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THERMAL INSULATION MATERIALS FOR GEOTECHNICAL APPLICATIONS SUCH AS SEASONAL THERMAL ENERGY STORAGES

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Abstract

In this thesis, in the first step, a study on thermal insulation for geotechnical applications is carried out. Different types of insulation materials have been thoroughly studied to see if it could be used in geotechnical applications.

Based on above studies, thermal energy storages (TES) have been analysed and studied and new ideas for the construction of TES have been suggested. The aim was to discuss different types of TES with energy efficient constructions using suitable insulation materials and techniques.

The TES are then compared based on their efficiency, Pros and Contras, by keeping the boundary conditions such as soil and ground water conditions constant.

Diaphragm wall and the technique for its thermal insulation as construction element of TES have also been given a light touch and discussed.

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λ	[W/mK]	Thermal conductivity
R-value	[ft2·°F·hr/BTU] / [m²K/W]	Thermal Resistance
t	[m]	Thickness
H	[watt] / [J/s]	Heat flow
ρ	[kg/m3]	Density
σ	[kN/m²] / [KPa]	Shear strength
σ_c	[kN/m²] / [KPa]	Compressive strength
T	[°C]	Thermal Tolerance

1 Introduction

Renewable energy technologies together with thermal energy storage, contributes widely in supplying heating for residential space and in domestic hot water (DHW) production. Both of these aspects i.e. space and heating water, plays a major role in energy sector and are accountable for a substantial portion of the energy requirements of residential buildings i.e. 79% in Europe and 62% in the US. Although the solar energy collector technologies have become widespread, economical, and progressively more productive, the discontinuous nature of solar energy during winter season poses a challenge. To overcome this limitation, solar seasonal thermal energy storage (STES) are produced to balance the temporary discrepancy between excessive solar yield in summer and higher heat demand in winter (on the north half of the globe) on a yearly basis. Investigations have been done in applying STES together with renewable energy sources, for a variety of configurations, including hot-water thermally stratified tanks integration in residential buildings for storing solar energy, combination of pit storage with waste heat utilization in district heating (DH) systems, biomass and solar power plants, huge underground water tanks and borehole thermal energy storage in district heating networks system for storing heat from industrial waste. The long term (seasonal) thermal energy storages can provide heat energy by approx. 70 % of the total annual heating demand (Elrahman, pp. ,2014).

In general, there are three main methods for storing thermal energy i.e. chemical, latent, and sensible. Chemical storage (energy or heat stored in the form of endothermic chemical reaction), in spite of being potentially beneficial in terms of having high energy densities and insignificant heat losses, still does not provide any comprehensible advantages in building applications due to its complex nature, unreliability, and high costs etc. Although, chemical storage technology is still considered at laboratory stage, the other methods i.e. sensible heat technologies (heat stored by changing the temperature of a storage medium e.g. water) and latent heat technologies (heat stored by changing the phase of a material e.g. from gas to liquid or from liquid to solid) are fully developed and at industrial stage. Beside their lower energy densities, one of the major drawback of latent and sensible storage is the unpreventable heat losses that occurs when storing thermal energy at higher temperature.

Furthermore, when energy is stored e.g. in seasonal thermal storage systems in the form of hot water over a longer period of time, energy or heat losses become more significant if the storage container is not adequately insulated. That’s how energy or heat losses represent a big concern in sensible seasonal storage systems (Willy.V).

One of the most significant ways to optimize cost and heat losses of a storage is to thermally insulate it. The description and selection of the insulation material and its method not only conclude the related costs, but also the thermal efficiency of the thermal energy storage system over its life period (Willy.V, 2019).

1.1 Background & Motivation of the Thesis

Thermal insulation in building and industrial sector have been given much attention in the literature to achieve energy efficiency throughout a structure’s lifespan as there is a completely developed knowledge and information about the strong correlation between the energy utilization of a building and the features (properties) of its envelope. Similarly, in terms of economics studies related to thermal insulation, a number of studies have been done that shows different methodologies for optimizing the thermal insulation of buildings, insulated from external and internal walls. In the field of thermal energy storages (TES), similar research studies and articles are not broadly available in the literature (Willy.V, 2019).

The primary motivation of this work is to present a thorough review and discussion on thermal insulation materials that could be used in geotechnical applications or cases such as in hotel basements or other under grade structures in geotechnical frame with main focus of the insulation materials on TES applications with temperatures up to 90 °C. By providing appropriate material characteristics, thermo-physical properties, it aims to serve as a concise reference tool in an attempt to collect together the many studies available in literature related to thermal insulation methods for energy efficient construction and to present different ideas (variants) related to the method of construction of thermal Energy storages (TES).

1.1.1 Why do we need Thermal Energy Storages?

In future, there is a growing need of storing the energy in various forms such as water, in thermal energy storage systems and likewise. Some of the essential aspects related to the need of TES are discussed as follows:

- TES systems has the capacity to deliver flexible energy network including efficient response to demands, storage of energy and intelligent system operations.
- It is also helping the EU plans to de-carbonize the Europe with slogan “Clean Energy for All Europeans” by delivering energy at the lowest possible cost (Clerens,2017).
- With the increase in renewables penetration, long-term thermal energy storage

solutions would be required to balance the monthly and seasonal variations in energy demand and supply (Clerens,2017).

- It is considered as one of the most inexpensive energy conservation options compared to other methods and technologies.

1.1.2 Cases

As discussed, the materials that could be used as insulation in different geotechnical applications (cases) such as basement insulation of a building or hotel in plains showing in Figure 1 or in sloppy area showing in Figure 2, to prevent or reduces the heat transfer, as there is always the tendency of heat transfer between the internal and external boundaries of the wall, base slab and also with shear stresses due to lateral earth loads in Figure 2.

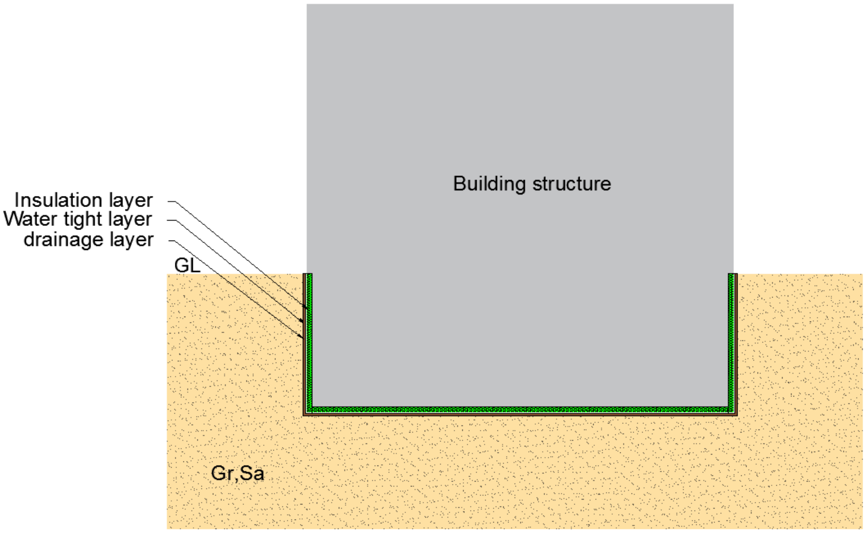

Figure 1. Basement slab and walls insulation of a building in plain area

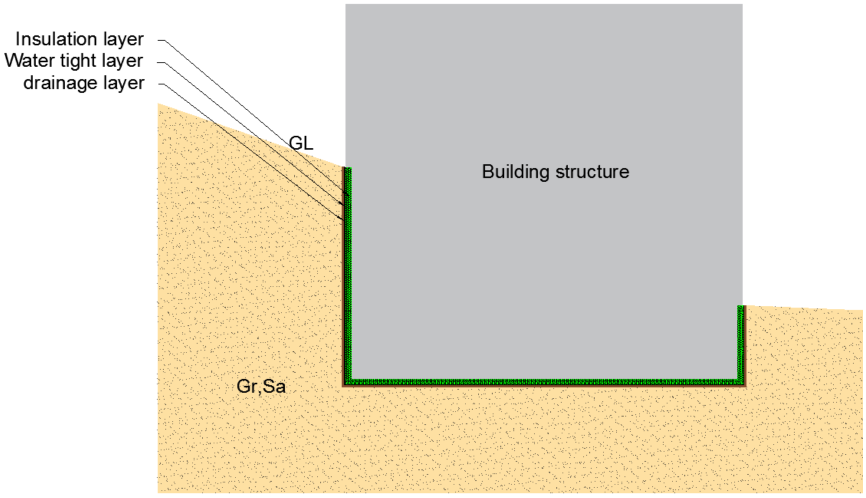

Figure 2. Basement & its walls insulation of a building in a sloppy area

Similarly, the construction and insulation of underground seasonal thermal energy storages (STES) where energy is stored in the form of hot water over a longer period of time, there are significant energy or heat losses between the stored medium and the surrounding soil mass due to comparable differences in temperature as illustrated in the example in Figure 3.

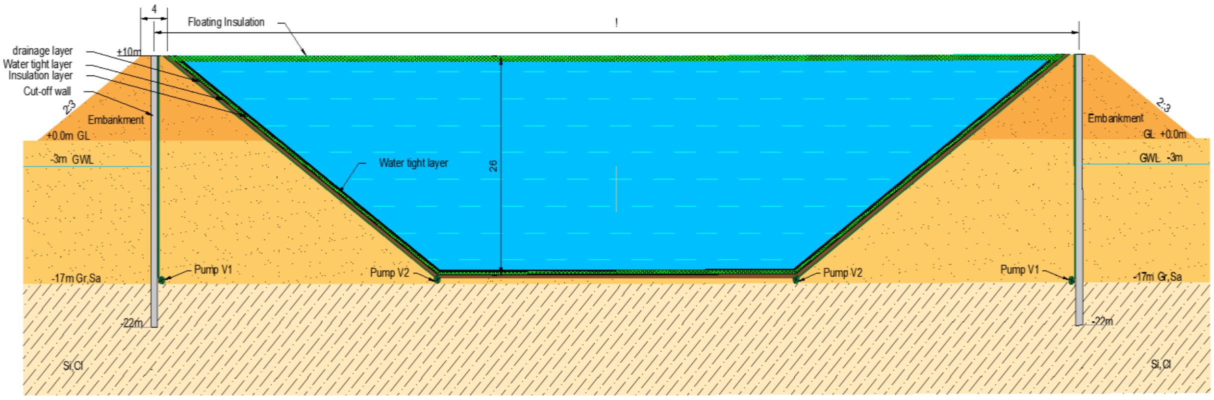

Figure 3. Construction and insulation of an underground seasonal thermal energy storage (STES)

1.2 Aims of Work

- The aim of this thesis is to evaluate the concept of thermal insulation and selection of most suitable insulating materials for geotechnical applications.
- To specify suitable insulating materials for the underground construction i.e. in under grade part of buildings which is prone to shear stresses and lateral earth loads etc.
- To discuss different variants of seasonal thermal energy storages (STES) and select the most suitable and optimal STES for our upcoming projects.
- Based on these insulating materials properties, selection of the type of materials that we can use in our STES project for insulation purpose.
- Comparison of all these materials in detail, based on their properties, for other geotechnical applications.
- To develop an idea about the diaphragm wall with insulation and its technique of installation

1.2.1 Highlights

To achieve above mentioned goals, the thesis is structured in an optimised way and is divided into three major parts. Every chapter is described briefly and in simple words for the purpose of making it understandable for technical as well as non-technical readers.

Chapter 2 is related to the categorization and types of insulation materials in general and specifically in geotechnical applications. These materials have been discussed in details with their applications, Pros and Contras.

Chapter 3 describes different variants of seasonal thermal energy storages (STES). These STES have been discussed in detail including their pros and contras. Also for some of the storage variants, the techniques for insulation installation have also been suggested.

Chapter 4 discusses the diaphragm wall and its insulation techniques.

Finally, chapter 5 summarise the whole thesis and leaves open questions for further research.

2 Insulation Materials for Geotechnical Applications

2.1 Description

Insulation Materials are those materials that reduces or prevents the transmission of heat or sound or electricity from one medium to another. Thermal insulation materials specifically, are those which can resist heat transfer i.e. by conduction, convection or radiation, between different mediums.

There are numerous kinds of thermal insulation materials. They are usually defined by their low thermal conductivity i.e. below 1 W/mK. It cannot be denied that the low thermal conductivity of a material is related to its low density and air gaps, since air or gas exhibit low thermal conductivity, with a value of approximately 0.02 W/mK.

Reduction in the heat flow of a thermal insulation material, is typically occurring due to the microscopic dead gas bubbles or air cells. But if these air voids are not isolated properly from external infiltrations of air then there is a possibility that convection losses occur.

Moreover, heat transfer could also occur in the form of radiation especially during the high temperature. Better thermal insulation could be achieved with the materials having low thermal conductivity. Although, environmental and public health aspects of an insulation material should also be given considerations including hazard of fire, effects of moisture etc. and also its maintenance (Pei-Wen Li, pp. ,2017).

Generally, insulation materials can be made in different forms i.e. loose-fill form, blanket form, rigid form, reflective form etc.

The choice of the proper insulation material types and form, depends on the type of application as well as the desired materials physical, thermal and other properties.

2.2 Categories of Insulation Materials

Insulation materials can be categorized based on their chemical or physical structure. The most broadly used insulating materials can be categorized accordingly as shown in the flow chart in Figure 4 (Papadopoulos, 2005).

2.2.1 Inorganic Materials

Inorganic materials include rock wool, glass fiber, calcium silicate, and foam concrete

2.2.2 Organic Materials

Organic materials include cellulose, cotton, wood, pulp, cane, synthetic fibres, cork, foamed rubber, polystyrene, polyethylene, polyurethane, polyisocynurate and other polymers.

2.2.3 New Technology Materials

New technology materials include vacuum insulated panels (VIP), transparent material such as silica aerogel, closed cell foam, gas filled panel, phase change material (PCM) etc.

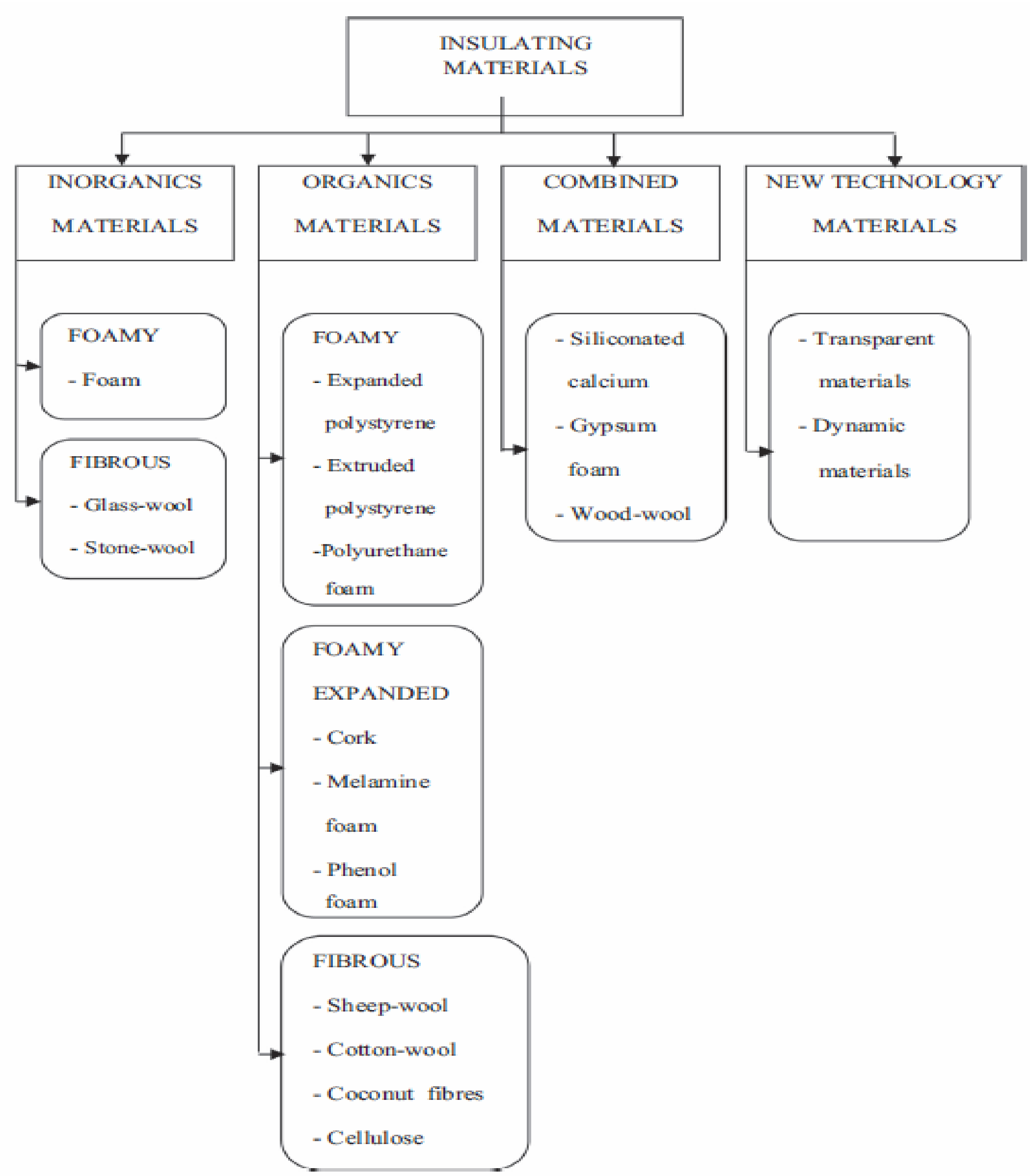

Figure 4. Mostly used insulation materials classification *(Papadopoulos, 2005)*

2.3 Properties of Insulation Materials

Some of the important properties of insulating materials are discussed below

1. **Insulation Properties**

- Thermal conductivity (λ)
- Density
- Specific heat capacity
- Vapor permeability
- Thermal resistance

2. **Mechanical Properties**

- Compressive strength
- Shear strength etc.
- Heat resistance (against high temperatures)
- Durability
- Rodents resistance (Ants, termites, Rats)

2.3.1 Insulation Properties Definitions

Some of the important properties for insulating materials are defined below.

1. **Thermal conductivity (λ)**

A good thermal insulator will have a low thermal conductivity. It measures, how well a material can conduct heat through its mass. In simple words, the lower the conductivity of a material, the lower heat conduction will occur. Thermal conductivity can be expressed in watt (W) m^{-1} $°C^{-1}$ or kcal m^{-1} $°C^{-1}$ in SI units and Btu ft^{-1} $°F^{-1}$ in imperial units. Thermal conductivity could also be expressed as k-value.

2. Density

The factor that influence the thermal conductivity of a material is its density. The density of a material is the mass (or 'weight') per unit volume. Less density means, less material for heat conduction, follows more air (gas) to resist the flow of heat. It is measured in kg/m^3.

3. Specific Heat Capacity

The amount of heat required to raise the temperature of 1kg of the material by 1K (or by 1°C) is called Specific Heat Capacity. A good insulator will have a higher Specific Heat Capacity as it will take time to absorb more energy (heat) before it heats up and heat transfer occur. It is expressed in Kcal, J and Btu (British thermal unit).

4. Vapor Permeability

It is the amount to which a material allows the passage of water through it. It is measured as the rate of flow of vapor (water) through a unit area of a material with a unit thickness produced by the difference in vapor pressure between two surfaces under certain conditions of humidity and temperature.

5. Heat Resistance

Heat resistance or thermal tolerance is the amount of heat that a material can tolerate before melting, experience a severe strength loss or burning. Thermal insulators with a low heat resistance will likely get damaged when it comes in contact with higher temperatures.

6. Thermal Resistance (R)

Thermal resistance is the capability of a material to resist the heat flow and is the factor which connects the thermal conductivity with its thickness. It can be expressed in m^2K / W. More thickness of a material means, less flow of heat and so does low thermal conductivity. The equation is written as:

Thermal Resistance = Thickness (m) / Conductivity (W/mK)

2.4 Types of Insulation Materials

In this chapter only those types of Insulation materials will be discussed which are or can be used in geotechnical applications. The properties of these materials including the prices are accumulated from the stated sources in each material descriptions qualitatively and also from other authentic sources and references, in a Table of properties i.e. Table 6 in chapter 2.4.13 quantitatively.

2.4.1 Extruded Polystyrene (XPS)

Extruded polystyrene is developed by melting polystyrene grains, with the addition of expansion gas e.g. CO2 or HFC etc. into an extruder. XPS consists of a closed pore structure with mass density of 15 – 85 kg/m3. The typical thermal conductivity of XPS ranges in between 0.025 – 0.040 W/mK. These values vary with moisture content, temperature, and density. Considering one example in which the thermal conductivity value shows an increment from 0.034 – 0.044W/mK with the increase in moisture content from 0 - 10 vol%, respectively. XPS products could be cut, adjusted and perforated, without any thermal performance loss as shown in Figure 5 (Jelle, 2011).

Figure 5. Extruded Polystyrene boards (adex.ca)

2.4.1.1 Applications

Some of the most common geotechnical insulation applications of XPS are as follows

- Above and below ground construction insulation
- Under slabs on flat roofs, concrete floors, foundation walls and base etc.
- Areas vulnerable to frost and heave

2.4.1.2 Pros

Some of the essential properties of XPS are as follows

- Semi impermeable
- Low thermal conductivity
- Good compressive strength
- High shear strength
- Frost penetration resistance
- Economical (see Table 6 in chapter 2.4.13)

2.4.1.3 Cons

Some of the drawbacks of XPS are as follows

- Rodents attractive
- Toxic
- Heat resistance declination for temperatures higher than 80°C
- Flamable
- Performance depletion over time (trapped blowing agent gases escapes due to ageing)

2.4.2 Expanded Polystyrene (EPS)

Expanded polystyrene is produced from small beads of polystyrene i.e. obtained from crude oil, with the addition of an expansion agent (e.g. pentane gas). These expanded spheres are bonded together and form a bright, rigid closed cell foam material. The thermal conductivity of a typical EPS ranges in between 0.030 – 0.043 W/mK. These values vary with moisture content, temperature, and density. Considering one example in which the thermal conductivity value shows an increment from 0.030 – 0.054W/mK with the increase in moisture content from 0 - 10 vol%, respectively. EPS products could be cut, adjusted and perforated, without any thermal performance loss as shown in Figure 6 (Jelle, 2011).

Figure 6. Expanded Polystyrene board (Nuclear-Power.net)

2.4.2.1 Applications

Some of the most common geotechnical insulation applications of EPS are as follows

- Exterior of foundation walls.
- Floor insulation.
- Load-bearing component in residential, commercial, and industrial floor systems.
- Retaining walls and abutments

Figure 7. EPS boards on basement walls (breastultrasound.org)

2.4.2.2 Pros

Some of the essential properties of EPS are as follows

- Long Lasting servicebility
- Thermal resistance
- Compressive resistance
- Lightweight fill material (to reduce loads on subsoils or structures)
- Moisture resistance better than XPS
- Freeze-thaw resistance
- Drainage capabilities
- Economical (see Table 6 in chapter 2.4.13)

2.4.2.3 Cons

Some of the drawbacks of EPS are as follows

- Rodents Attractive
- Brittle
- Toxic
- Heat resistance declination for temperatures higher than 80°C
- Flamabale

2.4.3 Graphite Polystyrene (GPS)

The basic chemistry of Graphite Polystyrene is the Polystyrene as its primary raw material with highly pure form of graphite, infused in polymer matrix which provide a reflective and IR absorber property and a distinctive dark gray color. It could also be considered as the updated form of Expanded polystyrene as graphite carbon particles is added instead of pentane evaporating into gas phase to the polystyrene grains during the manufacturing process, and these materials have a lower thermal conductivity i.e. 0.03 W/mK, compared to the pure EPS (Á. LAKATOS, 2018).

GPS works in the very similar way as traditional insulation, with one particular difference i.e. the highly pure graphite particles provide a reflective property to the insulation which ultimately increases the (energy) efficiency of the material. Since, the traditional insulation slows or decrease down the transfer, still heat (energy) find its way out through the most direct way into the insulation. But in case of GPS, the graphite component makes the reflection of heat by hundred times when it moves through the insulation material illustrated in the Figure 8. This action remarkably slows down the heat transfer, making GPS more energy efficient compared to the traditional EPS insulation.

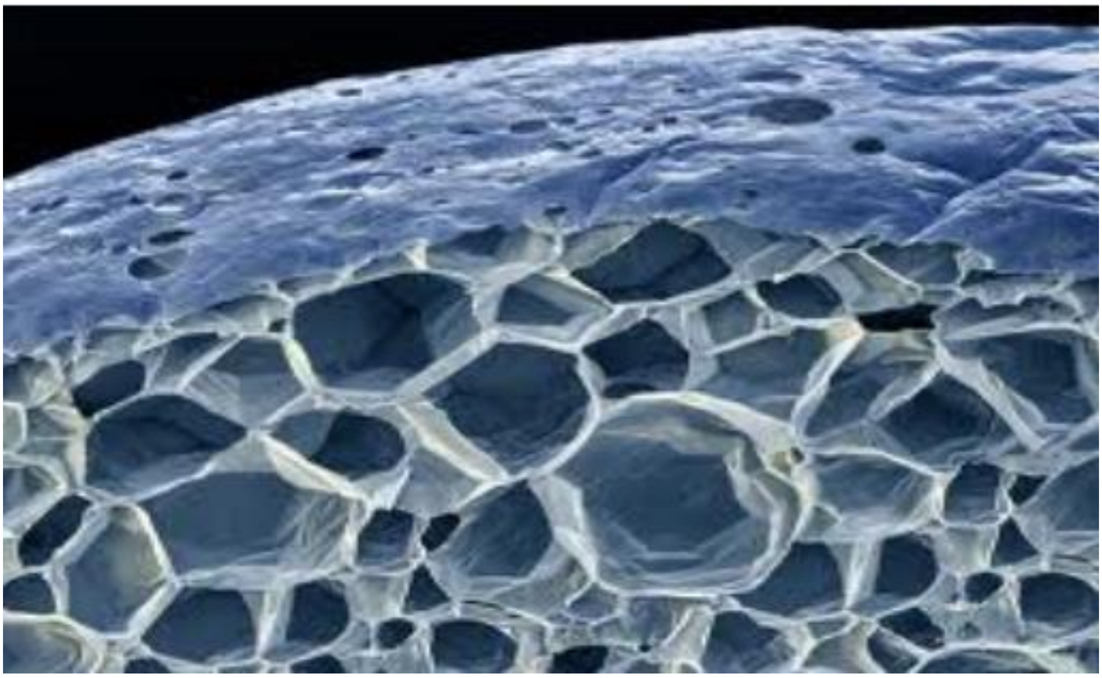

Figure 8.Close up of graphite contained within the polymer matrix (insulfoam)

Figure 9.Graphite Polystyrene Sheets

2.4.3.1 Applications

Some of the most common geotechnical insulation applications of GPS are as follows

- Perimeter and Foundation insulation
- Under the slab insulation.
- Interior and basement walls
- Continous insulation sheeting

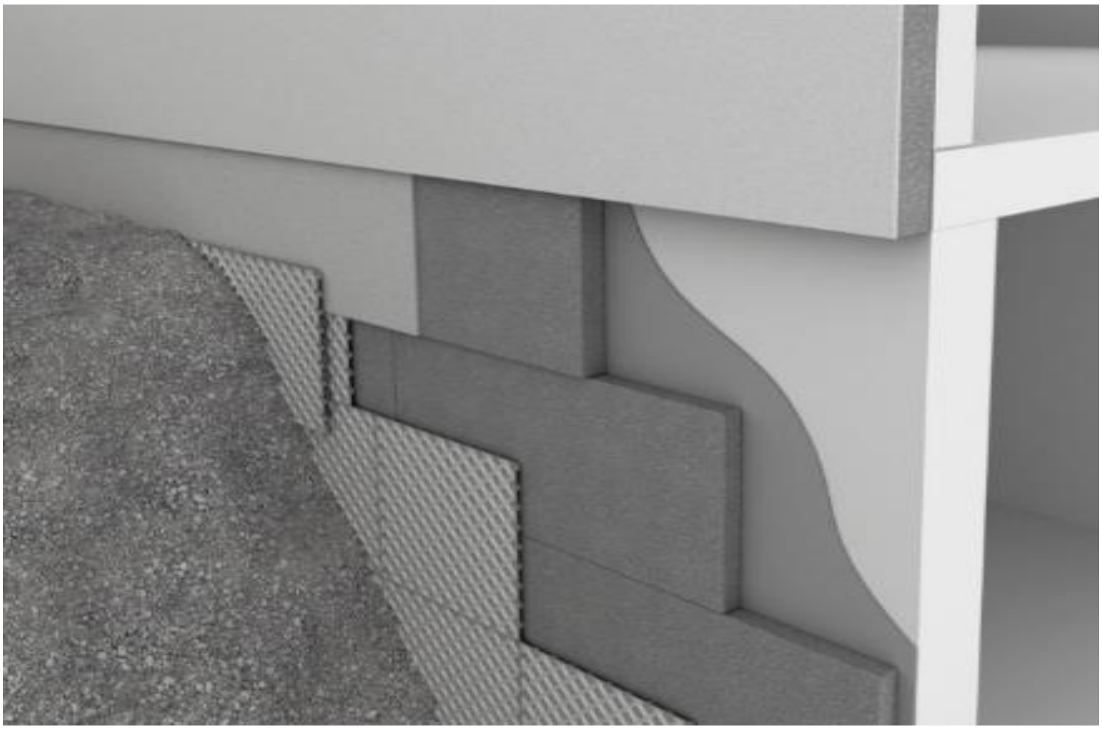

Figure 10.GPS sheets in Foundation Perimeter (insulfoam)

2.4.3.2 Pros

Some of the essential properties of GPS are as follows

- Long Lasting servicebility
- High Thermal resistance factor
- Low thickness
- High compression strength and bulk density
- Light weighted
- Moisture resistance
- Drainage capabilities

2.4.3.3 Cons

Some of the drawbacks of GPS are as follows

- Rodents Attractive
- Brittle
- Flammable
- Toxic
- Heat resistance declination for temperatures higher than 80°C

2.4.4 Silica Aerogel

A synthetic porous ultra-light material derived from gel in which the liquid components are replaced with gas, resulting into solid with very low density/ thermal conductivity. Silica aerogel is the most common aerogel comprises of silica of only 3% by volume and the remaining 97% is composed of air generally (Nano pores).

Aerogels are considered as one of the most promising and modern thermal insulation materials, although they are still commercially not available or limited. Silica aerogel consists of a nanostructured network of SiO_2 with highly translucent nature and approx. 99.8% porosities and low thermal conductivity values as shown in the Figure 11. At higher temperatures (mostly above 200 °C), radiative heat transfer become dominant and decrease the insulating capability of silica aerogels because of their low extinction coefficient with a wavelength ranges from 3 and 8 μm. The advantage of using aerogels as insulating material in Thermal energy storage (< 100 °C) is that the radiative heat transfer component remains small enough that the insulating capabilities of the material remains intact. Which in turn decrease the complexity and subsequently the cost of synthetization of the material (Willy.V, p. 2019).

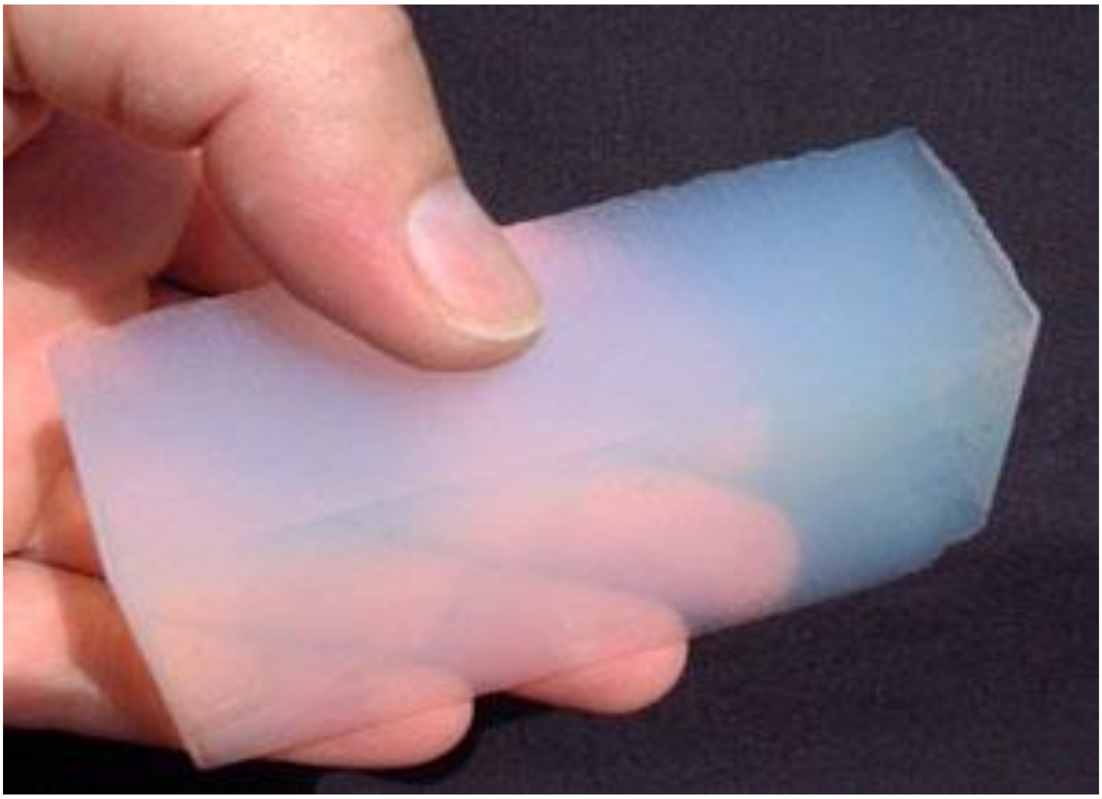

Figure 11.Silica Aerogel

2.4.4.1 Pros

Aerogels have high compression properties (high strength), that's why they are commonly used as a sandwich in constructions. The compressive strength (σc) of aerogels, as shown in Table 1, is usually sensitive to the density of the material. Aerogels with densities higher than 200 kg/m3 or lower than 100 kg/m3, are either too brittle or too ductile. Only those with moderate densities shows elastic properties which make them recover even after being compressed to its original shape (Willy.V, 2019).

Besides, Aerogels are highly thermal resistant and have high thermal tolerances. The other advantageous properties include its transparent nature which makes it more attractive compared to the other insulating materials. Similarly, it is environment friendly and also can be easily fabricated during construction.

Figure 12. Silica Aerogel foundation stairwell (mipsbe)

2.4.4.2 Cons

Silica aerogels have some drawbacks i.e. moisture vulnerability, high fragility, and lower tensile strength. The mechanical properties can be upgraded by mean of mechanical reinforcement but only at the cost of increasing their densities which ultimately increases the thermal conductivity. Similarly, the greatest obstacle in the silica aerogel application as thermal insulation is their very high production costs as illustrated in Figure 13 (Willy.V, p. 2019).

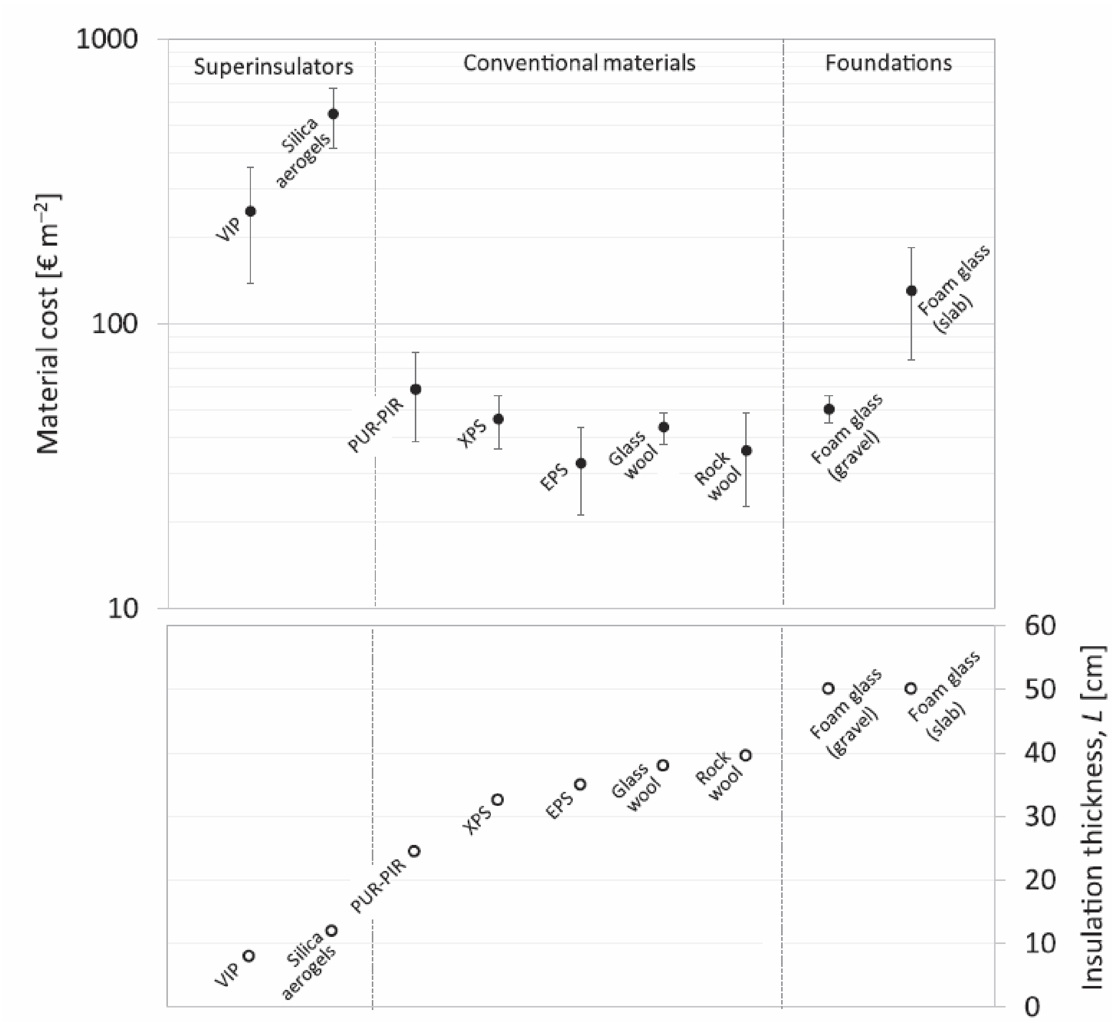

Figure 13.Material cost at top and insulation thickness at bottom required to achieve an R-value of 10m2 K W–1 with various thermal insulation materials *(Willy.V, p. 2019)*

Some of the commercial and state of the art insulating materials cost with an R-value of 10m2 K/W are shown in Table 1.

Insulation material	λ [mW m^{-1} K^{-1}]	Cost [€ m^{-2}]
EPS	35	32
Rock wool	40	36
Glass wool	38	43
XPS	33	46
Foam glass (gravel)	50	50
PUR-PIR	25	59
Foam glass (slab)	50	131
VIP	8	247
Silica aerogels	12	547

Table 1. Costs for specific materials insulating layer with an R-value of 10 m2K/W *(Willy.V, p. 2019).*

2.4.5 Lightweight expanded Clay Aggregate (LECA)

With the durability of more than 100 years, LECA, a lightweight aggregate, are commonly manufactured from bloating clays which are heated up to around 1,200 °C in a rotary kiln. The gases that are yield during the process expand the clay by thousands of small bubbles with a high proportion of semi-closed pores. The porous structure (honeycomb structure) of loosely expanded clay granulates is produced by the voids between discrete grains and also by the opening (air filled) in the grain (base) as shown in Figure 14.

LECA being a natural product contains no deleterious substances. It is chemically inactive and have a neutral pH value, resistance capability to chemicals and frost, does not break down in water, non-biodegradable, non-combustible and has also excellent acoustic and thermal insulation properties (Siamak.B, pp. ,2008).

Figure 14.The appearance of LECA *(Siamak.B, 2008)*

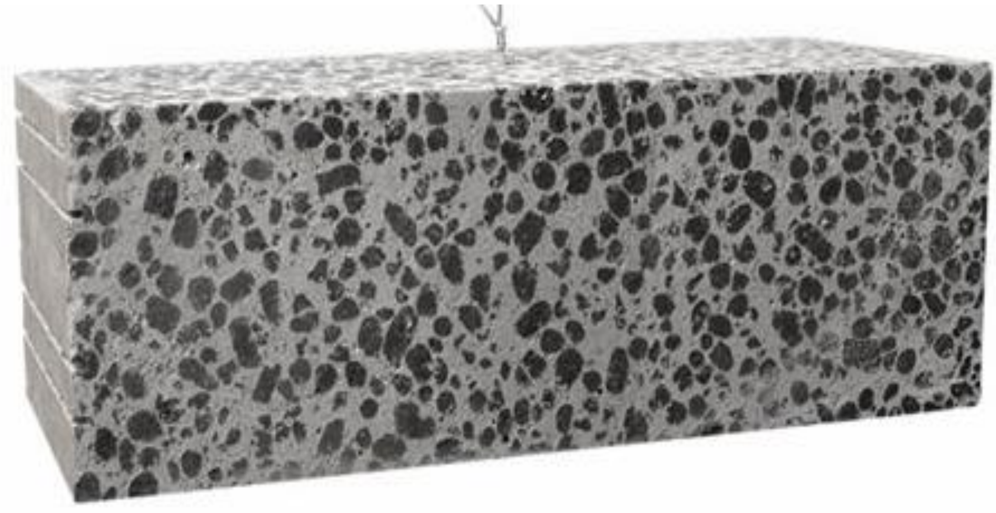

Figure 15. LECA block

2.4.5.1 Applications

LECA is a remarkable versatile material, and is exploited in a variety of applications such as in construction industry, as backfill material in foundations, bridges, retaining walls etc.
Inside the construction industry, it is broadly used for the manufacturing of lightweight concrete blocks, as soundproofing material due to its high acoustic resistance capability. Similarly, with its high thermal resistance and low thermal conductivity value, it is used as thermal insulation material in both super and sub structures. Due to its light weight and easy movement and transportation, it is also used as backfill to reduce the earth pressure by about 75% compared to other conventional back fill materials, and increases the structure stability while minimizing settlements and deformation of structures as illustrated in Figure 16,17 (Siamak.B, 2008). The grading of LECA that is suited for geotechnical applications is in the range of 10-20 mm for its lightweight, insulating properties and free draining (leca.co.uk).

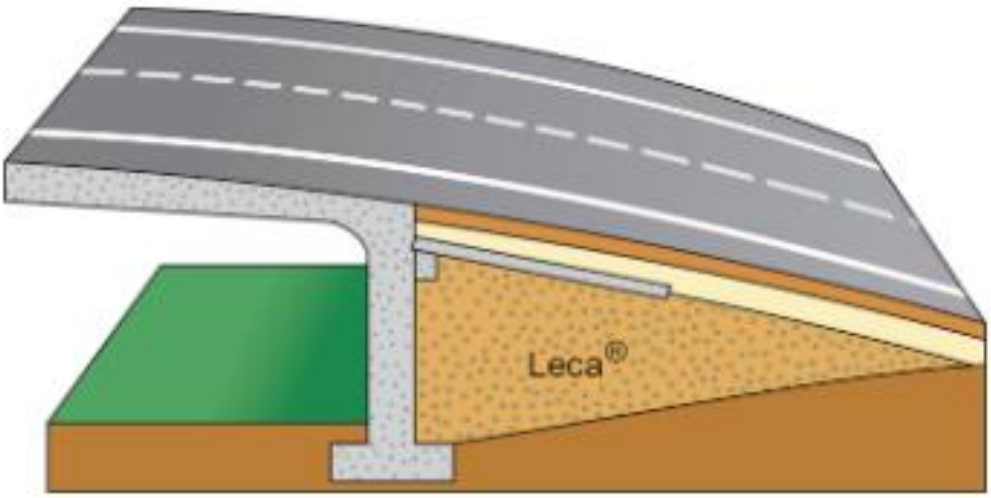

Figure 16. LECA as bridge abutment (leca.co.uk)

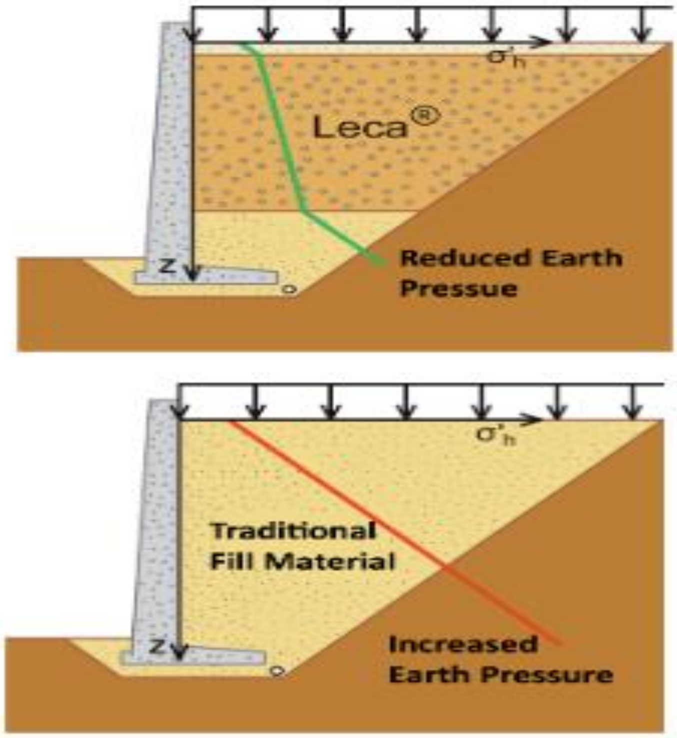

Figure 17. LECA in Retaining structures (leca.co.uk)

2.4.5.2 Pros

Some of the essential properties of LECA are as follows.

- Light weight
- Low thermal conductivity
- Acoustic resistance
- Incompressible under permanent pressure/ gravity loads
- Non–decomposition against severe condition
- Fire, freezing and melting resistance
- Easy movement and transportation
- Lightweight backfill and finishing (high friction angles despite granular shape)

2.4.5.3 Cons

Some of the drawbacks of LECA are as follows

- Nonhomogeneous Leca concrete mixture (if the required amount of water is not properly controlled)
- Leca concrete has lower strength compared to ordinary concrete under concentrated load (CLC)

- With the increase in density, the strength increases while thermal resistance decreases

2.4.5.4 Categorizing LECA

The size categorization is done after the process of production. The categorization is done based on the LECA application. Table 2, shows the LECA categorization by its constructional application.

Leca Wide Applicability	Leca Gradation (mm)	Density (kg.m-3)
Leca Light Weight Concrete,Light Weight Block, Prefabricated Panels & Slabs.Light Filler.	0-4	610
Light Weight Concrete, Light Weight Block.	4-10	430
Light Weight Filler Concrete, Sewage System Landscaping.	10-25	380
Floor & Roof Sloping, Road Construction.	0-25	430

Table 2. Common Size Categorization of LECA *(Siamak.B, 2008)*

It is also possible to do LECA categorization based on the density grade. This kind of categorization is mentioned in Table 3.

Type	Density grade	Packing density ($kg.m^{-3}$)	Compression strength (MPa)	Water absorptio n rate (%)
Light Weight LECA	400	310 – 400	2.0	16.5
	500	410 – 500	3.6	13.0
High Strength LECA	600	510 – 600	4.2	7.50
	700	610 – 700	5.6	6.00
	800	710 – 800	6.4	4.50
	900	810 – 900	6.8	4.20

Table 3. Common Density Categorization of LECA *(Siamak.B, 2008)*

2.4.6 Perlite

Perlite is a kind of rock (volcanic glass) that is mined in the form of perlite ore. The ore is crushed and rapidly heated to a temperature of about 900°C (1,700°F). This process makes the volcanic glass soft, thus generating entrapped water molecules in the rock that turns to steam and expand the particles to form a low-density cellular structure. The expanded particles made, are basically minute clusters, with lightweight and insulating glass bubbles that makes it to a highly efficient insulation material as illustrated in Figure 18 (Perlite.org, 2019).

Figure 18.Perlite (greengoldfarms)

Figure 19. Perlite Cement block (Santuario Gaia)

2.4.6.1 Applications

Due to efficient thermal insulation properties, Perlite is used as insulating concrete pool base, which can considerably reduce the heat losses to the surrounding soil mass thus keeping pool water warmer as shown in Figure 20.

Expanded perlite is also used in masonry wall applications. It provides a robust, economic and enduring method in insulating the masonry walls. Reduction in the transmission of heat can be achieved when Perlite loose fill is used in void cores of concrete block or cavity kind of masonry walls, based on design boundary conditions. Silicone treated perlite can reduce the water transmission, tested in laboratory, conducted on water transmission by 'Structural Clay Products Research Foundation' in which a cavity wall that is filled with Silicone treated Perlite does not show the transmission of water through it even under critical conditions. It is a non-flammable, industrial mineral that produces an excellent thermal performance as shown in Figure 22.

Perlite can also be used in under-slab insulation in the form of perlite bags as it does not rot nor allow rodents habitat as shown in Figure 21. It is also very useful in the construction of chimneys, stoves and pizza ovens as it can sustain high temperatures (Perlite.org, 2019).

Figure 20. Refurbishment of an outdoor in-ground pool with (insulating) perlite-concrete pool bottom (perlite.org)

In Table 4, the typical cement to perlite mix ratio is shown, in which it can be concluded that, by increasing the cement ratio increases the strength but decreases the thermal insulating performance of the concrete produced.

TYPICAL PROPERTIES		
Cement to Perlite Ratio (mix)	Thermal Conductivity "k"	
	k [Btu in/(h ft2 °F)]	**λ** [W/(m °K)]
1:5	0.71	0.102
1:6	0.64	0.092
1:8	0.54	0.078
Standard Concrete	6.75	0.973

Table 4. Typical mixing formulas for insulating perlite aggregate concrete *(Perlite.org, 2019)*

The apparent thermal conductivity of perlite is also density dependent. Tests have been performed on the same density perlite at different thicknesses in accordance with (ASTM C 518) standard. Table 5, shows the measured conductivity in various samples of perlite at different thickness (Perlite.org, 2019).

Test Density lb/ft^3	Test Thickness in.	Apparent Thermal Conductivity at °75F $Btu \cdot in/h \cdot ft^2 \cdot °F$
4.55	2	0.298
4.55	6	0.296
6.35	3.7	0.34
6.35	6.0	0.33
7.0	2.0 6.0	0.34 0.34
7.4	2.0 6.0	0.35 0.35

Table 5. Apparent thermal conductivity of Perlite *(Perlite.org, 2019)*

Figure 21. Perlite bags tightly placed on grade

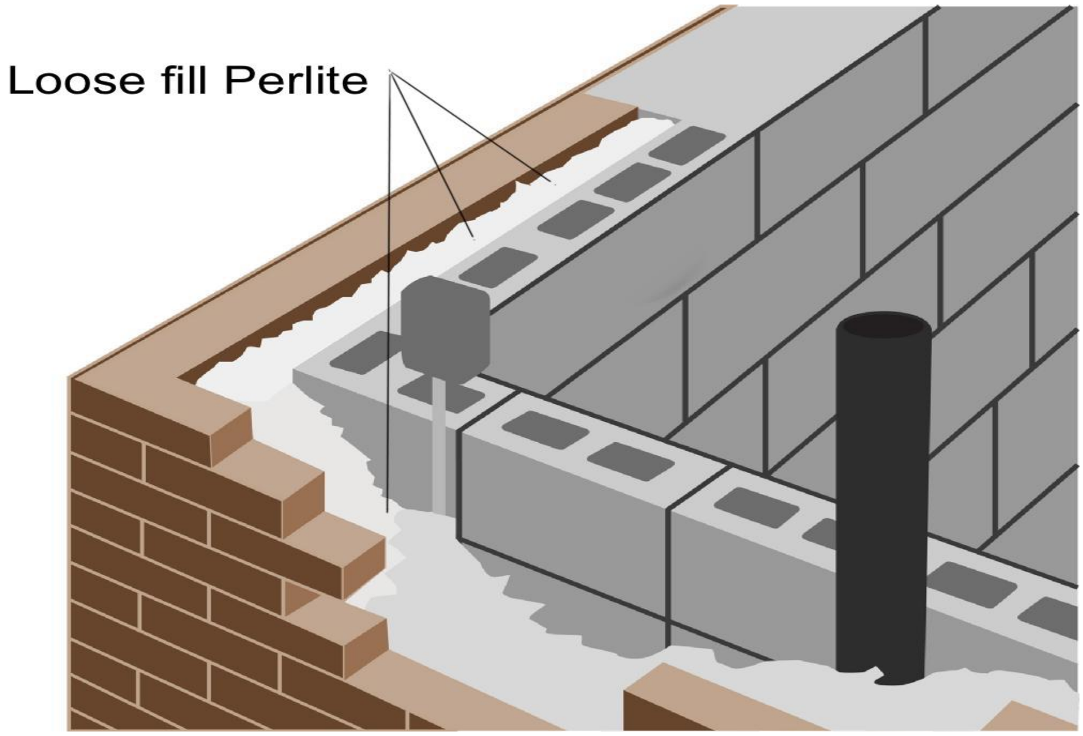

Figure 22. Loose fill perlite (marccharlessteakhouse)

2.4.6.2 Pros

Some of the essential properties of perlite are as follows.

- Moisture/ Corrosion/ Fire Resistance
- Thermal Performance
- High Rigidity (strength)
- Ease of fabrication (easily cut & placed)
- Vermin Proof (Rodents resistive)

2.4.6.3 Cons

Some of the drawbacks of perlite are as follows

- Moisture in perlite can have a significant effect on its insulating and heat retaining properties
- Perlite dust can cause chronic poisoning
- Little fragile during installation

2.4.7 Vacuum Insulated Panels (VIP)

Vacuum insulation panels (VIP), amongst the insulation materials, have the lowest thermal conductivity (as low as 4mW/mK) and is symbolized as one of the most favorable high-performance insulation (thermal) solutions with reduced thickness nowadays as illustrated in Figure 13 and Table 1. A common VIP product consists of an open, extremely porous core, from which the air has been evacuated and wrapped in an air tight sealed envelope of polymer laminate layers. Most commonly used core materials consists of fumed silica, aerogels, expanded perlite, fiber glass, PUR-foam, expanded cork, polystyrene foam etc. as shown in Figure 23. Among these, the most commonly used core-material is fumed silica, which is used in the building sector due to its lowest thermal conductivity and also its high life expectancy i.e. more than 50 years (Willy.V, 2019).

In high temperature applications i.e. around or above 100 °C, prototypes of VIP have been created with panel envelope films of HR-CPP (polypropylene) and PBT (polybutylene terephthalate). Using a PBT film, it was shown that even if the VIP specimen is exposed to a temperature of 105°C for 200 days with the initial thermal conductivity value of λ = 3.5mW/mK, the λ is maintained to the value which is lower than 6.5mW/mK at the end of the test. While, the thermal conductivity of a VIP with conventional aluminum coating, exposed to the same temperature (105°C) deteriorated, reaching to almost 20m W/mK after testing of only 80 days (Willy.V, 2019).

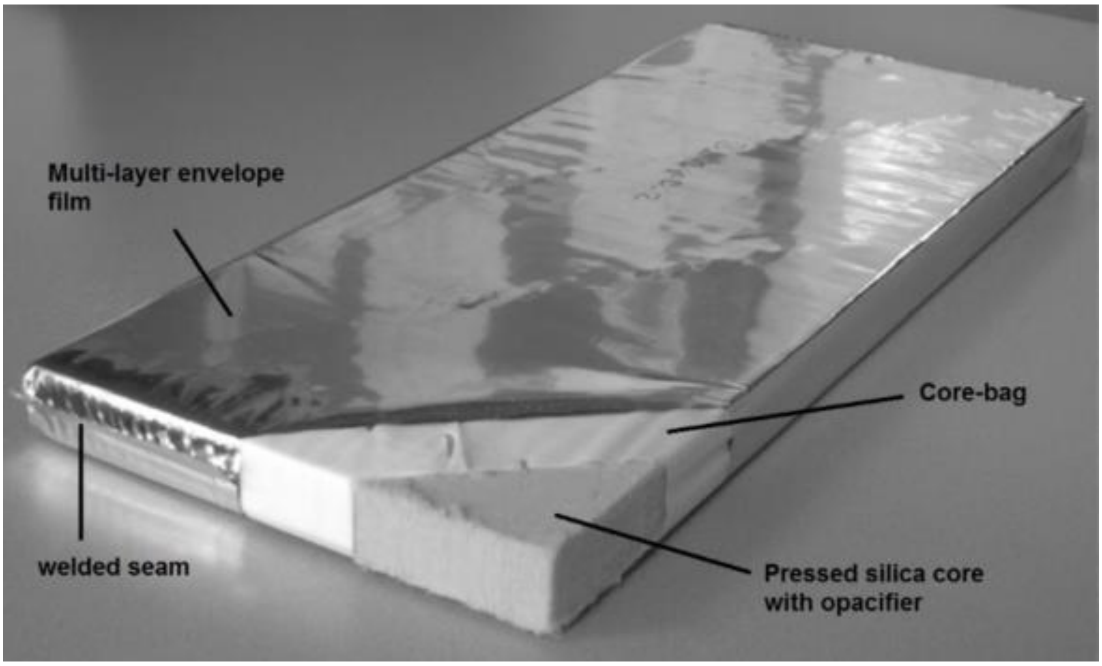

Figure 23. Regular VIP with pressed silica core (Peyman Karami)

Similar to VIPs, in principle, is the gas-filled panels (GFP) technology. In which gas is used instead of vacuum, which have less thermal conductivity than air, e.g. krypton (Kr), xenon (Xe), and argon (Ar) (Jelle, 2011). The puzzle structure and foil barrier of a GFP is shown in Figure 24.

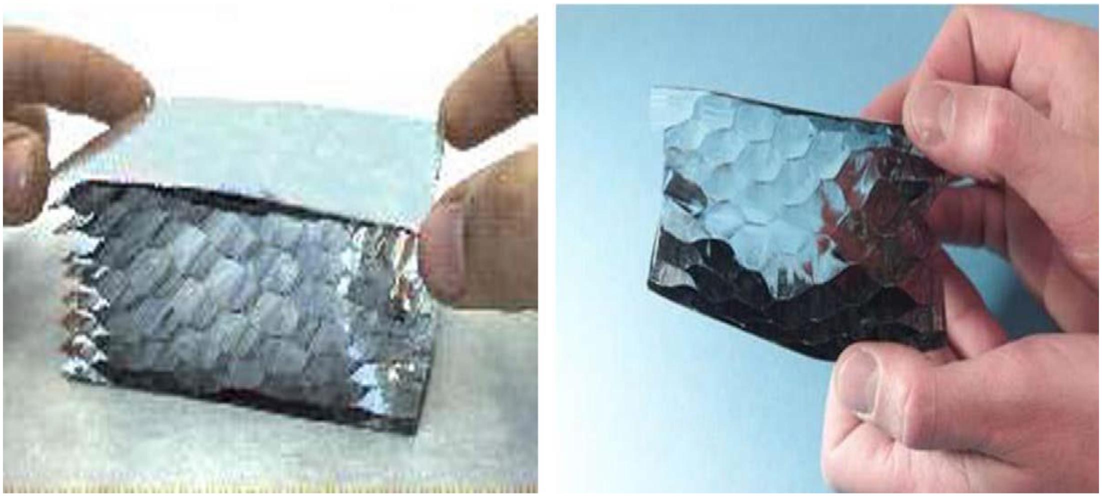

Figure 24. Puzzle structure and barrier foil of a GFP (Jelle, 2011)

The future of gas-filled panels (GFPs) is considered uncertain, while vacuum insulated panels (VIPs) appears to be a preferred choice due to its capability of attaining a very low thermal conductivity and being more tough, for now and in the coming future (Jelle, 2011).

2.4.7.1 Applications

Some of the most common geotechnical insulation applications of VIP are as follows

- Building construction
- Underground construction
- Used in High living area (market value per square meter)
- Used where High thermal insulation required

Figure 25.VIP on internal basement wall (buildingcentre)

2.4.7.2 Pros

Some of the essential properties of VIP are as follows

- Moisture/ Corrosion/ Fire Resistance
- Excellent thermal performance
- Rigidity (strength)
- Highly thermal resistant
- Excellent water resistant
- High compressive strength
- Lowest thickness
- Vermin proof (Rodents resistive)

2.4.7.3 Cons

Some of the drawbacks of VIP are as follows

- Expensive (see Table 1,6 in chapter 2.4.4.2 & 2.4.13 resp.)
- Difficult to manufacture
- Strict quality control of the membrane manufacture and sealing joints
- Sensitive to damage
- Upon puncturing causes increase in thermal conductivity
- Complex fabrication
- Cannot be cut to fit as with conventional insulation as it would destroy the vacuum

2.4.8 Cellular glass (Foam Glass)

Cellular glass (CG) or also known as Foam glass (FG) comes in the category of inorganic insulation material having a closed cell structure. It is mainly consisting of glass (including high proportioned waste and recycled glass) with calcium fluoride, sodium carbonate, sodium sulfate, sodium nitrate, iron oxide, and manganese oxide, melted at 1400 °C to produce glass, in which carbon is added as a blowing agent and then baked in a furnace at high temperature. The backed product is then passed through a tunnel where the temperature is gradually decreased to cool it down and eventually cut into desirable shapes e.g. boards (Figure 27) and slabs and also in grains which is specifically named as foam glass. While this process the chemical features of the inorganic glass is well preserved. The foamed glass can be manufactured in variety of grain sizes (2 mm - 50 mm) for different applications as illustrated in Figure 26.

Cellular glass is considered as ‘permanent thermal insulating material with no need of renewal’, due to its features such as environmental friendly nature and durability in extreme conditions i.e. cryogenic temperature and hot temperatures up to approx. 430°C.

For the installation of CG boards or slabs, bitumen could be used as suitable adhesive material for bonding the joints and facings. This might affect the reaction to fire rating according to Euro classification (Gellert, 2010).

Figure 26.Foam glass granulates (Pinterest)

Figure 27.Foam glass block

2.4.8.1 Applications

Some of the most common insulation applications of Foam Glass are as follows

- Below slabs and underground construction
- Underground pipelines and tank foundations.
- building exterior wall and roof insulation
- Used as sound insulation in cinemas
- Places which requires heat insulation equipment, Leak prevention

Figure 28.Foam glass board installation on basement walls (BuildingGreen)

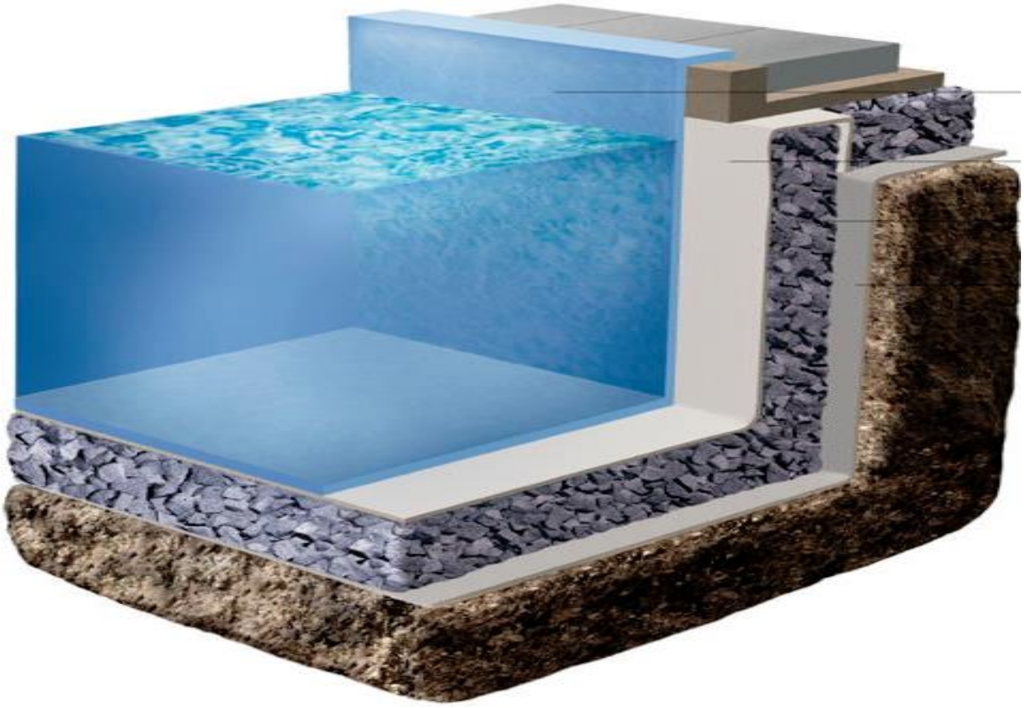

Figure 29.Foam glass granulates under pool to reduce the heat transfer (MISAPOR)

Figure 30.Foam glass granulates under grade applications (MISAPOR)

2.4.8.2 Pros

Some of the essential properties of cellular or foam glass are as follows

- Low thermal conductivity

- Low Density
- Good Thermal resistant
- Fire resistant (Incombustible)
- High compressive strength
- Water/Moisture impermeable
- Totally inert
- Environment friendly
- Long Lasting serviceability
- Durable in extreme conditions i.e. cryogenic temperature
- Rodent, Vermin resistant
- Economical in the form of gravels (see Table 6 in chapter 2.4.13)

2.4.8.3 Cons

Some of the drawbacks of foam glass are as follows

- Fergile
- Susceptible to vibration
- High installation cost

2.4.9 Foam Concrete (FC)

Foamed concrete (FC) or sometimes referred as cellular concrete (CC) belongs to a vast majority (category) of closed cells concrete in which the air-voids are trapped in the cement-based mortar matrix using aerating agents. It contains no large aggregates but only fine sand with extremely lightweight materials containing cement, water and at least 20% by volume air as shown in Figure 31, 32 (Xianjun Tan, 2014). It has a low density between 300 kg/m3 - 1600kg/m3 with thermal conductivity between 0.10W/mK - 0.66 W/mK and compressive strength of about 1 – 60 MPa compared to normal concrete which have compressive strength of up to100MPa (Nooraini MZ, 2009).

Figure 31.Foam concrete panels preparation

Figure 32.Foam concrete

The air bubbles in the Foam Concrete plays an important role with respect to better thermal insulation properties. These bubbles, also known as closed cell restrain or reduce (prevent air movement) heat flow, thus the air entrapped in the material provide high thermal resistance values (R- value) as illustrated in Figure 33 (Nooraini MZ, 2009).

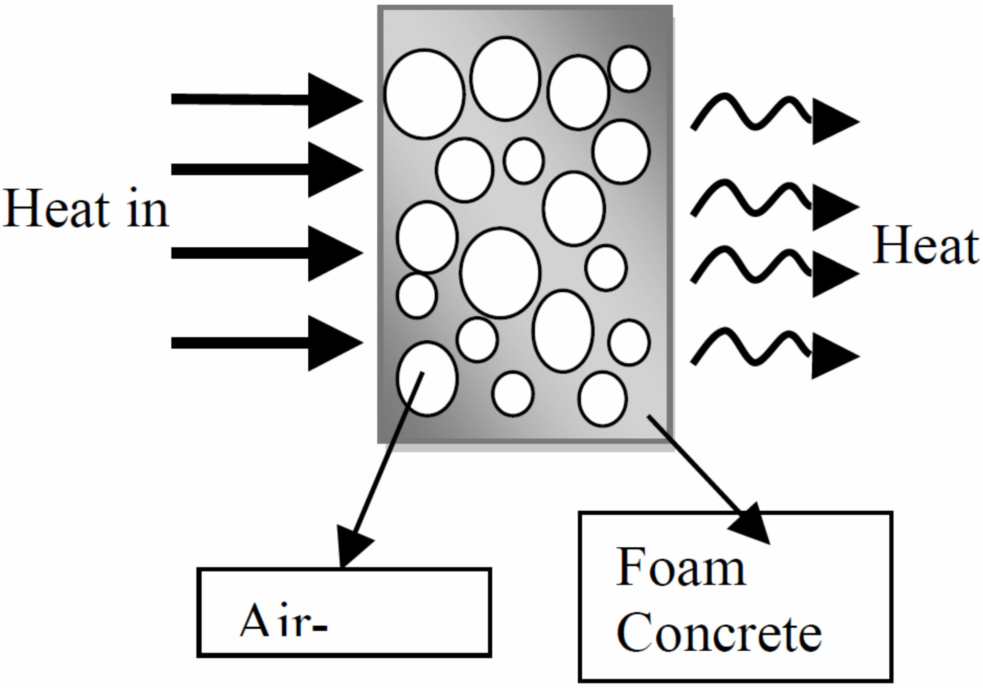

Figure 33. Air voids in foam concrete preventing heat flow *(Nooraini MZ, 2009)*

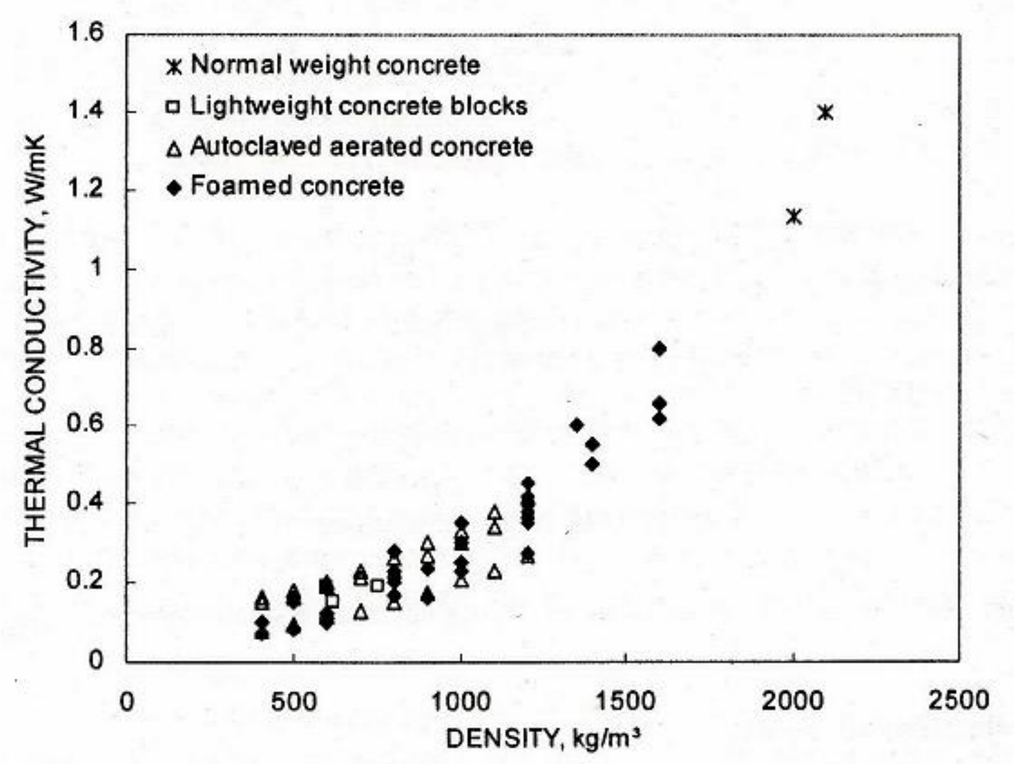

Figure 34.Relation of Density with Thermal conductivity of FC, ACC, LC and NC *(Nooraini MZ, 2009)*

According to the Figure 34, the thermal conductivity values of foam concrete are decreasing in the range of 0.1 W/mK - 0.7 W/mK with decreasing densities i.e. in the range of 600 kg/m3 - 1600 kg/m3. There is a big difference compared to normal weight concrete which attains a thermal conductivity of about 1.6 W/mK with a density of about 2200 kg/m3.

2.4.9.1 Applications

Some of the most common insulation applications of foam concrete are as follows

- Foundations, and other geotechnical applications
- Mine fill applications
- Oil-well cementing projects
- Backfill material in excavation projects
- Sound and heat insulation in building panels
- Fire-protection wall

2.4.9.2 Pros

Some of the essential properties of foam concrete are as follows

- Light weight (compared to classical concrete)
- Moisture resistant
- Fire resistant
- Good compressive strength
- Sound insulation
- Freeze and thaw resistant
- Long Lasting serviceability
- Rodent resistant

2.4.9.3 Cons

Some of the drawbacks of foam concrete are as follows

- Foam concrete is very sensitive to water (water content) during the mixing procedure
- With the decrease in density the compressive strength and flexural strength decreases
- Expensive compare to AAC (60-100€/m^3 for the same strength)

2.4.10 Autoclaved Aerated Concrete (AAC)

Autoclaved aerated concrete (AAC), also known as porous concrete consists of fine aggregates, quartz sand, calcite gypsum, lime, cement, and an expansion agent (e.g. aluminium powder) that develops the fresh mixture to expand like bread dough. In ACC, the concrete comprises almost 80 percent of air (entrapped in the mortar matrix). After the initial set, the material is moulded and cutted into required dimensioned units. The end products are then baked in an autoclave under pressure as shown in Figure 35 (cement.org, 2018). The thermal conductivity of ACC depends on its density, moisture content and the material ingredients. Since, the thermal conductivity of a material is mostly a function of its density, it may not be a problem for its thermal conductivity, if the product is autoclaved or moist cured. The number of pores (voids) and their distribution also effect the thermal insulation of the material. So, the finer the pores, the better the insulation. The thermal conductivity of ACC is also influenced by the moisture content (i.e. by increase of 1% in moisture by mass, increases thermal conductivity by 42%).

ACC provides a good thermal insulation and also save a considerable amount of material due to its porous structure. With suitable production methods, it can be obtained in a wide range of densities (i.e. 300±1800 kg/m3) that can be used for different applications such as structural, partition and insulation grades as shown in Figure 36 (N. Narayanan, 2000).

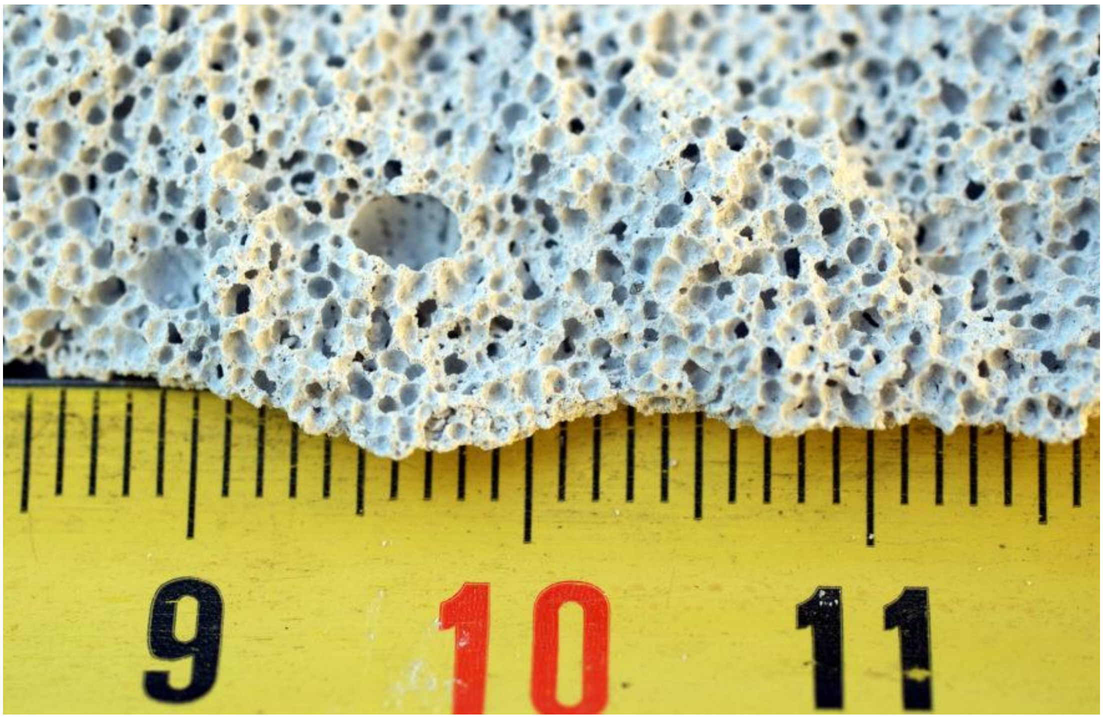

Figure 35. Autoclaved aerated concrete (CompuDAS)

2.4.10.1 Applications

ACC are commonly used as follows

- Building constructions
- Underground constructions

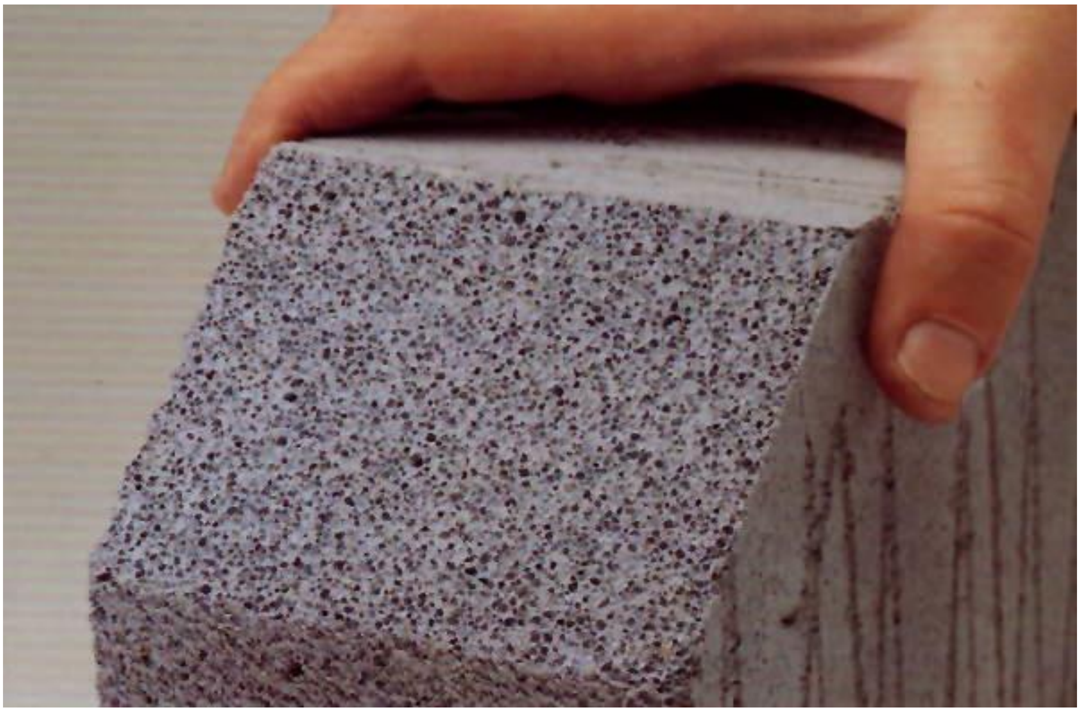

Figure 36.Autoclaved aerated concrete Block (building green)

2.4.10.2 Pros

Some of the essential properties of autoclaved aerated concrete are as follows

- Medium Thermal resistant
- Fire resistant
- Light weight composite
- Good compressive strength
- Easily fabricated & Transported
- Environment friendly
- High thermal tolerance
- Long lasting
- Rodent resistant
- Initial costs are higher compare to normal concrete but economical in long run (costs are 45-80 / m^3 with density of ≤ 525kg/m3)

2.4.10.3 Cons

Some of the drawbacks of autoclaved aerated concrete are as follows

- Not as strong as conventional concrete
- Possibly a higher thickness required for better insulation
- Brittle in nature

2.4.11 Difference between aerated autoclaved concrete and foam concrete

Aerated autoclaved concrete and foam concrete belong to the same cellular concrete category, but their main difference lies in their production (manufacturing) technology. During the manufacturing of aerated concrete, the porous structure of concrete is formed with the help of gas bubbles being the result of a chemical reaction between cement and aluminium powder contained in the gas-forming agent.

When manufacturing foam concrete, the porous structure is formed with the help of air bubbles (by adding a foaming agent into the cement mixture while mixing), uniformly distributed throughout the cement mixture. Foam concrete compared to aerated concrete has a closed-cell structure which ensures less moisture absorption.

In comparing the strengths, it can be concluded that aerated concrete is stronger material than foam concrete. For instance, for a certain class of material strength (e.g. B2) the material density for foam concrete should be at least 700-800 kg/m³, while for aerated concrete, it can be achieved with the density of 500-600 kg/m³. This also conclude that foam concrete is more expensive to manufacture than aerated concrete (Serbian Constructing technology).

2.4.12 Future thermal insulation materials

Thermal insulation materials for tomorrow are insulation materials which will have higher performance in terms of thermal conductivity and age limitations etc. There are several insulation materials that are thought to be or has been experimentally developed, the most effective in handling the thermal activities of a structure such as heat transfers. Based on material characteristics, these materials can be divided into six categories i.e. Vacuum insulation materials (VIM), Gas insulation materials (GIM), Nano insulation materials (NIM), Dynamic insulation materials (DIM), NanoCon, and other future materials as shown in Table 7 (L. Adityaa, 2017).

Material	Characteristic	Structure filled	Thermal Conductivity	Advantages	Disadvantages
Vacuum insulation	Homogeneous with a closed small pore structure	with vacuum	less than 4 mW/(mK)	The VIM can be cut and adapted at the building site with no loss of low thermal conductivity	Need to prevent air and moisture penetration into their pore structure during their service life for at least 100 years.
Gas insulation	Homogeneous with a closed small pore structure	with a low-conductance gas,e. g. argon (Ar), krypton (Kr) or xenon (Xe)	less than 4 mW/(mK)	The GIM can be cut and adapted at the building site with no loss of low thermal conductivity	Need to prevent air and moisture penetration into their pore structure during their service life for at least 100 years.
Nano insulation	Homogeneous with a closed or open small nano pore structure	The pore size within the material is decreased below a certain level, i.e. 40 nm or below for air	less than 4 mW/(mK)	The NIMs achieve their low thermal conductivity without applying a vacuum in the pores by utilizing the Knudsen effect, thereby also the overall thermal conductivity, becomes very low (< 4 mW/(mK) with an adequate low-conductivity grid structure) even with air-filled pores.	The large thermal radiation is only centered around a specific wavelength (or a few). That is, this might suggest that the total thermal radiation integrated over all wavelengths is not that large. The solid state lattice conductivity in the NIMs has to be kept as low as possible in order to obtain the lowest possible overall thermal conductivity.
Dynamic insulation	Phonon thermal conductivity, i.e. atom lattice vibrations, and the free electron thermal conductivity.		it could be possible to dynamically from very low to very high.	Thermal conductivity can be controlled within a desirable range and may be achieved by controlled ● The inner pore gas content or concentration including the mean free path of the gas molecules and the gas-surface interaction. ● The emissivity of the inner surfaces of the pores. ● The solid state thermal conductivity of the lattice.	
NanoCon	Homogeneous with a closed or open small nano pore structure	with construction properties matching or surpassing those of concrete.	less than 4 mW/(mK) (or another low value to be determined)	the potential impact of NanoCon is tremendously huge, For example, joining NIM and carbon nanotubes in one single material	
Other future materials	*Think Thoughts Not Yet Thought Of*				

Table 6.Future thermal insulation materials *(L. Adityaa, 2017)*

2.4.13 Table of Properties for different insulation materials

Materials	Insulation Properties						Mechanical properties				
	Thermal conductivity (λ) [W/mK]	Thermal Resistance R-Value per inch [ft2·°F·hr/BTU] / [m²K/W]	Thickness for (R-20/3.5) [m]	Heat flow (1*1 block with 1m thickness) [watt] / [J/s]	Density [kg/m3]	Perm rating 0(impr)-10(perm) imperial unit-perms	Compressive strength (10% def.) [KPa]	Price [€/m³]	Durability [years]	Rodents Resistance [-]	Thermal Tolerance [°C]
Extruded Polystyrene (XPS)	0.025-0.040	5.0-4.7 / 0.088-0.095	0.088	2.55	15-85	semi-impermeable (1.1)	150-690	46-50 (30-50 kg/m3)	25	no	80
Expanded Polystyrene (EPS)	0.030-0.043	4.0 / 0.7	0.105	3	10.0-80	semi permeable (5)	60-260	30-35 (30-50 kg/m3)	75-100	no	80
Graphite Polystyrene (GPS)	0.020-0.040	5.0 / 0.088	0.070	1.70	15-30	semi-permeable (4.0-2.5)	70-170	35-40 (30-50 kg/m3)	75-100	no	80
Silica Aerogel	0.012-0.021	10.0	0.042	1.02	200	semi permeable	2-100	17 [€/m²] (10mm blanket)	100	-	650
LECA	0.14-0.18	1.3	0.490	12.00	600-750	semi permeable	3500-5000	55-95	>100	yes	650
Perlite	0.07-0.08	2.7	0.245	6.00	50-200	semi permeable	500	35-50	-	yes	650
VIP	0.005-0.010	50-30	0.025	0.50	150-300	impermeable (0)	140-250	18 [€/m²] (20mm blanket)	50-60	-	around 90
Cellular Glass (Foam Glass)	0.041	3.4	0.144	3.49	115	impermeable	>600	45-50 (115-220 kg/m3)	>100	yes	430
Foam Concrete	0.11-0.77	1.0-0.5	0.385	9.40	300-1800	semi permeable	1000-60000	60-100	100	yes	Yes (no value specified)
AAC , Porous Concrete	0.12-0.20	1.0-1.25	0.420	11.00	450-750	semi-permeable (5)	3000-7500	45-80 (525kg/m3)	>100	yes	700
Normal concrete	0.8-2.5 (1.6)		2.8-8.8	68.00	2200	permeable	1500-70000	70-95 (2400 kg/m3)	50-60	no (depends on type)	300

Table 7. Properties of the insulated materials that could be used in geotechnical applications (Data collected from various sources and standards

Note: The prices for the insulation materials are collected from an online trading company website called Alibaba.com. The range of prices could be different in case of local manufacturing company for different countries. Also, it must be noted that the price range for some of the materials are dependent on the density or thickness of the materials.

2.4.14 The potential of various thermal insulation materials and solutions

Table 8, basically summarizes the potential of some of the traditional, modern or state of the art insulation materials and also the thermal insulation materials which could possibly be on the market in the coming future, possessing a higher performance thermal insulation for tomorrow. Table 8, could also be utilized in terms of future thoughts or plans of how to excel or proceed beyond present day modern thermal insulation solutions. The current status of the state of the art solutions in present day and the foreseen status of the future tech materials, where is some need to be discussed and subjected to certain changes. The NIM could be a promising thermal insulation solution with highest performance, and low thermal conductivity. Similarly, NanoCon and DIMs shows a huge potential, having both, load-bearing capability in combination with good thermal insulation properties (Jelle, 2016).

Materials	Low pristine/aged thermal conductivity	Perforation robustness	Possible building site adaption cutting	Load-bearing capabilities	A thermal insulation material and solution of tomorrow?
Traditional thermal insulation					
Mineral wool	No	Yes	Yes	No	No
EPS	No	Yes	Yes	No	No
XPS	No	Yes	Yes	No	No
Cellulose	No	Yes	Yes	No	No
Cork	No	Yes	Yes	No	No
PUR	No	Yes	Yes	No	No
State-of-the-art thermal insulation					
VIP	Yes/maybe	No	No	No	Today and near future
GFP	Maybe	No	No	No	Probably not?
Aerogel	Maybe	Yes	Yes	No	Maybe
PCM	–	–	–	–	Heat storage and release
Possible future thermal insulation					
VIM	Yes/maybe	Yes	Yes	No/maybe	Yes
GIM	Yes/maybe	Yes	Yes	No/maybe	Maybe
NIM	Yes	Yes, excellent	Yes, excellent	No/maybe	Yes, excellent
DIM	Maybe	Not known	Not known	No/maybe	Yes, excellent
NanoCon	Yes	Yes	Yes	Yes	Yes, excellent
Others	–	–	–	–	Maybe

Table 8.The potential of traditional, state-of-the-art and possible future thermal insulation materials (Jelle, 2016)

3 Solar Seasonal Thermal Energy Storages (STES)

3.1 Description

Humanity have been utilizing the underground for many purposes since the birth of culture. One of the observation was that the underground temperature was generally very different from the atmospheric temperature. Thus, underground could serve as protection from coldest and hottest days in winter and summer respectively.

The temperature of the ground at some depth below surface approximately between 10m-15m, which is unaffected by the surface seasonal temperature variation, is almost equal to the yearly mean temperature of the air (Nordell, pp. ,2012).

In the last 40-50 years, thermal energy is diligently stocked in the underground thermal storage technology. This energy is stored by heating or cooling an underground storage medium so that the stored energy can be used at later time for heating and cooling applications and power generation at scales ranging from individual process, building, multiuser-building, district, town, or region.

Most commonly these thermal energy storages are constructed and used as long-term or seasonal storage. Some are also used as both short term and seasonal purposes (Nordell, pp. ,2012).

Most of the district heating systems are converting from fossil fuels to different renewable energies. Particularly, the solar heating system, as the technology is well developed and proved. However, the energy production in solar heating systems is mostly or completely dependent on solar radiations.

Furthermore, according to statistics, at Marstal District Heating 2010-2012, the solar heating system usually covers only 10 - 20% of the total heating consumption. The percentage of solar energy systems in the district heating could be increased by storing it in a seasonal thermal energy storage. The storage capacity of the system must be large enough to store the energy (solar) produced during the summer season till the winter season (Dannemand Andersen J., 2013).

In sensible storages such as Large Scale Seasonal thermal energy storages (STES), heat or energy is stored by changing the temperature of a storage medium e.g. water, soil, PCM etc. Water as a storage medium exhibit excellent transportation capabilities. It is also relatively cheap and has a sensible high heat capacity compared to the other materials.

Seasonal thermal energy storages (STES) can be created as one of the following systems i.e.

Pit thermal energy storage (PTES), Tank Thermal Energy Storage (TTES), Aquifer thermal energy storage (ATES) or Borehole thermal energy storage (BTES).

The PTES system consist of an excavated pit, usually lined with a water tight membrane and filled with energy storing medium i.e. water. In case of large scale storages, PTES system is considered as very cost-effective. Usually, the operational temperatures of the system ranges in between 30°C - 90°C.

The TTES system comprise of a water filled and insulated (steel) tank and is mostly used for short-term management purpose to balance the consumption and production of the heat at heating plants. A typical volume of around 1000-5000 m3 for most of the Danish (medium-sized) district heating systems, is often adequate. Usually, the operational temperatures ranges in between 30°C - 90°C.

The ATES system stores the energy in the form of heat in a groundwater aquifer. In this system, it is important to know the features and the extend of the aquifer as the groundwater is pumped from a number of wells which is then passed through a heat exchanger where the heat energy is extracted and then directed through to the other part of aquifer. This type of storage system requires a high permeable aquifer. Usually, the operational temperatures ranges in between 5°C - 30°C.

The BTES system comprises of a number of boreholes with heat pipes in the form of loops installed. Brine is circulated in these heat pipes to transfer the heat to the soil and vice versa when consuming heat. Typically, the boreholes depths go to 50-100 meters. Usually, the operational temperatures ranges in between 20°C - 60 °C (Dannemand Andersen, 2013).

Seasonal thermal energy storage can be designed in different forms, depending on the boundary conditions i.e. Location, land value, scale, requirement etc. For that reason, different variants of STES are discussed in details (by keeping the boundary conditions such as ground water and soil conditions, constant).

3.1.1 Introduction to the following examples

To discuss different types (variants) of STES in the following, subsoil conditions and ground water conditions which are typically to a region south of Graz in Styria (Austria) are assumed and kept the same.

The subsoil condition can be defined in a simplified way as follows. Down to a depth of about 17 m there are Sand-Gravel mixtures with a low amount of fines (less than about 15%) and a changing percentage of stones (and some boulders) originated as quartarny river sediments form the river Mur. Below this depth over-consolidated fine sediments, mainly sandy to clayey Silts with (thin) layers (and lenses) of silty Sands from the Neogen are existent.

The ground water table differs between about 3 to 7 m below ground surface. The main ground water flow occurs in the river sediments (down to a depth of about 17 m) with a high permeability of about 1E-3 to 1E-4 m/s. In the Neogen bottom layer a low (smeared) horizontal permeability of about 1E-7 to 1E-8 can be expected, whereas the horizontal permeability is about a factor of 10 to 100 higher than the vertical permeability.

3.2 Variant 1

3.2.1 Description

Variant 1 is the simplest form of TES with shallow depth almost till the ground water level. The idea is to construct such a storage where there is no need to build a cut-off wall as water barrier. An embankment is a key parameter to increase the volume of the storage. A water tight layer on the surrounding surface of the storage is installed to keep the stored water tight inside the storage basin. Since variant 1 is constructed above the ground water table, therefore the surrounding soil mass is mostly dry and the heat transfer between hot water in the TES and surrounding soil mass is low. Therefore, the insulation layer in this case is not considered as essential as illustrated in Figure 37.

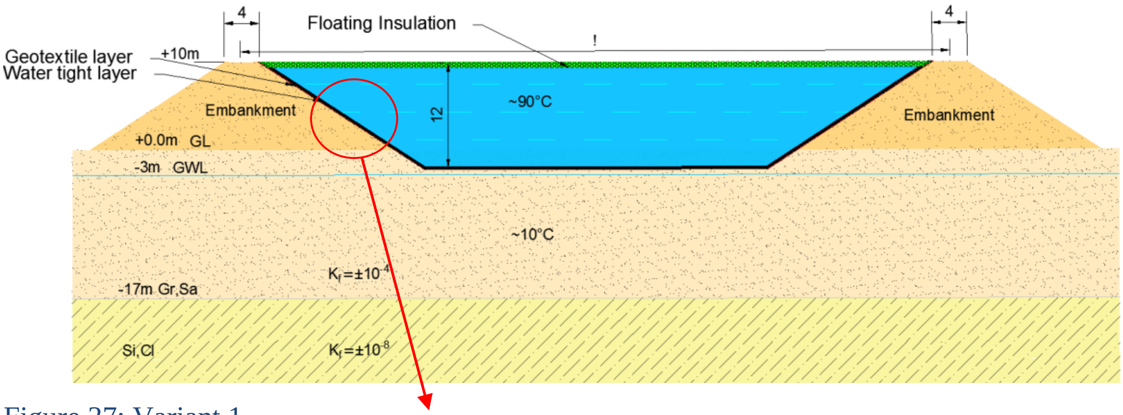

Figure 37: Variant 1

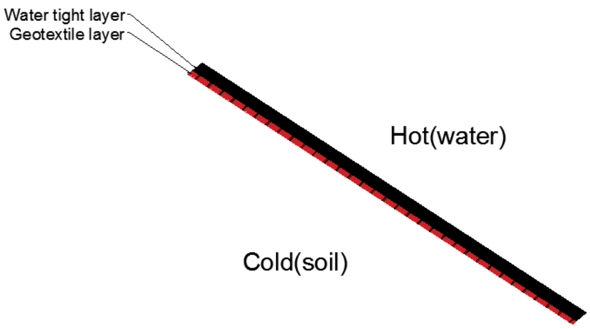

Figure 38. Magnified view of layers' sequence in variant 1

3.2.2 Pros

Some of the essential properties of variant 1 are as follows

- Easy to construct
- Low construction costs
- Maintenance possible

- No special equipment required for construction
- No anchors required for structure stability

3.2.3 Cons

Some of the drawbacks of variant 1 are as follows

- Low storage capacity
- Depth dependent (and limited) by the ground water level
- Ground water level increment could affect the system performance
- Possibility of water tight layer damaging

3.2.4 Other Possibilities

Other possibilities or additions that could be applied to variant 1 are as follows

- Height Increment of Embankment when more volume is required (where a higher dam construction need a higher contact area which is a disadvantage)
- Steeper Embankment slopes e.g. reinforced earth works to reduce the contact area of the dam construction which enable a higher storage volume
- Insulation layer provision in case of heat loss

3.2.5 Open Questions

- During (seasonal) extreme high ground water tables and a direct contact of the ground water with the storage, the efficiency of TES can decrease significantly (dependent of the groundwater flow).

3.3 Variant 2

3.3.1 Description

Although it is not the most energy efficient TES but still it is economical and uncomplicated in construction. In this variant, a cut-off wall is constructed and developed till a depth of about 22 meters (at least 5 m into the bottom soil layer). Here the cut-off wall act as a water barrier, and enables the excavation of the storage with higher depths compared to variant 1 (after the water table in the storage is decreased permanently in variant 2). The depth of the TES is chosen 1.5 - 2 meters above the bottom soil layer (with very low permeabilities). With this depth the storage will be somehow protected from direct ground water contact. A water tight layer on the surrounding surface of the storage is installed to keep the stored water tight inside the basin. Due to this water tight layer and the decreased water table within the cut off walls, the surrounding soil mass is mostly dry (low water content up to about 10%) and the heat transfer between hot water in the TES and soil mass is low. In this variant, no insulation layer is considered and provided between the storage and the surrounding soil mass as illustrated in Figure 39.

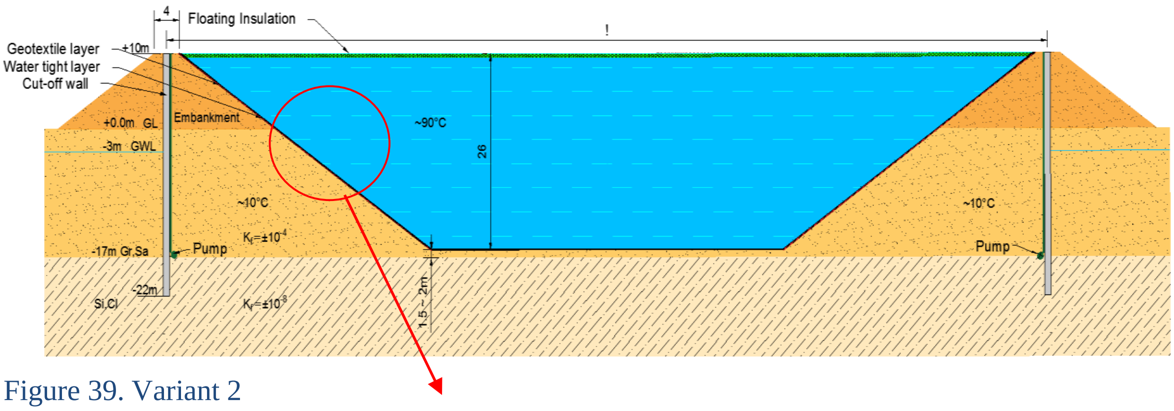

Figure 39. Variant 2

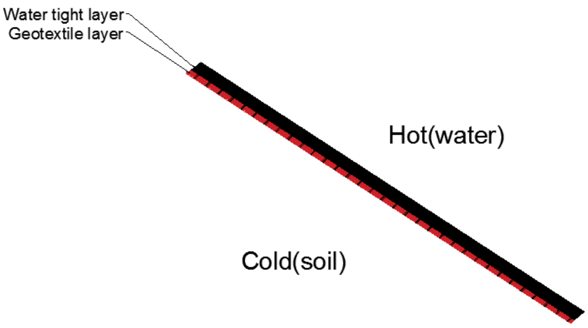

Figure 40. Magnified view of layers' sequence in variant 2

3.3.2 Pros

Some of the essential properties of variant 2 are as follows

- Not complex construction (important is a dense and good functional cut off wall)
- High depth
- High volume retaining capability
- Maintenance possible
- No anchors required for structure stability

3.3.3 Cons

Some of the drawbacks of variant 2 are as follows

- Heat transfer possible in case of increment of ground water level
- Permanent control of ground water table with (more or less) permanent ground water management (with well pumps) within the cut off wall is necessary
- Possibility of water tight layer damaging

3.3.4 Other Possibilities

Other possibilities or additions that could be applied to variant 2 are as follows

- Higher Embankment for more volume (where a higher dam construction need a higher contact area which is a disadvantage)
- Insulation of storage (between storage and earth mass) - see variant 3

3.3.5 Open Questions

- A dense and good functional cut off wall with a proper designed depth of the wall into the Neogen bottom layer is essential for an economical storage operation.

3.4 Variant 3

3.4.1 Description

In this variant, similar to variant 2, the cut-off wall is constructed and developed till the depth of about 22 meters (into the bottom soil layer). Hereby the cut-off wall act as a water barrier, and enables the excavation of the storage with higher depths. The depth of the TES is chosen 1.5 - 2 meters above the bottom soil layer (with very low permeabilities), which will keep it somehow safe from direct ground water contact. Also, a water tight insulation layer is directly installed on the surface of TES (between water storage and surrounding soil mass), which makes it an energy efficient structure due to low rate of heat transfer between hot water in the storage and surrounding soil mass. This insulation layer is the difference of variant 2 and variant3. Similar measures as for variant 2 are necessary for the ground water control within the cut off walls. The excess has to be pumped up with the help of pumps from both sides of the drainage layer at the base of the storage illustrated in the Figure 41.

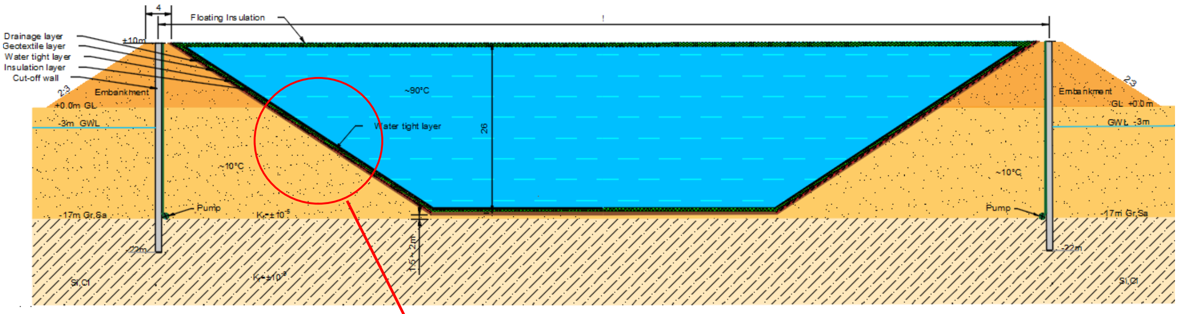

Figure 41. Variant 3

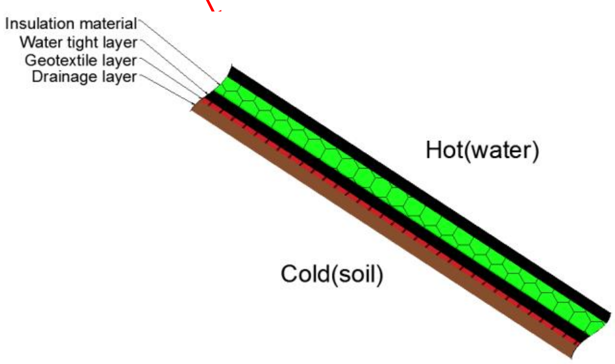

Figure 42. Magnified view of layers sequence in variant 3

NOTE: All the water tight layer or insulation layer should take the inclination of 2:3.

3.4.2 Pros

Some of the essential properties of variant 3 are as follows

- One of the most efficient TES in terms of Energy conservation
- High water volume retaining capacity
- Formwork mechanism for the insulation layer installation
- Drainage layer provision, keeping the insulation layer dry
- Pumping of the drained water with active pumps

3.4.3 Cons

Some of the drawbacks of variant 3 are as follows

- Compared to variant 1 and 2 complex and expensive construction.
- Permanent water management as mentioned for variant 2.
- Possibility of water tight layer damaging (same as variant 1 and 2).

3.4.4 Special Features

- A dense and good functional cut off wall with a proper designed depth of the wall into the Neogen bottom layer is essential for an economical storage operation.

3.4.5 Installation steps

The possible installation sequence of the tight insulation layer system is shown in Figure 43,44 and is listed as follows

- Beam structures Installation
- Drainage layer (if necessary)
- Water tight layer (with geotextiles to protect the tight layer)
- Form Work Installation
- Insulation layer
- Water tight layer

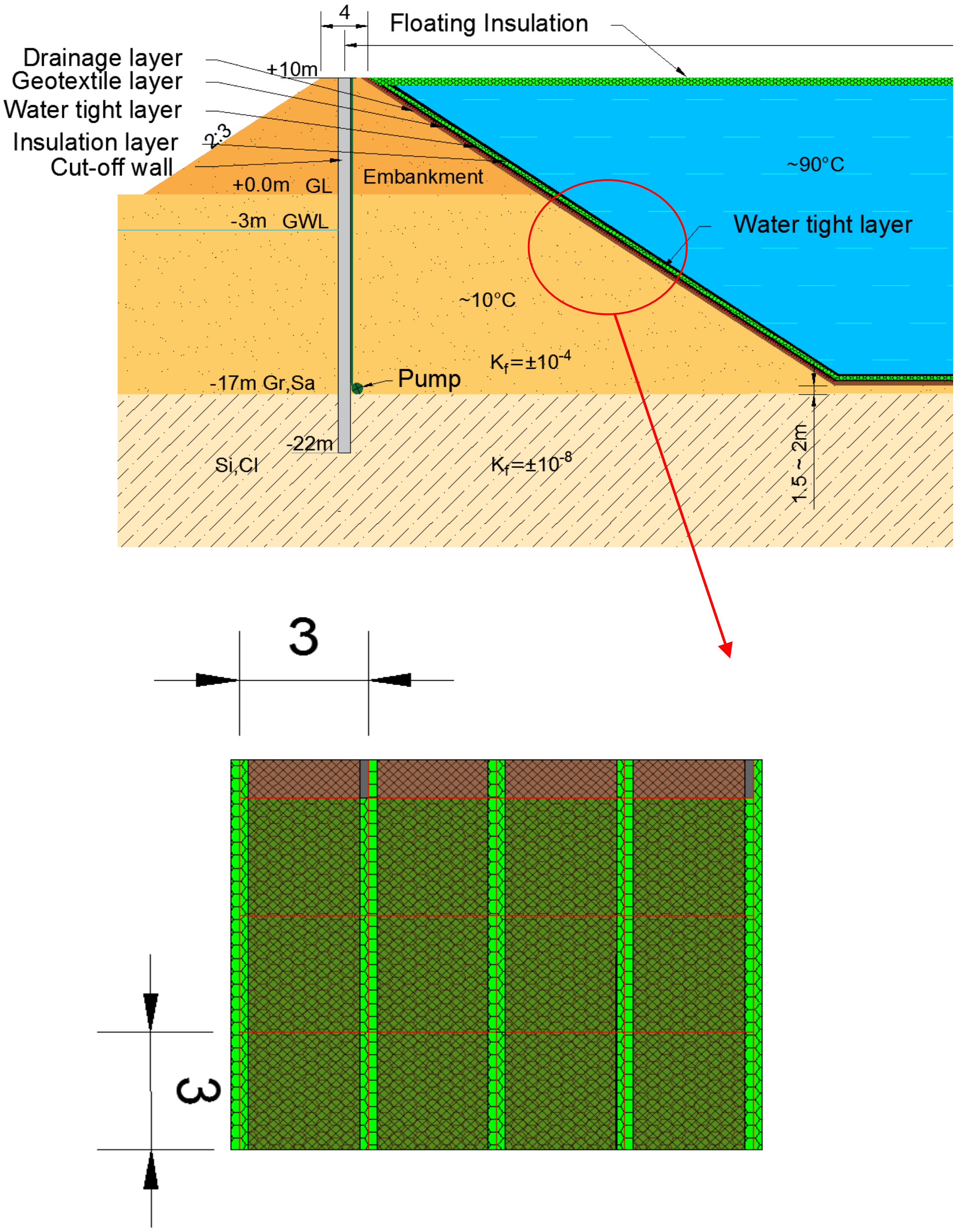

Figure 43. Top view of TES layers surface in variant 3

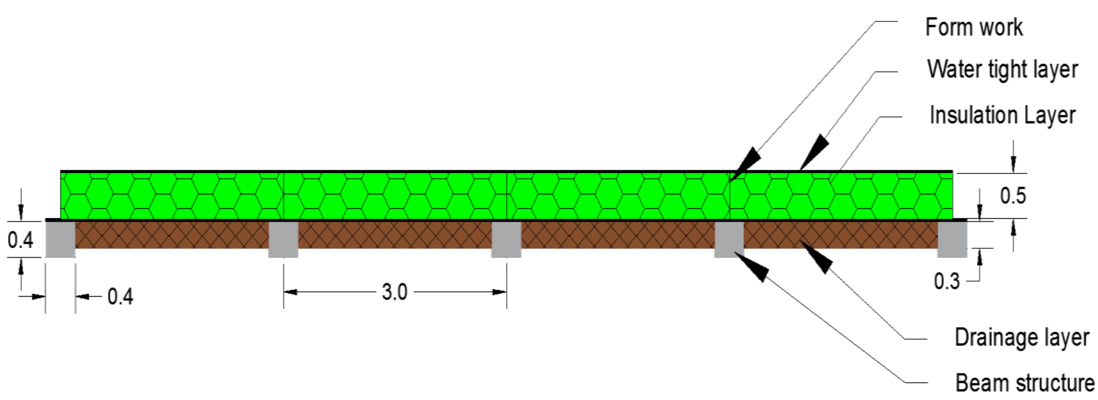

Figure 44. Cross section view of layers' sequence in variant 3

It should be noted that the installation sequence is an individual idea, therefore, the sequence and the method of installation could be changed and suggested differently. Here in this case, due to the inclination of the storage slopes, the beam structure and form work installation are necessary for developing different layers efficiently as illustrated.

3.4.6 Open Questions

- Serviceability of pumps after some years
- Serviceability of the insulation material after some years

3.5 Variant 4

3.5.1 Description

In this variant, a diaphragm wall with a length of about 22 meters is constructed till the less permeable bottom soil layer. The main aim of the diaphragm wall is to act as water barrier as well as a heat barrier. The depth of the TES is chosen ~2 meters above the low permeable bottom layer. The idea in this variant is to use the water in the TES as well as soil and pore water within the diaphragm wall as storage medium.

Insulating the diaphragm wall (D-wall) is a bit tricky but it could thermally guard the TES efficiently (indirectly). The heat transfers between hot water in the storage and surrounding soil mass is allowed as no water tight layer is provided in this case. With the D-wall, the whole system is then protected from surrounding soil mass and ground water in- respectively outflow. This makes the system, energy efficient and sustainable as shown in Figure 45.

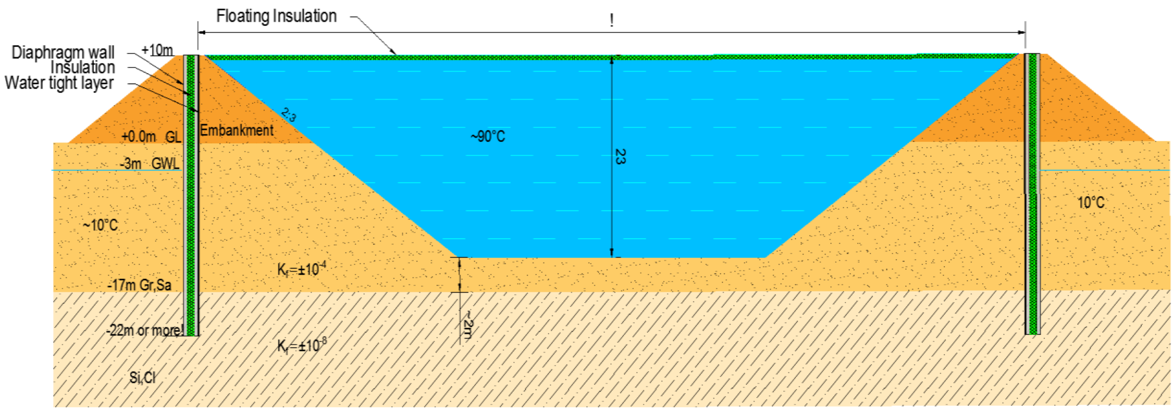

Figure 45: Variant 4

Note: The insulation of Diaphragm wall is explained in detailed in chapter 4.

3.5.2 Pros

Some of the essential properties of variant 4 are as follows.

- High volume retaining capability
- Maintenance possible
- No Formwork for insulation installation required
- No tight layer (geo-membrane) for the water storage
- No anchors required for structure stability

3.5.3 Cons

Some of the drawbacks of variant 4 are as follows

- Complex due to the construction of a diaphragm wall which has tightening and insulation function (see chapter 4)
- Extra machines required for this special type of diaphragm wall.

3.5.4 Special Features

- Thermally insulated diaphragm wall.

3.5.5 Open Questions

- Risks of a proper construction and long term behavior of tightening and insolation properties for this new system of a diaphragm wall

3.6 Variant 5

3.6.1 Description

In this variant, a circular shaft with a diameter of 50m is considered. The main idea is to fulfill the requirement of a Giga scale TES, by occupying less area. In this method, due to the circular structure, the loads are distributed around the circumference of the TES and thus, the structure remains stable without taking structure stabilizing measures i.e. anchors, struts etc.

When it comes to high land value problems in urban area, circular shaft TES are an efficient choice compared to the other types of TES, as it has the capacity to go deep (depending on the structure stability and the limitations of the fabrication) and can retain a huge amount of water. With the direct insulation of the Walls and base of TES, the system is completely energy efficient with least heat transfer between the mediums as shown in Figure 46.

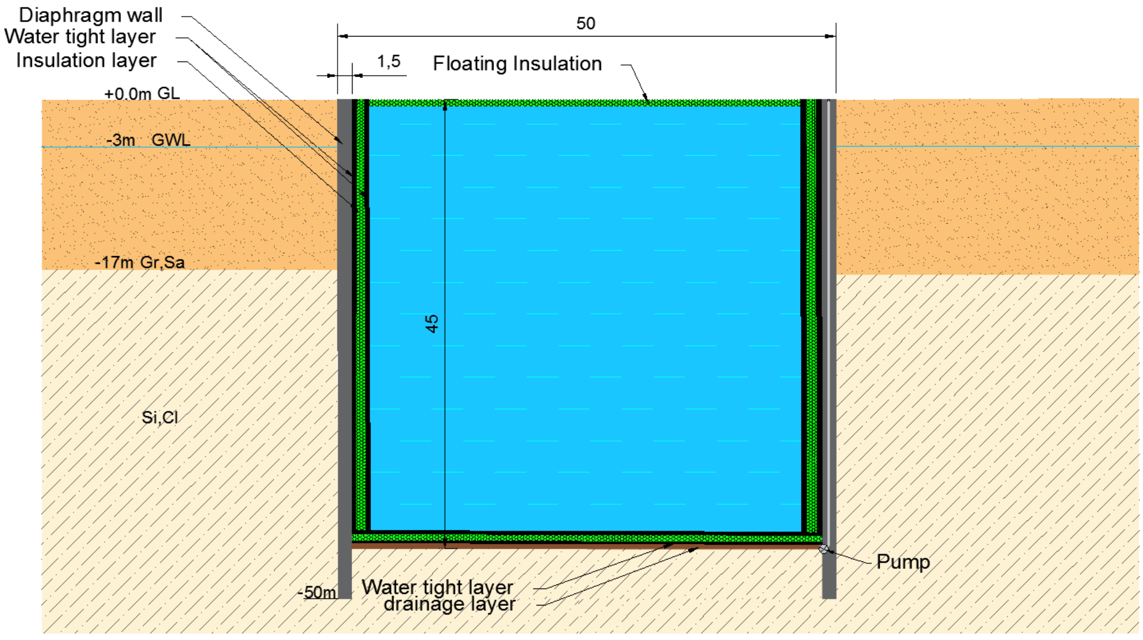

Figure 46. Variant 5 (circular shaft)

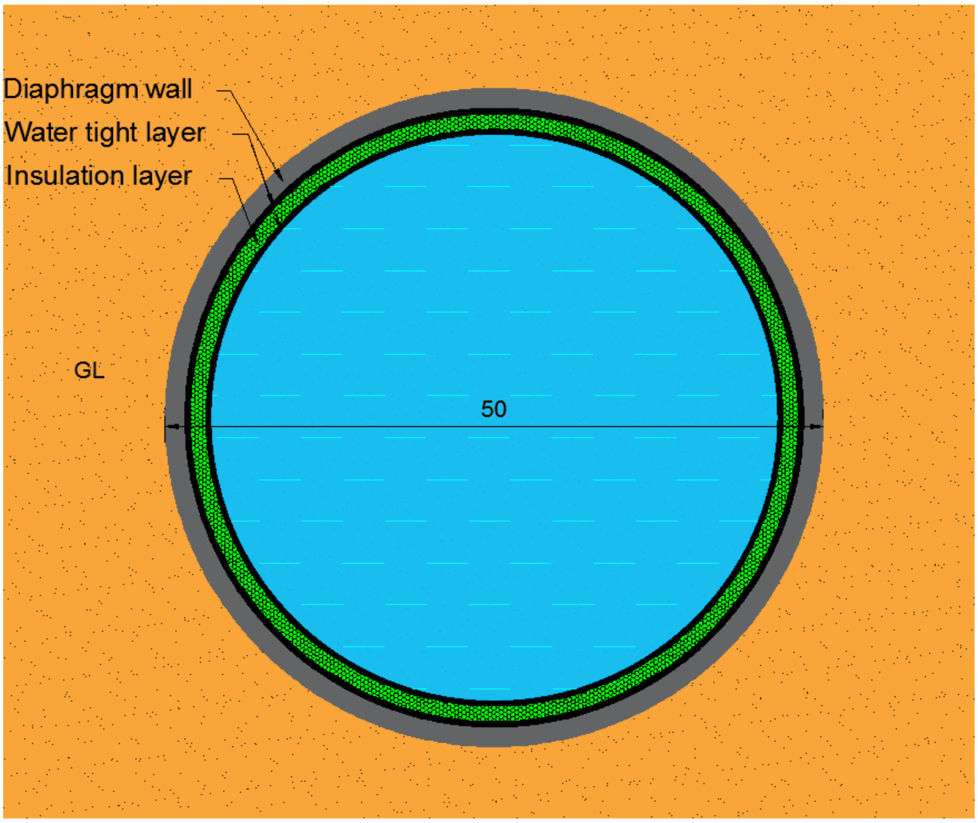

Figure 47. Top view of Circular shaft

3.6.2 Pros

Some of the essential properties of variant 5 are as follows

- Less surface area required with deep excavation
- Self-stability of loads due to circular structure
- Directly thermally insulated walls and base slab
- High volume retaining possibility with increasing depths
- Formwork possible for insulation installation
- No anchors required for structure stability

3.6.3 Cons

Some of the drawbacks of variant 5 are as follows.

- Challanging insulation installation
- Constrained diameter of the shaft due to structure stability
- Deflection of diaphragm walls at higher depths

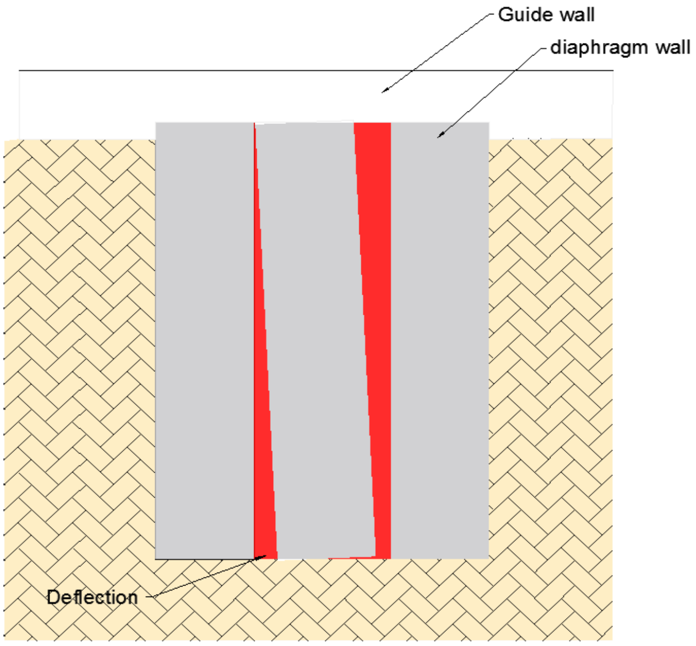

Figure 48. Cross section view Diaphragm wall Deflection concept at higher depths

As the allowable deflection (due to standards) rate is 1% per 1m depth, so to cope with this problem, new technology machine such as hydro cutter (hydromills), could be used as shown in Figure 49. With these machines the probability of deflection at depths is minimum and the excavation can go to higher depths e.g. till 250m.

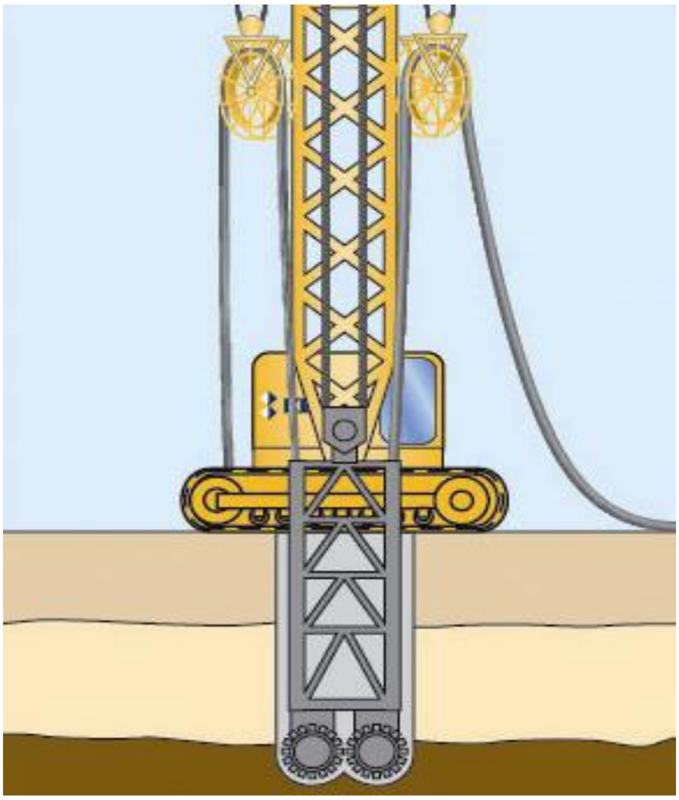

Figure 49. Hydro cutter machines for Diaphragm wall excavation

3.6.4 Special Features

- Drainage layer at the base directly above the excavated area
- Water management in case of high water level and uplift problems

3.6.5 Other Possibilities

Other possibilities or additions that could be applied to variant 5 are as follows

- Injected seal slab could also be used in case of water uplift
- Cut-off wall could be used as water barrier in case of high water flow
- Construction of embankment for storage capacity increment, as illustrated in the Figure 50.

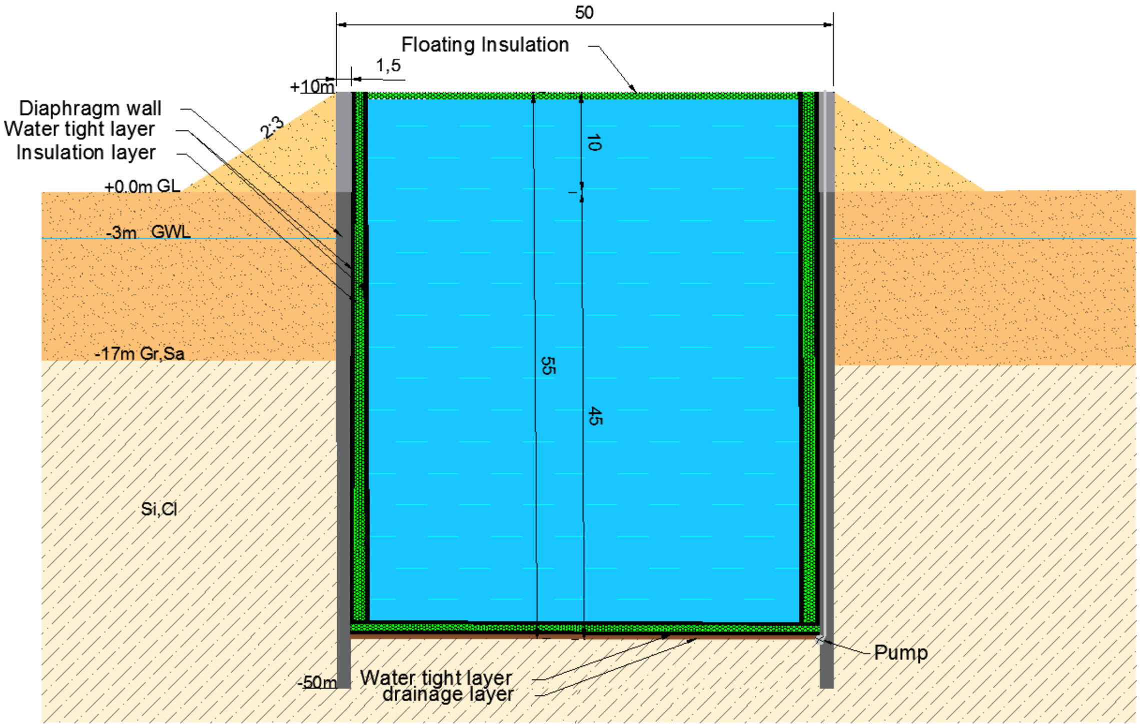

Figure 50. Variant 5 with embankment

3.6.6 Open Questions

- Structure stability of circular TES with increasing diameter and depths.

3.7 Variant 6

3.7.1 Description

In this variant, the concept is similar to the variant 5 but with a modification of combining more than one circular TES together with the help of cross diaphragm walls. The circular diameter of the TES remains 50 meters with the same depths and thickness of the diaphragm wall. The cross D-wall is introduced in such a way that the structure load is completely distributed along the shaft and then taken by the cross D-wall. The biggest advantage of this method is that we can combine as much shafts (acting independently) as we need based on our requirements and increase enormously the storage capacity of the system.

Identical to variant 5, with the direct insulation of the walls and base of TES, the system is completely energy efficient with least heat transfer between the two mediums i.e. hot water and surrounding soil mass as shown in Figure 51.

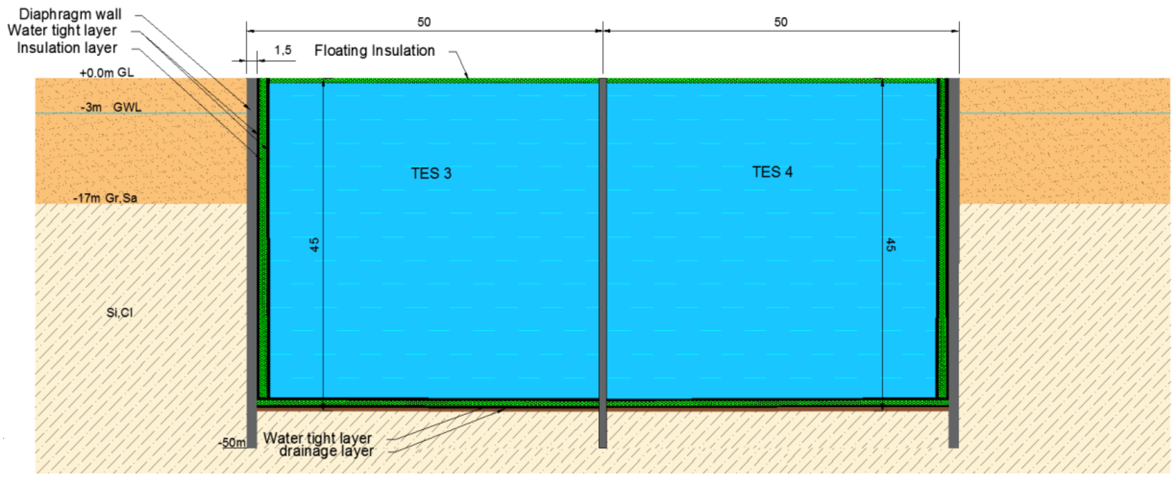

Figure 51. Variant 6 (Combined C-shafts)

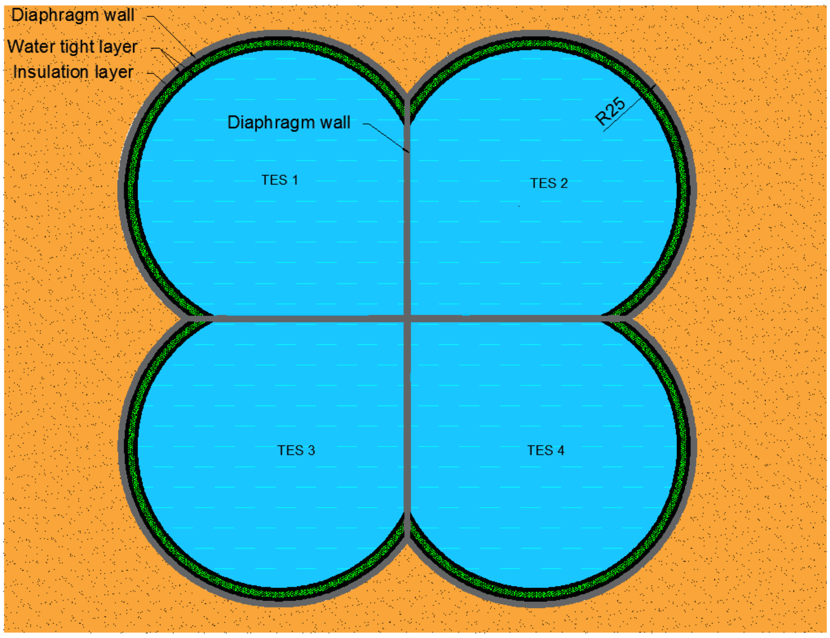

Figure 52. Top view of 4 Combined C-Shafts

It can be seen in the Figure 52 that the number of circular shafts (C-shafts) connected are only 4. In fact, this number could be increased to 6 or 8 etc. depending on the requirements of the project.

3.7.2 Pros

Some of the essential properties of variant 6 are as follows

- Combination of circular shafts TES
- Higher volume retaining capability compare to Variant 4
- Other properties, identical to V5

3.7.3 Cons

Some of the drawbacks of variant 6 are as follows

- Challanging construction and installation of insulation
- Possibility of deflection of diaphragm wall at higher depths

3.7.4 Special Features

Combining the shafts through diaphragm wall

3.7.5 Open Questions

- Structure stability of circular TES

i. With increasing diameter and depths

ii. With connecting circular shafts

3.8 Variant 7

3.8.1 Description

In this variant, similar to variant 5, circular shaft is considered with no constraints on the diameter of the shaft. In this method the storage capacity can be stretched to the required amount needed, by increasing the diameter. Cut-off wall is constructed to stop the water infiltration/water barrier. After the excavation of the area, the circular reinforced segmented concrete wall is constructed step by step. With the installation of insulation material surrounding the TES, the system is made as energy efficient as shown in Figure 53.

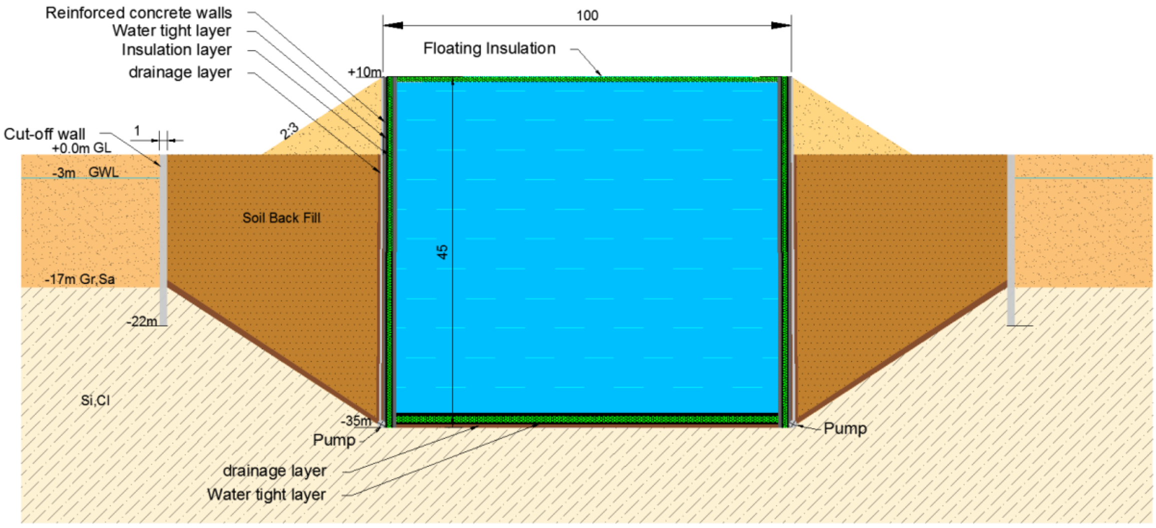

Figure 53. Variant 7

3.8.2 Pros

Some of the essential properties of variant 7 are as follows.

- The soil backfilled area at ground level, could be used for other purposes i.e. Solar panels installation
- Stable structure even with higher diameter due to backfill support
- Directly thermally insulated walls and base slab
- High volume retaining capability with increased diameter and depths
- No anchors required for structure stability

3.8.3 Cons

Some of the drawbacks of variant 7 are as follows.

- Complex and very cost intensive construction
- More machinery required for segments installation
- More excavation required compared to variant 5
- Less stable nature

3.8.4 Special Features

- Drainage layer around the TES
- Soil backfilling, as supporting mass for structure stability

3.8.5 Installation steps

The installation sequence of development is listed as follows

i. Cut-off wall installation
ii. Excavation of the ground till the depth required (35m in this case)
iii. Installation and insulation of the circular segments step by step
iv. Soil backfilling and storage liquid filling in parallel manner.
v. Top floating insulation

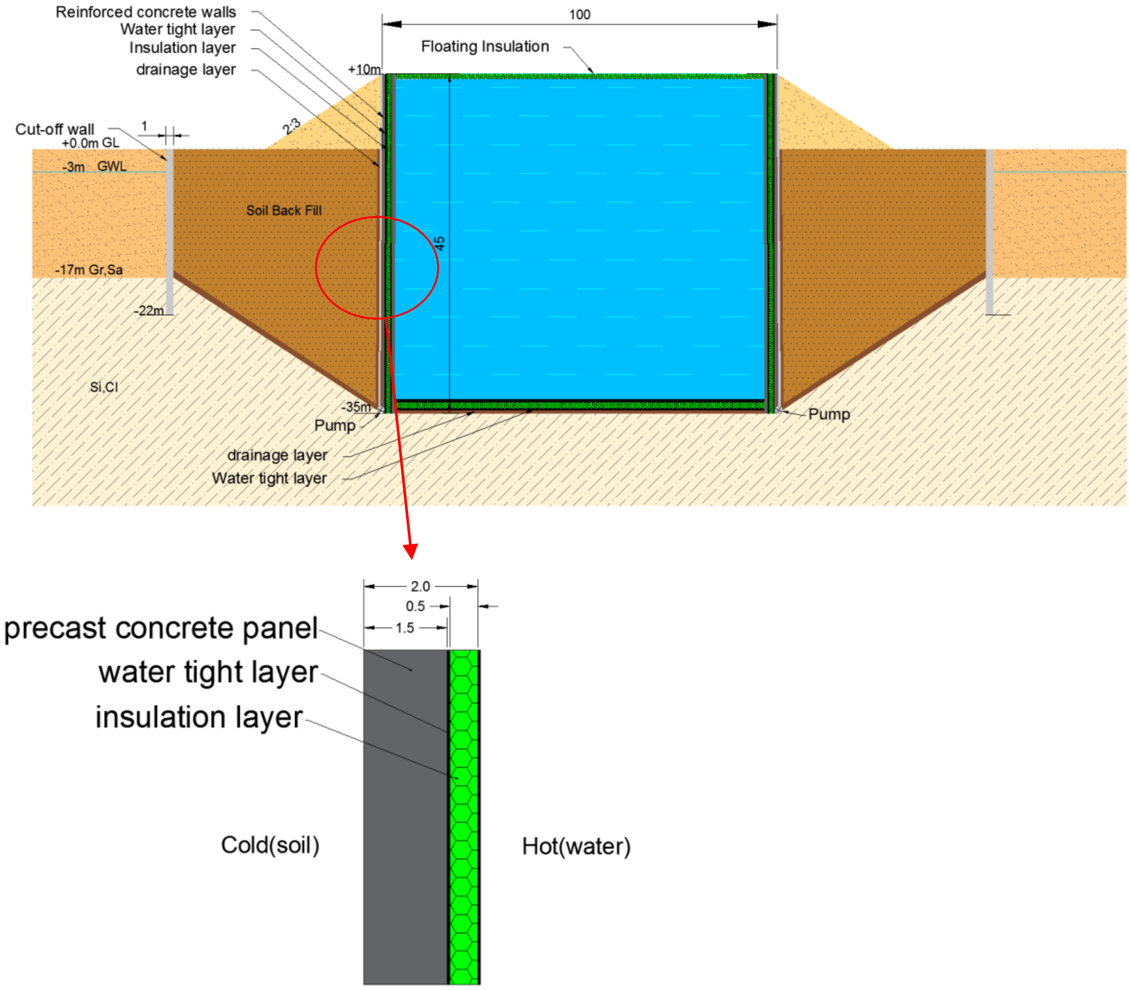

Figure 54. Cross section of Segmented Concrete wall with other layers in variant 7

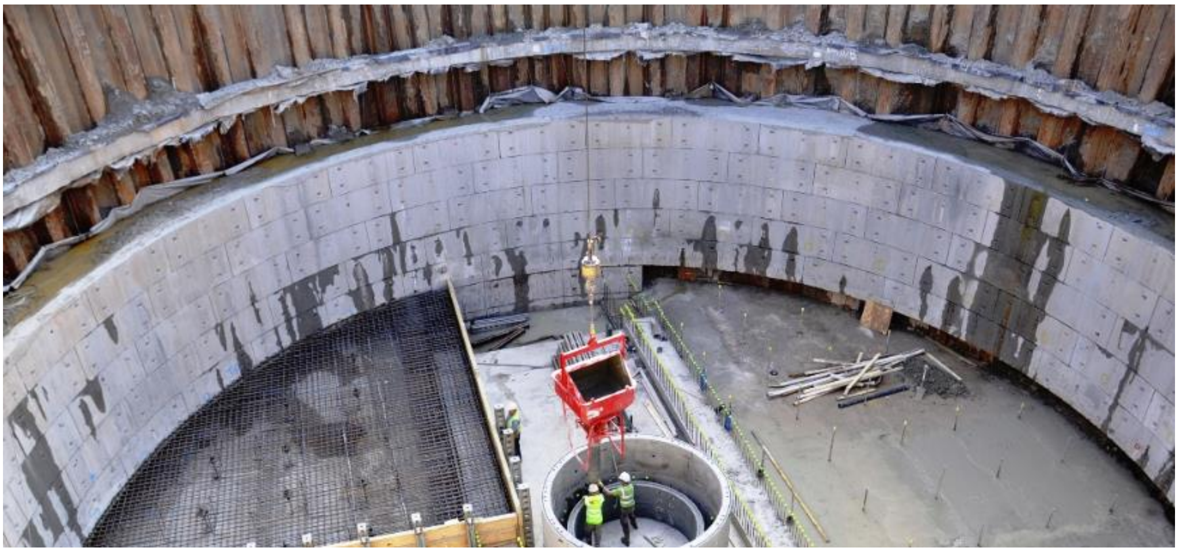

Figure 55:Avonspark Street segmented Shaft Installation

3.8.6 Open Questions

- Structure stability with big diameter circular shaft
- Pump servicebility after some years

3.9 Variant 8

3.9.1 Description

This variant has the same features as variant 7 but with double precast concrete panels instead of RC segments as shown in Figure 56.

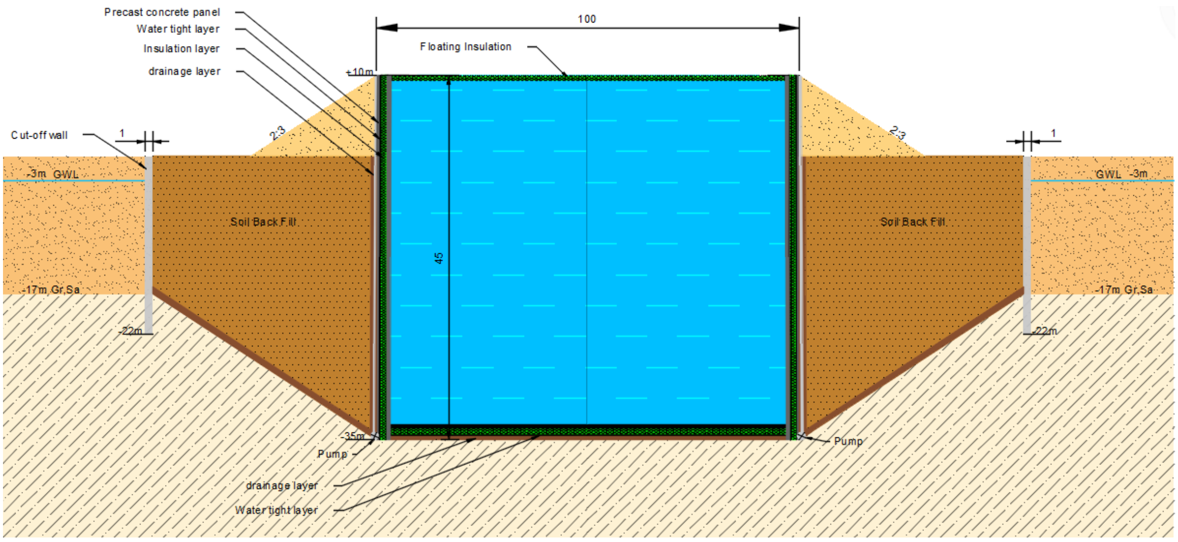

Figure 56. Variant 8

3.9.2 Special Features

- Drainage layer around the TES
- Soil backfill as supporting mass for structure stability

3.9.3 Installation Steps

i. Cut-off wall installation
ii. Excavation of the ground till the depth required (35m in this case)
iii. Installation of the circular precast double segments with cavity in-between, layer by layer.
iv. Pouring of the insulation in the cavity, once the panels installation is finished.
v. Soil backfilling and storage liquid filling in parallel manner.
vi. Top floating insulation

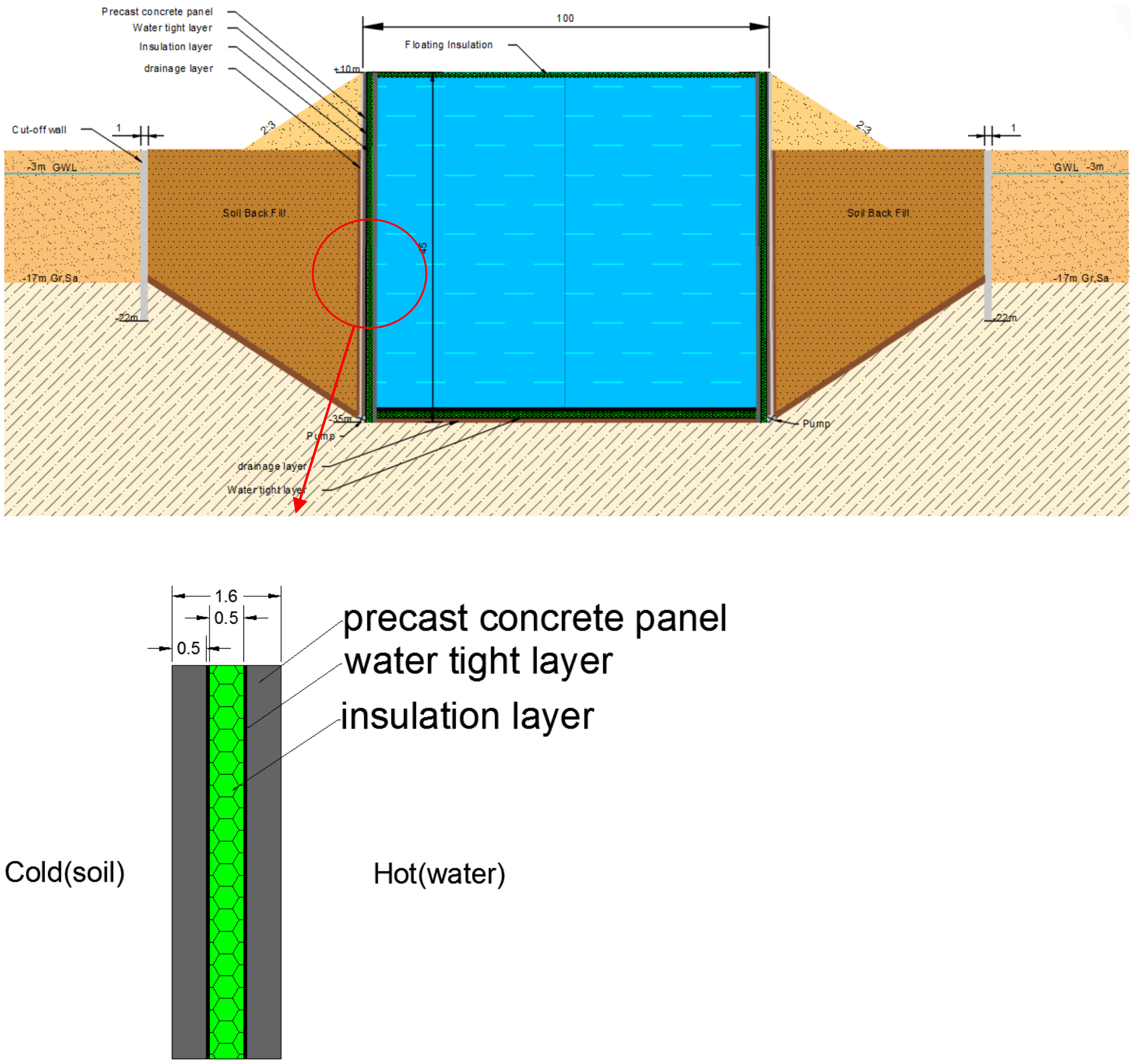

Figure 57. Magnified view of layers' sequence in variant 8

3.9.4 Open Questions

- Effect of heat on inner side compare to outer side panel wall
- Structure stability
- Pumps servicebility

4 Diaphragm Wall with Insulation

As discussed in the previous chapter i.e. chapter 3, for some variants and especially for variant 4 with diaphragm wall insulation, it is necessary to discuss the possibilities of different techniques for insulation installation in diaphragm walls and construct a load bearing as well as energy efficient structure.

4.1 Description

Diaphragm walls are continuous vertical concrete or reinforced concrete walls constructed either cast in situ, in a slurry-supported (usually a bentonite suspension) excavated trenches below ground surface or pre-cast concrete components (panels). The depth of such walls could reach till 100 meters or more with state of the art technology and with widths of 0.45 to 1.5 meters (greater can be provided). The cast in situ diaphragm wall construction is done using Tremie installation method for concrete placement (Implenia). The Vertical tolerance during the wall excavation are normally up to 1:200 and is monitored on-board to provide a real-time monitoring of the excavation directional accuracy.

Prior to the excavation of the diaphragm wall, two parallel concrete beams (temporary) known as guide walls, are constructed to stabilize the upper ground and to guide the excavation machinery. The excavation of the trench is typically done using rope-suspended hydraulically or mechanically operated grabs. For special applications and ground conditions, hydromills are used, operated hydraulically and are known as reverse circulation trench cutter. In this method the technique for excavation is by cutting (opposed to digging). This technique is suitable for diaphragm walls with higher depths and for walls that are located in soft rock and granular materials (skanska, 2009).

Diaphragm wall could serve in many applications and considered as the most favorable options compared to other solutions i.e. as a retaining wall in excavation pits, as a cut-off wall which act as water barrier and support deep excavation, as a final wall in basement or underground structure e.g. shaft and tunnel, as a separating wall (structure) between major under grade facilities and as a foundation element to carry concentrated axial structural loads like large drilled piles e.g. barrette piles or rectangular piles (Implenia).

The diaphragm wall can be constructed in two common types i.e. single phase diaphragm wall and two phase diaphragm wall, they are explained as follows.

4.1.1Two Phase diaphragm wall

The Two phase diaphragm wall construction always comprises of the following steps. The first step consists of an excavation work of a defined area, which is performed either with a grabber or cutter, stabilized with bentonite slurry. The regeneration of the bentonite mix slurry is done afterwards, with the installation of the reinforcement cage in the slurry for the wall and the joint element. The final step includes the concreting of trench using the tremie pipe illustrated in Figure 58,59 (Bauer).

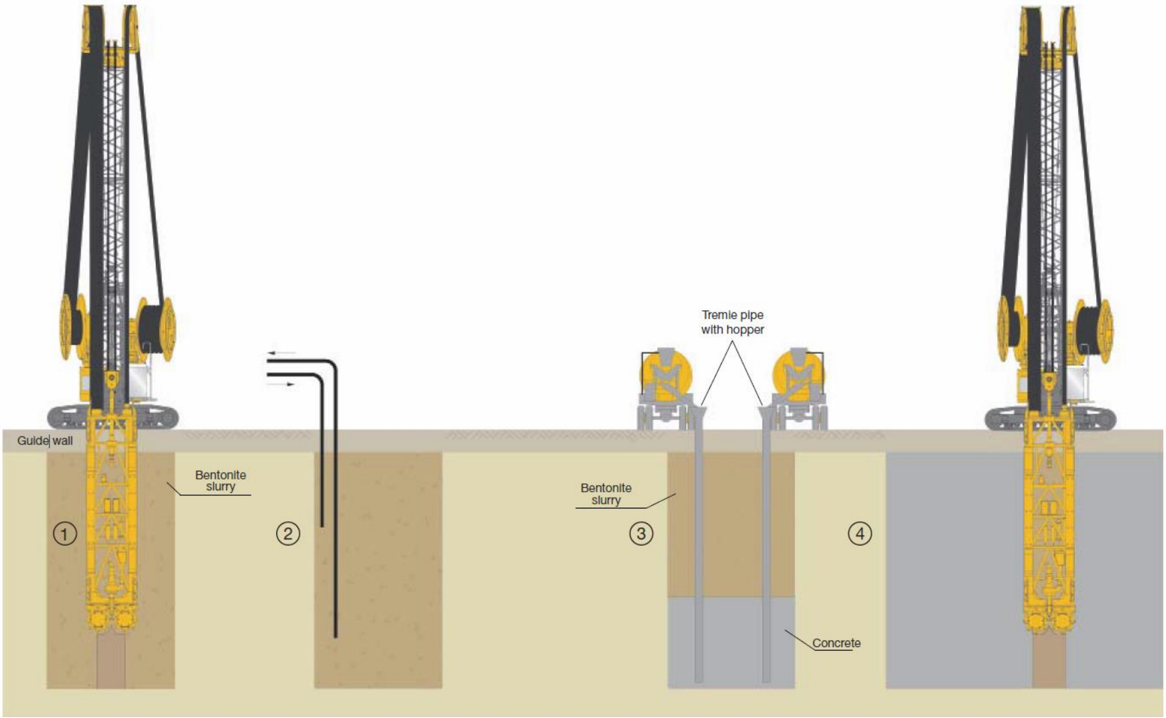

Figure 58. Two phase diaphragm wall construction sequence *(Bauer)*

Construction sequence for Two phase diaphragm wall

- Primary panel excavation
- Bentonite slurry regeneration
- Concreting with tremie pipe
- Secondary panel excavation

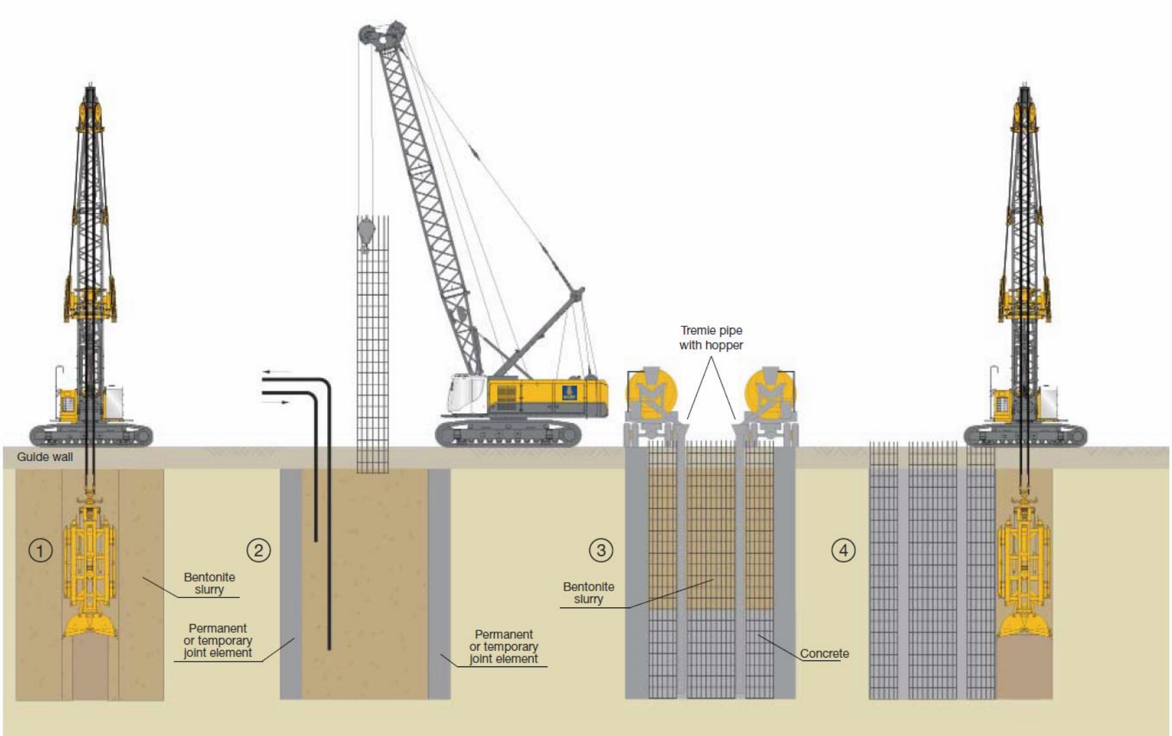

Figure 59. Two phase diaphragm wall construction sequence reinforcement cage *(Bauer)*

Construction sequence for Two phase diaphragm wall with reinforcement cage

- Panel excavation
- Bentonite slurry regeneration / joint elements installation / reinforcement installation
- Concreting with tremie pipe
- Another panel excavation

4.1.2Single Phase diaphragm wall

The single phase diaphragm walls, also known as Vertical cut-off walls are not considered as load-bearing structures but they are installed in the subsurface to control the horizontal groundwater movement and contaminants. They could be useful in decreasing the permeability of high permeable layers such as sand and gravel, etc. overlying an impermeable soil layer (Rafalski, 1994). The one-phase or single phase diaphragm wall construction is done in proper steps. The first step consists of an excavation work which is performed either with a grabber or cutter, whereas the stabilizing slurry comprises of a bentonite-cement mix slurry with the self-hardening capability. Eventually, sheet pile walls or reinforcement beams can be installed in the self-hardening (not yet hardened) as static element as illustrated in Figure 60,61 (Bauer).

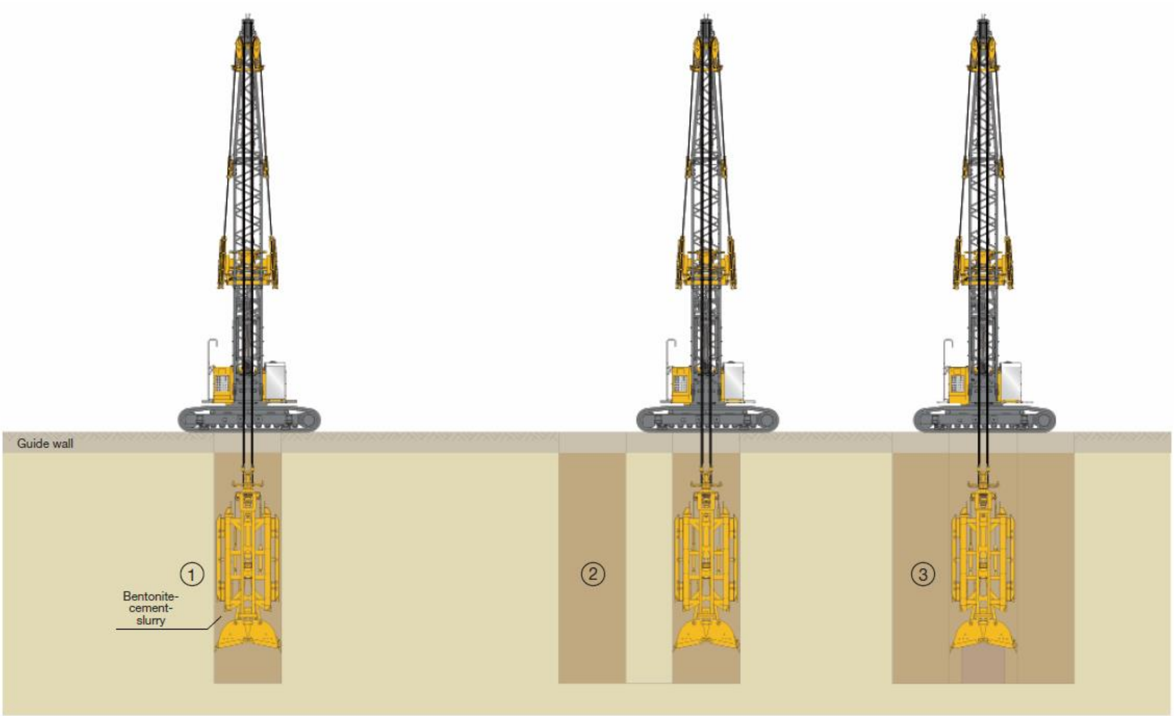

Figure 60. 1 phase diaphragm wall construction sequence *(Bauer)*

Construction sequence for single phase diaphragm wall

- 1st Excavation
- 2nd Excavation
- Middle cut / panel excavation

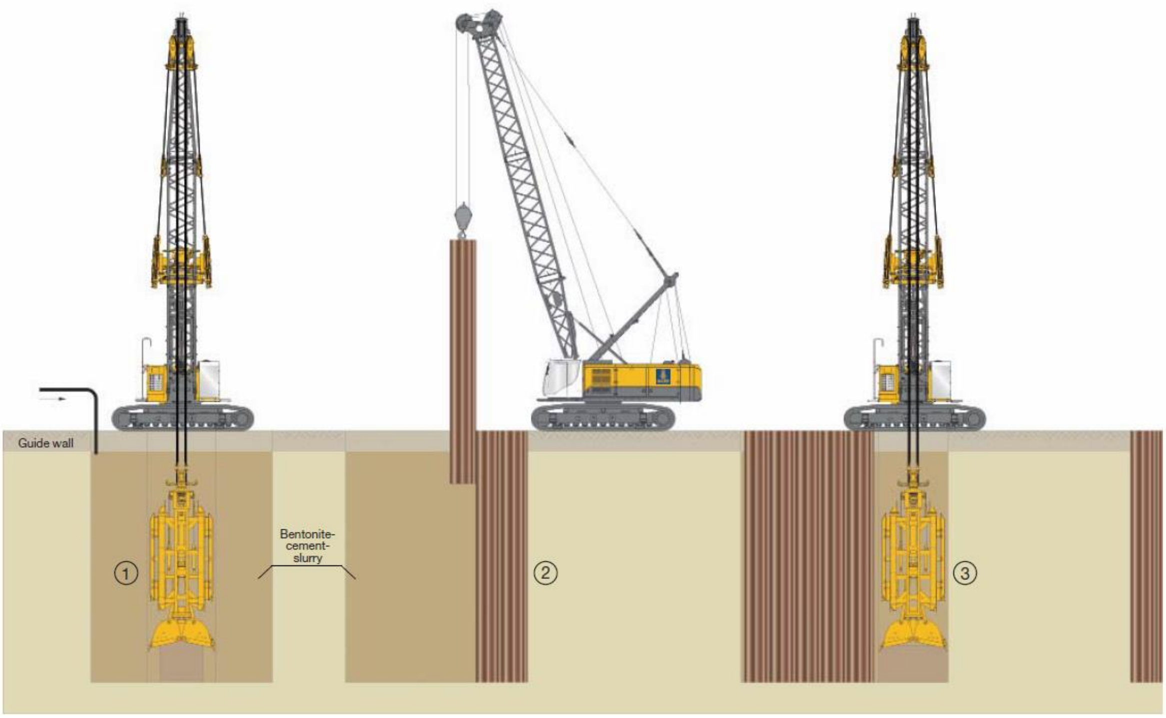

Figure 61. 1 phase diaphragm wall with sheet pile walls *(Bauer)*

Construction sequence for single phase diaphragm wall with sheet pile walls

- Middle cut / panel excavation
- Sheet pile walls Installation in the self-hardening slurry as static element
- New panel excavation, followed by installation of adjacent sheet pile wall.

4.2 Problem Definition

In this chapter two different techniques have been suggested to develop an insulated diaphragm wall. The first method is to develop a two phase diaphragm wall with some possible techniques, to insulate it. The second method is to develop a single phase diaphragm wall and apply the same insulation technique as suggested in the previous method.

4.3 Variants with open question

4.3.1 Two Phase diaphragm wall Insulation

Concrete gains its strength with the passage of time after placement. It takes an unknown period of time to gain 100% strength and may differ for different types. The rate at which the concrete gains its compressive strength is higher during the initial 28 days of placement and decreases gradually afterwards. Table 9, illustrates the concrete compressive strength that is gained after 1 day, 3 days, 7 days, 14 days and 28 days w.r.t the grade of common concrete. It can be seen that during the 3^{rd} and 4^{th} day of concrete placement, it gains almost 40% to 45% of the total compressive strength (Mishra). During this period when the concrete is half-hardened, it is possible to construct secant pile drilling in the diaphragm wall as shown in the Figure 62, which can be filled later with insulation material (e.g. foam glass, foam concrete). Because of this narrow time window it is not practicable, when the strength of the concrete is too high. Therefor the concrete material used for the diaphragm wall should not be of high strength as it would be difficult to drill secant piles (e.g. usage of a so called Earth Concrete). A water tight layer (Plastic liner sheet) could also be installed on the surface of diaphragm wall to protect it from direct contact with water reservoir (towards TES) as shown in Figure 63.

To check the behaviour of concrete material in hot water storages or tanks, experiments have been performed in real conditions such as done by Elrahman in 2014. In these experiment, the concrete shows no deterioration at a temperatures of 90°C and 165°C. Moreover, no micro cracks or any other determinant influences have been observed on the concrete surface.

Age	Strength per cent
1 day	16%
3 days	40%
7 days	65%
14 days	90%
28 days	99%

Table 9. Compressive strength of concrete gained during 28 days (theconstructor.org)

Construction sequence of two phase diaphragm wall and its insulation

- Excavation of a panel
- Pouring of concrete in the panel without reinforcement cage installation
- Secant pile drilling in the wall on 3rd – 4th day of concrete placement
- Pouring of insulation material in the drilled piles
- Installation of the plastic liner on the wall towards the TES
- Continuing the process again for other panels

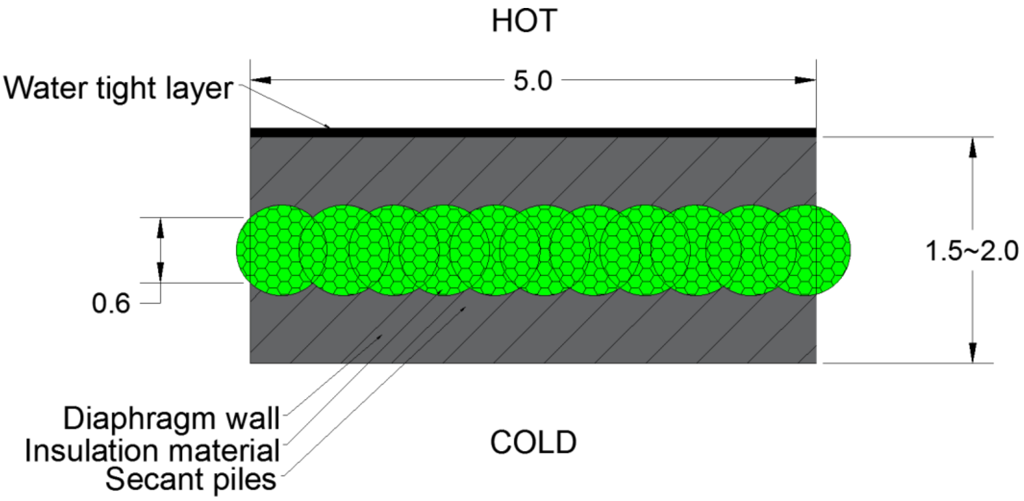

Figure 62: Top view of Diaphragm wall

Figure 63 : Installation of plastic liner sheet in D-Wall, Central Waste Dump, Huenxe

4.3.2 Single Phase diaphragm wall Insulation

Sodium bentonite, which is the main ingredient in developing the single phase diaphragm wall, has the temperature tolerance of up to 1180°F (600 °C), above which the material starts to deteriorate and ceased to do bonding with sand (ZRIMSEKJ, 1964). While, no literature research has been found related to the behaviour of bentonite cement slurry wall against hydrothermal conditions for a comprehensive period of time.

Similar to two phase diaphragm walls, single phase walls could also be developed and insulated in case of variant 4. After the construction of a cement-bentonite slurry wall, the same procedure could be followed as discussed in two phase wall insulation procedure shown in Figure 63.

4.3.3 Open Question

- Deeper investigation of how the bentonite behaves in-contact with 90°C water temperature over longer period of time.
- Secant pile drilling effect on the strength of the diaphragm wall.

5 Summary and Outlook

Traditional and state of the art insulation material for geotechnical applications in general and for STES in particular are researched and accumulated in this thesis work. Future insulation materials have also been briefly discussed.

With the appropriate material characteristics and thermo-physical properties, the thesis aims to serve as a concise reference tool in an attempt to collect together the many studies available in the literature related to thermal insulation methods for energy efficient geotechnical constructions.

Furthermore, different variants of STES with special features and specification were discussed in detail. Every variant has pros and cons depending on the project boundary condition. Insulation materials for these variants have also been suggested which in turn are dependent on factors such as the availability of materials and project requirements. These insulation material could conclude the thermal efficiency of the storage system over its life period. As all these variants are developed and designed, based on technical ideas and professional experience, for that reason, static analysis for some of variants are necessary.

In addition, construction methods and an idea for insulation of a diaphragm wall have been discussed. In single phase wall technique, the behaviour of sodium bentonite-cement slurry wall which is directly in contact with a hot water (90°C) storage, needs to be practically checked and investigated in detail.

As an endnote, it can be concluded that future research need to be conducted in the field of insulation in Geotechnics, specifically on the behaviour of insulation materials that come directly in contact with the (hot) water. Similarly, insulation of diaphragm wall need to be further researched with other ideas and methods.

This research studies could be considered as a reference study for developing energy efficient seasonal thermal energy storages with different possible methods and techniques.

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