Finite Element Modeling of Thermal Insulation Effects in a Borehole Thermal Energy Storage

By

Jungjin Lee

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Mining Engineering

Department of Civil and Environmental Engineering

University of Alberta

©Jungjin Lee, 2017

Abstract

A recent application of borehole thermal energy storage (BTES) technology to residential properties in Canada shows a significant reduction in the use of natural gas thereby saving energy consumption and reducing the generation of greenhouse gases. However, due to the construction principles of the BTES, the systems are not thermally insulated on the sides and the bottom. Hence, almost all injected heat into a single borehole dissipates into surrounding ground over the night when heat injection stops. In order to minimize thermal energy dissipation, construction of thermal insulation barrier using expanded perlite aggregate (EPA) was proposed to reduce the heat flow and increase the efficiency by providing a soilcrete thermal insulation layer around the BTES system.

The initial research proposed to utilize jet grouting technology for construction of the EPA mixed soilcrete thermal insulation layer. However, due to the nature of the jet grouting technology, the construction process of jet grouting is lengthy and therefore expensive for this application. Besides, the high buoyancy forces exerted created potential risks of aggregate segregation. To improve constructability and to mitigate the risks of aggregate segregation, this research proposes to employ one pass deep trenching method construction of the soilcrete thermal insulation layer.

Full-scale numerical models using two finite element analysis (FEA) software: Abaqus and Temp/W were developed to investigate the effectiveness of the soilcrete insulation layer constructed with one pass deep trenching method. The numerical model provides theoretical evidence for the application of soilcrete thermal insulation layer in reducing the thermal energy loss and thereby improving the efficiency of the system. The FEA modeling results showed that the thermal insulating soilcrete successfully entrapped more thermal energy within the system compared to the system without thermal insulation and reduced the annual average heat flux up to 46 % with three-meter thickness insulation barrier.

Acknowledgements

I would like to express my sincere gratitude to my supervisor Dr. Derek Apel for the continuous help, encouragement and the opportunity to pursue the Master of Science program at the University of Alberta. I would also like to thank Dr. Wei Victor Liu for the guidance, support and advice. I would like to extend my gratitude to all the committee members for your precious time, comments and suggestions in my final exam: Dr. Robert Hall, Dr. Wei Victor Liu and Dr. Derek Apel.

I am grateful to the Faculty of Graduate Studies and Research (FGSR) at the University of Alberta for supporting me through the Master of Science program with Queen Elizabeth II Graduate Scholarship.

Technical and material support for this work was provided by De Wind Wells & De Watering company, GEO-SLOPE International Ltd and National Concrete Accessories. I wish to give my gratitude to PCL Industrial Management Inc. and colleagues for supporting me throughout the M.Sc. program. I would like to thank Dr. Babak

Nikbakhtan for providing the acquired data from an experiment to continue work on the research.

Many people encouraged and supported me on various occasions during the study. I would also like to extend my gratitude to Dr. John Kennelly and Louise Kennelly for their great support and BBQs, Christmas dinners and Guinness, and to Mr. John Collier, Mrs. Judy Collier, Jacquelyn Collier and Michalycia family for the encouragement and Thanksgiving dinners. I would have not been able to complete the M.Sc. program without their support.

Finally, I am extremely grateful for the support and love I received from my parents in law, Dr. Man-Kang Song and Hyang Sook Lee, and my sister in law, Dr. Helene Song. I would also like to thank my parents Won-Jae Lee and In-Hyun Song, and brother James Jung-Jun Lee for continued support and love throughout my life and the program. Lastly, my greatest grateful words are dedicated to my wife, Dr. Aleida Louise Jee-Hye Song for being a mentor and helping me completing the program in every possible way she could. I would have not been able to accomplish this without her support and love.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

BTES	Borehole thermal energy storage
EPA	Expanded perlite aggregate
FEA	Finite element analysis
FEM	Finite element method
HTF	Heat transfer fluid
LCOE	Levelized cost of electricity
OHS	Occupational health and safety

Chapter 1. Introduction

1.1 Research Background

Thermal energy is required in space heating for residential and commercial buildings. In order to provide sufficient thermal energy to a typical new house in Canada, 126 GJ (119 x 106 BTU) of natural gas (approximately 250 propane cylinders used on most gas BBQs) is required annually, and 6.3 tonnes of greenhouse gases (CO_2 equivalent) are generated (McClenahan & Gusdorf, 2006). Traditionally, firewood or fossil fuel has been the major source of energy that provides the required thermal energy to these properties. As the population has continued to grow, the required amount of energy increases, the government reinforce regulations as to energy efficiency, and hence, citizens and industries become in need of alternative energy sources that are sustainable, environmentally-friendly and financially economic.

Renewable energy refers the energy generated by infinite resources, namely the energy sources such as solar energy, wind energy, hydroelectric energy, geothermal energy, tidal energy, and even volcanic activity and lightning (Ellabban, et al., 2014). Over the past decades, the renewable resources generation cost has significantly decreased: The Crystalline silicon PV module price from $77 per MW to less than a dollar per MW in the last 40 years. (Bloomberg New Energy Financing, 2016). Despite the significant reduction in the cost of power generation using renewable resources, one of the biggest challenges for the renewable resources power generation is the dispatchability. Unlike most conventional power generation methods, renewable resources power generation is the non-dispatchable generation which cannot be adjusted upon request depending on the load, peak, frequency, and backup requirements. One of the ideal solutions to overcome the challenge is to have a utility scale energy storage which can compensate for the intermittency of the renewable resources.

Thermal energy storage is a utility scale energy storage system where thermal energy (heat or cold) is injected into thermal energy storing sources for later use (Andersson & Hägg, 2013). The BTES is one of the modern heat storage systems consist of bore holes with U shape pipes in those and work as heat exchange system (Diersch, et al., 2011). There are different types of heat exchanger construction depending on the numbers and types of U shape pipes in a single bore hole. The high conductive material filled in the boreholes (usually grout material) helps the heat transfer process (Zizzo, 2010), and the heat pump circulates the heat transfer fluid (HTF) within the closed pipes (closed loop system) and transfers the thermal energy (Gil, et al., 2010). Figure

1.1 shows the schematic diagram of the Drake Landing Solar Community's BTES with a closed loop system. These energy storage systems have shown potentials to manage the dramatic changes in seasonal energy consumption patterns in residential scale (Sibbitt, et al., 2012). In fact, this recent application of Underground Thermal Energy Storage technology to residential properties in Canada shows a significant reduction (97 %) in use of natural gas thereby saving energy consumption and reducing the generation of greenhouse gases (Sibbitt, et al., 2011). Although energy storage systems being capable of storing thermal energy for later use, these systems need improvement in terms of their efficiencies due to highly rapid heat dissipation to the surrounding soil. According to a recent study by Lanini et al. 95 % of injected heat into a single borehole was dissipated into surrounding ground over the night when heat injection stops (Lanini, et al., 2014).

In an effort to provide a solution to the heat dissipation problem, Dr. Apel and Dr. Nikbakhtan at the School of Mining Engineering at the University of Alberta initiated a research to entrap the injected thermal energy and mitigate the thermal energy dissipation from the system by providing a thermal insulation layer around the borefield (Nikbakhtan, 2015). The EPA, known to have a very low thermal conductivity (Khan, 2002; Topçu & Işıkdağ, 2007), was proposed as the insulating material within the insulation layer. The research also suggested a possible solution to the problems with the costly and challenging installation of insulation by using EPA and jet grouting technology (Nikbakhtan, 2015). Jet grouting technology, initiated in the United Kingdom is a widely used in-situ soil improvement method for various types of soil (Moseley & Kirsch, 2004). The jet grouting system involves high pressurized water to physically disrupt the ground and cementitious grouting material simultaneously at high velocity (Burke, 2004). The eroded soil is mixed with the grouting material to form a soil-cement column, thereby improving ground properties. The application of jet grouting in the BTES will enable the installers to easily create a soil-cement column, in other words, a soilcrete layer around the system regardless of the depth of the structure without much restriction. In Alberta region, particularly in Edmonton area, coal seams are located at various depths (Taylor, 1971). The coal material is an excellent insulating material with very low thermal conductivity 0.22 to 0.55 W/m·K (Herrin & Deming, 1996) and these coal seam layers can be easily reached with jet grouting technology and used as an insulator without any additional cost (Nikbakhtan, 2015).

However, due to the nature of the jet grouting technology, soilcrete columns can only be installed one column at a time. Therefore, installation of the insulation layer using jet grouting technology is a time-consuming process which will increase the construction cost. Besides, the high buoyancy force exerted to perlite aggregate creates a potential risk of aggregate segregation due to the huge difference in density between perlite aggregate and the water used in the jet grouting to disrupt the soil. Hence, the soilcrete installed by the jet grouting in the ground may not be homogeneous, and the anticipated thermal insulation effect may not be achieved throughout the structure.

In order to mitigate the risks and effectively construct the thermal insulation layer, this study proposes to employ one pass deep trenching method. One pass deep trenching method is a cost-effective slurry wall construction method that can create a top to bottom homogeneous and continuous linear wall from the beginning to the end (DeWind Wells & De Watering, 2012). The construction method utilizes soil bentonite or cement bentonite in building a slurry wall (DeWind Wells & De Watering, 2012). Adding expanded perlite into the slurry wall mixes will add thermal insulation properties to the slurry wall and form an insulation layer around the system that will prevent dissipation of collected the heat into surrounding soil. As a result of its low cost and low bulk density (Bolen, 2004; Liu, et al., 2011), adding expanded perlite into grouting material is not much of a financial impact in one pass deep trenching construction applications. This insulation layer around the thermal energy storage unit theoretically can act as a thermo-barrier to efficiently block the heat flow from inner side to the outer side of the energy storage. However, no detailed research has been conducted as to the application of insulation around thermal energy storage. Hence, the scope of this research is to investigate the effectiveness of the application of the insulation barrier around underground thermal energy system and potential financial benefits from it.

1.2 Research Scope

The research has concentrated on the thermal properties analysis of the insulation layer using two FEA software: Abaqus by Dassault systems and Temp/w by GeoStudio to compare the results and cross check for any potential errors in modeling. Models utilized the hand mix insulation soilcrete sample data obtained by precedent research which proposed the application of thermal insulating soilcrete in the BTES (Nikbakhtan, 2015). Based on the thermal properties of the hand mix sample, numerical thermal energy storage models were developed to simulate the effect of the insulation layer in full-scale thermal energy storage.

1.3 Research Objective

The primary objective of this pilot research is to investigate the effectiveness of the soilcrete insulation layer in minimizing the thermal energy dissipation and improving the overall efficiency of thermal energy storage system using theoretical analysis software. This research proposes to employ the one pass deep trenching method for installation of the insulation layer and focuses on the analysis of the effectiveness of the low thermal conductive insulation layer. Based on the analysis result, the economic benefits are assessed and concluded for the residential and industrial application.

Figures in Chapter 1

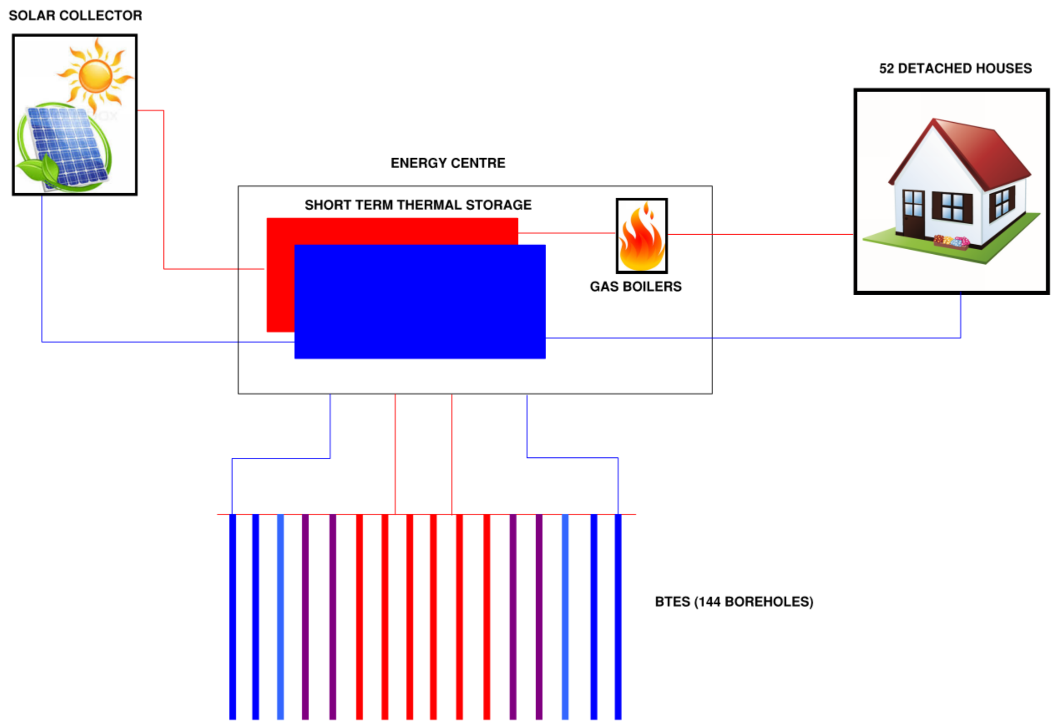


Figure 1-1 Schematic diagram of borehole thermal energy storage of Drake Landing Solar Community

References

Andersson, O. & Hägg, M., 2013. Preliminary design of a seasonal heat storage for ITT Flygt, Emmaboda, Sweden. *Integration of geothermal energy into industrial applications,* Volume 21, pp. 72-79.

Bloomberg New Energy Financing, 2016. *Bloomberg New Energy Finance Summit.* s.l., Bloomberg New Energy Financing.

Bolen, W. P., 2004. Perlite. In: *Mineral Commodity Summaries.* s.l.:U.S. Geological Survey (USGS).

Burke, G. K., 2004. *Jet grouting systems: advantages and disadvantages..* Orlando, American Society of Civil Engineers.

DeWind Wells & De Watering, 2012. *DeWind Trenching is the leader Deep One Pass Trenching used for Environmental and Civil Construction.* [Online]
Available at: http://www.dewindonepasstrenching.com/
[Accessed 24 March 2016].

Diersch, H. J. et al., 2011. Finite element modeling of borehole heat exchanger systems Part 2. Numerical simulation. *Computers & Geosciences,* Volume 37, pp. 1136-1147.

Ellabban, O., Abu-Rub, H. & Blaabjerg, F., 2014. Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy,* Volume 39, pp. 748-764.

Gil, A., Medrano, M. & Lázaro, A., 2010. State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization.. *Renewable and Sustainable Energy Reviews,* Volume 14.1, pp. 31-55.

Herrin, J. M. & Deming, D., 1996. Thermal Conductivity of U.S. coals. *Journal of Geophysical Research: Solid Earth,* 101(B11), pp. 25381-25386.

Khan, M. I., 2002. Factors affecting the thermal properties of concrete and. *Building and Environment,* pp. 607-614.

Lanini, S. et al., 2014. Improvement of borehole thermal energy storage design based on experimental and modelling results. *Energy and Buildings,* pp. 393-400.

Liu, W. V., Apel, D. B. & Bindiganavile, V., 2011. Thermal characterisation of a lightweight mortar containing expanded perlite for underground insulation.. *International Journal of Mining and Mineral Engineering,* pp. 55-71.

Liu, W. V., Apel, D. B. & Bindiganavile, V. S., 2014. Thermal properties of lightweight dry-mix shotcrete containing expanded perlite. *Cement and Concrete Composites,* Volume 53, pp. 44-51.

McClenahan, D. & Gusdorf, J., 2006. *Okotoks: Seasonal Storage of Solar Energy for Space Heat in a New Community.* Pacific Grove, CA, American Council for an Energy-Efficient Economy, pp. 121-131.

Moseley, M. & Kirsch, K., 2004. *Ground improvement.* s.l.:CRC Press.

Nikbakhtan, B., 2015. Development of Thermal-Insulating Soilcrete using Laboratory Jet Grouting Setup.

Sibbitt, B., McClenahan, D. & Djebbar, R., 2011. *Measured and simulated performance of a high solar fraction district heating system with seasonal storage.* Kassel, Germany, International Solar Energy Society, Villa Tannheim, Wiesentalstrasse 50, D-79115, Germany, pp. 3037-3048.

Sibbitt, B., McClenahan, D. & Djebbar, R., 2012. The performance of a high solar fraction seasonal storage district heating system – five years of operation. *Energyt Procedia,* Volume 30, pp. 856-865.

Taylor, S., 1971. *Atlas : Coal-mine Workings of the Edmonton Area,* s.l.: Spence Taylor and Associates.

Topçu, İ. B. & Işıkdağ, B., 2007. Manufacture of high heat conductivity resistant clay bricks containing perlite. *Building and Environment,* pp. 3540-3546.

Zizzo, R., 2010. Designing an optimal urban community mix for an aquifer thermal energy storage system. *M.S. Thesis, University of Toronto, Toronto, Canada.*

Chapter 2. Literature Review

In Canada region where heating is needed during the winter season, thermal energy is required in space heating for residential and commercial buildings. Traditionally, fossil fuel such as coal, petroleum and natural gas has been the major source of thermal energy and approximately 70 % of electricity generation (U.S. Energy Information Administration, 2011). As energy requirements reinforce, population grows, and the government tightens up regulations with regards to energy efficiency, citizens and industries become in need of alternative energy sources that are sustainable, environmentally-friendly and financially economic. The government of Alberta in Canada recently introduced “Carbon levy and rebates” to provide financial incentives for Albertans and businesses in Alberta to lower their emissions (Government of Alberta, 2017). The government of Alberta also initiated the “no charge energy efficiency program” as part of the energy efficient Alberta initiative (Energy Efficiency Alberta, 2017). This initiative provides both direct and indirect financial assistance to the families in Alberta and the initiative makes their life more affordable by helping them conserve energy. Similar to the government of Alberta’s energy efficient Alberta initiative, the international society is challenging the significant amount of greenhouse gases fossil fuel generates while burning and its negative effects on the environment (United Nations foundation, 2013). Furthermore, any energy savings can be crucial in any nation's energy strategy not only due to the environmental benefits but also the economic benefits especially for the underdeveloped countries without adequate energy resources (Hassan, 1999), and therefore, international society as well as the academia are looking for a new form of energy sources that are sustainable and renewable to replace conventional energy sources such as fire wood, coal, oil, natural gas and other fossil fuel without harming our environment (Environment and Climate Change Canada, 2016).

Renewable energy refers to the energy generated by infinite resources, namely the energy sources such as solar energy, wind energy, hydroelectric energy, geothermal energy, tidal energy, and even volcanic activity and lightning (Armstrong & Hamrin, 2000). Over the past decades, the cost of renewable resources power generation has significantly decreased. Moreover, as Figure 2.1 indicates, levelized cost of electricity (LCOE: The LCOE represents the cost per kilowatt-hour of different power generating technologies over their life and duty cycle.) of renewable resources power generation has reached close to or even less than LCOE of conventional generation methods for coal and natural gas (New Climate Economy, 2014; U.S. Energy information Administration, 2015).

Despite the significant reduction in the cost of power generation using renewable resources, another challenge that the renewable resources power generation is facing is the dispatchability. Unlike most conventional power generation methods, renewable resources power generation is the non-dispatchable generation which cannot be dispatched or adjusted upon request depending on the load, peak, frequency and back-up requirements. One of the ideal solutions to overcome the challenge would be the utility scale energy storage which can compensate for the intermittency of that renewable resource.

2.1 Loop systems

Archeologic evidence shows the first geothermal energy use in North America was 10,000 years ago when Peleo-Indians cooked using hot springs (Lund, 1995). The modern application of geothermal energy started at the beginning of the 20th century after the metal pipe and radiators were introduced (Fridleifsson & Freeston, 1994). The geothermal energy system can be divided into two main categories that extract thermal energy for direct usage for heating and cooling: open loop system and closed loop system. The primary difference between the two systems is the thermal energy transferring medium (Self, et al., 2013).

2.1.1. Open Loop System

Open loop system as shown in Figure 2.2 utilizes the local ground water or surface water such as aquifer, lakes and ponds as a direct thermal energy transfer medium. The ground water source goes through the heat exchanger to transfer thermal energy then is discharged back to the source. One of the advantages of the system is that in most cases open loop system is the less expensive method of installation since the system have a simpler ground connection design and involves less drilling compared to vertical closed loop system. Another advantage for open loop system is that the temperature of water entering the system remains nearly constant throughout the year (Hanova & Dowlatabadi, 2007). However, due to the nature of the system, the quality of the water needs to be maintained to meet the clean water and surface water regulation (Hanova & Dowlatabadi, 2007), and the ground water should have fairly neutral chemistry and low in mineral contents since the mineral contents may require more frequent maintenance or more frequent user involvement (Ma & Chai, 2004; Omer, 2008).

2.1.2 Closed Loop System

In closed loop systems, the HTF circulates through the system. In contrast to open loop system using ground water directly to transfer thermal energy, heat transfer in closed loop system occurs through the piping material (Cui, et al., 2011) and the HTF has no direct contact with the ground. The close loop system can also be divided into four categories: vertical, horizontal, spiral and pond.

2.1.2.1 Vertical closed loop system

A vertical closed loop system is the most common installation of for a geothermal heat pump since it only requires minimal spaces (Yang, et al., 2009). As shown in Figure 2.3, The system consists of vertically oriented heat exchanger pipes in the loop field. Depending on the application, typically 45 to 75-meter-deep holes for residential application and 150 meters or deeper for industrial application are bored into the ground (Self, et al., 2013). Pairs of pipes connected by a U-shape connector at the bottom are installed in the pre-drilled bore holes (Office of Energy Efficiency and Renewable Energy, 2010). The holes then filled with high conductive grout material to enhance the thermal conduction. This vertical closed loop system is advantageous when space is limited since drilling has a less impact compared to trenching method.

Another advantage of the system is that installation of piping deeper in the ground where the temperature of the ground is constant will allow consistent performance of the system (Yang, et al., 2010). However, vertical loop system typically is more economic for larger applications due to the drilling cost which normally is costlier than trenching (Omer, 2008).

2.1.2.2 Horizontal closed loop system

In contrast to a vertical closed loop system, horizontal closed loop system is more suitable when ample ground area is available (Figure 2.4). The ground loop is laid below ground surface and back filled. The ground loop is laid typically no more than a couple of meters deep. The horizontal closed loop system is normally more cost effective than the vertical closed loop system for residential applications. However, active interaction between soil and the ambient temperature affects the heat transfer and the system performance and these factors may cause the system to require more piping compare to vertical closed loop system to obtain required performance. The system also requires antifreeze mix to prevent the system failure in cold climate since the system is located well within frost depth in cold climate (Omer, 2008)

2.1.2.3 Spiral closed loop system

Spiral closed loop system is very similar to the horizontal closed loop system, but the piping is laid circular loops shape within the trenches. The spiral system requires less area than the conventional horizontal closed loop system but requires more piping for the same load (Cui, et al., 2011). The spiral closed loop can be economically beneficial compared to conventional horizontal closed loop system since the system allows different trenching methods. However, it can be more costly when materials costs are high (Office of Energy Efficiency and Renewable Energy, 2010). Due to the longer pipe length, the system typically requires greater pumping requirements and the performance can be less efficient.

2.1.2.4 Pond closed loop system

Pond closed loop system is the least common system type amongst the four system types. The coiled spiral loop piping system is submerged in the water body at least 1.8 meters below the surface of the water but typically supported 23 to 48 cm above the bottom of the pond for heat convection flow around the piping (Office of Energy Efficiency and Renewable Energy, 2010). Appropriate antifreeze shall be used when the water temperature around the system falls below the freezing point. The pond closed loop system can be highly economical as the system typically has superior heat transfer characteristics and requires less piping compared to other closed loop systems and does not require any drilling or trenching (Omer, 2008). However, limitations include that the system requires sufficiently a large body of water which is not always available.

The BTES is the vertical closed loop energy storage systems where thermal energy (heat or cold) is injected into thermal energy storing sources for later use. This energy storage system has successfully managed the dramatic changes in seasonal energy consumption patterns in a residential scale. In fact, a recent application of the BTES technology to residential properties in Canada shows a 97% reduction in the use of natural gas thereby saving energy consumption and reducing the generation of greenhouse gases (Sibbitt, et al., 2011). Since 2008 under Micro-generation regulation in Alberta, Canada, micro generators in Alberta receive credits for the electricity they produced but not used: Depending on the size of the micro-generators, 150 kW and under receive credits for the electricity they sent back to the grid at the retail rates and 150 kW and above receive credits at hourly wholesale rates (Government of Alberta, 2017). In other words, any improvements in the efficiency of the system or reducing thermal energy dissipation into surrounding ground will allow to optimize the size of the heat field or to receive credits for a quicker recovery of the project investment.

The technology also enables to capture and store excess thermal energy available during the warm season, and extract during the cold season when the demand for heat occurs. Similarly, cold can also be captured and stored underground for later use and utilized when cooling demands increase during warm seasons. This seasonal thermal energy storage is possible mainly because the ground temperature below a certain depth (10 – 15 m) is not influenced much by the seasonal temperature changes and it remains relatively constant at the annual mean temperature of air (Omer, 2008; Nordell, 2012). Besides, the thermal energy storage system does not require any structural member, structural improvement of ground or components to store heat since the soil itself is the structure and the heat storing media. This environmentally friendly technology can also be applied in a larger or industrial scale such as mining industry where there are constant needs of energy to heat up mine sites during cold seasons and cool down during warm seasons.

2.2 The mining industry in Canada

The mining industry in Canada takes a significant part of the nation's economy and has contributed 4.5 % of the Gross Domestic Product for the past two decades (Levesque, 2014) and is a high energy consuming industry. Mine stope heating is required mostly due to the severe climate in Canada which gets extremely cold during the winter seasons and mine drifts need to be adequately heated as per Occupational health and safety (OHS) requirements in order for workers to safely conduct their daily tasks in underground mining operations (Government of Alberta, 2014). This dreadfully cold weather would also cause problems to hydraulic structures of massive mechanical equipment or serious abrasion on motor cylinder walls which may potentially increase maintenance cost if not warmed up properly prior to operating in surface mine operations. The lower the temperature drops, the longer it takes for mining equipment to warm up to a sufficient temperature to operate. This longer period of warming up due to the cold weather will financially impact projects not only from increased fuel consumption but also from reduced production rate. On the other hand, the temperature of earth's crust increases as it gets closer to the earth's core and therefore underground mines temperature increases average 1 – 3 ˚C per 100 meters in most countries

(Fridleifsson, 2008). Consequently, sufficient cooling shall be provided for underground mining operations at greater depths in order to keep workers heat exposure at an acceptable level set by mining OHS regulations (Government of Alberta, 2014). Ventilation is another critical requirement in underground mining operations to control the climate and maintain the quality of the air provided to workers working at mines. These activities are crucial in mine operations, yet cause of the substantial increase in energy consumption which will result in a financial burden on mines.

When providing required energy at mine sites in remote areas, most times it is more economical and feasible to generate electricity on-site than to drag power grid lines from the nearest community to supply required electricity. Rio Tinto's Diavik Mine, for example, is located in northern Canada where no electricity supply from the grid line is available. This mine is fully dependent on diesel power generators to supply required electric power in the mine operation, and the diesel fuel is hauled and stored on site which costs about $ 20 – 30 Million annually. Hence, any reduction in diesel fuel, when there is no impact on production, will be economically beneficial to the mine (Rio Tinto, 2014). This considerable energy cost in mine operation can be managed and reduced by applying underground energy storage system. Energy storage systems can capture and store any waste heat generated by site or other forms of energy from other renewable energy sources when there are fewer demands in heating. The stored thermal energy can later be extracted to heat up the mine site as heating demand increases. Similarly, cold can be stored and utilized later to cool down the mine sites during the warmer seasons.

As described, mining industry consumes a significant amount of energy throughout the mine life cycle and this remarkable energy consumption directly relates to increased energy cost and the higher spending in maintaining environmental sustainability for mines to meet government regulations. Therefore, any improvement in energy efficiency, reduction in energy consumption, and optimization of working hours can be economically and environmentally beneficial for any mining projects and mining companies. Amongst various renewable resources options, geothermal energy holds the most favorable advantages to the mining industry that can economically and environmentally benefit since extracted mine stopes in underground mines can provide easy access to huge areas of the ground (Abbasy, 2013). With this advantage, mining projects and industry can utilize geothermal energy to reduce energy consumption such as heating and cooling depending on the climate, geological conditions, mining methods and other factors.

Even though energy storage systems are capable of storing thermal energy for later use, these systems need improvement in terms of its efficiency due to rapid heat dissipation to the surrounding soil. According to a recent study by Lanini in 2014, 95 % of injected heat into a single borehole dissipates into the surrounding ground over night when heat injection stops as shown in Figure 2.5 (Lanini, 2014).

The operational BTES system of the Drake Landing Solar Community (Okotoks, AB, Canada) has 200 mm extruded polystyrene insulation on the top of the system to mitigate heat dissipation to the atmosphere. However, the systems are not thermally insulated on the sides and the bottom due to the construction principle of the BTES. In fact, any additional insulation layer around the walls of the system can reduce the heat flow and increase the efficiency. Therefore, construction of a thermal insulation layer around the system is proposed by Nikbakhtan at the school of mining engineering at the University of Alberta to mitigate the lateral heat dissipation problem (Nikbakhtan, 2015).

In order to mitigate the lateral heat dissipation problem, the author recommends that the insulation layer shall have following properties:

1) Sufficient thermal insulation property;
2) Uniformity of the insulation layer; and
3) Sufficient structural integrity to bear ground pressure

2.3 Materials

Precedent research at the University of Alberta proposed the EPA (Figure 2.6), known to have a very low thermal conductivity (Khan , 2002; Topçu & Işıkdağ , 2007) as the primary insulating material to provide thermal insulation property for the insulation layer around the BTES system.

Raw perlite is a naturally occurred amorphous volcanic mineral that contains 2 – 5 % water (Mladenovič , et al., 2004). The water contained in the mineral evaporates upon heating at 900 – 1,100 °C and forms bubbles which allow the raw perlite to expand 15 to 20 times of its original volume (Gunning , 1994). Expanded perlite is the result of this intense expansion caused by the evaporation of water. With its outstanding thermal insulation properties, extensive researches have been conducted on expanded perlite, and it has been widely used in building industries (Singh & Garg, 1991).

Maintaining uniform mixture throughout the insulation layer and preventing segregation of the mix is extremely important in providing optimal insulation property to the system. However, there are potential segregation risks due to the huge difference in density (bulk) among major ingredients within the insulation concrete mix (cement (3,150 kg/m^3); water (1,000 kg/m^3); and expanded perlite (71 kg/m^3)). One of the main reasons of the segregation is the tendency of cement particles irresistibly drawn towards each other when mixed with water. This density difference creates a high risk of segregation of the ingredients within insulation concrete mix.

2.3.1 Chemical admixture

2.3.1.1 Superplasticizer

Superplasticizer is a dispersant additive which temporarily neutralizes the cement particles' dragging forces, and it gives the concrete mixes better liquid consistency (Gelardi & Flatt, 2016). This dispersing characteristic of superplasticizer can help preventing cement particles from drawing towards each other and form flocs which will result in aggregate segregation. Superplasticizer also provides greater workability to fresh concrete and reduces water demand by up to 40 % without substituting flow-ability (Zhao, et al., 2016). In fact, it improves the strength of concrete mix by reducing water demand of concrete mix while maintaining the same workability (Papayianni, et al., 2005). Superplasticizer in the mix will also improve structural strength and durability by reduced water cement ratio and lowered permeability of the structure (Gagne´, et al., 1998). The durability of concrete is decided by the concrete core, but most of the times by the concrete cover which more often possesses cracks. Hence, adding superplasticizer into the insulation concrete mix can improve the ability of the concrete skin to block the chemical attack and ultimately helps to refine the durability of concrete (Kreijger, 1984).

2.3.1.2 Anti-washout admixture

Fresh concrete placed under water is essentially susceptible to washout, laitance, segregation and water entrapment (Sam X. Yao, 2004). Thermal insulation application using jet grouting technology involves a considerable amount of water. Hence, thermal insulation mix injected in the drilled hole will be exposed to the risks of washout and segregation. In other words, injection of thermal insulation mix without appropriate chemical admixture may not have sufficient workability, and anti-washout admixtures can be used to enhance the stability of thermal insulation mix for jet grouting application.

Underwater concrete mix's workability is defined by three basic performance: flowability, self-consolidation and cohesion.

1) Flowability: The concrete mix shall be able to flow easily underwater and fill voids without trapping water.
2) Self-consolidation: Since consolidating concrete placed underwater with mechanical vibration is not practical, the concrete shall be able to consolidate.
3) Cohesion: The primary objective of the underwater concrete is to remain cohesive underwater. The cohesion of concrete is difficult to quantify but in practice, U.S. Army Corps of Engineers' washout test is widely used (United States Army Corps of Engineers, 2006).

Adding anti-washout admixture in thermal insulation mix is used to enhance the stability of freshly placed concrete, and it can improve the flowability, the ability to self-consolidate and cohesion. The use of anti-washout admixture can reduce or eliminate the dewatering costs and minimize the environmental impact due to cement washout.

2.4 Construction Methods

Although the extensive research in application of expanded perlite in concrete mixture for the insulation layer has been conducted, and its potential in providing substantial insulation effect has been proven (Steiger & Hurd, 1978; Sengul, et al., 2011; Topçu & Işıkdağ, 2008), conventional excavation and concrete pouring around the BTES system appears to be challenging and extremely costly due to the significant depths to be met and the scale of the project. Therefore, an appropriate ground modification method at a reasonable cost is required to inject the thermal insulating material into the soil structure. In recent years, various cutting and mixing methods have been developed that can repeatedly carry out mixing process vertical and horizontal direction.

Nikbakhtan at the school of Mining engineering at the University of Alberta initiated research to provide a solution to the problems with the challenges by using jet grouting technology (Nikbakhtan, 2015). Jet-grouting technology has been widely used in in-situ soil improvement for various types of soil (Moseley & Kirsch, 2004). For jet grouting operations, initially, the jet grouting equipment is set up at the location where soil will be treated, and boreholes with a diameter of 100 to 150 mm are drilled to the desired depth using rotating drilling system (Schaefer, et al., 1997). The jet grouting equipment then starts injection process. The nozzle is raised and rotated slowly to create the column with eroded soil and the fluid injected. During the injecting process, part of mud in the bore hole with fluid mix will rise to the top which is called as spoil. Jet grouting, depending on the geometry requirements, has three main variants of jet grouting nozzle systems: single fluid system, double fluid system and triple fluid system as shown in Figure 2.7 (Burke, 2004). The simplest form of jet grouting utilizes the single fluid system that ejects fluid to erode and mix with soil. However, spoil may not be able to travel to the surface and consequently, heave may occur. The double fluid system, the most utilized and often most economical amongst the three systems, has enhanced the erosive effects because of the air which shrouds the grout jet. However, due to the airlift, a considerable portion of injected grout may be lost. The third method is the triple fluid system which utilizes three fluids: grout, jetting water, and compressed air shrouding the jetting water. The triple fluid system's grouting nozzle typically is located half a meter below the water jetting nozzle. This arrangement allows limiting ejection of grouting material in the holes while conveying as much excavated soil as possible. Because the triple fluid system is capable of achieving erosion of soil and injection of grout independently, the system can be optimized for required performance, and thereby achieve the highest quality amongst the three (Burke, 2004; Essler & Yoshida, 2004). Table 2.1 shows the summary of the advantages and disadvantages of the three systems.

In this research, a modified triple fluid jet grouting system employed high pressurized water to physically disrupt the soil and cementitious grouting material mixed with perlite aggregate were injected simultaneously at high velocity (Nikbakhtan, 2015). The eroded soil is mixed with the grouting material and perlite aggregate to form a soil-cement column, thereby improving ground's thermal insulation properties. The application of jet grouting in the BTES can easily create insulating soil-cement columns, and the soilcrete layer around the system regardless of the depth of the structure without much restriction. This jet grouting technology's reachability allows the installers to reach and utilize coal seams which are an excellent insulator with very low thermal conductivity (0.22 to 0.55 W/m·K), in Alberta region to insulate the bottom of the system (Herrin & Deming, 1996; Nikbakhtan, 2015).

However, the high buoyancy force exerted to perlite aggregate in jet grouting process creates higher risks of aggregate segregation due to the significant difference in density between perlite aggregate and the amount of water used in jet grouting to disrupt the soil. Hence, the soilcrete installed by jet grouting in the ground may not be homogeneous and anticipated thermal insulation effect may not be achieved throughout the soilcrete structure. Therefore, a mechanical mixing mechanism can be utilized without using an excessive amount of water can mitigate the risks of segregation and effectively construct the thermal insulation layer by mechanically mixing soil, cement and perlite aggregate at an optimal ratio.

One pass deep trenching is a cost-effective slurry wall installation technology which enables 12 to 48 inches (300 mm to 1200 mm) wide and up to 125 feet (38 m) deep 200 – 500 linear feet (60 m to 150 m) trenching per day without open cut excavation. Also, a recent study shows the temperature of the ground increased the quickest and kept the heat the longest at 30 m depth range (Lanini, 2014). The one pass deep trenching method is ideal for the 30 m depth range projects. This high capacity wet mixing system Fräs-Misch-Injektionsverfahren method was developed in Germany in 1994 and was first applied in 1996 (Pampel & Polloczek, 1999). The one pass deep trenching machines were then patented by Gregory DeWind in early 2000s (DeWind, 2002). The machine utilizes cutting blades rotated by two chain systems.

One pass deep trenching mechanism utilizes chain driven multiple buckets which allow the excavated soil material upwards out of the trench while digging. The unique blade configuration allows the machine to mix the soil with slurry supplied through an injection pipe (Topolnicki, 2004). While excavation takes place, excavated soil is continuously mixed with the slurry wall material (commonly soil bentonite, soil cement bentonite or cement only) to form a homogeneous soil-cement slurry wall from top to bottom throughout the structure as the machine moves as shown in Figure 2.8.

2.5 Rationale

At the University of Alberta, Liu et al. introduced the application of expanded perlite in shotcreting to provide thermal insulation to hot deep underground mines drifts (Liu , 2013). Liu et al. prepared cast samples and analyzed thermal properties of cast samples. Cast concrete samples in his research showed an increase in thermal conductivity and diffusivity with an increase of the EPA in cement mix (Liu , et al., 2014). Liu's research showed the application of expanded perlite mixed with concrete can significantly improve the thermal properties. Besides, because of its low cost and low bulk density (Bolen , 2004; Liu , et al., 2011), adding expanded perlite into thermal insulation material is not a considerable financial impact. Another research conducted by Nikbakhtan et al. suggested application of expanded perlite into cementitious grouting material as an insulating material for an insulation layer around thermal energy storage systems that could prevent dissipation of collected heat towards surrounding soil using jet grouting technology (Nikbakhtan, 2015). However, due to the natural phenomenon of cement when mixed with water, the particles are irresistibly dragged by each other. (Kendall & Stainton, 2001). This leads the author to concern that the phenomenon possesses higher risks of segregation of insulation material particles and cement particles within insulation concrete mix under the effect of gravity if the amount of water used in jet grouting application is not well controlled.

Since superplasticizer can temporarily neutralize the cement particles dragging force and improves flow-ability of concrete mix (Fritz-Pak Corporation, 2005), the use of superplasticizer can mitigate the potential risks of the segregation within insulation concrete mix. Both thermal and mechanical properties can also be improved by eliminating congregation phenomenon of cement particles and reducing the water demand in the concrete mix.

Figures in Chapter 2

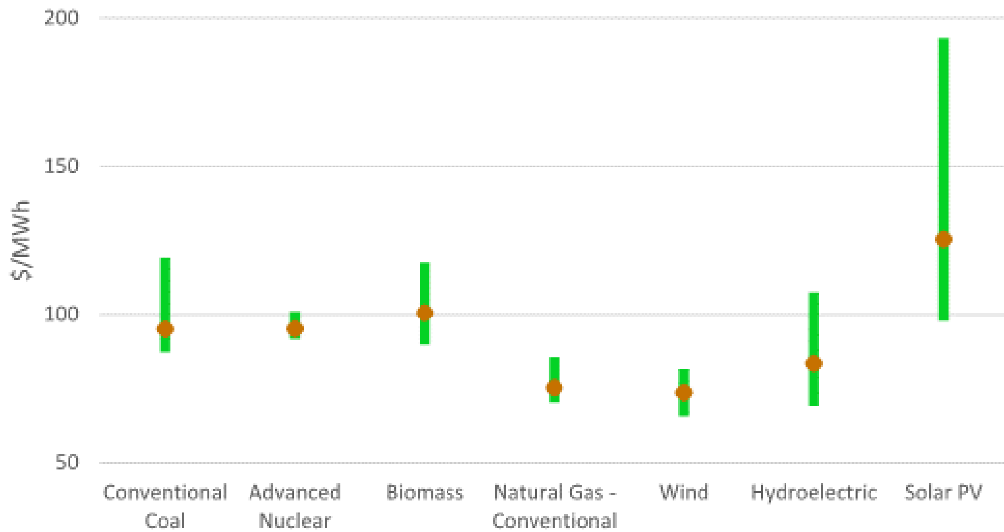


Figure 2-1 Projected LCOE in the U.S. by 2020 (as of 2015)

(U.S. Energy information Administration, 2015)

Note: The Levelized cost of electricity (LCOE) is a convenient tool for measuring and comparing the overall competitiveness of different power generation methods. The LCOE represents the cost per kilowatt-hour of different power generating technologies over their life and duty cycle.

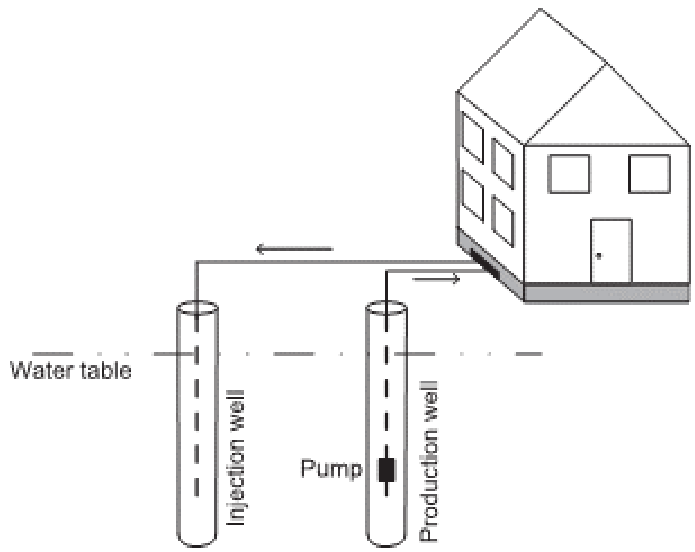


Figure 2-2 Open loop geothermal cycles (Self, et al., 2013)

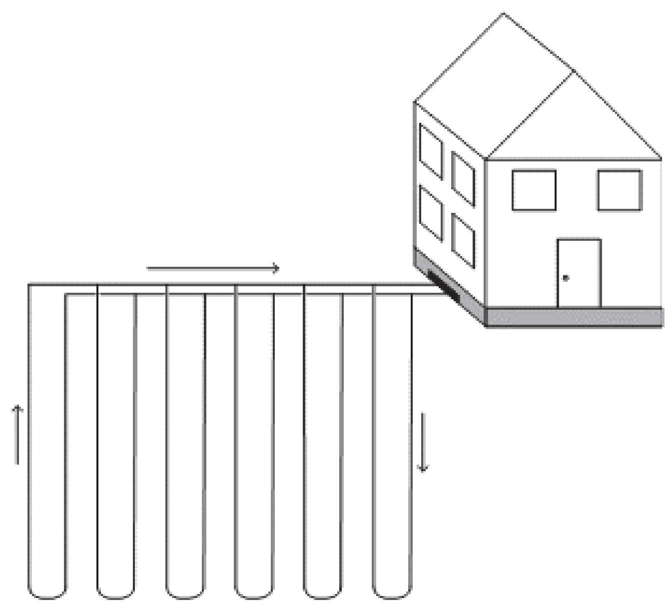


Figure 2-3 Vertical borehole heat exchangers (Self, et al., 2013)

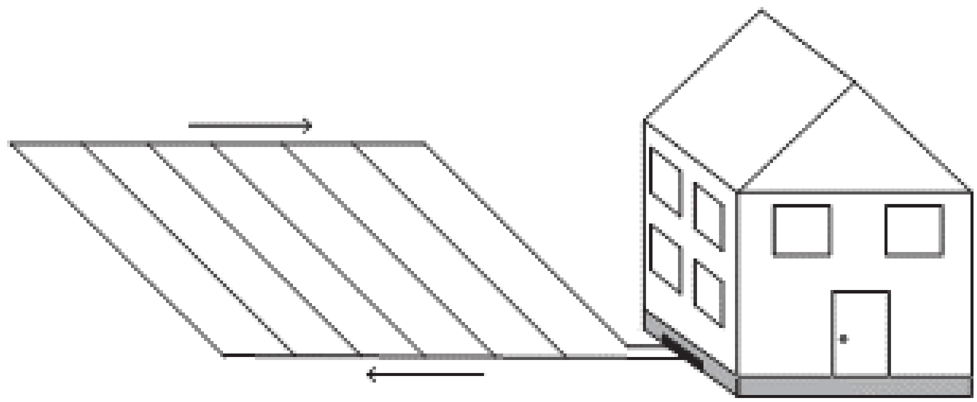


Figure 2-4 Horizontal ground heat exchangers (Self, et al., 2013)

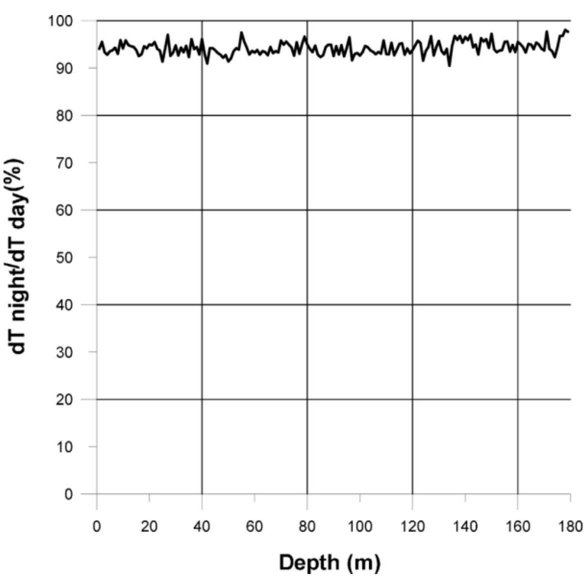


Figure 2-5 Evolution with the depth of the ratio between the temperature variation during a night and the previous day. Temperature is measured on the single injection borehole for a representative summer injection day (Lanini, 2014).

Figure 2-6 Expanded perlite aggregate

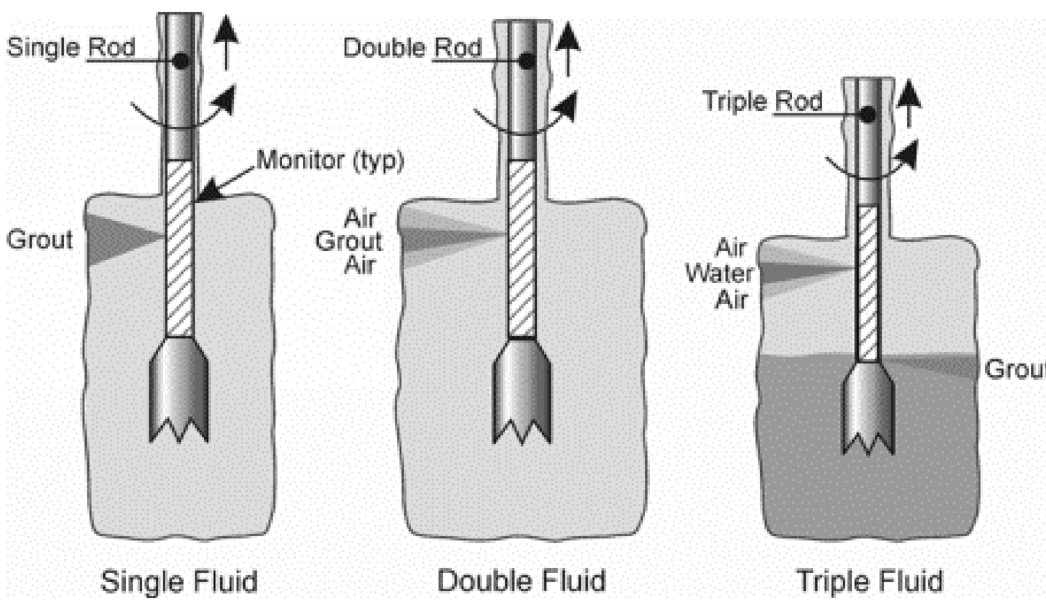


Figure 2-7 The three most common jet grouting systems (Burke, 2004)

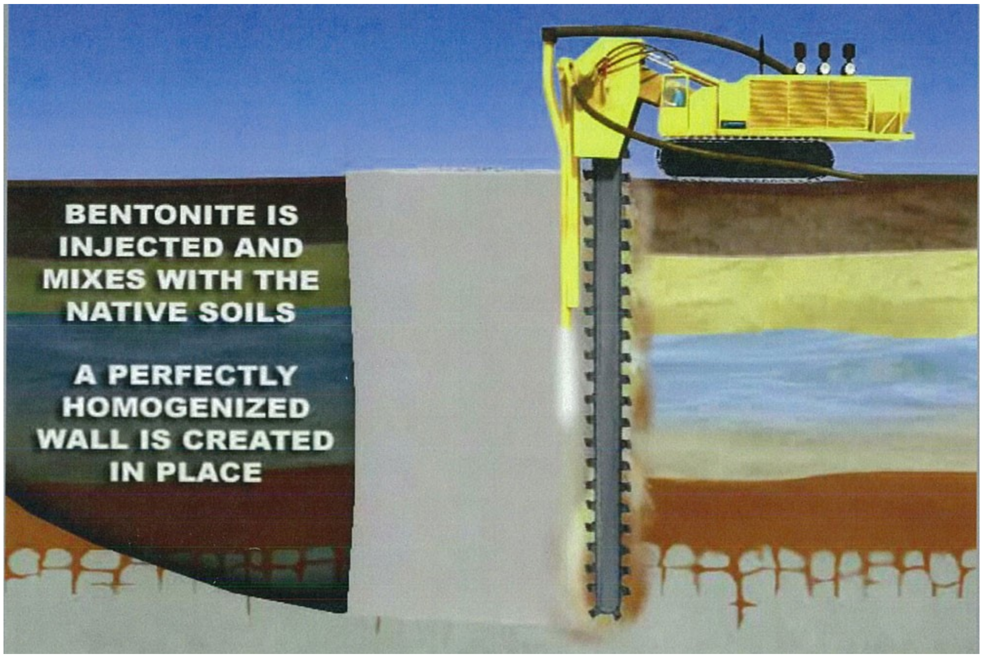


Figure 2-8 One pass deep trenching machine

(DeWind Wells & De Watering, 2012)

Tables in Chapter 2

Table 2-1 Jet grouting systems Advantages and Disadvantages (Burke, 2004)

System	Advantages	Disadvantages
Single Fluid	• Simplest system and equipment • Good to seal vertical joints • Good in cohesionless soil	• Smallest geometry created • Hardest to control heave • Difficult to control quality in cohesive soils
Double Fluid	• Most utilized system • Availability of equipment and tooling • High energy, good geometry achieved • Most experience • Often most economical	• Very difficult to control heave in cohesive soils • Spoil handling can be difficult • Not usually considered for underpinning
Triple Fluid	• Most controllable system • Highest quality in difficult soils • Best underpinning system • Easiest to control spoil and heave	• Complex system and equipment • Requires significant experience

References

Abbasy, F., 2013. *An Investigation into Application of Geothermal Energy in Underground Mines.* Montreal: McGill University.

Armstrong, J. A. & Hamrin, J., 2000. *The Renewable Energy Policy Manual,* Washington, D.C.: United States Export Council for Renewable Energy.

Bolen , W. P., 2004. Perlite. In: *Mineral Commodity Summaries.* s.l.:U.S. Geological Survey (USGS).

Burke, G. K., 2004. *Jet grouting systems: advantages and disadvantages..* Orlando, Florida, GeoSupport 2004: Drilled Shafts, Micropiling, Deep Mixing, Remedial Methods, and Specialty Foundation Systems.

Cui, P., Li, X., Man, Y. & Fang, Z., 2011. Heat transfer analysis of pile geothermal heat exchangers with spiral coils. *Applied Energy,* 88(11), pp. 4113-4119.

Cui, P., Li, X., Yi, M. & Fang, Z., 2011. Heat transfer analysis of pile geothermal heat exchangers with spiral coils.. *Applied Energy,* 88(11), pp. 4113-4119.

DeWind Wells & De Watering, 2012. *DeWind Trenching is the leader Deep One Pass Trenching used for Environmental and Civil Construction.* [Online]
Available at: http://www.dewindonepasstrenching.com/
[Accessed 24 March 2016].

DeWind, G. A., 2002. *Shaft driven trencher.* United States, Patent No. 6351900.

Energy Efficiency Alberta, 2017. *Energy Efficiency Alberta.* [Online]
Available at: https://www.efficiencyalberta.ca/
[Accessed 19 May 2028].

Environment and Climate Change Canada, 2016. *National Inventory Report 1990–2014: Greenhouse Gas Sources and Sinks in Canada,* Gatineau, QC: Environment and Climate Change Canada.

Essler, R. & Yoshida, H., 2004. *Jet grouting. Ground improvement.* 2nd ed. Abingdon, Oxon: s.n.

Fridleifsson, I. B., 2008. *The possible role and contribution of geothermal energy to the mitigation of climate change..* Luebeck, Germany, s.n., pp. 20-25.

Fridleifsson, I. B. & Freeston, D. H., 1994. Geothermal energy research and development. *Geothermics,* 23(2), pp. 175-214.

Fritz-Pak Corporation, 2005. *Supercizer 7 Technical Data Sheet.* Dallas, TX: Fritz-Pak Corporation.

Gagne´, R., Ollivier, J. & Latreille, Y., 1998. Effects of Superplasticizer, Retarding Agent, and Silica Fume on the Air Permeability of High-Performance Concrete. *Cement, Concrete, and Aggregates,* Volume 20, pp. 248-256.

Gelardi, G. & Flatt, R. J., 2016. Working mechanisms of water reducers and superplasticizers. In: *cience and Technology of Concrete Admixtures.* s.l.:Woodhead Publishing, pp. 257-278.

Government of Alberta, 2014. *Best Practice - Working Safely in the Heat and Cold,* Edmonton: Government of Alberta.

Government of Alberta, 2017. *Alberta Government.* [Online]
Available at: https://www.alberta.ca/climate-carbon-pricing.aspx
[Accessed 10 February 2017].

Government of Alberta, 2017. *Government of Alberta.* [Online]
Available at: http://www.energy.alberta.ca/Electricity/microgen.asp
[Accessed 01 06 2017].

Gunning , D. F., 1994. *Perlite Market Study Report,* s.l.: Gunning and Mc Neal Associates Ltd.

Hanova, J. & Dowlatabadi, H., 2007. Strategic GHG reduction through the use of ground source heat pump technology.. *Environmental Research Letters,* 2(4), pp. 1-8.

Hassan, A., 1999. Optimising insulation thickness for building using life cost. *Applied Energy,* Issue 63, pp. 115-124.

Herrin, J. M. & Deming, D., 1996. Thermal Conductivity of U.S. coals. *Journal of Geophysical Research: Solid Earth,* 101(B11), pp. 25381-25386.

Kendall, K. & Stainton, C., 2001. Adhesion and aggregation of fine particles. *Powder Technology,* Volume 121, pp. 223-229.

Khan , M. I., 2002. Factors affecting the thermal properties of concrete and. *Building and Environment,* pp. 607-614.

Kreijger, P. C., 1984. The Skin of Concrete: Composition and Properties. *Materials and Structures,* 17(100), pp. 275-283.

Lanini, S., 2014. Improvement of borehole thermal energy storage design based on experimental and modelling results. *Energy and Buildings,* pp. 393-400.

Levesque, M., 2014. Energy and mining-The home truths. *Journal of Cleaner Production,* pp. 233-255.

Liu , W. V., 2013. *Development and Testing of Insulating Shotcrete for the Application in Underground Tunnels,* Edmonton: University of Alberta.

Liu , W. V., Apel , D. B. & Bindiganavile , V., 2011. Thermal characterisation of a lightweight mortar containing expanded perlite for underground insulation.. *International Journal of Mining and Mineral Engineering,* pp. 55-71.

Liu , W. V., Apel , D. B. & Bindiganavile , V. S., 2014. Thermal properties of lightweight dry-mix shotcrete containing expanded perlite aggregate. *Cement & Concrete Composites,* pp. 44-51.

Lund, J. W., 1995. Historical Impacts of Geothermal Resources on the People of North America. *Geo-Heat Center Quarterly Bulletin,* Volume 8, pp. 1-14.

Ma, G.-y. & Chai, Q.-h., 2004. Characteristics of an improved heat-pump cycle for cold regions.. *Applied Energy,* 77(3), pp. 235-247.

McClenahan, D. & Gusdorf, J., 2006. *Okotoks: Seasonal Storage of Solar Energy for Space Heat in a New Community.* Pacific Grove, CA, American Council for an Energy-Efficient Economy, pp. 121-131.

Mladenovič , A., Šuput , J. S., Ducman , V. & Škapin , A. S., 2004. Alkali–silica reactivity of some frequently used lightweight aggregates. *Cement and Concrete Research,* pp. 1809-1816.

Moseley , M. & Kirsch , K., 2004. *Ground improvement.* s.l.:CRC Press.

Moseley, M. P. & Kirsch, K., 2004. *Ground Improvement.* 2 ed. Abingdon, Oxon: CRC Press.

New Climate Economy, 2014. *BETTER GROWTH BETTER CLIMATE: The New Climate Economy Report,* Washington, D.C.: New Climate Economy.

Nikbakhtan, B., 2015. Development of Thermal-Insulating Soilcrete using Laboratory Jet Grouting Setup.

Nordell, B., 2012. *Underground Thermal Energy Storage (UTES).* Lleida, Spain, Innostock 2012.

Office of Energy Efficiency and Renewable Energy, 2010. *Types of geothermal heat pump systems.,* Washington, DC: US Department of Energy.

Omer, A., 2008. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews,* 12(2), pp. 344-71.

Pampel, A. & Polloczek, J., 1999. Einsatz des FMI- und HZV-Verfahrens bei der. *Der Eisenbahningenieurbau,* Volume Nr. 3.

Papayianni, I., Tsohos, G., Oikonomou, N. & Mavria, P., 2005. Influence of superplasticizer type and mix design parameters on the performance of them in concrete mixtures. *Cement & Concrete Composites,* Volume 27, pp. 217-222.

Rio Tinto, 2014. *Diavik Diamond Mine 2013 sustainable development report,* Yellowknife: Diavik Diamond Mines (2012) Inc.

Sam X. Yao, a. B. C. G. J., 2004. Underwater Concrete Part 2: Proper Mixture Proportioning. *Concrete International,* 26(2), pp. 77-82.

Schaefer, V. R., Abramson, L. W., Drumheller, J. C. & Sharp, K. D., 1997. *Ground improvement, ground reinforcement and ground treatment: developments 1987-1997..* Paeonian Springs, VA: ASCE.

Self, S. J., Reddy, B. V. & Rosen, M. A., 2013. Geothermal heat pump systems: Status review and comparison with other heating options. *Applied Energy,* Volume 101, pp. 341-348.

Sengul, O., Azizi, S., Karaosmanoglu, F. & Tasdemir, M. A., 2011. Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete.. *Energy and Buildings,* 43(2), pp. 671-676.

Sibbitt, B., McClenahan, D. & Djebbar, R., 2011. *Measured and simulated performance of a high solar fraction district heating system with seasonal storage.* Kassel, Germany, International Solar Energy Society, Villa Tannheim, Wiesentalstrasse 50, D-79115, Germany, pp. 3037-3048.

Singh, M. & Garg, M., 1991. Perlite-based building materials -- a review of current applications. *Construction and Building Materials,* Volume 5, pp. 75-81.

Steiger, R. W. & Hurd, M. K., 1978. Lightweight insulating concrete for floors and roof decks.. *Concrete Construction,* 23(7), pp. 411-422.

Topçu, . İ. B. & Işıkdağ , B., 2007. Manufacture of high heat conductivity resistant clay bricks containing perlite. *Building and Environment,* pp. 3540-3546.

Topçu, İ. B. & Işıkdağ, B., 2008. Effect of expanded perlite aggregate on the properties of lightweight concrete.. *Journal of materials processing technology,* 204(1), pp. 34-38.

Topolnicki, M., 2004. In situ soil mixing. In: *Ground Improvement.* New York, NY: Spon Press, pp. 331-428.

U.S. Energy Information Administration, 2011. *Annual Energy Review,* Washington, DC: U.S. Energy Information Administration.

U.S. Energy information Administration, 2015. *Annual Energy Outlook,* s.l.: Energy Information Administration.

United Nations foundation, 2013. *United Nations foundation.* [Online]
Available at: http://www.unfoundation.org/what-we-do/issues/energy-and-climate/
[Accessed 19 May 2107].

United States Army Corps of Engineers, 2006. *CRD-C 661-06: Specification for Antiwashout Admixtures for Concrete.* Washington D.C.: s.n.

Yang, H., Cui, P. & Fang, Z., 2010. Vertical-borehole ground-coupled heat pumps: A review of models and systems.. *Applied Energy,* 87(1), pp. 16-27.

Yang, W., Shi, M., Liu, G. & Chen, Z., 2009. A two-region simulation model of vertical U-tube ground heat exchanger and its experimental verification.. *Applied Energy,* 86(10), pp. 2005-2012.

Zhao, M., Zhang, X. & Zhang, Y., 2016. Effect of free water on the flowability of cement paste with chemical or mineral admixtures. *Construction and Building Materials,* Volume 111, pp. 571-579.

Chapter 3. Finite Element Modeling for Thermal Insulation Effects in a Borehole Thermal Energy Storage

3.1 Introduction

The finite element method (FEM) which also generally referred to as the FEA is a numerical problem-solving method widely used in engineering and other fields. The FEM was first used in structural analysis, and it has also been widely applied to thermal analysis, fluid flow analysis, mass transport and many others (Liu & Quek, 2013). This numerical method yields approximate unknown values at a discrete number of points over the domain. The FEM subdivides a large problem domain into a smaller, simpler and a finite number of parts that are called elements. The subdivision of the large domain into simpler and smaller parts provide benefits in accurately representing complex geometry, including dissimilar material properties, and capturing of local effects (Reddy, 2006). The simple equations of the finite elements are assembled into a larger system of the equations to seek a best-approximated solution (may not be exact) in the problem domain (Logan, 2011).

Computational modeling using the FEM consists of four steps:

Step1. Modeling of the Geometry

Step 2. Meshing (discretization)

Step 3. Specifying material properties

Step 4. Specifying boundary and initial conditions

After a FEM model is created, the FEM software solves the discretized system of equations based on the mesh generated, material properties and the given initial and boundary conditions.

The primary objective of this study is to provide further theoretical evidence for the application of the thermal insulating soilcrete in the thermal energy storage system. Since the scale of the project is complicated and huge, it makes more economical sense to build a model using the FEM and check the numerical values and simulated results. A standard method can also be used in checking the results of the computer models: physical test models, run verification models to confirm the results match previously simulated results. However, since this study is a pilot research, the initial performance analysis was completed to provide numerical values and visible results prior to building complicated and costly physical models. Among different analysis methods, the FEM is a very acceptable and commonly used analytical tool for the primary objective. In this study, the improved performance of the BTES with the application of thermal insulating soilcrete was simulated, and potential cost saving analysis was performed using two finite element modeling software: Abaqus by Dassault systems (Dassault Systemes Simulia Corp, 2012) and Temp/W by Geo Studio (GEO-SLOPE International Ltd., 2014).

The reduction in thermal energy loss by heat dissipation have been closely observed by comparing overall efficiency of the system with a different thickness of thermal insulating soilcrete and without it. The properties of soil and various thermal and mechanical properties of thermal insulating soilcrete were obtained from hand mix samples by precedent research conducted at the University of Alberta.

3.2 Numerical model

3.2.1 Geometry of model

The geometry of the full-scale model was developed based on the field dimensions of the Drake Landing Solar Community's BTES system per Figure 3.1 (Drake Landing Solar Community, 2007). The Drake Landing Solar Community's BTES system is set up in approximately 34,000 m^3 of the earth with a grid of 144 boreholes, 35 m deep, with single U-tube heat exchangers as shown in Figure 3.2 (Sibbitt, et al., 2012). Each borehole is planned in a grid with 2.25 meters in the distance and the heat transfers from the center to the outer edge.

A few assumptions were made for simplification in developing the model:

1. The cross sections of the thermal energy system were deemed to be symmetrical and constant from top to bottom.
2. The materials assigned for insulation layers and the soil were assumed to be isotropic and homogeneous.
3. Constant heat (55 °C) is injected into the core of the BTES.
4. The initial temperature of the soil is 10 °C at all location.

The shape of elements of the geometry can be controlled by the FEA software. Depending on the dimensions and the purpose of the FEA, the kind of meshes within the region can be different.

The entire model was simulated with Abaqus and a quarter section was simulated with GeoStudio Temp/W software to reduce the amount of time for simulation since the simulated model is symmetrical. For meshing quadrilateral, quad-dominated, and triangular meshing techniques can be used for two-dimensional regions, and hexahedral, hex-dominated, tetrahedral and wedge meshing technique can be used for three-dimensional regions. In this modeling, two-dimensional 8-node quadratic quadrilateral meshing technique with quad-dominated advancing front mesh control was used with Abaqus, and default meshing technique was utilized with GeoStudio.

3.2.2 Simulated scenarios

In order to assess the effectiveness of the thermal insulating soilcrete containing the EPA, the composition of the model contained two solid materials: soil and thermal insulating soilcrete. The thermal properties of the in-situ soil as shown in Table 3.1 and the hand mixed thermal insulating soilcrete as shown in Table 3.2 obtained from precedent research (Nikbakhtan, 2015) were used in modeling. The annual mean ambient temperature was used for the temperature of the soil in the simulation (Omer, 2008; Nordell, 2012; Statistics Canada, 2007). For the simulation purposes, the BTES system without an insulation layer was used as a control model as shown in Figure 3.3. Additional three models with different thickness of thermal insulating barriers, namely:

one, two and three-meter thermal insulating soilcrete barrier, were also created as shown in Figure 3.3 and was run for 365 days.

According to a recent study by Sibbitt in 2012, the core temperature of the BTES in Okotoks, AB reaches more than 45 °C within five months of operation and stays approximately 40 to 65 degrees in centigrade depending on the season (Sibbitt, et al., 2012). The temperature of the BTES core changes significantly depending on the time of the day and the season. For simulation purposes and simplification, the average BTES core temperature obtained from five-year system performance monitoring was used for modeling at an average of 55 °C as shown in Table 3. 3 and the model was run for 365 days for all cases (Sibbitt, et al., 2012).

3.2.3. Heat transfer modeling in the FEM software

To understand the heat-transfer simulation better, it is highly valuable to describe the general procedure of the problem-solving in the FEM software.

1. The object (parts) was created and meshed by elements consist of nodes.
2. Thermal properties of the material (soil and insulating material) were assigned to the parts.

3. Temperature and boundary conditions within elements were inserted and time increment was assigned.

As for the initial boundary conditions, the soil mass was considered to be constant at average annual ambient temperature. The boundary conditions for the boreholes were also applied for the injected thermal energy. The transient heat transfer was simulated for a one-year period for the model for both Abaqus and Temp/W. Table 3.3 summarizes the values used in the finite element modeling for both software.

3.3 Results

Closer attention was paid to the savings from reducing the annual thermal energy loss (kW) of the overall thermal energy storage system as well as the temperature changes throughout the system. The average heat flux, the rate of thermal energy transfer through a surface area per unit time, was obtained after running the model for 365 days. The annual average heat flux for both systems (with the insulating soilcrete and without insulation) was multiplied by the inner total surface area to compare the amount of energy dissipated to the surrounding soil from each system.

3.3.1 Temperature distribution

The temperature distribution results show that the system with thermal insulating soilcrete contains thermal energy more efficiently. Hence, the thermal insulation significantly slows down dissipation of the thermal energy to the surrounding soil compare to the system without a thermal insulating barrier. The Figure 3.4 and 3.5 showed the aerial view of the full-scale modeling results performed with two FEM software: Abaqus and Temp/W. As shown in Figure 3.6 and Figure 3.7, the two software returned almost identical results that show more thermal energy was entrapped inner side of the thermal insulating soilcrete for the models with the insulation. The application of an insulation layer successfully increased the temperature of the inner side of the system by 3 to 7 °C throughout the year. In other words, the application of the insulation layer helped the system to heat up quicker and kept more thermal energy within the boundary that boreholes can reach for heat extraction in the future. On the other hand, the insulation layer lowered the temperature of the outer side of the insulation by almost 11 °C compared to the model without the insulation for the same location. The obtained results by two FEA software indicate the thermal insulation helped keeping the thermal energy within the system and the boundary that more thermal energy can later be extracted when demanded, and dissipates less thermal energy for 365 days.

3.3.2 Heat dissipation reductions

As it was observed from the temperature distribution, the more thermal energy remained inside the thermo-barrier, and less thermal energy penetrated the thermo-barrier. The thermal insulating soilcrete functions as a thermo-barrier and therefore, the rate of thermal energy transferred through a surface area per unit time was reduced. The analysis shows that the thermal insulating soilcrete reduced the annual average heat flux by 30 – 46 % depending on the thickness of the insulation.

3.3.3 Effective thickness of jet grouted thermal insulating soilcrete

Thermal insulating soilcrete constructed with jet grouting technology was also simulated in this study and compared with constant thickness thermal insulating soilcrete constructed with a one-pass deep trenching method. Due to the nature of jet grouting technology, thermal insulating soilcrete constructed with jet grouting technology will always have a cylindrical shape from the top to the bottom as shown on the left in Figure 3.8. Hence, the cylindrical soilcrete insulation effect at locations vary unlike the thermal insulation barriers with a constant thickness. Besides, it is more complicated to analyze and determine the overall insulation effect due to the shape of the jet grouted thermal insulation soilcrete. The effective thickness modeling was based on the no-overlap condition in the construction of soilcrete columns using jet grouting because of the economic feasibility since overlapping will require approximately 50 % more number of holes and 35 – 40 % more materials to form constant thickness wall.

In order to more effectively predict the “effective thickness” for jet grouted thermal insulation soilcrete, several models with various diameters and thickness of insulation layers have been simulated and compared. Figure 3.9 shows that the model with a constant thickness insulation layer performs very closely to the model with jet grouted thermal insulating soilcrete with the diameter of 1.5 times the thickness. This model indicates the actual effective thickness of the jet grouted thermal insulating soilcrete is 1.5 times less the diameter. However, considering the insulated area/volume within the same plane, it appears that thermal insulating soilcrete in constant thickness works more efficiently and economically for the same amount of material.

3.3.4 Estimated financial benefits

In Figure 3.10, the reductions in heat dissipation from the system represents the benefits of application of the thermal insulating soilcrete to the BTES system. Based on the 365 days of simulation results, the potential cost saving calculation per kW was calculated based on total annual cost of electricity ($ 1,235) for a typical EPCOR residential customer and average annual consumption (7,200 kWh per year) for the typical Albertan residential customer (Market Surveillance Administrator, 2014) and this came to 17.2 ¢ per kWh.

The Table 3.4 summarizes heat flux comparison for models with different thickness thermal insulating barrier and shows the reductions in heat loss from the system by having a thermal insulating barrier around the BTES systems depending on the thickness of the insulation. The heat dissipation was reduced by 64.5 kW to 98.1 kW for the entire BTES system, in regard to the insulating wall thickness from one-meter to three-meters. Different mix designs of the hand mixed samples obtained by Nikbakhtan (Nikbakhtan, 2015) is summarized in Table 3.5, and the material cost was calculated based on the mix design 3 which was used for the simulation. As shown in Table 3.5, the amount of cement by volume in soilcrete is approximately 10 % and the material cost was calculated as shown in Table 3. 6 based on the bulk density (1,000 – 1,250 kg/m^3) and the cost of Portland cement in the United States in 2016 (statistica, 2017). With the material cost and estimated installation cost, installation cost for both 35 m and 25 m depth thermal insulation systems were calculated and one-meter thickness insulation took the shortest until the break even as shown in Table 3. 7 and Table 3. 8.

3.4 Conclusion

Based on the finite element modeling simulation results, following conclusions were made:

- Thermal insulating soilcrete containing the EPA significantly improves (up to 46 % at three-meter thickness) the overall efficiency of the thermal energy storage system compared to the thermal energy storage system without an insulation layer.
- The thicker the insulating soilcrete layer gets, the less thermal energy dissipates from the system.

- Constant thickness thermal insulating soilcrete layer performs very closely to jet grouted thermal insulating soilcrete with the diameter of 1.5 times the constant thickness.

Figures in Chapter 3

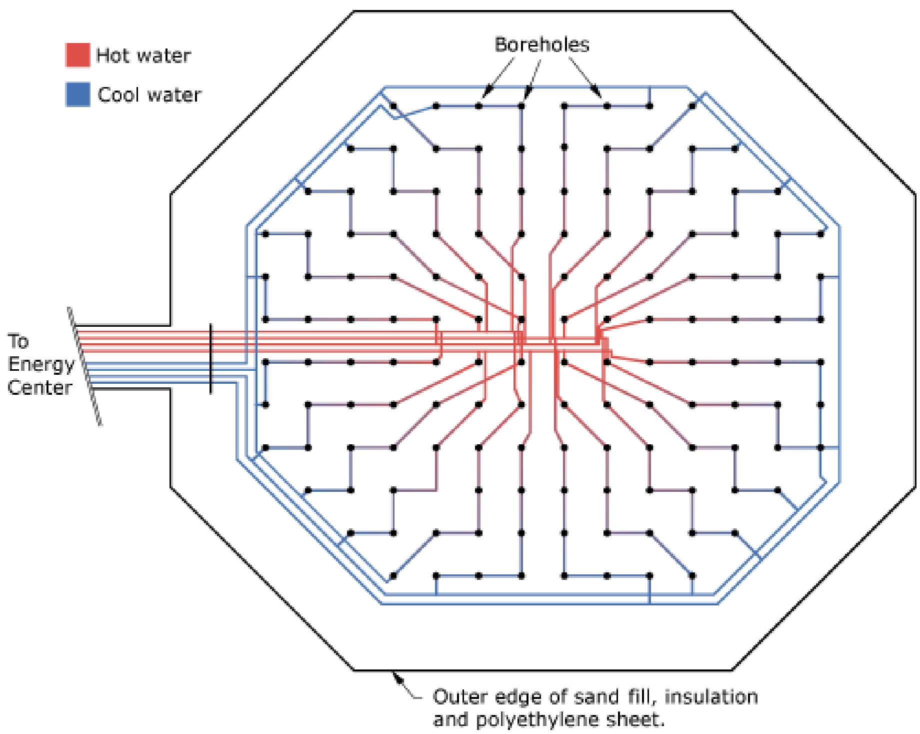


Figure 3-1 Aerial view of borehole thermal energy storage

(Drake Landing Solar Community, 2007)

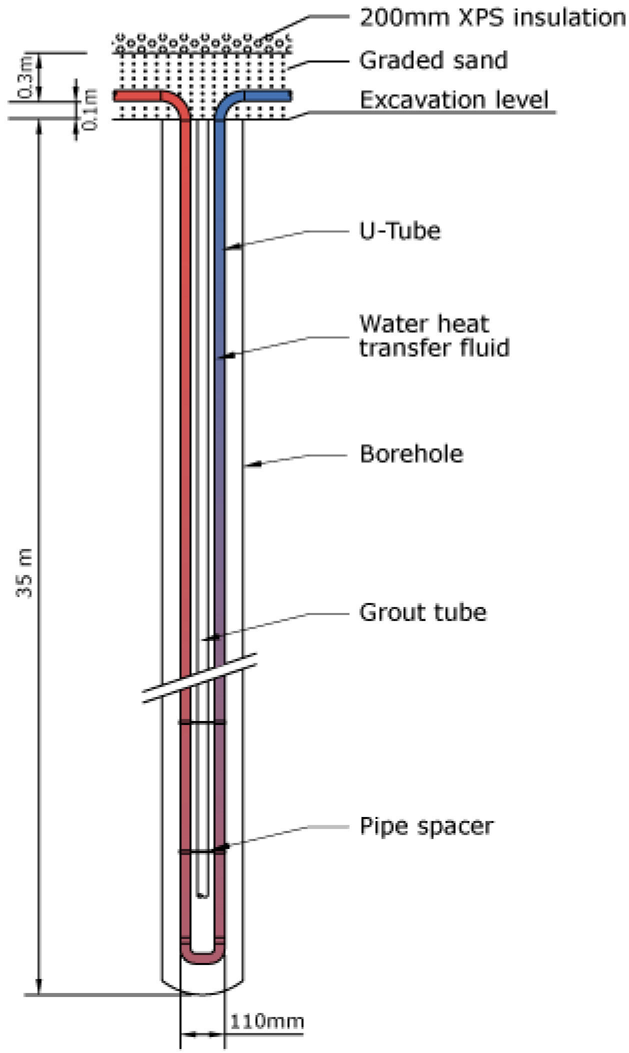
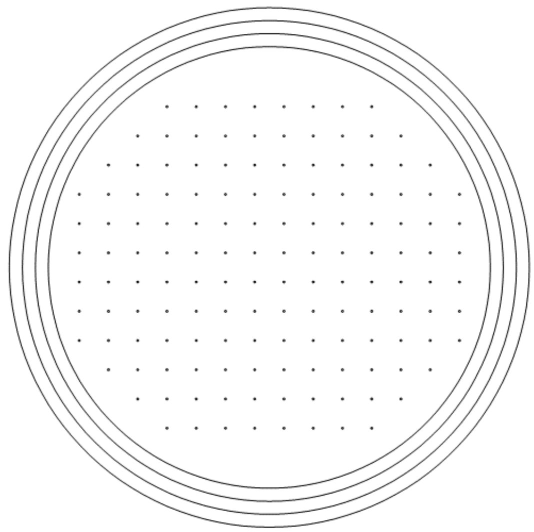
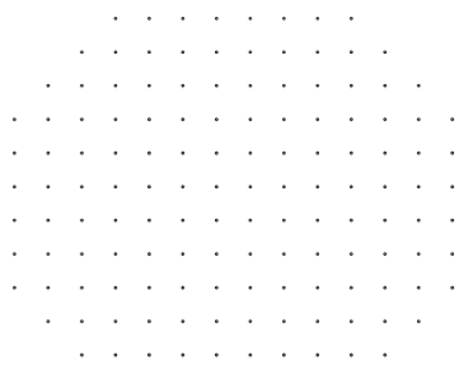


Figure 3-2 Side view of single borehole thermal energy storage tube

(Drake Landing Solar Community, 2007)

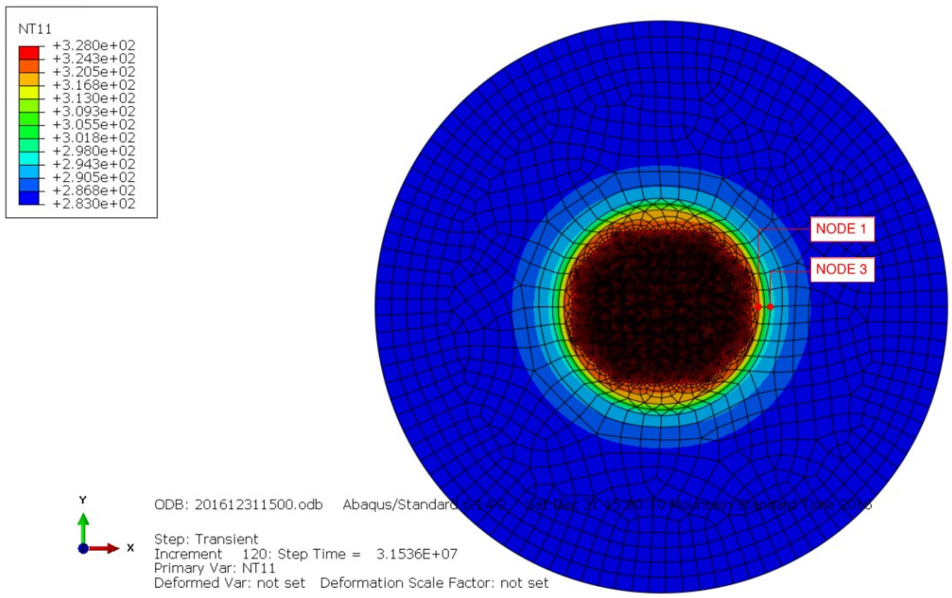


(A) Fully insulated with thermal insualting soilcrete

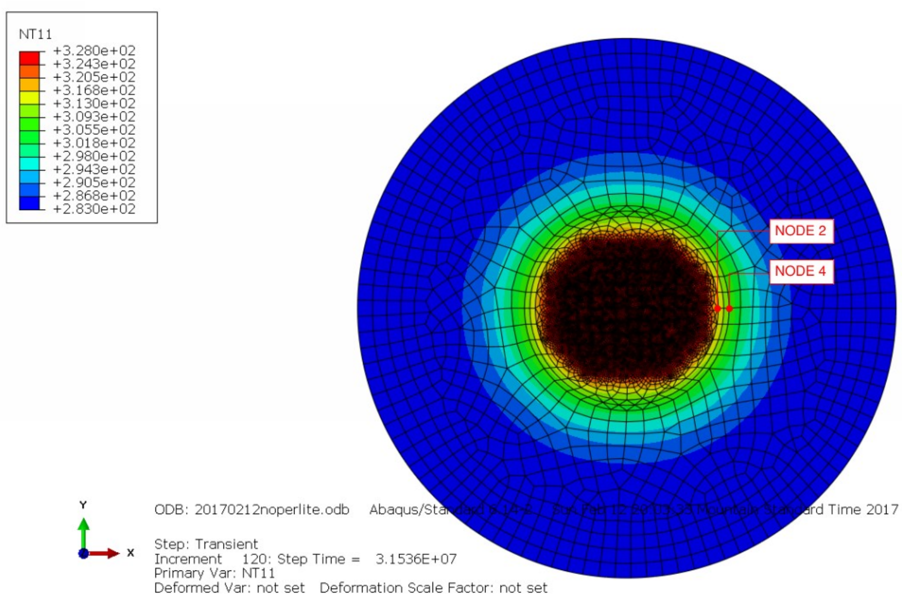


(B) Not insulated

Figure 3-3 Full-scale model geometry

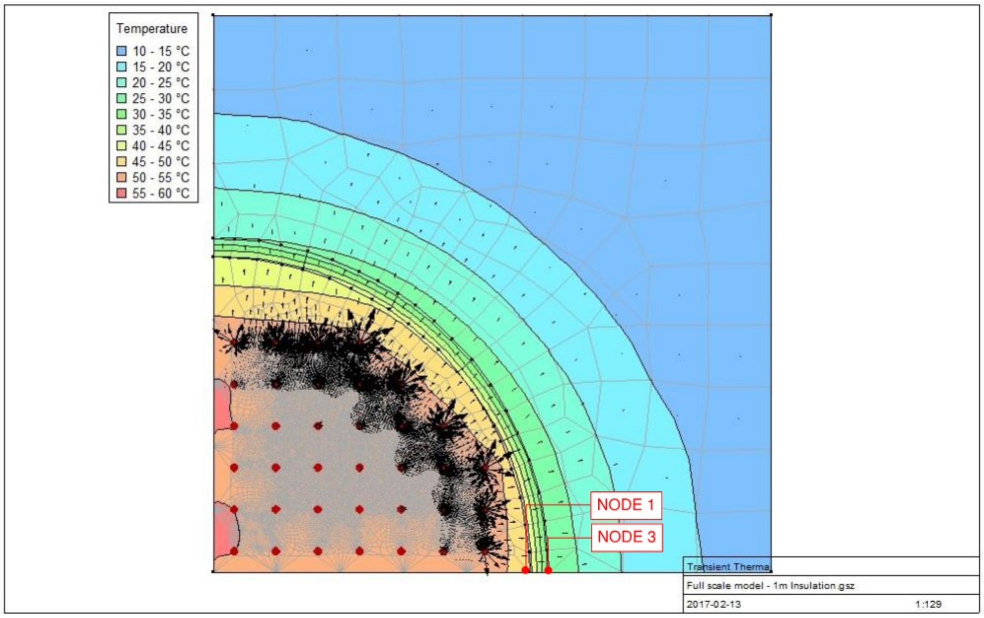


(A) Temperature distribution at 365-day result with insulation

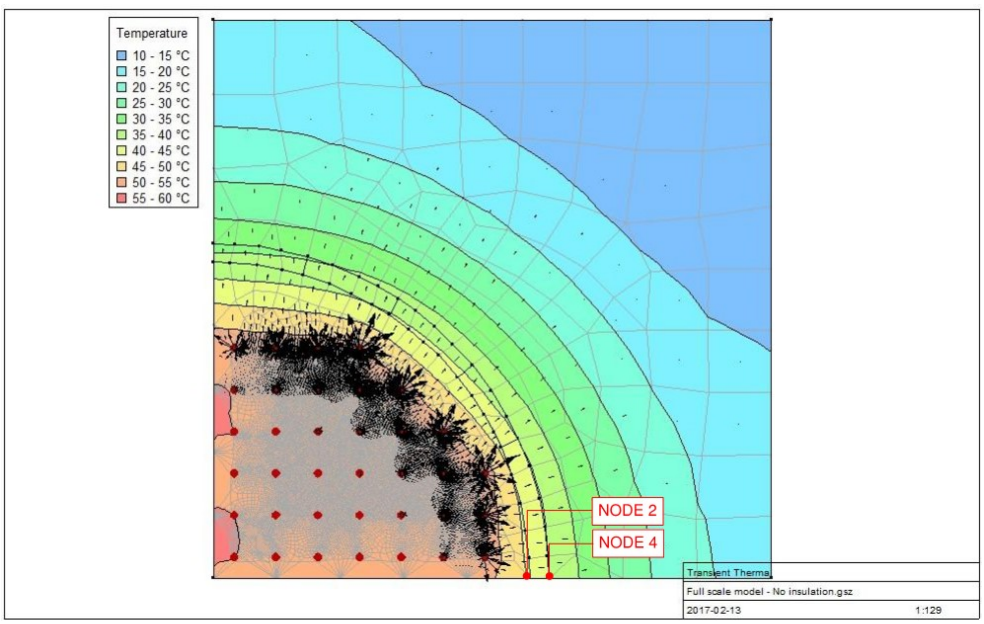


(B) Temperature distribution at 365-day result without insulation

Figure 3-4 Temperature distribution in full-scale model with Abaqus



(A) Temperature distribution at 365-day result with insulation



(B) Temperature distribution at 365-day result without insulation

Figure 3-5 Temperature distribution in full-scale model with Temp/W

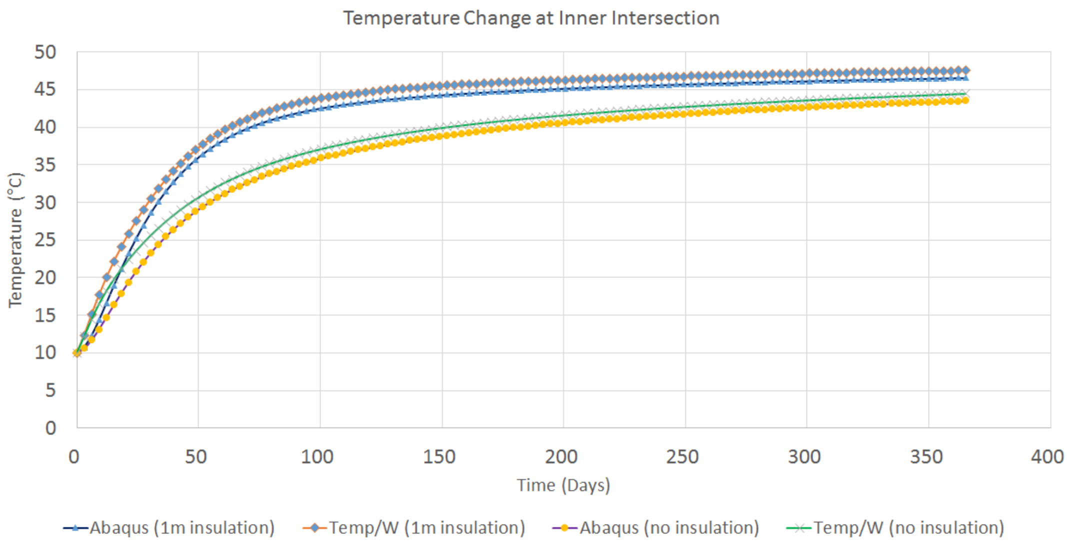


Figure 3-6 Temperature change at node 1 and node 2 over time

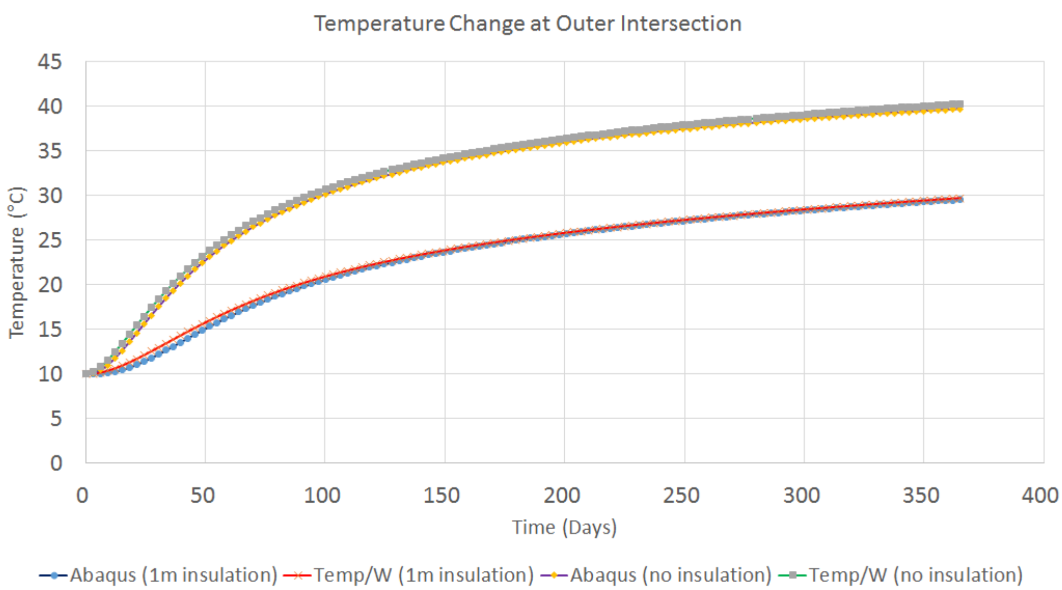


Figure 3-7 Temperature change at node 3 and node 4 over time

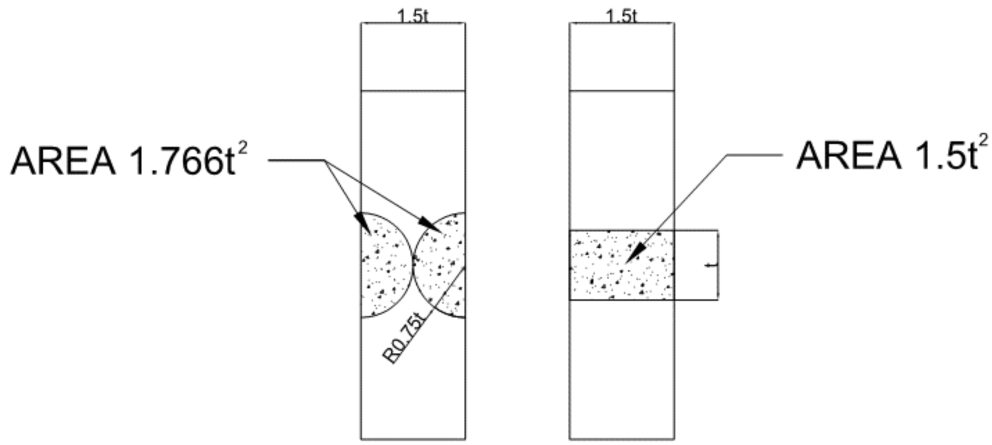


Figure 3-8 Jet grouted insulating soilcrete and constant thickness insulating soilcrete Diagram

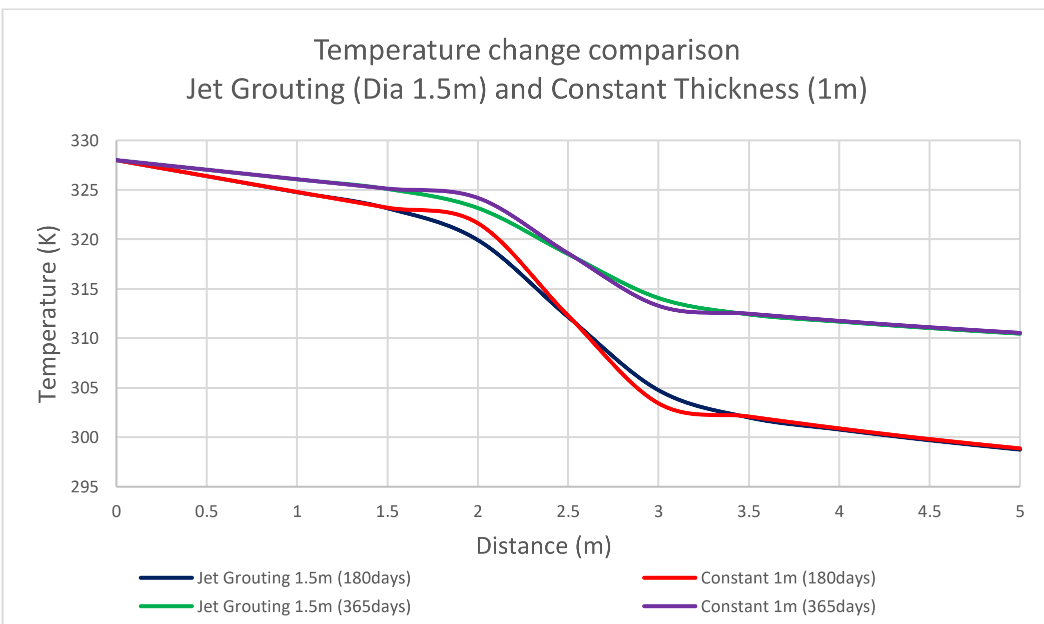


Figure 3-9 Temperature change comparison for two different types of thermal insulating soilcrete with the same effective thickness

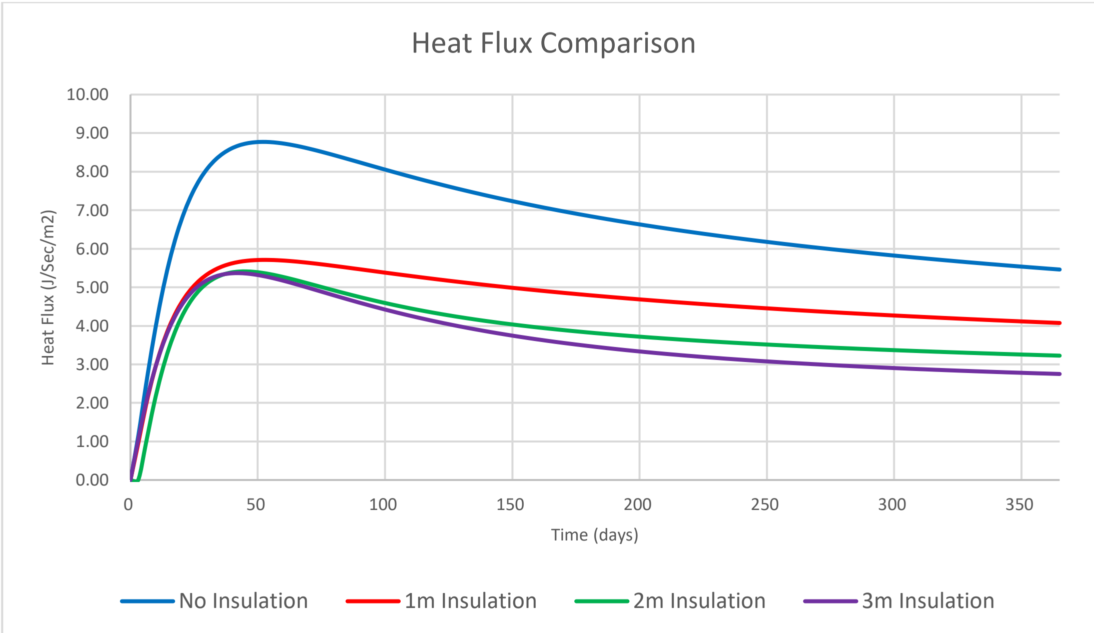


Figure 3-10 Heat Flux comparison for model with different thickness thermal insulating barrier

Tables in Chapter 3

Table 3-1 Properties of in-situ soil (Nikbakhtan, 2015)

Properties	Values
In-situ moisture content	15.5 %
Liquid limit	36.4 %
Plastic limit	19.57 %
Plasticity index	16.83 %
UCSC soil classification	CL
Specific gravity	2.7
Optimum moisture content	14.75 %
Dry density	1785 kg/m^3
UCS (Unconfined Compressive Strength)	370 kPa
Modulus of elasticity	48 kPa
Thermal conductivity	1.41 W/m·K
Thermal diffusivity	1.56 mm^2/s
Volumetric heat capacity	0.83 MJ/m^3·K
Specific heat capacity	465 J/kg·K

Table 3-2 Properties of thermo-insulating soilcrete (Nikbakhtan, 2015)

Properties	Values	
28-day old soilcrete density	1661.53 kg/m^3	Wet
	1127.37 kg/m^3	Dry
Bulk density	1094.3 kg/m^3	
28-days Unconfined Compressive Strength	1.814 MPa	Wet
	1.978 MPa	Dry
28-days modulus of elasticity	222.64 MPa	Wet
	156.43 MPa	Dry
28-days splitting tensile strength	0.463 MPa	Wet
	0.324 MPa	Dry
28-days moisture content	46.55 %	Wet
Thermal conductivity	0.52 W/m·K	Wet
	0.23 W/m·K	Dry
Thermal diffusivity	0.42 mm^2/s	Wet
	0.25 mm^2/s	Dry
Volumetric heat capacity	1.19 MJ/m^3·K	Wet
	0.92 MJ/m^3·K	Dry
Specific heat capacity	719.81 J/kg/K	Wet
	819.4 J/kg·K	Dry

Table 3-3 Properties used in finite element modeling

	Abaqus	**Temp/W**
Model size	Full Model	A quarter of the full model
Number of Boreholes	144	36
Mesh Type	Quadratic quadrilateral	Default
Total Number of Mesh	20481	31126
Initial temperature	10 °C	10 °C
Injected Heat Temperature	55 °C	55 °C
Duration	365 days	365 days

Table 3-4 Estimated annual financial benefits

Thickness of Insulation	**Dissipated Thermal Energy (kW)**	**Reduction (kW)**	**Reduction (%)**	**Cost saving ($)**
None	9142.74	-	-	-
1 meter	6371.69	2771.05	30.3	11,385.71
2 meter	5279.95	3862.79	42.3	15,871.44
3 meter	4930.35	4212.39	46.1	17,307.86

Table 3-5 Final proportions of aggregates in the soilcrete body

(Nikbakhtan, 2015)

Aggregates	Measure	Soilcrete 1	2	3	4	5
Soilcrete	Lit	21.34	31.02	40.70	53.61	66.52
	Kg	30.28	30.28	30.28	30.28	30.28
Amount of ELP in soilcrete	By volume (%)	0.00	34.04	51.88	65.65	74.07
	By weight (%)	0.00	4.36	8.72	14.53	20.34
Amount of soil in soilcrete	By volume (%)	34.25	23.56	17.95	13.63	10.99
	By weight (%)	43.91	43.91	43.91	43.91	43.91
Amount of cement in soilcrete	By volume (%)	27.40	16.02	10.05	5.45	2.64
	By weight (%)	29.06	24.70	20.34	14.53	8.72
Amount of water in soilcrete	By volume (%)	38.36	26.39	20.11	15.27	12.30
	By weight (%)	27.03	27.03	27.03	27.03	27.03

Table 3-6 Material cost break down comparison

Thickness of Insulation	Total Volume (m^3)	Cementitious Material Volume (m^3)	Cost of Cement (USD)	Cost of Perlite (USD)	Total Material Cost (USD)
None	-	-	-	-	-
1 meter	3,848	384.84	$69,202.85	$35,638.89	$104,841.73
2 meter	7,916	791.68	$142,360.14	$73,314.28	$215,674.42
3 meter	12,205	1220.51	$219,471.88	$113,026.19	$332,498.07

Table 3-7 Feasibility study (35 m deep thermal insulation)

Thickness of Insulation	Total Material Cost (USD)	Estimated Installation Cost (USD)	Total Cost (USD)	Annual Cost Saving (USD)	Time to Break Even (Years)
None	-	-	-	-	-
1 meter	$104,841.73	$150,000.00	$222,121.14	$11,385.71	19.5
2 meter	$215,674.42	$200,000.00	$348,365.63	$15,871.44	21.9
3 meter	$332,498.07	$250,000.00	$478,733.47	$17,307.86	27.7

Table 3-8 Feasibility study (25 m deep thermal insulation)

Thickness of Insulation	Total Material Cost (USD)	Estimated Installation Cost (USD)	Total Cost (USD)	Annual Cost Saving (USD)	Time to Break Even (Years)
None	-	-	-	-	-
1 meter	$74,886.95	$100,000.00	$174,886.95	$8,132.65	21.5
2 meter	$154,053.16	$125,000.00	$279,053.16	$11,336.74	24.6
3 meter	$237,498.62	$150,000.00	$387,498.62	$12,362.76	31.3

References

Bottomley, P., 1985. *The reduction in heat flow due to the insulation of rock surfaces in mine airways.* Reno, NV, s.n.

Dassault Systemes Simulia Corp, 2012. *Abaqus Users Manual,* Providence, RI: s.n.

Drake Landing Solar Community, 2007. *Drake Landing Solar Community Okotoks.* [Online]
Available at: https://www.dlsc.ca/borehole.htm[Accessed 31 December 2016].

EPCOR, 2016. *EPCOR Utilities.* [Online] Available at: https://www.epcor.com/products-services/power/rates-tariffs-fees/Pages/regulated-residential-power-rates.aspx
[Accessed 31 12 2016].

GEO-SLOPE International Ltd., 2014. *Thermal Modeling with TEMP/W,* Calgary, AB: GEO-SLOPE International, Ltd..

Khan, M. I., 2002. Factors affecting the thermal properties of concrete and. *Building and Environment,* pp. 607-614.

Lanini, S., 2014. Improvement of borehole thermal energy storage design based on experimental and modelling results. *Energy and Buildings,* pp. 393-400.

Liu, G.-R. & Quek, S. S., 2013. *The finite element method: a practical course.* 2nd ed. Waltham, MA: Butterworth-Heinemann.

Logan, D., 2011. *A first course in the finite element method.* 5th ed. Stamford, CT: Cengage Learning.

Nikbakhtan, B., 2015. Development of Thermal-Insulating Soilcrete using Laboratory Jet Grouting Setup.

Nordell, B., 2012. *Underground Thermal Energy Storage (UTES).* Lleida, Spain, Innostock 2012.

Omer, A., 2008. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews,* pp. 344-71.

Sibbitt, B., McClenahan, D. & Djebbar, R., 2012. The performance of a high solar fraction seasonal storage district heating system – five years of operation. *Energyt Procedia,* Volume 30, pp. 856-865.

Sibbitt, B. et al., 2012. The performance of a high solar fraction seasonal storage district heating system – five years of operation. *Energy Procedia,* Volume 30, pp. 856 - 865.

Statistics Canada, 2007. *http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/phys08b-eng.htm.* [Online] Available at: www.statcan.gc.ca[Accessed 29 December 2016].

Topçu, İ. B. & Işıkdağ, B., 2007. Manufacture of high heat conductivity resistant clay bricks containing perlite. *Building and Environment,* pp. 3540-3546.

Chapter 4. General conclusion

Thermal energy storage systems built underground use soil as a heat storing media and most types of soil materials exhibit high conductivity. Having high conductive soil materials as a heat storing media within the system can be an advantage in the short term. However, the high conductivity of soil also accelerates the thermal energy dissipation into surrounding ground. As a result, most of the thermal energy injected into the borefield will escape from the system. Therefore, the necessity of thermal insulating barrier for underground thermal energy storage system was proposed by precedent research at the University of Alberta in order to reduce the rate of heat flow from the borefield to the surrounding ground.

4.1 Research summary

One of the main focuses of this research was to determine the effectiveness of the thermal insulating soilcrete as a thermal insulation layer in underground thermal energy storage system to reduce the thermal energy dissipation to the surrounding soil. In order to simulate the effectiveness of the thermal insulation barrier, a full-scale cylindrical model was developed using the FEM numerical modeling software. The model was run with various conditions: zero insulation, one-meter, two-meter and three-meter thickness insulation respectively, for the establishment of theoretical fundamental. The full-scale numerical modeling described the heat flow into the surrounding ground in detail and predicted that the application of thermal insulating soilcrete reduced the annual average heat flux by 46 % with three-meter thickness insulation and saved $17,307 annually.

4.2 Contributions

This research focused on providing theoretical evidence for the application of thermal insulating soilcrete to the BTES using the FEM. Numerical models were established to evaluate the transient process of thermal insulation in the BTES. The outcome from the finite element modeling provided numerical evidence of improved efficiency in the application of thermal insulation barrier in the BTES.

4.3 Limitations

Jet grouting is a widely used in-situ soil improvement method for the various type of soil and able to reach almost any depth without much restriction. However, the amount of water used in jet grouting operation to disrupt soil creates higher risks of aggregate segregation.

In order to mitigate the risks, an alternate construction method, one pass deep trenching is proposed as well as adding superplasticizer, a chemical admixture. One pass deep trenching method is a high capacity wet mixing method that allows mixing of soil with the cementitious product while digging. However, due to the significant operation as well as mobilization and demobilization cost of one pass deep trenching, economic feasibility need to be thoroughly studied.

4.4 Recommendations for future research

In the areas of thermal insulating soilcrete for the BTES, a few recommendations for future research are listed as follows:

- Due to substantial operation and mobilization/demobilization cost of one pass deep trenching method, it is not economic feasible to check the mixing performance using the full-scale operation. A smaller scale operation using a smaller trencher using proposed soilcrete mix design can be performed, and samples can be obtained, and thermal and mechanical properties can be analyzed to compare with the properties of hand mix samples.

- The mix design and the thermal properties are the key factors in the development of thermal insulating soilcrete. Due to the significant difference in density among the major ingredients: cement, water and the EPA, there are potential risks of segregation when the thermal insulating soilcrete mix is mixed.

  Use of superplasticizer or anti-washout admixtures in the thermal insulation mix can be studied as a potential solution to the risks of segregation. Adding chemical admixtures can improve the workability of the thermal insulation mix and ultimately can mitigate the risks of aggregate segregation. Superplasticizer, a dispersant additive, temporarily neutralizes the dragging force of the cement particles and minimizes congregation phenomenon when mixed with water. Superplasticizer also allows having up to 40 % less water and this reduced water-cement ratio which improves the strength of thermal insulating soilcrete mix while maintaining concrete workability. Adding anti-washout admixture will provide strong increase in cohesion which can minimize washout, segregation, and bleeding under water application or jet grouting application for thermal insulation mix application. This admixture can also improve the flowability and self-consolidation ability of the thermal insulation mix. The admixture can enhance the stability of the fresh cementitious mix products for jet grouting application.

The improved mechanical properties of concrete would allow adding more perlite and less cement in the thermal insulating soilcrete mix and improve thermal properties. Cement is the most expensive material amongst the main ingredients of thermal insulating soilcrete. Any reduction of cement and addition of perlite in the development of the new thermal insulating mix will improve the economic feasibility.

- The application of cellular lightweight concrete or concrete mixed with a foaming agent with lower thermal conductivity can be studied for the BTES thermal insulating application. Cematrix is one of the examples of the cellular lightweight concrete product which has the thermal conductivity of 0.065 W/m·K. However, the biggest disadvantage of the cellular lightweight concrete is that the increment of height in the installation of cellular lightweight concrete is limited to 600 mm at a time due to the risks of a collapse of the bubble inside the mix. Any fix to this height limit will help application of cellular lightweight concrete or concrete mixed with the foaming agent in thermal insulation application in the BTES.

References

Abbasy, F., 2013. An Investigation into Application of Geothermal Energy in Underground Mines. Montreal: McGill University.

Andersson, O. & Hägg, M., 2013. Preliminary design of a seasonal heat storage for ITT Flygt, Emmaboda, Sweden. Integration of geothermal energy into industrial applications, Volume 21, pp. 72-79.

Armstrong, J. A. & Hamrin, J., 2000. The Renewable Energy Policy Manual, Washington, D.C.: United States Export Council for Renewable Energy.

Bloomberg New Energy Financing, 2016. Bloomberg New Energy Finance Summit. s.l., Bloomberg New Energy Financing.

Bolen, W. P., 2004. Perlite. In: Mineral Commodity Summaries. s.l.:U.S. Geological Survey (USGS).

Bottomley, P., 1985. The reduction in heat flow due to the insulation of rock surfaces in mine airways. Reno, NV, s.n.

Burke, G. K., 2004. Jet grouting systems: advantages and disadvantages.. Orlando, American Society of Civil Engineers.

Cui, P., Li, X., Man, Y. & Fang, Z., 2011. Heat transfer analysis of pile geothermal heat exchangers with spiral coils. Applied Energy, 88(11), pp. 4113-4119.

Dassault Systemes Simulia Corp, 2012. Abaqus Users Manual, Providence, RI: s.n.

DeWind, G. A., 2002. Shaft driven trencher. United States, Patent No. 6351900.

DeWind Wells & De Watering, 2012. DeWind Trenching is the leader Deep One Pass Trenching used for Environmental and Civil Construction. [Online]

Available at: http://www.dewindonepasstrenching.com/

[Accessed 24 March 2016].

Diersch, H. J. et al., 2011. Finite element modeling of borehole heat exchanger systems Part 2. Numerical simulation. Computers & Geosciences, Volume 37, pp. 1136-1147.

Drake Landing Solar Community, 2007. Drake Landing Solar Community Okotoks. [Online]

Available at: https://www.dlsc.ca/borehole.htm[Accessed 31 December 2016].

Ellabban, O., Abu-Rub, H. & Blaabjerg, F., 2014. Renewable energy resources: Current status, future prospects and their enabling technology. Renewable and Sustainable Energy, Volume 39, pp. 748-764.

Energy Efficiency Alberta, 2017. Energy Efficiency Alberta. [Online]

Available at: https://www.efficiencyalberta.ca/

[Accessed 19 May 2028].

Environment and Climate Change Canada, 2016. National Inventory Report 1990–2014: Greenhouse Gas Sources and Sinks in Canada, Gatineau, QC: Environment and Climate Change Canada.

EPCOR, 2016. EPCOR Utilities. [Online] Available at: https://www.epcor.com/products-services/power/rates-tariffs-fees/Pages/regulated-residential-power-rates.aspx

[Accessed 31 12 2016].

Essler, R. & Yoshida, H., 2004. Jet grouting. Ground improvement. 2nd ed. Abingdon, Oxon: s.n.

Fridleifsson, I. B., 2008. The possible role and contribution of geothermal energy to the mitigation of climate change.. Luebeck, Germany, s.n., pp. 20-25.

Fridleifsson, I. B. & Freeston, D. H., 1994. Geothermal energy research and development. Geothermics, 23(2), pp. 175-214.

Fritz-Pak Corporation, 2005. Supercizer 7 Technical Data Sheet. Dallas, TX: Fritz-Pak Corporation.

Gagne´, R., Ollivier, J. & Latreille, Y., 1998. Effects of Superplasticizer, Retarding Agent, and Silica Fume on the Air Permeability of High-Performance Concrete. Cement, Concrete, and Aggregates, Volume 20, pp. 248-256.

Gelardi, G. & Flatt, R. J., 2016. Working mechanisms of water reducers and superplasticizers. In: cience and Technology of Concrete Admixtures. s.l.:Woodhead Publishing, pp. 257-278.

Gil, A., Medrano, M. & Lázaro, A., 2010. State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization.. Renewable and Sustainable Energy Reviews, Volume 14.1, pp. 31-55.

Government of Alberta, 2014. Best Practice - Working Safely in the Heat and Cold, Edmonton: Government of Alberta.

Government of Alberta, 2017. Alberta Government. [Online]

Available at: https://www.alberta.ca/climate-carbon-pricing.aspx

[Accessed 10 February 2017].

Gunning , D. F., 1994. Perlite Market Study Report, s.l.: Gunning and Mc Neal Associates Ltd.

GEO-SLOPE International Ltd., 2014. Thermal Modeling with TEMP/W, Calgary, AB: GEO-SLOPE International, Ltd..

Hanova, J. & Dowlatabadi, H., 2007. Strategic GHG reduction through the use of ground source heat pump technology.. Environmental Research Letters, 2(4), pp. 1-8.

Hassan, A., 1999. Optimising insulation thickness for building using life cost. Applied Energy, Issue 63, pp. 115-124.

Herrin, J. M. & Deming, D., 1996. Thermal Conductivity of U.S. coals. Journal of Geophysical Research: Solid Earth, 101(B11), pp. 25381-25386.

Kendall, K. & Stainton, C., 2001. Adhesion and aggregation of fine particles. Powder Technology, Volume 121, pp. 223-229.

Khan, M. I., 2002. Factors affecting the thermal properties of concrete and. Building and Environment, pp. 607-614.

Kreijger, P. C., 1984. The Skin of Concrete: Composition and Properties. Materials and Structures, 17(100), pp. 275-283.

Lanini, S. et al., 2014. Improvement of borehole thermal energy storage design based on experimental and modelling results. Energy and Buildings, pp. 393-400.

Levesque, M., 2014. Energy and mining-The home truths. Journal of Cleaner Production, pp. 233-255.

Liu, W. V., Apel, D. B. & Bindiganavile, V., 2011. Thermal characterisation of a lightweight mortar containing expanded perlite for underground insulation.. International Journal of Mining and Mineral Engineering, pp. 55-71.

Liu, W. V., Apel, D. B. & Bindiganavile, V. S., 2014. Thermal properties of lightweight dry-mix shotcrete containing expanded perlite. Cement and Concrete Composites, Volume 53, pp. 44-51.

Liu , W. V., 2013. Development and Testing of Insulating Shotcrete for the Application in Underground Tunnels, Edmonton: University of Alberta.

Liu, G.-R. & Quek, S. S., 2013. The finite element method: a practical course. 2nd ed. Waltham, MA: Butterworth-Heinemann.

Logan, D., 2011. A first course in the finite element method. 5th ed. Stamford, CT: Cengage Learning.

Lund, J. W., 1995. Historical Impacts of Geothermal Resources on the People of North America. Geo-Heat Center Quarterly Bulletin, Volume 8, pp. 1-14.

Ma, G.-y. & Chai, Q.-h., 2004. Characteristics of an improved heat-pump cycle for cold regions.. Applied Energy, 77(3), pp. 235-247.

McClenahan, D. & Gusdorf, J., 2006. Okotoks: Seasonal Storage of Solar Energy for Space Heat in a New Community. Pacific Grove, CA, American Council for an Energy-Efficient Economy, pp. 121-131.

Mladenovič , A., Šuput , J. S., Ducman , V. & Škapin , A. S., 2004. Alkali–silica reactivity of some frequently used lightweight aggregates. Cement and Concrete Research, pp. 1809-1816.

Moseley, M. & Kirsch, K., 2004. Ground improvement. s.l.:CRC Press.

Moseley, M. P. & Kirsch, K., 2004. Ground Improvement. 2 ed. Abingdon, Oxon: CRC Press.

New Climate Economy, 2014. BETTER GROWTH BETTER CLIMATE: The New Climate Economy Report, Washington, D.C.: New Climate Economy.

Nikbakhtan, B., 2015. Development of Thermal-Insulating Soilcrete using Laboratory Jet Grouting Setup.

Nordell, B., 2012. Underground Thermal Energy Storage (UTES). Lleida, Spain, Innostock 2012.

Office of Energy Efficiency and Renewable Energy, 2010. Types of geothermal heat pump systems., Washington, DC: US Department of Energy.

Omer, A., 2008. Ground-source heat pumps systems and applications. Renewable and Sustainable Energy Reviews, 12(2), pp. 344-71.

Pampel, A. & Polloczek, J., 1999. Einsatz des FMI- und HZV-Verfahrens bei der. Der Eisenbahningenieurbau, Volume Nr. 3.

Papayianni, I., Tsohos, G., Oikonomou, N. & Mavria, P., 2005. Influence of superplasticizer type and mix design parameters on the performance of them in concrete mixtures. Cement & Concrete Composites, Volume 27, pp. 217-222.

Rio Tinto, 2014. Diavik Diamond Mine 2013 sustainable development report, Yellowknife: Diavik Diamond Mines (2012) Inc.

Sam X. Yao, a. B. C. G. J., 2004. Underwater Concrete Part 2: Proper Mixture Proportioning. Concrete International, 26(2), pp. 77-82.

Schaefer, V. R., Abramson, L. W., Drumheller, J. C. & Sharp, K. D., 1997. Ground improvement, ground reinforcement and ground treatment: developments 1987-1997.. Paeonian Springs, VA: ASCE.

Self, S. J., Reddy, B. V. & Rosen, M. A., 2013. Geothermal heat pump systems: Status review and comparison with other heating options. Applied Energy, Volume 101, pp. 341-348.

Sengul, O., Azizi, S., Karaosmanoglu, F. & Tasdemir, M. A., 2011. Effect of expanded perlite on the mechanical properties and thermal conductivity of lightweight concrete.. Energy and Buildings, 43(2), pp. 671-676.

Sibbitt, B., McClenahan, D. & Djebbar, R., 2011. Measured and simulated performance of a high solar fraction district heating system with seasonal storage. Kassel, Germany, International Solar Energy Society, Villa Tannheim, Wiesentalstrasse 50, D-79115, Germany, pp. 3037-3048.

Sibbitt, B., McClenahan, D. & Djebbar, R., 2012. The performance of a high solar fraction seasonal storage district heating system – five years of operation. Energyt Procedia, Volume 30, pp. 856-865.

Singh, M. & Garg, M., 1991. Perlite-based building materials -- a review of current applications. Construction and Building Materials, Volume 5, pp. 75-81.

Steiger, R. W. & Hurd, M. K., 1978. Lightweight insulating concrete for floors and roof decks.. Concrete Construction, 23(7), pp. 411-422.

Statistics Canada, 2007. http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/phys08b-eng.htm. [Online] Available at: www.statcan.gc.ca[Accessed 29 December 2016].

Taylor, S., 1971. Atlas : Coal-mine Workings of the Edmonton Area, s.l.: Spence Taylor and Associates.

Topçu, İ. B. & Işıkdağ, B., 2007. Manufacture of high heat conductivity resistant clay bricks containing perlite. Building and Environment, pp. 3540-3546.

Topçu, İ. B. & Işıkdağ, B., 2008. Effect of expanded perlite aggregate on the properties of lightweight concrete.. Journal of materials processing technology, 204(1), pp. 34-38.

Topolnicki, M., 2004. In situ soil mixing. In: Ground Improvement. New York, NY: Spon Press, pp. 331-428.

U.S. Energy Information Administration, 2011. Annual Energy Review, Washington, DC: U.S. Energy Information Administration.

U.S. Energy information Administration, 2015. Annual Energy Outlook, s.l.: Energy Information Administration.

United Nations foundation, 2013. United Nations foundation. [Online]

Available at: http://www.unfoundation.org/what-we-do/issues/energy-and-climate/ [Accessed 19 May 2107].

United States Army Corps of Engineers, 2006. CRD-C 661-06: Specification for Antiwashout Admixtures for Concrete. Washington D.C.: s.n.

Yang, H., Cui, P. & Fang, Z., 2010. Vertical-borehole ground-coupled heat pumps: A review of models and systems.. Applied Energy, 87(1), pp. 16-27.

Yang, W., Shi, M., Liu, G. & Chen, Z., 2009. A two-region simulation model of vertical U-tube ground heat exchanger and its experimental verification.. Applied Energy, 86(10), pp. 2005-2012.

Zhao, M., Zhang, X. & Zhang, Y., 2016. Effect of free water on the flowability of cement paste with chemical or mineral admixtures. Construction and Building Materials, Volume 111, pp. 571-579.

Zizzo, R., 2010. Designing an optimal urban community mix for an aquifer thermal energy storage system. M.S. Thesis, University of Toronto, Toronto, Canada.