# ANALYSIS OF THE PERFORMANCE OF UNDERGROUND CABLE LAYING CONFIGURATION

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**2024**

# ANALYSIS OF THE PERFORMANCE OF UNDERGROUND CABLE LAYING CONFIGURATION

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**A report submitted**
**in partial fulfilment of the requirements for the degree of**
**Bachelor of Electrical Engineering with Honours**

**Faculty of Electrical Technology and Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2024**

# DECLARATION

I declare that this thesis entitled "ANALYSIS OF THE PERFORMANCE OF UNDERGROUND CABLE LAYING CONFIGURATION is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature :

Name : AKIF ASNAWI BIN SAKRONI

Date : 19 JUNE 2024

# APPROVAL

I hereby declare that I have checked this report entitled "ANALYSIS OF PERFORMANCE OF UNDERGROUND CABLE LAYING CONFIGURATION", and in my opinion, this thesis fulfils the partial requirement to be awarded the degree of Bachelor of Mechatronics Engineering with Honours

Signature :

Supervisor Name : ANIS NIZA BINTI RAMANI

Date : 19 JUNE 2024

# DEDICATIONS

To my beloved mother and father

# ACKNOWLEDGEMENTS

I want to express my sincere gratitude and appreciation to those involved and the university for their excellent assistance and support in helping me complete my final year project. It is also a valuable opportunity and experience that I may not be able to get elsewhere.

First, I would like to express my sincere gratitude to my project supervisor, Mrs. Anis Niza Binti Ramani for her guidance, knowledge, and support over the 14-week project. My final year report benefited much from her insightful comments, word of encouragement, and helpful criticism, which raised the overall standard of my work.

In addition, I would like to express my sincere appreciation to my panel members, Dr. Nur Hakimah Binti Abdul Aziz (panel 1) and Dr. Nur Zawani Binti Saharuddin (panel 2) for their informative comments and recommendations during the evaluation and review process. My project has become significantly better due to their expertise and experience.

I appreciate the faculty, staff, and administration at Universiti Teknikal Malaysia Melaka (UTeM) for creating a supportive environment and giving me all the resources required to complete my final year project. Their dedication has been important to my accomplishment. Not to be forgotten are my friends and fellow students, whose support and motivation kept me going throughout this effort. Their support and encouragement helped me overcome challenges while I completed this report.

Last, I am grateful to my family and friends for their unwavering support, understanding, and motivation during our 14-weeks journey. Successes have been motivated by their unwavering support and belief in my potential.

My fellow postgraduate students should also be recognized for their support. My sincere appreciation also extends to all my colleagues and others who have aided me on various occasions. Their views and tips are useful indeed. I am grateful to all my family members.

# ABSTRACT

For the stability and effectiveness of electrical power distribution networks, subterranean power cables' lifespan and dependability are essential, especially in Malaysia's harsh climate, which is marked by high humidity and a variety of soil compositions. In order to maximise cable performance and increase its operating longevity in these particular environmental conditions, this research uses 2D COMSOL Multiphysics software simulation to examine the performance of various underground cable laying configurations. The study involves detailed simulations to analyze the thermal impacts of different cable configurations. The primary focus is on temperature distribution and the thermal conductivity of insulation materials. Special attention is given to the influence of soil thermal conductivity, as it plays a pivotal role in heat dissipation around the cable. Higher soil thermal conductivity is found to significantly enhance heat dissipation, thereby reducing the thermal stress imposed on the cables. This leads to lower operational temperatures and a subsequent reduction in thermal degradation, which is critical for extending the cable lifespan. The findings indicate that optimal configurations, combined with the use of appropriate insulation materials, significantly enhance the reliability and durability of underground cables. These configurations help in mitigating thermal hotspots, ensuring even temperature distribution against environmental stresses. Additionally, the research evaluates the effectiveness of low thermal conductivity insulation materials, such as XLPE (cross-linked polyethylene) and the comparisons are also made with HDPE (high-density polyethylene) to assess their suitability for underground installations in Malaysia. In conclusion, this project provides comprehensive guidelines for designing and installing underground cable systems tailored to Malaysia's environmental conditions in the COMSOL Multiphysics software simulation. The insights gained from the simulations underscore the importance of selecting the right combination of insulation materials and soil conductivity to ensure the long-term performance and cost-efficiency of power distribution networks. By addressing the specific challenges posed by Malaysia’s climate and soil diversity, this research contributes to the development of more resilient and sustainable underground cable systems.

# *ABSTRAK*

Bagi kestabilan dan keberkesanan rangkaian pengedaran kuasa elektrik, jangka hayat dan kebolehpercayaan kabel kuasa bawah tanah adalah penting, terutamanya dalam iklim Malaysia yang keras, yang ditandai dengan kelembapan yang tinggi dan pelbagai komposisi tanah. Untuk memaksimumkan prestasi kabel dan meningkatkan umur panjang operasinya dalam keadaan persekitaran tertentu, penyelidikan ini menggunakan simulasi perisian Multifizik 2D COMSOL untuk mengkaji prestasi pelbagai konfigurasi peletakan kabel bawah tanah. Kajian ini melibatkan simulasi terperinci untuk menganalisis kesan haba terhadap konfigurasi kabel yang berbeza. Fokus utama adalah pengedaran suhu dan kekonduksian terma bahan penebat. Perhatian khusus diberikan kepada pengaruh kekonduksian terma tanah, kerana ia memainkan peranan penting dalam pelesapan haba di sekitar kabel. Kekonduksian terma tanah yang lebih tinggi didapati dapat meningkatkan pelesapan haba dengan ketara, dengan itu mengurangkan tekanan haba yang dikenakan pada kabel. Ini membawa kepada suhu operasi yang lebih rendah dan pengurangan seterusnya dalam kemerosotan haba, yang penting untuk memanjangkan jangka hayat kabel. Penemuan menunjukkan bahawa konfigurasi optimum, digabungkan dengan penggunaan bahan penebat yang sesuai, dengan ketara meningkatkan kebolehpercayaan dan ketahanan kabel bawah tanah. Konfigurasi ini membantu dalam mengurangkan titik panas haba, memastikan pengagihan suhu walaupun terhadap tekanan alam sekitar. Di samping itu, penyelidikan menilai keberkesanan bahan penebat kekonduksian terma yang rendah, seperti XLPE (polietilena silang silang dan perbandingan juga dibuat dengan HDPE (polietilena berketumpatan tinggi) untuk menilai kesesuaian mereka untuk pemasangan bawah tanah di Malaysia. Kesimpulannya, projek ini menyediakan garis panduan yang komprehensif untuk mereka bentuk dan memasang sistem kabel bawah tanah yang disesuaikan dengan keadaan persekitaran Malaysia dalam simulasi perisian Multifizik COMSOL. Pandangan yang diperoleh daripada simulasi menekankan kepentingan memilih gabungan bahan penebat dan kekonduksian tanah yang betul untuk memastikan prestasi jangka panjang dan kecekapan kos rangkaian pengedaran kuasa. Dengan menangani cabaran khusus yang ditimbulkan oleh iklim dan kepelbagaian tanah Malaysia, penyelidikan ini menyumbang kepada pembangunan sistem kabel bawah tanah yang lebih berdaya tahan dan mampan.

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# LIST OF SYMBOLS AND ABBREVIATIONS

MV - Medium Voltage
SAIDI - System Average Interuption Duration Index
kV - Kilo Volt
XLPE - Polyethylene and Cross-linked Polyethylene
HDPE - High Density Polyethylene
PE - Polyethylene
2D - 2-Dimension
PVC - Polyvinyl Chloride
mm - Mili meter

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The transmission line which can be either overhead or underground, are used to carry electricity from the power plant to the consumer. As shown as in Figure 1.1, underground cables are power cables for electrical transmission and distribution that are buried beneath the surface of the earth. Underground cables are those that are buried beneath the surface of the soil and are invisible from the outside. They are frequently utilized in cities when installing overhead electricity lines is impractical for reasons of safety or aesthetics[1]. Underground cables are a practical solution in places where cable space is not so provided, particularly in urban areas. Most of transmission line is overhead, but underground is often used in urban areas and environmentally sensitive locations. Unlike underground cable, overhead lines have certain drawbacks, such as impacted by natural disaster, prone to more signal interference, transmission and service supply loss and others. Thus, these underground cables were created to overcome the problems. To shield them from outside influences especially from nature disaster such as storms, lightning, ice, trees, etc. [2].

Figure 1.1 The difference between overhead and underground cable[1]

Additionally, they are not subjected to extreme environmental conditions, collisions, or traffic accidents. There are numerous proposals in process to replace local overhead power lines to underground. In large cities, it is more cost-effective to replace overhead lines to underground lines. So, for conclusion, an underground cable is straightforward, well-designed, safe, and simple to maintain [3]. Underground cables generate heat during operation, and this heat needs to be managed effectively to prevent damage. The type of soil and the materials used for cable insulation play a significant role in heat dissipation. Higher soil thermal conductivity can help disperse heat more effectively, while insulation materials with lower thermal conductivity can better protect the cables from thermal stress [4].

Owing to the occurrence of cable insulation melting, the temperature of the cable conductor must not rise above 90ºC. The cable engineers build the underground power system such that the cable core temperature stays below the ideal temperature for cable operation (65ºC), based on the largely unclear data regarding soil thermal resistance [5]. Many studies have been developed that give valuable results according to changing conditions. The underground cable ampacity under different conditions of distance and depth were provide in [6], where the pattern of the temperature distribution around the cable were shown to determine the extent of cable ampacity. In [7], findings using finite element method were used to established an underground cable temperature distribution model. The thermal analysis of underground power cable in [8] were conducted by the effect of the soil and insulator thermal conductivity on the maximum temperature. In the soil qualities in the area undergo significant changes because of geological changes along the cable path. As a result, specialists and academics have started looking into the variables that affect the temperature dispersion around the surrounding cable.

## 1.2 Motivation

Malaysia toward world class electricity provider, SAIDI is an average duration of interruption in minutes experienced by a customer in a year. Malaysia, 64.2 mins interruptions per customer per year higher than Thailand is 49.45 by refereeing the Figure 1.3. A country with lower SAIDI has a highly reliable energy provider where it includes in upgrading infrastructure, machineries, generators, transmission networks and distribution system.

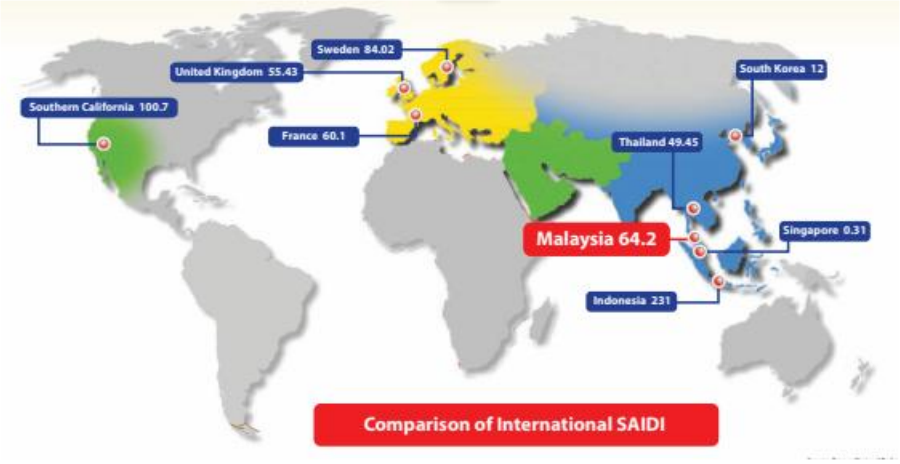


Figure 1.2 The SAIDI's value in certain country[9]

It is susceptible to higher power outages and its seen as inefficient [9]. The fact that, the losses occur in the transmission lines especially due to various factors. It can reduce the efficiency, quality, and the profit itself. Overhead lines tend to have higher losses than underground lines because of their higher resistance, lower voltage, and longer length. More technical losses occur on overhead lines than underground lines including line losses which is a loss brought on by the conductor’s resistance and the heat produced by the current flow. However, because underground lines have greater insulation and fewer line losses, they suffer from fewer technical losses. So, underground cable is recommended to be used for transmission line to achieved lower interruptions due to losses happen [2].

For several years, MV underground cable failures have accounted for almost 60% of the annualized SAIDI. Underground cables make up around 80% of the 33, 22, and 11KV networks, and there are about 180,000 km of MV underground cables in use [10]. The reliable and efficient functioning of such systems hinges on understanding how temperature distribution affects the performance of underground cables. Monitoring temperature variations is imperative for ensuring system reliability, safety, and the quality of the cable. Temperature is another crucial factor affecting the underground cable which is in this factor there are the things that can be taken which is the conductor temperature, insulation performance, heat dissipation, load variation, thermal expansion, and temperature rating[11]. Additionally, the project aims to optimize cable design and operation, by taking the impact of the thermal characteristics. By proactively assessing temperature-related challenges, the project seeks to implement preventive maintenance, reducing losses and enhancing the overall longevity of the cable. Furthermore, in the context of environment, the project addresses the need to adapt infrastructure to evolving environmental conditions. Ultimately, the analysis of underground cables due to temperature is motivated by an approach to enhance performance, efficiency, quality, and sustainability in power distribution systems especially in MV underground cable.

## 1.3 Problem Statement

Underground cable analysis due to temperature typically involves the thermal behavior and performance of electrical cables that are installed underground. Underground cables are subject to various environmental factors, and temperature is a crucial parameter that can significantly impact their operation. Electrical power is often transmitted through underground cables to minimize visual impact, reduce electromagnetic interference, and enhance safety. However, the underground environment exposes cables to temperature variations, which can affect their thermal characteristics and overall performance[11].

The researcher addresses key aspects including temperature profiles experienced by cables over time, heat dissipation characteristics in varying soil conditions, thermal stability under different temperature scenarios, the long-term effects of temperature on cable durability and the laying configuration of the cable[6]. Additionally, the research assesses the operational reliability of underground cables, considering factors such as power losses. Determining the temperatures that cables can withstand without developing any issues, such as insulation degradation, and ensuring they stay stable under various temperature settings and how temperature variations affect the cables' lifespan over time and how to keep them from wearing out too soon[12].

The reliable and efficient operation of power distribution systems in underground cables relies heavily on the ampacity. Ampacity refers to the maximum current-carrying capacity of a cable without exceeding temperature limits. The challenge of ensuring optimal cable performance and safety under varying load conditions and environmental temperatures [13]. Fluctuations in current demand, coupled with temperature variations, pose a risk of exceeding cable ampacity, and may lead to overheating, system failures, or reduced lifespan. It is comprehensively analyzing the factors influencing cable ampacity, develop strategies to mitigate potential issues, and enhance the overall reliability and longevity of underground power cables [10].

## 1.4 Objective

The main objective in this project is:

- To model a 2D 11KV XLPE single core underground cable in COMSOL Multiphysics software simulation

- To simulate and analyze the temperature distribution in 11KV XLPE single core underground cable for direct buried laying configuration.

- To compare the simulation result of the temperature field on 11KV single core underground cable with different parameters.

## 1.5 Scope of Work

The goal of this project is to maximize the lifespan and performance of underground cable by using a multifaceted strategy that includes multiple important duties. To comprehend current research, best practices, and obstacles pertaining to underground cable insulation, thermal management, and laying configurations, with a specific emphasis on Malaysia's environmental conditions, a comprehensive analysis of the literature will first be carried out. Subsequently, suitable insulating materials like HDPE and XLPE will be chosen, along with several soil thermal conductivity which is sand, loam and clay soil that arrange in the lay flat configuration. Using 2D COMSOL Multiphysics software, detailed simulations will be set up to model the selected cable configurations, incorporating relevant thermal properties of the materials and local soil conditions. The thermal analysis will focus on examining the temperature distribution around the cables and assessing the impact of soil thermal conductivity on heat dissipation and cable temperatures. Concurrently, considering factors such as soil pressure and environmental loads, the results of these simulations will be compared to identify the most effective configurations and materials for minimizing thermal stress and enhancing cable lifespan. This process will involve optimizing the thermal configurations and insulation materials based on performance metrics.

The simulation results will be validated against available experimental data or field measurements to ensure their reliability and accuracy. Based on the findings, practical guidelines and recommendations for the installation and maintenance of underground cables in Malaysia will be developed, providing insights into the selection of insulation materials and configurations that offer the best thermal management and durability.

## 1.6 Conclusion

There are five chapters in this thesis. The first chapter introduces my project, including the project background, problem statement, objectives, and scope. The literature review is based on issue of temperature distribution of cable will be highlighted in the second chapter, which may be used as a source of information to complete the project. This chapter will go over all the project completion ideas and tactics. The techniques employed to accomplish the project's objectives are described in full in Chapter 3, and the workflow chart will be displayed in accordance with the strategy adopted. In Chapter 4, we will summarize the results and the debate that occurred to achieve the project's goals. In Chapter 5, the project report, forthcoming projects, and necessary modifications for enhancements will all be examined.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Previous researches are important to be used as a reference in this project. To fulfill the objectives of this project, information and important facts and findings have been gathered for reference and research purposes. In this project, the studies include of dimensions of underground cable, soil properties, laying configuration, depth burial, internal and external thermal resistance, and mathematical modelling method. To complete this project and achieve project outcomes, numerous research papers have been done. The research performed contains the work of modeling of the installation of underground cable, real-life installation, thermal analysis, materials application, and system operation. To maximize the performance and dependability of underground cable networks, it is vital to comprehend these issues and investigate developments in cable technology, installation methods, and asset management tactics. This study of the literature attempts to give a thorough overview of the state of research and development in the subject of subterranean cables, emphasizing significant developments, difficulties, and potential research topics.

## 2.2 Cable Structure and Dimension

11KV XLPE single core 630 $mm^2$ insulated armoured encased PVC cupper cable in lay-flat configuration is the underground cable utilized in this project. Conductor, conductor insulation, sheath, and jackets make up the cable structure. The electrical insulating layer keeps the electrical conductor apart from other cable components and allows current to flow through it. To allow the generated current to flow to the ground, layers of concentrated neutral wires, also known as sheaths, are laid over the insulation surface. PVC (jackets) are required to prevent physical damage, corrosion from the outside, sun-induced deterioration, and environmental water damage [14] This structure ensures that single-core lay flat underground cables have the necessary electrical insulation, mechanical protection, and environmental resistance to perform reliably under various operating conditions. By using a high-quality insulation material like XLPE and ensuring proper thermal management through the lay flat configuration, these cables can achieve improved performance and an extended lifespan[15]. Based on the Figure 2.1, the configuration of the cable that is mentioned in above statement is shown and the real-life point of view as shown as in Figure 2.2.

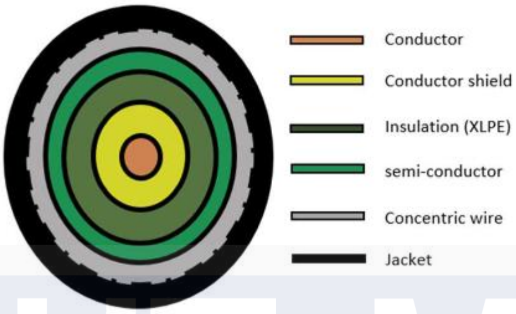


Figure 2.1 The cable-layers and diameter[6]

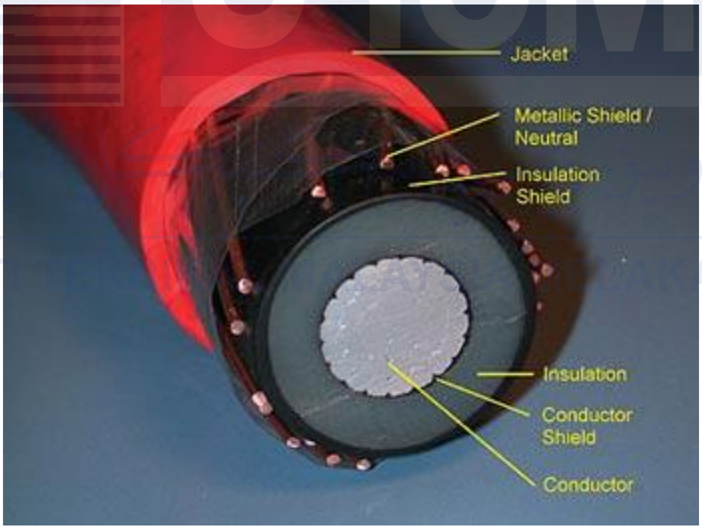


Figure 2.2 The real life cable-layers and diameter[15]

### 2.2.1 Conductor

Commonly in cable conductor, there are usually two materials are used which are copper and aluminum. In wiring and broad range of applications, both are having their advantages but copper is more popular than aluminum wire. This because it has greater conductivity and able to withstand better load surges. Moreover, it has higher tensile strength, thermal-conductivity, thermal-expansion properties, and high stress level prior to breaking because copper is very flexible. In this project, copper is used as the conductor material for 11KV XLPE single core underground cable. Additionally, conductor cross sections come in two varieties: solid and stranded. A collection of wires that can be compacted or segmented is referred to as stranded conductors, as opposed to solid cable, will offer greater flexibility [16].

Copper boasts superior conductivity compared to aluminum, making it an ideal choice for applications where minimizing energy losses is paramount. Its high conductivity allows for smaller cross-sectional areas, reducing the overall size and weight of the cable. Greater conductivity than aluminum, more resistant to oxidation and corrosion compared to aluminum, offering better long-term reliability in harsh environments. Copper is preferred for applications where superior conductivity, smaller size, and corrosion resistance are critical, despite its higher cost [16]. The characteristic of each conductor is as shown in Table 2.1 for comparison which is better used for underground power cable and the appearance for each cable is shown in  Figure 2.3.

Table 2.1 Characteristic comparison of conductor materials[16]

| **Characteristics** | **Copper** | **Aluminum** |
|---|---|---|
| Tensile strength (lb./in) | 50 000 | 32 000 |
| Tensile strength for same conductivity (lb.) | 50 000 | 50 000 |
| Weight for the conductivity (lb.) | 100 | 54 |
| Cross section for the same conductivity | 100 | 156 |
| Specific resistance (ohms-cir/mil ft) | 10.6 | 18.52 |
| Coefficient of expansion (per deg. C) | 16.6 | 23 |

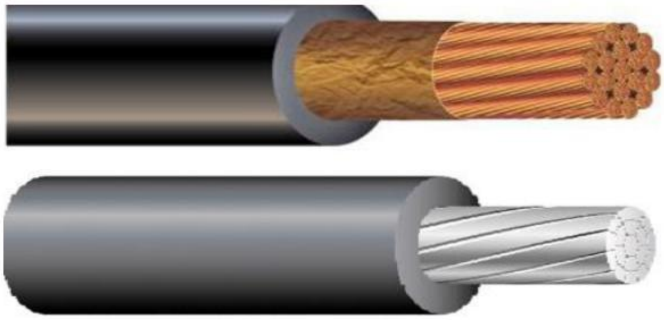


Figure 2.3 The aluminium and copper conductor[16]

### 2.2.2 Conductor Shield

The conductor or insulation shield is a layer that sits between XLPE and armored wires and is often composed of a semi-conductor material. The conductor shield is a layer that sits between conductor and insulation (HDPE, XLPE, PVC,etc). The primary function of the insulation and conductor shields is to envelop the electric field inside the cable core and to preserve a uniformly diverging electric field. Additionally, the goal is essentially too "smoothest" out the surface irregularities of the conductor contour in addition to creating a radially symmetric electric field. Semi-conducting insulation and conductor materials cannot withstand voltage yet cannot carry electricity well enough to be considered conductors. As Figure 2.4 show, the material's foundation is carbon black, which is distributed throughout a polymer matrix and needs to be high enough to guarantee [17].

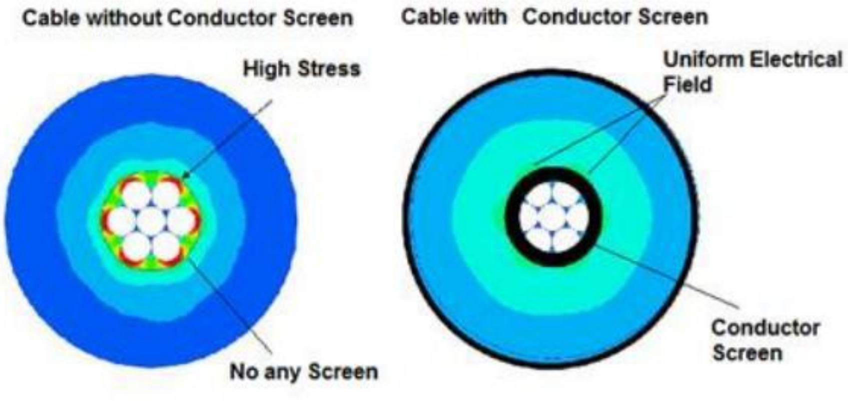


Figure 2.4 Cable with and without semiconductor layer [17]

### 2.2.3 Insulation

In those days, oil-impregnated paper was used to insulate the cable conductor but now in present mostly extruded solid dielectrics are used. There are several types of solid extruded insulations such as butyl rubber, natural rubber, Cross-linked polyethylene (XLPE), Polyethylene (PE), high molecular weight polyethylene (HMWPE) and high-density polyethylene (HDPE). Basically, insulation type and cable ratings have strong relationship. For this research cross-linked polyethylene XLPE cable was used because by taking advantage of low dielectric losses. XLPE stands for “cross-linked polyethylene” and it has linear molecular structure[18]. It exhibits excellent resistance to deformation even at high temperatures because as cross-linked polyethylene demonstrates as shown as Figure 2.5 below, it has bonded in a three-dimensional network while Polyethylene molecules are easily distorted at high temperatures because they are not chemically linked. Same as polyethylene, high-density polyethylene has a linear polymer chain with minimal branching, leading to higher crystallinity and density and stronger and more rigid due to its higher density and crystallinity. It has better tensile strength and impact resistance[19]. As shown as Figure 2.6, XLPE is a better polymer structure than HDPE and the difference of the XLPE and HDPE is shown in Table 2.2.

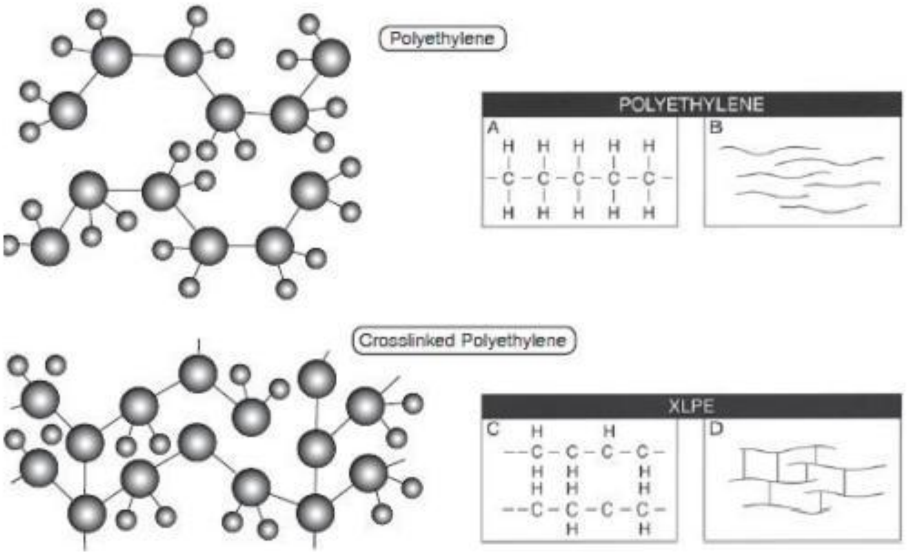


Figure 2.5 The molucule structure of polyethelene and crosslinked [18]

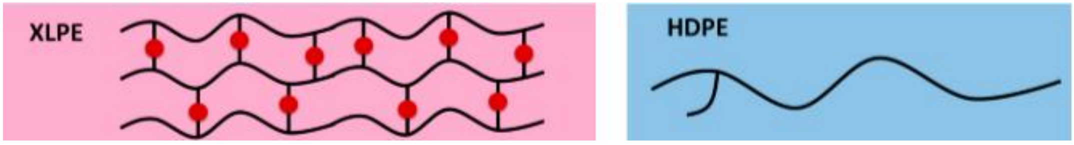


Figure 2.6 The polymer structure of XLPE and HDPE[19]

Table 2.2 Differnce between XLPE and HDPE[19]

| **Property** | **Cross-Linked Polyethylene** | **High-Density Polyethylene** |
|---|---|---|
| Molecular Structure | Cross-linked network | Linear with minimal branching |
| Thermal Properties | Higher thermal stability, melting point around 90-130°C | High melting point, typically around 130-145°C |
| Temperature Range | Suitable for higher temperature applications, up to 90°C continuous operation | Suitable for moderate temperature applications, up to 75°C continuous operation |
| Durability | Very durable, resistant to abrasion and aging | Very durable, resistant to abrasion and environmental stress cracking |

### 2.2.4 Armored Wires (Shield)

Most medium and high-voltage transmission lines have an armored shield layer made of copper or aluminum wires or tapes. Over the insulation, the armored wires are regarded as a protective layer (XLPE). Enhancing mechanical strength, preventing chemical corrosion, and shielding wires from physical damage and moisture are the primary purposes. This offers the fault currents' return path as well. In addition, since the induced current will travel on the armored wires, it needs to be linked to the ground at least once. By doing this, the circuit's maximum current rating will be reduced, but this current will still result in losses and heat [20]. Additionally, by distributing electrical stress evenly around the conductor, it directs any leakage current to ground. To limit the dielectric field to the interior of these wires that are armored[21]. The Figure 2.7 shows the position of armored wire in the cable where the cable is protected while resting underground and has an outer layer or layers of armor wired or taped to give it tensile strength throughout the cable-laying process.

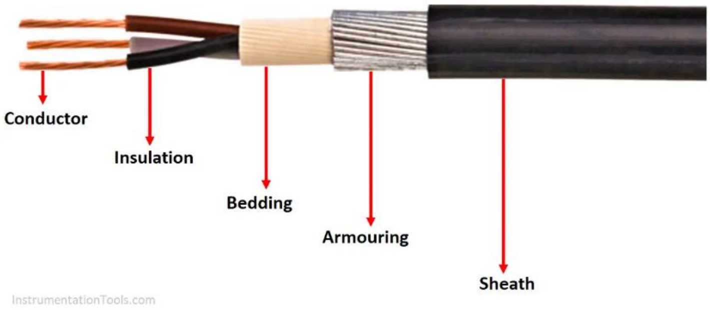


Figure 2.7 The position of armored wire[21]

### 2.2.5 Insulation Exterior (Jackets)

The outer layer of the cable's insulation shields the underlying conductor from external electrical or mechanical damage that could cause a cable failure. A variety of non-metallic materials, including polyvinyl chloride (PVC), polyethylene (PE), and ethylene propylene rubber (EPR), can be utilized for the cable's outer layer. Polyvinyl chloride (PVC) insulated cables are employed in this study. PVC is combined with plasticizers for electric cables and is utilized in a wide range of applications due to its inexpensive cost. It has high tensile strength, higher conductivity, better flexibility, and ease of joining. Basically, this material type of cable must take precaution not to overheat more than 90 °C, where it is suitable for a conductor up to 90 °C because it is a thermoplastic material[22].

## 2.3 Soil properties

The presence of multilayered soils, cable lines passing through different soil types, seasonal changes, as well as drying caused by the heat of the cables, complicate the determination of the thermal properties of the surrounding material along the cable route. In [23] [24] [25] the selecting soil were measured by two possible approaches where the thermal properties determined. The variation in the mother ground thermal conductivity changes the intensity of the heat transfer from power cables. The larger the conductivity, the faster the soil receives the heat, and thus also lowers the temperature of the cable conductor [5] Understanding the physical, chemical, and mechanical characteristics of soil is essential for assessing its suitability for specific uses and predicting its behavior under different loading and environmental conditions. Soil properties are influenced by factors including parent material, climate, topography, biological activity, and human activities, resulting in a wide range of soil types with diverse characteristics [26].

In Table 2.3 shows the selected soil properties that commonly used for underground cable laying based on the laboratory result in[24], [25]. The choice of soil for underground cable installations in Malaysia depends on factors such as local geology, soil properties, environmental conditions, and project requirements. Conducting soil investigations and geotechnical studies is essential to determine the most suitable soil type and design appropriate cable installation techniques to ensure the reliability and longevity of underground cable systems. The selection of the soil is as Figure 2.8.

Table 2.3 Thermal conductivity of soil reference value selected from [24], [25]

| Soil type | Thermal conductivity (W/Mk) in dry condition | | |
|---|---|---|---|
| | Min value | Max value | Recommended value |
| Sand | 1.00 | 1.90 | 1.40 |
| Loam | 1.10 | 2.90 | 2.40 |
| Clay Soil | 0.40 | 1.50 | 1.17 |

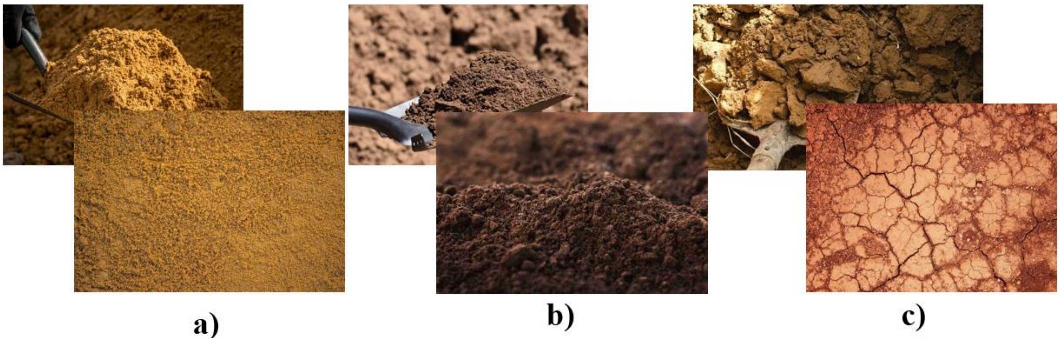


Figure 2.3 a)sand b)loam c)clay soil

## 2.4 Cable installation

An underground cable system's effectiveness and efficiency are dependent on branch connections, cable joints, and efficient cable placement. There are three ways to install cables underground which is direct laying, draw in system and solid system. The installation of underground cables is a critical aspect of ensuring reliable power distribution and telecommunications infrastructure. Various methods are employed to install these cables, each tailored to specific environmental conditions, mechanical protection requirements, and maintenance considerations. The other advantages of burying cables include lowering transmission losses, which help obtaining planning approval, removing worries about electromagnetic radiation's health effects, and lowering the possibility of service supply disruptions due to severe weather[3]. Each of these methods presents unique advantages and challenges, and the choice of method is influenced by factors such as installation environment, cost, and maintenance needs. Understanding these methods allows for the optimization of underground cable installations, ensuring efficient and long-lasting infrastructure. By selecting the appropriate configuration, the performance and longevity of underground cables can be optimized to meet the requirements of different scenarios[8].

### 2.4.1 Direct laying

Majority cables in Malaysia are directly buried as shown as Figure 2.8 where 1.5 m depth in the ground[13]. This type of installation is usually prone to third party digging which will lead to breakdown. If more than one cable is required to be laid in a trench then a horizontal or vertical inter-axial spacing of 30 cm is provided to prevent mutual heating. This configuration is the simplest and cheapest method of underground cable laying and the heat generated gets dispersed in the ground.

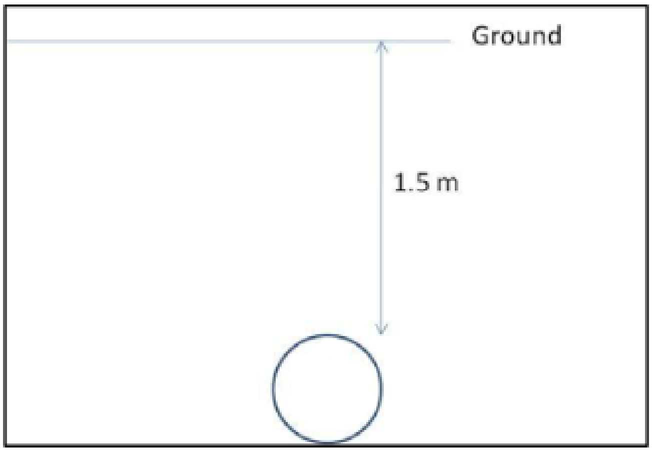


Figure 2.4 Cable laid directly buried underground [13]

### 2.4.2 Draw in System

The draw-in system, which consists of manhole-equipped cast iron, concrete, or glazed stone pipes or conduits positioned at strategic points along the cable route. The cable is pulled into place using the manholes.. This type of installation is used in the place where ‘no-dig’ policies were imposed. In Figure 2.9, duct bank is consisting of series of ducts (e.g. PE pipes) which are surrounded with concrete as shown in Figure 1.11. The cables are inserted through the ducts from one end to the other end. Usually in every 200 meter there will be a manhole[13]. An access point for creating joints or carrying out maintenance below ground is housed in a manhole, which is the top entry of an underground utility vault. Manhole covers are used to keep accidental or unauthorized access to the manhole from occurring.

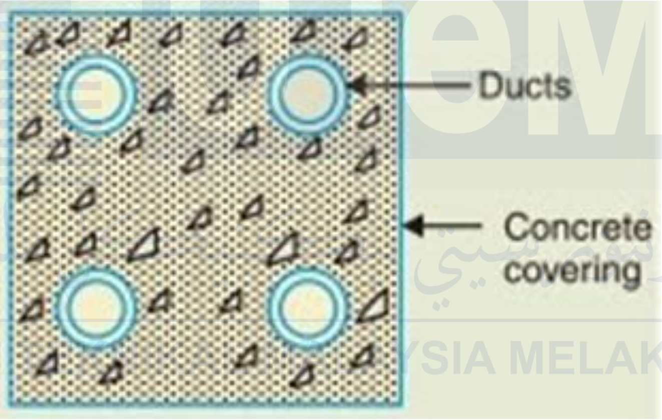


Figure 2.5 Draw in system with duct[4]

### 2.4.3 Solid System

The last method is, solid system where in this method the cable is laid into troughing of cast iron, stoneware, asphalt, or treated wood. In Figure 2.10 the following the placement of the cable, a bituminous or asphaltic compound is poured into the troughing and coated[3][4]. This kind of laying could even use lead covering for the cables because the troughing offers strong mechanical protection. Offering the highest level of mechanical protection and thermal management. Though more expensive and labor-intensive, this method is suited for high-risk environments where maximum durability is essential.

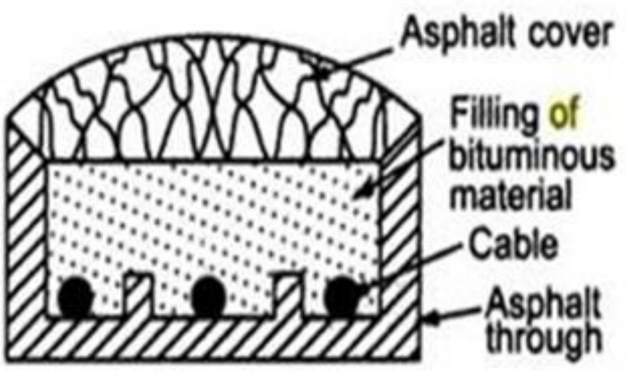


Figure 2.6 Solid System[4]

### 2.5 Laying configuration

The configuration in which underground cables are laid plays a crucial role in their performance, thermal management, and longevity. Proper cable laying configurations help ensure efficient power transmission and reduce potential risks associated with overheating and mechanical damage. This document examines three common cable laying configurations: lay flat, trefoil, and spaced configurations, each offering distinct benefits and applications[27]. The formation of this laying configuration is shown in Figure 2.11.

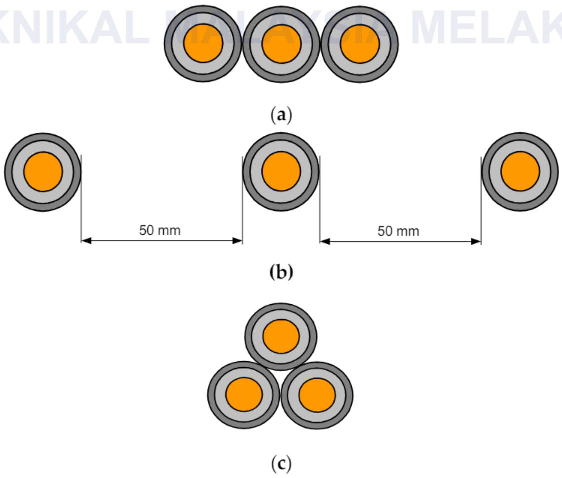


Figure 2.7 a) flat formation without spacing; b) flat formation with spacing 50mm; c) trefoil formation

### 2.5.1 Lay-Flat Configuration

In the lay flat configuration, cables are laid parallel to each other in a single horizontal plane. This method is straightforward and allows for easy installation and maintenance access, though it may result in higher thermal interference between adjacent cables[27]. The lay flat configuration remains popular due to its simplicity and lower initial installation costs. It is suitable for applications where ease of access and straightforward maintenance are priorities, and where the thermal load is manageable[3].

### 2.5.2 Trefoil Configuration

The trefoil configuration involves arranging three single-core cables in a triangular formation, equidistant from each other. This setup reduces electromagnetic interference and optimizes heat dissipation, making it ideal for high-voltage applications were minimizing mutual inductance and circulating currents is critical. It is more complex and costly to install compared to the lay flat configuration. It requires specific spacers and supports to maintain the triangular formation, and precise placement to ensure optimal performance. This makes it less suitable for situations where installation speed and cost are primary concerns[27].

### 2.5.3 Spaced Configuration

Lastly, the spaced configuration entails laying cables parallel to each other with a specified distance between them. By increasing the spacing, the surrounding soil or backfill material can better dissipate the heat generated by the cables, leading to lower operational temperatures and improved performance. However, the spaced configuration requires more trench space, which can increase the installation cost and the amount of excavation needed. The spaced configuration is advantageous in scenarios where thermal management is a priority, such as in high-capacity power transmission systems or in areas with limited natural cooling capabilities[27].

## 2.6 Thermal Resistance

The cable rating calculation considers the thermal circuit factors, such as heat transfer coefficients and soil resistivity[28]. As a result, the computation of cable carrying capability has reduced error when thermal circuit characteristics are highly accurate. Heat is produced by the conductor in the middle of the cable, and the power cable's dielectric composition restricts how much heat can move through it. The quantity of heat flow that it resists is indicated by the thermal resistance. The soil surrounding the cables has an exterior thermal resistance that has a significant impact on cable capacity ratings. As for the heat transfer of underground cables is done by transferring heat from hot areas (the conductor) to cold areas (the surrounding soil and environment)[6]. Because of its ampacity, the cable can carry the greatest amount of electric current while remaining within reasonable temperature ranges. The temperature of the conductor has a significant impact on the cable's current carrying capacity. Heat dissipation and diffusion from the conductor to the surrounding soil have an impact on the cable's capacity to transmit current, hence this process has a big impact on how well underground cable systems work.

## 2.7 Mathematical Modeling Method

The space- and time-dependent problems, the description of the laws of physics is typically given in terms of partial differential equations (PDEs). These PDEs cannot be solved analytically for the great majority of geometries and problems. Alternatively, an approximation of the equations can be built, usually using various discretization techniques. These discretization techniques generate numerical model equations that approach the PDEs and can be solved numerically. The solution to the numerical model equations is, in turn, an approximation of the real solution to the PDEs. The finite element method (FEM) is used to compute such approximations. It is widely used for simulating and analyzing complex structures and systems in fields such as structural mechanics, heat transfer, fluid dynamics, electromagnetics, and more[29], [30]. The method approximates the heat transfer equations over these elements, solving for temperature values at the nodes. Formulation of the govern by heat conduction equation;

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial T}{\partial y}\right)+Q=\rho c\frac{\partial T}{\partial t} \tag{2-1}$$

where $T$ is the temperature, $k$ is the thermal conductivity, $Q$ is the internal heat generation per unit volume, $\rho$ is the density, and $c$ is the specific heat capacity.

The governing equations are assembled into a global system of equations in the form $[K]\{T\}=\{F\}$[K]{T}={F}, where $[K]$ is the global conductivity matrix, {T} is the temperature vector, and {F} is the load vector representing heat sources and boundary conditions.

### 2.7.1 Finite Element Method (FEM)

The finite element method (FEM) is a numerical technique used to perform finite element analysis (FEA) of any given physical phenomenon. Any thorough understanding and quantification of physical events, including the proliferation of biological cells, thermal transport, wave propagation, and structural or fluid behavior, requires the application of mathematics. Typical problem areas of interest include the traditional fields of structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential[31]. So based on the project there are only two problem areas which is structural analysis and heat transfer. The temperature profile obtained with a thermal circuit approach for the cables is compared with a FEM approach. These findings can be determined by using a COMSOL Multiphysics software simulation where it used the FEM approach. It provides an Integrated Development Environment (IDE) and unified workflow for electrical, mechanical, fluid, and chemical applications[32].

Figure 2.8 The COMSOL Multiphysics Software

## 2.8 Summary Table for Literature Review

Table 2.4 The summary of Literature Review

| No | Title | Cable used | Content | Implementation |
|---|---|---|---|---|
| 1 | Fem-based thermal analysis of underground power cables located in backfills made of different materials | 8.7/15kV400 $mm^2$ XLPE electric cable, | Addresses the challenge of modern power transmission and distribution, where underground electric cables are widely used due to economic and space constraints. | The analysis of influencing factors shows that ampacity is directly affected by soil thermal. The paper concludes that soil thermal conductivity and environmental temperature significantly influence cable ampacity, with ampacity increasing with soil thermal conductivity and decreasing with environmental temperature. |
| 2 | Ampacity of MV Underground Cables: the Influence of Soil Thermal Resistivity | Medium Voltage (MV)underground cables with insulation made of ethylene propylene rubber | Sheds light on the variation of soil thermal resistivity under different conditions, providing insights for better understanding and management of underground cable systems. | By understanding how factors like soil thermal resistivity and ambient temperature affect cable ampacity. This knowledge can help improve the reliability of Medium Voltage underground cable networks |

| | | | | |
|---|---|---|---|---|
| 3 | MV Underground Cables: Effects of Soil Thermal Resistivity on Anomalous Working Temperatures | Medium voltage (MV) underground cables | Discusses the impact of soil thermal resistivity on the working temperatures of medium voltage underground cable | Highlights the importance of considering soil thermal resistivity in the design of underground cables and how variations in soil moisture content can lead to anomalous increases in cable temperatures, especially during the summer period |
| 4 | Calculation of Thermal Distribution and Ampacity for Underground Power Cable System by Using Electromagnetic-Thermal Coupled Model | 110 kV XLPE power cable | The development of an electromagnetic-thermal coupled model for underground power cables. | Involves using a finite element method (FEM) in the COMSOL Multiphysics platform to calculate the ampacity of underground power cable systems. The model combines the electromagnetic and thermal fields, making it easy to deal with and allowing for precise loss calculations. |
| 5 | Analysis of Influential Factors on the Underground | 15 kV XLPE cable with a copper conductor | It introduces a new numerical method programmed in COMSOL software based on | Involves creating a geometric model of cables laid in a trench, considering factors like cable spacing, external heat source, and |

|  |  |  |  |  |
|---|---|---|---|---|
|  | Cable Ampacity | and a cross-sectional area of 400 mm² | heat transfer and the Finite Element Method to calculate cable ampacity. | soil properties. This model is programmed using COMSOL software based on the principles of heat transfer and the finite element method. |
| 6 | The effect of soil and cable backfill thermal conductivity on the temperature distribution in underground cable system | Underground cable with copper conductor with a thermal conductivity of 400.00 W/(m·K) and XLPE insulation with a thermal conductivity of 0.3232 W/(m·K). | The thermal analysis and operation of underground power cables, focusing on the importance of considering thermal phenomena in designing underground electricity networks. It emphasizes the use of thermal backfill materials to prevent cable insulation meltdown and ensure optimal cable core temperature | Involves using a Finite Element Method (FEM) solver developed by the authors to discretize the computational domain and solve the heat conduction equation. The computational domain mesh is created using a PDE toolbox in MATLAB software. Use Jacobi iteration method to determine the temperature distribution within the entire underground power cable system. |
| 7 | Optimization of the Direct Buried Characteristics | 11kV underground cable with XLPE insulation and | The optimization of installation characteristics for 11kV underground cables, focusing on the direct buried method. The aims to enhance cable ampacity, increase operational lifespan, and | Involves changing the insulation material from XLPE to EPR and the backfilling material from washed river sand to FTB. These modifications have been proven to increase cable ampacity significantly |

|  |  |  |  |  |
|---|---|---|---|---|
|  | for 11kV Underground Cable Installation | aluminum conductor. | reduce cable faults through changes in insulation and backfilling materials | compared to the existing installation guidelines, leading to improved performance and reduced power loss in the distribution system network. |
| 8 | Improving MV underground cable performance: Experience of TNB Malaysia | - | The experience of TNB Malaysia in improving the performance of MV (medium voltage) underground cable joints. It highlights the high failure rate of these joints and the need for a long-term solution | Upcoming initiatives for further improvement and concludes by emphasizing the importance of finding a joint technology that is compatible with the operating environment. |
| 9 | Ampacity Simulation of Various Underground Cable Installation Systems | Three core/11Kv/ XLPE/240mm2/ Aluminum | Focuses on the ampacity of different medium voltage underground cable installation systems in Malaysia. It examines the factors affecting cable ampacity calculations, such as derating factors and heat sources. | The choice of installation type depends on local authority requirements. The study aims to assist engineers in making informed decisions, but emphasizes the need for more detailed comparisons before final decisions are made. |
| 10 | Thermal Analysis of Underground Power Cable System | XLPE (Cross-Linked Polyethylene) cable with a copper conductor | Focuses on studying the temperature distribution in the soil, thermal backfill, and power cables to analyze the impact of thermal conductivity on cable core temperature. The aims to optimize the design of underground | The computational domain mesh is created using a PDE toolbox in MATLAB. The FEM solver developed by the authors is implemented to analyze and determine the |

| | | | | |
|---|---|---|---|---|
| | | | power cable systems to prevent cable insulation meltdown by ensuring the cable conductor temperature does not exceed certain limits. | temperature distribution within the entire underground power cable system. |

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

This chapter describes the steps that will be taken to find solutions for the identified problems that have been proposed. Research procedures with phases and activities will be discussed more deeply. Each phase's associated activities are listed, and the following sections will provide further details on each one. The methods utilized to carry out and finish this project will also be covered in this chapter. Most of the methods and findings from this study were obtained from other sources to be improved upon in future studies. This method is also utilized to carry out the project's objectives as effectively as possible. The previous chapter on the literature review detailed how prior research was carried out to accomplish the aim.

## 3.2 Overview Project

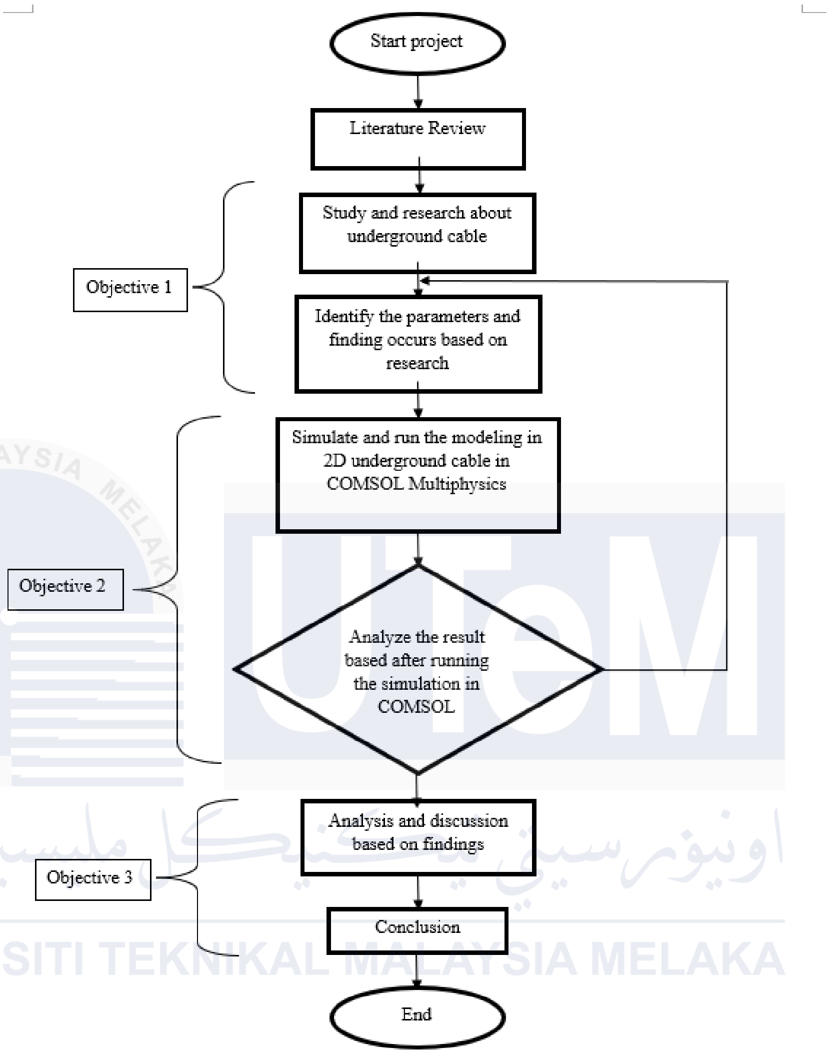


Figure 3.1 The overall flow of the methodology

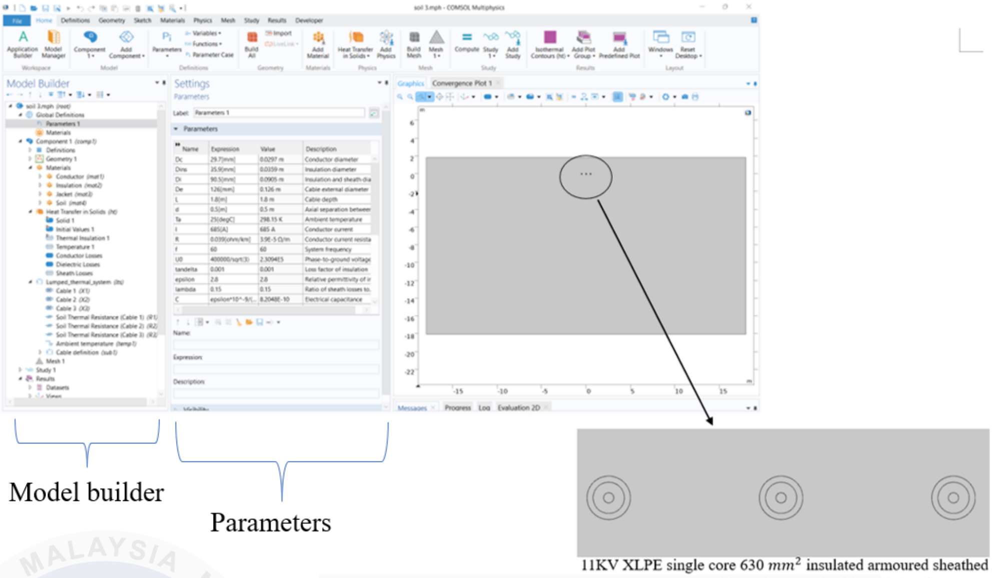
Figure 3.1 depicts the project's flow chart from start to finish. It is critical to use a flow chart to outline the processes required to finish the task. The project will follow the flow chart. The flow chart begins doing literature review. It provides a comprehensive understanding of the current state of knowledge in a specific field, enabling researchers to grasp key concepts, theories, and findings related to their topic of interest.

The following section entails completing a literature analysis, analyzing prior research, and reading internet papers from sources such as IEEE and Research Rabbit. The purpose of the literature review is to support the issue description and collect project-related data. The study will provide an overview of underground cable due to temperature distribution. The temperature distribution around the underground cable and the numerical grid was established using the finite element method. The study showed the importance of the temperature distribution around the cable on the cable ampacity to carry the current.

### 3.3 Modeling 2D Underground Cable in COMSOL Multiphysics

The simulation starts with identifying the model builder by choosing the geometry of the underground cable system, including the trench dimensions and the spatial arrangement of the cables, input of material properties for the cables, insulation, and surrounding soil, which are critical for accurately simulating heat transfer and electrical conduction and also apply appropriate physics interfaces to represent the heat generation due to electrical losses and the subsequent heat transfer through the cable insulation and into the surrounding soil.

After that, identifying the parameters of the underground cable. The parameters of the 11KV XLPE single core 630 $mm^2$ insulated armoured sheated PVC cupper cable underground cable with lay-flat configuration was shown in the Table 3.1. Once the parameters have been identified, the modeling of the cable in lay-flat configuration was developed in 2-D in COMSOL simulations and the parameter that need to be enter in the simulations are based on the selection value of the selected cable. Those models build and the parameters of the simulation as shown as Figure 3.2 and the simulation can be observe by side of this model build and parameters.



11KV XLPE single core 630 $mm^2$ insulated armoured sheathed PVC cupper cable underground cable with lay-flat configuration

Figure 3.2 The overview of simulation

Table 3.1 The parameter's value of cable layers and diameter in COMSOL simulation

| Name | Expression | Value | Description |
|---|---|---|---|
| Dc | 29.7(mm) | 0.0297 m | Conductor diameter |
| Dins | 35.9(mm) | 0.0359 m | Diameter Insulation |
| Di | 90.5(mm) | 0.0905 m | Insulation and sheath diameter |
| De | 126(mm) | 0.126 m | Cable external diameter |
| L | 1.8(m) | 1.8 m | Cable depth |
| D | 0.5(m) | 0.5 m | Axial separation between cables |
| Ta | 25(degC) | 298.15 K | Ambient temperature |
| I | 685(A) | 685 A | Conductor current |
| R | 0.039(ohm/km) | 3.9E-5 Ω/m | Conductor current resistance |
| f | 60 | 60 | System frequency |
| UO | 400000/sqrt(3) | 2.3094E5 | Phase-to-ground voltage |
| tandelda | 0.001 | 0.001 | Loss factor of insulation |

| | | | |
|---|---|---|---|
| epsilon | 2.8 | 2.8 | Relative permittivity of insulation |
| lambda | 0.15 | 0.15 | Ratio of sheath losses to conductor losses |
| C | epsilon*10^-9(18*log(Dins/Dc)) | 8.204E-10 | Electrical capacitance |
| Pd | (2*pi*f*C*U0^2*tandelta)[W] | 16.497 W | Dielectric losses |
| Pc | R*I^2*1[m] | 18.3 W | Conductor losses |
| Ps | lambda*Pc | 2.745 W | Sheath losses |
| I1 | sqrt((2*L)^2+(d)^2) | 3.6346 W | Intermediate distance for central cable |
| 12 | sqrt((2*L)^2+(2*d)^2) | 3.7363 W | Intermediate distance for edge cable |
| F1 | l1/(d)*l2/(2*d) | 27.16 | Mutual heating corrective factor (Cable 1) |
| F2 | (l1/(d))^2 | 52.84 | Mutual heating corrective factor (Cable 2) |
| F3 | F1 | 27.16 | Mutual heating corrective factor (Cable 3) |
| k0 | 370 [W/(m*K)] | 370 W/(mK) | Conductor thermal conductivity |
| k1 | 0.35 [W/(m*K)] | 0.1538 W/(mK) | Insulation thermal conductivity |
| k2 | 0.6145 [W/(m*K)] | 0.6145 W/(mK) | Jacket thermal conductivity |
| k3 | 1.4[W/(m*K)] | 1.4 W/(mK) | Soil thermal conductivity |

Initially simulating the cable structure's geometry using the three cables in use because it in the lay flat configuration. Cable 1, 2, and 3 has been labelled for these three cables. As shown as in Figure 3.2, these three cables have the same geometry, but because they were placed in a lay-flat horizontal posture, their positions will differ. The geometry of these three cables is the same except for the position of the cables will be different since it was set in lay-flat horizontal position. The modeling of the cable structure including the semi-conductor layer of copper conductor, copper conductor, XLPE insulation, armored sheath, and PVC jacket. The following cable which cable 2 and 3 are same as the cable 1.The surrounding surface which include the soil thermal resistivity, moisture, boundary conditions, installation depth and cable type and design.

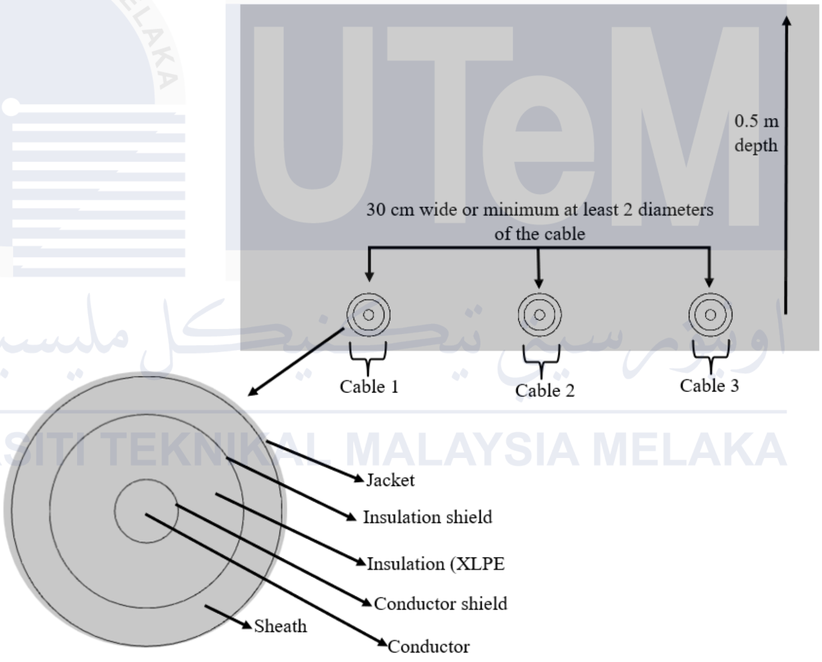


Figure 3.3 The cable specification in simulation

If the simulation fails, the settings may need to be changed or new components added to the 2D model. If the simulation runs successfully, the temperature distribution is captured and analyzed for discussion. Data from simulation results are also analyzed to verify logical validity and error minimization. Finally, the project finishes by analyzing whether the initial objectives were met. The goal is to determining the temperatures that cables can withstand without developing any issues, such as insulation degradation, and ensuring they stay stable under various temperature settings and how temperature variations affect the cables' lifespan over time.

## 3.4 COMSOL Simulation Test

Simulation test refers to a process in which a model or system is tested virtually through computer-based simulations rather than in real-world physical experiments. It involves creating a digital representation of the system, often using specialized software, to mimic its behavior and predict its performance under various conditions. For this project, the model will be the 11KV XLPE single core 630 $mm^2$ insulated armoured sheated PVC cupper cable underground cable with lay-flat configuration module that was created, and it will be run using COMSOL Multiphysics software.

### 3.4.1 Parameters

By choosing the selected parameters which is thermal conductivity for soil and insulation. The parameter for each as shown as Table 3.2 and Table 3.3 where the selected parameters will give six different simulation of temperature distribution, where each three for XLPE and HDPE insulation. The temperature distribution of an underground cable that will provide insights into the thermal performance of your underground cable system, highlighting areas where temperature management is critical and guiding decisions on material selection and system design to enhance reliability and longevity.

Table 3.2 For XLPE insultaion

| Thermal conductivity of XLPE (0.35)/ Soil(W/Mk) | |
|---|---|
| Clay soil | 1.17 |
| Sand | 1.40 |
| Loam | 2.40 |

Table 3.3 For HDPE insultaion

| Thermal conductivity of HDPE (0.45)/ Soil(W/Mk) | |
|---|---|
| Clay soil | 1.17 |
| Sand | 1.40 |
| Loam | 2.40 |

#### 3.4.1.1 Thermal conductivity of the soil

When analyzing the thermal performance of underground cables using COMSOL Multiphysics, the thermal conductivity of the surrounding soil plays a crucial role in heat dissipation. Based on literature review, three different values of soil thermal conductivity which is for clay soil is 1.17 W/(m·K), sand is 1.40 W/(m·K), and loam is 2.40 W/(m·K). These value used in the simulation and included in the soil thermal conductivity's section.

#### 3.4.1.2 Thermal conductivity of the insulation

Two commonly used insulation materials in electrical cable applications, each with distinct properties that affect their thermal performance. Thermal conductivity is a critical parameter that influences how well these materials can dissipate heat generated by electrical currents within the cables. XLPE typically exhibits a lower thermal conductivity compared to HDPE where for XLPE the value of thermal conductivity is 0.35(W/mK) while for HDPE is 0.45(W/mK).

### 3.5 Summary

In a COMSOL simulation of underground cable temperature distribution, the focus is on visualizing how heat spreads through the cable and surrounding soil. Contour plots and temperature profiles illustrate spatial variations and highlight hotspots, areas with high temperatures. The simulation provides insights into temperature gradients, transient behavior over time, and the impact of heat sources like electrical losses.. Optimization studies reveal how design changes affect temperature performance. Overall, the simulation offers a thorough understanding for making informed decisions about cable design, operation, and safety. In addition, a flowchart was constructed in COMSOL to define the process, which was followed by a full explanation of the simulation procedure. Finally, some ethics and safety considerations are made throughout the project to ensure the integrity of study findings, data privacy, and intellectual property rights.

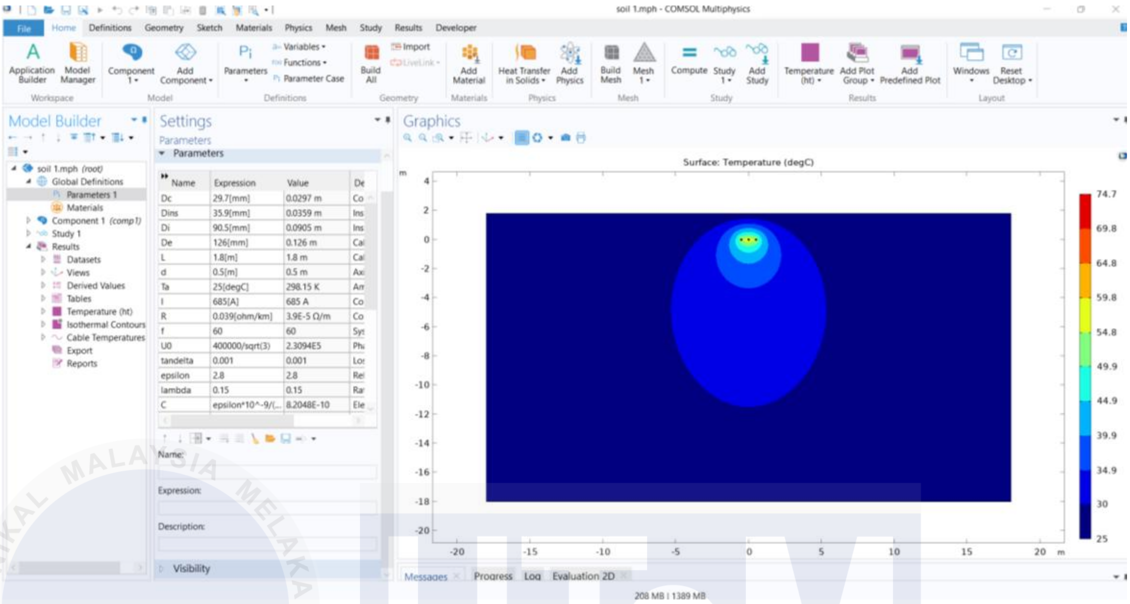
# CHAPTER 4

# RESULTS AND DISCUSSIONS

## 4.1 Introduction

This chapter summaries the methodology's preliminary data. This chapter will explain the preliminary results of my research on the simulation available which is COMSOL Multiphysics simulation that present the results of the Finite Element Method (FEM) simulation focused on analyzing the temperature distribution in underground cable systems. The thermal behavior of underground cables is of paramount importance in electrical engineering, as it directly impacts cable performance, reliability, and longevity. Understanding the temperature distribution within the cable and its surrounding environment is crucial for ensuring safe and efficient operation, particularly in environments with high electrical loads or varying climatic conditions. All methods are analyzed and compared to find the optimal way to investigate the temperature distribution happened surrounded by the underground cable simulations. The simulation findings for the entire project are discussed through a comprehensive analysis of simulation results and subsequent discussion, we endeavor to identify key findings, trends, and implications for the design, installation, and management of underground cable networks.

## 4.2 Modeling 2D Underground Cable in COMSOL Multiphysics



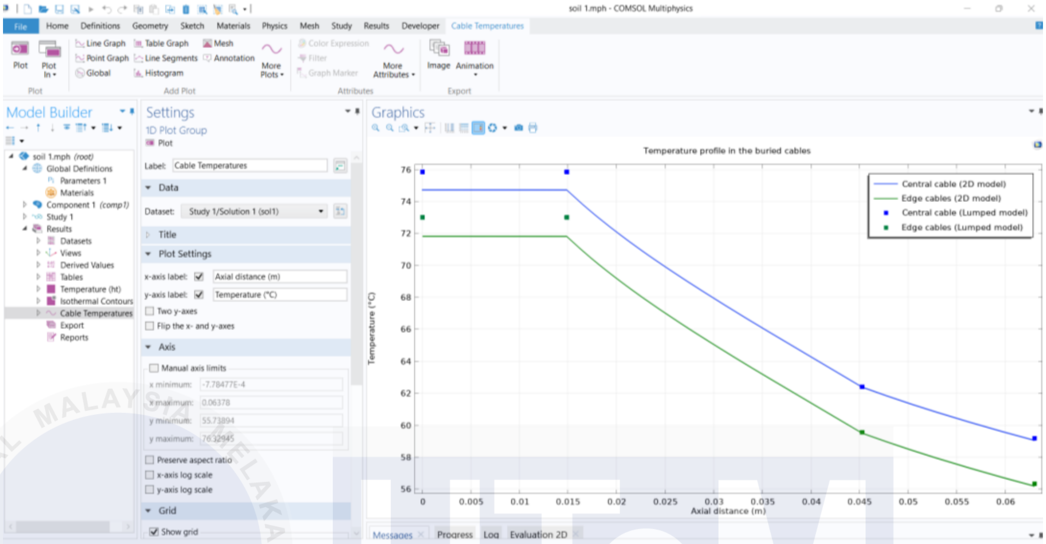
Parameters

| Name | Expression | Value | De |
|---|---|---|---|
| Dc | 29.7[mm] | 0.0297 m | Co |
| Dins | 35.9[mm] | 0.0359 m | Ins |
| Di | 90.5[mm] | 0.0905 m | Ins |
| De | 126[mm] | 0.126 m | Ca |
| L | 1.8[m] | 1.8 m | Ca |
| d | 0.5[m] | 0.5 m | Ax |
| Ta | 25[degC] | 298.15 K | Am |
| I | 685[A] | 685 A | Co |
| R | 0.039[ohm/km] | 3.9E-5 Ω/m | Co |
| f | 60 | 60 | Sy |
| U0 | 400000/sqrt(3) | 2.3094E5 | Ph |
| tandelta | 0.001 | 0.001 | Lo |
| epsilon | 2.8 | 2.8 | Re |
| lambda | 0.15 | 0.15 | Ra |
| C | epsilon*10^-9/(... | 8.2048E-10 | Ele |

Figure 4.1 The 2D model of lay flat underground cable configuration in simulation.

In Figure 3.1 shows the contour of the color in the simulation shows the temperature distribution happening surrounding the underground cable where after entering different selected thermal conductivity of soil and insulation, the contour of the thermal distribution will varies depending on those two different thermal conductivities. This distribution helps identify how heat generated within the cable is dissipated into the surrounding environment. By varying the thermal conductivity values of the insulation and soil in the simulation, the outputs will show how different materials impact the overall thermal performance. This helps in selecting the most suitable materials for optimizing heat dissipation and maintaining safe operating temperatures.

In this model, the temperature of the center and edge of the cable will be given in the graph that shows in Figure 3.2 that indicating the rate of temperature change over distance, are important for identifying areas with steep temperature changes. This can highlight potential thermal stress points that may affect the integrity of the cable insulation and the soil. Varying environmental conditions, such as soil thermal conductivity and ambient temperature, influence the thermal performance of the cable system. This is important for designing cable installations that can withstand different environmental scenarios. High temperatures can accelerate aging and degradation of the cable materials, so maintaining optimal temperatures is crucial for extending cable life.



Settings
1D Plot Group
Plot
Label: Cable Temperatures
Data
Dataset: Study 1/Solution 1 (sol1)
Title
Plot Settings
x-axis label: ☑ Axial distance (m)
y-axis label: ☑ Temperature (°C)
☐ Two y-axes
☐ Flip the x- and y-axes
Axis
☐ Manual axis limits
x minimum: -7.78477E-4
x maximum: 0.06378
y minimum: 55.73894
y maximum: 76.32945
☐ Preserve aspect ratio
☐ x-axis log scale
☐ y-axis log scale
Grid
☑ Show grid

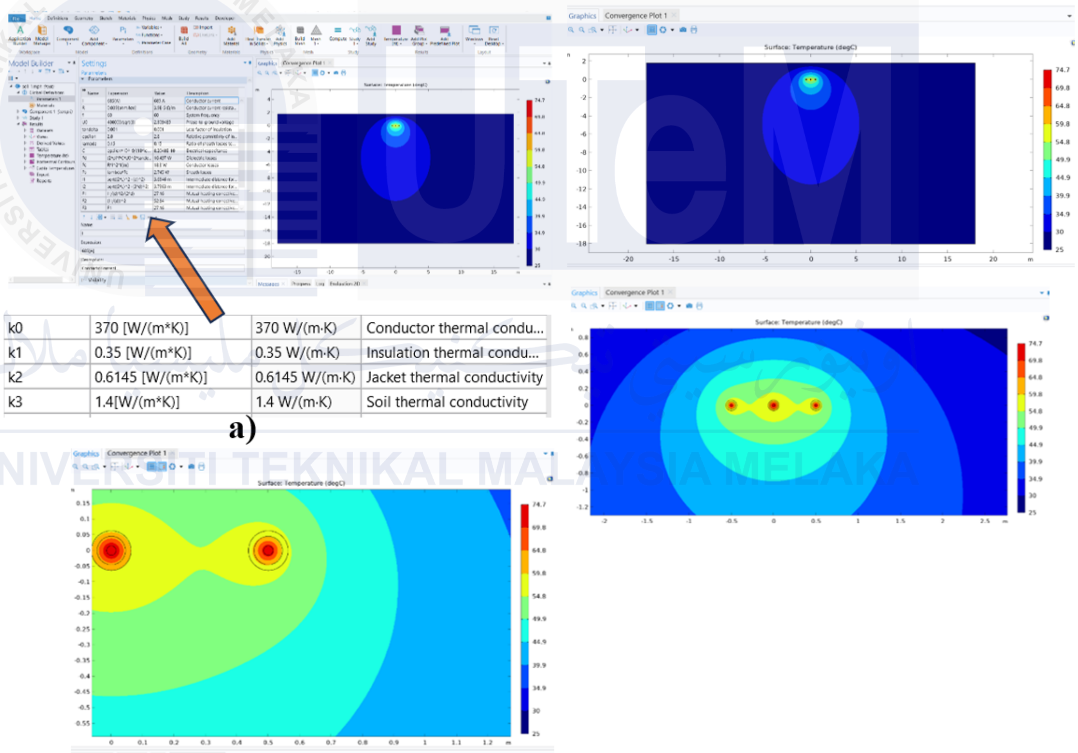
Figure 4.2 The graph of the center and edge temperature of the cable.

## 4.3 Temperature Distribution of XLPE Insulation

In this part, when running simulations in COMSOL Multiphysics for an underground cable system using XLPE insulation 0.35 W/(mK), with soil thermal conductivities of 1.17 W/(mK) for clay soil, 1.40 W/(mK) for sand, and 2.40 W/(mK) for loam, the key outputs will help in assessing the thermal performance and identifying optimal conditions for cable longevity. The application for these parameters is shown as in figure from Figure 4.3 until Figure 4.5 which is labeled as a) and the Figure 4.3 for clay soil , Figure 4.4 for sand and Figure 4.6 for loam.

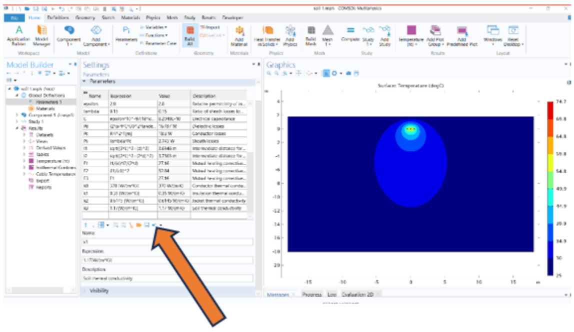
As Figure 4.3, Figure 4.4 and Figure 4.5 shows, the contour temperature distribution is expected to show higher temperatures around the cables when the soil thermal conductivity is 1.17 W/(m·K), due to lower heat dissipation, resulting in a steep temperature gradient from the cable to the surrounding soil. With a soil thermal conductivity of 1.40 W/(m·K), the temperatures around the cables will be moderate with a more balanced heat dissipation and less steep temperature gradients. When the soil thermal conductivity is 2.40 W/(m·K), the temperatures around the cables will be lower due to efficient heat dissipation, resulting in a gentle temperature gradient and effective thermal conduction away from the cables.

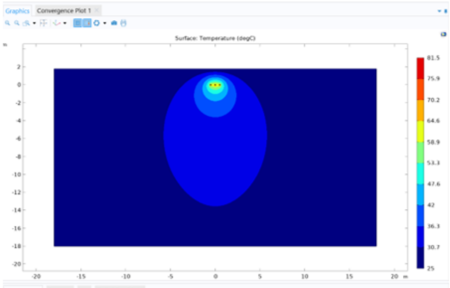
The efficiency of thermal management will vary, with poor efficiency observed with a soil thermal conductivity of 1.17 W/(m·K), necessitating additional cooling measures. Moderate efficiency will be observed with a soil thermal conductivity of 1.40 W/(m·K), potentially requiring fewer cooling enhancements, while high thermal management efficiency will be observed with a soil thermal conductivity of 2.40 W/(m·K), effectively dissipating heat and minimizing the need for additional cooling measures.



| | | | |
|---|---|---|---|
| k0 | 370 [W/(m*K)] | 370 W/(m·K) | Conductor thermal condu... |
| k1 | 0.35 [W/(m*K)] | 0.35 W/(m·K) | Insulation thermal condu... |
| k2 | 0.6145 [W/(m*K)] | 0.6145 W/(m·K) | Jacket thermal conductivity |
| k3 | 1.4[W/(m*K)] | 1.4 W/(m·K) | Soil thermal conductivity |

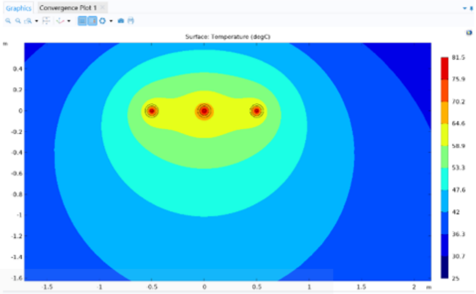
Figure 4.3 for clay soil.





| | | | |
|---|---|---|---|
| k0 | 370 [W/(m*K)] | 370 W/(m·K) | Conductor thermal condu... |
| k1 | 0.35 [W/(m*K)] | 0.35 W/(m·K) | Insulation thermal condu... |
| k2 | 0.6145 [W/(m*K)] | 0.6145 W/(m·K) | Jacket thermal conductivity |
| k3 | 1.17[W/(m*K)] | 1.17 W/(m·K) | Soil thermal conductivity |

a)



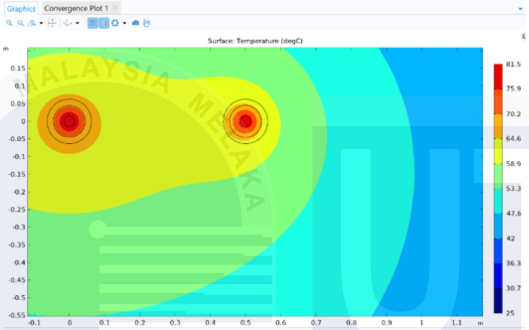
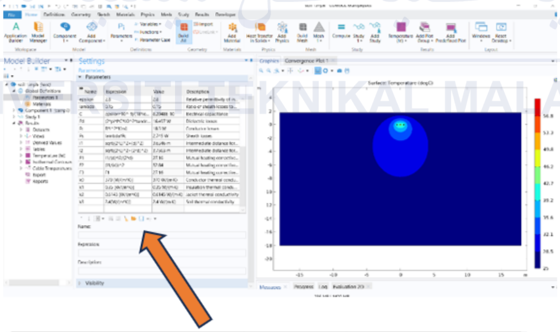
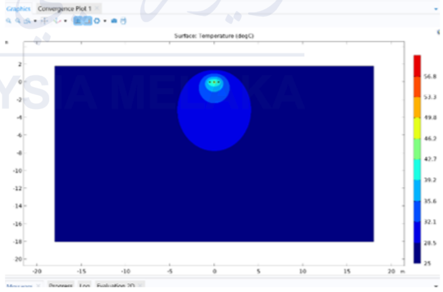
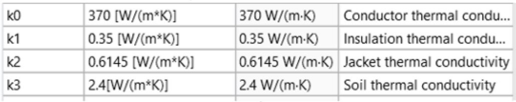


Figure 4.4 for sand.

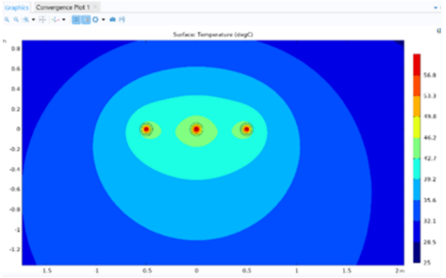






| | | | |
|---|---|---|---|
| k0 | 370 [W/(m*K)] | 370 W/(m·K) | Conductor thermal condu... |
| k1 | 0.35 [W/(m*K)] | 0.35 W/(m·K) | Insulation thermal condu... |
| k2 | 0.6145 [W/(m*K)] | 0.6145 W/(m·K) | Jacket thermal conductivity |
| k3 | 2.4[W/(m*K)] | 2.4 W/(m·K) | Soil thermal conductivity |

a)



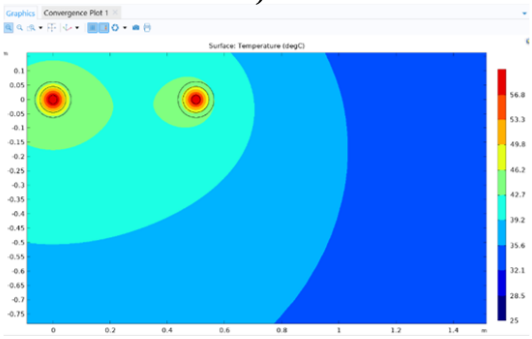


Figure 4.5 for loam.

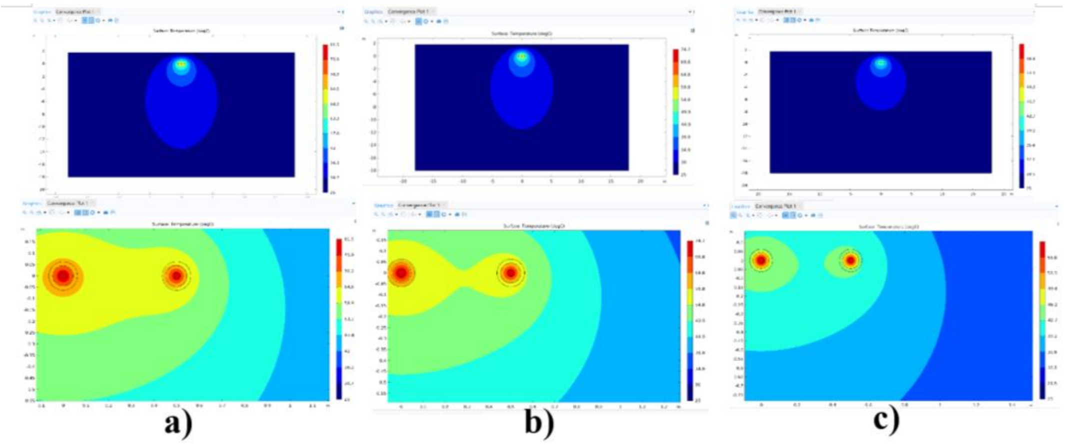


Figure 4.6 a) clay soil , b) sand and c) loam.

Table 4.1 The temperature of cable for XLPE insulation.

| Thermal conductivity of XLPE (0.35)/soils (W/Mk) | Temperature of centre cable (C) | Temperature of edges cable (C) |
|---|---|---|
| 1.17 (Clay soil) | 81.51 | 78.04 |
| 1.40 (Sand) | 74.74 | 71.83 |
| 2.40 (Loam) | 60.39 | 58.67 |

The comparison between 3 different thermal conductivity of soil as shown in Figure 4.6 where based on the simulations and based from the contour of temperature distribution and the temperature result for the cable in Table 4.1 conclude that higher soil thermal conductivity improves heat dissipation, lowers operational temperatures and reduces thermal gradients around XLPE insulated underground cables. This enhances the thermal management efficiency and extends the operational lifespan of the cables. Therefore, selecting soil with higher thermal conductivity for cable installations is crucial for optimizing thermal performance and ensuring the longevity and reliability of the cable system.

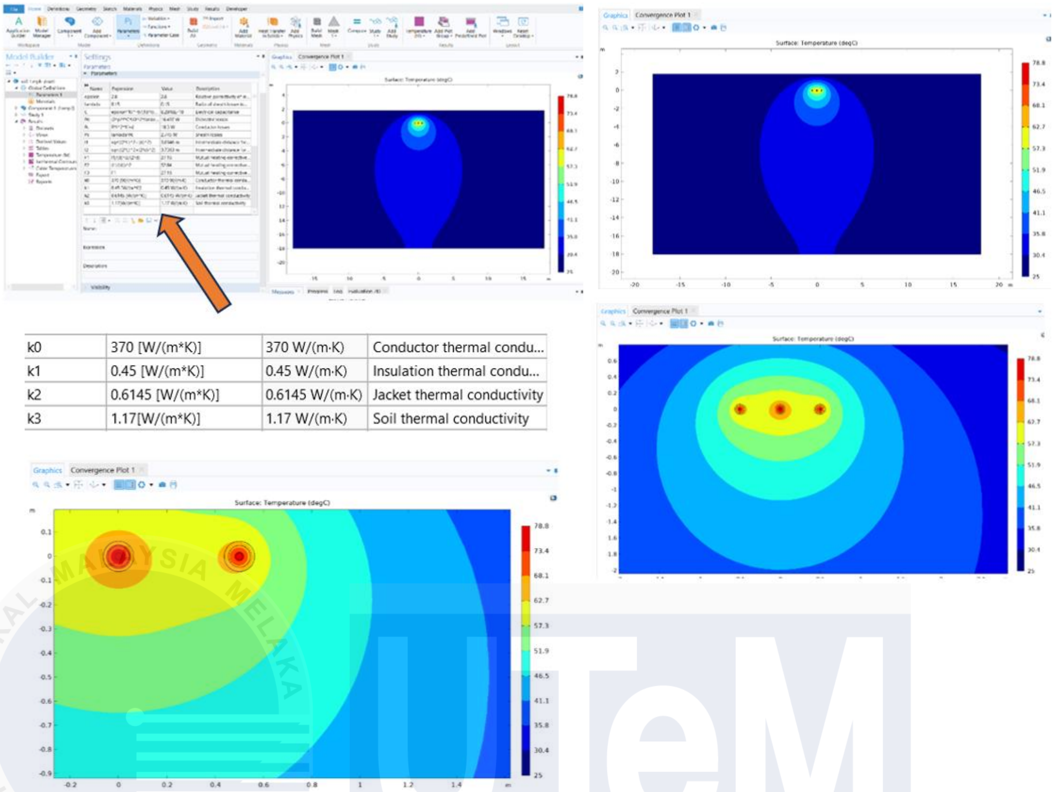
## 4.4 Temperature Distribution of HDPE Insulation

In this part, when running simulations in COMSOL Multiphysics for an underground cable system using HDPE insulation 0.45 W/(mK), with soil thermal conductivities of 1.17 W/(mK) for clay soil, 1.40 W/(mK) for sand, and 2.40 W/(mK) for loam, the key outputs will help in assessing the thermal performance and identifying optimal conditions for cable longevity. The application for these parameters is shown as in figure from Figure 4.7 until Figure 4.9 which is labeled as a) and the Figure 4.7 for clay soil , Figure 4.8 for sand and Figure 4.8 for loam.

As shown in Figure 4.7, Figure 4.8 and Figure 4.9, for soil with a thermal conductivity of 1.17 W/(m·K), the contour temperature distribution around the cables is expected to be higher due to poor heat dissipation capabilities. The retained heat within the HDPE insulation results in a steep temperature gradient from the cable to the surrounding soil. This high temperature can stress the cable insulation, causing potential reliability issues over time. Heat flux in this scenario will be relatively low, indicating less efficient heat transfer away from the cables.

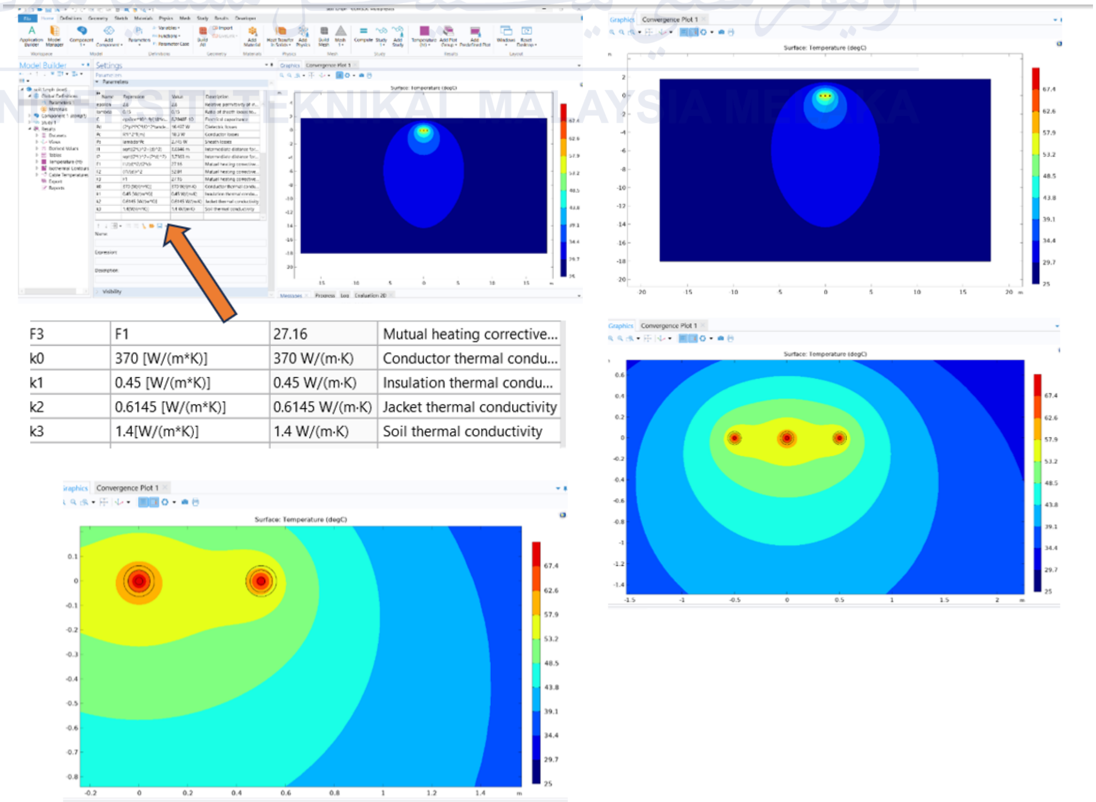
When the soil thermal conductivity is increased to 1.40 W/(m·K), the simulation will show more moderate temperatures around the cables. This level of conductivity offers a balance, with better heat dissipation than the lower conductivity soil, resulting in less steep temperature gradients. The improved heat flux demonstrates that more heat is being transferred from the cables into the soil, enhancing thermal management and potentially extending the cable's operational lifespan by reducing thermal stress.

For soil with the highest thermal conductivity of 2.40 W/(m·K), the temperature around the cables is significantly lower due to efficient heat dissipation. The temperature gradients are much gentler, indicating a smooth transition of heat from the cables into the surrounding soil. The heat flux in this scenario is high, reflecting effective thermal conduction, which minimizes hotspots and lowers the risk of overheating. The cable insulation experiences less thermal stress, which is critical for maintaining the cable's integrity and prolonging its lifespan.



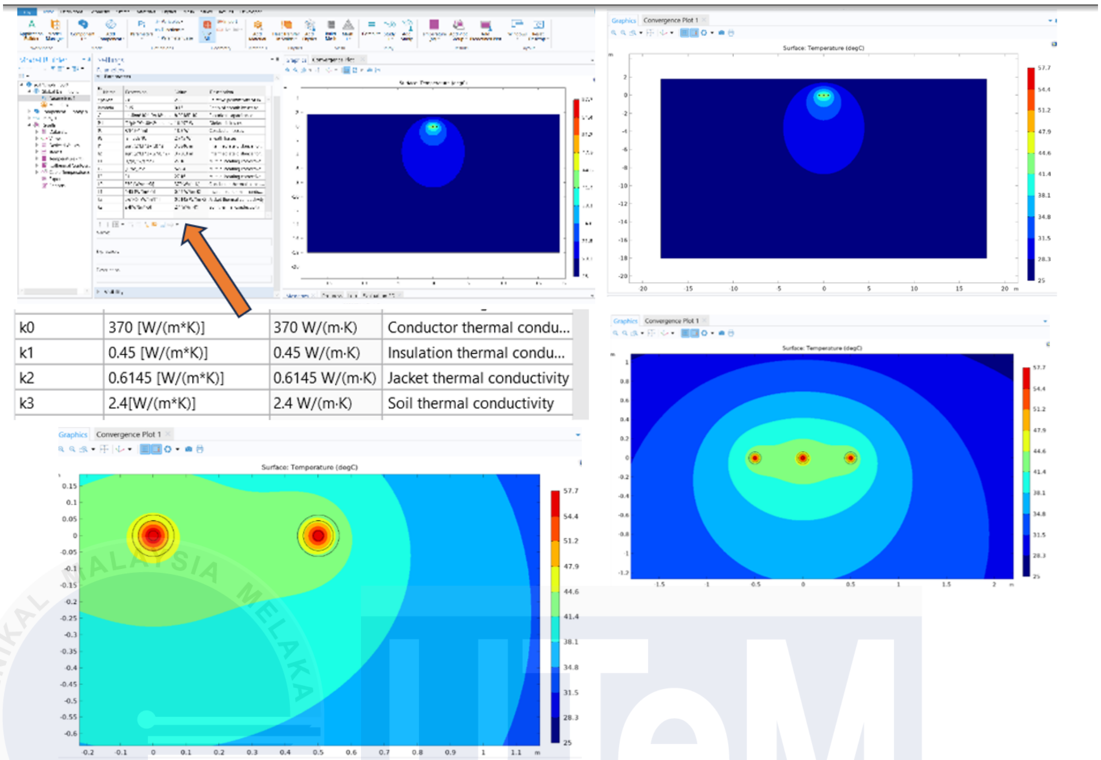
| | | | |
|---|---|---|---|
| k0 | 370 [W/(m*K)] | 370 W/(m·K) | Conductor thermal condu... |
| k1 | 0.45 [W/(m*K)] | 0.45 W/(m·K) | Insulation thermal condu... |
| k2 | 0.6145 [W/(m*K)] | 0.6145 W/(m·K) | Jacket thermal conductivity |
| k3 | 1.17[W/(m*K)] | 1.17 W/(m·K) | Soil thermal conductivity |

Figure 4.7 for clay soil



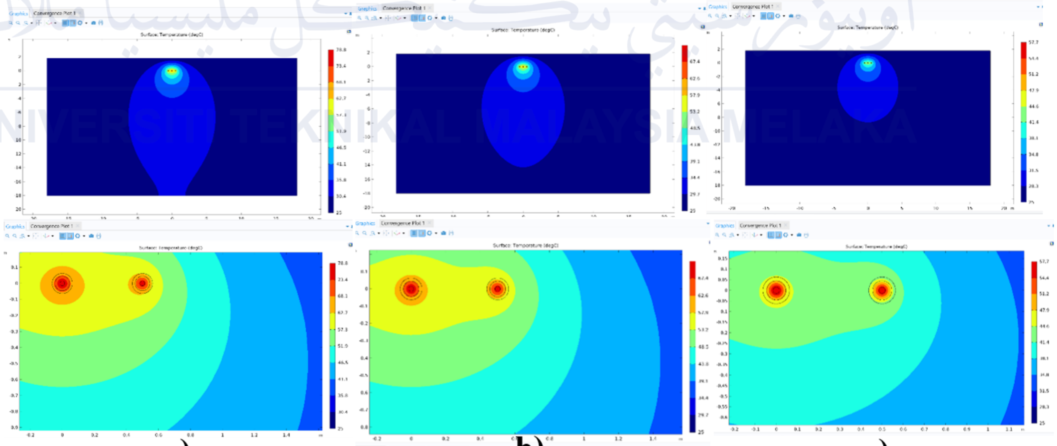
| | | | |
|---|---|---|---|
| F3 | F1 | 27.16 | Mutual heating corrective... |
| k0 | 370 [W/(m*K)] | 370 W/(m·K) | Conductor thermal condu... |
| k1 | 0.45 [W/(m*K)] | 0.45 W/(m·K) | Insulation thermal condu... |
| k2 | 0.6145 [W/(m*K)] | 0.6145 W/(m·K) | Jacket thermal conductivity |
| k3 | 1.4[W/(m*K)] | 1.4 W/(m·K) | Soil thermal conductivity |

**Figure 4.8 for sand**



| | | | |
|---|---|---|---|
| k0 | 370 [W/(m*K)] | 370 W/(m·K) | Conductor thermal condu... |
| k1 | 0.45 [W/(m*K)] | 0.45 W/(m·K) | Insulation thermal condu... |
| k2 | 0.6145 [W/(m*K)] | 0.6145 W/(m·K) | Jacket thermal conductivity |
| k3 | 2.4[W/(m*K)] | 2.4 W/(m·K) | Soil thermal conductivity |

Figure 4.9 for loam



a) b) c)

Figure 4.10 a) clay soil , b) sand and c) loam

Table 4.2 The temperature of cable for HDPE insulation

| Thermal conductivity of HDPE (0.45)/soils (W/Mk) | Temperature of centre cable (C) | Temperature of edges cable (C) |
|---|---|---|
| 1.17 | 78.82 | 75.04 |
| 1.40 | 72.06 | 769.16 |
| 2.40 | 57.71 | 56.00 |

The comparison between 3 different thermal conductivity of soil as shown in Figure 4.10 where based on the simulations and based from the contour of temperature distribution and the temperature result for the cable in Table 4.2 higher soil thermal conductivity improves heat dissipation, lowers operational temperatures and reduces thermal gradients around HDPE insulated underground cables. This results in enhanced thermal management efficiency and extends the operational lifespan of the cables. Therefore, selecting soil with higher thermal conductivity for cable installations is essential for optimizing thermal performance and ensuring the longevity and reliability of the cable system.

## 4.5 Summary

The simulations conducted using XLPE and HDPE insulated underground cables in soils with thermal conductivities of 1.17 W/(m·K), 1.40 W/(m·K), and 2.40 W/(m·K) reveal significant findings regarding their thermal performance and impact on cable lifespan. For XLPE insulation, soil with a thermal conductivity of 1.17 W/(m·K) leads to high temperatures around the cables due to poor heat dissipation and resulting in steep temperature gradients. This causes significant thermal stress on the XLPE insulation, accelerating aging and shortening the cable's operational lifespan, necessitating additional cooling measures. In contrast, soil with a thermal conductivity of 1.40 W/(m·K) improves heat dissipation, resulting in moderate temperatures and less steep gradients. This reduces thermal stress on the insulation, contributing to a longer operational lifespan and moderate thermal management efficiency. Optimal heat dissipation is achieved with soil at 2.40 W/(m·K), leading to the lowest temperatures, gentle gradients and imposing the least thermal stress on the insulation and significantly enhancing the cable's lifespan with high thermal management efficiency.

For HDPE insulation, the trends are similar. Soil with a thermal conductivity of 1.17 W/(m·K) results in high temperatures, steep gradients, and intense hotspots, causing significant thermal stress and potentially shortening the cable's operational lifespan, requiring additional cooling measures. Soil with a thermal conductivity of 1.40 W/(m·K) achieves more moderate temperatures and less steep gradients, improving thermal performance and reducing thermal stress, thus contributing to a longer lifespan and moderate thermal management efficiency. Soil with a thermal conductivity of 2.40 W/(m·K) offers efficient heat dissipation, significantly lower temperatures, gentle gradients, and minimal hotspots, ensuring excellent thermal management and significantly enhancing the cable's lifespan with high thermal management efficiency.

In summary, for both XLPE and HDPE insulated cables, higher soil thermal conductivity improves heat dissipation, lowers operational temperatures and reduces thermal gradients, leading to enhanced thermal management efficiency and extended operational lifespans for the cables. Therefore, selecting soil with higher thermal conductivity and lower thermal conductivity of insulator cable installations is crucial for optimizing thermal performance and ensuring the longevity and reliability of the cable system.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion

The simulations investigated the temperature distribution for a direct buried laying configuration, comparing results with different insulation materials (XLPE and HDPE) and soil thermal conductivities (1.17 W/(m·K), 1.40 W/(m·K), and 2.40 W/(m·K)). The results demonstrate that higher soil thermal conductivity improves heat dissipation around the cables, resulting in lower operational temperatures, gentler thermal gradients, and fewer intense hotspots. This reduces thermal stress on the cable insulation, thereby extending the cable's operational lifespan. Specifically, soil with a thermal conductivity of 2.40 W/(m·K) showed the most efficient thermal management and the least thermal stress on the cables. Comparing XLPE and HDPE insulations, the findings indicate similar trends in thermal performance across different soil thermal conductivities. However, the optimal soil thermal conductivity for minimizing thermal stress and enhancing cable lifespan remains consistent regardless of the insulation material used.

In summary, the project highlights the importance of selecting appropriate soil thermal conductivity for underground cable installations to optimize thermal performance and ensure the reliability and longevity of the cable system. These insights are particularly valuable for improving underground cable installations in Malaysia's specific environmental conditions.

## 5.2 Future Works

Moving forward, several avenues for future research can significantly enhance the findings of this project. Exploring alternative cable laying configurations beyond the lay-flat design, such as trefoil or triangular configurations, could reveal more efficient thermal management strategies. Additionally, examining the thermal performance of other insulation materials like Ethylene Propylene Rubber (EPR) could offer comparative insights into insulation effectiveness. Long-term aging studies are crucial to assessing how thermal stress impacts the durability of insulation materials over extended periods. Furthermore, evaluating thermal enhancement techniques such as using high thermal conductivity backfill materials or implementing active cooling systems could optimize heat dissipation and prolong cable lifespan. These future research directions aim to refine the understanding and application of thermal management strategies for underground cable systems, enhancing their reliability and longevity in diverse environmental conditions.

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# APPENDICES

## APPENDIX A: 11KV XLPE SINGLE CORE 630 $mm^2$ INSULATED ARMOURED SHEATED PVC CUPPER CABLE UNDERGROUND CABLE

nkt cables

Cu 6.35/11kV

MV cables with Longitudinal Water-Blocking System

| Standard | AS/NZS 1429.1 |
|---|---|

Construction:

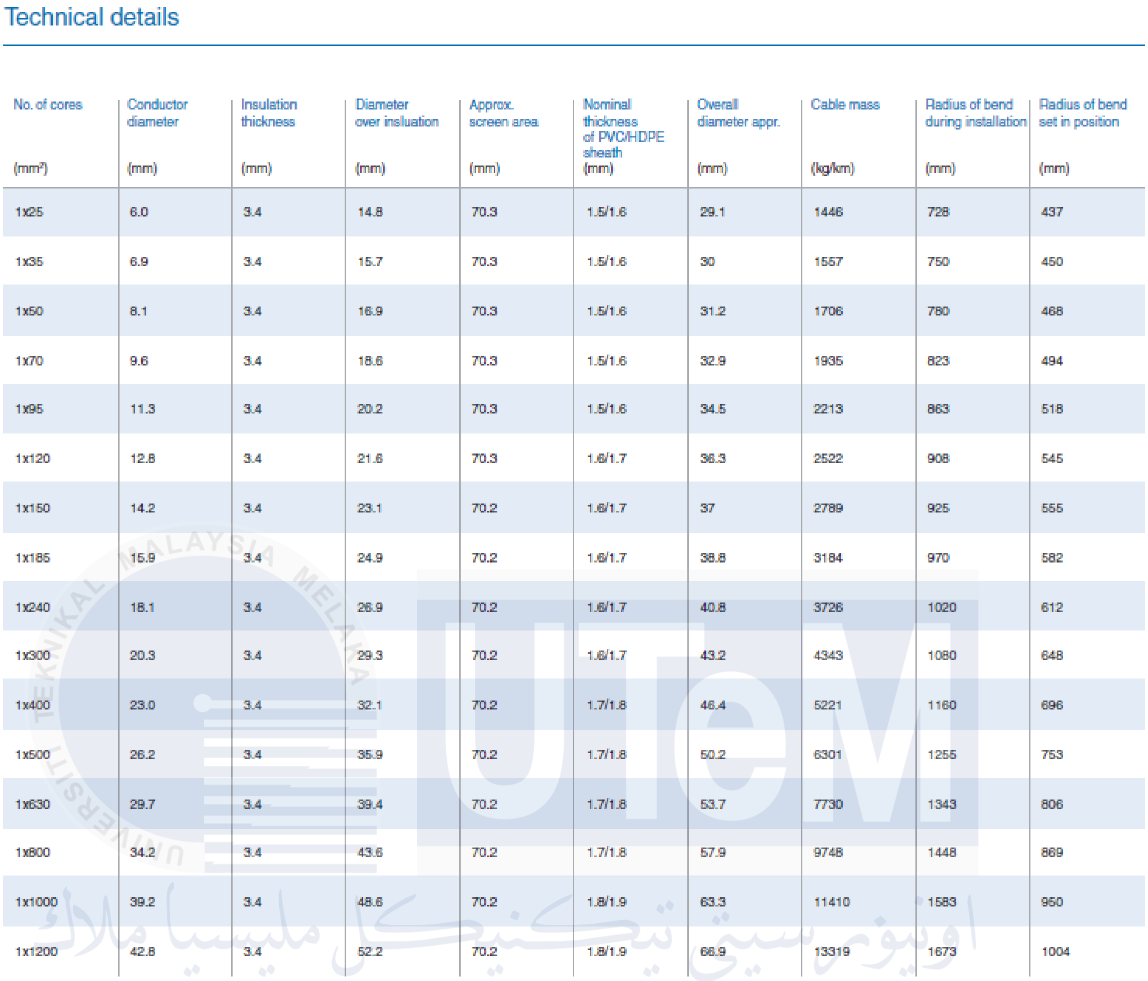
- ① Cu conductor
- ② Conductor screen
- ③ XLPE insulation
- ④ Insulation screen
- ⑤ Semiconductive water-blocking tape
- ⑥ Cu wire screen and Cu equalising tape
- ⑦ Non conductive water-blocking tape
- ⑧ PVC inner sheath
- ⑨ HDPE outer sheath

Application:

Cables are designed for fixed installation, for laying in the ground, for indoor applications and in cable ducts.

Properties:

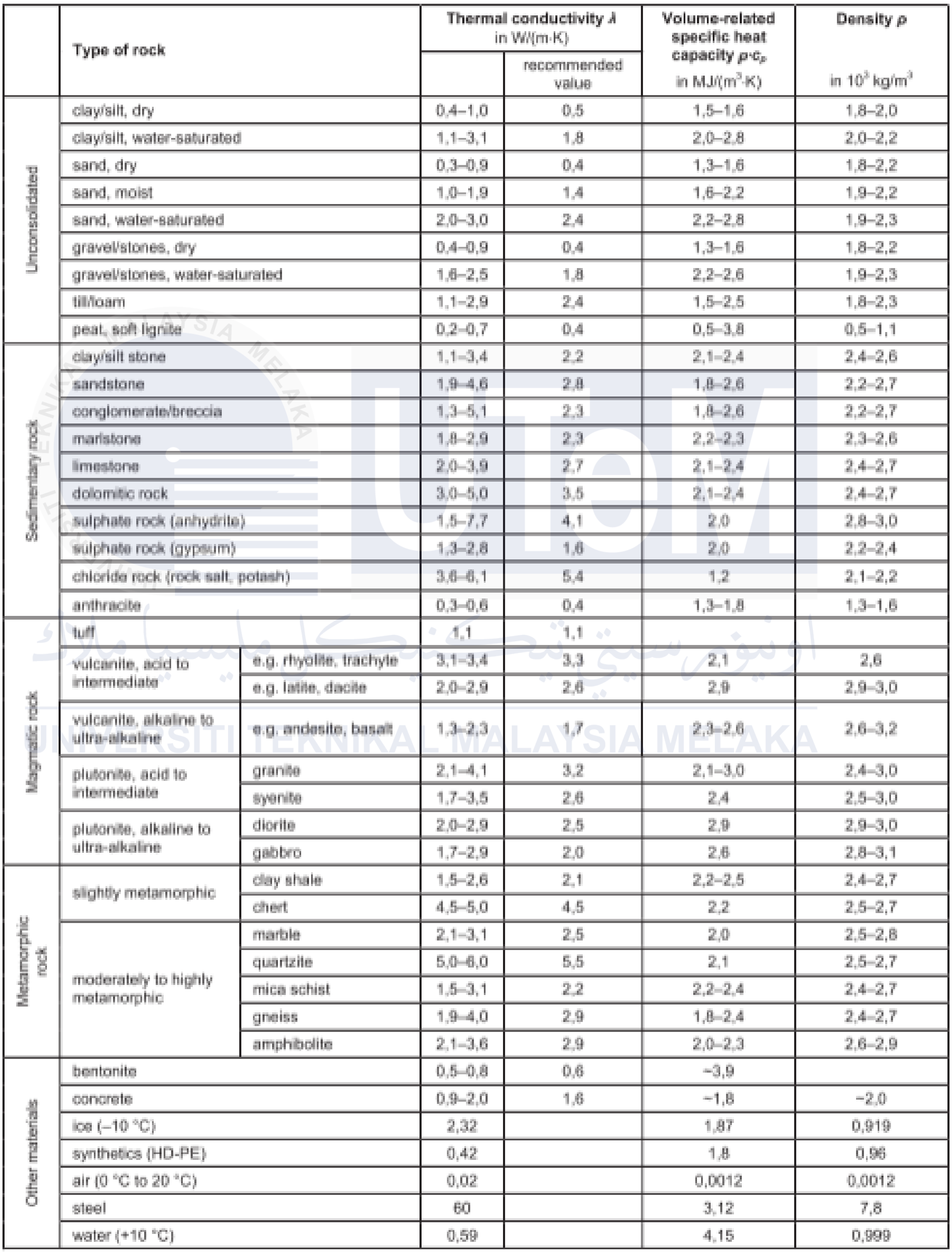
| | | | |
|---|---|---|---|
| Rated voltage U0/U (kV) | 6.35/11 | Min. temperature for laying (°C) | -20 |
| Test voltage (kV) | 25.5 | Min.storage temperature (°C) | -35 |
| Max.short-circuit temperature (°C) | +250 | Color of insulation | Natural |
| Operating cond. temperature (°C) | +90 | Color of inner / outer sheath | Client Requirement |
| Temperature range for handling (°C) | -35 up to +90 | Packaging | Steel Drums |



## Technical details

| No. of cores (mm²) | Conductor diameter (mm) | Insulation thickness (mm) | Diameter over insluation (mm) | Approx. screen area (mm) | Nominal thickness of PVC/HDPE sheath (mm) | Overall diameter appr. (mm) | Cable mass (kg/km) | Radius of bend during installation (mm) | Radius of bend set in position (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1x25 | 6.0 | 3.4 | 14.8 | 70.3 | 1.5/1.6 | 29.1 | 1446 | 728 | 437 |
| 1x35 | 6.9 | 3.4 | 15.7 | 70.3 | 1.5/1.6 | 30 | 1557 | 750 | 450 |
| 1x50 | 8.1 | 3.4 | 16.9 | 70.3 | 1.5/1.6 | 31.2 | 1706 | 780 | 468 |
| 1x70 | 9.6 | 3.4 | 18.6 | 70.3 | 1.5/1.6 | 32.9 | 1935 | 823 | 494 |
| 1x95 | 11.3 | 3.4 | 20.2 | 70.3 | 1.5/1.6 | 34.5 | 2213 | 863 | 518 |
| 1x120 | 12.8 | 3.4 | 21.6 | 70.3 | 1.6/1.7 | 36.3 | 2522 | 908 | 545 |
| 1x150 | 14.2 | 3.4 | 23.1 | 70.2 | 1.6/1.7 | 37 | 2789 | 925 | 555 |
| 1x185 | 15.9 | 3.4 | 24.9 | 70.2 | 1.6/1.7 | 38.8 | 3184 | 970 | 582 |
| 1x240 | 18.1 | 3.4 | 26.9 | 70.2 | 1.6/1.7 | 40.8 | 3726 | 1020 | 612 |
| 1x300 | 20.3 | 3.4 | 29.3 | 70.2 | 1.6/1.7 | 43.2 | 4343 | 1080 | 648 |
| 1x400 | 23.0 | 3.4 | 32.1 | 70.2 | 1.7/1.8 | 46.4 | 5221 | 1160 | 696 |
| 1x500 | 26.2 | 3.4 | 35.9 | 70.2 | 1.7/1.8 | 50.2 | 6301 | 1255 | 753 |
| 1x630 | 29.7 | 3.4 | 39.4 | 70.2 | 1.7/1.8 | 53.7 | 7730 | 1343 | 806 |
| 1x800 | 34.2 | 3.4 | 43.6 | 70.2 | 1.7/1.8 | 57.9 | 9748 | 1448 | 869 |
| 1x1000 | 39.2 | 3.4 | 48.6 | 70.2 | 1.8/1.9 | 63.3 | 11410 | 1583 | 950 |
| 1x1200 | 42.8 | 3.4 | 52.2 | 70.2 | 1.8/1.9 | 66.9 | 13319 | 1673 | 1004 |

# APPENDIX B: THERMAL CONDUCTIVITY AND VOLUME RELATED SPECIFIC HEAT CAPCITY OF SOIL



|  | Type of rock |  | Thermal conductivity $\lambda$ in W/(m·K) |  | Volume-related specific heat capacity $\rho \cdot c_p$ in MJ/(m$^3$·K) | Density $\rho$ in $10^3$ kg/m$^3$ |
|---|---|---|---|---|---|---|
|  |  |  |  | recommended value |  |  |
| Unconsolidated | clay/silt, dry |  | 0,4–1,0 | 0,5 | 1,5–1,6 | 1,8–2,0 |
|  | clay/silt, water-saturated |  | 1,1–3,1 | 1,8 | 2,0–2,8 | 2,0–2,2 |
|  | sand, dry |  | 0,3–0,9 | 0,4 | 1,3–1,6 | 1,8–2,2 |
|  | sand, moist |  | 1,0–1,9 | 1,4 | 1,6–2,2 | 1,9–2,2 |
|  | sand, water-saturated |  | 2,0–3,0 | 2,4 | 2,2–2,8 | 1,9–2,3 |
|  | gravel/stones, dry |  | 0,4–0,9 | 0,4 | 1,3–1,6 | 1,8–2,2 |
|  | gravel/stones, water-saturated |  | 1,6–2,5 | 1,8 | 2,2–2,6 | 1,9–2,3 |
|  | till/loam |  | 1,1–2,9 | 2,4 | 1,5–2,5 | 1,8–2,3 |
|  | peat, soft lignite |  | 0,2–0,7 | 0,4 | 0,5–3,8 | 0,5–1,1 |
| Sedimentary rock | clay/silt stone |  | 1,1–3,4 | 2,2 | 2,1–2,4 | 2,4–2,6 |
|  | sandstone |  | 1,9–4,6 | 2,8 | 1,8–2,6 | 2,2–2,7 |
|  | conglomerate/breccia |  | 1,3–5,1 | 2,3 | 1,8–2,6 | 2,2–2,7 |
|  | marlstone |  | 1,8–2,9 | 2,3 | 2,2–2,3 | 2,3–2,6 |
|  | limestone |  | 2,0–3,9 | 2,7 | 2,1–2,4 | 2,4–2,7 |
|  | dolomitic rock |  | 3,0–5,0 | 3,5 | 2,1–2,4 | 2,4–2,7 |
|  | sulphate rock (anhydrite) |  | 1,5–7,7 | 4,1 | 2,0 | 2,8–3,0 |
|  | sulphate rock (gypsum) |  | 1,3–2,8 | 1,6 | 2,0 | 2,2–2,4 |
|  | chloride rock (rock salt, potash) |  | 3,6–6,1 | 5,4 | 1,2 | 2,1–2,2 |
|  | anthracite |  | 0,3–0,6 | 0,4 | 1,3–1,8 | 1,3–1,6 |
| Magmatic rock | tuff |  | 1,1 | 1,1 |  |  |
|  | vulcanite, acid to intermediate | e.g. rhyolite, trachyte | 3,1–3,4 | 3,3 | 2,1 | 2,6 |
|  |  | e.g. latite, dacite | 2,0–2,9 | 2,6 | 2,9 | 2,9–3,0 |
|  | vulcanite, alkaline to ultra-alkaline | e.g. andesite, basalt | 1,3–2,3 | 1,7 | 2,3–2,6 | 2,6–3,2 |
|  | plutonite, acid to intermediate | granite | 2,1–4,1 | 3,2 | 2,1–3,0 | 2,4–3,0 |
|  |  | syenite | 1,7–3,5 | 2,6 | 2,4 | 2,5–3,0 |
|  | plutonite, alkaline to ultra-alkaline | diorite | 2,0–2,9 | 2,5 | 2,9 | 2,9–3,0 |
|  |  | gabbro | 1,7–2,9 | 2,0 | 2,6 | 2,8–3,1 |
| Metamorphic rock | slightly metamorphic | clay shale | 1,5–2,6 | 2,1 | 2,2–2,5 | 2,4–2,7 |
|  |  | chert | 4,5–5,0 | 4,5 | 2,2 | 2,5–2,7 |
|  | moderately to highly metamorphic | marble | 2,1–3,1 | 2,5 | 2,0 | 2,5–2,8 |
|  |  | quartzite | 5,0–6,0 | 5,5 | 2,1 | 2,5–2,7 |
|  |  | mica schist | 1,5–3,1 | 2,2 | 2,2–2,4 | 2,4–2,7 |
|  |  | gneiss | 1,9–4,0 | 2,9 | 1,8–2,4 | 2,4–2,7 |
|  |  | amphibolite | 2,1–3,6 | 2,9 | 2,0–2,3 | 2,6–2,9 |
| Other materials | bentonite |  | 0,5–0,8 | 0,6 | ~3,9 |  |
|  | concrete |  | 0,9–2,0 | 1,6 | ~1,8 | ~2,0 |
|  | ice (–10 °C) |  | 2,32 |  | 1,87 | 0,919 |
|  | synthetics (HD-PE) |  | 0,42 |  | 1,8 | 0,96 |
|  | air (0 °C to 20 °C) |  | 0,02 |  | 0,0012 | 0,0012 |
|  | steel |  | 60 |  | 3,12 | 7,8 |
|  | water (+10 °C) |  | 0,59 |  | 4,15 | 0,999 |