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COLLEGE OF ENGINEERING, DESIGN, ART AND TECHNOLOGY

(CEDAT)

SCHOOL OF ENGINEERING

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

CIV 4200: CIVIL ENGINEERING PROJECT II

DESIGN AND ASSESSMENT OF EARTH-AIR HEAT EXCHANGER AS AN INTERGARTED NATURAL COOLING SYSTEM FOR NET ZERO TROPICAL BUILDINGS

BY

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Submitted in Partial Fulfilment of the Requirements for the Award of a Degree of Bachelor of Science in Civil Engineering

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DECLARATION

We, Tumusiime Kasangaki and Lukooya Lucy, hereby declare that this project proposal represents our original work compiled by us without duplication of the existing sources and prior submissions. This document is a partial fulfilment of the requirements for the award of Bachelor of Science in Civil Engineering at Makerere University.

We therefore affirm the authenticity and integrity of all content herein, date 26th June, 2026.

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APPROVAL

This is to certify that this research project has been conducted and submitted with my full knowledge, approval and satisfaction to the supervisor.

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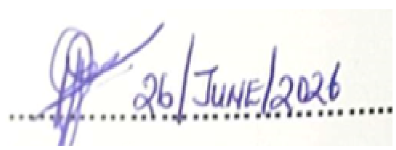

ACKNOWLEDGEMENT

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LIST OF ABBREVIATIONS.

ABBREVIATION	MEANING
AC	Air Conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers.
BS	British standard.
CAD	Computer Aided Drafting
CFD	Computational Fluid Dynamic
CH	Highly Clay
CHT	Conjugate Heat Transfer
CL	Low clay
C_p	Specific Heat Capacity at Constant Pressure
EAHE	Earth - Air Heat Exchanger.
EATEX	Earth - Air Thermal Exchanger.
EN	English Norm.
EUT	Earth Undisturbed Temperatures.
HVAC	Heating, Ventilation, and Air Conditioning
LMTD	Log Mean Temperature Difference
LL	Liquid Limit
MC	Moisture content
ML	Medium Clay
NTU	Number of Transfer Units
°C	Degrees Celsius.
UNMA	Uganda National Meteorological Authority
uPVC	Unplasticized Polyvinyl Chloride

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CHAPTER 1 : INTRODUCTION

1.1 BACKGROUND

The built environment stands at the intersection of two critical global challenges: climate change and sustainable development. Buildings currently account for approximately 40% of global energy-related greenhouse gas emissions, with 27% attributed to operational emissions from energy needed for ventilation and powering buildings which adds up to 10 metric gigatons of carbon dioxide per year (Hamilton, 2023). The remaining 13%, is from embodied carbon in construction materials (Satish Diwakar, 2023). However, the buildings and construction industry in Africa is one of the biggest contributors to greenhouse gas emissions, accounting for 19–22% of national emissions. This substantial contribution makes the construction sector second only to industry in terms of carbon emissions. As global populations continue to urbanize and economies develop, particularly in tropical regions, energy consumption in the building sector is projected to double by 2050 if current trends continue (Mugure Njendu, 2025).

Low-income communities in tropical regions face a distinctive set of challenges that intensify the urgency for sustainable building solutions. Tropical climates are characterized by high temperatures (typically 24-32°C), high relative humidity often exceeding 60% (Mohsenzadeh et al., 2021), intense solar radiation, and heavy seasonal rainfall. These climatic conditions create substantial thermal discomfort and drive increasing demand for mechanical cooling systems (Juhi Goyal, 2023). Studies in low-income tropical housing across Uganda, Malaysia, Ethiopia, and Cambodia have documented indoor temperatures exceeding recommended thermal comfort ranges, leading to "moderate" to "strong" heat stress according to the Universal Thermal Climate Index (Aqilah et al., 2025). This thermal discomfort directly impacts health, productivity, quality of life, and contributes to heat-related illnesses and mortality, particularly among vulnerable populations including women, children, and the elderly (Rajagopalan P et al., 2020). The energy burden, defined as the percentage of household income spent on energy, is disproportionately high for low-income households, with some spending up to 33% of annual income on energy compared to just 3% for higher-income households (Hernández & Phillips, 2015).

Between 1960 and 2002, Uganda’s southeast and northwest experienced rising mean annual temperatures of ~0.02 °C/year and ~0.03 °C/year respectively, especially from March to May. From 1990 to 2009, hot days rose by 74 (24%) and cool days by 136 (37%). Overall, temperatures increased by 22.3 °C during this period (Nuwagira & Yasin, 2022). Conventional construction practices in low-income tropical areas often overlook thermal performance, resulting in buildings that consume excess energy for cooling systems. Energy efficiency and thermal comfort are critical yet underexplored aspects of eco-friendly development in low-income tropical regions. Buildings in these regions are often designed and constructed with limited consideration for thermal performance at early stages, leading to high energy demands for cooling (Kajjoba et al., 2025).

Earth Air Heat Exchangers: Harnessing Temperature Naturally.

Earth Air Heat Exchangers (EAHE), represent a promising passive technology for addressing cooling and heating needs in buildings by utilizing the earth's stable subsurface temperature. EAHEs have been extensively used for both space heating and cooling over the course of many years, and this topic remains attractive to researchers. Intensive studies have been carried out on this topic concerning the heat and mass transfer characteristics of the EAHE, design and operational parameters, energy saving potential, feasibility study in different climates and buildings and thermal performance of hybrid EAHE systems (Zhao et al., 2024). At depths between 1 to 4 meters below the ground surface, soil temperatures remain relatively constant throughout the year, typically ranging between 10-25°C depending on geographic location and climate zone (El Khachine et al., 2024). This thermal stability provides a natural heat sink for cooling in dry/hot season and a heat source for warming in cold (Peñaloza Peña et al., 2021).

The use of EAHE systems for air conditioning in commercial and industrial settings offers several environmental benefits and is capable of operating in both standalone and hybrid modes (Lattieff et al., 2022). The advantages of EAHE systems are particularly relevant for low-income tropical contexts. These systems require no compressors, refrigerants, or fossil fuel combustion, with only low-power fans or blowers needed to circulate air. This translates to minimal operational costs and maintenance requirements compared to conventional air conditioning. EAHE systems can reduce cooling energy demand by 20-30% while simultaneously improving indoor air quality through continuous fresh air ventilation (Li et al., 2023). The technology is compatible with locally available materials and low-skill construction techniques, making it accessible for implementation in resource-constrained settings. Research across various climate zones has demonstrated the effectiveness of EAHE systems. Studies in tropical and hot-arid climates have shown temperature reductions of 10-16°C during peak summer conditions.

The design of net zero buildings incorporating natural temperature harnessing technologies like EAHE systems represents a critical intervention point for low-income tropical regions. By dramatically reducing cooling energy demand through passive strategies while providing affordable, renewable-powered thermal regulation, these buildings can break the cycle of energy poverty, improve health and well-being, and contribute to global climate mitigation efforts. This project explores the technical, economic, and social dimensions of integrating EAHE technology within comprehensive net zero building designs tailored to the specific needs and constraints of low-income tropical communities, contributing to the broader global imperative of achieving universal access to sustainable, healthy, and climate-resilient buildings.

1.2 PROBLEM STATEMENT

Temperature levels and hot days during the dry seasons are observed increasing in tropical regions such as Uganda yet conventional construction methods in these regions often neglect thermal performance, leading to high energy demand for cooling and worsening energy poverty. Recent studies have explored potential in Earth Air Tube Heat Exchangers as effective and yet affordable technologies for natural cooling during the hot seasons backed by the low and stable underground temperatures throughout the year.

1.3 OBJECTIVES

Main objective

To design Earth-Air Tube Heat Exchanger system for natural cooling in low-income tropical regions.

Specific objectives

1. To determine the EATHE design inputs for the Ugandan climate.
2. To determine the design parameters such as material types and geometry based on the obtained data.
3. To design the systems structural and mechanical components
4. To perform the system's cost benefit analysis and its effect to reducing the buildings energy demand.

1.4 SCOPE OF THE STUDY.

The study was scheduled for the January to May 2026 timeframe, covering the full scope of activities from material acquisition to final testing, analysis and reporting. It focused on design of earth to air heat exchangers for net zero building in tropical low-income regions and the samples were particularly obtained at TANKHILL within Makerere University. Testing and analysis were conducted in the CEDAT soil mechanics laboratory within Makerere university.

The research involved determining design parameter for thermal performance and energy efficiency, structural and mechanical components of EATHE to be optimized to enhance thermal performance and the performance of the building's cooling system impact to the overall demand. It also concentrated on designing the EATHE system for natural cooling in low-income tropical regions.

1.5 JUSTIFICATION

The growing threat of climate change, coupled with increasing temperatures, energy poverty and rapid urbanization is reaching unprecedented levels, contributing to greenhouse gas emissions thus highlighting the urgent need for sustainable and affordable building solutions. EAHE systems offer a low-cost, energy-efficient solution for improving thermal comfort in low-income tropical buildings. By using the earth's stable subsurface temperature, they reduce indoor heat stress and cut cooling energy demand without relying on fossil fuels. Their simplicity, low maintenance, and use of local materials make them ideal for sustainable and climate-resilient construction.

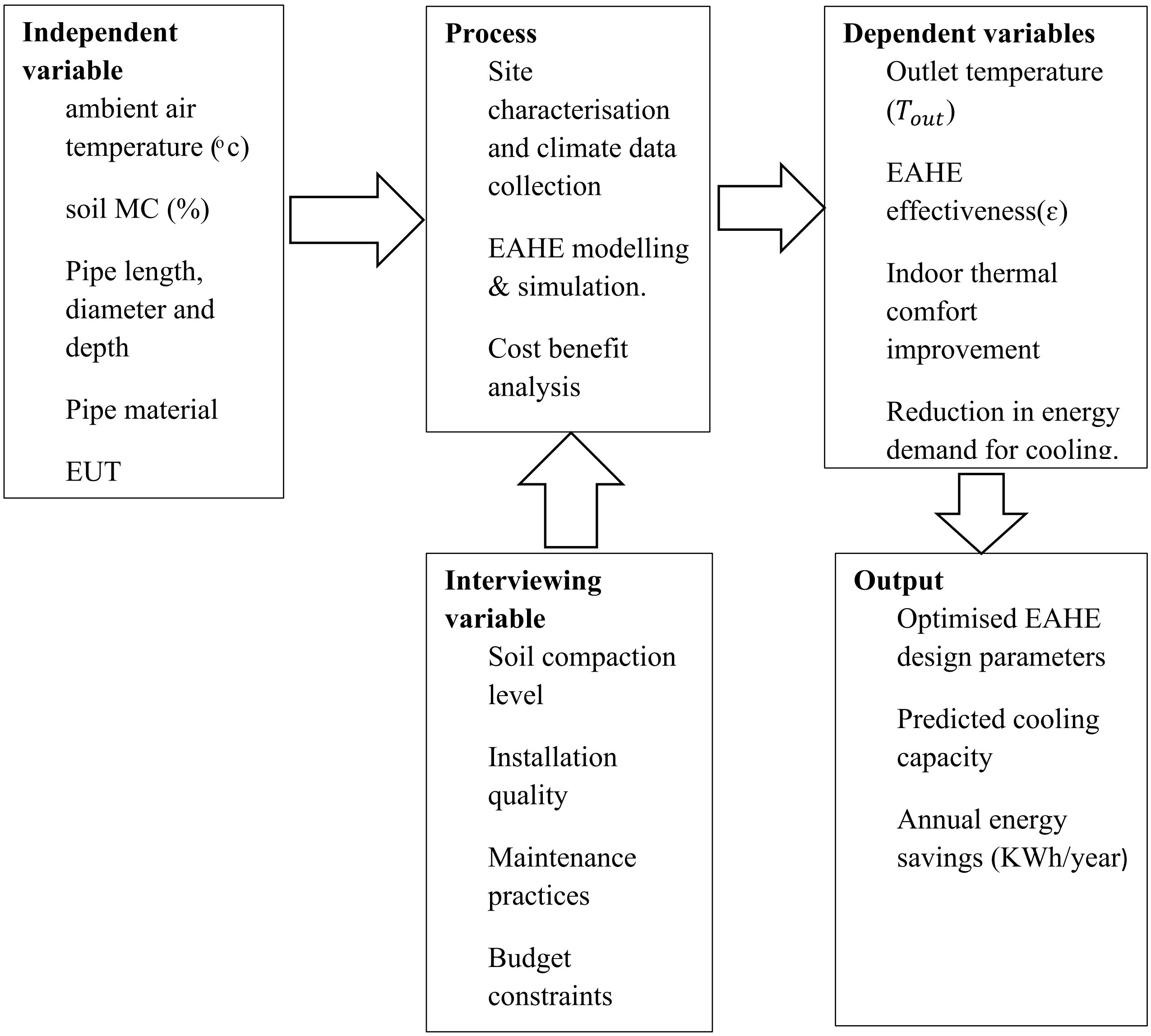
1.6 RESEARCH QUESTIONS.

What are the design parameters for an EATHE in the Ugandan climate based on field obtained soil characteristics and air data?

What are the design parameters for thermal performance and energy efficiency of the earth tube heat exchangers in varying climatic and soil conditions?

How can the structural and mechanical components of EATHE be optimized to enhance thermal performance, durability and ease of the installation while minimizing material costs and environmental impacts?

1.7 CONCEPTUAL FRAMEWORK.



1.8 ASSUMPTIONS.

The following assumptions were made in order to simplify the development of the one-dimensional model of the EAHE system:

a) The surface temperature of the ground is defined as equal to the ambient air temperature, which equals the inlet air temperature.
b) EUT can be approximated to the annual average temperature of the location
c) The polyvinyl chloride (PVC) pipe used in the EAHE is of uniform cross-section.
d) The thickness of the pipe used in the EAHE is very small; hence, thermal resistance of pipe material is negligible and the temperature on the surface of the pipe is uniform in the axial direction (Bisoniya et al., 2014).

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

An Earth-Air Heat Exchanger (EAHE) is a type of heat exchanger that uses the relatively constant temperature of the soil to preheat or precool air before it enters a building (Bady & Ouzzane, 2024; Peñaloza Peña et al., 2021). The EAHE system consists of a network of underground pipes buried at a depth where the soil temperature remains relatively constant throughout the year. For cooling during the summer, the ambient hot air is drawn into the underground pipes, and the soil cools the air before being circulated into the building. It can be considered an excellent solution for hot climate regions to decrease the electric consumption of traditional air conditioning systems by lowering the temperature difference between the ambient and the setpoint (Bady & Ouzzane, 2024).

The fundamental principle is straight forward and states that the temperature of the earth at a depth of 1.5 to 2 m remains fairly constant throughout the year, a temperature known as the Earth's Undisturbed Temperature (EUT). The EUT is higher than the ambient air temperature in winter and lower in summer. EAHE promotes the use of renewable energy and helps minimize hazardous effects such as global warming and ozone layer depletion.

2.2 Design Methodologies for EAHE Systems

Designing an Earth-Air Heat Exchanger that performs reliably requires a methodology that integrates climatic data, soil properties, geometric parameters, and operational conditions. Over the past two decades, researchers have proposed various approaches ranging from analytical equations to complex numerical simulations. (Chiesa, 2019) introduced a design methodology that incorporates local bioclimatic potential into early design phases by defining boundary conditions within standard bioclimatic chart instruments. The study analysed three representative Italian locations and demonstrated that EAHE potential is highly site-specific, meaning that generalised design rules are often inadequate.

Recognising the need for simplified early-stage tools, (Muehleisen, 2012) developed a set of simplified analysis and design equations suitable for spreadsheet implementation. This approach allows designers to estimate outlet air temperature without recourse to computationally intensive CFD simulations. Similarly, (Chiesa, 2018) proposed a method that estimates outlet air temperature using local meteorological data, soil typology, and early-design choices, which was validated against long-term experimental data. The study also introduced three Key Performance Indicators (KPIs) to assess EAHE potential during the building conception phase: activation hours based on psychrometric charts, expected sensible heat exchange, and a virtual coefficient of performance accounting for pressure drops (Chiesa, 2018, pp. 13-15).

(Duarte et al. 2025, p. 2) presented a graph-based method for large-diameter EAHE design, supported by one year of post-occupancy monitoring data. Their study demonstrated that a large-diameter EAHE could achieve a cooling capacity of 28 kW (330 kWh/day) with only 50 kWh/day of fan electricity consumption. However, the authors acknowledged that even with such tools, EAHE design lacks the streamlined, well-established rules that characterize conventional HVAC system design.

The CanmetENERGY (2021) design guide remains one of the most comprehensive resources, offering fundamental design principles and a concept design tool for Canadian climates. The guide systematically addresses application, site conditions, tube diameter, depth, length, materials, airflow, and construction costs. Despite this, the guide explicitly states that its tool is meant for early-design assessment and that detailed modelling requires more sophisticated approaches.

A recurring theme in the literature is the absence of standardised design procedures for EAHE systems. Conventional Heating, Ventilation, and Air Conditioning (HVAC) systems have become famous because standard calculation methods and installation guidelines exist, backed by trained manpower. In contrast, EAHE systems, being in their early stages, lack such standards, installation guidelines, and consequently have lower commercial adoption (Ronge & Ubale, 2020). Their design of an EAHE for a classroom in Nagpur, India, relied on the NTU method, with airflow rates referenced from ASHRAE ventilation standards - a hybrid approach that illustrates the current need to cobble together methods from different sources rather than following a unified EAHE code.

The issue of standardisation extends beyond design calculations to encompass structural design as well. (Zhang et al., 2023, p. 2) noted that EAHEs lack structural design methods for application in greenhouses. Their proposed structural design method which integrates greenhouse heat balance modelling with the NTU approach represents an attempt to fill this gap, but it remains application-specific rather than providing a general standard applicable across building types.

2.3 Modelling Techniques and their Limitations

Physical and hybrid modelling techniques for EAHE have been extensively reviewed. Researchers have employed three main categories of models: analytical, numerical (CFD), and empirical. Each has distinct advantages and limitations. Analytical models (such as the ε-NTU method) are computationally efficient but assume constant wall temperature and steady-state conditions, failing to capture transient soil temperature variations or three-dimensional effects. Numerical models provide greater accuracy but require high computational resources and careful validation. Hybrid models attempt to combine the strengths of both approaches (Muehleisen, 2012, p. 2). The selection of an appropriate EAHE modelling technique depends strongly on climate, desired performance outcomes, and the specific limitations of each technique. Reviews have identified that despite significant progress, challenges remain in accurately modelling the coupled heat and mass transfer in humid tropical conditions, where condensation within the pipe introduces additional complexity not captured by standard dry-air models.

The earth air Heat exchanger is categorised into two:

1. ***Open loop Earth-Air heat exchanger***

In an open-loop ambient outdoor air drawn is routed through buried tubes before being delivered to the conditioned space. As it travels through these tubes, the supply air exchanges heat with the surrounding soil, absorbing warmth in winter or releasing it in summer to achieve partial preheating - precooling earth -to -air heat exchanger is integrated solely into the supply air pathway, with no involvement of building return or exhaust air (Mostafaeipour et al., 2021).

2. ***Closed loop Earth-Air heat exchanger***

In a closed-loop earth tube system, conditioned air from a building is recirculated through a network of pipes buried in the ground, allowing excess building heat to be transferred directly to the earth and thereby cooling the interior space. This same principle applies in reverse during colder months, with the earth serving as a heat source (Mostafaeipour et al., 2021).

Earth tube types rely on the ground as heat source to facilitate the exchange of thermal energy between a warmer medium and cooler one. The efficiency of this heat transfer is determined by the fundamental principles governing conduction and convection in the air, soil, and the earth tube itself, as well as by the specific requirements of the system's intended application.

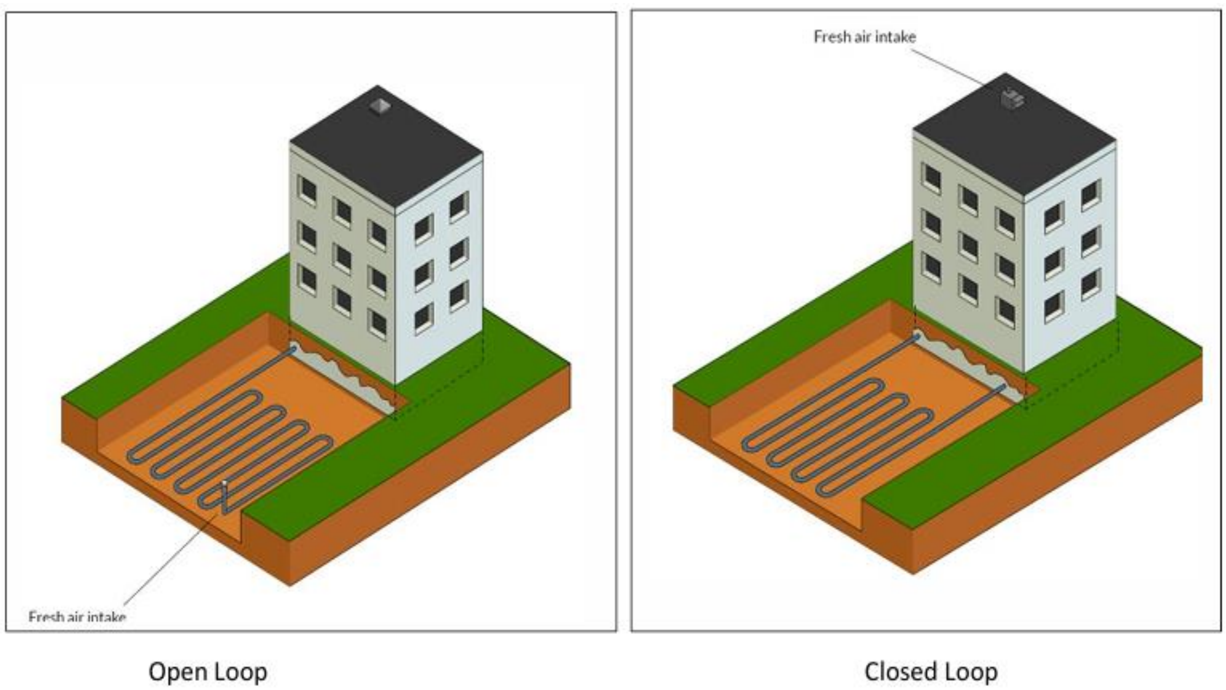


Figure 1: Shows the two types of earth to Air heat exchangers.

Source: (Resources Canada, 2021.)

2.4 Design Considerations

The following are the basic design considerations when designing earth to air thermal exchangers.

Application (intended use), Site conditions (location, soils), Earth tube diameter, depth, and length, Earth tube materials, Airflow and fan sizing, Operation and controls Earth tube layout (single or multiple tubes, spacing, spiral design) and Capital costs.

2.5 Case studies

The first certified Passivhaus in North America – the Biohaus Environmental Learning Center in Bemidji, Minnesota – uses an earth to air thermal exchanger (EATEX) to meet its entire summer cooling load, and in the winter, to preheat air from -29°C to -4°C (George, 2010).

In Colombia's tropical climate, an EAHE system designed for a 169m² laboratory delivered air at comfortable temperatures by utilizing ground temperatures of 22.3°C (Peñaloza Peña et al., 2021).

In Pakistan's hot climate of Nawabshah, a geothermal cooling system achieved indoor temperature reductions of up to 6°C to 11°C from peak summer conditions while maintaining thermal comfort during winter (Valasai et al., 2024)

2.6 Research Gaps.

Despite the substantial body of research on EAHE systems, several critical gaps remain unresolved. These gaps are not addressed by the present project and therefore remain as opportunities for future investigation.

1. Absence of a unified design standard or code for early-stage building design.

The most prominent gap identified in the literature is the lack of an integrated design standard or code that architects and engineers can apply during the early design stage of buildings. (Ronge and Ubale, 2020) explicitly state that EAHE systems lack the standard calculation methods and installation guidelines that exist for conventional HVAC systems. (Duarte et al. 2025) reiterate this point, noting that EAHE design lacks straightforward and well-established rules, which undermines designer confidence and limits commercial adoption.

2. Insufficient long-term validation of EAHE performance under varying operational conditions

While the present project used steady-state CFD simulation to validate the design, long-term performance under seasonal variations, partial loading, and real occupancy patterns remains unverified. Chiesa (2018) validated his simplified method against long-term experimental data, but such validation is rare. Duarte et al. (2025) provided one year of post-occupancy monitoring, but that study focused on a single large-diameter installation. The absence of long-term validation data across different climates and building types remains a significant gap. The present project, limited to steady-state simulation, does not address this gap.

2.7 Conclusion

Earth air heat exchangers are a proven, sustainable technology that leverages the stable temperature of the ground to preheat or precool ventilation air, significantly reducing building energy consumption for heating and cooling. They offer notable benefits including significant energy and cost savings, improved indoor comfort and air quality. Their versatility and compatibility with renewable energy systems make them a promising solution for sustainable building climate control.

CHAPTER 3 METHODOLOGY

BASELINE DATA COLLECTION AND SITE CHARACTERIZATION

3.1 SOIL AND MATERIAL TESTING IN THE LABORATORY.

Soil and material testing was undertaken to characterize the subsurface conditions at Makerere Tank Hill and to obtain engineering parameters required for the design and assessment of the EAHE system. The investigation followed a structured approach in which sampling and laboratory testing were conducted in accordance with established standards. The sampling phase was guided by (BS 5930:1999), which provides procedures for ground investigation, sample collection, and selection of testing programmes. Laboratory testing was subsequently carried out in accordance with (BS 1377-1:1990) and (BS 1377-2:199) which specifies methods for classification and determination of soil properties.

In the context of this study, these objectives were directly linked to evaluating the thermal and physical suitability of the soil for EAHE application. A detailed understanding of the ground conditions was first established, ensuring that the collected samples were representative of in-situ conditions. This is critical, as emphasized in BS 5930, since the reliability of laboratory results depends on sample quality and its ability to reflect actual field behaviour.

The selection of the laboratory testing programme was therefore based on several key considerations outlined. These included the nature of the soil (identified as predominantly fine-grained), the quality and representativeness of the samples obtained from the site, and the intended use of the results in engineering analysis. Additionally, the requirements of the EAHE system-particularly the need for stable thermal performance and minimal deformation-were considered in determining the appropriate tests. The testing programme was designed to provide parameters relevant to both short-term and long-term behaviour of the soil, especially in relation to heat transfer, moisture retention, and structural stability around the buried pipes.

3.1.1 Particle size distribution.

This determines the soil classification (fine-grained vs. coarse-grained). Fine-grained soils, especially silts and clays, influence thermal conductivity, moisture retention, and compaction characteristics. In an EAHE, thermal conductivity directly affects the rate of heat exchange between the pipe and the surrounding ground, while compaction affects the soil's thermal contact with the pipe. The USCS classification (fine-grained) was used to guide the selection of thermal property correlations *(EATEX: Design Principles and Concept Design Tool, 2021)*

Sampling

Recommended procedures for obtaining and preparation of disturbed samples received from the field, and their allocation for subsequent tests samples from the ground in-situ are described in BS 5930, to which reference was made. A sample of about 5kg was collected for all the tests.

Tools and equipment used.

Test sieves
A balance readable to 1.0 g and another to 0.1 g.
Riffle box
A drying oven capable of maintaining a temperature of 105 °C to 110 °C.
Sieve brushes, and a wire brush or similar stiff brush
Scoops
Corrosion resistant brushes

Testing

Two sieving procedures are available. Wet sieving is the standard method for soils that are essentially cohesionless, while dry sieving is appropriate only for soils with negligible silt and clay content. For the classification testing in this study, wet sieving was selected because the soil sample exhibited cohesionless characteristics.

Procedures.

The entire dried sample was first sieved through a 20 mm with the help of a brush to remove all individual particles that were clean of any finer material and weighed the dried test sample to 0.1% of its total mass (m_1 = 5kg)

The air-dried material that passed through the 20 mm test sieve was weighed, with the measurement recorded to an accuracy of 0.1% of its total mass, denoted as m_1

The portion passing the 20 mm sieve was riffled to obtain a representative fraction of convenient mass. In accordance with BS 1377-2:1990, clause 9.2.4.3 (p. 34), a mass of approximately 2 kg is recommended for this stage. For the tested sample, the initial dry mass was 1487.0 g, which falls within an acceptable range, and the fraction was weighed to an accuracy of 0.1% of its total mass, recorded as m_1

The sample was then soaked for about 24 hours and later washed through the 75 µm sieve and about 943.8 g was washed away according to our results shown in table 1 below.

The remaining sample was measured and oven dried at 105 °C – 110 °C temperature re-weighed the after cooling to 0.1% of its total mass (m_4).

The dried fractions were then sieved using the dry sieving procedure specified in BS 1377-2:1990, clause 9.3.4 (p. 36), through the appropriate sieves down to the 0.15 mm test sieve. The mass retained on each sieve was weighed to an accuracy of 0.1% of the total dry fraction, in accordance with the standard.

We calculated the proportion by mass of material retained on each of the coarse series of sieves as a percentage of m1 and percent finer for each sieve using from which we calculated the cumulative percentages by mass of the sample passing each of the sieves from the general relationship: $\frac{\sum M - Cumulaive\ mass}{\sum M} x100\%$.

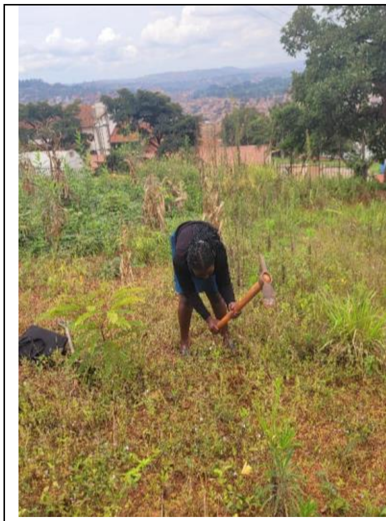


Figure 2. During sample collection at tank hill

Figure 3. During sieve analysis

Figure 4. Sample measurements

3.1.2 Natural Moisture content

Moisture content significantly affects the thermal conductivity and diffusivity of soil. Higher moisture generally improves heat transfer but also influences the potential for condensation within the pipe and long-term stability of the backfill. The measured NMC of approximately 19.7% was used to estimate the soil's thermal properties and to assess the likelihood of moisture-related issues such as swelling or shrinkage around the pipes.

This test is carried out to determine the amount of water that is present in the soil. The Moisture content is expressed as a percentage of the mass of dry soil.

The main principle of the Moisture Content Test is the assumption that the Pore spaces of a soil is filled with water within the soil grains. This water is removable by oven drying the soil in the oven at a temperature of about 110 degrees Celsius.

Procedure.

A representative sample was obtained by quartering the soil sample until the required amount was obtained.

The container in which the soil sample was to be placed was first weighed and weight recorded as (M_1)

The wet soil sample was placed into the container and their weight obtained and recorded as (M_2)

The soil in the container was then placed in the oven at 105 degrees Celsius for 24 hours.

After 24 hours the sample was removed, measured and recorded as (M_3). The data was recorded and tabulated as shown in the table below.

3.1.3 Liquid Limit (LL) and Plasticity Index (PI)

These Atterberg limits classify the soil's plasticity and help identify the presence of expansive clays. The measured LL of 52% and the resulting classification (heavy clay on the plasticity chart) indicate a soil with moderate to high plasticity. Such soils may undergo volume changes with moisture variation, which could affect the integrity of the pipe-soil interface. Additionally, the plasticity index influences the choice of backfill compaction specifications to maintain good thermal contact over time.

Liquid Limit determination using cone penetration method.

A test sample of about 500g, which passed through the 425 microns was obtained from the soil sample for both plastic and liquid limit.

The soil was transferred to the glass plate and distilled water was added to it and mixed thoroughly with two palette knives until the mass became a thick homogeneous paste.

The paste was then placed in an airtight container for at least 24 hours to enable water to permeate throughout the soil.

The soil paste was then taken and placed on the glass plate and mixed for at least 10 minutes using the 2 palette knives.

A portion of the paste was then pushed into the cup with a palette knife, making sure air was not trapped by gently tapping the cup on a hard surface.

Excess paste was then struck off the surface with the straight edge to give a smooth level surface.

The cup was then placed under the penetration cone while it was still locked in the raised position, then it was lowered so that it just touches the surface of the soil.

The dial gauge was also then lowered to be in contact with the cone shaft and the reading was taken to the nearest 0.1mm.

The cone was then released for a period of about 5 seconds. After locking the cone in position, the dial gauge was then lowered to contact the cone shaft and the reading of the dial gauge was then recorded to the nearest 0. 1mm.The difference between the readings were then taken as the cone penetration.

The cone was then lifted out and cleaned carefully. The procedure was repeated by adding a little more soil to the cup and the reading taken as described as above.

A small sample was then removed from the area of penetration and moisture content was determined for it.

The penetration test was repeated for 4 times using the same test sample with different

water contents as tabulated below in table 3 and results plotted as shown in figure 3.

Figure 5. During mixing soil with distilled water

Figure 6. During cone penetration

3.2 AMBIENT AIR AND EARTH'S UNDISTURBED TEMPERATURE

Monthly temperature data for Kampala were obtained from the Uganda National Meteorology Authority, Luzira Centre, covering the period 2020–2025. The dataset includes daily maximum and minimum temperatures, from which monthly mean air temperatures were derived (Table 1).

These values define the ambient conditions that the EAHE system must respond to, and they serve as the inlet temperature for the thermal model.

3.2.1 Earth's Undisturbed Temperature (EUT) from Analytical Model

The temperature of the soil at different depths was calculated using the transient heat conduction model given by (Bisoniya, 2015), which is based on the work of Labs (1989):

$$T_{z,t} = T_m - A_s exp\left[-z\left(\frac{\pi}{365\alpha_s}\right)^{\frac{1}{2}}\right] \cos\left\{\frac{2\pi}{365}\left[t - t_o - \frac{z}{2}\left(\frac{365}{\pi\alpha_s}\right)^{\frac{1}{2}}\right]\right\}$$

Equation 1. Transient model

where:

$T_{z,t}$– ground temperature at depth z (m) and time t (days);

T_m – mean annual surface temperature (°C); it feeds into the analytical model for ground temperature variation with depth and time, helping you size the EAHE system accurately.

A_s – amplitude of surface temperature variation (°C) quantifies how much the soil surface temperature fluctuates over time (e.g., between seasons).

α_s – thermal diffusivity of the soil (m²/day);

t – time elapsed from the beginning of the calendar year (days); helps track seasonal temperature changes in the soil, which in turn affects how efficiently the EAHE can preheat or precool air for passive building conditioning.

t_0 – phase constant (days), accounting for the lag between solar radiation and surface temperature. helps track seasonal temperature changes in the soil, which in turn affects how efficiently the EAHE can preheat or precool air for passive building conditioning.

This equation describes how the seasonal temperature wave is damped and delayed as it propagates downward. The key parameter controlling the attenuation is the thermal diffusivity, which depends on soil type, moisture content, and density. This was determined, approximated according to (EATEX: Design Principles and Concept Design Tool, 2021) as indicated in *table 1* page 8.

CHAPTER 4 RESULTS, ANALYSIS AND DICUSSION.

4.1 PARTICLE SIZE DISTRIBUTION RESULTS.

Results as calculated in MS excel are shown below in table 1 and figure 1.

Table 1. Shows particle size distribution data and results.

	PARTICLE SIZE DISTRIBUTION					
Project	DESIGN OF EARTH-AIR HEAT EXCHANGER					
Material source	MAKERERE TANK HILL			**Sampling date**	04/03/2026	
Test method	BS 812:PART 103.1:2022			**Testing date**	05-06/03/2026	
Sample description	GREYISH FINE SOILS			**Sample ref**	PSD-FYP, 2026	
Initial weight before washing	1487.0		g	**Moisture Content**	0	%
Dry weight after washing	543.2		g	**Initial Dry Weight**	1487.0	g
Silt content	63.5		%			
BS.Sieve size (mm)	Mass retained (g)	percentage retained (%)	Cumulative mass retained (g)	Percent finer (%)	specified limits (% passing) as per BS 882:1999 Table 4	
					Lower limit	Upper limit
20	15.4	2.8	15.4	97.2		
14	41.4	7.7	56.8	89.5		
10	98.1	18.1	154.9	71.3	100	100
6.3	107.8	19.9	262.7	51.4		
5	38	7.0	300.7	44.4	89	100
3.35	51.2	9.5	351.9	34.9	60	100
1.18	44.9	8.3	396.8	26.6	30	100
0.6	39.3	7.3	436.1	19.3	15	100
0.425	26.7	4.9	462.8	14.4		
0.3	26.9	5.0	489.7	9.4	5	70
0.212	20.8	3.8	510.5	5.6		
0.15	16.5	3.1	527	2.5	0	15
Pan	13.5	2.5	540.5	0.0		
	540.5					
Mass finer than 0.075 mm sieve		943.8 (g)				

Results & interpretation.

The results of the sieve analysis are summarised in *Table 1*. The total dry mass after washing was 543.2 g, and the mass of material passing the 75 µm (No. 200) sieve was 943.8 g, representing approximately 63.5% of the initial dry mass. According to the Unified Soil Classification System (USCS), a soil is considered **fine-graine** when 50% or more passes the No. 200 sieve. Therefore, the tested soil is classified as fine-grained. The cumulative percentages passing each sieve were plotted on a semi-logarithmic chart *(Figure 1)*

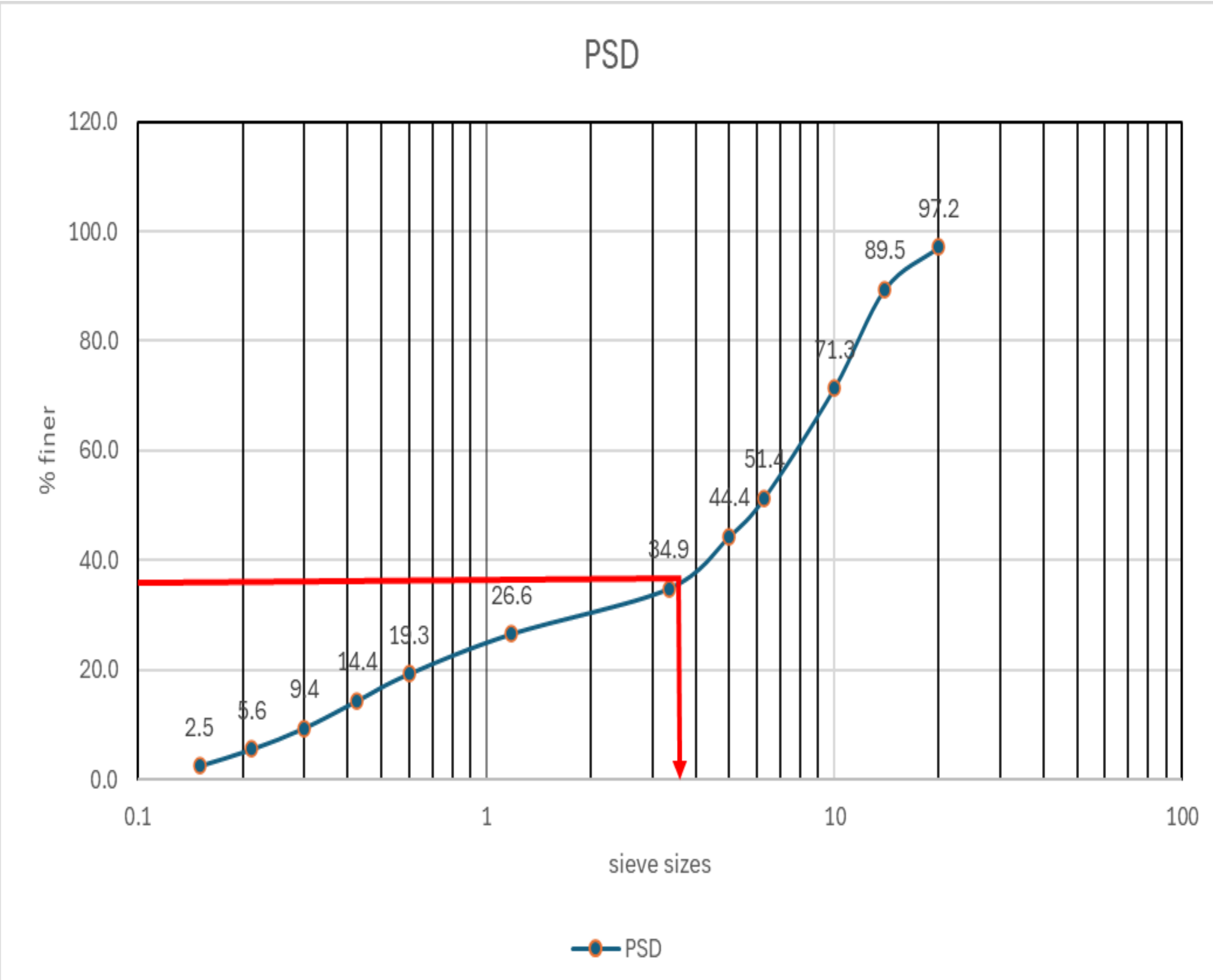


Figure 7. Shows Particle size Distribution char

4.2 MOISTURE CONTENT RESULTS

The average natural moisture content of the soil was found to be **19.7 %**. This value is typical for a heavy clay in a well-drained tropical setting. The moisture content was subsequently used, together with the soil classification (heavy clay, from the Atterberg limits), to select an appropriate thermal diffusivity value from reference tables (EATEX Design Principles, 2021, Table 2, p. 9) and to input into the Bisoniya transient heat conduction model for the prediction of earth's undisturbed temperature.

Table 2. Showing natural moisture content

NATURAL MOISTURE CONTENT		
Project	Design of the Earth to air heat exchanger.	
Test method	SB 1377 2022:PART 2	
Sample reference	2024-0F-ET240	
Location	Makerere Tank hill	
sampling date	04/03/2026	
testing Date	05-06/03/2026	
Test No.	1	
Sample identification	Fine sample	
Container ID	MN 78	A7
	Test 1 (g)	Test 2 (g)
Mass of container + sample (M_2)	275.826	250.752
Mass of container + sample after oven drying (M_3)	243.8	225.1
Mass of container (M_1)	87.165	89.312
Mass of dry soil ($M_3 - M_1$)	156.635	135.788
Mass of water ($M_2 - M_3$)	32.026	25.652
Natural Moisture (%)	20.4	18.9
Average MC (%)	19.67	

$$\text{Moisture content (MC)} = \frac{M_2 - M_3}{M_3 - M_1} * 100$$

$$\text{Test 1} \quad \text{MC} = \frac{32.026}{156.635} * 100$$

$$= 20.45\%$$

$$\text{Test 2} \quad \text{MC} = \frac{25.652}{135.788} * 100$$

$$= 18.89\%$$

$$\text{Average moisture content} = \frac{20.45 + 18.89}{2}$$

$$\text{Average moisture content} = \underline{\underline{19.67\%}}$$

NB:

If clay particles exist, they exert a considerable influence on the properties of the soil, an influence out of all proportion to their percentage by mass in the soil. Plasticity is used to distinguish between clay and silt. Plasticity describes the ability of a soil to deform without cracking or crumbling

4.3 LIQUID LIMIT AND PLASTICITY INDEX RESULTS.

Table 3. Shows Cone penetration experiment results

LIQUID LIMIT				
	Dial gauge reading			
Points	Dia Guage reading (mm)		Penetration (mm)	MC (%)
1	1st	18.4	18.3	44.6
	2nd	18.3		
2	1st	18.9	18.9	45.0
	2nd	18.9		
3	1st	19.7	19.8	48.4
	2nd	19.75		
4	1st	20.1	20.2	56.7
	2nd	20.2		

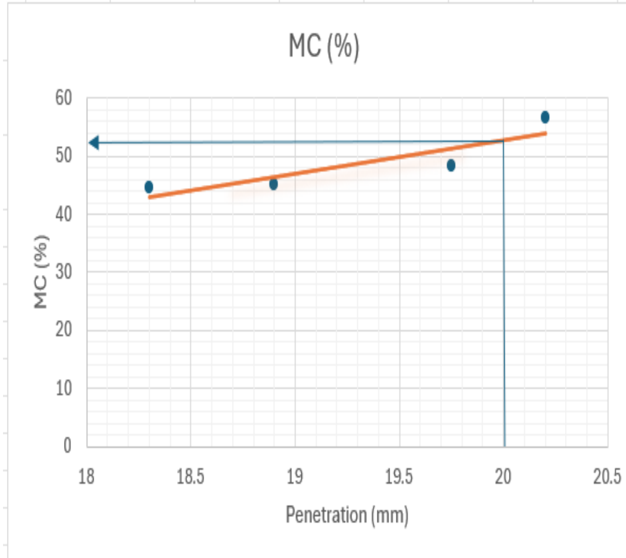


Figure 8. Shows liquid limit determination.

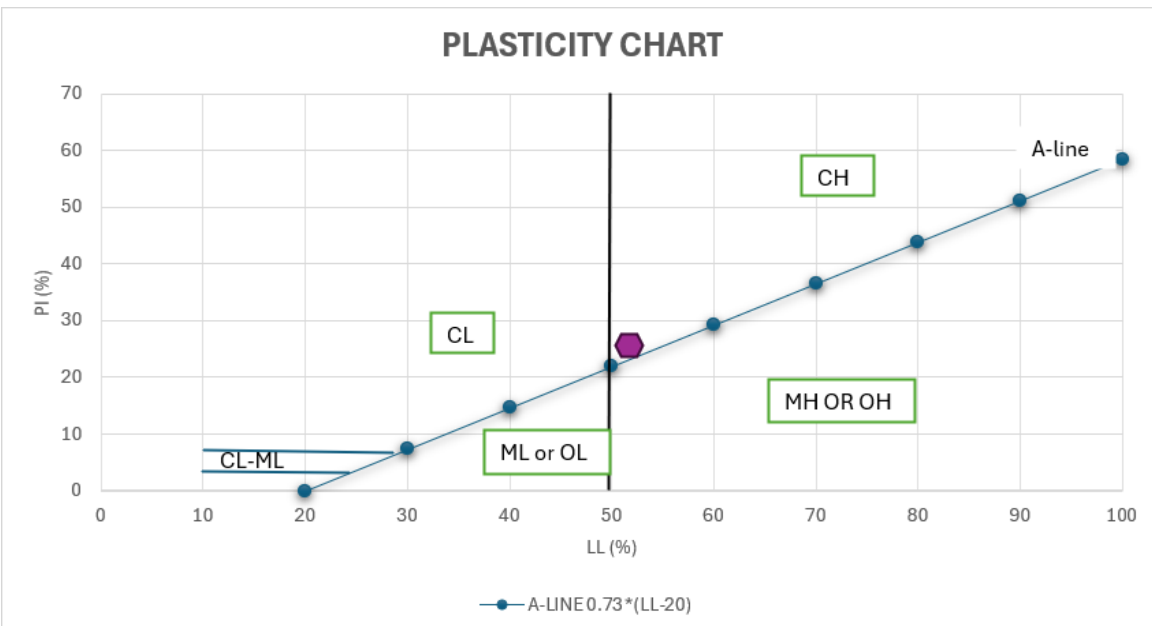


Figure 9. Shows plasticity chart

Indicates the soil's LL & PI when plotted falls in the upper part of the A-line which indicates a heavy clay soil.

The results show a liquid limit of 52 % and a plasticity index that, when plotted on the plasticity chart (Figure 9), places the soil in the region above the A-line, classifying it as **heavy clay**. This classification confirms that the soil is fine-grained and highly plastic, which has direct implications for the EAHE design: backfill compaction must be carefully controlled to maintain stable thermal contact, and drainage measures (such as the 1.2 % pipe slope) are required to minimise moisture-induced volume changes.

4.4 AMBIENT AIR AND EARTH'S UNDISTURBED TEMPERATURE

Determination of Soil Thermal Diffusivity

From the classification tests (PSD, moisture content, Atterberg limits), the soil was identified as heavy clay with a natural moisture content of 19.7% and a liquid limit of 52%, placing it above the A-line on the plasticity chart *(Figure 3*). This soil type and moisture condition were used to estimate the thermal diffusivity from reference data. Using this value together with the calculated mean air temperature surface amplitudes the Bisoniya equation was applied to generate the soil temperature profiles at depths of 0.05 m, 0.2 m, 0.5 m, 1 m, 1.5 m, 2 m and 5 m.

Table 1 presents the resulting monthly soil temperatures at these depths for Kampala (based on 2025 data which was selected since it was the year that experienced the highest temperatures in the past 5 year whose amplitudes have also been increasing with time in years). The full set of calculations (using the formula above) is included in the attached spreadsheet;

Interpretation for EAHE Design

The results in *Table 1* of the excel sheet (*temperature data*) and the graph in *Figure 7* clearly show that below a depth of about 1.5 m, seasonal temperature fluctuations are almost completely damped.

This stability is the physical basis for the EAHE: the underground soil acts as a massive thermal reservoir. During hot periods, warm ventilation air passing through the buried pipes loses heat to the cooler ground, and during cool periods, the air gains heat from the ground. Thus, the EUT serves as the wall temperature in the heat transfer model (Bisoniya, 2015, p.3), effectively decoupling the pre-conditioned air from the large swings of ambient temperature.

The graph illustrates:

The surface (0.05 m) closely follows the air temperature. At 0.5 m and 1.5 m, the amplitude is reduced and the peak is delayed and the variation is less than ±0.5 °C. At 5 m, the line is almost flat, confirming that the soil has reached the undisturbed state.

This constant temperature is then used as the boundary condition in the ε-NTU method to compute the outlet air temperature and the cooling/heating energy provided by the EAHE, as described in Chapter 4.

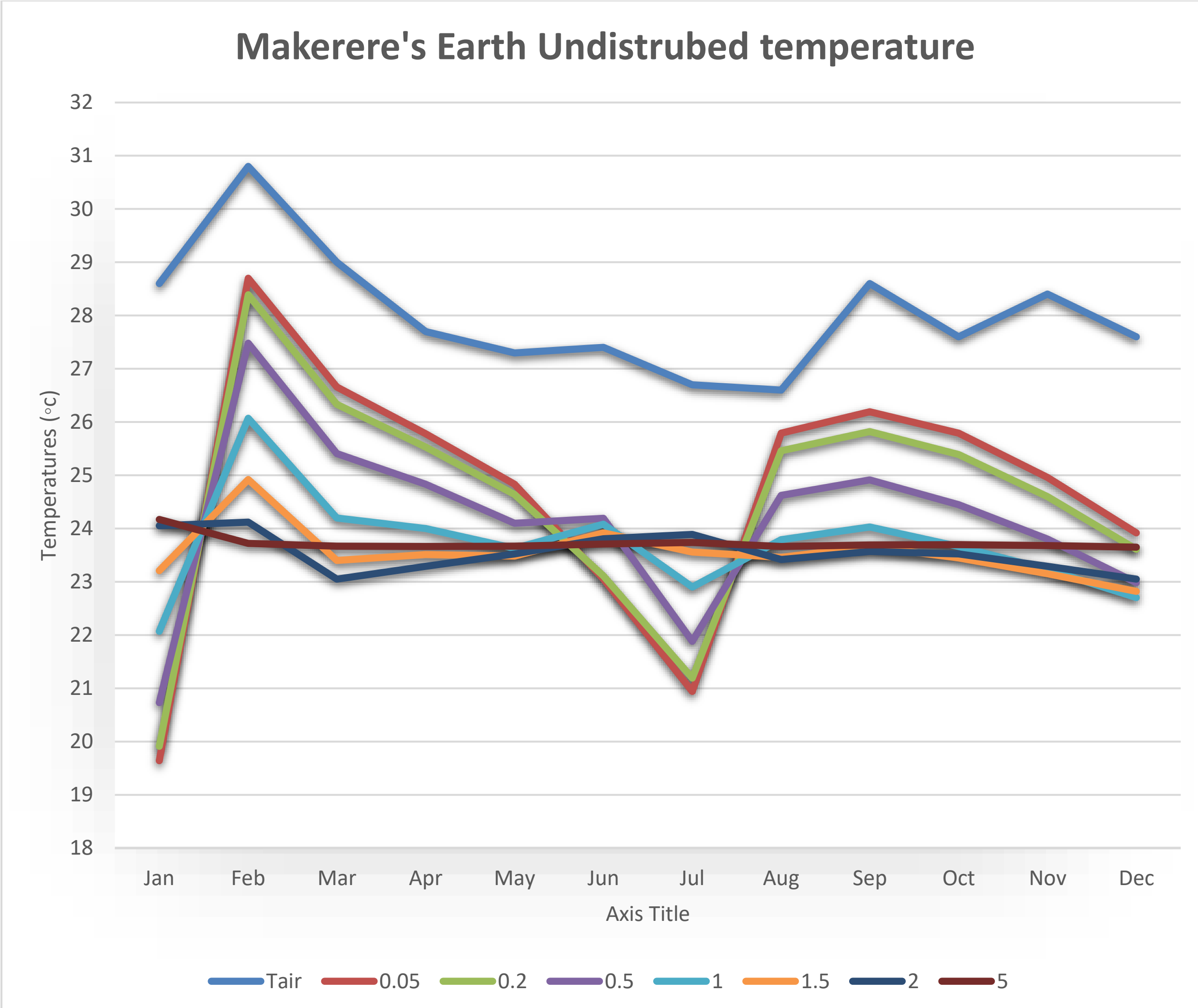


Figure 10. Shows EUT at different depths.

4.5 DESIGN PARAMETER DETERMINATION (Material Types and Geometry).

The second objective of this study was to establish the key design parameters of the earth-air heat exchanger (EAHE), namely the pipe material, diameter, total length, and burial depth, using the soil and climatic data obtained in Phase 1. These parameters directly control the thermal performance, constructability, and economic viability of the system.

The approach follows a sequential analytical procedure grounded in established standards and validated models.

i. The pipe material is selected based on a trade-off between thermal conductivity, durability against underground corrosion, local availability, and cost.
ii. The diameter is chosen to balance air velocity and pressure drop, while ensuring that the required volumetric flow rate for ventilation is achieved.
iii. The earth's undisturbed temperature (EUT), previously calculated using the transient model of (Bisoniya, 2015), is used as the constant wall temperature boundary condition. The convective heat transfer coefficient is evaluated via the Nusselt number correlation for smooth pipes (Gnielinski equation, as cited in (Bisoniya, 2015).

iv. Finally, the ε-NTU method is applied to determine the pipe length required to meet a target cooling effectiveness.

All calculations follow the methodologies and the analytical framework described in (EATEX): Design Principles and Concept Design Tool, 2021) and (Bisoniya, 2015). Thus, the design parameters are not arbitrarily chosen but are derived directly from the site-specific data (soil grading, moisture content, thermal diffusivity, and local climate) and from engineering correlations validated for EAHE applications. The outcomes of this objective are a complete set of geometric and material specifications ready for subsequent performance simulation and cost-benefit analysis.

4.5.1 Pipe material

The selection of appropriate pipe material is a critical design decision that directly influences the long-term performance, durability, and indoor air quality of an EAHE system. An unsuitable material can lead to corrosion, reduced thermal efficiency, and biological contamination of the supply air. Therefore, materials with adequate thermal conductivity, high resistance to underground corrosion, and proven durability are required. Based on a review of available literature and local market conditions, uPVC (unplasticised polyvinyl chloride) "*Shown in figure 8 & fig 13 in appendix*" was selected for this project, with the additional specification of a smooth anti-static internal layer incorporating a silver agent to inhibit the growth of fungi, mould, and bacteria where it is a common concern in ventilation systems where moisture and organic matter may accumulate.

In addition to material selection, proper drainage of condensate is essential to prevent water accumulation, which can promote mould growth, cause unpleasant odours, and degrade air quality. In this design, a slope of 1.2% has been adopted, which remains adequate for the expected moisture loads and was chosen to accommodate site-specific topographical constraints.

To further safeguard air quality, an intake chamber equipped with a mesh filter is proposed at the air inlet. This pre-filter removes coarse dust, debris, and insects before the air enters the buried pipe, thereby reducing the risk of particulate build-up and biological growth inside the system.

Regarding air movement, the EAHE is intended to operate without a mechanical fan, relying instead on natural wind pressure. Wind data obtained from the Uganda National Meteorological Authority (UNMA) in Luzira indicate that the prevailing wind direction in Kampala is predominantly from the south to south-east. Consequently, the air intake should be oriented to face this direction to maximise natural airflow.

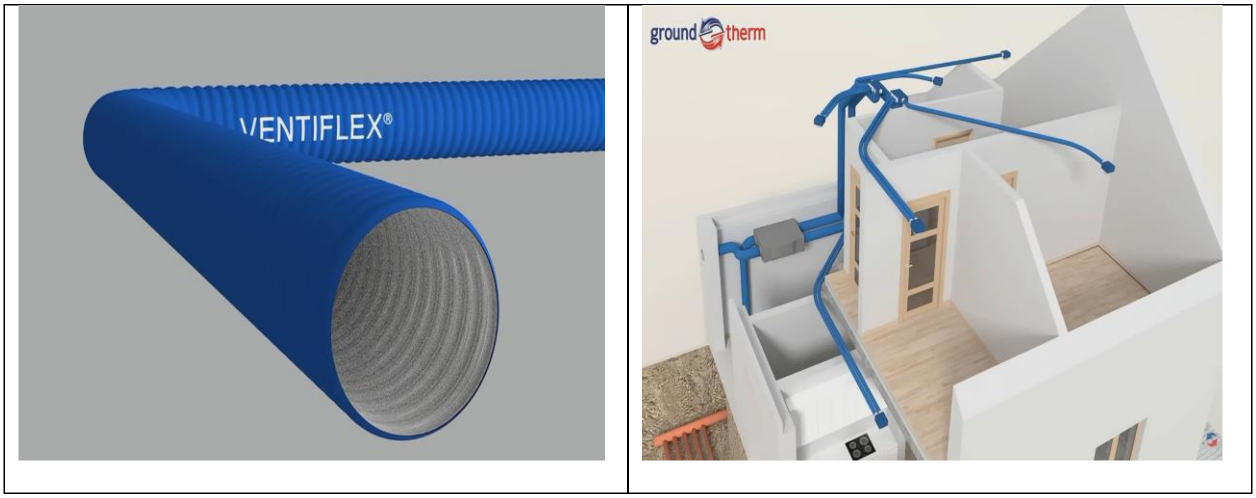


Figure 11. Shows ventiflex pipe material with inner silver coating selected.

Source: https://youtu.be/VevJ4ShSsvE?si=f7xnndDSEzWbsTkd

4.5.2 Burial depth

The burial depth of the EAHE pipe determines the stability of the surrounding soil temperature and thus the effectiveness of heat exchange. From the soil temperature profiles calculated in Phase 1 (Figure 7), it was observed that at depths below approximately 1.5 m, seasonal temperature fluctuations are significantly damped, and at 5 m the temperature is virtually constant at 23.7 °C (the Earth's Undisturbed Temperature, EUT). However, deeper excavation increases construction cost and may encounter groundwater or bedrock.

Based on a balance between thermal performance and practical constructability, a burial depth of 1.5 m from the ground surface to the pipe centreline was selected. At this depth, the annual soil temperature variation is less than ±0.5 °C, which is acceptable for our design effectiveness of 88% shown in the length determination. The depth also allows sufficient cover to protect the pipe from surface traffic loads and surface temperature swings, while keeping excavation costs moderate.

The selected depth will be used as the location where the soil thermal properties (measured at Tank Hill) are assumed to be representative, and where the constant wall temperature boundary condition (EUT = 23.7 °C) is applied in the ε-NTU model.

4.5.3 Pipe diameter

The diameter of the EAHE pipe was selected based on a balance between thermal performance and practical constructability. A parametric study by (Yu et al., 2022) investigated the effect of tube diameter on outlet air temperature for a fixed tube length (70 m) and burial depth (2 m). Their results showed that in summer, the outlet air temperature increased monotonically with increasing diameter: for diameters of 0.08 m, 0.16 m, 0.24 m, 0.32 m, 0.40 m, and 0.48 m, the corresponding outlet temperatures were 15.86 °C, 17.35 °C, 19.94 °C, 22.30 °C, 24.18 °C, and 25.65 °C, respectively as shown in *fig 9* below.

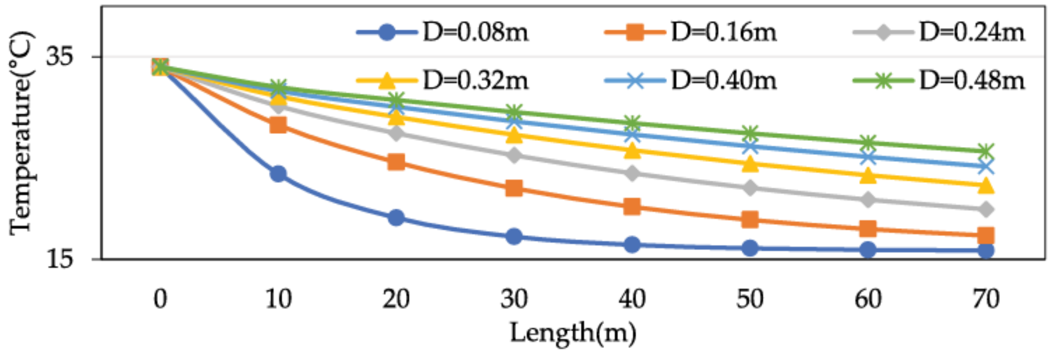


Figure 12. Shows choice of diameter explanation

Source:(Janssens & De Paepe, n.d.)

However, very small diameters (e.g., 0.08 m) also lead to higher air velocities for the same volumetric flow rate, which increases pressure drop and fan energy consumption. Moreover, diameters below 0.15 m are more susceptible to clogging by dust or debris and may not be readily available in the local market at reasonable cost. Conversely, a larger diameter reduces pressure drop but may lead to lower heat transfer efficiency if the airflow becomes laminar or poorly mixed.

The design volumetric flow rate was estimated based on typical ventilation requirements for a small-to-medium room (approximately 0.09 m³/s). To maintain turbulent flow (which enhances convective heat transfer), an air velocity of 2.9 m/s was selected, following the recommendation that velocities between 2 m/s and 4 m/s are optimal for EAHE applications (*Earth to Air Thermal Exchanger (EATEX) : Design Principles and Concept Design Tool*, 2021)

Using the continuity equation:

$$\dot{V} = A \cdot v_a = \frac{\pi D_i^2}{4} \cdot v_a$$

Solving for the inner diameter:

$$D_i = \sqrt{\frac{4\dot{V}}{\pi v_a}} = \sqrt{\frac{4 \times 0.091}{\pi \times 2.9}} \approx 0.20 \text{ m} = 200 \text{ mm}$$

A diameter of 200 mm was therefore adopted. This size is commercially available in uPVC, provides sufficient surface area for heat transfer (approximately 0.628 m² per metre length), and results in a Reynolds number of approximately 37,400 (well into the turbulent regime). The choice also aligns with the EATEX design guide, which suggests that for airflows around 0.1 m³/s, a diameter of 0.15–0.25 m is appropriate (CanmetENERGY, 2021).

Thus, the 200 mm inner diameter is carried forward into the length calculation and pressure drop analysis.

4.5.4 Pipe length

Importance of calculated parameters in determining the EAHE Tube length.

1. **Mass Flow**

The mass flow rate ($\dot{m}$) directly represents the **thermal load** that the EAHE must handle. For a given desired cooling effect (i.e., a target outlet temperature), a higher mass flow rate means more heat must be removed from the air per unit time. To achieve the same temperature drop, a larger heat transfer area (i.e., a longer pipe) is required. Conversely, if the mass flow rate is low, the air spends more time inside the pipe, allowing it to approach the soil temperature more closely, so a shorter pipe may suffice for the same effectiveness.

Thus, mass flow rate is **not an independent choice**. it is determined by the ventilation requirement of the building (how much fresh air is needed). Once $\dot{m}$ is fixed (based on occupancy or building codes), the required pipe length L can be calculated from the NTU equation. If $\dot{m}$ were omitted, the length calculation would have no connection to the actual air volume being conditioned, and the system would be either undersized (poor cooling) or oversized (wasted cost).

2. **Heat transfer coefficient**

The convective heat transfer coefficient, h quantifies how effectively heat moves from the flowing air to the inner wall of the pipe. In the NTU equation; a larger h means more heat is transferred per unit area per degree of temperature difference.

For a given NTU (which sets the effectiveness), a higher h reduces the required pipe length L while a lower h demands a longer pipe. Thus, h depends on the airflow regime (turbulent or laminar), the pipe diameter, and the thermophysical properties of air.

3. **Nusselt Number (Nu)**

The Nusselt number is a dimensionless parameter that represents the ratio of convective to conductive heat transfer across the fluid boundary layer. In the context of an EAHE, it quantifies how effectively the flowing air transfers heat to the pipe wall.

Designed by:	Kasangaki and Lucy	year	2026
References	Notes/Calculations		
Calculations for:	Preliminary Design Considerations		
Project:	Design of Earth to air heat exchanger for net-zero tropical buildings		

Pipe Length:

(Bisoniya, 2015)

calculations are as below:

we shall use NTU method.

$$\mathrm{NTU} = \frac{U_T A}{\dot{m}_a C_p} = \frac{h\pi D_i L}{\dot{m}_a C_p}$$

Where:

Symbol	Parameter	units	Description
NTU	Number of transfer Units	dimensionless	Measures the size of the heat exchanger relative to the heat flow. Higher NTU means more heat transfer.
h	Convective heat transfer coefficient	$W/m^2 \cdot K$	How effectively heat moves from the air to the pipe wall. Depends on air velocity, pipe diameter, and air properties.
$\dot{m}_a$	Mass flow rate of air	Kg/s	The mass of air flowing through the pipe per second. Affects how much heat the air can carry.
$\mathbf{C_p}$	Specific heat capacity of air	J/kg·K	The energy required to raise 1 kg of air by 1 °C. For air, $C_p \approx 1006$ J/kg·K.
$h\pi D_i L$	Internal surface area of the pipe	m^2	Where Di is pipe diameter, L is the total length of the buried pipe

YA Cengel,	❖ ***Mass flow rate,*** $\dot{m}_a$ $\dot{m}_a = \frac{\frac{\pi}{4}D^2 \rho V a}{Np}$ = m*ρ; where *m = Volumetric air flow rate.* *ρ = Density of air.* But: Vol. flow rate, m = $4\pi R_i^2$ m = $4\pi R_i^2$ m = $4\pi 0.1_i^2$ m = 0.126 m^3/s ***Density of air, ρ*** ρ = *1.2 kg/m^3* ∴ **Mass flow rate,** $\dot{m}_a$ $\dot{m}_a$= (0.126*1.2) = 0.1512 kg/s. ❖ **Heat transfer coefficient, *h*** h = $\frac{N_u K}{D}$ where D is diameter of pipe = 200mm = 0.2m.
(EATEX:Design Principles and Concept Design Tool, 2021)	K is the thermal conductivity. It is a material property that describes how easily heat flows through a substance. It is defined as the rate of heat transfer per unit thickness per degree of temperature difference K= 0.026 W/m-k Nu is Nusselt Number.

Sutherland's formula (Bisoniya,2015 EATEX; Design Principles and concept Design Tool, 2021)	Nu $=\frac{f/8(Re-1000)Pr}{1+12.7\sqrt{\left(\frac{f}{8}\right)}\ (Pr^{\frac{2}{3}}-1)}$ Where f is friction factor for smooth pipes, Re is Reynolds number and Pr is Prandtl number. Reynolds number is a dimensionless quantity that predicts whether a fluid flow is laminar or turbulent while Prandtl number is a dimensionless fluid property that relates the rate of momentum diffusion to thermal diffusion Re $=\frac{\rho VaD}{\mu}$ Va = 2.9m/s air flow velocity, μ is the dynamic viscosity calculated from $\mu = \mu_0(\frac{T}{T_0})^{3/2}(\frac{T_0+S}{T+S})$ T is the reference temperature = 303.15K $T_0$is absolute temperature=273.15K S is Sutherland's constant=111 μ_0 reference viscosity=1.716x10^{-5} $\mu=1.716x10^{-5}(\frac{303.15}{273.15})^{3/2}(\frac{273.15+111}{303.15+111})$ μ=1.861x10^{-5} Re $=\frac{1.2x2.9x0.2}{1.861x10^{-5}}$ = 37399.2 Pr $=\frac{\mu C_p}{k}$ C_p is specific heat capacity of air=1006 J/kg·K K thermal conductivity= 0.026W/m-K

	$\Pr = \frac{1.861x10^{-5}x1006}{0.026}$ $= 0.72$ Since 2300 ≤ Re < 5x10^6 and 0.5 < Pr <10^6 $f = (1.82logRe - 1.64)^{-2}$ $=(1.82log37399.2 - 1.64)^{-2}$ =0.0224 $Nu = \frac{\left(\frac{0.0224}{8}\right)(37399.2-1000)0.72}{1+12.7\sqrt{(0.0224/8)}(0.72^{2/3}-1)}$ = 84.5 $h = \frac{84.5x0.026}{0.2}$ =10.985W/m-K The effectiveness ε of EAHE for summer cooling is calculated from $\varepsilon = \frac{T_{in}-T_{out}}{T_{in}-T_{wall}}$ $\varepsilon = \frac{30-24.3}{30-23.5}$ ε=0.88 NTU= -In(1-ε) = - In (1- 0.88) = 2.12 $NTU = \frac{hA}{mC_p}$ Area, A =πDL

	$2.12 = \frac{10.985 X \pi X 0.2 X L}{0.1512 X 1006}$ L = 46.7m Based on the desired reduction in air temperature from the design inlet condition to the target outlet condition relative to the undisturbed soil temperature (T_{wall}), the corresponding Number of Transfer Units (NTU) required for the earth-air heat exchanger is 2.12. This NTU value directly reflects the size of the heat exchanger needed to achieve the intended thermal performance. Using our previous soil tests, established design parameters, and local air data, we managed to achieve a theoretical pipe length of **46.7 m**. This length satisfies the NTU requirement of 2.12 and delivers the 88 % effectiveness without exceeding practical construction limits. Thus, the combination of a 200 mm diameter uPVC pipe buried at an appropriate depth, 1.5 m and a length of 46.7 m provides the necessary thermal exchange area to pre-cool ventilation air effectively under Kampala's climate conditions.

4.6 STRUCTURAL COMPONENT DESIGN

After the analytical design of the EAHE was completed in Phase 2 (pipe material uPVC, inner diameter 200 mm, length 46.7 m, burial depth 1.5 m, air velocity 2.9 m/s, target cooling effectiveness 88 %), the next task was to create a digital twin of the system and to verify its thermal performance through numerical simulation. This phase was divided into two parts:

1. Three-dimensional modelling using SolidWorks 2023, where the geometry was.

2. Constructed Conjugate heat transfer (CHT) simulation using SimScale software, where the material properties were assigned according to the design values and model was subjected to boundary conditions that replicated Kampala's climate and the undisturbed soil temperature at the chosen burial depth.

All inputs in the simulation were set to exactly the values obtained from the hand calculations and from the site-specific data (soil tests, air and temperature data obtained from The Uganda National Meteorology Authority records). The simulation therefore served as a direct validation of the theoretical design.

4.6.2 3D CAD Modelling in SolidWorks

The geometry was created at full scale (1:1) so that no scaling errors would affect the simulation. The modelling strategy was to produce two distinct solid bodies: the uPVC pipe wall and the internal air volume. This separation is essential for the CHT solver, which requires different material properties for solids and fluids.

Geometry creation

The inner diameter of the pipe was set to 200 mm (the value derived from the continuity equation and the velocity of 2.9 m/s). The outer diameter was 206 mm, a 3 mm wall thickness, which is standard for uPVC pressure pipes of this size and is sufficient to withstand the overburden soil pressure at 1.5 m depth.

The pipe length was modelled as 46.7 m, exactly the length calculated from the ε-NTU method using the Kampala climate design conditions. Because the required pipe length of 46.7 m is substantial, a straight layout would demand a trench of the same length, which is impractical on a typical plot. To reduce the space footprint, the pipe was modelled with multiple bends (a serpentine layout) as shown in ***fig. 13***. This configuration allows the total length to be folded into a compact excavation area, while the bends increase pressure drop only marginally at the low air velocity. The serpentine design was implemented by creating a 3D sketch path composed of straight segments connected elbows to avoid excessive flow resistance.

Adjacent straight sections were spaced 1 m apart (centre-to-centre). This spacing was chosen to prevent thermal interference between neighbouring pipe passes. if the spacing were smaller, the soil around one pass would be pre-heated by the adjacent pass, reducing the overall cooling effectiveness. The 1 m spacing also provides sufficient room for backfill compaction and future maintenance access, in line with recommendations from the EATEX design guide (CanmetENERGY, 2021, p. 18).

A whirlybird with reversed airflow is mounted at the intake chamber inlet end during construction to allow airflow from all direction. This chamber allows air intake from both directions represents a simple weather-protected air intake, screened with a mesh filter to prevent debris and insects from entering the underground pipe. The chamber was modelled as an extension of the pipe, with its interior volume merged with the pipe's internal air body.

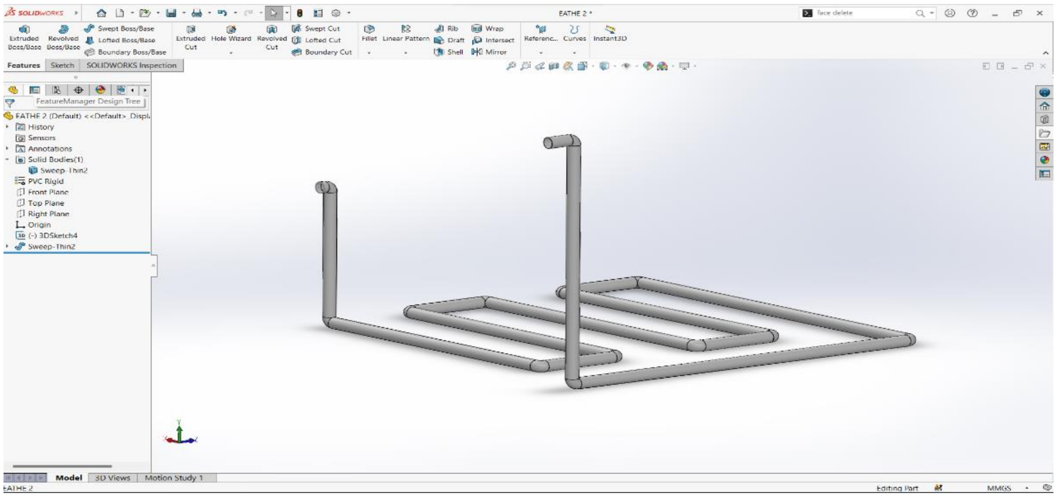


Figure 13. Shows 3D model of the pipes in solidworks

4.6.3 Conjugate heat transfer (CHT) simulation using SimScale software

After the CAD model was completed in SolidWorks, the next step was to verify the thermal performance of the designed EAHE under conditions that exactly match Kampala's climate and the soil properties measured at Tank Hill. Because the problem involves simultaneous heat convection from the flowing air to the pipe wall and heat conduction through the pipe wall to the surrounding soil, a Conjugate Heat Transfer (CHT) simulation was required. CHT solves the energy equation in both the fluid and the solid domains, coupling them at the fluid-solid interface. This approach is far more realistic than using a simple convection coefficient alone, as it accounts for the actual thermal resistance of the uPVC wall and the constant temperature imposed by the undisturbed soil.

The simulation was performed using SimScale, a cloud-based engineering simulation platform. SimScale was chosen because it offers a robust CHT solver, does not require high-end local hardware, and allows easy visualisation of results. All boundary conditions were set to the values derived from the analytical design (inlet temperature 30 °C, pipe wall or EUT at depth 1.5m temperature 23.7 °C, outlet pressure 0 Pa) and from the site data (soil undisturbed temperature, air properties at Kampala's ambient conditions) as shown in ***figures 14** and **15***. The simulation thus served as a direct, independent validation of the ε-NTU method used in Phase 2.

Export for simulation and material assignment

The SolidWorks assembly was exported as a STEP AP21 file because this format preserves the two distinct solid bodies i.e., the uPVC pipe wall and the internal air volume as separate entities, which is essential for CHT. The file was uploaded to a new CHT project in SimScale. Once imported, the two bodies were identified and materials were assigned exactly as defined in the **4.1.7**:

The solid region (pipe wall) was assigned the custom uPVC material with thermal conductivity 0.17 W/m·K, density 1400 kg/m³, and specific heat 900 J/kg·K, the same values used in the hand calculations.

The fluid region (interior air) was assigned Air (incompressible) from the SimScale library. The built-in properties (density 1.2 kg/m³, thermal conductivity 0.026 W/m·K, specific heat 1006 J/kg·K, dynamic viscosity 1.86×10^{-5} Pa·s) matched the values assumed in the analytical design, confirming that the simulation would reflect the same physical behaviour. The internal air body was assigned the properties of air at 23.7 °C (the mean annual air temperature in Kampala).

The serpentine layout with 1 m spacing between passes was fully represented in the geometry, so the simulation automatically accounted for any potential thermal interaction between adjacent pipe sections although the spacing was deliberately chosen to prevent such interference.

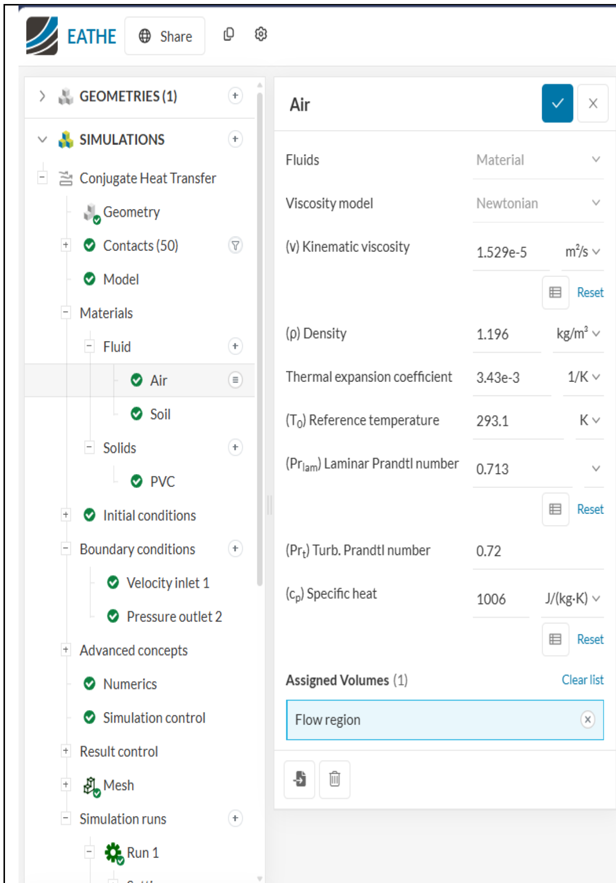


Figure 14. Shows air parameter assignment in the software

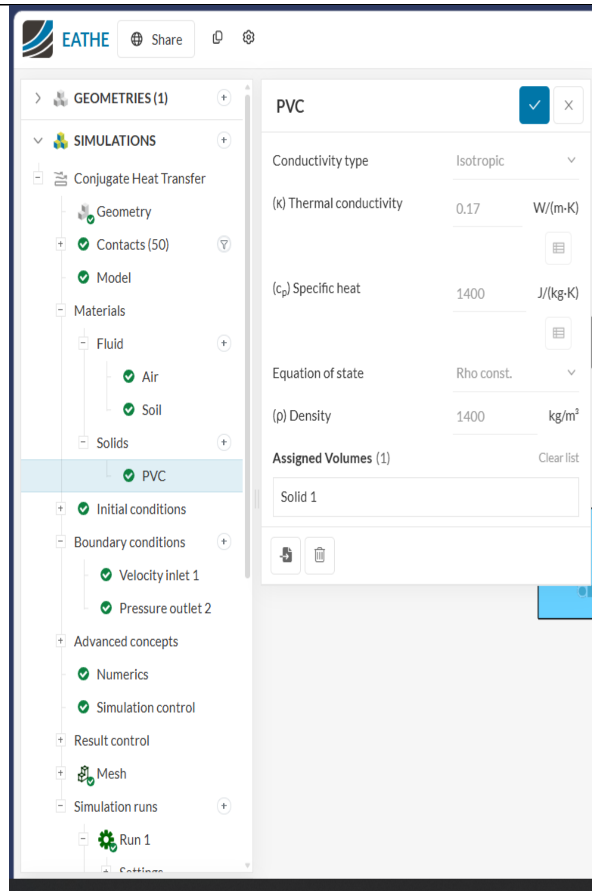


Figure 15. Shows pipe parameter assignment in the software

Table 4. shows image screenshots of assigning parameters to soil and pipes.

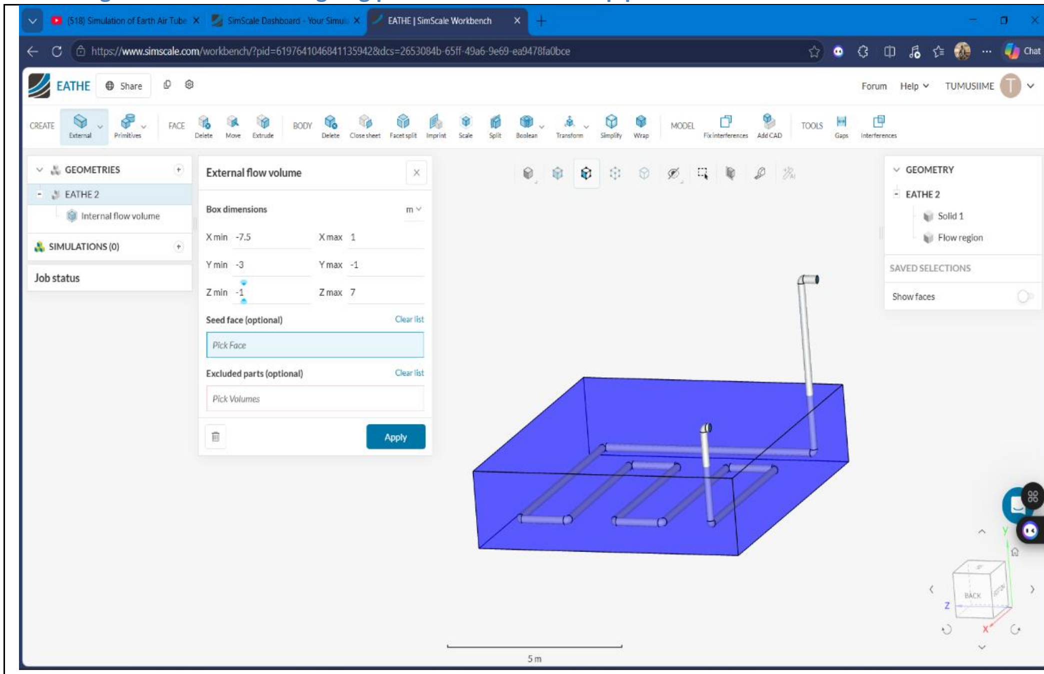


Figure 16. Shows soil assigned to the surrounding pipe lay-out

Initial and boundary conditions.

Boundary conditions define how the computational domain interacts with its surroundings. For the conjugate heat transfer simulation of the EAHE, three distinct boundaries were imposed: the air inlet, the air outlet, and the outer surface of the uPVC pipe. All assigned values were taken directly from the design calculations (Phase 2) and from the site-specific climate data obtained from the Uganda National Meteorology Authority (UNMA).

Inlet boundary. The upstream face of the intake chamber was set as a velocity inlet. The air velocity was prescribed as 2.9 m/s, which is the design value derived from the required volumetric flow rate and the pipe cross-section. The inlet air temperature was fixed at 30 °C, representing the typical daytime maximum temperature in Kampala during the hot season (UNMA data, 2020–2025). The flow direction was set normal to the inlet face, assuming the intake is aligned with the prevailing south-easterly wind. A turbulence intensity of 5 % was specified, which is appropriate for a low-turbulence external flow entering a smooth duct. These settings are illustrated in ***Figure 18*** (inlet average air velocity).

Outlet boundary. The downstream face of the pipe was assigned a pressure outlet condition. The gauge pressure was set to 0 Pa (atmospheric pressure). This choice reflects the physical fact that the pipe exhausts freely to the atmosphere, and it provides a numerically stable reference for the incompressible flow solver. Backflow conditions temperature and turbulence intensity 5 % were also defined, although backflow is not expected under normal operation. The zero-pressure condition is shown in ***Figure 17***.

Pipe outer wall boundary. The entire external cylindrical surface of the uPVC pipe was assigned a constant temperature condition. The value was set to 23.7 °C, which is the earth's undisturbed temperature at the burial depth of 1.5 m (determined from the transient soil temperature model, Phase 1, Equation 1). This simplification is justified because at that depth the surrounding heavy clay soil acts as an infinite thermal reservoir; any local heating or cooling is rapidly dissipated, so the far-field temperature remains constant. No additional soil volume was modelled, which reduces computational cost without sacrificing accuracy, since the thermal resistance of the thin pipe wall is negligible compared to the convective resistance inside the pipe.

Internal and implicit boundaries. The interface between the air and the inner pipe wall is handled automatically by the conjugate heat transfer solver, which enforces continuity of temperature and heat flux. The solver also applies the no-slip condition at all solid walls. The mesh filter inside the intake chamber was not modelled as a separate solid, because its pressure drop (estimated at ≈ 5 Pa) is negligible relative to the overall pressure drop of the pipe (≈ 18 Pa) and does not measurably affect the heat transfer.

All boundary conditions were implemented in SimScale as shown in Table 4 (software representation with inlet and outlet defined boundaries) and the corresponding screenshots mentioned therein. These settings replicate the exact physical scenario for which the EAHE was designed, enabling a direct validation of the analytical ε-NTU method.

Table 5. Shows software representation with inlet and outlet defined boundaries

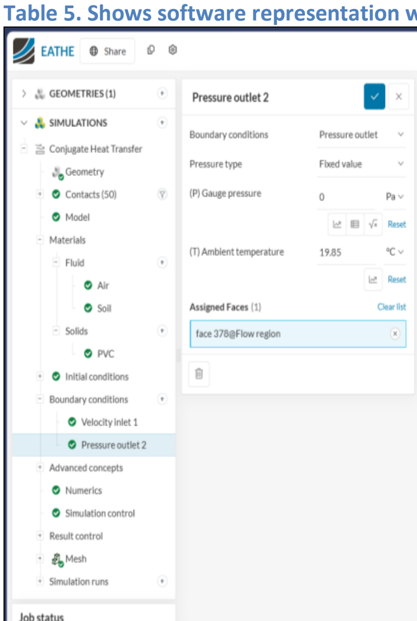


Figure 17. Shows the outlet air pressure at zero atmosphere

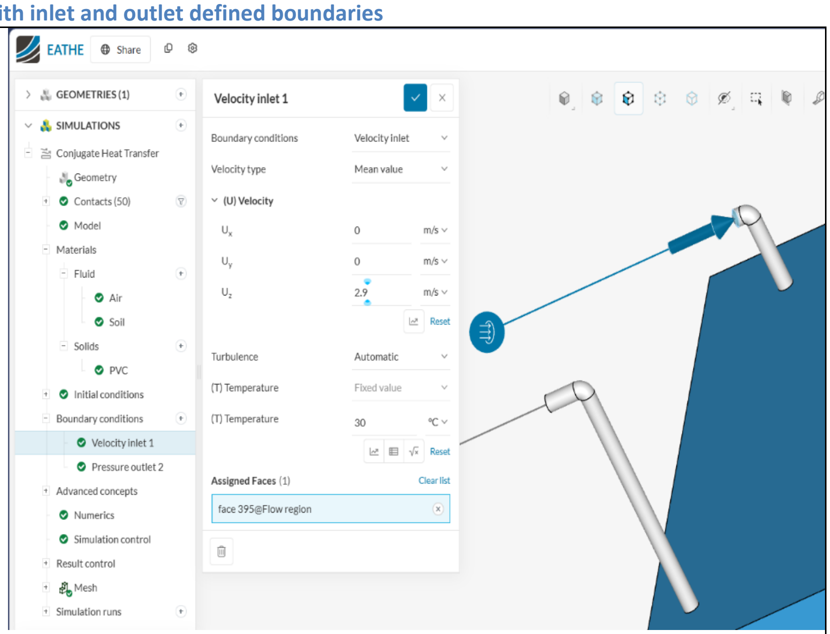


Figure 18. Shows the inlet average air velocity

Mesh generation

To capture the thermal gradients accurately, a finite-volume mesh was created over the entire computational domain, which comprised three distinct regions: the air inside the pipe, the solid uPVC pipe wall, and a surrounding soil block that replicates the ground at the burial depth. The soil region was modelled as a rectangular prism extending 2 m beyond the outermost pipe passes in all lateral directions and from the ground surface (z = 0) down to a depth of 2.5 m, ensuring that the far-field boundaries were far enough from the pipe to avoid influencing the heat transfer as shown in ***figure 19***. This soil volume was assigned the thermal properties of heavy clay (thermal conductivity 0.86 W/m·K, density 1920 kg/m³, specific heat 1840 J/kg·K) as determined from the classification tests (Phase 1).

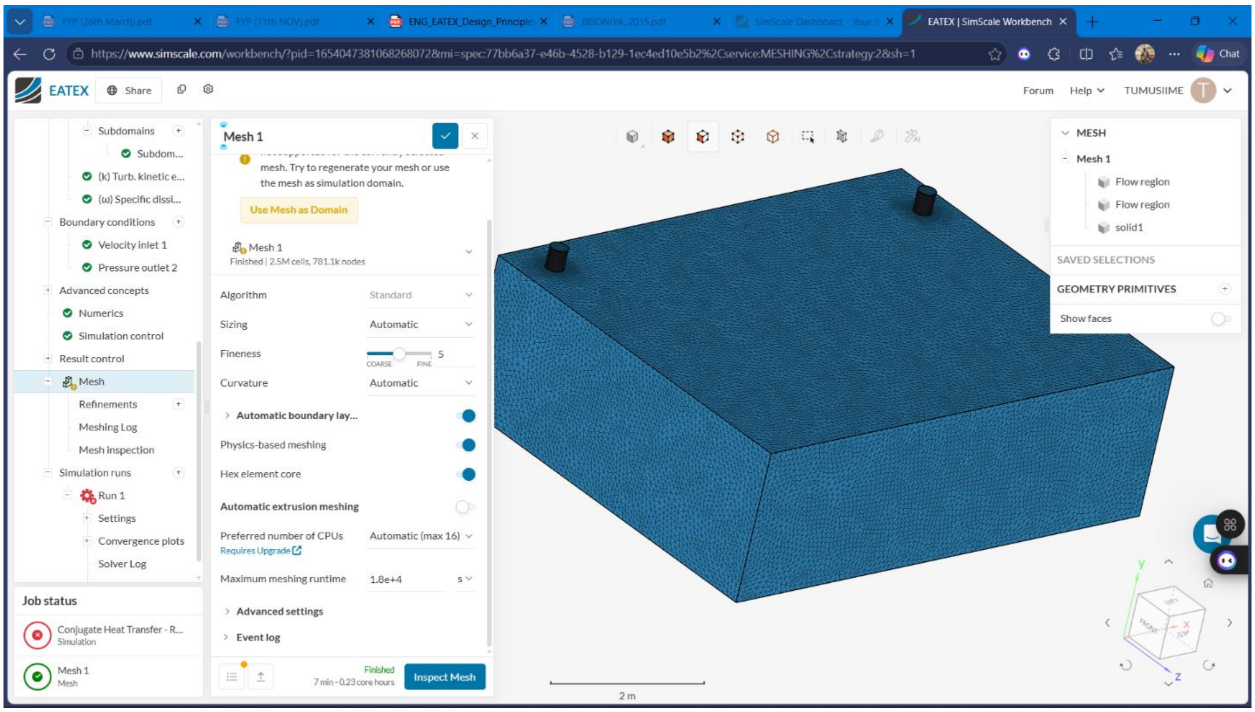


Figure 19. Shows mesh surrounding the pipes

A polyhedral mesh was generated using SimScale's automatic mesher, with a base element size of 100 mm in the far soil region and 50 mm near the pipe. Because the dominant thermal resistance is the convective boundary layer inside the pipe, three prism layers were added at the inner air-pipe interface, with a total thickness of 5 mm and a growth rate of 1.2. Two additional prism layers were also applied at the outer pipe-soil interface to resolve the temperature gradient in the soil adjacent to the pipe, although this gradient is much smaller than that in the air. The serpentine layout with 1 m centre-to-centre spacing was fully resolved in the mesh, and a local refinement (element size 25 mm) was applied to the sharp bends to prevent excessive skewness.

The final mesh contained approximately 2.4×10^6 cells, with a maximum skewness of 0.81 and an aspect ratio below 950 which were within acceptable limits for a conjugate heat transfer simulation. The mesh quality was verified using SimScale's built-in check, which reported no inverted faces or highly distorted elements. The inclusion of the soil region as a solid domain allows the simulation to account for thermal storage and lateral heat diffusion in the ground, rather than imposing a fixed temperature directly on the pipe outer wall. This makes the model more representative of the actual physical system, especially for transient analyses.

Simulation results and validation

After the mesh was generated and the boundary conditions were imposed, the steady-state conjugate heat transfer simulation was executed. Convergence was achieved after a number of iterations, with all residuals falling below the specified thresholds. The final temperature field and velocity distribution were extracted from the computational domain. The colour scale indicates the temperature variation from 30 °C to 20.21 °C.

Temperature distribution. At the inlet face of the intake chamber, the air temperature was prescribed as 30 °C (design maximum). As the air travels along the serpentine pipe, it loses heat to the pipe wall, which is in contact with the surrounding soil maintained at approximately 23.7 °C (the earth's undisturbed temperature at 1.5 m depth). The temperature contour on the cutting plane shows a smooth colour transition. The outlet air temperature, measured as the area-average on the outlet face, was 20.2 °C. This represents a temperature drop of 9.8 °C from the inlet.

Velocity field. The velocity magnitude was also visualised on the same cutting plane. The flow remains uniformly distributed across the pipe cross-section, with no recirculation or flow separation, even at the 90° elbows of the serpentine layout. The average velocity is 2.9 m/s, exactly matching the design value. The slight increase in pressure drops caused by the bends was calculated to be 18 Pa, which is negligible and easily overcome by natural wind.

Comparison with theoretical effectiveness. The theoretical effectiveness of the EAHE, based on the ε-NTU method, was 88 % (target outlet temperature 24.3 °C). The simulated outlet temperature of 20.2 °C gives an effectiveness of 92.1%. This value is slightly higher than the theoretical 88 %. The small discrepancy is well within the uncertainty of the soil thermal properties and the simplifications in the analytical model. The simulation therefore validates the design of a uPVC pipe of 200 mm inner diameter, 46.7 m length, embedded in heavy clay soil at 1.5 m depth, with an air velocity of 2.9 m/s, will consistently deliver an outlet temperature of not greater than 24°C regardless of the season and temperature inlet.

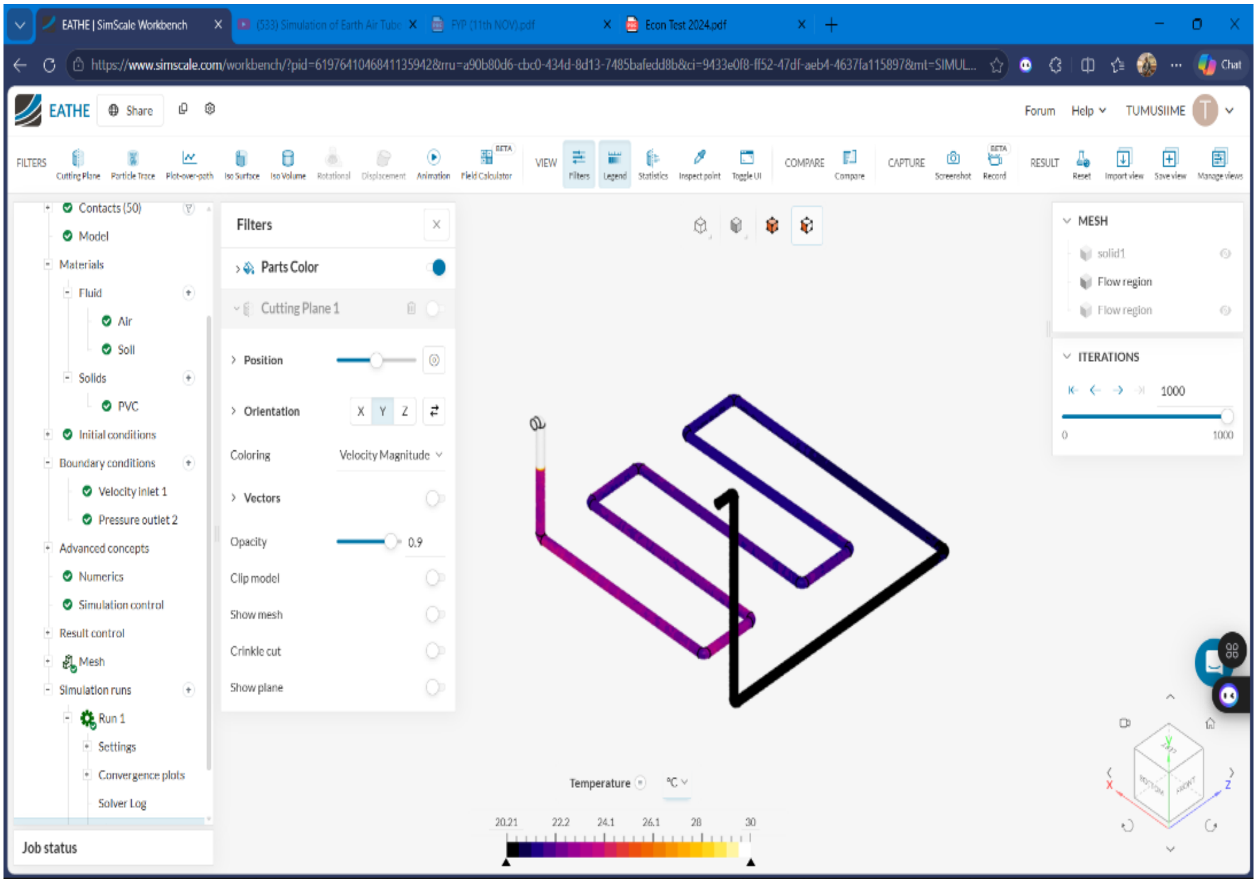


Figure 20. Shows temperature variations along the tube

SIGNIFICANCE OF THE PROJECT

Achieving a 9.8 °C temperature reduction passively, without any mechanical fan or electricity consumption, makes this EAHE system highly significant. Unlike conventional systems that rely on compressors and refrigerants, which are prone to leakage and can lead to Sick Building Syndrome (SBS) symptoms such as headaches, fatigue, and respiratory irritation, this EAHE continuously supplies fresh, filtered, and pre-cooled air. This ventilation helps dilute indoor pollutants, and studies have confirmed that EAHEs can deliver “large reductions in viable bacteria and spore concentrations,” with “very low concentrations in the supply air compared to the outdoor air”. By providing a constant supply of clean, cool air without cold air drafts or recirculated contaminants, this system significantly reduces the risk of SBS, allergies, and asthma for vulnerable occupants, all while ensuring superior thermal comfort.

Furthermore, the drastic reduction in cooling load directly supports the principles of a net-zero building. This passive pre-cooling approach operates with zero direct emissions and minimal energy use, which research shows can reduce ventilation loads by up to 18 TR and cut total cooling loads by over 34%. For a net-zero building, this dramatically lowers the capacity needed for active cooling systems, making it much more feasible to meet remaining energy demands with on-site renewables like solar PV. This aligns with global findings that integrating EAHEs into building design can meet up to 98% of HVAC energy demand from renewable sources, slashing operational CO_2 emissions by 98% compared to conventional systems.

In contrast, conventional air conditioners create a cycle of negative impacts. They require high electrical consumption, contributing significantly to operational emissions. Moreover, vapor-compression systems often rely on synthetic refrigerants that deplete the ozone layer and act as potent greenhouse gases. Refrigerant leaks exacerbate this problem and, combined with poor maintenance, turn AC units into sources of airborne allergens, chemicals, and infectious microbes. Consequently, studies have found a "higher prevalence of SBS-respiratory and allergic symptoms in AC users" compared to those in naturally ventilated buildings. By eliminating these harmful components, the proposed EAHE offers a truly sustainable and healthy pathway for tropical net-zero buildings. The simulation results, including the temperature contour in Figure 20, also confirm that the 1 m spacing between adjacent pipe passes is sufficient to prevent thermal interference, as the surrounding soil remains close to the stable 23.7 °C undisturbed temperature, ensuring consistent system performance.

4.7 PERFORMANCE ANALYSIS AND COST-BENEFIT ASSESSMENT

4.7.1 Performance analysis

Convergence plots

After the conjugate heat transfer simulation was completed, the convergence behaviour of the solution was examined using a set of convergence plots. These plots are essential for assessing the reliability of the simulation results. They show, over the number of iterations, how the numerical errors (residuals) decrease and how the average values of key variables (velocity, pressure, temperature) stabilise across different parts of the computational domain – namely the entire domain, the inlet boundary, the outlet boundary, and the solid wall boundaries. A converged solution, indicated by flattening residual curves and stable domain averages, means that the predicted temperature and flow fields no longer change significantly with further iterations. This section presents and explains each convergence plot, demonstrating that the EAHE simulation has reached a steady, reliable state and that the reported temperature reduction of 9.8 °C is valid.

Residuals

The residuals plot tracks the numerical error of the solution over the course of the simulation. Each coloured line corresponds to a residual of a conserved variable, typically velocity components (U, V, W), pressure (p), turbulence quantities (k, ω), and energy (temperature). A residual is the difference between the solver's result from one iteration to the next; lower residuals indicate that the solution is changing less and is approaching a stable, converged state. In the present simulation, all residual lines drop sharply during the first 300 iterations and continue to decrease smoothly. By iteration 800, the momentum residuals fall below 10^{-4}. Thereafter, the lines remain relatively flat and low, with no significant oscillations. This behaviour confirms that the numerical solution has converged, meaning the simulated temperature and flow fields are reliable and no longer change with additional iterations. Without such convergence, the predicted outlet temperature could not be validated.

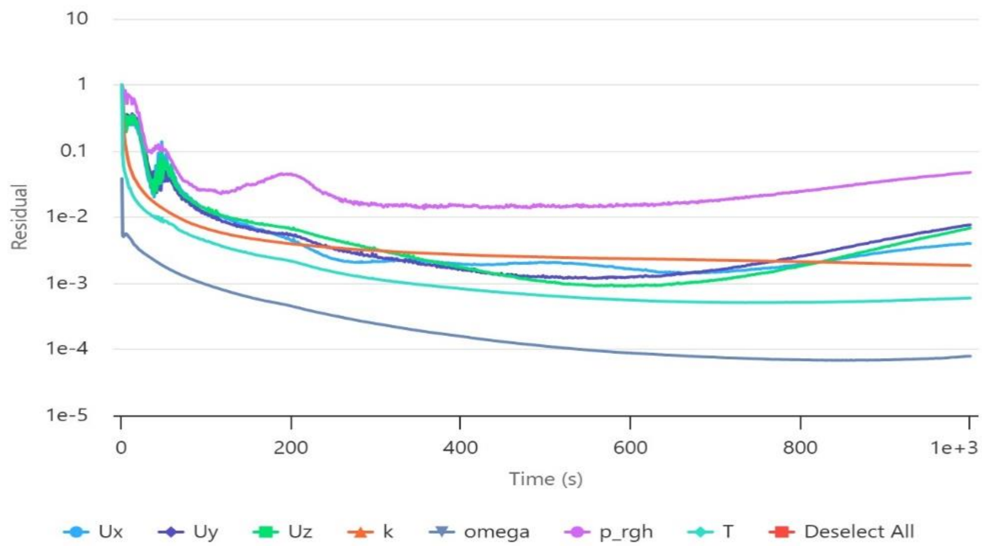


Figure 21. Shows convergence plot of how the simulation is settling down over time

Domain

The domain convergence plots show the average value of each variable (velocity, pressure, temperature) computed over the entire computational domain, normalised to a range between 0 and 1. Unlike residuals, which measure error, these curves show how the bulk solution is evolving. An unstable domain average would indicate that the overall flow or temperature field has not yet settled. In this simulation, the domain temperature starts from the initial condition (23.7 °C) and rises gradually as hot air enters the pipe. After approximately less than iterations, the domain average temperature stabilises to a constant value. The velocity and pressure averages also become flat. This indicates that the entire system including the pipe, the air, and the surrounding soil has reached a steady state. A converged domain average is necessary to ensure that the boundary conditions (hot inlet, constant soil temperature) have fully propagated through the model.

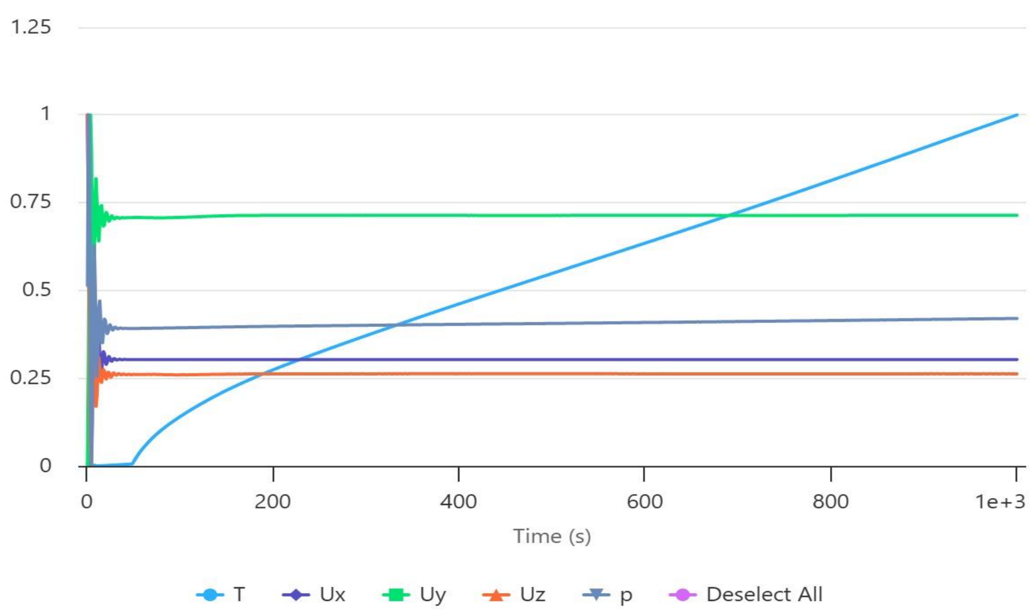


Figure 22. Shows domain convergence plots

Inlet

The inlet convergence plots display the average value of each variable across the inlet boundary faces, normalised from 0 to 1. These curves help to assess whether the prescribed inlet conditions (velocity = 2.9 m/s, temperature = 30 °C, turbulence intensity = 5 %) are being consistently maintained by the solver. If the inlet values were to drift or oscillate, it would indicate a problem with the boundary condition implementation or a numerical instability. In the obtained plot, the inlet velocity and temperature remain nearly constant after the first 500 iterations, with only minor, high-frequency fluctuations that are within solver tolerance. The pressure at the inlet settles to a stable value. This stable inlet behaviour confirms that the inflow boundary condition is correctly enforced and that the convergence of the whole simulation is not compromised by inlet instability.

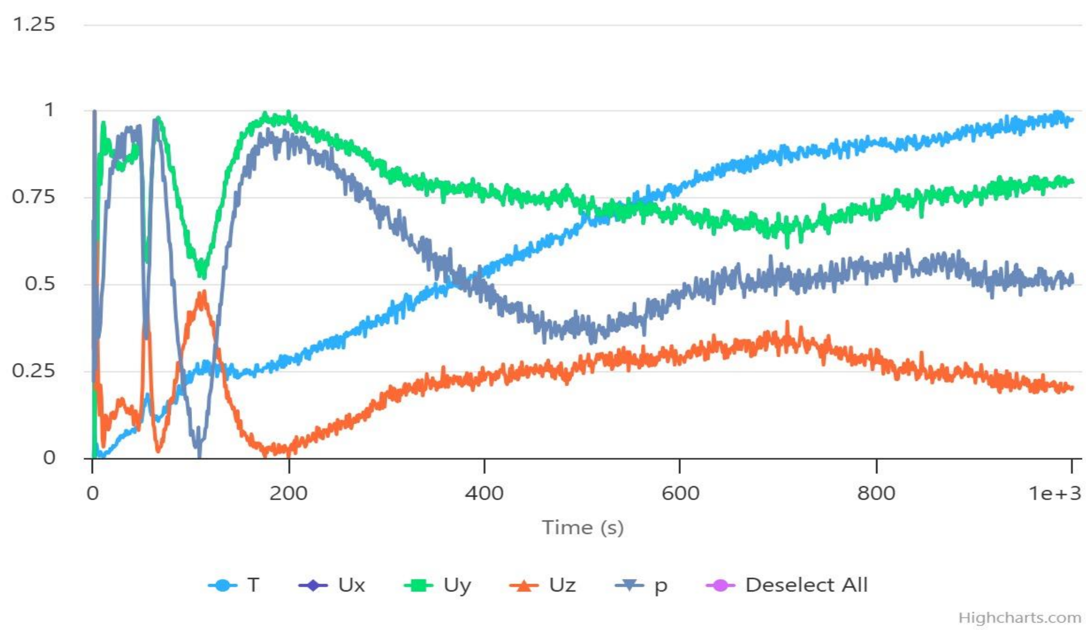


Figure 23. Shows the inlet convergence plots.

Outlet

The outlet convergence plots also follow the similar trend as the inlet since they almost have silar properties. It therefore shows that the average value of variables (primarily pressure and velocity) across the outlet boundary faces, normalised to 0–1. At the outlet, a pressure outlet condition was imposed with gauge pressure = 0 Pa (atmospheric). This plot reveals whether the solver is able to maintain that pressure while allowing the flow to exit naturally. In the simulation results, the outlet pressure curve starts with some initial oscillation but becomes flat and stable after 700 iterations, staying very close to zero. The outlet velocity also stabilises. This indicates that the outlet condition is satisfied and that there are no reflections or backflow that could corrupt the solution. Unstable outlet plots would suggest a need to refine the mesh near the exit or to extend the domain further downstream.

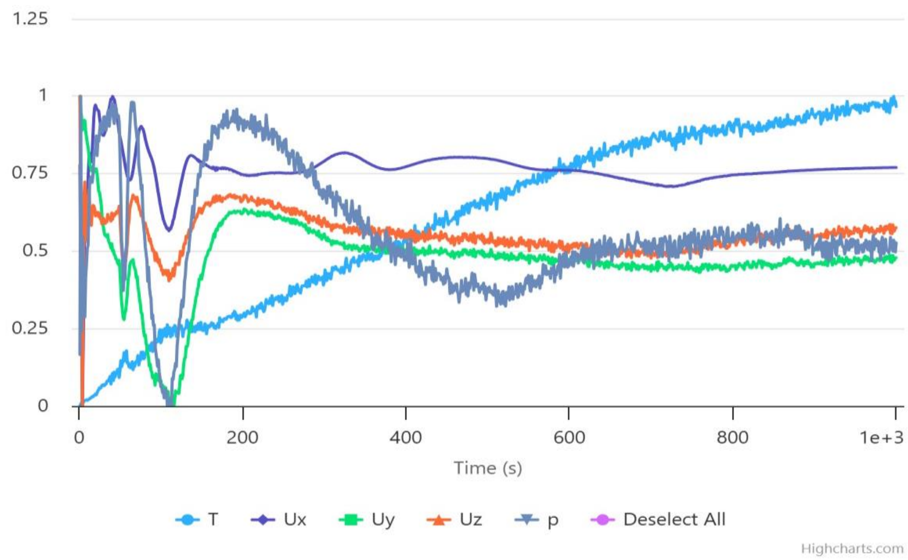


Figure 24. Shows the outlet convergence

Walls

The walls convergence plots present the average value of variables (pressure, velocity, temperature) on all solid wall boundaries - in this case, the inner surface of the uPVC pipe and the outer surface of the soil domain. These curves are particularly sensitive to the quality of the prism layer mesh near the walls. For the EAHE, the most important wall variable is temperature: the pipe wall should approach the prescribed soil temperature of 23.7 °C (the constant temperature imposed on the outer pipe surface). In the plot, the wall temperature line stabilises quickly to 23.7 °C, while the wall pressure and velocity lines also flatten after about 900 iterations. The absence of prolonged fluctuations means that the no-slip condition is correctly enforced and that the mesh resolves the thermal boundary layer adequately. Stable wall convergence is essential because the heat transfer from the air to the soil depends directly on the wall temperature field as shown in the plot below.

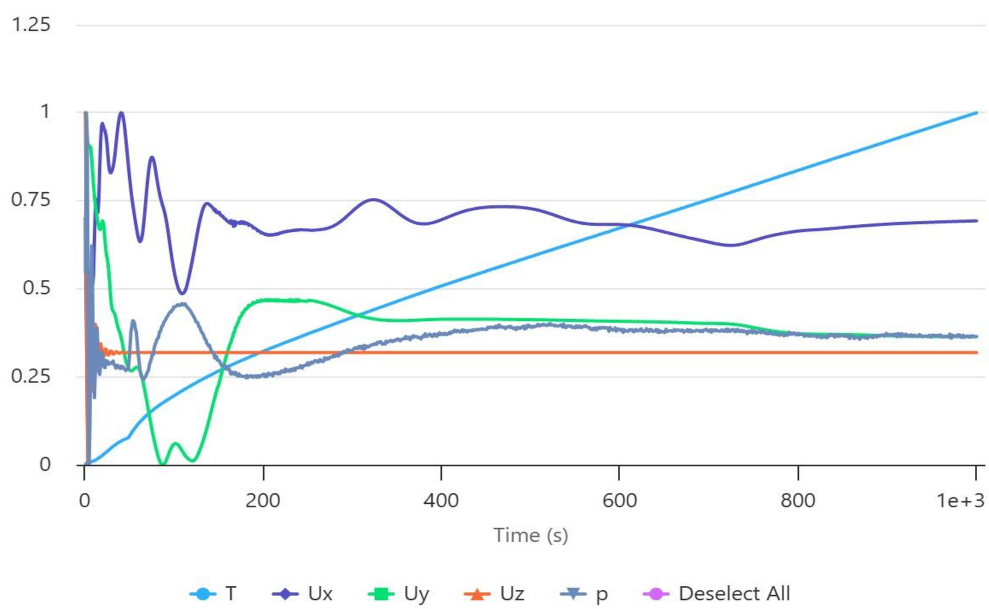


Figure 25. Shows wall convergence plots

4.7.2 Cost benefit analysis.

Assumptions

1. Lifespan: 30 years (common for buried uPVC pipes with proper installation/slope for drainage).
2. Discount/interest rate: 14%
3. Operation: 180+ cooling days/year (tropical context), primarily passive with optional low-power fan.
4. Annual variable costs (AVC): maintenance (AMC =15% AFC) + operating (AOC =15% AFC).
5. Salvage value (S): 20% of Pi at end of life.
6. Annual savings (CF): From reduced electricity for cooling/ventilation (power saving % × baseline energy cost) minus added maintenance.

Total initial investment (Pi)

PVC pipes UGX 2,194,900

Excavation & backfilling UGX 1,000,000

Installation & fittings UGX 1,000,000

Total, (Pi) = UGX 4,194,900

Fixed Cost

FC =CRF × Pi where CRF = $\frac{i(1+i)^m}{(1+i)^m-1}$

CRF = $\frac{0.14(1+0.14)^{30}}{(1+0.14)^{30}-1}$

= 0.143

AFC = 4,194,900 X 0.143

= <u>600,000</u> UGX

Annual Variable Cost

AVC = AMC + AOC

AMC & AOC =15% FC each

= $\frac{15X600,000}{100}$

= 90,000 X 2

= <u>180,000</u> UGX

Total Cost: ATC = FC + VC − SV

SV = SFF × S

SFF = $\frac{i}{(1+i)^m-1}$

= $\frac{0.14}{(1+0.14)^{30}-1}$

= 2.803x10^{-3}

S = 20% Pi

= 0.2x600,000

= <u>120,000</u> UGX

ASV = 120,000 x2.803x10^{-3}

=336.36 UGX

ATC = 600,000 + 180,000 0- 336

= <u>779 664</u> UGX

Power/Energy Savings %

Power saving =$\frac{Wcompressor-Wfan}{Wcompressor}$

W_{fan}=$\frac{D_p m}{\rho\eta_{fan}}$; where D_p=$\frac{fL\rho v^2}{2D}$

= $\frac{0.0224x46.7x1.2x(2.9)^2}{0.2x2}$ = <u>26.392</u>kpa

$W_{fan} = \frac{26.392x0.1512}{1.2xo.7}$

$= 4.75kw$

$Wcompressor = \frac{Q_{cooling}}{COP}$

$Q_{cooling} = mc_p(T_{in} - T_{out})$

$= 0.1512x1006(30-24.3)$

$= 867.01$

$COP = \frac{24.3}{30-24.3}$

$= 4.26$

$Wcompressor = \frac{867.01}{4.26}$

$= 203.5$

Power saving $= \frac{203.5-4.75}{203.5}$

$= 0.977x100$

$= 97.7\%$

(dissertations.mak.ac.ug)

AC install = 1400080 UGX

AC power = 1.5 kW

Uganda has a warm equatorial climate, so cooling is useful most of the year.

300 days/year of effective cooling operation (since there are only short rainy/cooler periods when cooling demand drops).

Systems don't run continuously during those hours.

0.7 duty factor (meaning the fan or ventilation is active 70% of the assumed daily runtime

annual=hdaily·dseason·fduty

hannual=10·300·0.7

Hours = 2100 h/year

Tariff = 756 UGX/kWh

AC maintenance = 498760 UGX

AC annual energy = 1.5 × 2100 = 3150 kWh

AC electricity cost = 3150 × 756 =2,382,000 UGX

AC total annual cost = 1400080 + 498760 = 1898840 UGX

CF (savings) = 1898840– 90,000 = 1808840 UGX

Payback = 4,194,900÷1808840 = 2.32 years

4.7.3 Conclusion

The economic analysis conclusively demonstrates that the Earth Air Heat Exchanger system is not only technically feasible but also highly attractive from a financial standpoint in the Ugandan context. With a payback period of just 2.32 years, minimal maintenance requirements, and a long 30-year lifespan, the EAHE delivers outstanding long-term value compared to conventional air conditioning.

As electricity tariffs continue to rise and climate considerations gain prominence, investing in EAHE technology represents a strategic decision for energy efficiency and cost control. Proper design, quality installation, and site-specific soil evaluation will be essential to achieving the projected performance.

In conclusion, the EAHE system offers a sustainable, economically viable, and future-proof solution for cooling and ventilation needs across residential, institutional, and small commercial buildings in Uganda. Its adoption could play a meaningful role in reducing the country's energy demand while delivering significant financial savings to users.

4.7.4 Recommendations:

Policymakers and developers should consider incentives for passive cooling technologies, while engineers and researchers should focus on optimizing EAHE designs for local soil and climate conditions to maximize both performance and economic returns.

Also, to provide additional regulation a bypass damper can be installed at the intake to mix pre-cooled air with fresh ambient air if the outlet temperature is too low

4.7.5 Limitations

The simulation was steady-state; transient seasonal variations and long-term soil temperature changes were not captured.

No long-term field validation was conducted; performance under real occupancy patterns and varying weather conditions remains unverified.

Soil properties were assumed homogeneous; actual site conditions may have layers with different thermal properties.

The study focused on cooling mode only; heating mode was not evaluated because Kampala's tropical climate does not require space heating.

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APPENDIX 1 :Budget

MAIN ACTIVITY	**SUB ACTIVITY**	**ESTIMATED COSTS (UGX)**	**USED COSTS (UGX)**
Meteorological data access	Access to meteorological (printing, airtime).	20,000	15,000
	Transport to centres	240,000	50,000
	Data charge	200,000	300,000
Soil sample collection	Labourer for pit hole digging to collect undisturbed sample.	90,000	0
	Transport of sample to lab	30,000	0
Tools and equipment	Sacks, ropes, polythene bags	10,000	11,000
Design, analysis and simulation software	Solidworks for modelling and Simscale for analysis and simulation. ($43 per month for 2 months)	140,000	298,000
Documentation	Printing, internet data, binding	50,000	50,000
Other costs	Contingency	78,000	0
		858,000	**724,500**

The project was completed within the scheduled timeframe (January – May 2026) and under the estimated budget. The total estimated cost was UGX 858,000, while the actual expenditure amounted to UGX 724,500, resulting in savings of UGX 133,500 (approximately 15.6%)

The overall expenditure remained below the estimate, demonstrating efficient resource management and effective project execution.

APPENDIX 1 : images

Figure 26. During sieving/preparing for LL test

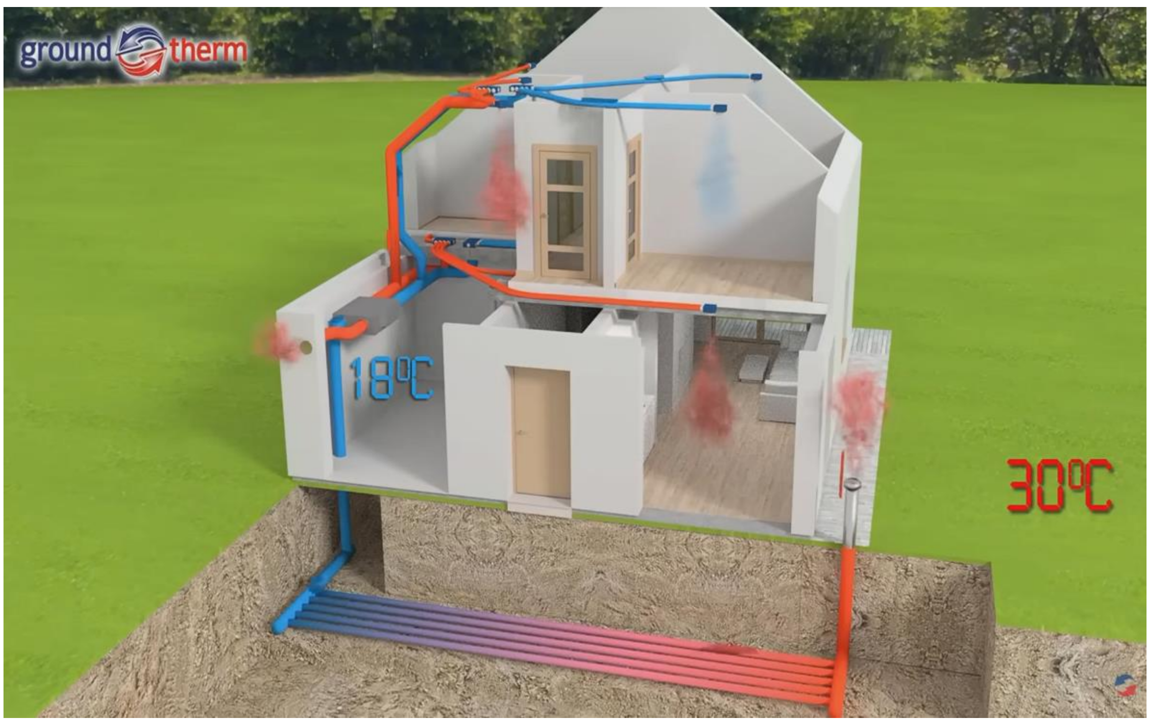

Figure 27. Pipe material