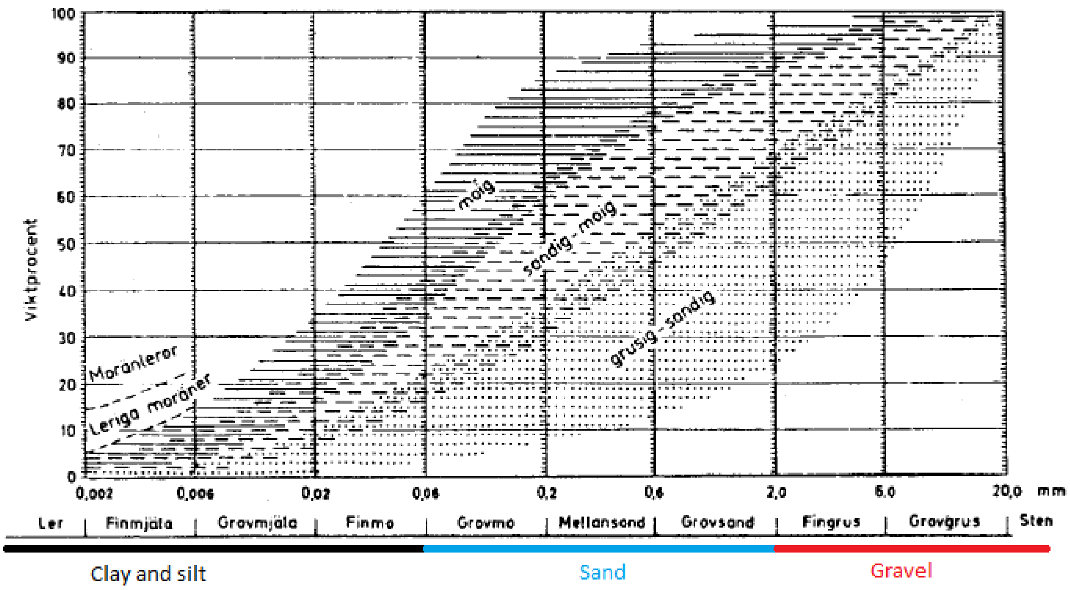
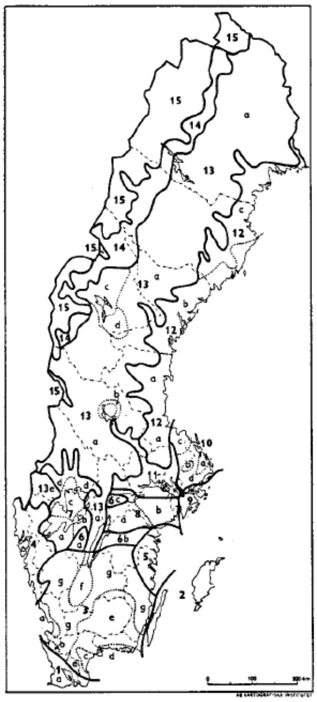


Figure 20 Grain size distributions of different types of moraine/till.

Classification of Swedish soil types can be done in geographic regions, see Figure 21 and Appendix 4. Moraine is the dominating soil type in Sweden. However, as can be seen in Appendix 4, the distribution of soil types differs between different regions. E.g. in the areas below the highest shore line, where most people are living, the sorted fine grained soils are dominating, see Figure 21.



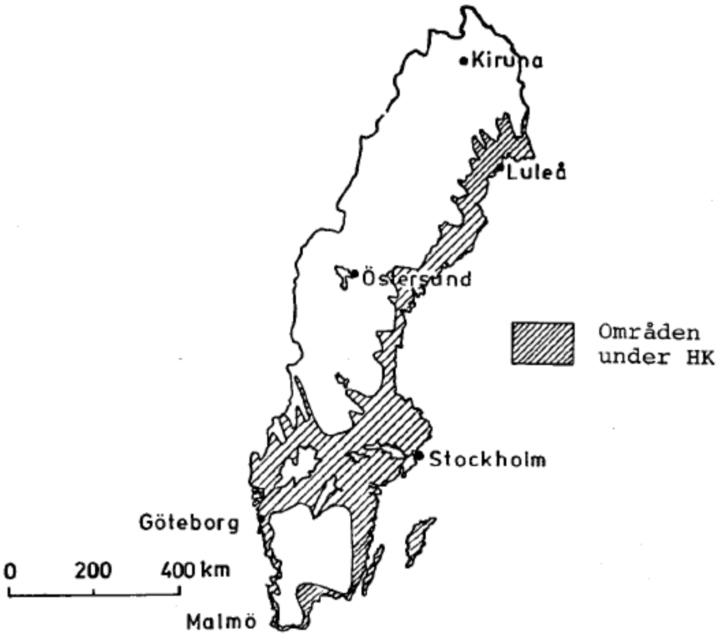


Figure 21 Classification of Swedish soil types in regions (left) and areas below the highest shore line (right). Atlas över Sverige, 1953 and Lundegårdh et al, 1970. Legend to the numbers is found in Appendix 4.

4.3 Groundwater level

Infiltration and evapotranspiration influences the ground water level together with water uptake in plants. Low ground water table influences the pressure potential in the ground, sucks water from the soil and results in a dryer soil. The influence from a lower ground water table on the water content in a soil depends on soil type and the timescale. The principal view of different ground water regimes in Sweden and typical water retention capacities are shown in Figure 22a and 22b respectively.

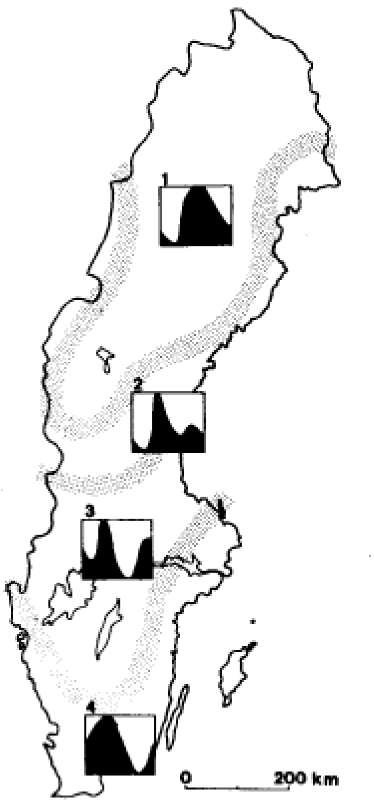


Figure 22a Principal view of the variation in the ground water level during the year (Nordberg & Persson, 1979).

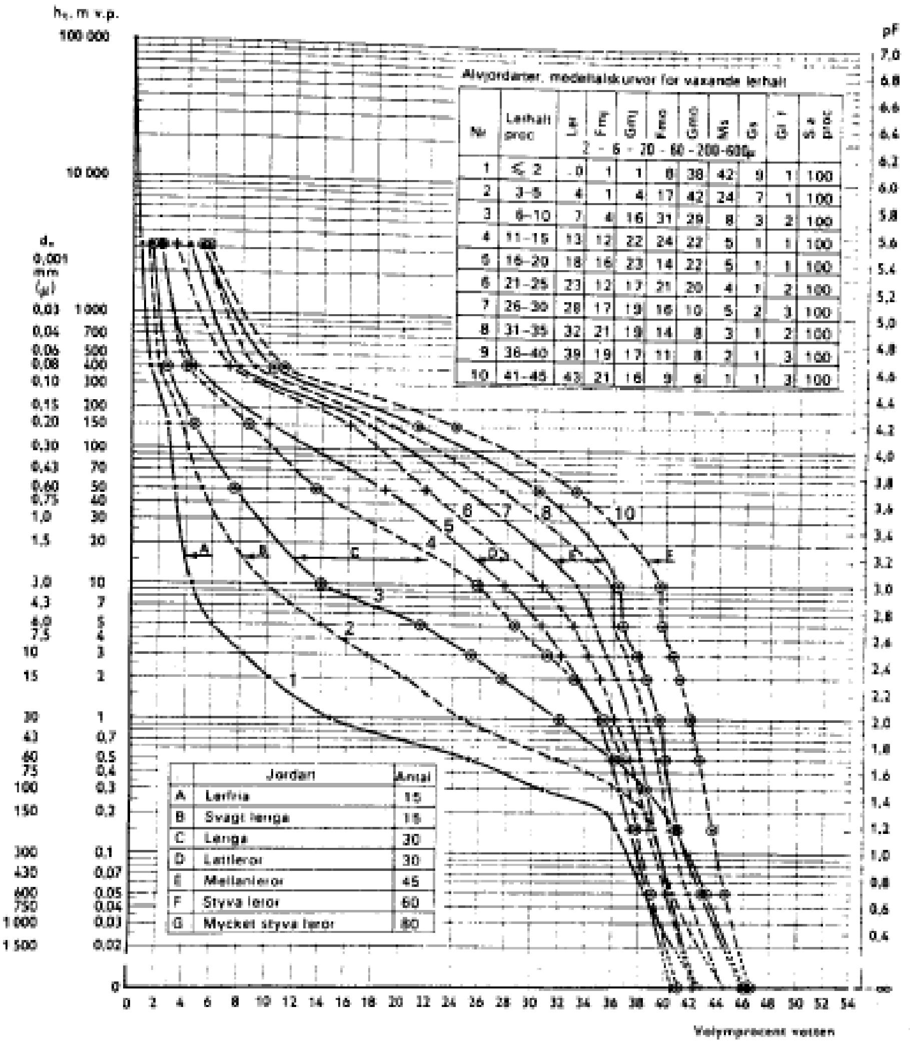


Figure 23b The water retention capacity for different soil types, from a sand to a clay (Andersson & Wiklert, 1972). The groundwater table can be assumed to be at zero on the vertical scale. Please observe that the vertical scale is logarithmic.

In the southern part of Sweden the lowest ground water level normally occur during late summer or autumn. In the northern part the lowest levels occur during late winter, before the snow melting starts and the soil has defrosted. The influence on the water content are potential highest in coarse soils (sand, gravel) due to the low water retention capacity. The ground water level in several soil types follows the ground surface, in a broad sense of view. However, the ground water table is normally highest in low land and lowest in high land, in relation to the ground surface.

It is necessary with long measurement periods in ground water pipes to established good statistics for a specified site. However, it is possible to establish highest and lowest ground water level by means of a developed statistical method (Svensson, 1984), and the use of long term measurements from SGU´s ground water network together with local ground water data for a shorter period and developed algorithms

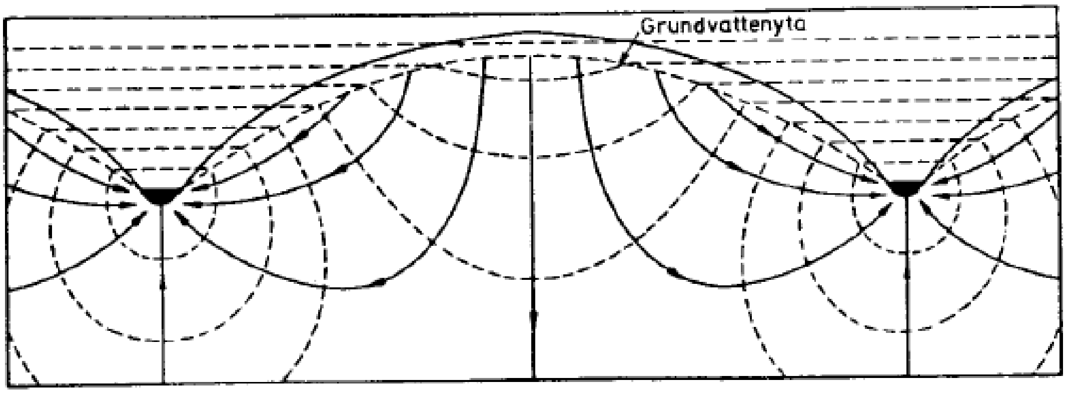


Figure 24 Schematic view of the ground water table in the terrain (Svensson, 1984).

4.4 Summary

The natural conditions around a buried cable can vary along time. Critical conditions are:

1. Low ground water table in combination with coarse grained soils, sand, gravel and coarse grained moraines.
2. High ground temperature

Point 1 refers to the increased soil thermal resistivity and point 2 to the additional temperature load compared to mean temperature. In the southern parts of Sweden these conditions can interact and be critical during late summer and fall.

5 Cable back-fill

5.1 Introduction

The back-fill material below and around the cable is exposed for the highest temperature and possible moisture movement. It is theoretical possible to use the natural material at the site for back-fill purposes. However, in order to ensure thermal, mechanical and other demands, it is most often good to use a material with specified requirements. By using such a material it is possible to compensate for less good natural materials and have much less uncertainty in the material with the highest demands. The literature review in Appendix 4 includes a review on different materials.

Back-fill material can be sub divided in different ways. Here is two examples:

- Natural material and mixed materials
- Granular and flowable

Natural materials are normally preferred of environmental reasons. Common natural materials are natural sands or crushed fine grained materials. However, natural materials can also be mixed and have natural or other additives.

Examples of mixed materials are: Natural materials together with cement, bentonite, graphite or ashes. Graphite is highly thermal conductive but rather expensive and used in boreholes around pipes for energy extraction; geo energy.

Mixed materials can however also be flowable. The additive is in this case the flowable component. It is not elementary to get low thermal resistivity in a flowable and pumpable mixture. Flowable materials can also consist of only one natural component e.g. some types of bentonite. Sometimes only water is the back-fill. It is perfectly flowable but need good sealing, to prevent from leakage, or surveillance in the long term run. In addition to the above material also water can be mentioned as an extremely flowable material. However, the usage is restricted to tubes or other concealed environments.

5.2 General demands on back-fill material

The following demands can be set on back-fill material in trenches in order to ensure long term durability:

1. Thermal:
    a. Have low overall thermal resistivity, also at low water content
    b. Resist moisture migration and drying-out through high water retention capacity
    c. Have properties that enables good thermal contact with the cable
2. Mechanical:
    a. Possible to compact and form a mechanical stable base for the cable work
    b. Not sensitive to surplus of water
    c. Protect the cable from external loads and threats
    d. The material itself shall not harm the cable mechanically (e.g. maximum allowed grain size)
3. Corrosion:
    a. The material itself or its leachate shall have no negative chemical or corrosive effect on the cable
4. Environment:
    a. The material itself shall not have increased content of environmental hazardous components compared to the surroundings
    b. The leachate from the material shall have acceptable impact on the environment
    c. The material shall meet the requirements from authorities
5. Maintenance:
    a. The material shall be sufficient easy to remove if maintenance is needed
6. Durability:
    a. The material properties shall not change over time
    b. The material itself shall not shrink or disappear over time

The following additional demands can be put on back-fill in tubes (below roads, areas with environmental protection etc)

7. Pump and remove:
    a. The material shall be able to pump long distances and still full fill thermal and other demands
    b. The material shall have low enough viscosity during installation to full fill the required thermal contact
    c. Higher demands on removability
    d. Special demands on durability

5.3 Desirable thermo dynamic properties

The heat generated by high voltage cables must be transferred through the soil. The soil closest to the cable is most important for the transfer. The thermal resistivity, m·K/W, controls the heat transfer at steady state conditions (if convection and radiation is negligible). Too high cable temperature results in increased ageing of the cable material. In serious cases it can result in a thermal breakdown or thermal runaway of the cable.

Except a low thermal resistivity there is also a need for thermal stability. This means that thermal properties in the backfill material are stable over time and no moisture migration occur. In all materials there is a tendency to moisture migration (caused by vapor diffusion) in the heat flow direction and suction in the opposite direction. In a stable material it is a balance between these two forces. In non-stable materials the suction is too low and results in a dry material closest to the cable. A dryer material has a significantly higher thermal resistivity. This is because air has approximately 25 times higher thermal resistivity than water, i.e. a potent thermal insulator.

6 Discussion

6.1 Thermal transport and drying out effects

6.1.1 Influence of hysteresis and water content

In Figure 24 water retention curves for different examined materials in the SW-link project (Sundberg 2012). The water retention curve is determined in laboratory from full water saturation towards increasing suction and lower water content. However, there is often a hysteresis in the water retention curve meaning that the vetting curve is left or lower of the drying curve in a graph. This means that for the same suction head the water content is lower when the sample is under wetting compared to drying. For instance, when the water table is lowered during the summer due to increased evotranpiration, the water content at the cable is reduced. When the water table is raised again in the fall, to the same level, the water content increases again but not to the same level as when the cycle started.

The water content is important for both the unsaturated hydraulic conductivity and the thermal resistivity. The unsaturated hydraulic conductivity decreases dramatically when the continuity in the water phase is broken. This means that if a cable is close to critical conditions for drying out, the hysteresis effect could be critical for the development of a dry zone.

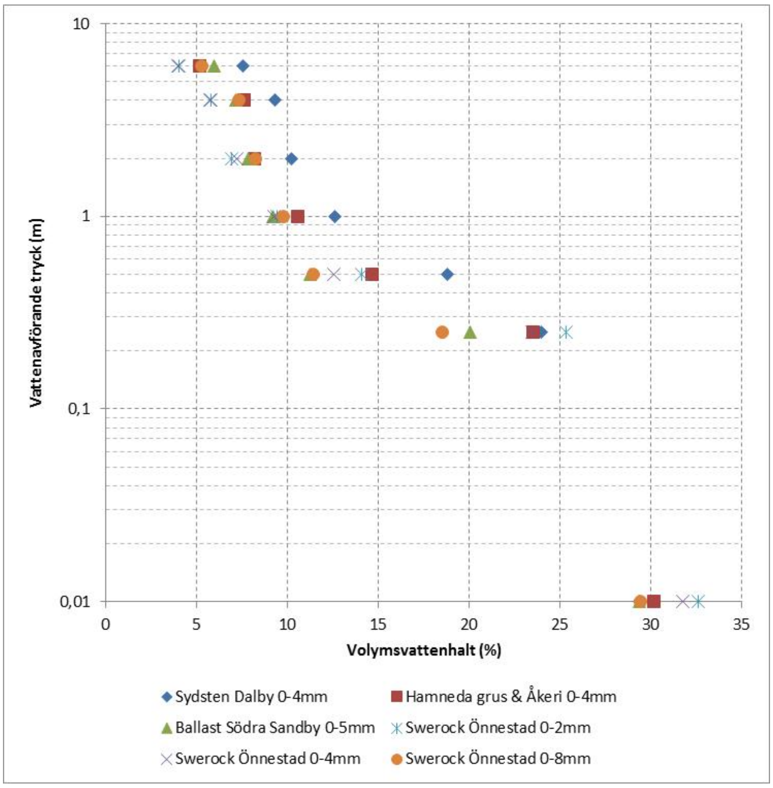


Figure 25 pF curves for different investigated cable backfills (Sundberg, 2012). The ground water table is assumed to be located at pF 0 = 0.01 m. The material with the blue dots has the highest water retention capacity meaning that for a specified suction head it has the highest water content.

6.1.2 Influence of geometry and boundary conditions in laboratory studies

In section 2.2.3 it is described experimentally how the effective thermal resistivity under unsaturated water conditions is largely decreased with increasing temperature. In section 3.2 the appearance of a dry zone around the cable is discussed with significantly increased thermal resistivity. If the thermal resistivity in the soil around the cable is lowered due to raised temperature, it should have a positive effect on the cable temperature and the risk for drying out should decrease, not increase.

Both these appearance have been demonstrated in laboratory with partly similar set up but the results are largely contradictory. This could be a result of differences in geometry and boundary conditions.

The 1D lab test for determination of the effective thermal resistivity is described in section 2.2.3. The test method consists of a cold and a warm plate with a soil sample in between. A constant temperature difference is maintained. At elevated temperature and unsaturated conditions a lower effective thermal resistivity is observed through a higher measured heat flow and the constant temperature difference. This is maintained until steady state have been established. Apparently the diffusion of water vapor towards the cold plate is balanced with suction of water to the hot plate. No drying out phenomena is established. However, the experiment set up do not allow the water to leave the soil sample and therefore the experiment is non-conservative.

The laboratory experiments on establishing a dry zone, described above, have been one dimensional. Both Gouda (Gouda et al, 1997, 2010, 2011) and Snijders & Vermeer (1981) have placed the heater at the top of the sample and at the bottom of the sample a negative pressure has been applied through a porous plate. This means that negative pressure relative to gravity and vapor diffusion interact in the same direction and that the heat flow is constant with distance. When the system is out of balance due to vapor diffusion, an initial increase in the water content is initiated further downwards in the sample. This increase could normally lead to an inversed transport of water in the opposite direction but since the water content has become higher than the equilibrium conditions, excess water tends to drain away through the porous plate in the bottom. The water retention capacity also decreases with increasing temperature.

In reality, in nature, it is mainly a 3D or radial problem, see Figure 25. This means that the heat flow and temperature decreases logarithmically with distance from the heat source. Furthermore interacts only the vapor diffusion and gravity of the soil below the cable's center. Thus, the performed laboratory investigations on the development of a dry zone seem to be conservative.

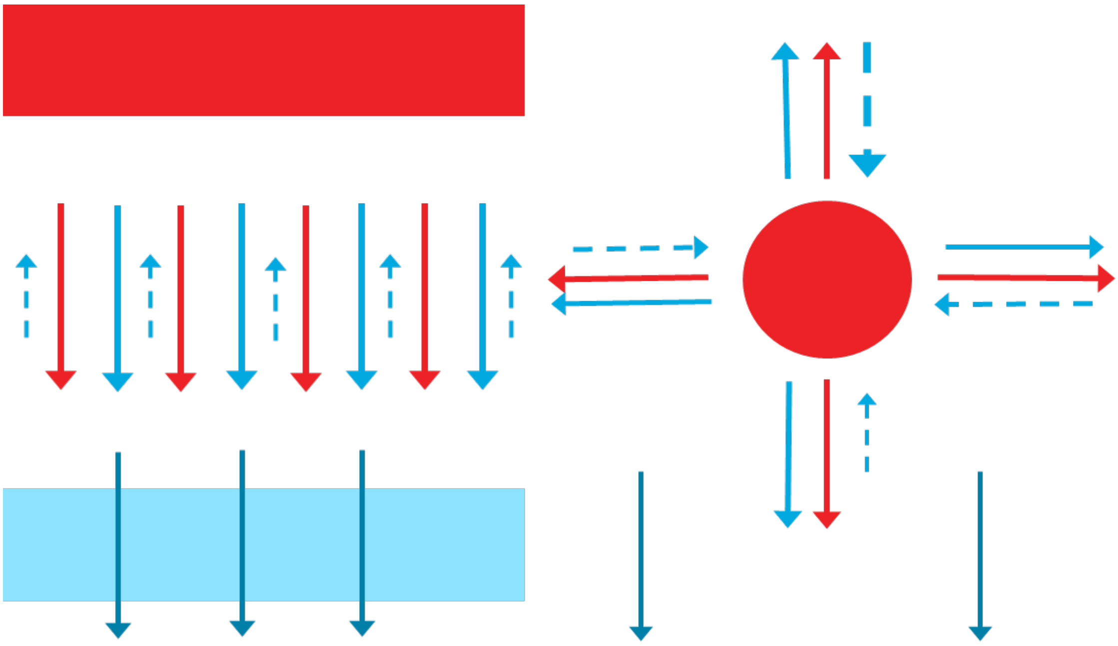


Figure 26 Simplified illustration of laboratory 1D conditions (left) compared with real 3D conditions (right) simulating a position above the ground water level. The heater is red and the porous plate in the lower part of the left figure is turquoise. Red arrows indicate the heat flow and blue arrows the corresponding water movement due to vapour diffusion. Dashed blue arrows show water movement due to local suction and gravity. Dark blue arrows in the lower part indicate water movement due to large scale suction.

6.1.3 Discussion of the experimental field studies

Both Gouda et al (1997) and Snijders and Vermeer (1981), performed field studies. They could observe a drying out process for investigated sands. Gouda´s field experiment are described in section 3.3.4. The conclusions from Gouda et al (1997) have been analysed here more carefully and alternative explanations to the measurements are discussed in Appendix 2.

The evidence presented for a dry zone was the discontinuity in the temperature gradient in surrounding soil and the measured water content.

The following observations can be made from the results in Appendix 2:

- The approximate relative temperature increase between the 0 and 1 cm curves, the 1 and 3 cm curves and the 3 and 8 cm curves respectively between late April and August, can be measured from the diagram in Appendix 2. The difference in temperature seem to increase 3-4 times during the period for all three pair of sensors.

- A decrease in water content from approximately 15% to 5%. However it is not quite clear if the water content is defined as m_w/m_{tot} or m_w/m_s. The first expression is more common and assumed here. The optimal proctor density is known (1850 kg/m^3 at w=14.7%) and we have assumed packing to 85% proctor in the field. This gives porosity of 42% and water saturation of the pores decreasing from 66 to 23 %. If 100% proctor is assumed the initial water content corresponds to full water saturation of the pores.

- During the period the current in the cables was increased from approximately 170-180 A to 250-270 A between April and the period May to August. A 50 % increase in current gives 2.25 times higher cable losses and since the cable temperature can be assumed to be proportional to the losses, a resulting relative higher cable temperature can be expected close to the cable.

- From the annual air temperature, approximately 25-30°C, the temperature rise is approximately three times at the cable and about 2 times for the distances 1 and 3 cm, between late April and August. This rise could be expected from the rise in power and 3D effects.

- The measured temperature at 8 and 13 cm varies very little even though the variation in ambient temperature and cable temperature is high.

The measured temperatures at different distances from the cable are a results of geometry, boundary conditions, cable power, soil surface temperature and the thermal conditions around the cables. A large part of the temperature increase can be explained by increased power. Some part of the different appearance of the sensors could be explained from 3D effects. Some distance away from the cables the heat flow is more or less radial, but very close to the central cable the heat flow is more 1D.

There seem to be a large lowering of the water content, down to 1/3 of the original (the exact location for the sampling is however not documented). However, this lowering of the water content do not correspond to a dramatic thermal resistivity and temperature increase, and the reason may be higher thermal transport caused by vapor diffusion, see e.g. Figure 6. An interesting detail is that the initial water content in the cable sand seem to coincide with the optimal water content at the proctor packing.

The almost constant temperature during the year at the 13 cm sensor above the central cable (approximately at 85 cm depth) seems a bit strange for the viewer. The combination of higher ground surface temperature and higher cable temperature ought to give higher temperatures in the whole area between the cables and ground surface.

There are undoubtedly a decrease in water from winter to summer period. However, it is possible that the initial water content (beginning of January), 15%, was not in equilibrium with the surrounding soil since it coincides with the optimal proctor water content and the water content in the end of the experiment is much lower (end of December), approximately 8-9%. A variation in water content during the year is common and the decrease during summer in the experiment may have natural causes.

A large part of the increased temperature can be explained by the increased power demand during summer period. It is possible and likely that we have a decrease in water content due to vapor diffusion However, no dry zone seem to be developed and the thermal resistivity seem to be on a quite low level.

6.1.4 Comparison with backfill in SW-link

In Figure 26 water retention curves for different examined materials in the SW-link project (Sundberg et al, 2011) are compared with the sand with the highest water retention capacity in investigations performed by Gouda et al (1997). Figure 26 shows that Sand 3 in Gouda´s investigation has approximately the same water retention capacity as the material with the highest water retention capacity in the investigation for the SW-link. Gouda et al (1997) concluded that all investigated sands formed a dry zone around the cable, see section 3.2. Repeating Gouda´s experiment for cable sands in the SW-link project would probably give the same results. However, the establishing of a dry zone may be a result of how the experiment was performed, see section 6.1.2.

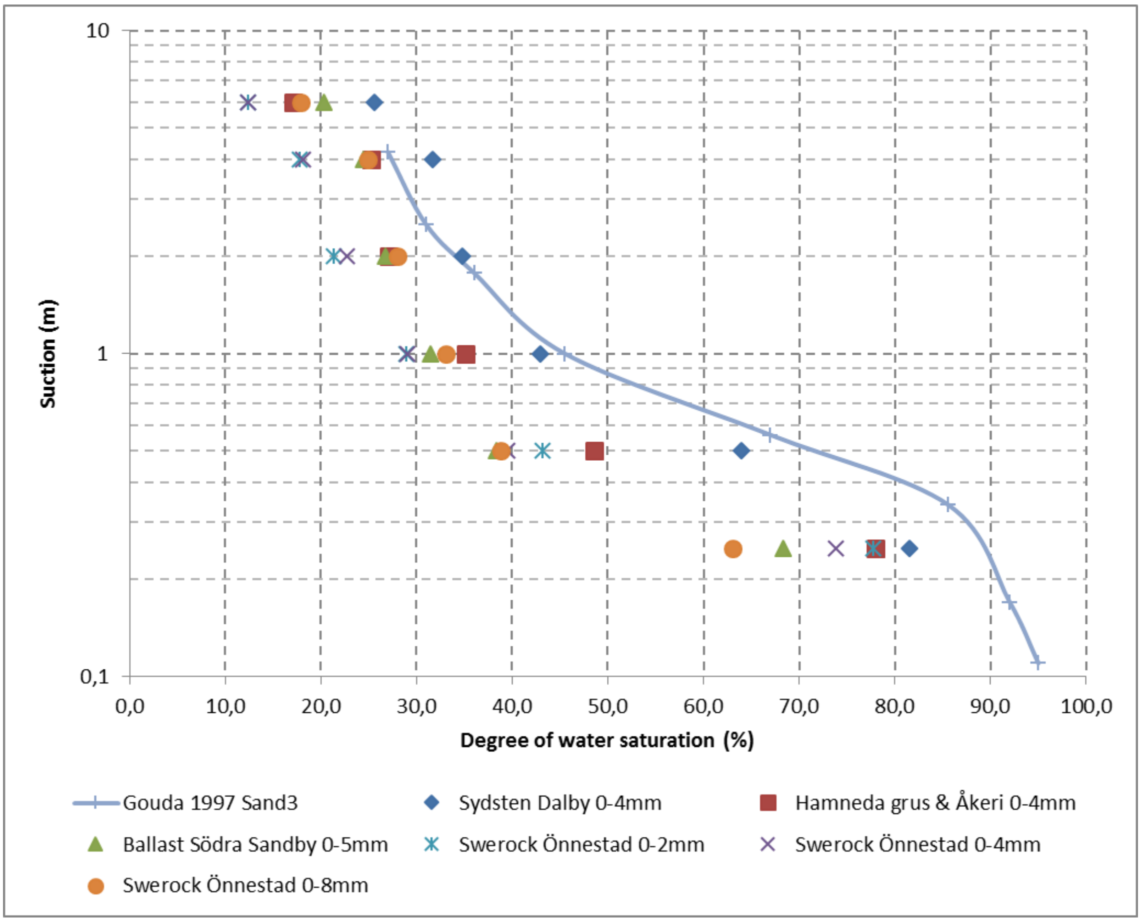


Figure 27 pF curves for different investigated cable backfills (Sundberg, 2012) for the SW-link project together with the sand with highest water retention capacity in Gouda et al, (1997).

6.1.5 Definition of the dry zone

Dry out phenomena is not clearly defined. Snijders and Vermeer, 1981, defined it as when the thermal resistivity increased with 50% percent from initial conditions at equilibrium. However, such an increased thermal resistivity may not necessarily be a problem for a certain installation. It depends on the absolute value of the resistivity and not the relative change. A possible definition on a drying out behavior may be expressed as: increased thermal resistivity with x % from a specified design level of thermal resistivity (above y m·K/W).

6.2 Ground temperature in Sweden

There are few measurements of the natural ground temperature. In Figure 15 - Figure 18 ground temperature data are shown from the middle and south of Sweden. The monthly maximum temperature at 0.2 m depth are 16-17°C. An extrapolation, based on Figure 19, to 1.2 m gives maximum temperature at approx. 14°C for a common soil. This figure can be compared to the ground temperature measurement in connection to the field measurements in different soils SW-link, see Figure 28. The temperatures for the corresponding depth are in the interval 10-12°C in peat and 10-15°C in all other soils. The extrapolated figures from Asa and Jädraås corresponds fairly well with the measured.

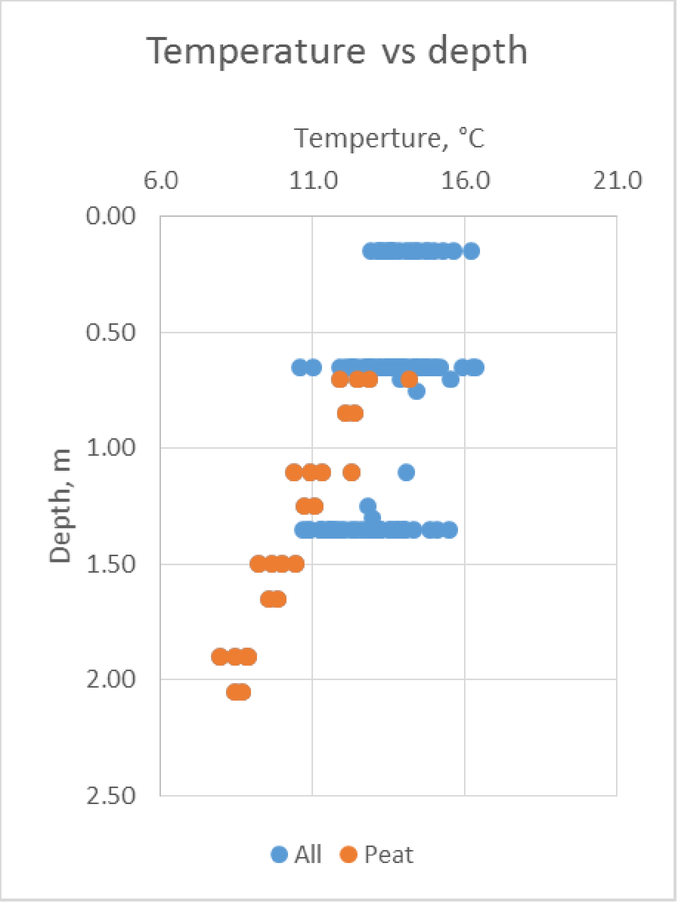


Figure 28 Ground temperatures at field investigations for the SW-link performed between 2011-08-22 – 2011-09-15. "All" stand for the temperature in all soils types except peat. The measurement in peat are real in-situ measurement with a probe. All the other are measured with

short probe 15 cm below the floor in dug pits. For the latter, a small change of temperature compared to the real in-situ value, cannot be excluded despite the precautions undertaken to prevent this, such as insulation of the bottom associated with pit excavation made one or two days earlier.

7 Conclusions

Thermal transfer around cables

- The results of 1-dimensional laboratory steady state heat transfer experiments at high temperature shows contradictory results depending on the boundary conditions

  - ✓ Highly *decreased* apparent thermal resistivity at unsaturated conditions if the boundaries are confined

  - ✓ Occurrence of drying out effects and *increased* thermal resistivity near the heat source, if the lower boundary have a high suction head (water is effectively sucked out of the system)

  - ✓ The results are depending on the boundary conditions in the experiment. The water retention capacity in combination with the ground water level seem to be the most critical conditions, besides the temperature. The performed laboratory investigations on the development of a dry zone seem to be conservative and the confined thermal resistivity measurements at unsaturated conditions seem to be non-conservative.

- Experiments with realistic boundary conditions are needed to investigate drying out effects around cables. Theoretical modelling is possible as complement but cannot replace the experiments since that knowledge are comparably low about critical properties temperature and water content dependence.

Formation of a dry zone

- Proposed formation of a dry zone (Field experiment by Gouda et al, 1997). The lowering in water content around the cable can have natural causes. No formation of a dry zone seem to have developed, in the meaning of a zone with very small water content. The lowest measured water content is equivalent to a water saturation between 20% and 30% depending on degree of compaction etc. and cannot consider to be low during summer in Cairo. The increase in temperature can to large extent be explained with higher cable power output.

- Criteria for formation of a dry zone must be defined somehow in an absolute way. A relative definition is not enough and don´t necessarily mean that a problem has occurred.

Critical conditions in the nature

- The natural ground temperature. The amplitude of the annual temperature wave is damped to approximately 50-60% at 1 m depth in common soil. The mean ground temperatures are slightly higher compared to the mean air temperatures in the southern part of Sweden.

- Prognosis of extreme values on ground water level may be made from statistical analysis based on short time measurements in local ground water pipes and long term measurements from SGUs groundwater stations.

Cable back-fill

- Drying out effects around the HVDC cables in the SW-link cannot be excluded. Experiments on back-fill material, with similar pF curve as used in the SW-link, shows drying out effects at 40-55°C or 55-60°C. However, the used heat flow in the experiments are much higher compared to heat flow from HVDC cables.

- A cable back-fill shall fulfil a number of different demands. It is possible to produce a material with significant lower thermal resistivity but it may have impact on costs, sustainability and environmental issues.

- It may be possible by engineering means to increase the positive effects of vapor diffusion and decrease the negative by engineering measures, meaning that a substantially lower thermal resistivity could be expected.

- Good thermal contact between the cables and the back-fill are essential for the thermal performance of the cable in the long term rum. Development may need to insure that requirements on good contact is fulfilled during installation.

8 References

Andersson S, Wiklert P, 1972. Markfysikaliska undersökningar i odlad jord. Grundförbättring 25 (2-3), p 53-243, Uppsala.

Atlas över Sverige, 1953. Svenska sällskapet för antropologi och geografi.

Blackwell JH, 1954. A transient-flow method for determination of thermal constants of insulating materials in bulk. J. Appl. Phys., 25, (2), 137-144.

Gouda, O. E., Abdel-Aziz, A. M., Refie, R. A. & Matter, Z. 1997. Experimental Study for drying-out of Soil Around Underground power cables. Journal of King Abdulaziz University Eng. Sci, 9, 23-40.

Gouda, O. E., El Dein, A. Z., AMER, G. M. 2010. Improving the Under-Ground Cables Ampacity by using Artifical Backfill Materials. 14th International Middle East Power System Conference (MEPCON'10), December 19-21, 2010 2010 Cairo, Egypt. Cairo University.

Gouda, O. E., El Dein, A. Z. & Amer, G. M. 2011. Effect of the Formation of the Dry Zone Around Underground Power Cables on Their Ratings. Power Delivery, IEEE Transactions on, 26, 972-978.

Gustafsson S E, 1991. Transient plane source techniques for thermal conductivity and thermal diffusivity measurements of solid materials. Rev. Sci. Instrum. 62(3), 797 (1991).

Horai K, 1971. Thermal conductivity of rock-forming minerals. J. Geophys. Res., 76, 1278–1308.

Lindroth A, 1982. Skogliga försöksområden och forskningsresurser i Jädraås. SLU, Inst. F. ekologi och miljövård, Rapport 10.

Lundegårdh, P H, Lundqvist J, Lindström M, 1970. Berg och jord i Sverige, 3:e upplagan. Almqvist & Wiksell, Stockholm.

Mossmark F, Sundberg J, 2007. Field measurements of thermal properties. Multi probe measurements in Laxemar. Oskarshamn site investigation. SKB P-07-77, Svensk Kärnbränslehantering AB

Nikolaev, I. V., Leong, W. H. & Rosen, M. A. 2013. Experimental Investigation of Soil Thermal Conductivity Over a Wide Temperature Range. International Journal of Thermophysics, 34, 1110-1129.

Nordberg L, Persson, G, 1979. Vårt vatten. Tillgång - utnyttjande. LTs förlag. Stockholm.

Philip, J. R. & de Vries, D. A. 1957. Moisture movement in porous materials under temperature gradients. Eos, Transactions American Geophysical Union, 38, 222-232.

SLU, 2001. Referensmätning av klimat vid skogliga försöksparkerna. Årsrapport 2001.

SLU, 2014. Pernilla Löfvenius. Personal communication

Snijders, A. L., Vermeer, J., 1981. Moisture migration and drying-out sand around hear dissipating cables and ducts. A theoretical and experimental study.

Stålhane B. & Pyk S., 1931. Ny metod för bestämning av värmeledningskoefficienter. Teknisk Tidskrift nr 28, Sweden.

Sundberg J., 1979. Metoder for bestämning av termiska parametrar i berg och jord. Chalmers Tekniska Högskola och Göteborgs Universitet, Geologiska institutionen, Publ. B132, Göteborg, Sweden.

Sundberg J, 1988. Thermal Properties of Soils and Rocks. Publ. A 57, Dissertation. Geologiska institutionen, Chalmers University of Technology, and University of Göteborg.

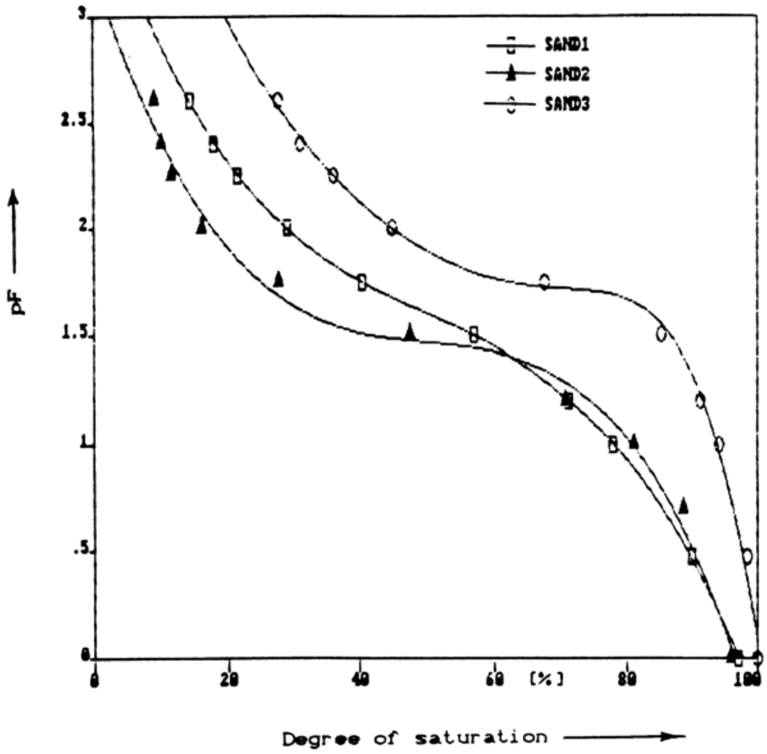
Sundberg J, Wrafter J, Mossmark F, Sundberg A, 2008. Anisotropy of thermal properties in metagranite at Forsmark. Comparison between large-scale field measurements, small-scale field measurements and laboratory measurements. Forsmark site investigation. SKB P-07-194, Svensk Kärnbränslehantering AB

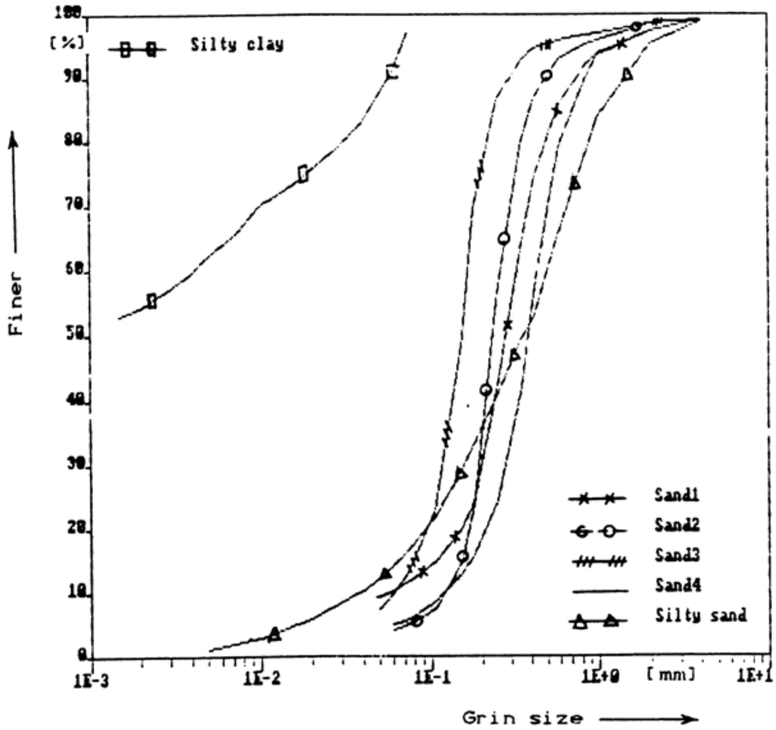
Sundberg J, Sundberg, A, Wrafter, J, 2011. Termiska egenskaper Sydvästlänken, Mätningar in-situ och i laboratorium samt statistisk analys. Vectura 2011-12-16.

Sundberg J, 2012. Termiska egenskaper för mark - Sydvästlänken, Sammanfattning av mätning, beräkning och analys. Vectura 2012-12-17.

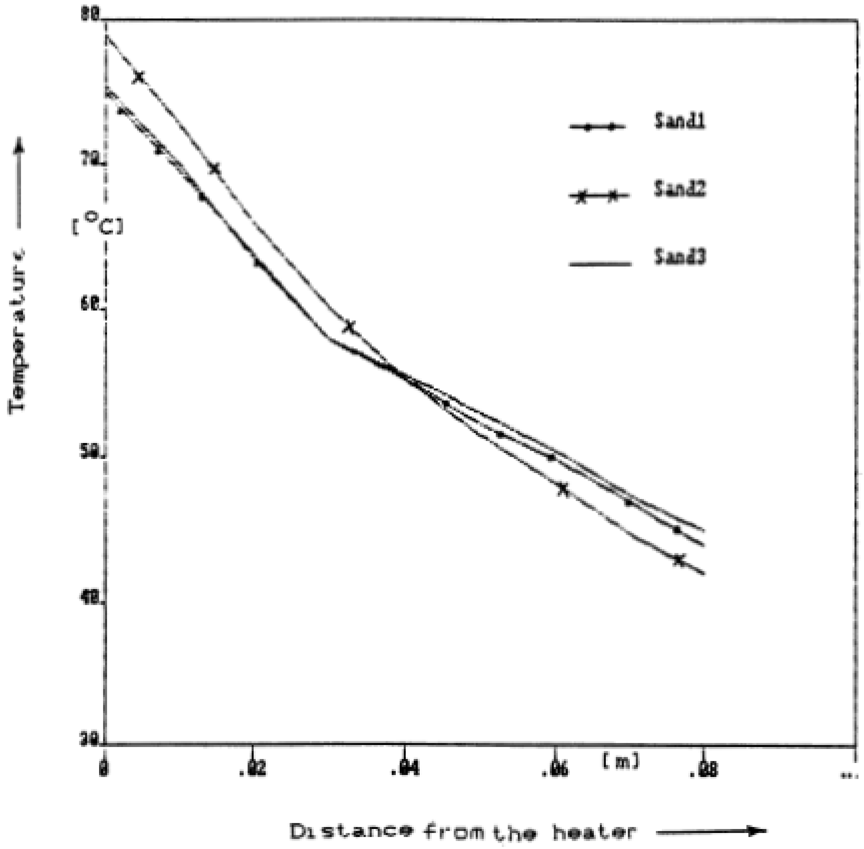
Svensson C, 1984. Analys och användning av grundvattennivåobservationer. Chalmers tekniska högskola/Göteborgs universitet. , geologiska institutionen, Publ. A 49.

Appendix 1, pF curves, grain size distribution and results, Gouda et al. 1997





Appendix 1 cont.



Appendix 2 Field experiment, Gouda, 1997

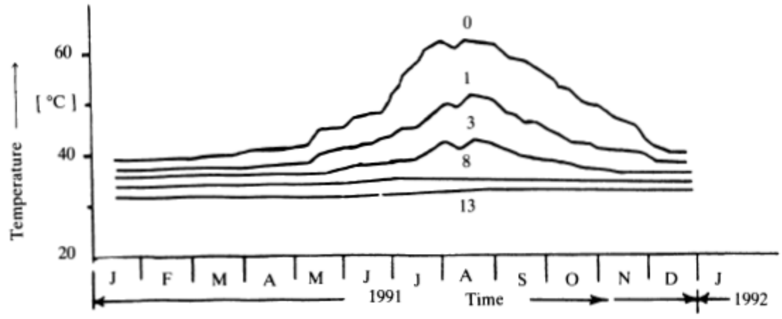


FIG. 9(a). Temperature at cable surface and at 1, 3, 8 and 13 cm above it.

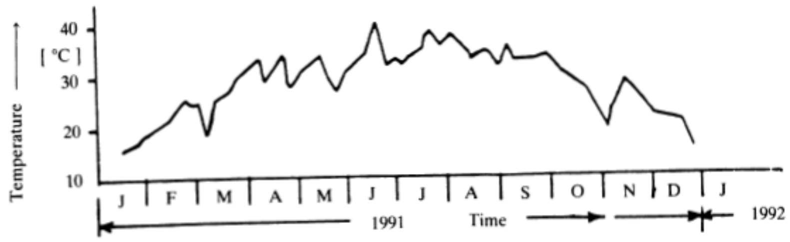


FIG. 9(b). Variation of ambient temperature measured directly at ground surface all over one year.

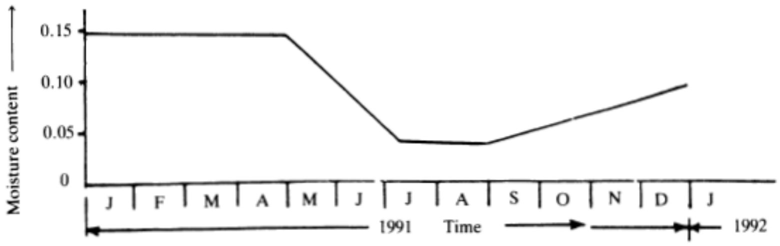


FIG. 9(c). Variation of moisture content during one year period in soil around cable surface.

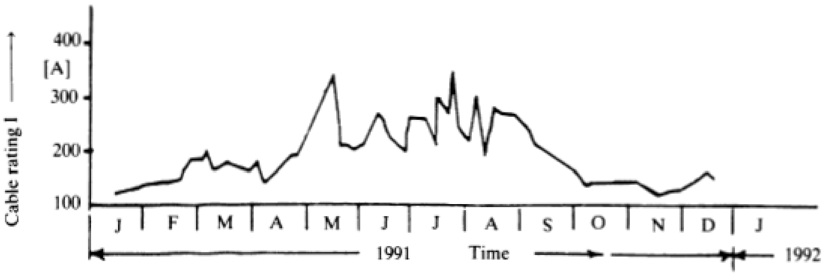
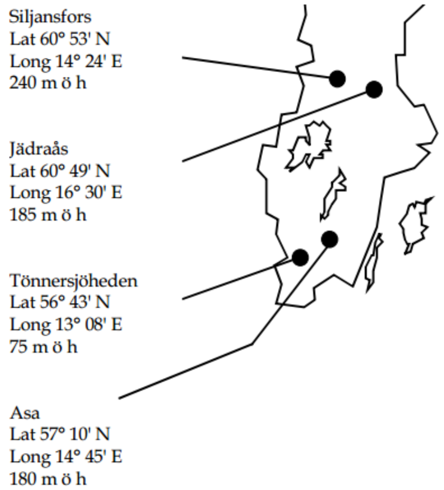


FIG. 9(d). Variation of measured cable rating during one year period.

Appendix 3. Location and description of the SLU experimental sites Asa and Jädraås

Location



Location of 4 of SLU:s 7 “Skogliga försöksparker” (test sites) (SLU, 2001)

Site description Jädraås

Jädraås experimental park is located on a moore, Ivantjärnsheden. It is a relatively flat sedimentary land and consists of glacial deposit (185 m above sea level) and partially rearranged in the form of sand dunes. The soil is stratified into layers of varying texture, from fine sand to sand, which, for example, are important for the soils ability to store water.

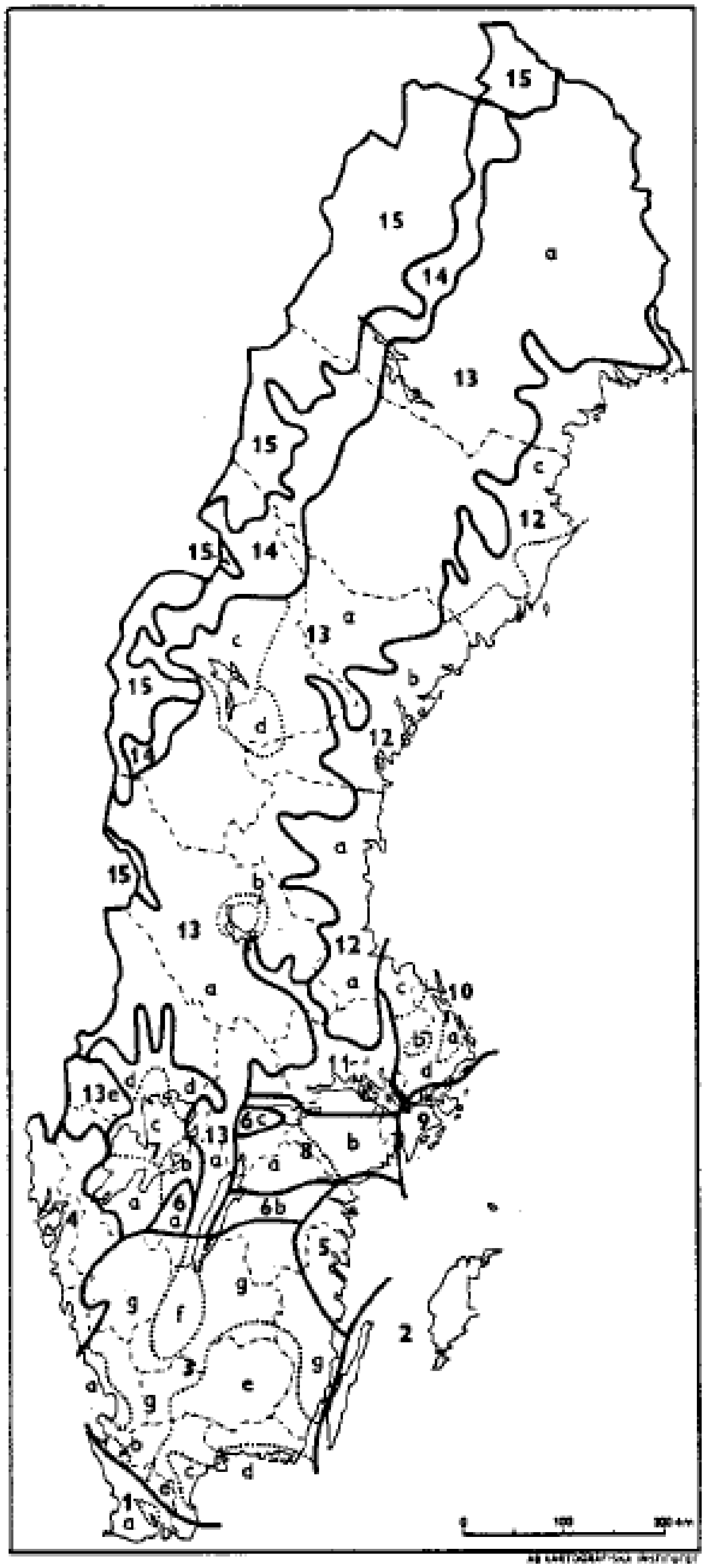
The mean values of the upper soil layers thickness varies between 1-7 cm humus layer (A0), 0.2-1.6 for the mixing layer (A1) and 2-7 cm for bleaching earth (A2). Vegetation type is pine forest (Cladonio Pinetum Boreale) with lichen, moss and lingonberry. Around the climate station the forest is kept away in a radius of 50 m. (Lindroth, 1982, and Christer Karlsson, 2014, pers comm). The RT 90 coordinates för the climate station inn Jädraås are: N 6744422, Ö 1538117.

Site description Asa

The climate station at Asa is located on a former pasture land in open and flat terrain. Soil profile is not analyzed. The soil is a sediment, probably sand with some silt and gravel. The area has been a shallow part of a seabed (during the last ice age). The soil is cultivated soil with humus and mineral soil at the uppermost 2 dm. At the top there is a fairly thick layer (about 10 cm) of mainly grass roots, which insulates the soil from the air. The surface is covered with a dense grass vegetation. In a radius of about 1 m the vegetation is cut down so it will not be higher than 5 cm (Ola Langvall 2014, pers comm). The RT90 coordinates for the climate station in Asa are: 6338063, 1438095.

Figure 29 The climate station in Asa.

Appendix 4. Classification of Sweden in geographic regions



Område	Kalk berg	Morän	Isälvsgrus	Sand	Lera	Moränlera	Myr
1. Sydvästra Skåne							
1a. Skånes moränlerområde	<1	<5	10	15	5	65	5
1b. Vombsjöbäckenets sandområde	—	<5	25	45	5	10	15
2. Kalköarna i Östersjön							
2a. Öland	25	5	<5	30	—	35	<5
2b. Gotland	25	—	5	30	<5	30	10
3. Sydsveriges moränområde							
3a. Hallandskustens sandslätt	10	15	<5	50	20	—	<5
3b. Ängelholmsslättens ler- och sandområde	—	15	<5	35	40	10	—
3c. Kristianstadsslättens sandområde	—	25	<5	55	10	—	10
3d. Blekinges berg- och lerområde	40	35	<5	15	5	—	5
3e. Sydöstra delens rena moränområde	5	70	5	<5	<5	—	15
3f. Sand- och grusområdet	5	40	10	20	<5	<5	20
3g. Morän- och grusområdet	15	55	10	5	<5	—	15
4. Västkustens berg- och lerområde	55	10	<5	10	20	—	5
5. Ostkustens berg- och lerområde	55	20	5	<5	15	—	5
6. Sydsveriges kambrosilurområden							
6a. Västergötlands kambrosilurområde	5	20	10	20	20	15	10
6b. Östergötlands kambrosilurområde	15	20	5	10	35	10	5
6c. Närkes kambrosilurområde	—	30	<5	10	40	—	20
7. Vänerbäckenets berg- och lerområde							
7a. Västergötlands- och Dalboslättens ler- och sandområden	15	10	<5	25	40	<5	5
7b. Mariestadstraktens morän- och lerområde	5	40	<5	15	30	—	10
7c. Värmlandsnäs- och Karlstadstraktens berg- och sandområde	55	5	5	20	10	—	5
7d. Nedre Värmlands morän- och lerområde	25	35	5	10	15	—	10
8. Södermanlands—Närkes morän- och lerområde							
8a. Västra morän- och bergområdet	20	45	<5	10	10	—	10
8b. Östra berg-, morän- och lerområdet	25	25	<5	10	25	—	10
9. Södertörns och Stockholms skärgårds bergområde	50	20	<5	5	20	—	<5
10. Upplands moränområde							
10a. Roslagens moränlerområde	25	35	<1	10	10	10	10
10b. Uppsalatraktens bergområde	50	30	<1	<1	<1	—	20
10c. Norra Upplands myrområde	5	45	<5	10	5	—	35
10d. Morän- och lerområdet	20	45	<1	<5	15	—	15
11. Mälarbäckenets ler- och moränområde	10	30	5	10	40	—	5
12. Norrländska kustzonen							
12a. Moränområdet	10	25	10	15	10	—	35
12b. Bergområdet	20	30	<5	20	10	—	20
12c. Morän- och sandområdet	10	25	<5	25	10	—	30
13. Inlandets morän- och myrområde							
13a. Morän- och myrområdet	10	45	5	5	<5	—	35
13b. Siljanstraktens kambrosilurområde	—	45	20	20	5	5	5
13c. Jämtlands kambrosilurområde	<5	—	5	<5	—	55	35
13d. Revsunds bergområde	20	45	5	—	—	5	25
13e. Sydvästra Värmland—Dalslandsområdet	25	55	10	—	<5	—	10
14. Förfjällens moränområde	<5	65	<5	<5	—	<1	25
15. Kalfjällsområdet	...	...	...	...	...	...	...

Arealsiffrorna äro erhållna genom punktinventering utförd vid Naturhistoriska riksmuseets mineralogiska avdelning. Mätningarna äro utförda för södra och mellersta Sverige på kartor i skalan 1 : 400 000 och för övriga delar av landet på kartor i skalan 1 : 1,5 milj. I första fallet var avståndet mellan punkterna 5 mm, i senare fallet 2,5. Värdena, avrundade till jämna 5- eller 10-tal, avse procent på landarealen.

Appendix 5

CHALMERS

Literature Review
Date: 2014-10-31
Description: Version 1

Processes involved in the thermal design of buried high voltage cables

Literature review

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1 Background of Work

The functionality of buried power cables depends to a degree on the rate of heat flow dissipation towards the surroundings soil; overheat in the power lines would eventually cause failure in the insulation of cables, melting of the coating and cracking open due to temperatures higher than what it was designed for. The rise in temperature is determined mainly by the heat flow from cables and thermal resistance of cables and surrounding material (backfill and resident soil).

The thermal resistance of surrounding material of cables is dependent on the resistivity of the different components (grains, water and air), their proportions and arrangement to one another. In general, assuming a homogeneous soil and constant thermal resistivity, this will be determined by soil properties, density, water and even quartz content. However, thermal resistivity of a soil changes over length of space and time, this can either be due to climate conditions or to the existence of thermal field in the soil, creating moisture (water vapour) paths from hot to colder areas (Radhakrishna, 1968). This last means that water vapour transportation occurs due to evaporation in the one end with high temperatures towards a colder end where condensation takes place and water flow will return to balance the system.

When there is an excess of moisture outflow (water vapour) from the system compared to the liquid water flow returning, drying-out areas are generated close to the cables increasing the thermal resistivity of the surroundings, and eventually the insulation of cables will fail. Therefore, care must be taken when designing buried high voltage power cables; an analysis of the cable’s surrounding material along the entire length of power lines should be done to determine quality of the surrounding soils of cables to identify critical points where these drying-out conditions may be reached and design accordingly.

In 2012, Svenska kraftnät (Swedish national grid) decided to conduct the construction of the South-West link with 200 km of buried high voltage power lines which is expected to be finished by the beginnings of 2015. For the design, the previously stated considerations on critical points had to be made and adapted to local soil and climate conditions. The level of knowledge and development required to accomplish this project is of interest to establish the current “state of the art” by collecting theoretic background, constructions experiences, and considering future applications of models developed.

2 Scope of Work

Initially this work will focus on establishing the current state of knowledge in the available information on the processes involved in the thermal analysis and design of material surrounding buried high voltage cables. To accomplish this, a literature review is required on the following:

- Theories and research methods developed about the processes around high voltage buried cables mainly focus on the coupled moisture and heat transport processes.
- Mathematical and computer models used to describe the processes affecting the thermal resistivity of the surrounding soils of buried cables and the different variables.
- Consider if available softwares such as COMSOL model and Coup Model from Royal Institute of Technology (KTH) that have been used with commercial purposes, could be a favourable model considering all input variables.
- Specific demands that backfill material around cables should meet, like thermal properties, grain sizes (fine and coarse content), and other material properties, as well as material capacity of providing protection for cables like density. It is of importance to keep a record from private sectors on specific demands for backfill material.
- Different types of backfill materials that are currently being used by power distribution companies.
- Finally, studying possible future applications of models and technologies developed to this date such as strategies for optimizing the dimensioning, design and construction of buried high voltage cables, using models to predict thermal properties of backfill material and behaviour.

3 Thermal processes involved in high voltage buried cables

3.1 General Overview in thermal processes

Electrical energy is usually transmitted from generating electric power plants to distribution stations by either overhead or underground (buried) power lines. Eventhough overhead power lines are the most common form of power transmission, these have some down sides that underground power lines improve such as being less susceptible to weather conditions, less electromagnetic field emissions to surroundings and take less space in urban areas. These however are dependent on the thermal capacity of cables, materials and soils, which conditions the design, construction and repairing of cables (if needed).

For construction purposes sandy materials are the most commonly used for buried cables; this is because these are less expensive, have higher availability and are easier to handle (to compact). On the other hand, theirs thermal properties and different variables are more complex; drying-out areas are more prone to occur due to the permeable nature of the material.

In soils, there are different properties that affect thermal transport capacity soils porosity, texture, grain size distribution, dry density, density of solids, mineral components, thermal conductivity of minerals and soils components (water, air, solids), temperature, water content, degree of saturation, and some others that might be more or less difficult to measure or calculate; even quartz content also has great influence on thermal conductivity since its conductivity is several times higher than other minerals components of rocks and soils (Sundberg, 1988).

Even though extensive research has been done over the years, a single universal model, considering all possible variables affecting the thermal conductivity of the backfill material and applicable to a full range of degree of saturation and all soils textures, has not been established yet. In the majority of cases of empirical studies, material tested has been built up in laboratory or taken from specific locations; this represents a greater difficulty to standardize a model for a variety of soils.

The main research works done over time on processes affecting the design of buried cables, theories, analytical and empirical models developed to study processes and variables, including a brief compilation of equations used will be summarized next. The entire system is ruled by heat and moisture (in vapour and liquid form) transfer through soil pores, both process are interconnected and affecting each other. An overlook on research done within this subject will be presented, as well as more detailed processes in soils like apparent thermal conductivity, water retention capacity, and drying-out occurrence, that directly affect the system.

3.2 Methods and models used to determine the coupled heat and moisture transport process in buried high voltage cables

Mickley (1951) first started considering the effect of moisture migration on the thermal conductivity process in soils. During the experimental tests it was intended to observe the moisture migration process under dynamic conditions (climate changes) of evaporation, vapour transfer and moisture renewal from rainfall. From the observations, it was clear that migration process takes longer time than predicted to occur. With time it was possible to observe a decrease in the thermal conductivity in the soil. By means of solving Neher's equation it was possible to obtain the so called "basic constant for the conductivity change" due to migration phenomena, with this constant it was concluded that it should be possible to determine the migration effect with any geometry (spherical or cylindrical), this was supported by experimental field tests (Mickley, 1951). Similarly, Philip and De Vries, (1957) found equations to describe moisture and heat transfer under temperature gradients, considering the interaction between the solid, liquid and vapour phases in porous media (such as in soils). This analysis was compared to experimental tests and was found to be in acceptable agreement (Philip and De Vries, 1957).

As stated before, the moisture migration process affects the thermal transfer capacity of the soil to the point that it can be critically reduced. In 1981, a publication was produced as a collaboration between "N.V. tot Keuring van Electrotechniische Materialen" and "N.V. Heidemij Beheer", as a result of an investigation to determine the physical mechanisms that generated the drying-out areas in the backfill material. In this report, a description of the transfer of moisture in soils with an invariable solid phase was done by Snijders et al., (1981). The moisture (water vapour) transport was divided into transfer of liquid water and water vapour. A dynamic equilibrium between the flow of vapour and the return flow of liquid water was created between different high temperature and lower temperature regions respectively. In cases when a certain temperature level was reached the equilibrium could be broken, meaning that migration of moisture (water vapour) was higher than the return flow of liquid water. A drying-out area was then created in the vicinities of the cables and the thermal resistivity was increased by a factor of 2 to 6 (Snijders et al., 1981); The moisture retention capacity of the soils was one of the most important characteristics to determine the critical points at which this balance was broken. Although in more recent research higher apparent thermal conductivity was obtained for high temperatures ranges for different soils tested (Nikolaev et al., 2013).

Using the theory developed by Philip and De Vries, (1957), a mathematical model was built to describe the temperature and moisture distribution in specific types of soil, strictly 3 different types of sands with specific properties and characteristics were tested. The model was built for a wide range of temperature, including the hysteresis effect of suction tension and the moisture content. During this investigation, it was found that the hysteresis phenomena played an important role in the combined transfer of heat and moisture (Snijders et al., 1981). It was recommended to always include this variable. In this research it was considered as part of the diffusion coefficient, since the suction tension applied and rewetting was always constant because of the moisture gradient.

The mathematical model was used as a predictive model for field tests and was checked using experimental tests. In order to use the model against laboratory results some assumptions and simplifications were done to the analytical initial model, such as only one dimension was considered (longitudinal direction) and no changes in time were considered (based on stationary conditions). A constant thermal load was also assumed as a simplification since the thermal load has a usual cyclic pattern for 24-hour periods.

The mathematical model developed in this investigation does not fully cover the hysteresis effect in the pf relation and water content, the temperature effect on the pf curve, the periodic changes in thermal loads and at which point the drying-out zone starts to be generated (Snijders et al., 1981). The mathematical model considering both the combined heat and moisture transfer of liquid and vapour water is described with the following expressions:

Continuity equation for moisture transfer,

$$\left[1+\frac{P_V}{\rho_l}\left(\frac{M}{RT}\right)^2 g(\varepsilon-\theta_l)\left(\frac{\partial\psi}{\partial\theta_l}\right)_T-\frac{M}{RT}\frac{P_V}{\rho_l}\right]\frac{\partial\theta_l}{\partial t}+\frac{(\varepsilon-\theta_l)}{\rho_l}h\frac{M}{RT}\left(\frac{dP_V{}^{sat}}{dT}-\frac{P_V^{sat}}{T}\right)\frac{T}{t}$$
$$=\nabla\cdot(D_\theta\nabla\theta_l)+\nabla\cdot(D_T\nabla T)+\frac{\partial K}{\partial z}$$

Where ρ_l is the density of water [kg/m^3], K hydraulic permeability [m/s], g is the gravitational acceleration [m^2/s], z is the vertical coordinate [m], ψ is the suction tension, PV is partial pressure of water vapour [N/m^2], M is molar mass of water [kg/kmol], R is the universal gas constant [8.314 kj/(kmol·K)], P_{vsat} is the saturated water pressure above a flat liquid surface [N/m^2], h is a correcting factor for the saturated water vapour pressure in case the liquid surface is curved, ε is a pore fraction (the pore volume per unit volume of porous material)[m^3/m^3]. D_θ is the general diffusion coefficient for moisture transfer as a consequence of a moisture gradient [m^2/s], DT is the general diffusion coefficient for moisture transfer as a consequence of a temperature gradient [m^2·s·K].

Continuity equation for heat transfer,

$$C_{tot}\frac{\partial T}{\partial t}+L\left\{P_V\left(\frac{M}{RT}\right)^2 g(\varepsilon-\theta_l)\left(\frac{\partial\psi}{\partial\theta_l}\right)-\frac{M}{RT}P_V\right\}\frac{\partial\theta_l}{\partial t}$$
$$+L(\varepsilon-\theta_l)h\frac{M}{RT}\left\{\frac{dP_V^{sat}}{dT}-\frac{P_V^{sat}}{T}\right\}\frac{\partial T}{\partial t}$$
$$=\nabla\cdot(\lambda\nabla T)+\rho_l\nabla\cdot(LD_{\theta V}\nabla\theta_l)+\rho_l c_l\{D_\theta\nabla\theta_1+D_T\nabla T+K\vec{e_z}\}\cdot\nabla T$$

Where c1 is the specific heat of water, L refers to heat of vaporization of water [J/kg], λ is the apparent thermal conductivity [W/(K·m)], C_{tot} is the heat capacity per unit volume of the porous medium (including moisture) [J/(m^3·K)].

From theory and laboratory measurements, it was demonstrated that the factors that produce the drying-out area in sands are the density, the water content (considering both groundwater level and the suction tension effect and moisture characteristics by pf-curve), the heat flux from cables and the temperature of cables. Changes in these factors will alter thermal resistivity.

Soil samples were tested to determine under which critical conditions the drying-out phenomena started taking place. For the laboratory testing, two methods were used, the dynamic and stationary method. It was found that measures were performed within minutes in the dynamic method. As well stationary conditions for temperature distribution in the laboratory were reached within 1-2 days for the stationary method, after which with altering one of the main parameters a discontinuity in the temperature gradient would manifest, representing the drying-out process (Snijders et al., 1981). It was concluded that as the density of the sand is lower the drying-out phenomena will develop faster affecting the time required for the drying-out process to start. Under the test conditions and for the types of sand tested, the period required to reach the critical conditions was longer than 60 days, and it was expected that for higher density sands it might take longer periods of time.

It was noticed that for equal densities, temperature and heat flux, drying-out occurred at a much lower suction tension in one of the type of soils than the others; this was considered to be due to the difference in the water retention capacity of each type of soil (Snijders et al., 1981). Then, it was concluded that the position and shape of the pf-curve had a significant influence in the drying-out behaviour of each sand type.

The water retention capacity of the sand was the main determining factor for its heat dissipation capacity. This was observed to be related to the pf-curve position (the suction tension versus the water content relation), as well as to the grain size distribution of the sand. As a conclusion, the authors indicated that an optimum thermal dissipation capacity in sands would be given by a good gradation and relatively high loam content (Snijders et al., 1981). Authors also concluded that thermal resistivity is reduced as density increases. The sensitivity of the critical conditions to small variations in suction tension and temperature was also indicated.

Field experiments using dummy buried cables were performed during years 1974-1980 for the same types of sands. In comparison with laboratory tests and computational analysis, the same conclusions were reached with the respect of temperature, thermal load and pf-curve as factors influencing the appearance of drying-out in soils.

In a posterior publication, a review on the heat and moisture transfer theory, experiments done in both laboratory and field, and other ideas were presented on the initial De Vries method in 1957 (De Vries, 1987). The method was developed to estimate the apparent thermal conductivity where the contribution from latent heat due to vapour movement in pores filled with air was incorporated, instead of adding the values of other forms of heat transfer. The main limitations of De Vries method were that it does not consider the hysteresis effect between moisture content and moisture potential, the medium is considered homogenous and isotropic, boiling and freezing were not analysed, among others.

De Vries theory has been used and compared to experimental laboratory and field tests done on specific soils with acceptable results, some discrepancies arose and in some cases adjustments had to be made. It was concluded that apparent thermal conductivity experimental values can be obtained using non-stationary methods with little to no evident moisture migration. It is still not possible to assure that proper and accurate predictions can be made with only the theory (De Vries, 1987), this might be due to the limitations of the method and as well as to the diverse nature of soils.

As it is known, moisture migration flows due to a temperature gradient, compensated by a return of liquid flow due to condensation. A modification of the vapour apparent thermal conductivity was suggested, by including a ratio between the liquid return flow and the total flow only for steady states (De Vries, 1987). It was remarked that in order to estimate thermal conductivity from experimental data, a proper expression of heat flux density should be used. Attention should also be paid to the initial moisture conditions. In order to analyse practical situations it was recommended to solve the coupled partial differential equations (De Vries, 1987), numerically using proper computational tools.

In a more recent publication a theoretical model was proposed to describe heat and moisture migration considering air flow for unsaturated soils. A 3D model using Finite Element Analysis was developed (Yang et al., 1998). Unsaturated soils are based on three basic phases solid, liquid and air. Yang et al., (1998) assumed solid as a continuous medium, the liquid phase as well with dissolved “dry“ air, and the air phase composed of two continuous phases: vapour and dry air. “Dry” air refers to air with no water vapour. It was remarked that the pore-liquid water and pore-air transfer occurred according to Darcy’s law, while pore-water vapour occurred due to the molecular diffusion (according to Fick’s law), and as part of the main flow of the pore air (Yang et al., 1998). It was also assumed that heat transfer combined conduction, convection and latent heat transfer of vapour.

Laboratory tests were done to estimate all parameters involved in the heat, moisture and air flow governing equations, such as saturated permeability matrix and unsaturated relative permeability both for pore-liquid phase, permeability matrix under dry conditions and unsaturated relative permeability, both for the pore-air phase. The degree of saturation was found to be an important parameter; this is related to matric suction which can be determined as a function of volumetric water content (Yang et al., 1998).

In order to validate and verify the model developed by Yang et al., (1998), this was compared with results obtained by previous research. Results from calculations were compared to experimental results from tests done on the rate of evaporation from soil with a column drying test. This column drying test was simulated using Yang et al., (1998) model. It was concluded that there was a good agreement between computational and experimental results, therefore it was noted that the model might be useful for predictions of water content and temperature profiles. It was concluded that this program may be useful as well for different problems, including isothermal and non-isothermal flow in saturated and unsaturated soils, or seepage in saturated and unsaturated soils (Yang et al., 1998). It was recommended, however, that more case studies should be analysed to validate this model for more cases.

3.3 Moisture migration and drying-out phenomena

It is of great importance to predict when thermal instability might occur in buried high voltage cables in order to make a reliable design. Instability is caused mainly by moisture migration to the point where moisture content reaches a critical point, meaning vapour migration flow is higher than water liquid return flow (Radhakrishna et al., 1980). This critical point is conditioned by soil type and water retention capacity (WRC).

In Radhakrishna et al., (1980) research, the heat flow and moisture migration was evaluated for two (2) types of soils (typical material used as backfill for buried cables) through laboratory tests. Here it is pointed out that main heat transport takes place through conduction between solid and water, and a small percentage occurs due to phase change from liquid to vapour and vapour diffusion (Radhakrishna et al., 1980). Conduction occurs through the bridges formed between liquid water and solid particles, when this is broken a critical moisture limit is reached causing high thermal resistivity. When thermal resistivity increases a large thermal gradient is produced (higher temperatures of soils and cables), and instability of the system begins, this is thought to occur due to net moisture migration.

Moisture migration refers to the process where water in vapour phase diffuses from a warm region to a colder one through the soil pores. This diffusion generates a drying process of the soil, increasing the capillary tension; therefore a return of water liquid flow is generated from cold to warmer regions. This return flow is governed by suction pressure and permeability.

After experimental verification was performed, Radhakrishna et al., (1980) concluded that the main factors determining the stability of the system are moisture content and degree of compaction, in spite of the thermal gradient. Heat flux and permeability only determined the rate at which drying-out takes effect. However, thermal resistivity in an already unstable soil is found to be a function of heat flux and time.

The idea of this research was to develop a method to estimate thermal resistivity of a material of known properties using a two-power method. Nonetheless, it was concluded that field tests would be required to evaluate the utility of the method and future use in design and construction of high voltage buried cables projects.

In later investigations different tests on soils were done, more specifically six types of soils with established properties; in order to determine the beginning of the drying-out phenomena formation and its effect on the material surrounding cables (Gouda et al., 1997). As indicated before, moisture migration causes thermal resistivity of soils to increase, and eventually after years of cable operation drying-out areas are formed. Gouda et al., (1997) indicated that drying-out is affected by moisture content, heat flux density and the cable surface temperature. Authors showed that when drying-out occurred cable current ratings decrease for as much as 27% (Gouda et al., 1997). It is also recommended that the backfill material used should be well graded, have high loam content and high compaction levels at dry state.

The soils main features, grain size distribution, permeability, specific gravity and compaction, were initially determined by laboratory tests. For three out of the six tested soils additional measures were performed, such as water retention capacity (WRC) by gravity and thermal test (temperature versus time and space, and moisture versus space) (Gouda et al., 1997). It was noted that as part of the experiment, temperature was recorded every hour until the temperature distribution became stationary. It was remarked that the drying-out process was evident when the gradient of temperature showed a discontinuity. To determine whether migration took place or not, test conditions were left unchanged for 13 to 15 days. Soil samples were compacted to 90% of the maximum proctor density. Unstable and stable regions were detected by establishing the pf and heat flux density curves.

It was stated that the drying-out phenomena occurred when an increase in temperature, for a given heat flux density and water suction head, creates an increase in the vapour pressure generating more vapour transport. As well with high temperatures soils water retention capacity decreases (Gouda et al., 1997). Therefore, more vapour transport occurs than liquid water returns. From results obtained, it was found that critical temperature ranged between 54ºC-57ºC. For these temperatures, the moisture content was approximately zero. Small differences were found in results from the different tested soils, probably due to the differences between pf-curves from each.

Field experiments were also carried out by the authors. A trench was done, and thermocouples were placed at different distances from the cable's surface, where air temperature was also monitored (Gouda et al., 1997). Temperature was measured for several months, noticing that for summer months (July-August) a difference in the thermal behavior was noticed. Later during that period, temperature increased rapidly and a discontinuity in temperature gradient became evident. For this period, it was found that it had the lowest moisture content measure. As a conclusion, authors recommended to use backfill material with high loam content to improve thermal properties and water retention capacity (Gouda et al., 1997).

The same author in a later research indicated that some soils and backfill materials are more prone to loose moisture content faster than others, creating dried areas faster (Gouda et al., 2010). Different types of soils were tested to determine the most suitable backfill material features that will allow the maximum current capacity of cables. To achieve this, different types of sand mixed with different percentages of lime as artificial backfill were tested. A relation between lime + sand percentage against the thermal resistivity was determined, concluding that the relation 25% lime + 75% sand had the lowest thermal resistivity and the longest time to generate drying-out areas; therefore, this mix is recommended to reach the maximum current capacity of cables. It was concluded that current carrying capacity is affected by suction tension as well.

In 2011, Gouda presented estimations of the derating factor which refers to the ratio of the ampacity of the cables when the drying-out area is formed and when there is no drying-out formation, the current carrying cables capacity reduction due to the drying-out area formation and the influence of the types of soils in this phenomenon (Gouda et al., 2011). To achieve this, experiments were done on different soil types under different loading conditions. Thermal resistivity of soils was tested for $pf=\infty$, which was estimated to occur when the degree of saturation was 5% or less or when the water column was approximated to be zero. It was remarked that dry zones started to be formed, reaching a steady state for a range time between 24-48 hours depending on soil tested. It is remarked that the critical temperature, at which drying-out started, is dependent on the soils components, regardless of the load on the cable (Gouda et al., 2011). It is suggested that the heat flux at surface of the cable affects the time required for the drying-out area to be formed. It was noticed that the critical temperature in these tests was found to be between 57-65ºC, depending on soil type. Among the most relevant findings there was the effect of the silt content in soils, altering the temperature and speed at which the drying-out area started to be formed. It was found that the slowest dry zone formation occurred for samples with silt content (Gouda et al., 2011).

3.4 Methods and models developed on water retention capacity (WRC) on soils

Water retention capacity (WRC) of soils, including parameters and conditions affecting it, is one of the two main variables to be considered and understood to design long lasting and reliable high voltage buried cables systems. Soil-water retention curve is defined as the relation between the volumetric water content and the suction tension in the soil (Leong and Rahardjo, 1997). This curve is usually used to determine the water volume changes in the soil against the matric suction changes. This retention function is hysteretic when periods of dryness and wetting alternate (Bachmann and van der Ploeg, 2002), this effect is thought to be caused by different mechanisms: haines jumps, pores shape, grain surface roughness, water-solid contact angles, temperature and/or entrapped air bubbles. It was concluded that the capillary bundle model does represent the temperature effects for capillary pressure.

In this research, Bachmann and van der Ploeg (2002) stated that the amount of water adsorbed depends on the particle size distribution of soils, and the significance of liquid water and water vapour for moisture adsorption and transport in dry soils. Here it is also mentioned the contact angle between grain and water film as a relevant factor in the water retention and adsorption processes, with the remark that soil has a nonzero contact angle with water or soil solution (Bachmann and van der Ploeg, 2002). From an evaluation of contact angles compared to liquid pressure and degree of saturation ratio, it was determined a correlation between contact angles taken from WRC and apparent contact angles measured in capillaries; as well that water retention is strongly influenced by the matrix of wettability of pure and mixed soil components (Bachmann and van der Ploeg, 2002). It was stated that WRC in dry soils is determined by residual water content, meaning when liquid flow stops, however changes in surface properties during adsorption are considered in this.

It was found that surface tension decreases linearly with high temperatures. As well, at a certain degree of saturation the reduction in the liquid surface tension would cause a decrease in contact angle and capillary pressure; at zero contact angle surface tension of liquid equals tension of solid (Bachmann and van der Ploeg, 2002). The surface tension of soil solutions (soil with different amounts of organic matter, soil humus, microbial biomass, etc.) was less than on pure water; surface tension of soil solution is highly influenced by temperature effects than pure bulk water. It was found as well, a decrease in interfacial tension between soil solid surfaces and gas when water vapour is adsorbed which is proportional to the temperature (Bachmann and van der Ploeg, 2002).

Water transport in soils depends on hydraulic conductivity and WRC (Schneider and Goss, 2011). In this research it is considered that WRC are equivalent to adsorption isotherms (water content as function of matrix pressure or relative humidity). Authors measured the temperature dependence of the WRC for different textures soils. It was found that temperature dependence became evident for low values of relative humidity (water activity in the soil) since there are more interactions between water films and minerals. It was concluded that increasing dryness would cause an increase in the temperature dependence of WRC, as well as the soil type has small effect on this dependence. It was concluded that this would allow the use of the determined average values of enthalpy of adsorption to other soils (Schneider and Goss, 2011).

3.5 Methods and models developed on apparent thermal conductivity on soils

In 1949, Kersten initially developed a model to estimate the thermal conductivity for frozen and unfrozen soils as a function of water content and dry density. However, the results were not acceptable for low degree of saturation down to the dry state as well as for degree of saturation above 90%. This method should also not be applied to both too low or high quartz content, some deviations regarding quartz content are expected so attention should be paid when applying the method (Farouki, 1981). Tarnawski et al., (2000b) used Kersten's function to develop a new model.

Then, in 1957 De Vries developed a method to estimate thermal conductivity for unfrozen soils; this method has been used as base for many posterior investigations and developments of predictive models. In this method, the particles of soil were assumed to be rotated oblate ellipsoids and composed by the solid phase and fluid phase (water and/or air); thermal conductivity is analysed as a function of the solid volume fraction and thermal conductivities of fluid phase and solids components (Philip and De Vries, 1957). Nonetheless, results obtained did not estimate correctly thermal conductivity for the dryness state. This method is the base for Tarnawski et al., (2000a) investigation as well as Snijders et al., (1981).

In 1975, a model presenting thermal conductivity as a function of the degree of saturation was developed by Johansen. This model was applied to fine and coarse soils in frozen and unfrozen state, with suitable results only for degrees of saturation upto 20%. This model was modified and extended to high temperatures range using a temperature dependant function (Tarnawski et al., 2000b).

Another method used by different authors, including Tarnawski et al., (2000b), is the model developed by Gori, (1983), where the thermal conductivity was evaluated as a function of the thermal conductivity of the continuous fluid (air or water). Here the soil was considered as cubic cells each cell containing a central cube (representing solids); the space outside this cube was considered to be filled with air, water or combination of both (Gori, 1983). This model was initially developed only for frozen soils.

Later Sundberg, (1988) using and modifying the self-consistent approximation method to include a contact resistance between grains described the thermal conductivity in crystalline rock and porous soils. Here the analytical method was verified measuring different crystalline and sedimentary rocks and approximately 600 soils; however, it was found that using the mean value from the Hashin-Shtrikman's method might carry significant errors (Sundberg, 1988).

Thermal conductivity of soils is one of the two main variables together with WRC conditioning the performance of the high voltage cables system; therefore, it is of great importance to understand thermal behaviour of soils, how it is affected and by which parameters. Previous stated authors and respective investigations were used as basis for more recent research presented below. These have been updated and modified to be adapted to soil samples tested.

3.5.1 Methods and models of apparent thermal conductivity (at medium to high temperatures) as function of soil properties

In the year 2000, using a FORTRAN package named Soil Thermal & Transport properties-expert system (ST&TP-ES), three predictive models to estimate the thermal conductivity of soils under high temperature (under 90 ºC) were developed where an additional evaluation of Hadas and Sepaskhah-Boersma postulates made on "the mass transfer enhancement factor" were also considered (Tarnawski et al., 2000a). Two models based on de Vries model (deV-1 and deV-2) and a third one based on Gori, (1983) model were developed in this research.

To test all three predictive models and verify the need of a mass transfer enhancement factor thermal conductivity data by Campbell was used; when some data was missing this was generated through the geometric mean particle diameter and the effective thermal conductivity of the mineral fraction. Experimental regression curves (ERC), covering the entire wetness range, were created since certain measured values were found to be inconsistent for a range of high temperature (70-90 ºC degrees).

For the deV-1 model, the initial de Vries assumptions were used, it was assumed that air is the continuous medium from full dryness to a "critical moisture content" (values differ for coarse and fine materials) and from this critical state to total saturation, water was considered as the continuous medium; the "critical moisture content" was assumed to be as the PWP (permanent wilting point); this model uses de Vries evaluation of the air pocket shape factor and latent heat transfer model, the latent heat transfer (LHT) due to water vapour diffusion is not considered so that a linear interpolation between thermal conductivity and PWP can be done; and finally De Vries model uses a matching factor of β= 1.25 for dry sands, but in this investigation it was set as default to β= 1.00 (which can be changed by the user). Some additional changes were done for the deV-1 model such as the use of five (5) standard minerals, mineral shape factors were obtained from Carslaw and Jaeger and Neiss and thermal conductivity values were taken from Neiss and Landolt-Boernstein.

The deV-2 model was developed to eliminate some inconvenients that deV-1 model presented such as it had a severe steep change of thermal conductivity at the pwp, where water became the continuous medium, and the deV-2 simplified the air pocket shape factor evaluation following the relation proposed by Neiss. In the deV-2 model, it was assumed also for the full range of wetness the latent heat transport and water as the continuum medium. The rest of changes made in this model were the same as the ones done for deV-1 model. This model was considered to be close to the experimental data under moderate temperatures and moisture values near the field capacity.

The ST&TP-ES based on bulk soil density, texture and mineralogical content, specifically 5 standard minerals (quartz, feldspar, calcite, clay minerals and mica) was designed to estimate thermal and hydraulic properties of soils. Then, based on deVries, the software sub-routine represented the enhanced heat transfer in moist soils under high temperatures using the expressions presented in Appendix 1.

As well, the model by Gori, (1983) was modified and integrated to ST&TP-ES. Modifications in the model, allowed to be used to model heat transfer in moist soils at high temperatures. This model analysed a grain of soil considering dry conditions (air), saturated conditions (water) and unsaturated conditions (combination of air and water). Under unsaturated conditions, the model worked under two ranges of volumetric water content θ compared to adsorbed volumetric water content θ_{AW}. ST&TP-ES estimated θ_{AW} as a function of the soil surface area calculated for each soil texture input, thermal conductivity for dry soils was done using the deV-1 model; the mathematical expressions used were given in the Appendix 2.

Soil suction pressure head evaluation was based on Campbell model; this was also extended to the full range of saturation. The latent heat transfer effect of the condensation of water in the pore space was considered for the thermal conductivity simulation, and evaluated using the deV-2 model. The latent heat thermal conductivity varies with soil type (texture), temperature and the degree of saturation. According to results obtained the peak values of the degree of saturation were also dependant on the type of soils. Coarse soils were found to experience the steepest change of suction pressure for low degree of saturation range this generated rapid changes of air relative humidity and latent heat transfer. For medium to fine and only fine soils, the change in latent heat transfer is delayed or even reduced. The most evident latent heat thermal conductivity contribution appeared to be at the highest temperature 90ºC degrees for all soils tested, Figure 1.

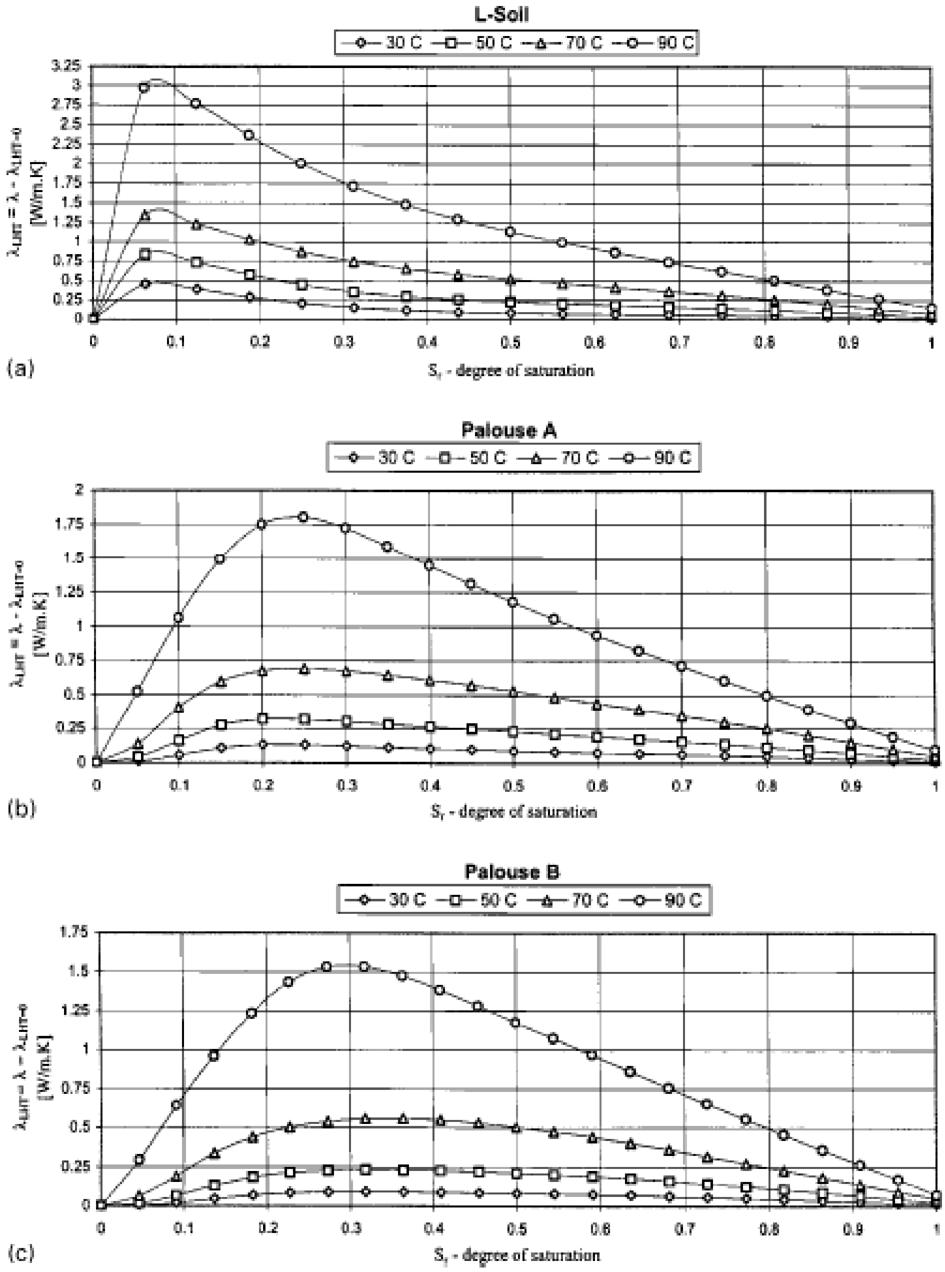

Figure 1. Results obtained for latent heat thermal conductivity λ_{LHT} as a function of temperature (T) and degree of saturation (Sr) for three different soils representing different textures

For the deV-1 model, a linear interpolation of thermal conductivity from dryness to the permanent wilting point or field capacity was assumed, latent heat transfer is considered for a degree of saturation higher than the degree of saturation at the field capacity. Two options were tested for the deV-1 model: first considering the latent heat transfer from the field capacity to full saturation, and second considering the latent heat transfer from the permanent wilting point for full saturation. For medium to fine soils the option 2 was found to be most beneficial. For coarse soils both options generate similar errors compared to the experimental regression curve. It was found for a degree of saturation between the permanent wilting point and the field capacity, option 1 over predicts thermal conductivity and option 2 under estimates the results. It was found that both these options required "a mass transfer reduction factor" instead of the mass transfer enhancement factor. However, the use of this "mass transfer reduction factor" was recommended to be re-investigated.

Results obtained indicate that deV-1 model is acceptably similar to the experimental regression curve obtained for temperature of 90 ºCelsius and low moisture content. It was thought that the cause of this might be due to: over simplified model of enhanced heat transfer, mineralogical inaccuracy, grain size distribution data, and/or measurement error due to the drying-out formation area. In general, in this research was concluded that deV-1 model has good to very good results for temperature range 30-50 ºC for most soils tested, but for a temperature range 70-90ºC this model tended to over predict as well as it over predicted at full dryness of soil. In general, good or acceptable results can be obtained from a linear interpolation of thermal conductivity at low degree of saturation. For medium to fine soils, the deV-1 option 1 generated better results. This model was considered to be the best for computer modelling of heat and moisture flow under high temperatures.

As for the deV-2 model acceptable results were generated for degree of saturation below the field capacity but over predicted for lower degree of saturation. This model was considered to be the best predictions for full dry soils.

It was also concluded that the model of Gori was simple compared to the other two models (deV-1 and deV-2); it generated good results for a temperature range of 30-50 ºC. For higher temperatures and low moisture content it tended to over predict, but it generated good results for degree of saturation higher than the field capacity. This model can be used for computer simulations for moisture content higher than the permanent wilting point, or for temperatures lower than 50 ºC.

Later the same year 2000 Tarnawski et al., (2000b) described how to obtain an extension of the thermal conductivity from Johansen model for high temperatures; this was done including a temperature dependent Kersten function as addition to the degree of saturation dependence of this function. For this research, eight known soils representing three different texture groups were used; each soil's quartz content, approximate texture and thermal conductivity under dry and saturated conditions were established and known.

It was found that this function allowed the prediction of thermal conductivity of unsaturated soils even under high temperatures (Tarnawski et al., 2000b). According to Johansen model the thermal conductivity for unsaturated soils was obtained using the Kersten function (Ke) and an interpolation between thermal conductivity (λ) at dry (λ_d) and saturated (λ_{sat})states. However, it was found that the Ke function required thermal conductivity data for a full range of saturation and data used did not meet this (Tarnawski et al., 2000b); using the deV-1 model data was complemented to fulfil the requirements. The expressions used in this model are shown in Appendix 3.

An experimental regression curve (ERC) was used to fit the points obtained from measured values that showed to be erratic (especially at 70 to 90 ºC) to a smoother λ vs.

Sr curve. For the ERC data was used from both Johansen and deV-1 original models for both the thermal conductivity at dry (λ_d) and saturated (λ_{sat}) state, respectively. It was found from an initial analysis that Ke function had a non-linear dependence to temperature and degree of saturation; then a new Ke function dependant on both variables was developed (Tarnawski et al., 2000b).

It was found then that the soil water properties among other factors influenced changes in the latent heat transfer due to water condensation in pores and therefore a more evident change in the Ke number. A rapid rise in the air relative humidity, therefore reaching the maximum latent heat transfer as soil is wetting, was thought to be the cause of the this rapid change in the Ke number.

Using a non-linear regression analysis to relate the Ke function to the degree of saturation (Sr) and temperature (T) (including high temperatures 90 ºC), a general expression , fitted to the thermal conductivity and the ERC data (r2>0.905, Sr>Sr-lin=0.125), was obtained:

$$K_e = \frac{a+bT+cS_r+dS_r^2}{1+eT+fS_r+gS_r^2}; \text{ Eq (1)}$$

Where a,b,c,d,e,f,g= fitting coefficients of each type of soil tested, see Appendix 4. This new Kersten value was included in this model to create the Simple Model.

For low degrees of saturation (Sr<0.125) the expression resulting from a linear interpolation was given by:

$$\mathrm{K_e} = \mathrm{Ke}_{0.125} \frac{\mathrm{S_r}}{\mathrm{S_{r0.125}}}; \text{ Eq (2)}$$

A new model called Simple Model was then developed during this research by including the temperature dependence to the Kersten function, already dependent on the degree of saturation. This was tested against predictions done by de Vries model modified as deV-1 (Tarnawski et al., 2000a). Close predictions of thermal conductivity were obtained for soils tested at temperature range 30 to 50ºC, however higher temperatures were considered to be more relevant in this research. Si-Mo was found to over predict compared to experimental results for moisture content above the pwp (permanent wilting point) for temperatures between 70-90ºC.

The Simple Model was evaluated compared to the experimental regression curve using an error analysis by the root mean square error dividing into ranges the degree of saturation. In general, it was concluded that the Simple Model performed better than the deV-1 model, RMSE was between 0- 30% for the full range of wetness. A found disadvantage was that its application is limited to the tested soils.

It was concluded that the use of the new developed Ke function introduced in the Johansen model showed good agreement with the experimental data for a range of temperatures between 30- 90 ºC. The Si-Mo generated better results for the full range of wetness compared to the deV-1 model for temperatures between 30-50 ºC, all temperatures at low moisture content, and for high temperatures (70- 90 ºC) for moisture contents above the permanent wilting point. It was considered that in case of disagreements with experimental data, it might be caused by the uncertainty of experimental data at high temperatures. It was suggested that in order to apply the Si-Mo to different soils than those tested, additional data like reliable soil conductivity for temperatures over 50 ºC should be considered. Further research on predictive models of thermal conductivity under high temperatures and low moisture content were recommended in this research.

Moving forward to the year 2002, a research conducted to enhance previously developed Gori's thermal conductivity model was done considering the nature of soils investigated such as Permanent Wilting Point and Field Capacity (Gori and Corasaniti, 2002). It is known that the effective thermal conductivity is dependent on many different factors from mineral composition of soil, density, porosity, temperature and water content. In this paper it was considered the soil as a multiphase porous medium, meaning that a fully dry or saturated soil would be considered as two-phase medium (composed of solids and air/water) and an unsaturated soil would be considered a three-phase medium (solids particles, liquid water in porous and gas), this last case was the major interest in this research for temperatures between 30-90 ºC.

In this paper was also assumed that the unit cell of the soil was composed of a cubic space with the cubic solid in the centre Figure 2. The main assumption done is the spherical particles with a point of contact which is a negligible cross section for heat transfer, when water is present it was assumed that the major heat conduction contribution happened by the cross section of the water bridge between two particles (Gori and Corasaniti, 2002). The dimensions of the cubic cell were given by ratio between the cell and the solid particle called β.

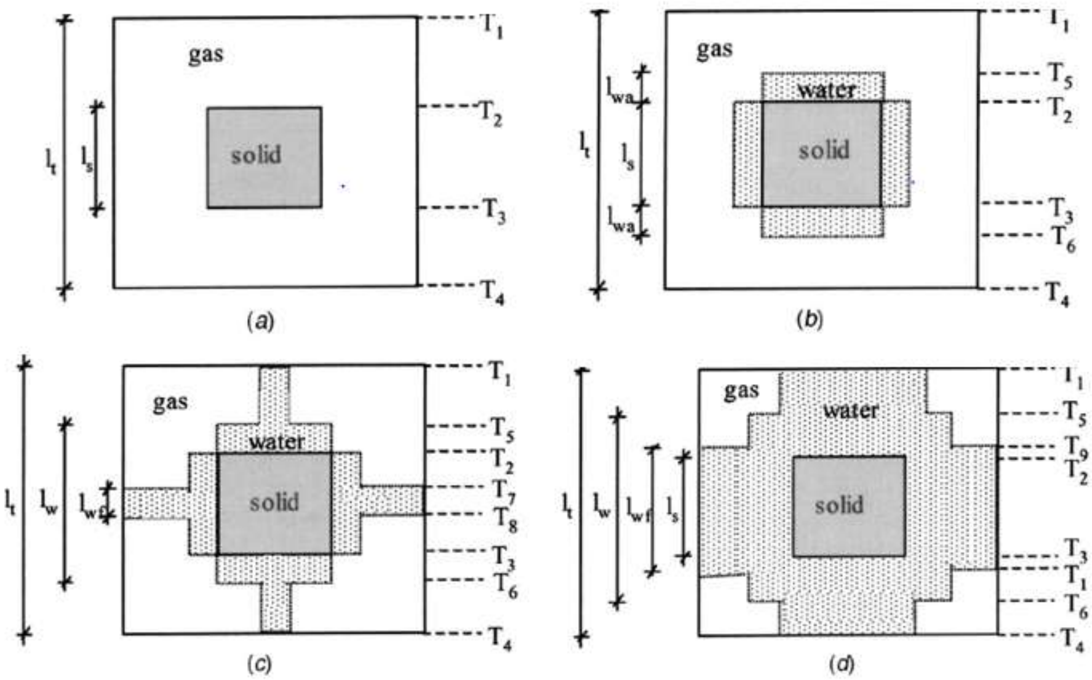

Figure 2. (a) Cubic cell for two-phases dry soil; (b) cubic cell for three-phase soil at low water content; (c) cubic cell for three phases soil in unsaturated conditions; (d) cubic cell for three-phases soil near saturation conditions (Gori and Corasaniti, 2002).

Water in soils was assumed to be distributed by effects of adsorption and capillarity. The adsorbed water (W_C) was assumed to be a fraction of the water content at the permanent wilting point *PWP* according to Tarnawski, (2000). In this research a constant C≈0.375 dependent on type of soil was assumed, this relates the adsorbed water WC to permanent wilting point *PWP*. If the total water content W is higher than the adsorbed water W_C, it was assumed that water bridges were formed among the six solids particles surrounding the cubic cell, depending on the amount of water. The effective thermal conductivity of this cell was then evaluated assuming the parallel isotherms hypothesis (or parallel heat flux) used by Gori (1983) and (1986), this was called KT, the mathematical expression can be found in Appendix 5.

Predictions in this model were subdivided into four regions. First from dryness (zero water content) to adsorbed water (Wc) which was found to give the lowest thermal conductivity due to the absence of water bridges between joining particles. In the second region from adsorbed water (WC) to the field capacity (Wf) where a continuous increase of the thermal conductivity was predicted since the variation of the relative humidity. The third region goes from field capacity to the transition of the water configuration (particular of this model). At the two highest temperatures (70 ºC and 90 ºC) the effective thermal conductivity decreases for water content higher than field capacity (W>Wf), because the apparent thermal conductivity of water is lower than the calculated with the Kapp equation.

In this paper, it was concluded that a good agreement was obtained by comparing the theoretical model to the experimental results for temperatures between 30– 50 ºC for three-phase porous soils. From dryness to field capacity and under 70 ºC, it was found a fair correlation between theoretical model and experimental results, however above the field capacity theoretical results were found higher than experiments. As well for temperatures of 90 ºC predictions were found to be higher than experimental results for all wetness range (Gori and Corasaniti, 2002). It was found a better fit if a reduction in the apparent thermal conductivity was done on the water vapour and air mixture.

In the year 2012, a modification of previous series-parallel models of heat flow through a unit cell of soil where the unit cell soil was thought to be formed by three heat flow paths: solid contacts, solids + minuscule (smallest) pores (filled with air and water), and a fluid path, see Figure 3, (Tarnawski and Leong, 2012). The goal in this research was to obtain a model that in comparison with previous empirical and physical-based models were more accurate and easy to use, as well as applicable to all soil textures and full range of degree of saturation, which had not been accomplished so far by previous authors.

A one-dimensional heat flow was assumed to go through the cubic cell of unsaturated soil, where it splits along three paths, all adiabatically insulated to the sides. It was considered for this model: a solid contact path (Θ_{sb}), a series-parallel path of solids (Θ_s) in a series arrangement with a parallel arranged path of miniscule portion of soil water (nw) and miniscule portion of air (na), and a path of water (Θ_w) and air (Θ_a) in a series arrangement. The initial expression obtained to describe the effective thermal conductivity for the soil cubic cell paths was given by:

$$\lambda_{S-II-S} = \lambda_S \Theta_{sb} + \frac{(1-n-\Theta_{sb}+n_{wm})^2}{\frac{1-n-\Theta_{sb}}{\lambda_S} + \frac{n_{wm}}{\lambda_W \frac{n_w}{n_{wm}} + \lambda_a\left(1-\frac{n_w}{n_{wm}}\right)}} + \frac{(n-n_{wm})^2}{\frac{nS_r - n_{wm}\frac{n_w}{n_{wm}}}{\lambda_S} + \frac{n(1-S_r)-n_w\left(1-\frac{n_w}{n_{wm}}\right)}{\lambda_a}}\text{; Eq (3)}$$

An alternative option was considered, if the fluid of water and air in the third path of the soil unit cubic cell was done in parallel arrangement:

$$\lambda_{S-II-II} = \lambda_S \Theta_{sb} + \frac{(1-n-\Theta_{sb}+n_{wm})^2}{\frac{1-n-\Theta_{sb}}{\lambda_S} + \frac{n_{wm}}{\lambda_W \frac{n_w}{n_{wm}} + \lambda_a\left(1-\frac{n_w}{n_{wm}}\right)}} + \lambda_w \left(nS_r - n_{wm}\frac{n_w}{n_{wm}}\right) + \lambda_a \left[n(1-S_r) - n_{wm}\left(1-\frac{n_w}{n_{wm}}\right)\right]\text{; Eq (4)}$$

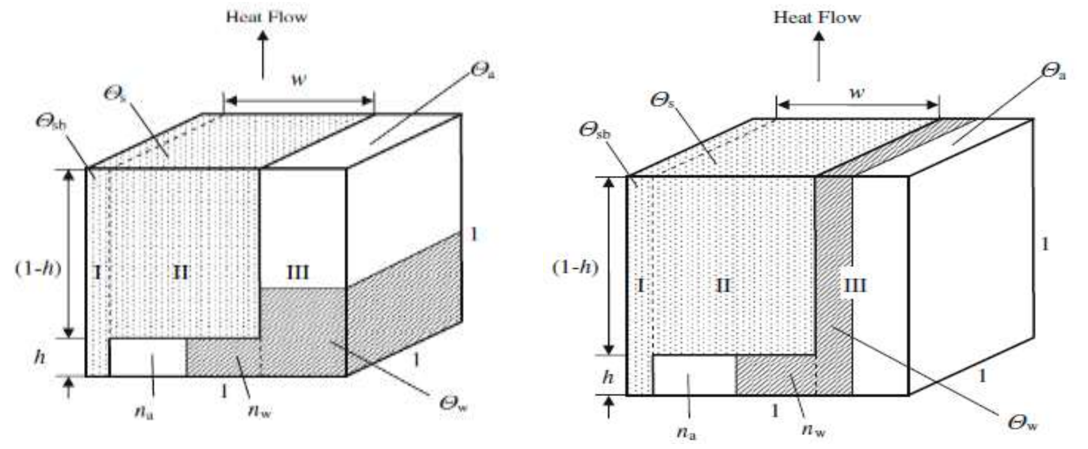

Figure 3.The unit cell soil modeled by Tarnawski 2012.(left) original cell unit assumption, (right) modification of path III

Where:

$$n = \Theta_w + \Theta_a + n_{wm};\ n_{wm} = n_w + n_a;\ w = 1 - n - \Theta_{sb} + n_{wm}\text{ ; Eq (5)}$$

$$\Theta_s = 1 - n - \Theta_{sb};\ \Theta_w = nS_r + n_w;\ \Theta_a = n(1-S_r) + n_a\text{; Eq (6)}$$

$$h = \frac{n_{wm}}{w}\text{; Eq (7)}$$

$$S_r = \frac{n_w + \Theta_w}{n}\text{; Eq (8)}$$

This was analysed using experimental data, from the analysis of three types of soils: Ottawa sand (C-109 and C-190), and Toyura sand (TS) representing coarse soils; and Cumberland (sandy soil) and Acadia (silt loam) representing medium and fine textures, the physical characteristics are shown in Appendix 6.

After a sensitivity analysis was done, it was determined that the terms representing the heat flow through the second path (second terms in equations 3 and 4) were the most relevant. It was found, since the only variable in the expressions was the degree of saturation of the smallest pore space, that the difference in the soil water retention in the miniscule pore space capacity was the reason for the difference in results of thermal conductivity obtained for each soil evaluated. A miniscule (smallest) pore water retention factor (X) was developed. This was dependent on the soil texture, structure and compaction, and it was inversely proportional to the geometric mean diameter of soils grains (particle size distribution). Therefore, a new expression for the degree of saturation (sr) considering soils miniscule pore water retention capacity was developed:

$$s_r = \frac{n_w}{n_{wm}}; \text{ Eq (9)}$$

$$s_r = 0 \text{ for miniscule pores; if } S_r = 0 \text{ for soils; Eq (10)}$$

$$s_r = \exp\left(1 - S_r^{-X}\right); \text{ if } 0 < S_r \leq 1; \text{ Eq (11)}$$

This new parameter was considered, making the mathematical model applicable for a full range of wetness (0<Sr≤1), and the expressions of thermal conductivity were changed to:

$$\lambda_{eff} = \lambda_{S-II-S} = \lambda_S \Theta_{sb} + \frac{(1-n-\Theta_{sb}+n_{wm})^2}{\frac{1-n-\Theta_{sb}}{\lambda_S} + \frac{n_{wm}}{\lambda_W \exp\left(1-S_r^{-X}\right) + \lambda_a\left(1-\exp\left(1-S_r^{-X}\right)\right)}} + \frac{(n-n_{wm})^2}{\frac{nS_r - n_{wm}\exp\left(1-S_r^{-X}\right)}{\lambda_s} + \frac{n(1-S_r) - n_w\left(1-\exp\left(1-S_r^{-X}\right)\right)}{\lambda_a}}; \text{ Eq (12)}$$

$$\lambda_{S-II-II} = \lambda_S \Theta_{sb} + \frac{(1-n-\Theta_{sb}+n_{wm})^2}{\frac{1-n-\Theta_{sb}}{\lambda_S} + \frac{n_{wm}}{\lambda_W \exp\left(1-S_r^{-X}\right) + \lambda_a\left(1-\exp\left(1-S_r^{-X}\right)\right)}} + \lambda_w\left(nS_r - n_{wm}\exp\left(1 - S_r^{-X}\right)\right) + \lambda_a\left[n(1-S_r) - n_{wm}\left(1 - \exp\left(1 - S_r^{-X}\right)\right)\right]; \text{ Eq (13)}$$

This modified series-parallel model was calibrated using five soils of known mineralogy and other properties, representing different textures (coarse, medium and fine soil textures). Even though the predictions obtained with the model were considered to be close to the obtained experimental data, it was recommended to amplify this research with more thermal conductivity data of different field soils.

Most recently Gori and Corasaniti, (2013) developed a theoretical method, without the use of empirical constants, to evaluate the thermal conductivity of three phase-soils (solids, air, liquid water or ice). It was concluded that the predictions obtained are in good agreement compared to experimental data for frozen and unfrozen soils. In this research the steady- state heat conduction was solved under the parallel assumptions for heat flux, and the effective thermal conductivity was found to be function of degree of saturation and soil porosity (Gori and Corasaniti, 2013).

In this research the elementary cell was presented as a quasi-spherical solid grain, within a cubic cell with side equal to 2·l, with radio R·1 without six sections, since R·1>l. The water was as well set as a spherical shell without six sections, since R·2>l. A three-dimensional representation of the cubic cell, a view from above, and a view from the side can be seen in Figure 4.

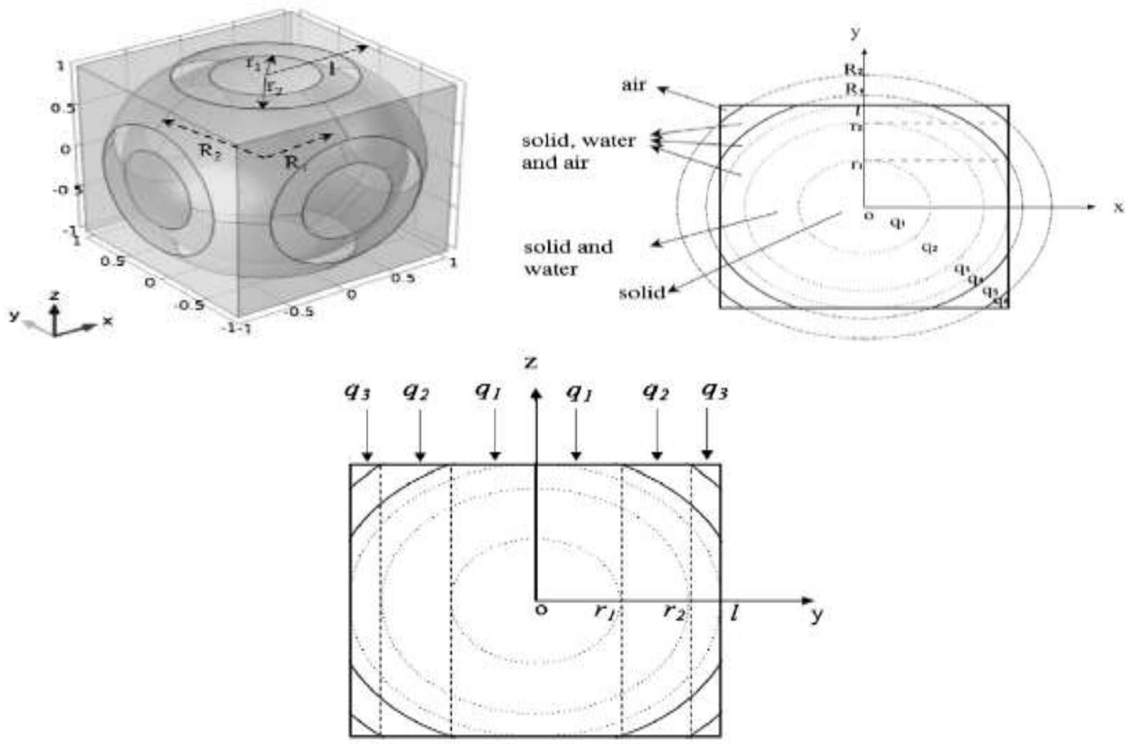

Figure 4. (Top left) Elementary cubic cell, (top right) view from above, (bottom) View from the side, Gori 2013

The steady-state heat conduction equation was solved analytically assuming parallel heat fluxes along the z-direction and the isotherms were parallel to x-y plane, see Figure 5. The total heat flux across the cubic cell was then assumed to be the sum of all parallel heat fluxes, and temperature variation in one-dimensional along z direction. Expressions used were:

Total heat flux, $q_{tot} = k \cdot 4 \cdot l^2 \cdot \frac{\Delta T}{2 \cdot l} = q_1 + q_2 + q_3 + q_4 + q_5 + q_6$; Eq (14)

The effective thermal conductivity, $\lambda = \frac{q_1+q_2+q_3+q_4+q_5+q_6}{2 \cdot l \cdot \Delta T}$; Eq (15)

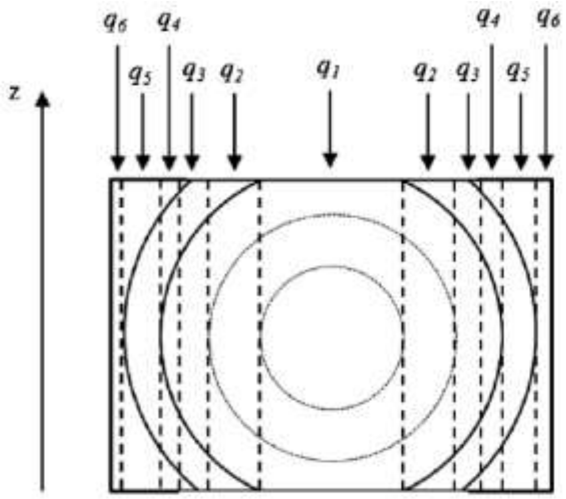

Figure 5. Diagonal section of the cubic cell and heat fluxes across the cell, (Gori and Corasaniti, 2013)

The predictions on the effective thermal conductivity obtained with this model were compared to experimental data for frozen and unfrozen previously known soils, characteristics and properties. As stated before, it was concluded that a good agreement between experimental data and the analytical model was obtained for the soils tested.

3.5.2 Methods of experimental investigation on effective thermal conductivity for high temperatures and wide range of degree of saturation

In a research paper done by Nikolaev and Leong, (2013) different previous models to determine the effective thermal conductivity in soils that have been developed over the years were reviewed, and it was found that there is still not a precise estimation method for soil thermal conductivity (Nikolaev and Leong, 2013). These models correlate soil thermal conductivity and specific soils properties and have been limited to specific types of soils and properties; therefore none can be generalized to a universal model. This research was intended to develop an accurate high temperature model of soil thermal conductivity for two types of soils with established physical and mineralogical properties for a wide range of temperatures (2ºC to 92ºC).

An experimental thermal conductivity study was initially done and later a Kersten function of the soils thermal conductivity was used to correlate model and experimental results. From two types of soils Ottawa sand and Richmond Hill fine sandy loam, the effective thermal conductivity was obtained for a wide range of temperatures and for a full range of water content. The effective thermal conductivity was measured using a guarded hot plate (GHP) apparatus which involved monitoring a specimen fixed between parallel plates while a uniaxial heat flux flowed through it. The main principle of the method was to generate a known steady heat flux moving from the hot plate to the cold plate, with a temperature difference of ΔT=4ºC. The two soil samples were prepared according to different volumetric water contents in order to obtain a trend of the thermal conductivity variation as function of water content shown in Figure 6 and Figure 7.

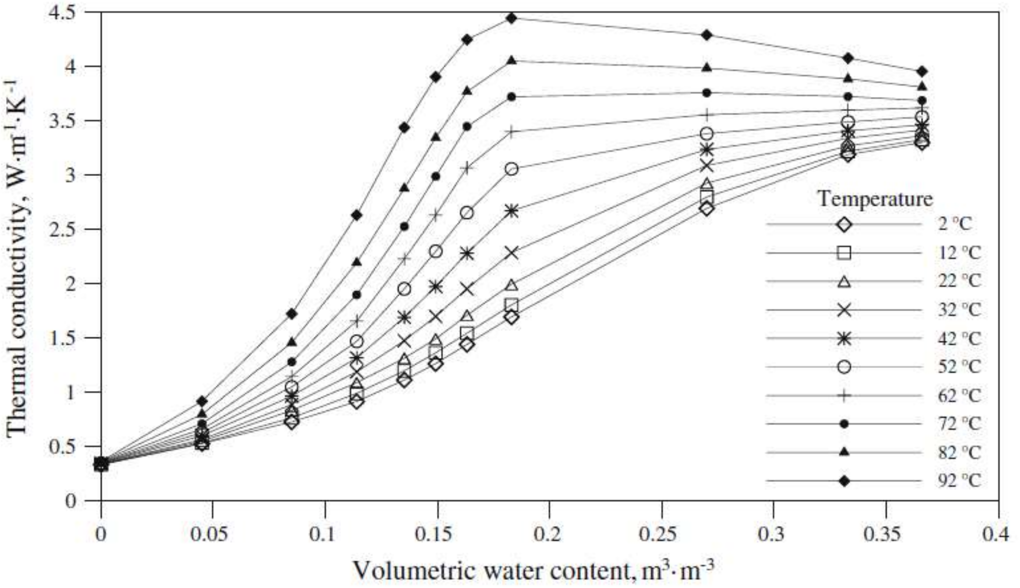

Figure 6. Variation in thermal conductivity of Ottawa sand with volumetric water content and temperature (Nikolaev et al., 2013).

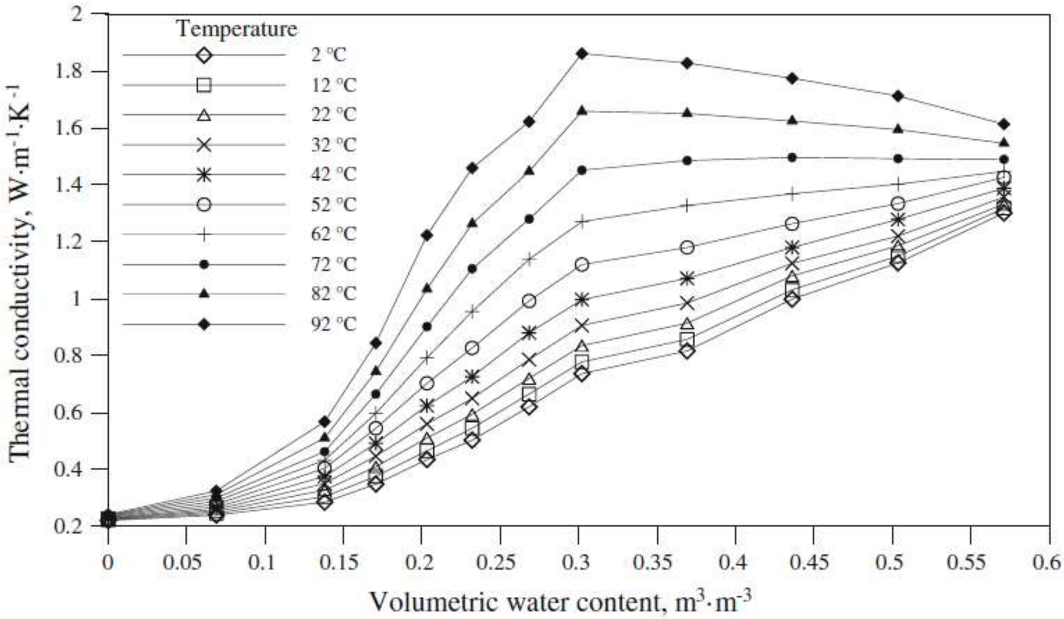

Figure 7. Variation in thermal conductivity of Richmond Hill fine sandy loam with volumetric water content and temperature (Nikolaev et al., 2013).

It was found ΔT=4ºC to be the best temperature difference between plates in the GHP apparatus since it maximized the sensitivity of the measuring equipment while minimizing the gradient across the thickness of the soil sample. It was estimated that the general error of each measurement can be thought to be a combination of several sources such as temperature non-uniformity, calibration of apparatus, and a possible effect due to moisture re-distribution in the soils layer and the homogeneity of the soil sample as well.

In order to verify results obtained, these were compared to several published values; it was found to be in excellent agreement with results of Bligh and Smith in 1983 and Moench and Evans in 1969. Nonetheless for the case of the saturated Ottawa sand, it was found that the trend obtained did not agreed with observations Tarnawski et al., (2011). In order to determine the difference in the observations, different steady-state balance equations of fluids mass and energy were used, Brinkman equation (1949) and Boussinesq buoyant flows (2011). A preliminary study to determine a probable value of the thermo-osmosis permeability was conducted, during which it was found that in the confined container, the Darcian and the heating from above buoyant flows almost counteracted the thermo-osmosis flow.

After many trials a value was obtained that was used for all the mean temperature cases, later obtaining the effective thermal conductivity of the soil layer. In general, it was found that the GHP apparatus is capable of producing results which are in good agreement with reference data, except for the case of the saturated Ottawa sand where the discrepancies in the trend of measured thermal conductivity was considered to be due to an artefact of the GHP apparatus which operated under steady-state conditions with an established temperature gradient.

Using Tarnawski et al., (2000b) empirical correlation of the soil thermal conductivity to both temperature and water content with modifications to be fitted to the experimental dataset where all coefficients for each soil remain constant for all temperatures and degree of saturations, and the expression obtained was given by:

$$\lambda_{(S_r,T)} = \lambda_{dry@22ºC} + \left(\lambda_{sat@22ºC} - \lambda_{dry@22ºC}\right)K_e(S_r,T); \text{ Eq (16)}$$

$$K_e(S_r,T) = \frac{a_1+a_2S_r+a_3S_r^2+a_4S_r^3+a_5T}{1+a_6S_r+a_7S_r^2+a_8T} + a_9T^2 + a_{10}T^3; \text{ Eq (17)}$$

$$S_r = \theta_W/\phi; \text{ Eq (18)}$$

From this research it was concluded that it was expected to aid the development of accurate theoretical and empirical high temperature models for soil thermal conductivity. The experimental Ke function was found to fit well to the empirical correlation as function of temperature and degree of saturation, with root-relative-mean-square percentage errors less than 7% for both soils. It was suggested to extend the investigation to additional soils types in both unfrozen and frozen states; this was suggested may lead to the development of a universal methodology for evaluating thermal conductivity.

4 Thermal backfill material

4.1 General overview

When designing underground transmission systems, thermal resistance in the surrounding of the cable is the main parameter to determine the maximum current carrying capacity. This was thought to be determined by the thermal aging of the electrical insulation, and the thermal properties of the backfill material (capacity to dissipate heat) (Chu, 1979). It was also considered that the thermal resistivity, diffusivity, and stability, of both the backfill material and the resident soil along the cables routes, to be of great influence for a safe design. These thermal properties of this material surrounding high voltage cables determine whether a cable overheats or not (Boggs, 1981).

4.2 Characteristics and properties (demands) for thermal backfill material around buried high voltage cables

Information regarding thermal backfill material surrounding high voltage cables was compiled indicating that there are three main systems of underground cables for which a selection of backfill material should be considered: directly buried cables, cables directly buried with an additional cooling system (cooling pipes through the backfill material), and cables in pipes directly buried in the backfill material (Sandiford, 1982). For each of these systems the backfilling operations procedures may differ as well as landuse (urban or rural areas) and the type of terrain.

Backfill material can be classified according to many parameters, based on the main components, use (trenches or pipes), whether it can be pumped or not, depending on the type of additives used i.e. as fluidizers. The main and most common classification can be done according to type of cable arrangements either trenches or pipes. Eventhough both applications require proper thermal properties (high conductivity and good capacity), materials used in pipes should additionally be easy to pump and to remove (Sundberg, 2010).

4.2.1 Types of thermal backfill material around buried high voltage cables

Radhakrishna, (1982) tested different mixture of aggregates, fluidizer and additives in order to generate a fluidize backfill material that would meet the requirements stated before to ensure the lifetime of the high voltage cables. The main mixtures were: SGFC, SGC and polyox, and limestone screenings slurry, the selection of these were based on the possibility of local availability and easy access like concrete making materials. A comparison of their characteristics and other mixtures tested by Radhakrishna, (1982) are presented in Appendix 8.

Among the quality control measurements proposed are: material strength, density, and grain size distribution analysis (for quality and construction purposes). These mixtures were developed to be mixed and delivered by either plant mix plus trucks or by on-site mixture. The materials developed were supposed to be hardening in less than 24 hours, in order to keep serviceability of roads, etc. These mixtures were found to be pumpable over long distances.

These mixtures were developed to keep the mechanical strength without affecting their thermal properties; it was thought that the mechanical properties could be altered by addition of cement without changing too drastically thermal properties. A summary of batching, mixing and handling the final mixtures tested by (Radhakrishna, 1982) are shown in Appendix 9.

Some companies design materials known as flowable thermal backfill, the company would provide with the mix design but in general is a concrete product. Among the characteristics that are claimed to have, it is supposed to be fluid and have high slump (this can be adapted according to local topography). This material is supposed to be weak, with less than 5MPa, and quickly hardening. (ConcretePromotionalGroup) also indicate a mixture of Portland cement or fly ashes, aggregates, water and some chemical to create a soil replacement, proportions and percentages are not indicated though. This mix is supposed to be self-compacting, flowable and cementatious; with 35 psi (0.2MPa) to 200psi (1.38MPa) for excavatable purposes.

4.3 Granular backfill materials used in trenches

Granular materials are the ones primarily used for trenches. Besides the capacity to dissipate heat, backfill material should likewise meet other requirements to perform as expected to sustain the system working (Sandiford, 1982),, thermal backfill material should:

I. Resist moisture migration and drying-out under weather conditions and/or cable overloading.

II. Resist mechanical demands of roads, railways, sewers, etc. This is determined by the type of soil and additional structures in the area. For this purpose granular materials are usually used in construction with proper compaction.

III. Perform well in confined areas like tunnels and trenches.

IV. “Environmentally acceptable” if leachates from the backfill are produced and corrosivity to the buried cable.

V. Resist erosion and undermining.

VI. Be easily removable for repairing or maintenance purposes; referring to qualities of diggability.

It is also recommended a proper quality control during backfilling operations, selection of material and installation. When resident soils do not meet with the required specifications a “corrective backfill” or “thermal backfill” will be used instead to replace the excavated resident soil, with thermal properties previously established by laboratory testing to determine moisture and density conditions; material should be available and easy to access. In the areas adjacent to the cables is where proper compaction and high density of the backfill material is the most relevant (Radhakrishna, 1982).

Well graded sands and well graded crushed stone screenings (particle size smaller than 10mm), specially limestone screenings, are commonly used in Northern America (Sandiford, 1982). In general, it is thought that well graded granular soils with a clay fraction (8 to 10 percent) should be considered as good thermal backfill, when a good inter-particle contact and thermal stability for a wide range of moisture contents exists.

It is also recommended that sands should be rather fine graded with considerable loam content, in order to enhance the suction capacity and thermal stability (Sundberg, 2010).

Granular materials are not commercial ready-to-use products but more a group of specifications that must be handed to local quarry or aggregate supplier (Sundberg, 2010). This material is thought to be available in most regions.

In order to find the most suitable artificial (soil mix) material to obtain the maximum current capacity of high voltage cables, it was chosen to use sand mixed with different proportions of lime, silt, and clay. Materials were tested and their properties such as density (dry and saturated) were measured before thermal resistivity tests were done. From results obtained, it was noticed that the drying-out process started to be formed at a critical temperature of approximately 60ºC for limes (Gouda, 2010). Out of the nine different materials measured, it was concluded that the mix of 75% sand+ 25% lime had the lowest thermal resistivity and maintained the highest current capacity of cables. It was also noticed in Gouda et al., (2011) that sand mixes with silt content required longer time to form the drying-out zones, as well as the movement of this drying-out zone around the cable was slower for material with silt content (Gouda et al., 2011).

4.4 Fluidized Thermal backfill materials

Thermal backfill materials can be used for both trenches and pipes (tunnels or difficult access), this mixtures can be pumped and create a good seal without air voids after hardening (Sundberg, 2010). In general, backfill materials are highly moisture content dependant and their thermal resistivity may rise by five to ten times when the soil moisture content decreases to zero (Radhakrishna, 1982). In order to improve backfill material properties, the idea of fluidizing it and place it in a slurry form has been developed. This material, after solidification, is supposed to form a low thermal resistivity, be mechanically strong to resist loads, and maintain long term quality as durability, diggability and corrosivity.

The thermal conductivity of the fluidize material will depend on the thermal conductivity of its components, proportions and nature (Radhakrishna, 1982). The concept was to develop a material with well solid to solid contact, and low resistance pore fluid, therefore a low thermal resistivity, some of the materials proposed are shown in Figure 8. A typical composition of a fluidize material should count with at least:

I. Natural or mixture of mineral aggregates to build up the bulk of volume. The grain size distribution of material used is shown in Figure 9.

II. Cementatious material to create the interparticle bond and strength. From experiments it was found that only using limestone screenings with 8 to 10 percent of fines and only 2 percent of cement resulted in a workable mix. Unlike other mixes of coarse material that required fluidizer, or the cement requirement would be too high (up to 10 percent) representing the risk of non-economical or poor flow properties in the mix.

III. Additives to improve thermal properties. The thermal properties of these are shown in Figure 10.

IV. Fluidizer or flow modifier to create a fluid consistency for easy handling. An open-ended steel mould (76mm diameter and 152 mm high) which was filled with the material and was allowed then to flow was used to measure flow characteristics of material. It was found after experimental testing, that a flow of 190 mm +- 5 mm gave a good consistency. Among the fluidizing agents used: fly ash, bentonite clay, polyox resin and emulsified wax.

Coarse Aggregate	Fine Aggregate	Cementing Material	Fluidizer	Additives
crushed stone (pass 20 mm)	stone screenings (pass 6 mm)	cement	fly ash bentonite	metal filings steel fibres
gravel (pass 20 mm)	sand (pass 6 mm)		polyox	iron ore pellets
			emulsified wax	hematite powder
				magnetite dust

Figure 8. Constituents of preliminary mix combinations, Radhakrishna 1982

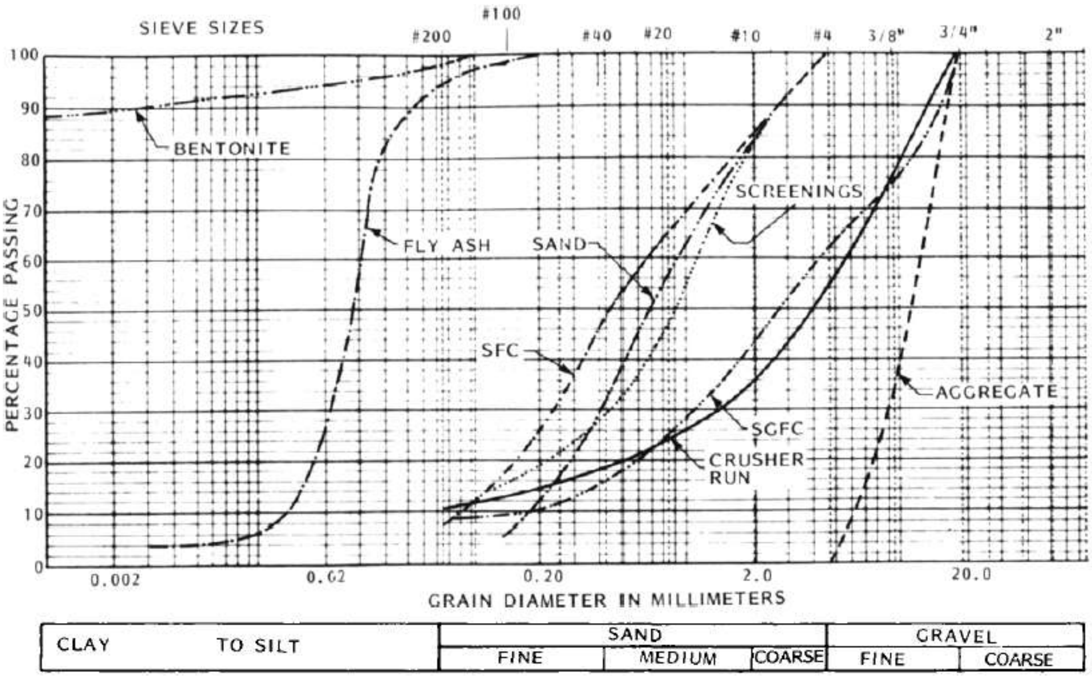

Figure 9. Grain size distribution curve of constituents and mixes, (Radhakrishna, 1982)

THERMAL RESISTIVITY OF ADDITIVES IN FLUIDIZED THERMAL BACKFILLS

Type of Additives	Dry Density* (kg/m³)	Specific Gravity	Porosity	T/R °C cm/watt
Crushed magnetite screenings (-10 mm size graded)	3130	4.42	0.292	114
Speculanite hematite powder (-#10 sieve size)	3346	4.95	0.324	135
Metal Filings (Ferraflow #260 #10 sieve size)	2769	7.02	0.606	178
Iron ore pellets (Dofasco)	2349	4.66	0.496	184
Bentonite powder (air dried)	1134	2.74	0.586	447
Fly Ash	1159	2.31	0.498	571
Cement	1610	3.15	0.489	515

*Samples prepared by hand packing materials at lower than Proctor energy.

Figure 10. Thermal resistivity of additives in fluidize thermal backfills, (Radhakrishna, 1982)

Experimental tests were done with different fluidizer additives such as: fly ash, bentonite, polyox. Fly ash is airborne coal ash generated in thermal generation stations; it is used as an aid to fluidize based cement mixes to make it more workable. Fly ash and cement mixes were built of sand, fly ash and cement mix (SFC); sand, gravel, fly ash and cement mix (SGFC); and crushed stones (19mm), fly ash and cement mix.

Polyox is a water soluble resin in form of powder which produces an effect on coagulation. Polyox is a resin used to reduce friction in fire hydrant and to aid the concrete pumping. This was added to mixes with fly ash, in percentages from 0.05 to 0.1. Sand, gravel, fly ash and cement mix (SGFC), had a thermal resistivity at totally dry state of 67 C·cm/W. Small portions of polyox resin were used instead of fly ash. If mixed with only rounded aggregates, it produced acceptable flow characteristics.

Bentonite was chosen for its availability. When mixed with water creates a gel acting as fluidizer of the mix. However, this material produces some shrinkage when drying and expansion when rewetting, as well as its thermal resistivity is higher. When large amounts of sand are used to improve the thermal conductivity, the mixture gets more difficult to pump (Sundberg, 2010).

It was concluded that bentonite-based mixture had higher thermal resistivity than fly ash and polyox mixes (Radhakrishna, 1982). It was found that fly ash and polyox mixed with rounded aggregates were the most promising mixtures. In general, it was found that, using previous mixtures, cement content could be kept under 2%. The measured thermal resistivity of the different mixtures can be seen in Figure 11 and properties tested in Appendix 7.

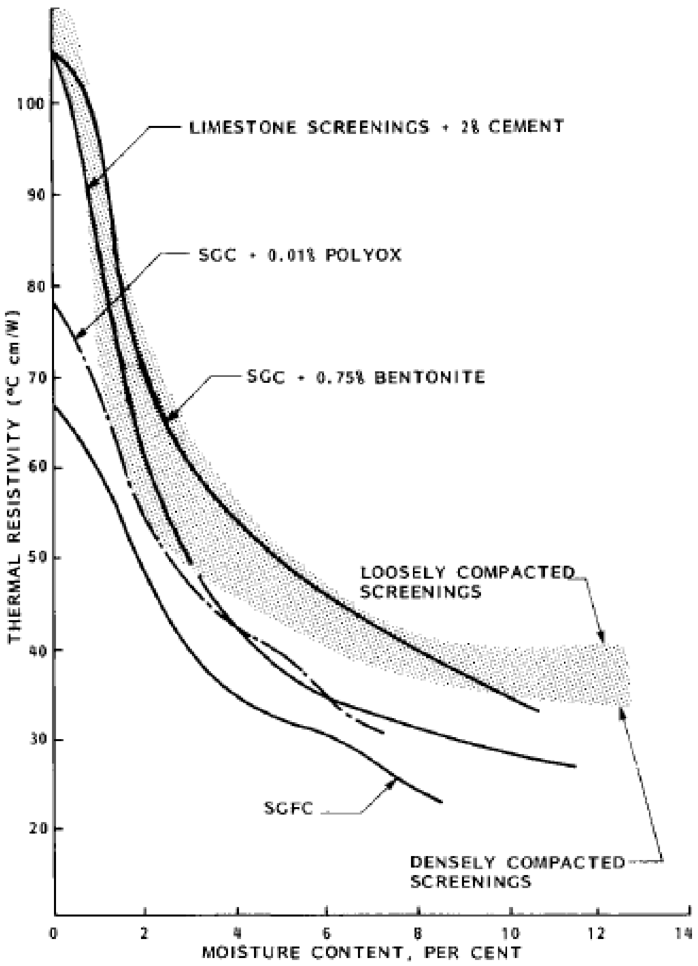

Figure 11. Thermal resistivity vs. Moisture content for the selected fluidize backfills, (Radhakrishna, 1982)

Fluidize materials requirements, besides thermal conductivity and thermal stability, include pumpability and diggability. Radhakrishna, (1982) noticed that:

- The SFGC mix was pumped without difficulties, using a 1000 to 1500 kPa pressure to pump it constantly.
- SGC with polyox, created a block in the pump due to lack of fines and paste. It was then added limestone screenings and cement (30 kg/m3 and 10 kg/m3 respectively) to improve mix. Extra polyox did not seem to alter results.
- Limestone screenings slurry was pumped with no difficulties.
- Bentonite was not pumped, since it was expected that additional fines (as cement) would be required.

- After 28 days the diggability test was done, indicating that a concrete saw or pneumatic spade is required to break the harden mixtures.

Additional information on the characteristics on these mixtures attributes can be seen on Appendix 10. Sundberg, (2010) indicated that graphite is also used as additive for fluidized backfill materials. It has high thermal conductivity and it is used in operations where the volume of the material needed is limited. This is a slightly more expensive material than others (Sundberg, 2010); on the other hand, it is considered to be a permanent solution meaning that it is not required to be removed or maintained every certain period of time according to some manufacturers (JamesDurransGroup, 2012).

4.4.1 Applications of technology fluidized thermal backfill materials

From (Radhakrishna, 1982) research a series of recommendations of possible applications for fluidized backfill materials was reviewed, and these were the recommendations done:

I. This material can be used as a corrective backfill material and mechanical protection against possible accidents caused by digging for low voltage and distribution cables.

II. It can also be used to confine transmission and distribution cables, instead of concrete duct banks.

III. It can be used as backfill for tunnels and pipes carrying cables across: railways, roadways and others.

IV. It is suggested that can be used as heat conducting material around power cables in hot spots where other services may dissipate heat into the cables locations.

V. It is suggested that this material can be used in general manholes, underground transformer wells, where compaction may be difficult due to space confinement.

5 Discussion

Since 1950's thermal behaviour of porous materials such as soils have been studied. Thermal conductivity in soils has been analysed, in most of research works, as one process dependant on the soils characteristics and properties, mainly density, porosity and degree of saturation. Nonetheless, under rising temperature a moisture migration process occurs affecting the thermal stability of the soil when a critical temperature is reached. This is known as coupled heat and moisture transfer equations, mainly developed by Philip and De Vries in 1957.

Among the parameters affecting the heat and moisture transfer process, the hysteresis effect is the least understood due to its complexity and it has not been possible to create a model describing entirely these variations. Therefore, it is not possible to generate a model that fully includes to all variables without accounting with this phenomenon and its effects on thermal behaviour of soils. As indicated by Gouda, (2010) the suction tension depends on the moisture content as much as it depends on the history of drying and wetting of the soil (hysteresis effect), this parameter affects as well the moisture migration and is an important factor in the drying-out zone formation.

Some of the models presented in this review focused mainly on soils properties and their effect on thermal soil behaviour; different research scientific and practical work done on heat and moisture transfer theory was also presented, as well as comparisons between results from field and laboratory tests. These have been part of the many different attempts to develop an analytical universal model, general enough to be used as a predictive model for all types of soils and conditions. However, this has not been accomplished yet.

It is assumed that different cable companies have based their analysis and design on one specific model, which has been adapted to local conditions. The most important factors in the system have been found to be soils properties (grain size distributions, density, porosity, mineral composition, water retention capacity, among others), thermal properties of soils and components, depending on local conditions. However, how these are considered in one single universal model was not further explored.

Two different commercial softwares that were considered as potential tools to simulate processes involved in the underground high voltage cables. COMSOL (heat transfer module) and Coup Model (coupled heat and mass transfer for soil-plant-atmosphere system). This last was developed by Royal University of Technology (KTH) in Sweden. COMSOL heat transfer model allows user to choose from different interfaces and combine them to create a model that describes the best the phenomena studied. As well, it was found that Coup Model also consists of different sub-models that can be integrated to analyse, in this case, thermal processes. However, if any of these have been used to simulate processes involved in the design of high voltage buried cables was not further investigated.

CIGRE refers to the Council on Large Electric Systems, an association whose main goal is to gather experts' knowledge and experiences and set current state of knowledge on subjects related to electric power, either referring to new methods, technologies, theories or improvements. Different information with facts and data regarding soil and backfill materials, as well as remarks on field experiences was analysed. Among relevant information found, it is worth mentioning;

- In Belgium, field work experience was recorded indicating that for high voltage (HV) cables a backfill product was always laid in the trenches (Burceanu, 2014). Specifically two types of soils could be used, dolomite and sand, it was remarked that compaction is verified along the trench (water content and dry density measurements). It was noted that through laboratory tests thermal resistivity varied if compaction was not enough; therefore, compaction was imposed to be done on site. In order to monitor soil characteristics and thermal properties, laboratory and on site tests were performed. Based on ELECTRA article the critical rise temperature and saturation degree was evaluated, reaching the conclusion that 60 ºC is the critical temperature of the material tested.

- In Finland, Helsinki Energy, after considering the high risks of drying-out areas formation in a major substation, considered to use "weak mix" (small percentage of cement) to improve the thermal resistivity's values of the existing material (Millar, 2014). This however, was initially challenging since the mix would harden to the point where access to cables was difficult and cables are expected to expand and contract during their lifetime. Therefore a "special weak mix" was tested (with lower percentage values of cement). It was concluded that these mix for backfill material were more thermally stable than most material tested to the date, showing thermal resistivity value of less than 1.0 Km/W at dry state.

- In Canada and USA, some companies remarked the importance of a proper thermal survey along the cables route. It was noticed that evaluation of exiting cables can be done by on site tests and by collecting samples of the drying-out areas. Portable test instrument such as Thermal Property Analyser by EPRI (USA) can be useful to estimate the "effective thermal conductivity" using measured parameters and compared to design values. Different parameters were defined to affect soil thermal resistivity, with specific values. On the field measure, it was remarked that if cables were buried under streets or roads, it was important to test the asphalt cover layer since this would interfere with heat transfer to the ground surface. It was concluded that if existing thermal environment measured does not keep up with design values cables must be "up-rated" in order to avoid failure.

Among literature reviewed, it became evident the importance of the heat and moisture transport in soils in many different fields. These processes are the main governing processes for high voltage buried cables systems, but these are also of great relevance for safe disposal of high nuclear waste where waste is buried to great depths and soils barriers have to be design to prevent leakage and migrations of radioactive material through soil. In the case of buildings heat loss, as well as geotechnical designs that involve freezing and thawing of soils, these processes are also of great relevance and the effects on structures and roads must be studied and considered. For agricultural purposes, in areas where climate conditions are mainly about dry seasons, understanding the process of moisture migration and heat flux may help adapt crops and develop technologies to ensure survival of crops. These processes are studied for other types of porous materials, such as concrete walls in buildings; where it is necessary to understand moisture and heat migration to design proper and efficient heat and ventilation systems, ensuring comfort and energy efficiency. Storage of materials like sugar, also use these theories and methods to prevent damages and losses in materials, moisture can affect the quality of sugar by crystallization of the material for example.

6 Final remarks and conclusions

Some models here presented focused on one or more parameters to evaluate their effects on thermal conductivity of the soils; however, it was found that not all parameters and variations were considered at the same time for one single model, this could explain why some authors have different results and conclusions.

From the models exposed earlier in this review, it is not possible to conclude on one general and accurate model to predict soils thermal behaviour when subjected to heat under varying climate conditions (like moisture content and temperature) or considering variations over time and space. However, some remarks were found from different authors, Snijders et al., (1981) pointed out the importance of the position and shape of pf-curve in the drying-out behaviour of sands; as well the density of the sand evaluated determines the speed at which drying-out areas start to appear requierng upto to 60 days in laboratory testing to reach the critical conditions.

In a similar approach Gouda et al., (1997) found that the drying-out process began when an increase in temperature would cause an increase in water vapour transport higher that the return water liquid flow, this process was noticed after 13-15 days reaching a critical temperature of 54-57ºC. It was concluded from the research the temperature has also an effect on soils water retention capacity; from field testing it was determined that water retention capacity and therefore thermal conductivity might be improved with high loam content samples.

In a following research, Gouda et al., (2010) concluded that a material with a combination of sand and lime is the most suitable to delate the drying-out formation. Gouda et al., (2011) indicated that dry zones started to be formed between 24-48 hours after testing begun at around 57-65ºC, and that the critical temperature was dependant on the soil components rather that the cable loads.

Bachmann and van der Ploeg, (2002) pointed out the influence of high temperature on and the decrease of surface tension in soil grains. Schneider and Goss, (2011) concluded that the water retention capacity of soils dependence of temperature was due to dry zones and that soil types have small effect on this relation.

It becomes evident that different authours have reached similar conclusions with relatively different values of what are considered to be critical conditions of temperature and time elapse for this to occur. Temperature values change between 50-65ºC and time has been varying in each research from hours upto nearly a couple of months.

It is worth mentioning that Nikolaev et al., (2013) recent findings on thermal conductivity of soils indicate that for high soils tested at higher temperatures, thermal conductivity seems to improve for the same water content; while observations made by Radhakrishna et al., (1980) indicated that higher temperatures in soils and cables would cause and increase in thermal resistivity.

There are many commercial artificial materials and additives such as fluidizers or substances used to speed hardening, which can be combined with granular materials to create backfill materials according to local requirements. Materials most commonly used are, besides natural aggregates, cement, fly ash with cement, bentonite and in some especial cases graphite. Limestone screenings slurry is also a good option for cables set in pipes or tunnels. However, information on proportions of mixtures, mixing procedures and/or field operations with these materials was not found.

Most information gathered in this report is of scientific nature. It is evident that companies involved in the electrical power provision sector, such as groups in charge of manufacturing products (fluidizers and/or mix additives), contractors and state own companies in charge of providing power to communities, are relevant sources of information. It is consider that they count with important information regarding both theoretical and practical approaches on the processes involved in the design of high voltage buried cables. However, during this collection of data, access to private companies' knowledge was difficult. Therefore, scientific data found to this date was used to establish the current state of knowledge on processes involved in the high voltage buried cables systems, mainly heat and moisture transfer processes in soils.

There are a number of different commercial softwares that might be used to design buried cables systems. However, information on which one is currently used by most private companies and consultants, as well as what specific models are used and how these are adapted to specific local conditions was not found.

7 References

BACHMANN, J. & VAN DER PLOEG, R. R. 2002. A review on recent developments in soil water retention theory: interfacial tension and temperature effects. *Journal of Plant Nutrition and Soil Science,* 165**,** 468-478.

BOGGS, S. A. C., F.Y.; RADHAKRISHNA, H.S. 1981. MEASUREMENTS FOR UNDERGROUND THERMAL TRANSMISSION DESIGN. Toronto, Canada: Ontario Hydro Research.

BURCEANU, M. 2014. Soil thermal characteristics investigation in Belgium CIGRE. LABORELEC.

CONCRETEPROMOTIONALGROUP. *Flowable Fills, aka...CLSM, Controlled Low Strength Material* [Online]. Available: http://www.concretepromotion.com/education_6.html.

CHU, F. Y. F., G.L. ; RADHAKRISHNA, H.S.; STEINMANIS, J. 1979. EPRI soils research program. *In:* MITCHELL, J. K. (ed.). Ontario: IEEE/PES Transmission and Distribution conference and Exposition.

DE VRIES, D. A. 1987. The theory of heat and moisture transfer in porous media revisited. *International Journal of Heat and Mass Transfer,* 30**,** 1343-1350.

FAROUKI, O. T. 1981. The thermal properties of soils in cold regions. *Cold Regions Science and Technology,* 5**,** 67-75.

GORI, F. THEORETICAL MODEL FOR PREDICTING THE EFFECTIVE THERMAL CONDUCTIVITY OF UNSATURATED FROZEN SOILS. 1983. 363-368.

GORI, F. & CORASANITI, S. 2002. Theoretical Prediction of the Soil Thermal Conductivity at Moderately High Temperatures. *Journal of Heat Transfer,* 124**,** 1001.

GORI, F. & CORASANITI, S. 2013. New model to evaluate the effective thermal conductivity of three-phase soils. *International Communications in Heat and Mass Transfer,* 47**,** 1-6.

GOUDA, O. E., ABDEL-AZIZ, A. M., REFAIE, R. A. & MATTER, Z. 1997. Experimental Study for drying-out of Soil Around Underground power cables. *Journal of King Abdulaziz University Eng. Sci,* 9**,** 23-40.

GOUDA, O. E., EL DEIN, A. Z. & AMER, G. M. The effect of the artificial backfill materials on the ampacity of the underground cables. Systems Signals and Devices (SSD), 2010 7th International Multi-Conference on, 27-30 June 2010 2010. 1-6.

GOUDA, O. E., EL DEIN, A. Z. & AMER, G. M. 2011. Effect of the Formation of the Dry Zone Around Underground Power Cables on Their Ratings. *Power Delivery, IEEE Transactions on,* 26**,** 972-978.

GOUDA, O. E. E. D., A. Z. ; AMER, G. M. 2010. Improving the Under-Ground Cables Ampacity by using Artifical Backfill Materials. 14th International Middle East Power System Conference (MEPCON'10), December 19-21, 2010 2010 Cairo, Egypt. Cairo University.

JAMESDURRANSGROUP. 2012. *Marconite* [Online]. Available: http://www.marconite.co.uk/benefits.html [Accessed November 2014].

LEONG, E. & RAHARDJO, H. 1997. Review of Soil-Water Characteristic Curve Equations. *Journal of Geotechnical and Geoenvironmental Engineering,* 123**,** 1106-1117.

MICKLEY, A. S. 1951. The Thermal Conductivity of Moist Soil. *American Institute of Electrical Engineers, Transactions of the,* 70**,** 1789-1797.

MILLAR, J. 2014. Results and analysis from special backfill tests in 2005. Espoo: Aalto University School of Electrical Engineering.

NIKOLAEV, I. V. & LEONG, W. H. 2013. Experimental Investigation of Soil Thermal Conductivity over a Wide Temperature Range. *International Journal Thermophysics***,** 1110-1129.

NIKOLAEV, I. V., LEONG, W. H. & ROSEN, M. A. 2013. Experimental Investigation of Soil Thermal Conductivity Over a Wide Temperature Range. *International Journal of Thermophysics,* 34**,** 1110-1129.

PHILIP, J. R. & DE VRIES, D. A. 1957. Moisture movement in porous materials under temperature gradients. *Eos, Transactions American Geophysical Union,* 38**,** 222-232.

RADHAKRISHNA, H. S. 1968. Heat Flow and Moisture Migration in Cable Backfills. Ontario: Ontario Hydro Research Quarterly, V 20, # 2.

RADHAKRISHNA, H. S. 1982. FLUIDIZED CABLE THERMAL BACKFILL. *In:* BOGGS, S. A., CHU, F. Y., RADHAKRISHNA, H. S. & STEINMANIS, J. E. (eds.) *Underground Cable Thermal Backfill.* Pergamon.

RADHAKRISHNA, H. S., CHU, F. Y. & BOGGS, S. A. 1980. Thermal Stability and its Prediction in Cable Backfill Soils. *Power Apparatus and Systems, IEEE Transactions on,* PAS-99**,** 856-867.

SANDIFORD, P. 1982. CABLE BACKFILL MATERIALS - STATE-OF-THE-ART. *In:* BOGGS, S. A., CHU, F. Y., RADHAKRISHNA, H. S. & STEINMANIS, J. E. (eds.) *Underground Cable Thermal Backfill.* Pergamon.

SCHNEIDER, M. & GOSS, K. U. 2011. Temperature dependence of the water retention curve for dry soils. *Water Resources Research,* 47**,** n/a-n/a.

SNIJDERS, A. L., GROENEVELD, G. J., VERMEER, J. & VAN DE WIEL, G. M. L. M. 1981. Moisture migration and drying-out sand around hear dissipating cables and ducts. A theoretical and experimental study.

SUNDBERG, J. 1988. *Thermal Properties of soils and rocks,* Linköping: Statens geotekniska institut, GEOLOGISKA INSTITUTIONEN. publ. A 57.

SUNDBERG, J. S., A. 2010. Thermal backfill report. Overview of different materials. Vectura.

TARNAWSKI, V. R., GORI, F., WAGNER, B. & BUCHAN, G. D. 2000a. Modelling approaches to predicting thermal conductivity of soils at high temperatures. *International Journal of Energy Research,* 24**,** 403-423.

TARNAWSKI, V. R. & LEONG, W. H. 2012. A Series-Parallel Model for Estimating the Thermal Conductivity of Unsaturated Soils. *International Journal of Thermophysics,* 33**,** 1191-1218.

TARNAWSKI, V. R., LEONG, W. H. & BRISTOW, K. L. 2000b. Developing a temperature-dependent Kersten function for soil thermal conductivity. *International Journal of Energy Research,* 24**,** 1335-1350.

YANG, D., RAHARDJO, H., LEONG, E. & CHOA, V. 1998. Coupled Model for Heat, Moisture, Air Flow, and Deformation Problems in Unsaturated Soils. *Journal of Engineering Mechanics,* 124**,** 1331-1338.

8 Appendix

Appendix 1. DeV-1 model expressions based on de Vries model

$$\lambda = \beta * \frac{k_w * \theta_w * \lambda_w + \sum_4^9 k_i * \theta_i * \lambda_i + k_a * \theta_a * \lambda_a}{k_w * \theta_w + \sum_4^9 k_i * \theta_i + k_a * \theta_a}$$

Λ*= λ_w for water as the continuous medium or λ_a for air as the continuous medium

$$K_i = \frac{1}{3}\left[\frac{2}{1+\left(\lambda_i/_{\lambda *}-1\right)g_i} + \frac{1}{1+\left(\lambda_i/_{\lambda *}-1(1-2g_i)\right)}\right]$$

$$\lambda_a = 2.454 * 10^{-2} + 7.27 * 10^{-5} T_C$$

$$\lambda_W = 0.569 + 1.884 * 10^{-3} - 0.0772 * 10^{-5} T_C^2$$

$$m_{cl} + m_{si} < 0.5$$

$$\lambda_q = 6.574 - 0.01633 T_c$$

$$m_{cl} + m_{si} > 0.5$$

$$\lambda_q = \frac{713.33}{T^{0.85172}};\ \lambda_a = \frac{267.7}{T^{0.7731}}$$

$$\lambda_f = 2.16;\ \lambda_{cl-m} = 1.8;\ \lambda_m = 0.5;\ \lambda_{org-m} = 0.25$$

$$n_q = 3;\ n_f = 100;\ \ n_{ca} = 2;\ \ n_m = 10;\ n_{org-m} = 0$$

$g_i = \frac{n^2}{2(n^2-1)^{1.5}}\left(\frac{\Pi}{2} - acrtan\left(\frac{1}{(n^2-1)^{0.5}}\right) - \frac{(n^2-1)^{0.5}}{n^2}\right)$; n>1 flatt ellipsoid

$\mathrm{g_i} = 0.5\left[\frac{1}{1-\mathrm{n}^2} - \frac{\mathrm{n}^2}{2(1-\mathrm{n}^2)^{1.5}}\ln\frac{1+\sqrt{1-\mathrm{n}^2}}{1-\sqrt{1-\mathrm{n}^2}}\right]$; n<1 flatt ellipsoid

$g_i = 0.333$; n=1, sphere

Dry soils, air is the continuous medium:

$K_a = 1;\ \theta_W = 0;\ \theta_a = \phi;\ \lambda * = \lambda_a$

Saturated soils, water is the continuous medium:

$K_w = 1;\ \theta_W = \phi\ ;\ \theta_a = 0\ ;\ \lambda * = \lambda_w$

Unsaturated soils

$$K_a = \frac{1}{3}\left[\frac{2}{1+\left(\left(\lambda_{app}/_{\lambda *}\right)-1\right)g_a} + \frac{1}{1+\left(\left(\lambda_{app}/_{\lambda *}\right)-1\right)(1-2g_a)}\right]$$

$$\lambda_{app} = \lambda_a + \xi.\Phi.\lambda_{VS}$$

$$\Phi = \left(\frac{\psi}{\rho_w.R.T}\right) = \frac{P_v}{P_{VS}}$$

$$\lambda_{VS} = \frac{H_L.D}{R_V.T}.\frac{P_b}{P_b - P_{VS}}.\frac{\partial P_{VS}}{\partial T};\ R_V = \frac{R}{M_W};\ H_L = 2503 - 2.4321.T_C$$

$$D = 2.25 * 10^{-5}\left[\frac{T}{173.15}\right]^{1.72}$$

$\theta_{fc} \leq \theta_W \leq \varphi$, $\Phi = 1.0$

$$g_a = 0.333 - 0.298\frac{\phi - \theta_W}{\phi}$$

$0 < \theta_W < \theta_{fc}$,

$$g_a = 0.013 - (g'_a)\frac{\theta_W}{\theta_{fc}}$$

$$g'_a = 0.333 - 0.298\frac{\phi - \theta_{fc}}{\phi}$$

$\Theta_{pwp} \leq \theta_W < \varphi$,

$K_w = 1;\ \theta_a = \phi - \theta_w\ ;\ \lambda *= \lambda_w$

$0 \leq \theta_W < \theta_{pwp}$,

$K_a = 1;\ \theta_a = \phi - \theta_w\ ;\ \lambda *= \lambda_a$

$\lambda = \lambda_{dry} + (\lambda_{pwp} - \lambda_{dry})\dfrac{\theta_w}{\theta_{pwp}}$

Appendix 2. Modification of Gori model expressions

Dry soils

$$\frac{1}{\lambda} = \frac{\beta - 1}{\lambda_a\beta} + \frac{\beta}{\lambda_s + \lambda_a[\beta^2 - 1]}$$

Saturated soils

$$\frac{1}{\lambda} = \frac{\beta - 1}{\lambda_w\beta} + \frac{\beta}{\lambda_s + \lambda_w[\beta^2 - 1]}$$

Unsaturated soils:

$\Theta_w \leq 0.083*\varphi$

$$\frac{1}{\lambda} = \frac{\beta - 1 - \left({}^{\delta}/_{3}\right)}{\lambda_a\beta} + \frac{\beta\delta}{3(\lambda_w + \lambda_a[\beta^2 - 1])} + \frac{\beta}{\lambda_s + \frac{2}{3}\delta * \lambda_w + \lambda_a(\beta^2 - 1 - \frac{1}{2}\delta)}$$

$$\beta = \sqrt[3]{\frac{1}{1-\phi}}\quad \delta = \frac{\theta_w}{1-\phi}$$

$\Theta_w > 0.083*\varphi$

$$\gamma = \sqrt[3]{\frac{V_w}{V_s} - \frac{V_{wf}}{V_s} + 1}\ \gamma_f = \sqrt{\frac{{}^{V_{wf}}/_{V_s}}{3(|\beta-\gamma|)}}$$

$$\frac{V_{wf}}{V_s} = \frac{V_{wf}}{V_v}(\beta^3 - 1) = \left[0.183 + \frac{0.226 + .0183}{0.4764 - 0.2595}(0.4765 - \phi)\right](\beta^3 - 1)$$

$\Theta_w > 0.083*\varphi$, $\Upsilon_f < 1$

$$\frac{1}{\lambda} = \frac{\beta^2 - \beta_\gamma}{\lambda_a(\beta^2 - \gamma_f^2) + \lambda_w\gamma_f^2} + \frac{\beta_\gamma - \beta}{\lambda_w\gamma^2 + \lambda_a[\beta^2 - 1]} + \frac{\beta - \beta\gamma_f}{\lambda_s + \lambda_w(\gamma^2 - 1) + \lambda_a(\beta^2 - \gamma^2)} + \frac{\beta\gamma_f}{\lambda_s + \lambda_w(\gamma^2 - 1 + 2\beta\gamma_f - 2\gamma\gamma_f) + A}$$

$$A = \lambda_a(\beta^2 - \gamma^2 - 2\beta\gamma_f + 2\gamma\gamma_f)$$

$\Theta_w > 0.083*\varphi$, $\Upsilon_f > 1$

$$\frac{1}{\lambda} = \frac{\beta^2 - \beta_\gamma}{\lambda_a(\beta^2 - \gamma_f^2) + \lambda_w\gamma_f^2} + \frac{\beta_\gamma - \beta\gamma_f}{\lambda_w\gamma^2 + \lambda_a[\beta^2 - \gamma^2]} + \frac{\beta\gamma_f - \beta}{B + \lambda_a(\beta^2 - \gamma^2 - 2\beta\gamma_f + 2\gamma\gamma_f)} + \frac{\beta}{\lambda_s + \lambda_w(\gamma^2 + 2\beta\gamma_f - 2\gamma\gamma_f - 1) + C}$$

	$B = \lambda_w(\gamma^2 + 2\beta\gamma_f - 2\gamma\gamma_f)$; $C = \lambda_a(\beta^2 - \gamma^2 - 2\beta\gamma_f + 2\gamma\gamma_f)$
Effective thermal conductivity of soil solid components	$\lambda = \lambda_q.\theta_q + \lambda_f.\theta_f + \lambda_{cl-m}.\theta_{cl-m} + \lambda_{ca}.\theta_{ca} + \lambda_{mi}.\theta_{mi} + \lambda_{org-m}.\theta_{org-m}$ q= quartz; f= feldspar; cl-m= clay minerals; ca=calcite; mi= mica; org-m= organic matter

Appendix 3. Johansen model expressions modified by Tarnawski 2000

Dry soils	$\lambda_d = \frac{A\rho_{db} + B}{\rho_s - C\rho_{db}}$ $\lambda_s/\lambda_a > 120$	$\rho_s = 2700 kg.m^{-3}$ A=0.1809 (L-soil, Royal, Volkmar); A= 0.23 (remaining soils) B=64.7 C=0.947
Saturated soils	$\lambda_{sat} = \lambda_w^{\phi}\lambda_s^{1-\phi}$	$\lambda_s = \lambda_q^{\theta_q}\lambda_{min}^{(1-\theta_q)}$ $\lambda_{min} = \sum_{i=1}^{n}\lambda_i\theta_i$; $\sum_{i=1}^{n}\theta_i = 1 - \theta_q$ $\lambda_q = 7.7\ WmK^{-1}$; $\lambda_{min} = 2.0 - 3.0\ W\ mK^{-1}$ For this paper $\lambda_{min} = 2.75\ W\ mK^{-1}$
Unsaturated soils	$\lambda = \lambda_d + (\lambda_{sat} - \lambda_d)K_e$	$K_e(S_r) = \frac{\lambda - \lambda_d}{\lambda_{sat} - \lambda_d}$ Coarse soils (Sr>0.05), $K_e = 0.68 \log Sr + 1$ Fine soils (Sr>0.10), $K_e = 0.94 \log Sr + 1$

Appendix 4. Fitting coefficients of each type of soil tested for new Johansen model modified by Tarnawski 2000

TEMPERATURE-DEPENDENT KERSTEN FUNCTION

Table II. Coefficient data for Equation (2).

Coeff.	Coarse L-soil, Royal, Volkmar	Medium Palouse A, Salkum Mokins, Walla Walla	Fine Palouse B
a	0.128052	0.045688854	−0.014219
b	−0.0012	1.7E-06	1.516E-04
c	0.556044	0.0199313	0.238408
d	1.167329	1.235599025	0.658362
e	−0.0074	−0.00542714	−0.002556
f	−0.84135	−1.6558303	−1.800168
g	2.098585	2.332491118	1.888900
r^2	0.93168	0.904066	0.975223

Appendix 5. The effective thermal conductivity of the cell used by Gori's model

Thermal conductivity

$$\frac{1}{K_T} = \frac{\beta - 1}{K_C.\beta} + \frac{\beta}{K_C(\beta^2 - 1) + K_S}$$

K_C thermal conductivity of gas (air and water vapour)

K_S thermal conductivity of solid particle

For Adsorbed water: $W_C = cW_p$; empirical assumption, C≈0.375 assumed

For W< W_C

$$\frac{1}{K_T} = \frac{\beta - 1 - \delta/3}{K_{app}.\beta} + \frac{\beta.\delta}{3\left[K_{app}(\beta^2 - 1) + K_w\right]} + \frac{\beta}{K_S + \frac{2}{3}.\delta.K_w + K_{app}\left(\beta^2 - 1 - \frac{2}{3}.\delta\right)}$$

$$\delta = \frac{W}{1 - \varepsilon} = 6.\frac{l_{wa}}{l_s}$$

For W> W_C

$$\gamma_f = \frac{l_w}{l_s} = \sqrt[3]{\frac{V_w}{V_s} - \frac{V_{wf}}{V_s} + 1}; \quad \gamma = \frac{l_{wf}}{l_s} = \sqrt{\frac{V_{wf}/V_s}{3.(\beta - \gamma)}}$$

$$\frac{V_{wf}}{V_s} = \frac{V_{wf}}{V_p}(\beta^3 - 1) = \left[0.183 + \frac{0.226 - 0.183}{0.4764 - 0.2595}(0.4764 - \varepsilon)\right](\beta^3 - 1)$$

This was assumed linearly variable with real porosity

For W> W_C; Y_f<1

$$\frac{1}{K_T} = \frac{\beta^3 - \beta.\gamma}{K_{app}.\left(\beta^2 - \gamma_f^2\right) + K_w.\gamma_f^2} + \frac{\beta.\gamma - \beta}{\left[K_{app}(\beta^2 - \gamma^2) + K_{w.}.\gamma^2\right]} + \frac{\beta - \beta.\gamma_f}{K_S + K_w(\gamma^2 - 1) + K_{app}(\beta^2 - \gamma^2)} + \frac{\beta\gamma_f}{K_s + K_w\left(\gamma^2 - 1 + 2.\beta.\gamma_f - 2.\gamma.\gamma_f\right)}$$

$$A = K_{app}.\left(\beta^2 - \gamma^2 - 2.\beta.\gamma_f - 2.\gamma.\gamma_f\right)$$

For W> W_C; Y_f>1

$$\frac{1}{K_T} = \frac{\beta^3 - \beta.\gamma}{K_{app}.\left(\beta^2 - \gamma_f^2\right) + K_w.\gamma_f^2} + \frac{\beta.\gamma - \beta.\gamma_f}{\left[K_{app}(\beta^2 - \gamma^2) + K_{w.}.\gamma^2\right]} + \frac{\beta.\gamma_f - \beta}{K_w\left(\gamma^2 + 2.\beta.\gamma_f - 2.\gamma.\gamma_f\right) + K_{app}\left(\beta^2 - \gamma^2 - 2.\beta.\gamma_f + 2.\gamma.\gamma_f\right)} + \frac{\beta}{K_s + K_w\left(\gamma^2 - 1 + 2.\beta.\gamma_f - 2.\gamma.\gamma_f\right) + K_{app}.\left(\beta^2 - \gamma^2 - 2.\beta.\gamma_f + 2.\gamma.\gamma_f\right)}$$

$$\beta = \frac{l_l}{l_s} = \sqrt[3]{\frac{\rho_s}{\rho_d}} = \sqrt[3]{\frac{1}{1 - \varepsilon}}$$

l_l is the cell dimension

Unsaturated soil

l_s is the solid particle dimension

ε is the porosity of soil

ρs is the solid particle density ρd the dry density of the soil

$$K_w = 0.569 + 1.88\ 10^{-3}T_C - 7.72\ 10^{-3}T_C^2$$

$$K_a = 0.02408 + 0.0000792T_C$$

$$K_{app} = K_a + \phi . K_{vs} . \xi$$

ξ: mass transfer enhancement factor, assumed as 1 in the investigation

$$K_{vs} = \frac{H_L . D}{R_V . T} . \frac{p_B}{p_b - p_{VS}} . \frac{dp_{VS}}{dT}$$

$$R_V = \frac{R}{M_W}$$

$$H_L = 2503 - 2.3.T_C$$

$$D = 2.25.10^{-5}\left[\frac{T}{273.15}\right]^{1.72}$$

$\phi = W/W_p$; In this research a linear variation was assumed with respect to the water content from dryness to field capacity

Appendix 6. Physical properties of soils used to analyse theoretical model. Tarnawski 2012

Table 1 Physical characteristics of reference soils

Soil name	m_{sa}	m_{si}	m_{cl}	n	λ_{dry}	λ_{sat}	θ_{qtz}	λ_s	$n_{wm\text{-}fit}$	$\Theta_{sb\text{-}fit}$
C-109	1	0	0	0.32	0.33	3.37	1	7.70	0.047	0.006
				0.4	0.25	2.93	1	7.70	0.047	0.002
C-190	1	0	0	0.32	0.33	3.31	1	7.70	0.050	0.007
				0.4	0.25	2.88	1	7.70	0.049	0.003
TS	1	0	0	0.38	0.27	2.65	0.9	6.73	0.059	0.010
				0.4	0.25	2.63	0.9	6.73	0.054	0.007
Cumberland	0.61	0.34	0.05	0.45	0.25	1.93	0.7	5.14	0.078	0.023
Acadia	0.33	0.57	0.1	0.55	0.18	1.46	0.5	3.92	0.078	0.021

m_{sa} sand mass fraction, m_{si} silt mass fraction, m_{cl} clay mass fraction, θ_{qtz} quartz content, λ is expressed in $W \cdot m^{-1} \cdot K^{-1}$

Appendix 7. Initial evaluation tests on fluidized backfill materials, Radhakrishna 1982

RESULTS OF PRELIMINARY EVALUATION TESTS ON FLUIDIZED MIXES

Mix Type	Basic Mix Proportions % by Weight $A_F + A_C + C$	Fluidizer Type	Fluidizer %	Additives** Type	Additives** %	Water Content (%) Slurry	Water Content (%) Hardened	Dry Density kg/m³	Thermal Resistivity °C cm/watt Hardened	Thermal Resistivity °C cm/watt Dry
Fly ash based mix										
SFC	91 + 0 + 2.3	fly ash	6.7	none	0	16	13	1850	35	110
SFC	81 + 0 + 2.3	fly ash	6.7	flue dust	10	19	15	1897	43	145
SFC	71 + 0 + 2.3	fly ash	6.7	flue dust	20	23	14	1860	40	118
SFC	81 + 0 + 2.3	fly ash	6.7	magnetite powder	10	17	15	2081	30	128
SFC	91 + 0 + 2.3	fly ash	6.7	heavy duty oil	2	13	10	1851	57	128
SFC	91 + 0 + 2.3	fly ash	6.7	emulsified wax	4	12	11	1736	49	121
SGFC	51 + 39 + 2.5	fly ash	7.5	none	0	12	9	2160	31	76
SGFC	44 + 46 + 2.5	fly ash	7.5	none	0	12	8	2175	29	79
SGFC	41 + 49 + 2.5	fly ash	7.5	none	0	12	7	2187	23	65
SGFC	36 + 54 + 2.5	fly ash	7.5	none	0	12	8	2197	31	68
SGFC	51 + 39 + 2.5	fly ash	7.5	iron ore pellets	10	12	9	22.5	32	69
SGFC	51 + 39 + 2.5	fly ash	7.5	steel fibres	2	16	9	2171	20	57
SGFC	51 + 39 + 2.5	fly ash	7.5	steel fibres	4	18	8	2149	25	72
SGFC	51 + 39 + 2.5	fly ash	7.5	steel cuttings	2	12	9	2228	31	62
SGFC	51 + 39 + 2.5	fly ash	7.5	steel cuttings	5	12	8	2237	29	58
Limestone Screenings Based	100 + 0 + 2	none	0	none	0	19	15	1959	26	102
	98 + 0 + 2	bentonite	0.5	none	0	22	18	1909	33	136
Limestone Screenings with crusher run	49 + 49 + 2	bentonite	0.5	none	0	18	15	2016	32	136
"	44 + 44 + 2	fly ash	10	none	0	20	14	2031	29	83
Bentonite based mix SGC	51 + 46 + 2.5	bentonite	0.5	none	0	18	15	1910	45	120
Polyox based mix SGC	51 + 47 + 3	polyox	0.02	none	0	14	10	2010	30	76

NOTES: A_F = fine aggregate (eg sand, crushed limestone screenings (-5 mm size)
A_C = coarse aggregate (eg medium to coarse gravel; cursher run)
F = fluidizing component (eg fly ash, bentonite)
C = cement or cement based material

SGFC = sand + gravel + fly ash + cement
SGC = sand + gravel + cement
SFC = sand + fly ash + cement

** Additives used are for thermal conductivity and water retention properties

Underground Cable Thermal Backfill

Appendix 8. Comparison between fluidize material mixtures, Radhakrishna 1982.

COMPARISON BETWEEN THE CANDIDATE FLUIDIZED BACKFILL

Attribute or Property	SGFC Mix	SFC Mix	Limestone Screenings + Cement Slurry	SGC + Bentonite Slurry	SGC + Polyox Slurry	Concrete or Cement Mortar
1. thermal resistivity						
- moist	31	35	32	31	30	25
- dry	65	120	96	120	80	45
2. flow	excellent	excellent	very good	good	fair (some segregation)	good
3. bleed water	rapid	rapid	slow	slow	rapid	no blend water
4. strength (28 days) (KPa)	700-3500	700-3500	700	500	600	21,000
5. strength (1 day) (KPa)	200	200	100	50	50	1,000
6. diggability	requires some effort	requires some effort	easy	easy	easy	impossible
7. mechanical protection	very good	very good	good	same as soil	same as soil	excellent
8. density (kg/m^3)	2000	1850	1850	2000	2000	2500
9. corrosion	non-corrosive	non-corrosive	non-corrosive	non-corrosive	non-corrosive	non-corrosive
10. shrinkage	only short term	only short term	some long term	some long term	only short term	-
11. thermal expansion	negligible	negligible	negligible	negligible	negligible	-
12. mixing method	Ready-mix	Ready-mix	on site	Ready-mix + on site blending	Ready-mix + on site blending	Ready-mix
13. unit cost/m^3 (installed)	$30.0*	$25.0*	30.0**	35.0**	35.0**	50.0

* Based on 2 jobs done in Metro Toronto
**Based on experimental program at Kleinburg TS

Appendix 9. Summary of field evaluations on different mixtures, Radhakrishna 1982

Thermal Backfill Materials

SUMMARY OF FIELD EVALUATION OF BATCHING, MIXING AND HANDLING OF CANDIDATE MIXES

Mix Type	SGFC	SGC + Polyox	SGC + Bentonite	Limestone Screenings Slurry
volume (m^3) lift (m) poured	38 1.0	7 1.0	7 1.0	7 1.0
Field mixing procedure used in the experiment	plant mix supplied in ready mix trucks	polyox added to SGC mix in ready mix truck	Bentonite and water blended to a slurry beforehand. Added to SGC in ready mix truck	limestone screenings, cement and water were batched and mixed on site in ready mix truck
Preparation and mixing time	none	no preparation 15 minutes of mixing	2 hours for blending bentonite slurry 20 minutes for adding and mixing with SGC	batching and mixing 1 hour
consistency	free flowing	good flow	good flow	very good flow
segregation	none	some	none	none
bleeding of excess water	30 min.	30 min.	2 hours*	1 hour*
hardening time	12 hours	12 hours	1 day	1 day
overall performance	excellent	good	fair	very good
remarks	suitable for plant mixing and supply by ready mix companies	polyox to be added on site to SGC mix	somewhat tedious and slow operation in field. Ready mix companies do not handle bentonite. Separate batching plant is required.	suitable for either plant mixing or on site mixing

* some shrinkage cracks on the surface of fill after 1 day.

SGFC = Sand + Gravel + Fly Ash + Cement

SGC = Sand + Gravel + Cement

Appendix 10. Attributes or properties comparisons of mixtures tested, Radhakrishna 1982

TABLE 6

COMPARISON BETWEEN THE CANDIDATE FLUIDIZED BACKFILL

Attribute or Property	SGFC Mix	SFC Mix	Limestone Screenings + Cement Slurry	SGC + Bentonite Slurry	SGC + Polyox Slurry	Concrete or Cement Mortar
1. thermal resistivity						
- moist	31	35	32	31	30	25
- dry	65	120	96	120	80	45
2. flow	excellent	excellent	very good	good	fair (some segregation)	good
3. bleed water	rapid	rapid	slow	slow	rapid	no blend water
4. strength (28 days) (KPa)	700-3500	700-3500	700	500	600	21,000
5. strength (1 day) (KPa)	200	200	100	50	50	1,000
6. diggability	requires some effort	requires some effort	easy	easy	easy	impossible
7. mechanical protection	very good	very good	good	same as soil	same as soil	excellent
8. density (kg/m^3)	2000	1850	1850	2000	2000	2500
9. corrosion	non-corrosive	non-corrosive	non-corrosive	non-corrosive	non-corrosive	non-corrosive
10. shrinkage	only short term	only short term	some long term	some long term	only short term	-
11. thermal expansion	negligible	negligible	negligible	negligible	negligible	-
12. mixing method	Ready-mix	Ready-mix	on site	Ready-mix + on site blending	Ready-mix + on site blending	Ready-mix
13. unit cost/m^3 (installed)	$30.0*	$25.0*	30.0**	35.0**	35.0**	50.0

* Based on 2 jobs done in Metro Toronto
**Based on experimental program at Kleinburg TS

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