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Use of Geothermal Energy for Deicing Approach Pavement Slabs and Bridge Decks, Phase 1: Final Report

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16. Abstract
Deicing using geothermal energy can provide TxDOT a better alternative than the existing method of using deicing with sands and/or salts. This research project will address this topic with a primary focus of comprehensive synthesis study. As a part of this synthesis, the available literature on geothermal energy along with success application case studies in the world on the use of geothermal energy for bridge decks and pavement deicing applications will be compiled. The review of geothermal underground structures will be focused on underground thermal energy storage (UTES), which is used to inject or extract heat into/from underground soil for seasonal cooling and heating needs. A preliminary finite element analysis of bridge deicing using geothermal energy will also be performed using typical Texas soil and climate conditions to demonstrate feasibility along with potential cost-benefit analysis of the recommended geothermal deicing system for field application. Recommendations will be made on candidate geothermal structures and bridge deck/pavement heating systems for field demonstration studies as a part of follow-up validation studies.

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List of Terms

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTES	borehole thermal energy storage
CTES	cavern thermal energy storage
DE	district energy
FEM	finite element method
GEP	geothermal energy piles
GLHE	ground-loop heat exchanger
GSHP	ground-source heat pump
PCM	phase-change material
SERSO	solar energy recovery from road surface
UTES	underground thermal energy storage

Chapter 1. INTRODUCTION

1.1. Research Background

Adverse weather conditions have a major impact on the safety and operation of our roads, from signalized arterials to interstate highways. Weather affects driver behavior, vehicle performance, pavement friction, and roadway infrastructure. This is especially true for many drivers in Texas, who are unfamiliar with driving in winter road conditions (Figure 1). When weather turns wintry with snow and ice, it can change daily habits and be deadly. Over 70% of the nation's roads are located in snowy regions, which receive more than five inches (13 cm) of snowfall annually. Nearly 70% of the U.S. population lives in these snowy regions. Snow and ice reduce visibility, pavement friction and vehicle maneuverability, causing slower speeds, reduced roadway capacity, and increased crash risk. Over 17% of all fatal crashes occur during winter weather conditions. Of those, 60% happen in rural areas. Snow accumulation obstructs lanes and roads, reducing capacity and increasing travel time delays. More frequent extreme weather can be foreseen in the new future; therefore, it is urgent to implement new deicing technologies to minimize the impact of icy conditions on public safety.

Ross Hailey of the Fort Worth Star-Telegram captured this truck driving over cobblestone ice in Haltom City, TX

Figure 1 Cobblestone ice creates danger travel conditions

1.2. Scope and Objectives

Using geothermal energy for deicing can provide TxDOT with a better alternative than the existing method of deicing sand and/or salt. However, the usage of geothermal energy is limited in the U.S. due to the lack of research into practical applications, including field demonstrations. This research project is an attempt to address this topic by providing a comprehensive synthesis study. As a part of this synthesis, the available literature on geothermal energy was compiled, along with successful application case studies on the use of geothermal energy for bridge decks and pavement deicing applications. The review of geothermal underground structures focuses on underground thermal energy storage (UTES), which is particularly suitable in Texas for storing summer heat to use in deicing under winter conditions. In addition, a preliminary finite element analysis of bridge deicing using geothermal energy was performed, with assumed soil and climate conditions, to demonstrate feasibility along with potential cost-benefit analysis of the recommended geothermal deicing system for field application. Recommendations are made on candidate geothermal structures and bridge deck/pavement heating systems for field demonstration.

The following are the main objectives of the one-year synthesis project:

- Perform a one-year synthesis study to investigate the current capability of a geothermal system for Texas weather conditions to store and reuse heat that has been collected in an underground soil system to warm bridge decks and pavement structures above the freezing point.
- Collect the available knowledge base including case studies all over the world on the UTES technology and determine its effectiveness in warming bridges deck and pavement surfaces during freezing temperature conditions. Preliminary numerical modeling demonstrating thermal temperature distribution in the bridge deck/pavement systems, along with cost benefit studies using these technologies, will be performed and included as a part of the synthesis report.
- Recommend geothermal structure and bridge deck heating systems that are ready for field demonstration studies.

The major benefit of this study is to enhance the safety of the traveling public by alleviating treacherous road conditions during winter conditions. Over the last three years, severe winter conditions, including snowstorm events, have resulted in the closure of bridges and pavements due to icing conditions. These cold conditions have caused the closure of roads and bridges, as icy road conditions result in accidents, including those in which human lives are lost. This geothermal technology can potentially alleviate this concern and enhance the safety of the traveling public by warming the roads and bridge decks so that the surface conditions are much more conducive to safe traveling.

Chapter 2. LITERATURE REVIEW

2.1. Use of Geothermal Technologies for Bridge and Pavement Deicing

Geothermal energy is characterized as a renewable, sustainable, clean (i.e., zero-carbon emission) and direct use energy, which has been widely used in many engineering applications, such as ground-source heat pumps (GSHP), geothermal energy piles, and soil borehole thermal energy storage (BTES). This project examines the use of geothermal energy for deicing pavement slabs and bridge decks. The research background is presented first, with respect to the related application of geothermal energy. The working principle and design criteria of the geothermal system are then presented for future field applications where the soil thermal conductivity is a key parameter that can be studied by our newly-developed thermo-time domain reflectometry probe. Several case studies in Europe, Asia, and the U.S. are reviewed to further demonstrate the feasibility and applicability of this innovative technology. Lastly, the long-term cost-benefit is analyzed, and some recommendations for field implementation are provided.

2.1.1. Introduction

Ice and snow on pavement slabs and bridge decks always cause serious driving conditions for motorists, both in safety and their ability to accelerate and climb grades, decelerate on downgrades, or maneuver superelevated curves. They are also responsible for traffic jams and accidents every year because the movement of cold air above and below bridge decks leads to icing on the surface of the elevated structures. Hence, deicing pavement slabs and bridge decks is very essential under certain weather conditions in winter. The commonly-used deicing methods include plowing, salting, and sanding, or the use of heat from various sources to melt ice and snow. However, the relatively high cost of sand, salt, fuel, repairs, and labor limit the utilization of these methods.

Geothermal energy is considered a new heating source for deicing and keeping roads and bridges usable in winter. It is harmless and free, as well as climate-neutral energy, and can be obtained much easier than any other heating sources. Most importantly, it is independent from the weather in most areas. Consequently, the exploration and utilization of geothermal energy for deicing pavement slabs and bridge decks is a promising and cost-effective approach to better handling the above issues. Even in summer, the pavement slabs and bridge decks will be cooled down to reduce the intensity of ruts, resulting in a longer lifespan for the pavements and bridges. Jiang et al. (2011) reported a review study on the technology for snow and ice control for winter road maintenance. The classifications of snow and ice control techniques are shown in Figure 2.

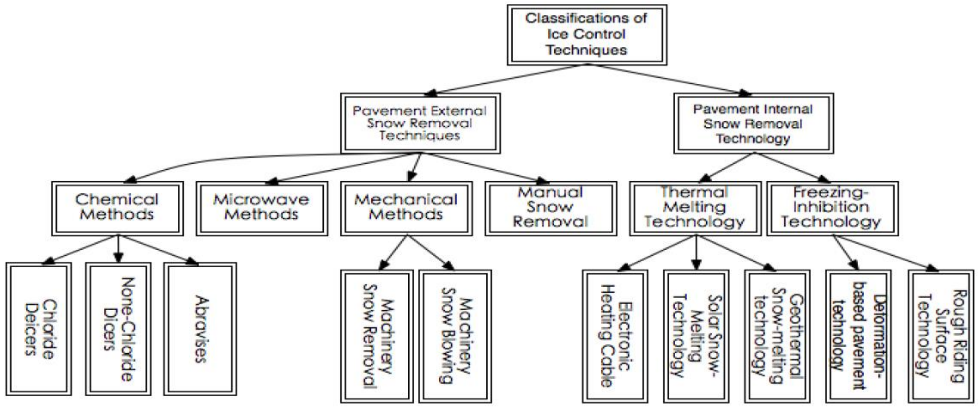
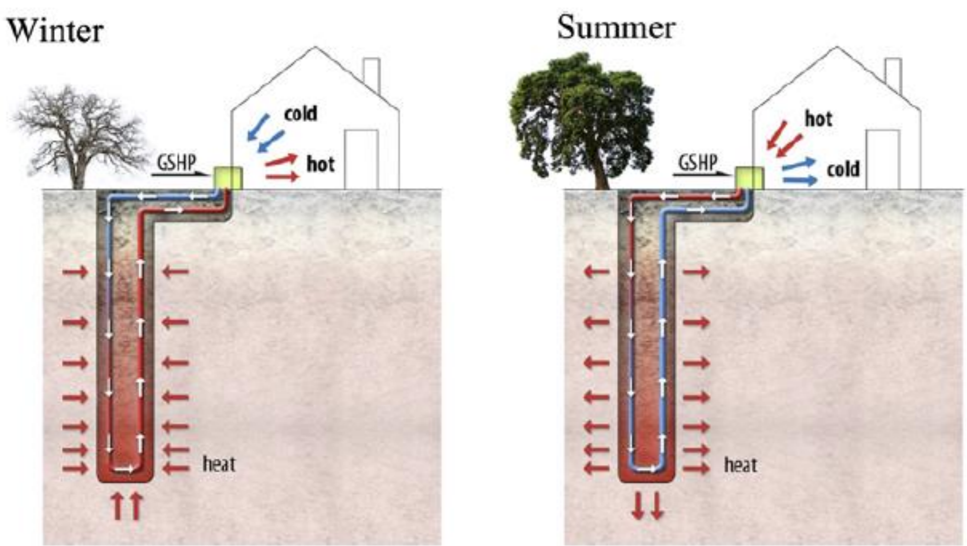


Figure 2 Classifications of snow and ice control techniques (Jiang et al., 2011)

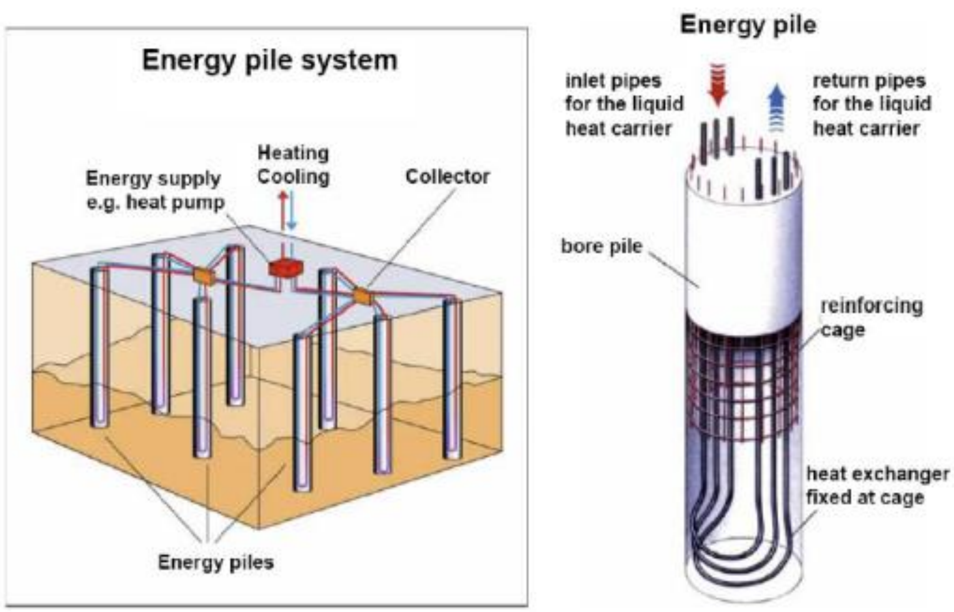
2.1.2. Geothermal Energy

Heat can be extracted from the ground at "normal" temperatures, (i.e., non-hydrothermal temperatures close to average atmospheric temperatures), by using a device called heat pump. The heat pump was invented by Lord Kelvin in 1852, but it is only in the last 10 to 20 years that there has been a dramatic increase in the use of GSHPs to heat and cool buildings. GSHPs operate in two modes: heating and cooling. In the heating mode, fluid is typically circulated through pipes built into horizontal trenches, vertical boreholes, or building foundations. Heat is extracted from underground soils and carried in the circulating fluid. It is exchanged in a heat pump to heat the building, and, as a result, the cooler fluid is returned to the underground loop where it absorbs heat and completes the cycle. In the cooling mode, the system is reversed, with heat taken out of the building and transferred into the ground via the heat pump and circulating fluid. Systems such as these are developing rapidly around the world, particularly in parts of Europe, North America, and China. Figure 3 shows a schematic view of a direct heating and cooling system using ground loops inserted in vertical boreholes. Note that Figure 3 is not to scale, and the boreholes need only to be 4 to 8 in. (100 to 200 mm) in diameter.

The geothermal energy discussed so far is related to relatively shallow sources, either as preheated hydrothermal water or steam, or at normal earth temperatures for which heat is extracted or dumped with a GSHP. Other sources of geothermal energy are from considerable depths (typically 4 to 5 km, or 2.5 to 3 miles) below the ground surface, where, as will be discussed later, significant temperatures (approximately 200^{o}C/392 F) can be found. Over the last few years, there has been much activity to harness this form of energy. The basic system comprises drilling a deep injection well and a production well within the same hot fractured rock mass. Water is forced down the injection well, passing through the hot fractured rock mass to absorb heat and then return to the surface via the production well. This hot water is then used to produce steam or another more volatile gas to drive turbines to produce electricity. Waste water resulted from hydraulic fracturing has a low temperature, around 100^{o}C, and usually is disposed of in surface ponds, which is a great heat source for bridge/pavement deicing.



(a)



(b)

Figure 3 (a) Schematic plot of a GSHP for space heating and cooling; (b) Energy piles as the host of the absorber pipes (Johnston et al., 2011)

Lund and Freeston (2001) reviewed the world wide application of geothermal energy for direct utilization. Table 1 summarizes the peak flow rates, capacity, annual energy utilization, capacity factor, wells drilled, and professional person-years and investment reported by the various researchers. There are 58 countries currently reporting use, as compared to 28 in 1995 and 24 in 1985. The maximum total flow rate is at least 52,746 kg/s, an increase of 42.4% over 1995; total capacity is 15,145 MWt, a 74.8% increase over 1995; and energy utilization is 190,699 TJ/year, a 69.6% increase over 1995. These numbers correspond to a 7.3% annual compounded growth for flow rate, an 11.8% annual compounded growth for capacity, and an 11.1 % annual compounded growth for utilization over this 5-year period. Thus, it appears that the growth rate has increased recently, despite the low cost of fossil fuels, economic down turns, and other factors. It should be noted that part of the growth depicted from 1995 to the present is due to better reporting and includes some countries with geothermal uses that were missed in previous reports.

The capacity factor is an indication of the amount of use (i.e., a capacity factor of 1.0 means that the system is used continuously for a whole year without any interruption). The worldwide average for the capacity factor is 0.40, compared to 0.41 in 1995. Again, as in 1995, the countries with the largest utilization are China, Iceland, and the U.S., with Japan and Turkey moving into the top five, together accounting for over half (63.5%) of the world's geothermal energy utilization. Austria, Canada, Germany, Sweden, Switzerland, and Turkey have produced the largest increase in the past 5 years by almost doubling their use in both capacity and energy use; the increase in the first five of these countries is due to geothermal heat pump installations, and that of Turkey is due mainly to the construction of numerous new district heating systems that supply the heating needs of a district instead of a single home/building in an individual space heating system. In 1985, there were only 11 countries reporting an installed capacity of over 100 MWt. This number was increased to 14 by 1990, and 15 by 1995. At present, there are 23 countries reporting 100 MWt or more of installed capacity.

Lund and Freeston (2001) also categorized the utilization of geothermal energy, as shown in Table 2. For comparison, the data from 1995 and 2000 were divided among the various uses in terms of capacity and energy utilization. Attempts were made to distinguish individual space heating from district heating, but this was often difficult, as reporters did not make this distinction. An approximate separation was made based on the personal knowledge of the situation in the particular country. A preliminary estimate places 75% (27.6% of the total) of the space heating use in district heating. Snow melting represents the majority of the cooling and now melting category (0.44, or 0.06% of the total). The other category includes earthquake monitoring in China, tourism in Japan, and animal husbandry in Tunisia.

2.1.3. Geothermal Energy Foundations

An energy pile is a main type of geothermal energy foundation that uses precast, pre-stressed concrete piles, or cast-in-place concrete piles that are outfitted with a set of high-density polyethylene U-tubes to circulate water (or other fluids) via a heat pump to extract geothermal energy from the foundation soil. Energy piles have been used for many years in Asia and Europe for heating/cooling multi-story buildings (Amatya et al., 2012; Bourne-Webb et al., 2009; Knellwolf et al., 2011; Laloui, 2010; Laloui et al., 2006; and Suryatriyastuti et al., 2012).

Table 1 Summary of geothermal energy direct use data from individual countries

(Lund and Freeston, 2001)

Country	Flow kg/s	MWt	TJ/year	GWh/year	Capacity factor	Wells drilled	Person-year	Funds 10^6 $
Algeria	516	100.0	158.6	441	0.50		27	
Argentina	2515	25.7	449	125	0.55	9	202	6
Armenia		1.0	15	4	0.48			
Australia	90	34.4	351	98	0.32	0	60	
Austria	210	255.3	1609	447	0.20	17		
Belgium	58	3.9	107	30	0.87			
Bulgaria	1690	107.2	1637	455	0.48		85	0.13
Canada		377.6	1023	284	0.09			
Caribbean Islands		0.1	1	0	0.62		0	0.3
Chile		0.4	7	2	0.55			
China	12,677	2282.0	37,908	10,531	0.53			
Colombia	222	13.3	266	74	0.63		68	6.15
Croatia	927	113.9	555	154	0.15	1	91	1.9
Czech Republic		12.5	128	36	0.33		106	0.3
Denmark	44	7.4	75	21	0.32			
Egypt		1.0	15	4	0.58			
Finland		80.5	484	134	0.19			
France	2793	326.0	4895	1360	0.48	1		
Georgia	894	250.0	6307	1752	0.80			
Germany	371	397.0	1568	436	0.13	16		
Greece	258	57.1	385	107	0.21	75	200	
Guatemala		4.2	117	33	0.88	1	10	
Honduras	12	0.7	17	5	0.76		14	
Hungary	677	472.7	4086	1135	0.27	4	20	0.5
Iceland	7619	1469.0	20,170	5603	0.44	241	250	90
India	316	80.0	2517	699	1.00	73	14	
Indonesia		2.3	43	12	0.59			
Israel	1672	63.3	1713	476	0.86			
Italy	1656	325.8	3774	1048	0.37	1	50	10
Japan		1167.0	26,933	7482	0.73			
Jordan	574	153.3	1,540	428	0.32			
Kenya		1.3	10	3	0.25			
Korea	1054	35.8	753	209	0.67	164	42	276
Lithuania	13	21.0	599	166	0.90	6	102	23.94
Macedonia	761	81.2	510	142	0.20	1	55	15
Mexico	4367	164.2	3919	1089	0.76		20	0
Nepal	25	1.1	22	6	0.66		8	0.007
Netherland		10.8	57	16	0.17			

Country	Flow kg/s	MWt	TJ/year	GWh/year	Capacity factor	Wells drilled	Person-year	Funds 10^6 $
New Zealand	132	307.9	7081	1967	0.73	1	200	50
Norway		6.0	32	9	0.17			
Peru		2.4	49	14	0.65			
Philippines		1.0	25	7	0.79			
Poland	242	68.5	275	76	0.13		166	12
Portugal	49	5.5	35	10	0.20	7		
Romania	890	152.4	2871	797	0.60	4	181	24
Russia	1466	308.2	6144	1707	0.63	306	1043	
Serbia	827	80.0	2375	660	0.94	5	23	

Table 2 Categories of utilization of geothermal energy worldwide (Lund and Freeston, 2001)

	Capacity MWt		Utilization TJ/year	
	2000	1995	2000	1995
Geothermal heat pumps	5275	1854	23,275	14,617
Space heating	3263	2579	42,926	38,230
Greenhouse heating	1246	1085	17,864	15,742
Aquaculture pond heating	605	1097	11,733	13,493
Agriculture drying	74	67	1038	1124
Industrial uses	474	544	10,220	10,120
Bathing and swimming	3957	1085	79,546	15,742
Cooling and snow melting	114	115	1063	1124
Others	137	238	3034	2249
Total	15,145	8664	190,699	112,441

A typical cross-section of a cast-in-place energy pile consists of concrete, steel reinforcement, and high-density polyethylene tubing (Figure 4). The tubing and steel reinforcement are tied together before being lowered into a drilled shaft or borehole and filled with concrete. Once all piles are in place, the tubing is connected to a GSHP, which circulates a heat-transferring medium throughout; however, the heat transfer efficiency of energy piles is hindered by the thick layer of concrete (a poor heat conductor) that surrounds the high-density polyethylene tubing, making energy piles less efficient than anticipated.

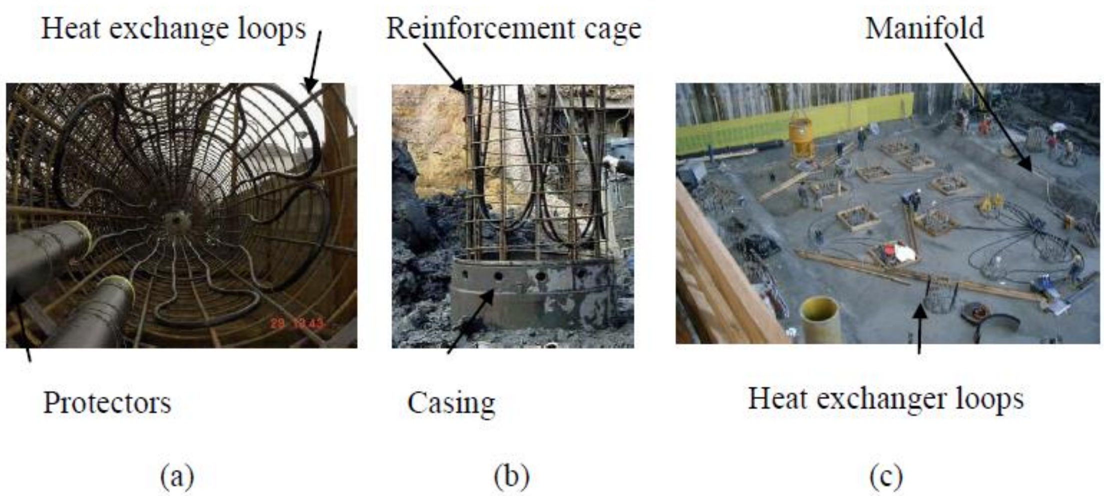


Figure 4 Installation of heat exchangers in thermo-active foundations (a) Heat exchange loops on reinforcement cage; (b) Inserting reinforcement into cased hole; (c) Connection of heat exchangers after installation (Amatya et al. 2012; Bourne-Webb et al. 2009; Knellwolf et al. 2011; Laloui 2010; Laloui et al. 2006; Suryatriyastuti et al. 2012)

2.1.4. Geothermal Heat Pumps

A geothermal heat pump is a central heating or cooling system that transfers heat to or from the ground. It uses the earth as a heat source in the winter or a heat sink in the summer. This design takes advantage of the moderate temperature in the ground to boost efficiency and reduce the operational costs of heating and cooling systems, and may be combined with solar heating to form a geo-solar system with even greater efficiency. Although the heat does not come primarily from the center of the earth, GSHPs are known as “geothermal heat pumps” as well. They are also known by other names, including geo-exchange, earth-coupled, and earth energy systems. The engineering and scientific communities prefer the terms “geo-exchange” or “ground source heat pumps” to avoid confusion with traditional geothermal power, which uses a high temperature heat source to generate electricity. GSHPs harvest heat absorbed from solar energy at the earth’s surface. The temperature in the ground below 6 m is roughly equal to the mean annual air temperature at that latitude at the surface. The principle of the geothermal heat pump is illustrated in Figure 5.

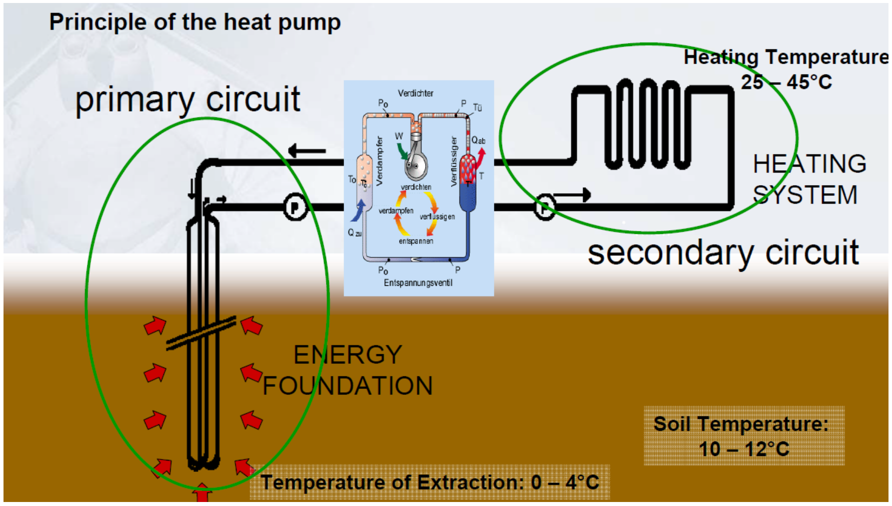


Figure 5 Principle of the geothermal heat pump (Rosenberg, 2010)

Depending on latitude, the temperature beneath the upper 6 m of the earth’s surface maintains a nearly constant temperature between 10 and 16°C if the temperature is undisturbed by the presence of a heat pump. Like a refrigerator or air conditioner, these systems use a heat pump to force the transfer of heat from the ground. Heat pumps can transfer heat from a cool space to a warm space, against the natural direction of flow, or they can enhance the natural flow of heat from a warm area to a cool one. The core of the heat pump is a loop of refrigerant pumped through a vapor-compression refrigeration cycle that moves heat. Air-source heat pumps are typically more efficient at heating than pure electric heaters, even when extracting heat from cold winter air, although efficiencies begin dropping significantly as outside air temperatures drop below 5°C. A GSHP exchanges heat with the ground. This is much more energy efficient because underground temperatures are more stable than air temperatures throughout the year. Seasonal variations drop off with depth and disappear below 7 m to 12 m due to thermal inertia. A GSHP extracts ground heat in the winter for heating and transfers heat back into the ground in the summer for cooling. Some systems are designed to operate in one mode only, heating or cooling, which depends on the climate.

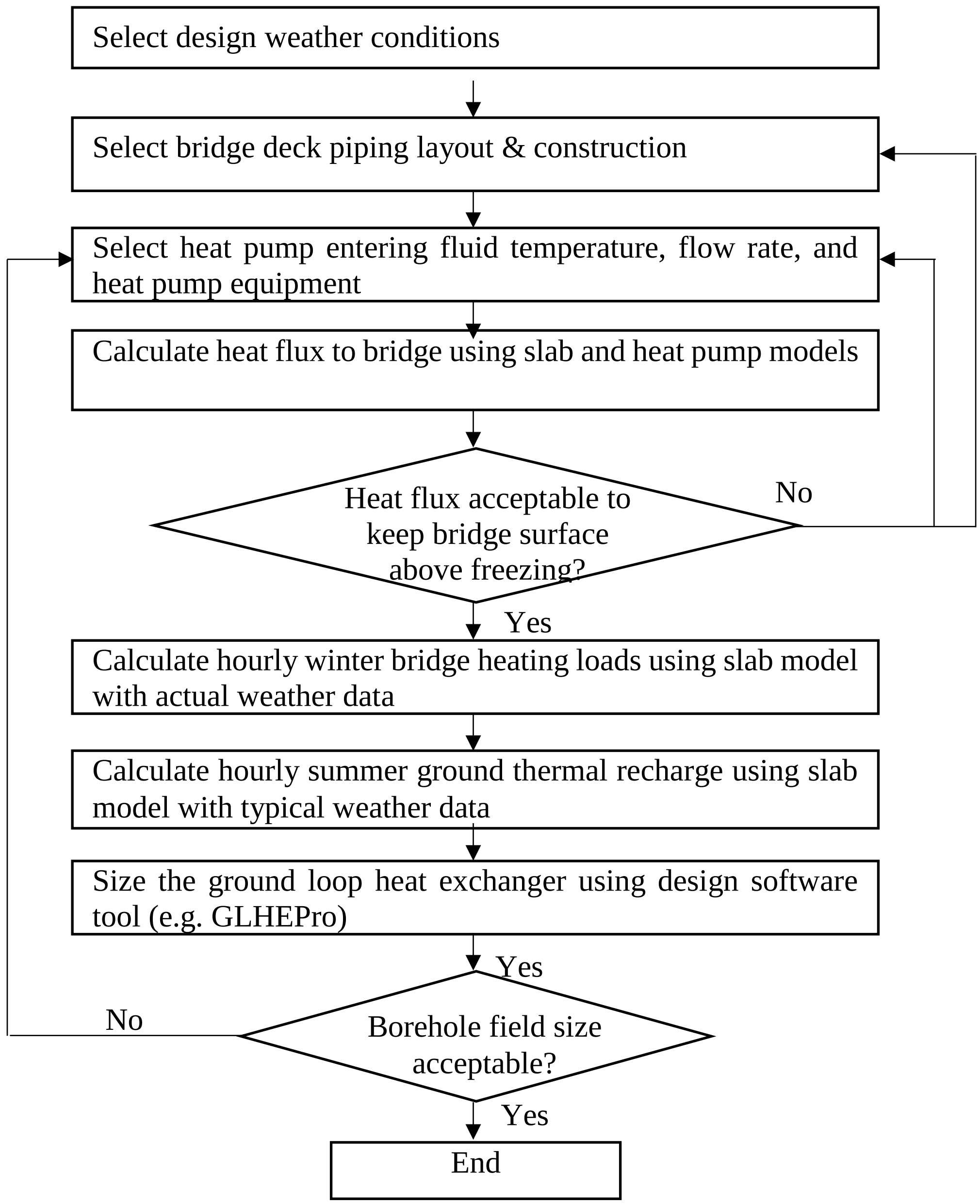
Geothermal pump systems reach a fairly high coefficient of performance (typically greater than 3 and less than 6, 6 indicating the best performance) on the coldest of winter nights, as compared to 1.75 to 2.5 for air source heat pumps on cool days. Setup costs are higher than for conventional systems, but the difference is usually returned in energy savings in 3 to 10 years, and even shorter lengths of time with federal, state, and utility tax credits and incentives. Geothermal heat pump systems are reasonably warranted by manufacturers, and their working life is estimated at 25 years for inside components and 50+ years for the ground loop. In 2004, there were over a million units installed worldwide, providing 12 GW of thermal capacity, with an annual growth rate of 10%.

2.1.5. Design of Geothermal Heating System

Basically, the geothermal heating system for deicing pavement slabs and bridge decks consists of two parts: (1) a ground-loop heat exchanger (GLHE) system and (2) hydronically-heated pavement slabs and bridge decks. The design of the entire system is divided into four phases (Kaller, 2007): (1) establish the required heat flux to the bridge surface; (2) estimate the bridge heating loads; (3) estimate the energy available for thermal recharge of the ground in summer; (4) design the GLHE system, including the number, spacing, diameter, and depth of the boreholes, perhaps with the help of software such as GLHEPro 4.1, (Chiasson and Spitler, 2001). The design chart for the GSHP bridge deck deicing system is shown in Figure 6.

The purpose of estimating the required heat flux is to ensure that the average temperature of the pavement slabs and bridge decks is higher than the freezing point under icy or snowy weather conditions. The heat flux needed for efficient operation of the system is affected by many factors: (1) environmental heat transfer mechanisms; (2) the material properties of the pavement slabs and bridge decks, such as thickness, area, and orientation; (3) the material properties of embedded hydronic tubes, such as the diameter, spacing, and burial depth; (4) the properties of the circulating fluid, such as the flow rate and inlet temperature; and (5) thermal properties of concrete and soils underground, such as thermal conductivity, diffusivity, and heat capacity. In addition, the common way to determine the heat flux is to use the heat pump model, coupled with the slab model, by inputting design weather conditions (air temperature, wind speed, and snowfall rate) and varying design parameters (number of heat pumps, flow rate, and inlet temperature).

The heat flux determined previously was based on extreme weather conditions but was not the actual energy use of the system for deicing the pavement slabs and bridge decks. Thus, the heating loads generated from both the heat pumps and geothermal energy are also necessary for estimating according to the selected weather conditions and for designing a more reliable and cost-effective system. Thermal recharge of the ground in summer is the reverse process of the thermal discharge in winter for deicing, which reduces the number or the size of boreholes and, therefore, the cost of the GLHE. In summer, the pavement slabs and bridge decks are considered as solar energy collectors, and their temperatures are supposed to be greater than those of the air. The potential thermal recharge rate of the ground can be estimated using the numerical slab or bridge deck model on the basis of temperature difference between slabs or decks and the air. Then, the GLHE is designed using GLHEPro 4.1 (Spitler 2000). The input parameters include the heating loads, the thermal recharge rate, thermal properties of the ground, geometry of the boreholes, physical and thermal properties of the heat carrier fluid, and information about the selected heat pumps.



(Chiasson and Spitler, 2000)

Figure 6 Design chart of GSHP bridge deck deicing system

Lund (Spitler 2000) also presented the design criteria of pavement and bridge deck deicing systems based on the established handbook of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Based on the ASHRAE Handbook (1999), the heating requirement for snow melting depends on four atmospheric factors: (1) rate of snow fall, (2) air temperature, (3) relative humidity, and (4) wind velocity. Generally, the system will first melt snow or ice, and then evaporate the resulting water film. The rate of snowfall determines the heat required to warm the snow to 0°C and to melt it. The evaporation rate of the melted snow from the pavement is affected by the wind speed and by the difference in vapor pressure between air and melted snow. Convection and radiation loss from the melted snow are dependent on the film coefficient and the difference in temperature between the surface and air. In addition, the film coefficient is mainly affected by the wind speed, so the convection and radiation loss vary with changes in air temperature and wind speed (Lund 1999).

Chapman and Katurnich (1956) derived a general equation for the required pavement heat output (q_o) in Btu/h⋆ft^2,

$$q_o = q_s + q_m + A_r(q_e + q_h)$$

where q_s is the sensible heat transfer to the snow, Btu/h⋆ft^2; q_m is the heat of fusion, Btu/h⋆ft^2; A_r is the ratio of snow-free area to total area; q_e is the heat of evaporation, Btu/h⋆ft^2; q_h is the heat transfer by convection and radiation, Btu/h⋆ft^2.

The sensible heat q_s to bring the snow to 0°C is,

$$q_s = sc_p\rho(32 - t_a)/c_1$$

where s is the rate of snowfall (inch of water equivalent per hour); ρ is the density of water equivalent of snow, lbs./ft^3; c_p is the specific heat of snow, Btu/lb⋆°F; t_a is the air temperature, °F; c_1 is the conversion factor, in/ft.

For hot water (hydronic) system, the above reduces to:

$$q_s = 2.6s(32 - t_a)$$

The heat of fusion q_m to melt snow is:

$$q_m = sh_f / c_1$$

where h_f is the enthalpy of fusion for water, Btu/lb.;

For hot water (hydronic) system, the above reduces to:

$$q_m = 746s$$

The heat of evaporation q_e is (for hydronic):

$$q_e = h_{fg}(0.0201V + 0.055)(0.188 - p_{av})$$

where h_{fg} is the heat of evaporation at the film temperature, Btu/lb.; V is the wind speed, mph; p_{ave} is the vapor pressure of moist air, inch of mercury

The heat transfer q_h is (for hydronic):

$$q_h = 11.4(0.0201V + 0.055)(t_f - t_a)$$

where t_f is the temperature of water film, °F.

The solution of the general equation for q_o, for the required pavement heat output, requires the simultaneous consideration of all four climatic factors: rate of snowfall, air temperature, relative humidity, and wind speed. A critical combination of them should be considered, based on previous several years of data, for an efficient design of a snow-melting system (ASHRAE Handbook, 1995).

Ramsey et al. (American Society of Heating and Engineers, 1995) reviewed and identified recommended revisions to the current ASHRAE snow melting load calculation procedures and presented sample results based on the revised procedures. As discussed previously, the load at the melting surface includes the heat fluxes needed to raise the snow to the melting temperature and to melt the snow, along with the heat losses due to convection, radiation, and evaporation. The changes made in the calculation procedures are primarily in the way heat losses are determined. Using 12 years of weather data, loads were calculated for 46 U.S. locations. The results clearly pointed out the need for concurrent data in order to accurately estimate snow melting loads.

Stephen and James (1999) introduced the "Smart" control system designed for a geothermal bridge deck heating system. A typical system integrates the concepts of model predictive control with a first-principles bridge deck model and hourly computerized National Weather Service forecasts to prevent bridge icing without use of salt or other deicing chemical materials. Table 3 summarizes the control systems used in earlier investigations of heated bridge decks (HBD), which was derived from a report by Stephen (2003), published by the Office of Bridge Technology. The schematic of a smart bridge heating system is shown in Figure 7. The three key components used to provide smart control include (1) bridge deck model; (2) model predictive control technology; and (3) utilization of real-time, site-specific weather forecast information provided by the National Weather Service.

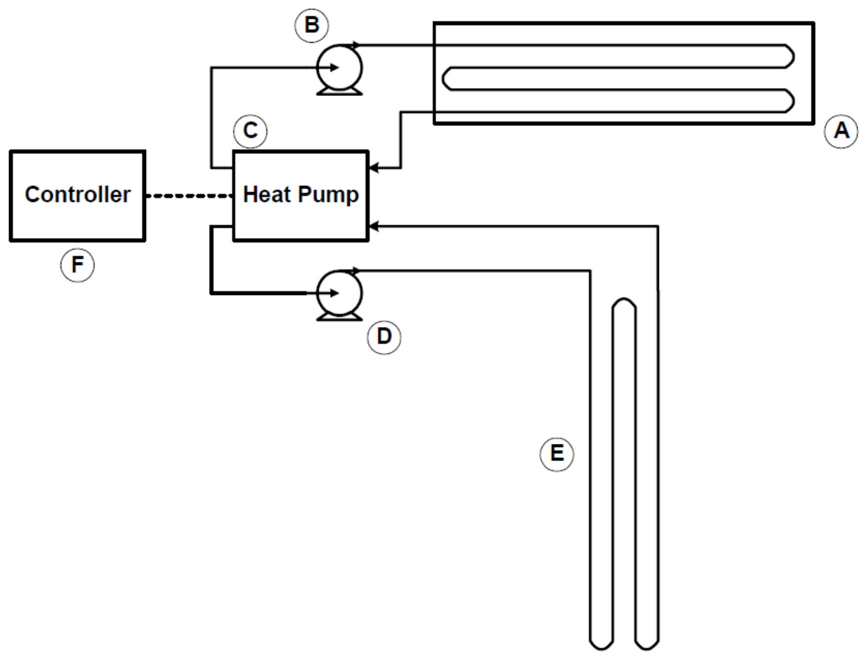
The main design objective of a geothermal heating system is considered to achieve a certain specified snow or ice melting performance, which can be classified according to the permissible amount of snow accumulation and melting rate on it. The snow-free area ratio (A_r), which is defined as the ratio of snow-free area of a surface to its total area, is one measure of the snow melting performance. Accordingly, Chapman (1956) presented definitions of snow-melting performance classes as follows:

- Class 1 (residential): During the snowfall, the entire surface may be covered with snow (A_r=0). After the snowfall, the system is expected to melt the accumulated snow.
- Class 2 (commercial): During the snowfall, 50% of the surface may be covered with snow (A_r=0.5).
- Class 3 (industrial): During the snowfall, the entire surface is kept free from snow accumulation (A_r=1).

Table 3 Control system summary for existing heated bridge decks (Stephen, 2003)

Bridge	Conditions required to turn heating system on	Conditions required to turn heating system off
Tenth Street Pedestrian Viaduct-Lincoln, Nebraska	Pavement T<39^{o}F AND Air T<36^{o}F AND Moisture on Bridge Deck	Pavement Temperature > 55^{o}F
Silver Creek-Salem, Oregon (Control rules partially proprietary)	Air T<Specified Value AND Moisture on Bridge Deck	Air T>35–37^{o}F OR Pavement T> Specified Value
Highland Interchange-Portland, Oregon	20^{o}F <Air T<33^{o}F AND Dew point >0^{o}F	Unknown
Second Street Overcrossing- Hood River, Oregon	Air T<35^{o}F AND Relative Humidity > 95%	30-minute minimum runtime AND Pavement T>36^{o}F
U.S. 287- Amarillo, Texas	Pavement T<35^{o}F AND Precipitation Forecast	Unknown
Route 60 Bridge-Amherst Country, Virginia	Snow or Ice on Pavement OR Precipitation Present AND Air T<35^{o}F OR Moisture on Bridge Deck AND Pavement T<35^{o}F	No Moisture on Pavement for 10 minutes OR Pavement T>40^{o}F

There are only two design objectives in the 1999 report on heated bridge technology (Minsk, 1999), which are “snow-free” and “anti-ice.” The objective of a “snow-free” system is to keep the surface clear of snow and ice under all precipitation conditions; while the objective of the “anti-ice” system is to prevent bonding of ice and compacted snow to the deck during and after a snowstorm. In contrast, the design objective is a system that is able to melt the snow or ice earlier than that on a normal road (Yoshitake et al., 1997). For such systems, the required amount of heat is relatively low; therefore, ground water or a GLHE may be used as the heat source. Consequently, the determination of the design objective is dependent on the specific site climate conditions. It should be noted that the geothermal heating system might not be suitable for some very cold regions.



(Stephen, 2003)

Figure 7 Smart bridge heating system: (A) hydronically-heated bridge deck; (b) bridge loop circulating pump; (c) heat pump; (d) ground loop circulating pump; (e) ground heat exchanger; (f) controller

2.1.6. Experimental Investigation

In 1974, Bienert demonstrated the technical feasibility of using the earth's heat, in combination with heat pipes, for deicing and removing snow/ice from pavement surfaces in the Baltimore/Washington area. The test was performed at the Fairbank Highway Research Station located in McLean, Virginia for two winters. Ferrara (1975) described the efforts to investigate the use of heat pipes to prevent the preferential freezing of highway pavement slabs and bridge decks. Griffin (Minsk, 1999) attempted to explore a new system for deicing roadway structures in Colorado and focused on the conceptual designs, life expectancy, performance, and cost estimates for all the potential systems.

In 1994, Wadivkar (1982) built a test setup of an active GSHP system to prevent ice formation on a concrete bridge deck. Cress (1997) designed a hydronic bridge/pavement deck heating system and applied it to a test site. His system was installed in the deck of a 367 m long and 3.7 m wide viaduct in Lincoln, Nebraska, and was monitored for 12 months after installation. It was demonstrated that the heating system could remove ice and snow from the slab and deck surfaces and eliminate the possibility of frosting and preferential icing for several days following a storm event. Chiasson and Spitler (1995) proposed a modeling approach to design a hydronic snow/ice melting system for bridge deck deicing on an interstate highway in Oklahoma. The typical construction of a hydronic snow-melting system and the heat transfer mechanism in a hydronically-heated bridge deck are shown in Figure 8 and 9. The heat source was provided by a vertical borehole, closed-loop, and GSHP system to meet the heating requirement. The advantage of his design was demonstrated successfully through numerical simulation. A system with 16 heat pumps of nominal 30-ton capacity and 250 boreholes, each 250 ft. deep, was finally selected.

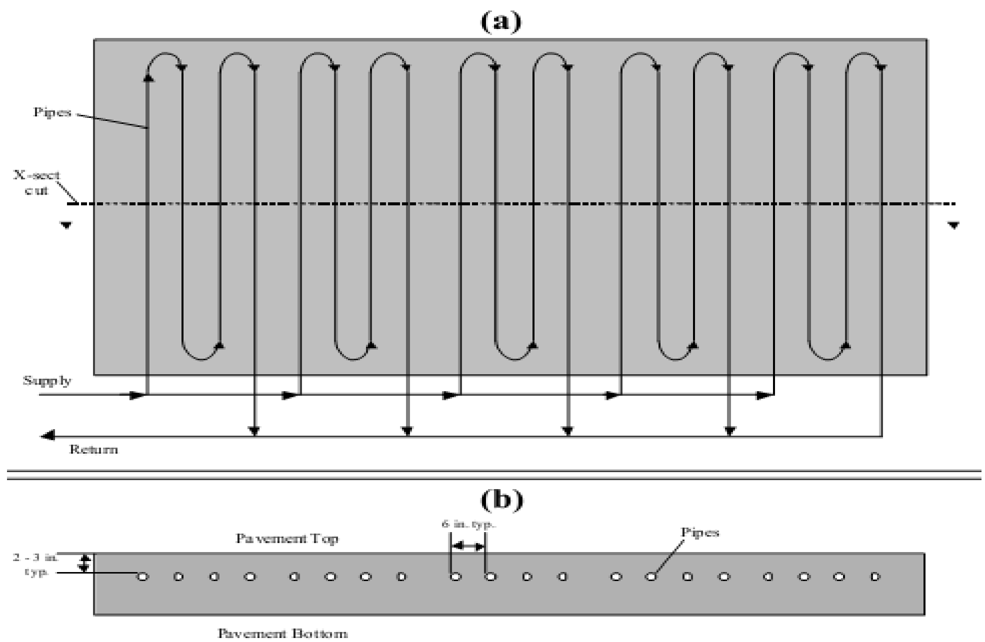


Figure 8 Typical construction of a hydronic snow-melting system in (a) plan view and (b) cross section view (Chiasson and Spitler, 2000)

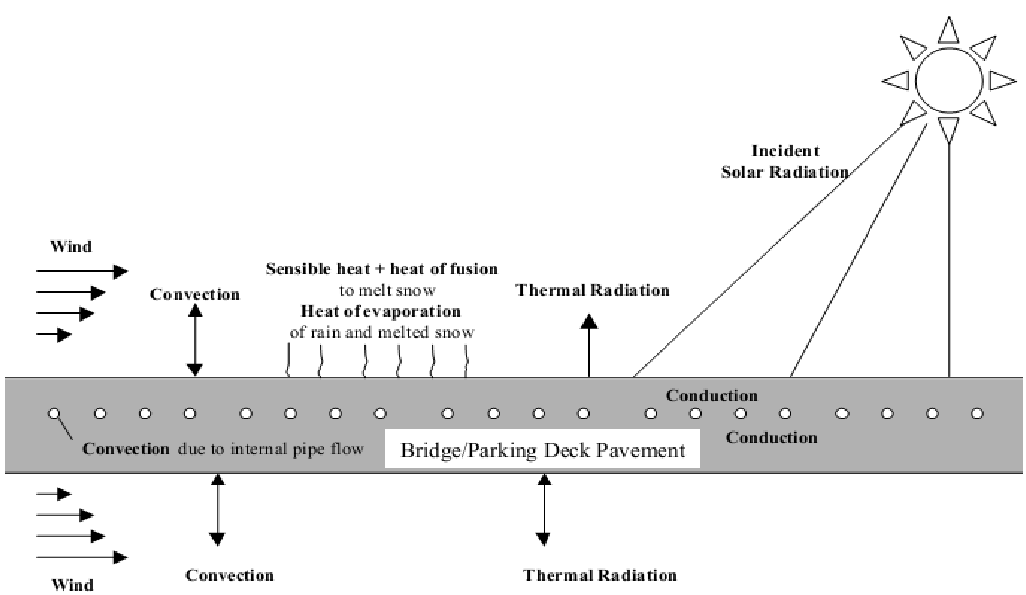


Figure 9 Heat transfer mechanism heated bridge deck (Chiasson and Spitler, 2000)

Wadivkar (2000) performed a series of field experiments to investigate the thermal performance of a bridge deck deicing system. Figure 10 shows the test section of a bridge deck placed in an open environment to simulate the real field conditions, including actual weather conditions. A steel frame was built to support and raise the slab to a height of 7 ft. above the ground. An additional heat pump (as shown in Figure 11) was also used to raise the fluid temperature for deicing purpose. The system was found to be very slow in melting the ice due to the relatively low temperature of the circulating fluid.

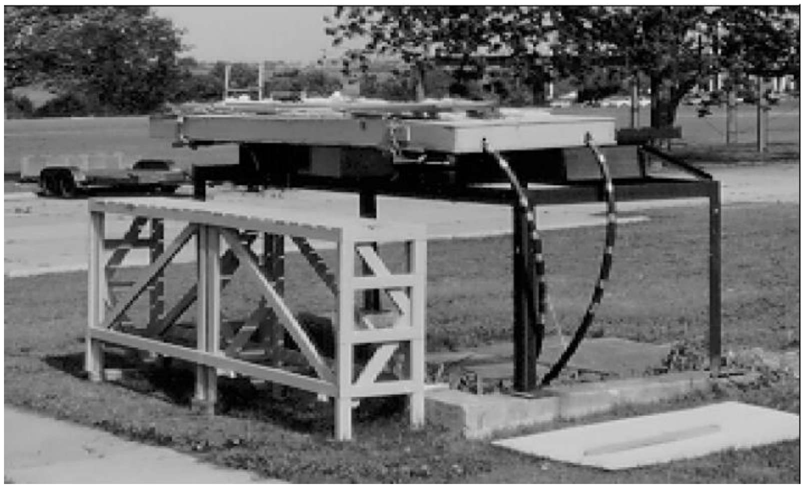


Figure 10 Experimental bridge deck section (Wadivkar, 1997)

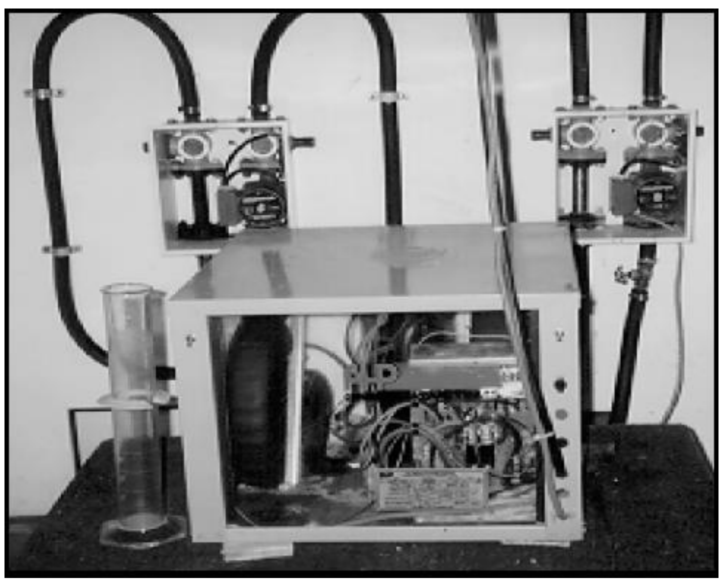


Figure 11 Heat pump (Wadivkar, 1997)

In 1997, Wadivkar (1997) performed experiments to investigate the use of a GSHP system to meet the heating requirement for the snow/ice melting process. The system studied in their work considered the effect of borehole depth on the efficiency of the system for melting snow and ice. It consisted of ground borehole heat exchangers with three different depths (30, 60, and 90 m), a water-to-water heat pump, and heating pipes buried under the bridge slab and pavement slab. Figure 12 shows the photographs of the initial and intermediate snow melting processes on slabs.

Balbay and Esen (2010) presented the operational principles of a geothermal heating system for deicing pavement slabs and bridge decks. Figure 13 shows the relevant conceptual schematic of their study. These principles were related to the design parameters of the bridge deck deicing systems. A series of parametric studies were performed to investigate the bridge deck heating process. The parameters analyzed consisted of tube spacing, inlet fluid temperatures, flow rates, wind speeds, ambient temperatures, and thicknesses of concrete cover over the circulation tubes.

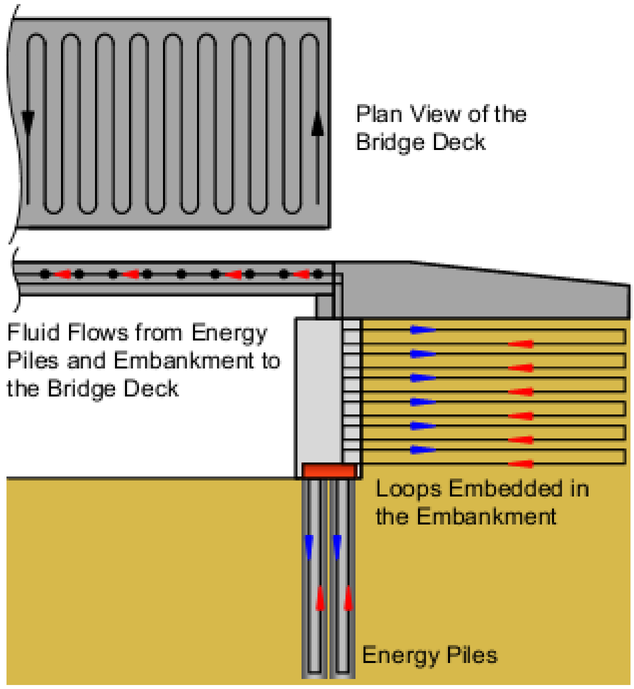
Iwamoto et al. (2013) performed field experiment of the snow-melting system at Hokkaido University in Japan. Figure 14 indicates the outline of the system, which was composed of a vertical ground heat exchanger, heat dissipation pipes, and a heating carrier circulating pump. A set of double pipes with embedded depth of 100 m was used in the experiment. Solar energy was stored in the system during the summer for deicing purposes in winter. Figure 15 shows the total measured solar energy and the heat collected during the summer. It was reported that the integrated solar energy and heat collection were 25.2 and 9.0 GJ, respectively, and the collection efficiency was around 36%.

(a)

(b)

(Balbay and Esen, 2010)

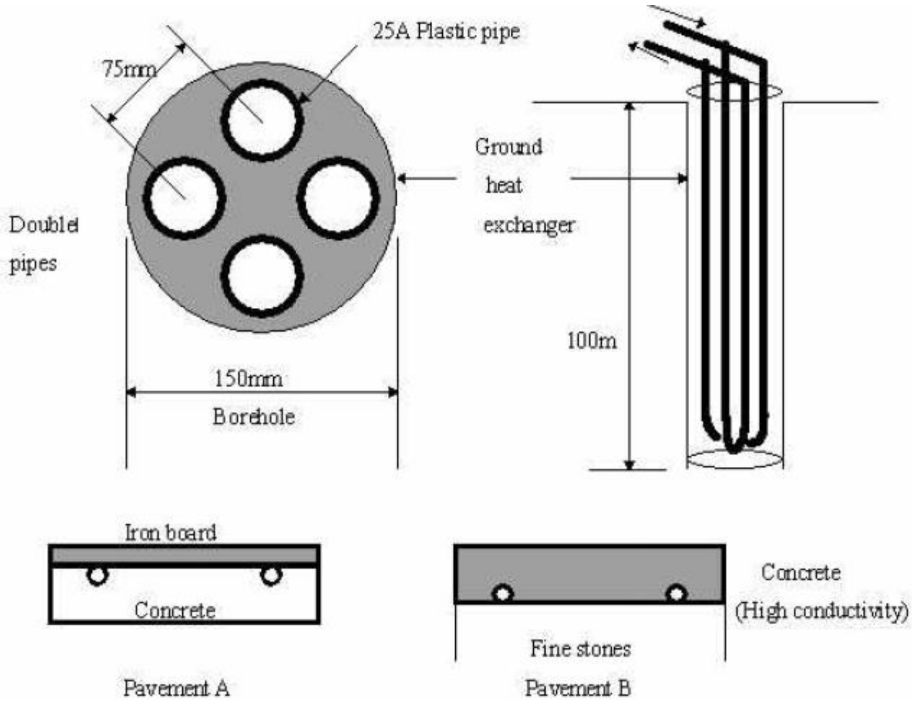
Figure 12 Photographs of initial and intermediate snow melting process on slabs: (a) initial state (t=0) for bridge and pavement slabs; (b) intermediate state (t=30 min) for bridge and pavement slabs



(Olgun and Bowers, 2013)

Figure 13 Conceptual schematic of ground-source bridge deck deicing

Liu (Iwamoto et al. 1998) performed an experimental study to validate a newly developed numerical model of the snow-melting process on heated pavement surfaces. An experimental hydronic bridge snow melting system was built at Oklahoma State University. The bridge deck was 18.3 m in length and 6.1 m in width (two lanes wide). The embedded hydronic tubing was a 19-mm diameter cross-linked polyethylene pipe with 0.3 m centers at a depth of 89 mm. An aqueous solution of propylene glycol at 39% concentration by mass was used as the heat carrier fluid circulated in the embedded pipe network. Figure 16 shows the image of the bridge surface condition taken by a digital camera along with estimates of the snow-free area ratio. It was observed that stripes appeared until the snow clearance was achieved. It was also found that some snow drifted from unheated surrounding regions to the heated portion of the bridge deck.



1. Purpose — Snow-melting
2. System composition — Ground heat exchanger Pipes buried in pavement circulation water pump Antifreeze liquid heated to ground temperature level circulates in the pipes buried in pavement
3. Energy source — Power supply of circulation pump (Electric)
4. Operation — Summer: Solar heat energy is stored in the ground
   Winter: Ground heat energy is dissipated in the pavement
5. Structure of pavement — Total area is 26 m^2 divided into 2 blocks (13 m^2) and 2 types Which are composed of concrete and iron board.
6. Thermal performance of ground heat exchanger
   Circulation flow rate 8~10L/min Inlet temperature 1~5°C
   Outlet temperature 6~10°C

Figure 14 Outline of experiment at Hokkaido University in Japan (1998)

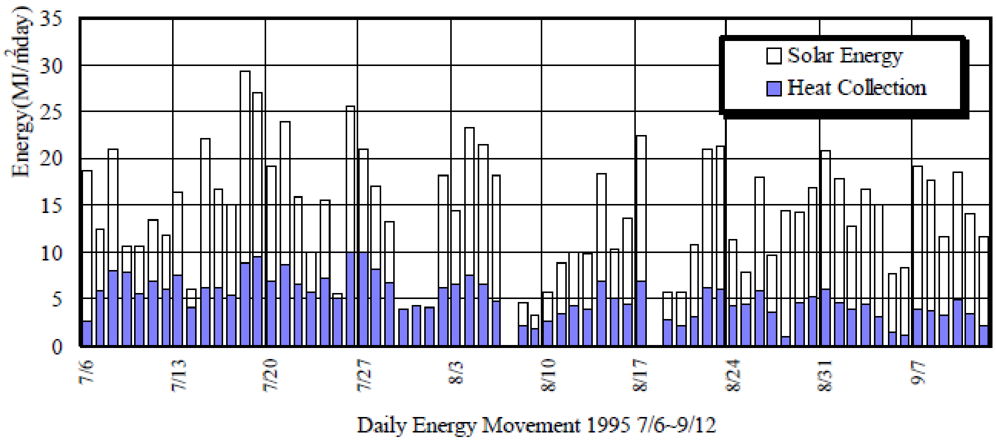


Figure 15 Solar energy and heat collection in summer (Iwamoto et al. 1998)

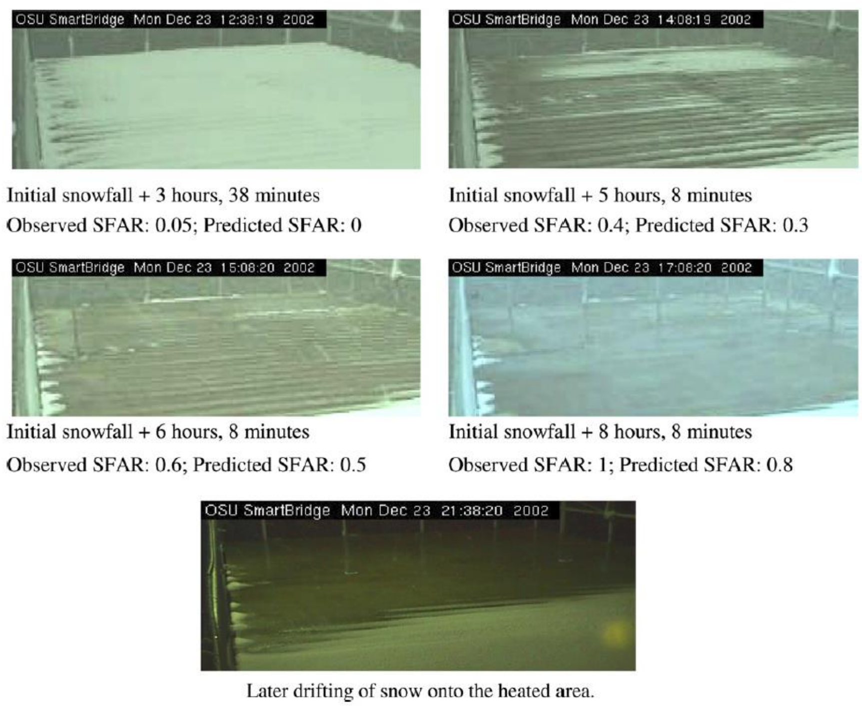


Figure 16 Images of bridge surface condition taken by a digital camera, along with estimates of the snow-free area ratio. The last image shows drifted snow on the heated surface after snowfall. (Liu, 2007)

Wang et al. (2007) used geothermal tail water to conduct an experimental investigation of the ice and snow-melting process on pavement. Experiments of the dynamic melting processes of crushed ice, solid ice, artificial snow, and natural snow were conducted on concrete pavement. Figure 17 shows the melting process of natural snow. The results revealed that the melting process of ice and snow includes three phases: a starting period, a linear period, and an accelerated period. Moreover, the physical properties of ice and snow, linked with ambient conditions, have no obvious effect on the melting process. The feasibility of using geothermal tail water of about 40°C for deicing pavement was successfully demonstrated.

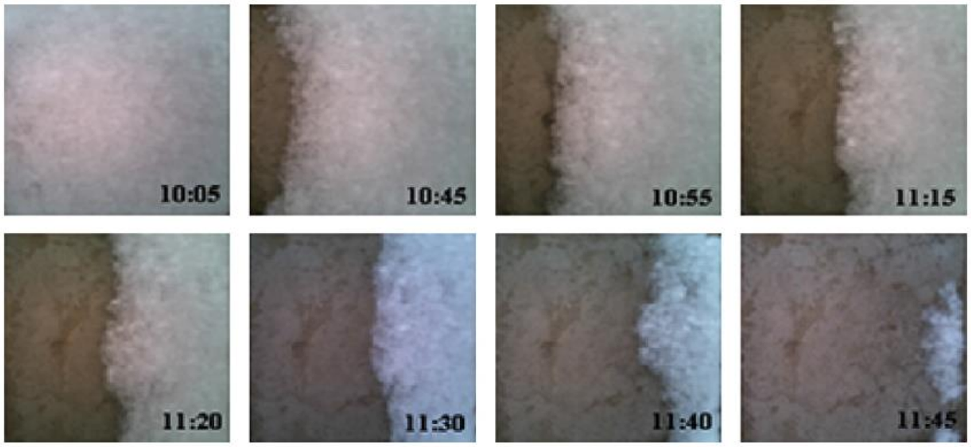


Figure 17 Melting process of natural snow (Wang, 2008)

2.1.7. Numerical Studies

The process of melting snow or ice on a bridge deck and pavement is complicated. The heat-transfer mechanism involved in the snow-melting process includes the phase change of water (melting and evaporation), solar radiation, thermal radiation, convective heat transfer on the surface, and the conductive heat transfer from the pavement slab. In addition, snow is a porous material which is composed of ice crystals and air. The melting process is characterized by the permeation of melted water due to capillary action. The snow can be fully saturated with water, which is usually called slush, or retain its air-filled porous structure, which is recognized as dry snow. Because of the variations of weather conditions and the discrete layout of the embedded pipes, the surface conditions can vary both temporally and spatially. Figure 18 indicates the variations of surface conditions in snow melting.

In terms of modeling hydronic snow melting systems, previous developed models can be divided into two categories: steady-state method and transient state method. The steady-state method assumes the snow melting is in steady state; therefore, the transients due to the intermittent heating operation and varying weather conditions are not considered.

Chapman et al. (1952) described a one-dimensional steady state analysis of heating-based snow melting systems. It was stated that the required heat output on a snow-melting surface was dependent on the sum of five terms: heat of fusion, sensible heat for increasing the snow temperature to the melting point, heat of evaporation, heat transfer by radiation and convection, and the back loss to the ground. Schnurr and Rogers (1970) developed a two-dimensional finite difference model of the hydronically-heated slab. The model accounted for the variations of surface temperature resulting from the discrete layout of hydronic piping. It assumed steady state heat transfer in the slab, uniform pipe surface temperature, and a snow-free surface. Due to the symmetry and small temperature difference between adjacent pipes, the solution domain was reduced to half of the pipe, as shown in Figure 19. Kilkis (1994b) developed a steady-state model of the hydronically-heated slab based on a composite fin model (Kilkis, 1992). The model was able to consider the varying surface conditions of the slab.

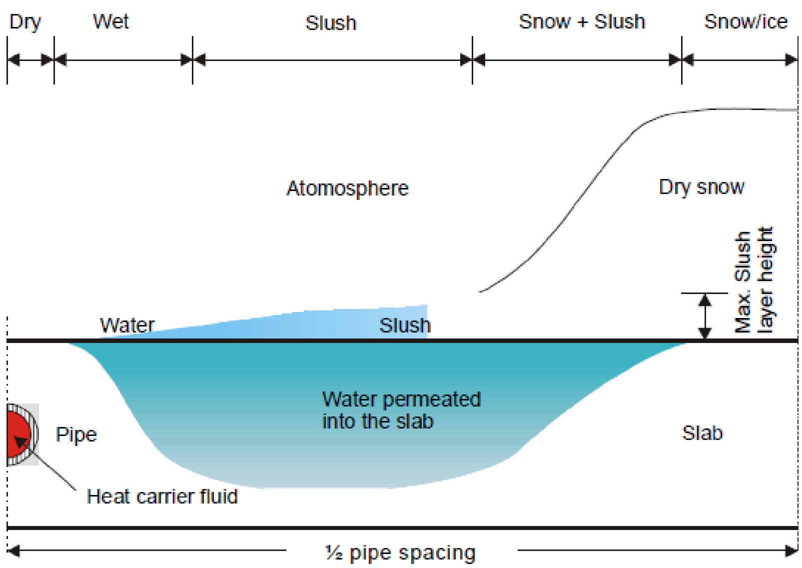


Figure 18 Variations of surface conditions in snow melting-a cross section view of the slab while snow is melting on it (2008)

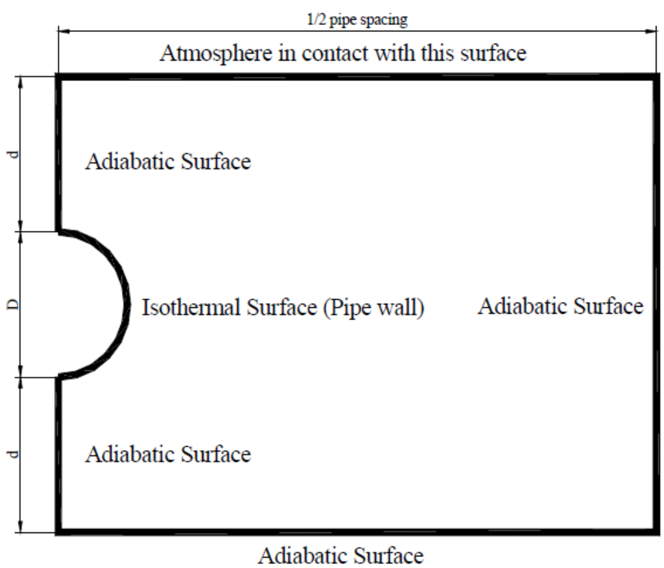


Figure 19 The model domain and boundary conditions (Liu and Spitler, 2004)

Differing from the steady state method, several other models accounted for the transient conduction heat transfer in the slab, using the transient state method. Other models developed also account for the varying surface conditions of a snow-melting surface during a storm event. For example, Leal and Miller (1972) extended the two-dimensional steady state model developed by Schnurr and Rogers (1970) by accounting for the transient conduction heat transfer in the slab. But the model assumed a linear relationship between the heat flux and the temperature at the top surface of the slab, which might not be valid for a surface where melting of snow (i.e., a phase-change process) is involved. Schnurr and Falk (1973) proposed another extension of the model developed by Schnurr and Rogers (1970). The transient conduction heat transfer in the slab was solved with a fully explicit finite difference method. Chiasson and Spitler (Liu, 2005) presented a model for a hydronically-heated slab. With respect to solving the heat diffusion problem inside the slab, this model was very similar to that developed by Schnurr and Falk (1973). The only difference was that the grid size was specified by default as the radius of the pipes embedded in the slab. Rees et al. (2000) developed a two-dimensional transient model for analyzing performance of the heating-based snow-melting systems that use hydronic piping or electric cables as the heating element. The two-dimensional and transient conduction heat transfer in the slab was calculated using the finite volume method, with the general elliptical multi-block solver (GEMS2D) developed by Rees (2002).

Faccini (2002) developed a model which realistically simulated a heat pipe, as used in an earth-heated bridge deck. The model was also capable of using actual environmental data and simulating the response of the heat pipe, bridge deck, and earth-to-the-environmental data. Radiative and convective heat transfers of bridge deck surface were also considered in the modelling.

Kilkis (1976) developed a simple model to predict the transfer of heat in a snow-melting slab while retaining sufficient accuracy. The model was able to distinguish several different classes of snow-melting and load intensities for periods, including the time before and after the snowfall event. Finite element analysis was also performed to validate the accuracy of the model.

Because traditional steady-state methods of load calculation for snow-melting systems are not able to take into account the thermal history of the system or the transient nature of storm weather, Rees (2002) investigated the transient response of snow melting systems for pavements, which have a significant effect on overall system performance. A numerical method was incorporated into a transient analysis for practitioners to examine the transient effect on system performance. A program was also developed which is capable of modeling control systems, in which the system is automatically turned on when snow is detected.

In order to investigate the temperature distribution of pavement slabs heated by using vertical ground source heat pump to deice snow/ice during cold periods, Balbay and Esen (1994) developed a 3D finite element method (FEM) to simulate the heating process and obtain the temperature distribution of bridge and pavement slabs. The meshed model and typical temperature distribution of pavement slabs (30 m) are shown in Figures 20 and 21, respectively.

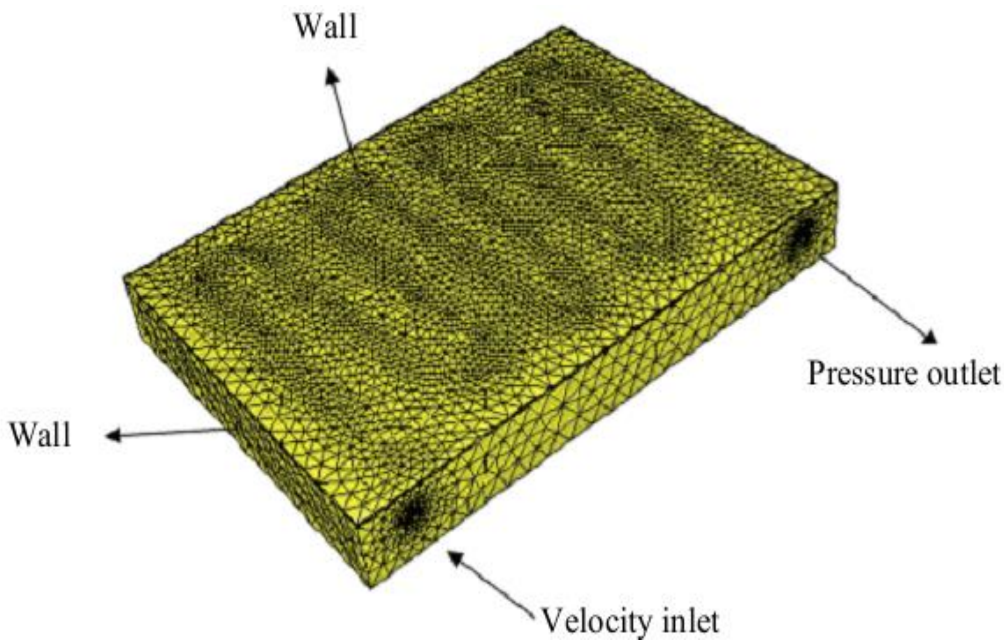


Figure 20 FEM mesh of bridge deck imbedded with heating pipes (Balbay, 2013)

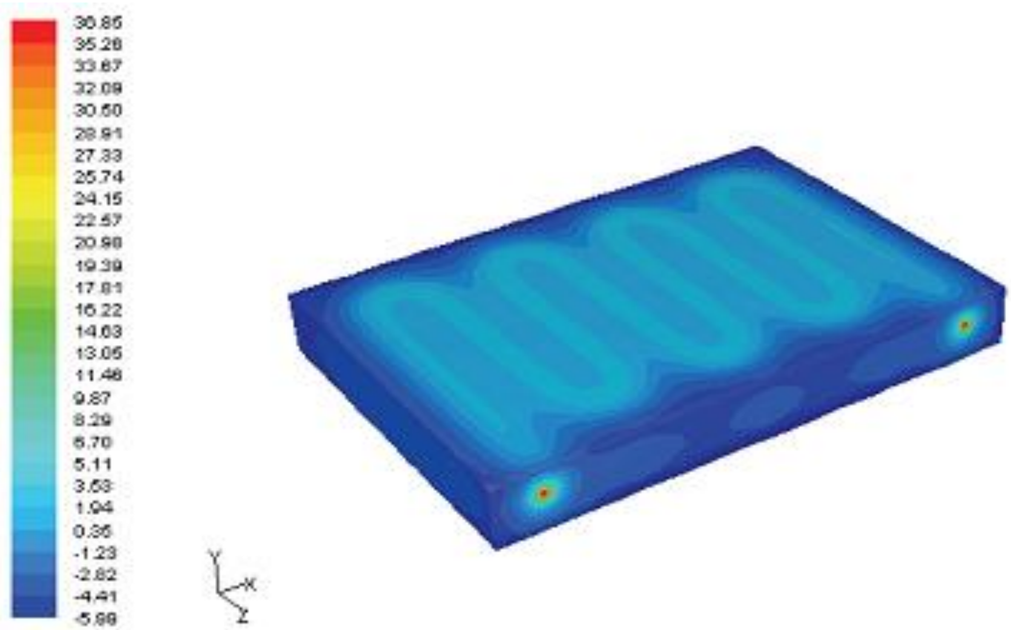


Figure 21 Temperature distribution of pavement slab (30 m) (Balbay, 2013)

Liu et al. (2013) and Liu and Spitler (2003) studied the long performance of heated bridge deck anti-icing systems under certain weather conditions, through numerical simulation, based on the finite difference method. The schematic of the model domain is shown in Figure 22. Hydronic tubing and a ground-coupled heat pump system with vertical borehole heat exchangers were regarded as the heat source in the system. Validation of the modeling method was also accomplished by comparing the operating data, collected from an experimental heated bridge deck installation, with simulation results.

Sass (1992) presented a description and sensitivity testing of a physical model which was used for predicting road surface temperature distribution according to the recorded data from a single road station in Denmark from February 14 to 28. This model was based on the balance of surface energy through fluxes of radiation, sensible heat, latent heat, and heat conduction through the ground. The model was also examined for accuracy and sensitivity to several parameters such as road properties and weather components. The simulation results revealed that the road surface temperature predicted by the model was strongly related to the observed temperature. The limitations of the model originated from assumptions, such as the road being fully exposed to solar radiation, not taking into account the frictional heat source from traffic, and the inadequate understanding of cloud distribution in both vertical and horizontal directions. Shao (1993 and 1995) developed an ice-formulation prediction model, called ICEBREAKER, which is used in Europe. This model can predict road surface temperatures. The predicted surface temperature values were verified against observations and the MORIPM model. It was proven that the ICEBREAKER model significantly outperformed the MORIPM model at bridge sites during the winter of 1990–1991. For some bridge sites, however, the Ray Hall (using the data from the Weather Centers in Birmingham and Glasgow), the ICEBREAKER model was found to be much better than the MORIPM model. A summary of the results showed that the ICEBREAKER Model has a near-zero bias and about 1°C standard deviation overall, and minimum temperature predictions.

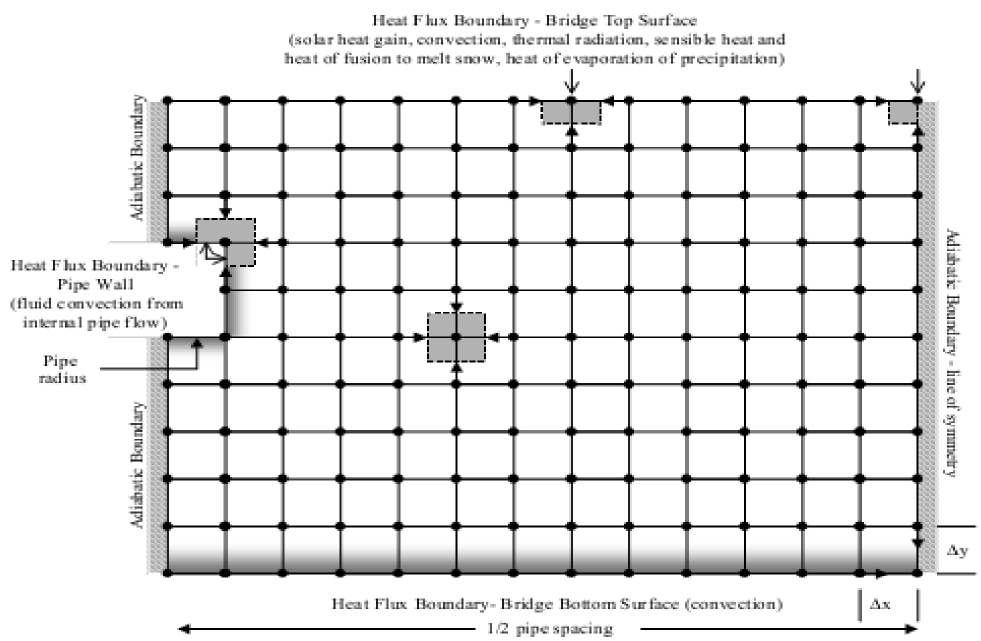


Figure 22 The bridge deck model domain showing the finite-difference grid and boundary conditions (2004)

Nagai et al. (2009) developed programmed software, to numerically simulate time variations of temperature fields and snow depths around a pipe-in-pile snow-melting system, using meteorological data. The system used underground piles as a heat exchanger between underground soil and water flowing inside the piles (shown in Figure 23). In this study, unsteady three-dimensional heat conduction inside the pavement and the underground soil was numerically solved. Some experiments were also performed to validate the software. The obtained simulation results showed good agreement with experimental data, which demonstrates the utility and validity of the software.

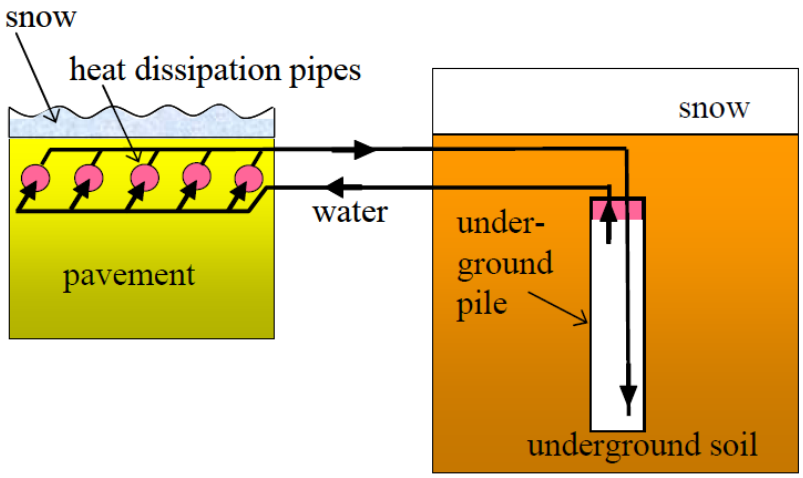


Figure 23 Outline of a pipe-in-pile snow-melting system (Nagai et al. 2009)

2.1.8. Case Studies

This section will introduce several case studies in Europe, Asia, and the U.S. regarding the use of geothermal energy for deicing pavement slabs and bridge decks. More examples on this topic can be found in the review paper by Nagai et al. (2009).

2.1.8.1. Switzerland

The solar energy recovery from road surfaces (SERSO) system was invented and designed in the early 1990s and has been working continuously since then. The function of this system is to guarantee passable road conditions on bridge decks and other normal roads. In summer, the heat from solar radiation is collected and stored in a rock storage volume, and is reused to control the surface temperature of pavement slabs and bridge decks to avoid formation of snow and ice in winter (as shown in Figure 24). Typical road surface temperatures controlled by the SERSO system are shown in Figure 25. The photo of the SERSO system in operation is shown in Figure 26.

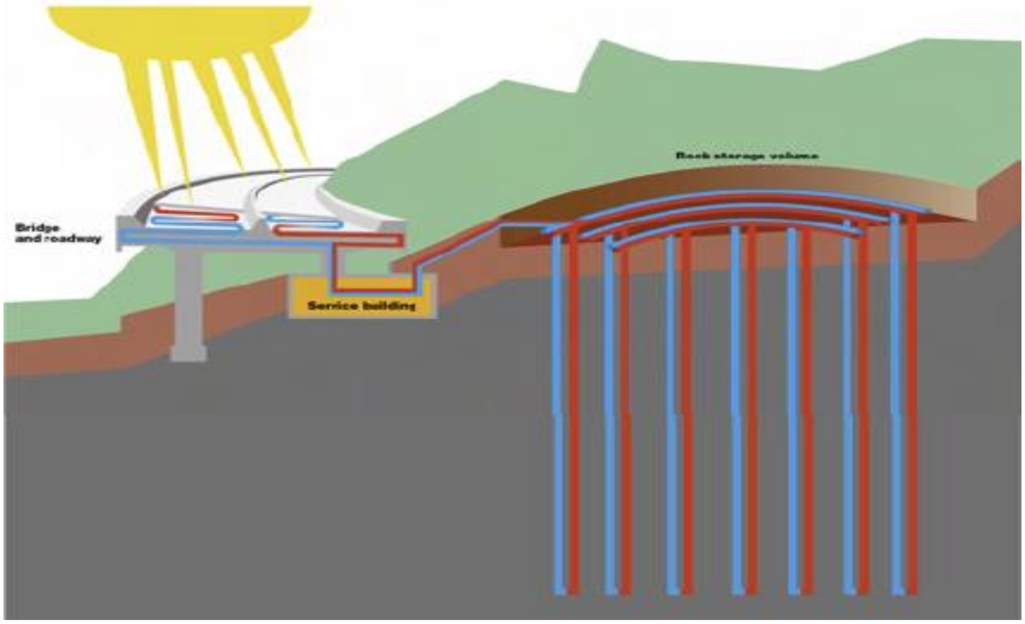


Figure 24 Swiss solar storage system (Eugster, 2007)

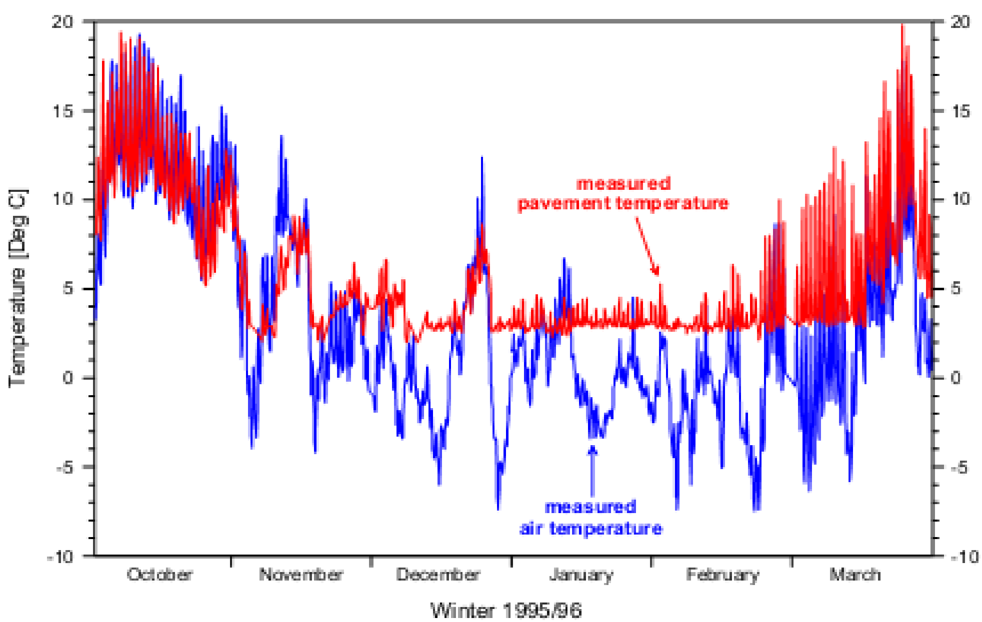


Figure 25 Road surface temperature controlled by the SERSO system (Eugster, 2007)

Figure 26 SERSO system in operation (Eugster, 2007)

2.1.8.2. Japan

Iwamoto et al. (1998) introduced the snow-melting system in Japan, as shown in Table 4. This system became popular in the 1990s, and at least 19 of them are currently in existence. The system circulates hot water in pavements at the soil temperature level and uses power supplied only from circulation pumps. Since the 1990s, some new systems which can collect solar energy in summer have been utilized for deicing pavements in winter. The snow-melting system is most often used for parking lots, bridges, entrances and exits of road tunnels and slopes, and entrances and parking spaces of houses. It is noted that the horizontal heat exchangers were used at the beginning of 1990s, but vertical heat exchangers have become more popular since then.

Two sidewalk heating systems were constructed to melt snow on sidewalks in Aomori City, Japan in 2002. The city has more than 300 thousand people and is known as the snowiest city in Japan, with the annual snowfall sometime exceeding 10 m. Consequently, it is essential to deice snow/ice on road surface. The design heat output of the system is 170 W/m^2. The annual operation time was around 500 hours during the first two years. The total heat output of a unit is roughly 35 MWh. The operating costs of this sidewalk heating system are 6 $Euros/m^2/year$ for the electricity consumption only. A schematic plain view of the site is shown in Figure 28. The sidewalk heating system in operation is shown in Figure 29.

Table 4 Snow-melting system in Japan (Iwamoto, 1998)

No.	Location		Construction year	Snow melting area/applications	Earth heat exchanger/heat storage
	Prefecture	*Town*			
1	Niigata	Nagaoka	1989	(Sidewalks)	
2	Akita	Kyowa	1990	200 m^2 (Roads) Heat pipe type	(Horizontal heat exchanger) Storage in soil (3000 m^3)
3	Okayama	Kawakami	1991	300 m^2 (Sidewalks in parking areas) Heat pipe type	(Horizontal heat exchanger) Storage in soil
4	Niigata	Kochidani	1991	400 m^2 (parking)	(Horizontal heat exchanger)
5	Fukui	Fukui	1992	400 m^2 (parking)	(Vertical heat exchanger) 35 m depth 48 (D=400 mm
6	Aomori	Aomori	1992	118 m^2 (parking)	(Vertical heat exchanger) 30 m depth 3 pipes
7	Aomori	Aomori	1992	Parking for 80 houses	(Horizontal heat exchanger)
8	Tottori	Yonago	1992	150 m^2 (parking) Heat pipe type	(Horizontal heat exchanger) Storage in soil (4.5 m depth)
9	Tottori	Tottori	1993	Pedestrian bridges	(Vertical heat exchanger)
10	Niigata	Kasiwazaki	1994	900 m^2 (parking)	
11	Hiroshima	Saijoh	1994	(Parking)	(Vertical heat exchanger)
12	Hiroshima	Tokawanai	1994	(Roads)	(Vertical heat exchanger)
13	Hokkaido	Kitami	1994	100 m^2 (roads)	(Vertical heat exchanger) 8 m depth 27 pipes
14	Iwate	Ninohe	1995	266 m^2 (roads)	(Vertical heat exchanger) 150 m depth 3 pipes
15	Hyogo	Haga	1995	(Road tunnels)	(Vertical heat exchanger)
16	Hiroshima	Yokotani	1995	44 m^2 (roads)	(Vertical heat exchanger)100 m depth (D=150)
17	Hyogo	Muraoka	1996	310 m^2 (parking)	(Vertical heat exchanger)
18	Fukui	Kanatsu	1996	(Roads)	(Vertical heat exchanger)
19	Shiga	Imatsu	1996	(Base camps)	(Vertical heat exchanger)

A case study of the snow-melting/deicing operations on a bridge roadway at the foot of a mountain in Hiroshima was also presented by Iwamoto (1998). The snow-melting system consisted of a vertical ground heat changer, heat dissipation pipes in the concrete pavement, and a heating carrier circulating pump, as shown in Figure 27. The inlet temperature of circulating fluid in the heat dissipation pipes was 5–6^{o}C, which was the level of soil temperature. The integrated amount of heat collection and heat dissipation were 27.8 GJ and 31.8 GJ, respectively. It was demonstrated that the heat stored during the summer was efficiently used during the winter.

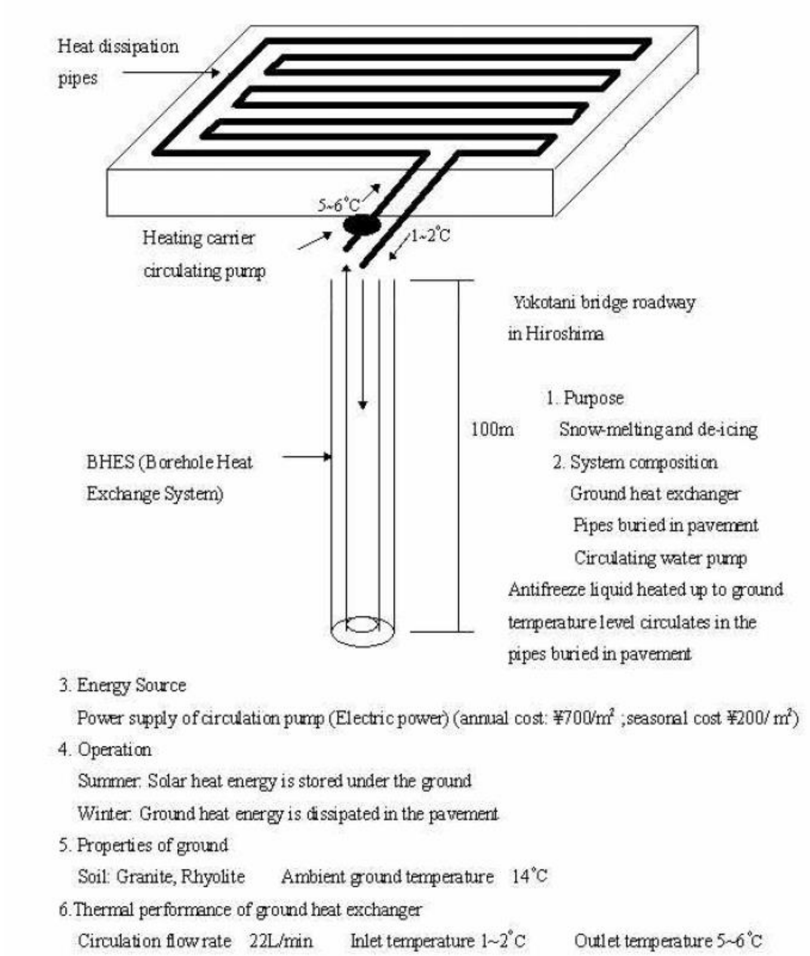


Figure 27 Outline of snow-melting system in Hiroshima, Japan (Iwamoto, 1998)

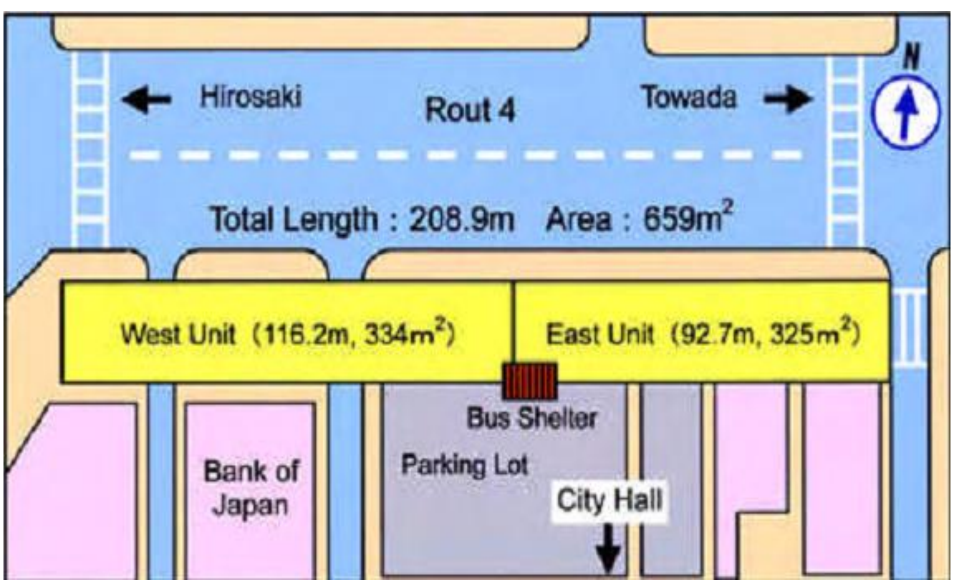


Figure 28 Schematic plain view of the site (Eugster, 2007)

Figure 29 Sidewalk heating in operation (Eugster, 2007)

Kamimura et al. (Eugster 2007) presented the construction of a practical snow-melting system that utilizes shallow-layer geothermal energy for pedestrian walkways in Nagaoka City. A geothermal heat exchange well (Figure 30) was used in this project, based on the environmental factors and soil conditions. Coaxial pipes were put down a borehole of 200 mm diameter, and cold water was fed into the space between the outer and inner pipes, then exchanged heat with ground soil while running through the pipe toward the bottom of the pipe. Warmed water returned to the ground surface through the inner pipe, then it was delivered to the snow-melting panels. In addition, heat-carrying water was circulated in a closed circuit; therefore, it did not pump any ground water, only ground heat. Performance tests of the system for two winter seasons revealed that it is able to keep the pavement clear.

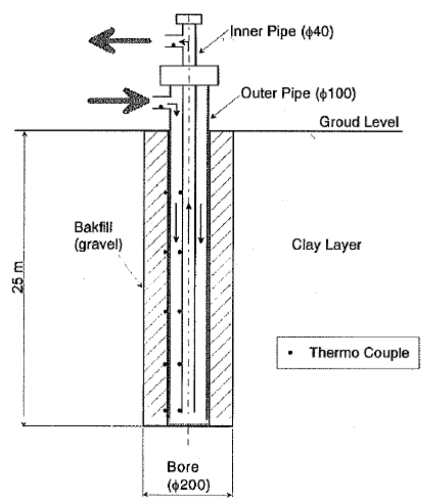


Figure 30 Schematic of geothermal heat exchange well (Kamimura, 2000)

Yoshitake et al. (2000) developed a new pipe heating system that uses only groundwater that is stored in a large underground tank. The underground tank provides geothermal energy, i.e., groundwater of constant temperature, through heating pipes embedded in concrete pavements, with no electric heater or fuel boiler. It is noted that the system was constructed at approximately 50% of the cost of comparable systems; moreover, the operating cost was also reduced by 10% compared with the previous system. Figure 31 shows the schematic of the pipe heating system with an underground water tank. Figure 32 illustrates the typical surface conditions of the road, with and without heating pipes. It is obvious that there was an accumulation of snow on the normal roads without heating pipes. In addition, the pipe-heated road surface always dried earlier than the normal roads. Figure 33 presents an infrared photograph of the boundary between the heated road in the foreground and the normal road in the background. It is evident that the concrete pavement with the heating pipes has a higher temperature than the unheated road. The system was demonstrated to be an economical and effective solution for thawing snow and preventing ice on bridge decks.

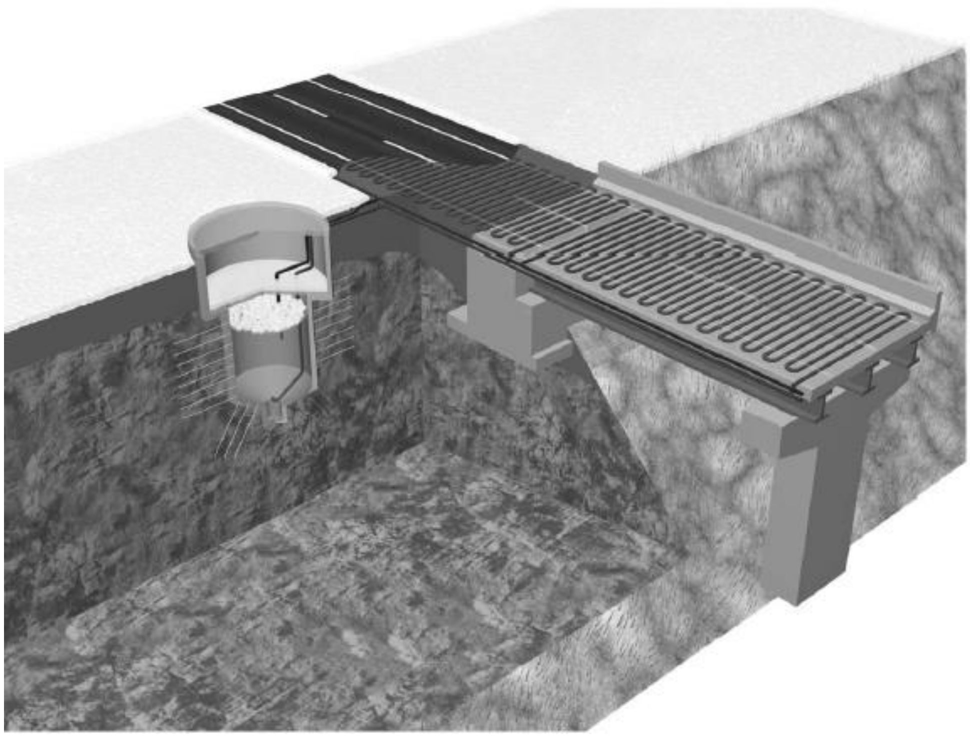
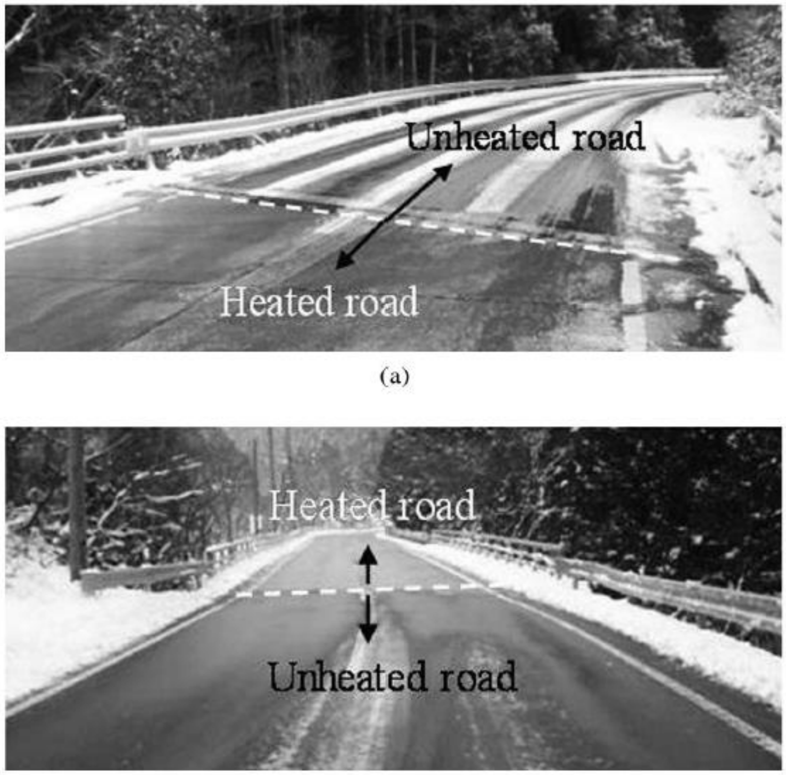


Figure 31 Pipe heating system with underground water tank (Yoshitake, 2011)



(b)

Figure 32 Example of road condition in snowy season (Yoshitake, 2011)

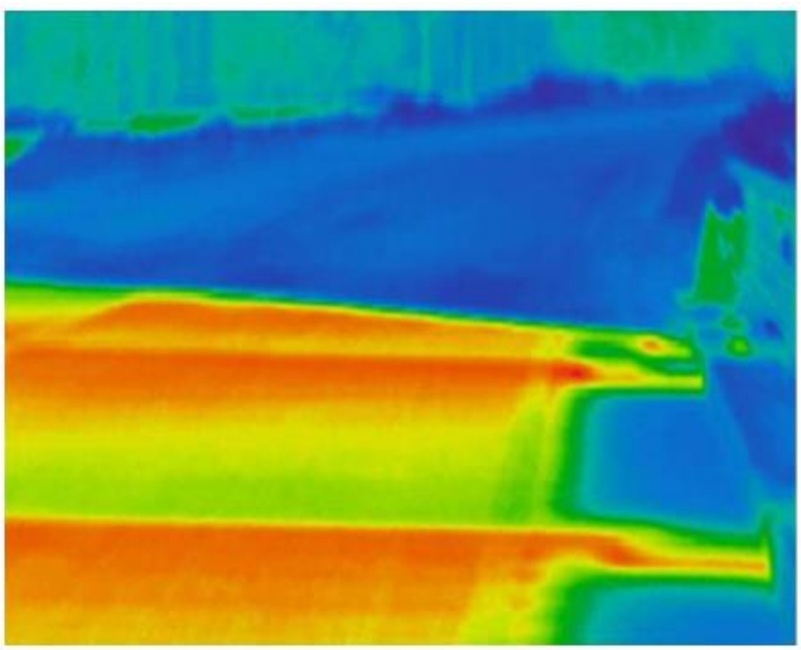


Figure 33 Infrared photograph of the boundary of the heated and unheated roads (Yoshitake, 2011)

2.1.8.3. Germany: Geothermal train platform heating

The first geothermal heating system in Germany went into operation in 2005 on the platform of a train stop in the Harz region. This project used exactly the same idea as the SERSO system described previously. The platform is 200 m in length. The underground heat storage is tapped with 9 borehole heat exchangers with a length of 200 m each. The project is actually working, as shown in Figure 34.

Figure 34 The Harz platform heating in operation (Eugster, 2007)

2.1.8.4. Poland

Heloasz and Ostaficzuk (2011) reviewed the use of waste heat and geothermal energy for melting snow and deicing in Poland. In terms of the geothermal de-icing method, the Gaia system (2001) is most commonly used. It employs the heat of the earth indirectly. The heat is collected from the wells about 150 m deep by a concentric-pipe heat exchanger (Morita and Tago, 2000). The liquid from the heat exchanger is transmitted to a heat pump, then it goes to the subsurface pipes, as shown in Figure 35. After the winter season is over, both water loops are interconnected automatically. The liquid is pumped through the pipes under the road, from where the solar heat is absorbed, and is passed to the water in the wells. The result of the deicing installation on part of the road is shown in Figure 36.

The use of waste heat for deicing was also introduced by Heloasz and Ostaficzuk. Some roads are constructed to overlap with the heat pipelines in a municipal district heating system. Hence, heat lost from the pipelines distributing hot water from the district heating system to the local centers was used as a heating source. In addition, a great deal of heat is also expelled from coal mines, with the ventilation air and discharge water. The temperature of water pumped out from the mines is over 20^{o}C and can be used directly for road deicing purposes. It should be emphasized that, compared with other heat sources, both the investment cost and maintenance cost is reduced considerably by using waste heat.

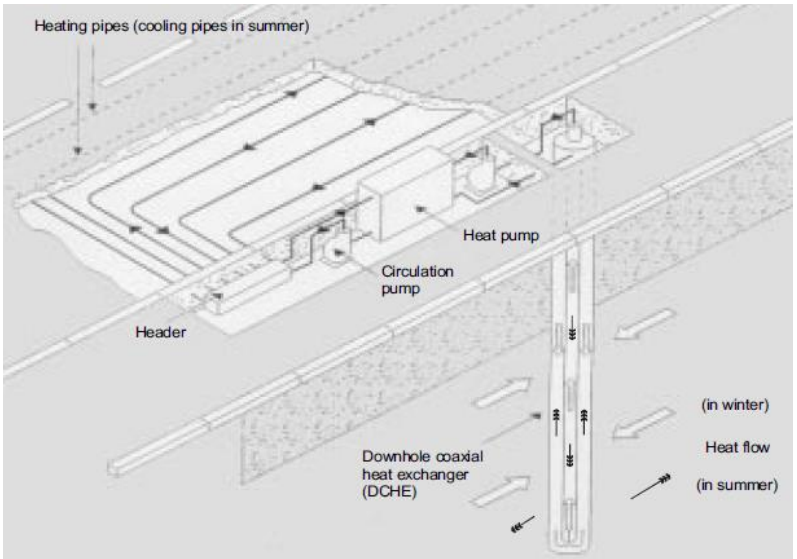


Figure 35 Layout of the snow-melting system (Heliasz, 2001)

Figure 36 Result of deicing installation work on a part of road (Heliasz, 2001)

Zwarycz (Morita et al., 1992) proposed a design for a snow melting system for the airport at Goleniow, Poland. The system is based on utilization of geothermal energy from the Szczecin region, close to the town of Goleniow, and used heat pumps that extracted heat from geothermal water with a temperature of 10 to 60^{o}C. A comparison was also made of the performance of different heat pump system arrangements. It was found that the direct heat pump approach is more efficient and economical than the indirect heat pump approach.

2.1.8.5. United States

Within the United States, we examined six states: Texas, Colorado, Wyoming, Nebraska, New Jersey, and Oregon.

2.1.8.5.1. Texas

In Amarillo, Texas, conventional geothermal wells (not piles) were used to heat concrete decks on the north and south-bound two-lane bridges on US 287 in Amarillo over N. 15th Avenue. The bridges were of the box beam type, 58 feet wide, and 146 feet long (Minsk, 1999). The heated area on each bridge was 8600 ft^2. The design objective was ice prevention (deicing), not snow melting, with a heat flux of 12 W/ft^2 (or 41 Btu/ft^2-hr). A hydronic system with conventional geothermal wells (not piles) provided the heat source. Each structure used 50 geothermal wells that were located between the bridges and on the east side of each bridge. Each 4-inch diameter geothermal well was 176-feet deep, did not reach ground water, and contained two pipe loops. Approximately 3,000 gallons of fluid circulated through each bridge deck, 700 gallons of which were in the deck. Each bridge had 32 zones of 3/4-inch ID hydronic tubing that were continuous between supply and return headers. To monitor the road conditions in the Amarillo region, a Vaisala road weather information system was installed, which also controlled the operation of the bridge heating system. Type K thermocouples were located in the deck near the surface in the centers of the three spans on each structure, in each approach slab at the outside shoulder, and in the right travel lane line. Heating was automatically initiated when the deck surface temperature reached 35°F and weather reports forecasted precipitation. Minsk (1999) indicated that the heating system operated as designed and experienced no problems. Operation over two winters had demonstrated that sufficient thermal energy can be extracted from the ground. Figures 37 and 38 show the construction detail for the heated pipes for the bridge deck. The costs of construction and operation were $1,200,000 and $7,500, respectively.

Figure 37 Close-up of supply and return manifolds (pipes in center) and thermocouple conduits terminating in enclosure at right

Figure 38 Heating hoses in place and ready for concrete pour; hoses are on 152 mm (6-in.) centers, placed 76 mm (3 in) under top of slab, affixed below #4 rebars

2.1.8.5.2. Colorado

Swanson (2002) and Donnelly (1980) reported the evaluation of geothermal energy for heating highway structures to determine the feasibility of using geothermal energy to prevent icing of bridge decks in Colorado. A preliminary reconnaissance of known geothermal springs was made for the Glenwood Canyon corridor, through which Interstate 70 was constructed. In addition, a prototype bridge structure was built to test the feasibility of using geothermal water and heat pipes to prevent preferential icing. It was the first time that geothermal water and heat pipes were combined at a header, with the concrete deck kept warm to prevent ice formation. The results of this pilot project guided the later design and construction of similar highway structures that are susceptible to icing in the Glenwood Spring area.

2.1.8.5.3. Wyoming

Griffin (1981) investigated controlling bridge icing with heat sources not generated by the consumption of fossil fuel. Different heat sources for deicing were summarized, which included groundwater, earth, sanitary sewer or domestic water lines, and alternatives in the heat pipe technology field. Design was based on controlling preferential icing rather than maintaining an ice-free bridge.

A small bridge over Spring Creek was constructed in Laramie, Wyoming, and heated to prevent preferential icing, as shown in Figure 39. One-hundred-foot-long sections of 3-inch pipes acted as the evaporator section of the system. Each pipe was placed in a hole drilled in the ground and grouted into place. Each evaporator pipe was manifolded to four condenser pipes cast into the bridge deck to form a continuous heat pipe. Others have used circulating liquid or contact conduction to transfer the heat from heat pipes in the ground to the heat pipes in the bridge.

Figure 39 Earth system at Laramie, WY (Griffin, 1982)

2.1.8.5.4. Nebraska

Cress (1982) described the construction and operation of a hydronic bridge/pavement deck heating system in Lincoln, Nebraska. The system was installed in the deck of a 367 m long by 3.7 m wide viaduct and monitored for evaluation of its performance for 12 months. The hydronic deck heating system was manufactured by Delta-Therm Corporation. A natural gas boiler heats a propylene glycol and water solution that is pumped into the hoses embedded in the deck, and the concrete deck is heated to melt snow and ice. Figure 40 shows the advanced snow melt on the surface of the deck. The costs of design, construction, and operation are \$150,000, \$161/m^2, and \$9.25/hr, respectively.

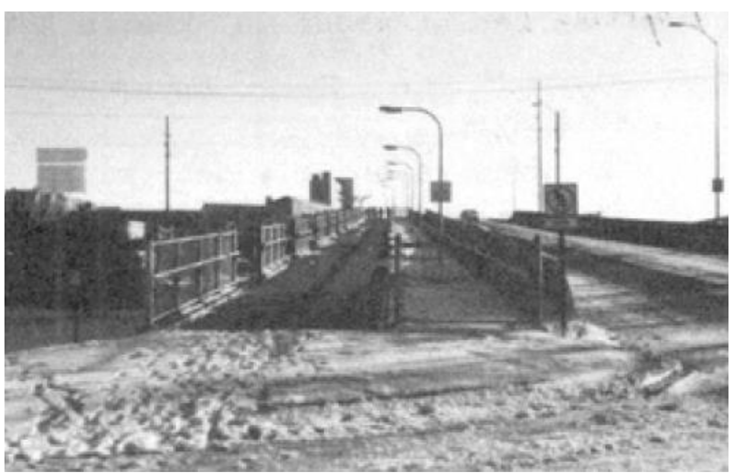


Figure 40 Advanced snow melt on the surface of the deck (Cress, 1995)

2.1.8.5.5. New Jersey

Heat pipes were used in Trenton, New Jersey, in 1969 (Nydahl, et al., 1984) for deicing a bridge deck. This system circulated an ethylene glycol-water mixture between pipes embedded 2 inches below the pavement surface and a horizontal grid buried 3 to 13 feet below the pavement on 2-foot levels. The total length of the ground pipes was twice as long as the pipes in the pavement. Typical measured snow melting rates were 1/4 and 1/2 inches per hour when the air temperature ranged between 20 and 35^{o}F. The performance of this ground system proved to be superior to that of a companion 68 Btu/h/ft^2 electric pavement heating system and required only about 2% of the electrical power to operate the circulation pump.

2.1.8.5.6. Oregon

A hydronic system, supplied by a GSHP, was installed in a two-lane bridge with a Portland cement concrete deck. The bridge is located on a curve over the north fork of Silver Creek, in the Cascade Mountain foothills at 274 m elevation. The heated deck is 32 m long at the centerline and 12.2 m wide. The heated end panels are each 6.1 m long and 12.2 m wide. The total heated area is 576 m^2. The system has been operational since January of 1995 and has successfully cleared the bridge deck of all observed snow and ice since then. The costs of construction, annual maintenance, and operation are $411,000, $5,800, and $3,400, respectively.

Boyd (1995) presented a wall-street bridge project that used geothermal energy to deice bridge deck and sidewalks. The project has approximately 10,330 ft.^{2} of snow melting surface. The bridge deck and sidewalk snow melt areas are 88.6 ft. by 42 ft., for a total of 3720 ft.^{2} of surface area. The approach road and sidewalk snow melt area are 157.5 ft. by 42 ft., for a total of 6613 ft.^{2}, with an estimated heat output of 180 W/m^2. The loop system for the bridge was placed longitudinally on the bridge deck, with the loops ending on the roadside approach of the bridge, as shown in Figure 41. The loop systems for the bridge and road approach sidewalks were placed longitudinally, as shown in Figure 42. The approach road loop system was placed transversely, with the loops ending on the south side of the road, as shown in Figure 43. All the loops were attached to reinforcing steel by wire at approximately 200 mm on center.

Figure 41 Bridge decking loops attached to the reinforcing steel (Boyd, 2003)

Figure 42 Bridge sidewalk loops (Boyd, 2003)

Figure 43 Installation of horizontal loops under the approach road (Boyd, 2003)

The Oregon Institute of Technology placed a snow melt system in an existing stairway by the College Union building. The project consisted of placing a slurry concrete mix over the existing stairway, then tying the tubing to the formwork longitudinally with the stairway. A two-loop system, for a total of 565 ft. of tubing, was placed. The surface area where the snow is melted is 540 ft.^{2}, as shown in Figure 44 (Keiffer, 2003).

Figure 44 Detail of the snow melt system for the stairs (Boyd, 2003)

2.1.9. Cost Analysis

This section compares the cost-benefit of traditional chemical methods and innovative thermal heating technology. The applicability and cost of various chemical methods depends on several factors, including eutectic temperature, availability of raw materials, and process methods. Zhang et al. (2003) presented the cost of various chemical methods, as shown in Table 5, and the estimated cost of thermal heating technology, as shown in Table 6. It is evident that the cost of the thermal heating method is much higher than that of the chemical methods; however, the chemical methods cause some detrimental effects on the environment. For example, chloride, at high concentration, tends to accumulate and change the natural chemical balance, and repress the growth of roadside vegetation. Some organic matter in chemicals will also pollute the air and water if they are used in large amounts.

Table 5 Cost of deicing chemicals and their temperature range and application rate

(Zhang et al., 2007)

Deicing Chemicals	**Temperature Range**	**Application Rate**	**Approximate Cost in Volume**	**Approximate Cost in Area**
Sodium Chloride (NaCl)	-10ºC to 1ºC (14ºF to 34ºF)	13 to 68 g/m^2 (170 to 890 lb./12 ft. lane-mile)	\$29/m^3 (\$26/ton)	\$0.0003/m^2
Calcium Chloride ($CaCl_2$)	-25ºC (-13ºF)	Not used alone in the U.S.A	\$294/m^3 (\$267/ton)	\$0.03/m^2
Salt mixed with calcium chloride (NaCl and $CaCl_2$)	-17ºC to 0ºC (0ºF to 32ºF)	21–50 l/m^3 salt (5 to 12 gal/ton)	\$108/m^3 (\$98/ton)	\$0.01/m^2
Calcium Magnesium Acetate (CMA)	-5ºC to 0ºC (23ºF to 32ºF)	15 to 39 g/m^2 (200 to 500 lb./12ft. lane-mile)	\$738/m^3 (\$670/ton)	\$0.004/m^2
Urea	-9ºC (16ºF)	26 to 136 g/m^2 (340 to 1780 lb./12ft lane-mile)	\$145–290/m^3 (\$130–260/ton)	\$0.007/m^2
Magnesium chloride ($MgCl_2$)	-15ºC (5ºF)	8 to 11 g/m^2 (100 to 150 lb./12 ft lane-mile)	Not available	\$0.0002/m^2
Formamide	-18ºC (0ºF)	Not available	\$290–435/m^3 (\$290–390/ton)	\$0.002/m^2

Table 7 shows the estimated annual cost of typical deicing operations for the Knik Arm Bridge. It is indicated that the total cost of the chemical method is substantially less than that of the thermal method. Although the cost of equipment and installation of the thermal method is much higher than that of the chemical method, the cost of labor is much lower. It therefore has a potential for saving money over the long-term operation. More importantly, the impact of the thermal method on the natural environment is considerably less than that of the chemical method.

Table 6 Cost of estimates for various thermal heating systems (Zhang et al., 2007)

Heating	Approximate Capital Cost	Power Consumption	Operating Cost
Infrared Heat Lamp	$96/m^2$ ($8.9/ft^2$)	75 W/m^2 (7 W/ft^2)	Not available
Electric Heating Cable	$54/m^2$ ($5/ft^2$)	323–430 W/m^2 (30–40 W/ft^2)	$4.8/m^2$ ($0.45/ft^2$)
Hot Water	$161/m^2$ ($15/ft^2$)	473 W/m^2 (44 W/ft^2)	$250/Storm, 3-inch snow
Heated Gas	$378/m^2$ ($35/ft^2$)	Not available	$2.1/m^2$ ($0.2/ft^2$)
Conductive Concrete Overlay	$48/m^2$ ($4.5/ft^2$)	516 W/m^2 (48 W/ft^2)	$5.4/m^2$ ($0.5/ft^2$)

Table 7 Estimated annual cost of typical deicing operations on the Knik Arm Bridge (2007)

Cost		Chemical Method		Thermal method
		Calcium chloride	Potassium acetate	
NPC	Equipment	20	20	300
	Installation	5	5	400
	Lifecycle	2	2	30
	Utility incentive payment	0	0	0
COO	Materials	60	120	100
	Labor	60	60	2
Total cost=NPC+COO		147	207	832

Notes: NPC is the net participants cost; COO is the operation cost.

The initial cost of a snow-melting system in Japan is usually expensive because of the necessity to dig vertical boreholes, which costs approximately $80–$120 per m in depth. The cost of operation is much less than the conventional system, however, which uses primary energy. For instance, in the case in Hiroshima, as presented previously, the cost of running a snow-melting system is 1/8 to 1/20 that of a conventional system (Zhang et al., 2009). Thus, it is indicated that it takes 10 to 20 years to recover the cost of installing a snow-melting system.

2.1.10. Summary

The use of geothermal energy for deicing pavement slabs and bridge decks is an innovative, feasible, and environment-friendly technology to improve the movement of traffic and increase public safety (as shown in Figure 45) in Texas. The development and utilization of geothermal energy was reviewed and summarized based on previously related experimental and numerical studies. The design of a geothermal heating systems, including the GLHE system and hydronically-heated pavement slabs and bridge decks, was presented in four steps. Many case studies were also introduced to further demonstrate the feasibility and applicability of this new technology. The advantages of the long-term operation cost-benefit of the geothermal methods was analyzed and corroborated, and compared with the traditional deicing methods, i.e., chemical methods.

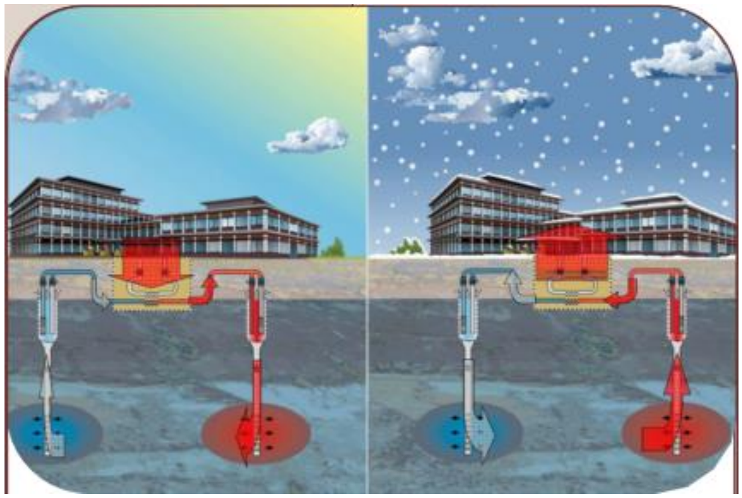
Figure 45 Geothermal road heating should keep traffic running (Eugster, 2007)

2.2. Underground Thermal Energy Storage (UTES) for Bridge Deck/ Pavement Deicing

2.2.1. Introduction

Many different methods are used to generate renewable energy by utilizing energy sources such as solar radiation, wind, waves, or earth. Unfortunately, the supply and demand of renewable energy often doesn’t occur at the same time. This is true for both renewable electricity and renewable heat. For example, renewable energy sources such as solar radiation are often most productive when the demand is relatively low. This mismatch can be solved by storing the energy. A solution to bridging this gap or balancing the difference between the supply and demand is to store excess heat during summer and extract it during the winter. This is known as seasonal thermal energy storage, also referred to as UTES.

Iwamoto (1998) stated that thermal energy is a new technology to adjust the time discrepancy between power supply and demand. Nordell et al. (2010) indicated that nature provides an energy storage system between different seasons because thermal energy is passively stored into the ground or groundwater by the seasonal climate changes. Below a ground depth of 10–15 meters, the ground temperature remains relatively constant. This temperature is colder than the ambient during summer and hotter than the ambient during the winter. As a result, energy can be extracted from the ground during the winter for heating purposes or injected into the ground during summer for cooling purposes. UTES in both summer and winter is illustrated in Figure 46.



(Network "Communities of a sustainable Europe" (CoSE), http://communities-of-sustainable.eu/, 2013)

Figure 46 Operation of UTES in summer (left) and winter (right)

This section introduces the working principles, the type of system and heat storage materials of UTES systems. An overview of successful applications in China, Belgium, Japan, Sweden, Germany, Canada, and the Netherlands are presented to demonstrate the feasibility and applicability of this new technology. The installation, implementation, and cost of this system are also briefly discussed.

2.2.2. Underground Thermal Energy Storage

The concept of earth energy and the related research began after World War II. Penrod (2007) first proposed the potential use of heat pumps to utilize geothermal energy. Margen (1949) later presented the storage of heat in the form of hot water in underground caverns. Brun (1959) also proposed the concept of underground storage of solar energy. Meyer (1965) developed a theoretical model on well-storage of heat in aquifers. Mathey (1974) conducted experiments for the injection of Lake Neuchatel water in aquifers at different temperature levels. Iris (1975) introduced the use of heat pumps for space heating and domestic hot water, using an aquifer at Aulnay-sous-Bois near Paris. The system was designed to serve 224 collective dwellings.

The earliest use of energy storage in the U.S. started at the Lawrence Berkeley Laboratory of the University of California (1988). Then, Kannberg (Tsang, 1976) studied the feasibility and operating characteristics of aquifer thermal energy storage (ATES) systems sponsored by the US Department of Energy. Some field test facilities in the US include the Mobile site of Auburn University, Alabama (1985); the University of Recreation Centre on the Tuscaloosa campus of the University of Alabama (Molz, 1979); and the physical plant at the University of Minnesota's St. Paul campus (Schaetzle, 1981). The BTES method was first proposed by Hoyer in 1985. Both mathematical modeling of such heat stores and pilot projects have been pioneered in Sweden by the Ground Heat Group at the Lund Institute of Technology and Lulea University of Technology (Brun 1967).

As reported, a large percentage of Canada's energy needs are for space heating and cooling. This energy is used to alter the temperature of air and water from the natural ambient temperature to human comfort levels. During the winter, the ambient air is cold, and natural gas is burned to increase the temperature of the air to a comfortable level. During the summer, ambient air is hot, and electricity is used to run condensing air conditioners which cool the air. The required winter resource, heat is abundant in the summer. Similarly, the required summer resource, chill, is abundant in the winter. When viewed from this elementary perspective, it can be seen that the need for space heating and cooling is in fact a result of thermal and temporal disparity. To solve this mismatch, thermal energy must be stored in the season when it is abundant and utilized in the season when it is scarce. This process is known as seasonal thermal energy storage.

Countries in temperate climates experience four seasons. The energy source charges a subsurface store for use at a later season, which is the basis of UTES. For example, the use of winter's cold can be used to charge a store which will be used in summer to cool a building. Similarly, solar energy can be collected and stored in summer for heating purposes in winter. Such seasonal storage of thermal energy can usually be accomplished in rocks, caverns, tanks, gravel beds, and soils.

Typically, a UTES system has four main components: a heat source, the method or technology of storing the energy, the distribution of heat or cold, and a heat exchanger. The heat source can be solar thermal, solar absorbers, or the heat from industrial waste. The method or technology of storing the energy is generally divided into two categories: open system and closed system. The heat or cold is often distributed through a district-heating network. The heat exchanger is used to exchange energy between the building and the ground.

UTES includes various systems, as illustrated in Figure 47. The soil boreholes used for geothermal energy storage and extraction can be installed in either vertical boreholes (called vertical GHE) or horizontal trenches (horizontal GHE). In the horizontal ground-coupled heat pump systems, the GHEs typically consist of a series of parallel pipe arrangements laid out in trenches dug approximately 1–2 m below the ground surface. A major disadvantage is that the horizontal systems are more affected by ambient air temperature fluctuations because of their proximity to the ground surface. Another disadvantage is that the installation of the horizontal systems requires much more ground area than vertical systems.

Advantages of UTES systems are that they can be installed anywhere in the world, have a good balance between efficiency and installation cost, and have the technical maturity to be implemented on a large scale. Most UTES systems involve storage of heat at temperatures between 50 and 95°C. ATES systems involve extracting water from the subsurface, transferring heat, then re-injecting it into the subsurface. The primary UTES method investigated in the U.S. is the aquifer system, which has been implemented on a utility scale in Turkey, Greece, and the Netherlands for direct cooling (Clesson, 1981; Jahansson, 1980; Nordell, 1994). However, aquifer heat storage is not feasible in many of the US states because of water rights issues, issues with mass balance of water extraction and injection, and concerns of groundwater contamination or thermal mobilization of contaminants. Another major issue with aquifer systems is the spreading of thermal energy away from the point of injection, making it difficult or impossible to later extract.

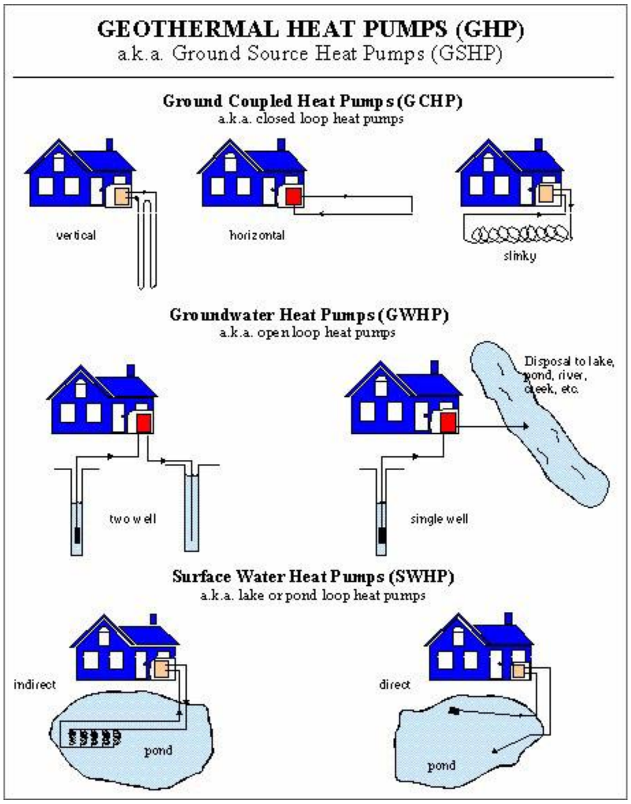


Figure 47 UTES Systems used for cooling and heating (http://geothermalenergy.web.unc.edu/about/)

The UTES provides many environmental benefits compared to other conventional energy sources. For example, UTES has the potential to considerably reduce the consumption of non-renewable energy such as petroleum, natural gas, coal, etc. The pollutants (e.g., carbon dioxide, sulphur dioxide, nitrous oxide, etc.) released into the atmosphere, hydrosphere, and lithosphere through fossil fuel combustion is also reduced. Similarly, the displacement of conventional chillers with UTES cooling reduces the incidence and risk of CFC being released into the atmosphere. Some other advantages include the increase in efficiency of energy use for electrical energy, the potential for short and long-term storage of available solar energy, indoor air improvement, and the increasing efficiency of land use in developed areas. However, the UTES system also has some limitations. For example, poorly designed, constructed, or maintained boreholes are potential conduits for transmission of contaminants from the surface environment to the subsurface, and possible leakage of fluid in loops embedded in boreholes results in groundwater contamination.

2.2.3. Type of UTES System

Nordell (McCartney et al. 2016) presented three types of UTES systems, including ATES, which are usually the open systems; BTES; and rock cavern thermal energy storage (CTES), which are primarily the closed systems. The outline of the most common UTES system is shown in Figure 48. ATES is most widely used in large-scale applications; BTES is the most adaptable system since it can be applied in all scales; and CTES is best used when loading/unloading powers vary greatly or are extremely high. Each type of UTES system mentioned above will be presented in detail.

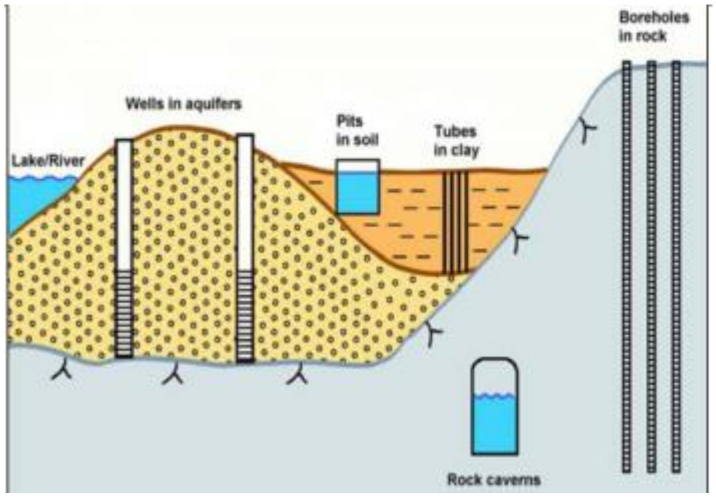


Figure 48 Outline of the most common UTES system, ATES, BTES and CTES (2000)

The ATES system uses groundwater and the minerals in an aquifer to store the energy. Wells are drilled for the injection and extraction of groundwater, which is considered as heat-carried fluid, in the system, as shown in Figure 49. ATES has two possible concepts: (1) alternating flow for loading and unloading the store, thus switching the production and injection wells and creating "warm wells" and "cold wells;" and (2) continuous flow in one direction, with varying temperatures in the injection well and mean temperatures in the production well. This is used for cooling applications. An ATES system can be utilized for both short-term and long-term storage, and it has been demonstrated to be feasible in many applications (Nordell et al., 2007). The main problem is the conflicts of interest in groundwater use. In addition, a number of computer models are needed to design and simulate the thermal behavior of the ATES system for different loads and geological conditions. Groups in the Netherlands, Sweden, and the United States are currently the best at designing and simulating ATES.

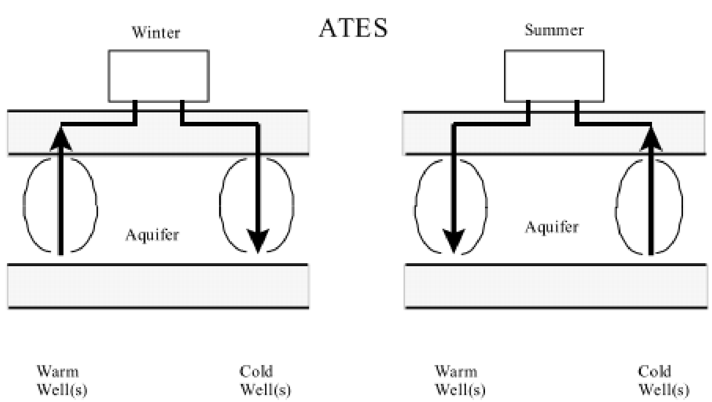


Figure 49 Schematic of ATES system (Dickinson et al. 2009; Lee, 2010; Nordell, 2000; Nordell et al., 2007; Sanner et al. 2005)

ATES takes advantage of natural groundwater storage in the form of aquifers. There are two modes of operation: cyclic regime and continuous regime (Nordell, 2000). The continuous regime is feasible only for plants where the load can be met with temperatures close to natural ground temperatures, and the storage part is more an enhanced recovery of natural ground temperatures. With a continuous flow, designs and control of the system are much easier and simpler; only one well or group of wells needs to be equipped with pumps. The disadvantage is the limited temperature range. In a continuous flow regime, water is continuously pumped from one well. Basically, hot water is injected through the other well in the summer, and cold water is injected in the winter. Thus, this type of system is very similar to a GSHP, and the temperatures within the storage aquifer will be close to ground temperature. In a cyclic flow regime, two wells are usually drilled into the aquifer. During periods of heat recharge in summer, warm water is injected, and a warm reservoir is developed. During periods of abstraction, the heat reservoir is exploited from the other well. In such a cyclic system, both sets of wells must be designed to produce or accept groundwater (Socaciu, 2011).

The BTES system is a more commonly used UTES system than the ATES system. In this system, bedrock or the soils are used as a heat-storage medium. The boreholes are penetrated into the medium as a heat exchanger, and a pipe system is installed in the borehole to enable the circulation of a heat-carrier fluid. The BTES system can be applied in both small scale and large scale. For small-scale systems, a single borehole can be either used for cooling or heating, with a heat pump. For large-scale systems, the boreholes can be used for heat extraction with a heat pump and recharge of extracted energy. Figure 50 shows the sections of a single borehole and a group borehole systems (Socaciu, 2011). BTES systems are most suitable for base-loading and unloading conditions for seasonal thermal energy storage.

Many hundreds of thousands of BTES systems have been constructed around the world. The Geothermal Heat Pump Consortium estimates that, within a few years, 400,000 BTES systems will be built each year in the U.S. Most of them are borehole systems, of one or a few boreholes. There are, however, an increasing number of large-scale systems (more than 10 to 20 boreholes). BTES systems are most favorable for direct cooling, i.e., without heat pumps, even though heat pumps sometimes are required. Another type is a high-temperature store that delivers heat for low-temperature heating. Only a few high-temperature BTES have been built since the first large-scale high temperature BTES at Lulea University, Sweden, in 1982 (Nordell, 2000). When a BTES system is constructed in soils or clays, it is usually called duct thermal energy storage, which will be presented later. Europe has many such plants, constructed with horizontal or vertical plastic pipes in the ground. Some of them are operating at high temperatures, but most of them are connected to heat pumps and are thus operating close to the undisturbed ground temperature.

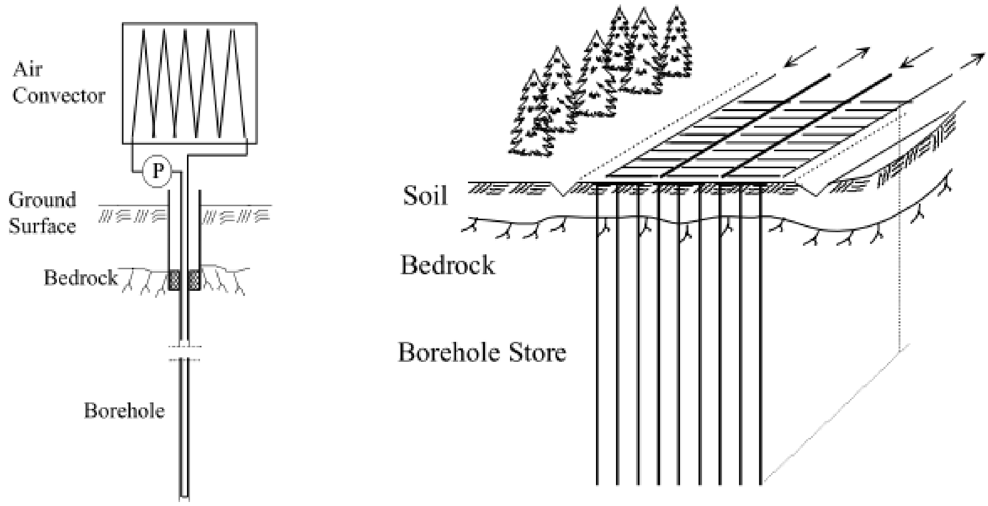


Figure 50 Section of a single borehole and a group borehole system (Nordell, 1994)

CTES is also considered a UTES system and can be applied under specific conditions. In the CTES system, energy is stored as hot water in an underground cavern, as shown in Figure 51. In such a system with a large volume of water, it is of great importance to maintain a stratified temperature profile in the cavern. Hot water is injected at the top of the store, while colder water is extracted from the bottom. Two such storage systems were built in Sweden: Avesta, with a volume of 15,000 m^3 and Lyckebo, with a storage volume of 115,000 m^3. The Avesta CTES was built in 1981 for short-term storage of heat produced at an incineration plant. The Lyckebo store, which is partly heated by solar energy, has been in operation since 1983. A few more CTES systems have been built, but, in these cases, the caverns used were not initially constructed for CTES. There are examples of shut-down mines and oil-storage caverns that have been reconstructed for hot water storage (Nordell 2000). Rock caverns are very expensive to construct, but have a high storage capacity, which is a big advantage. Hence, CTES systems can be used to meet very high thermal energy demand.

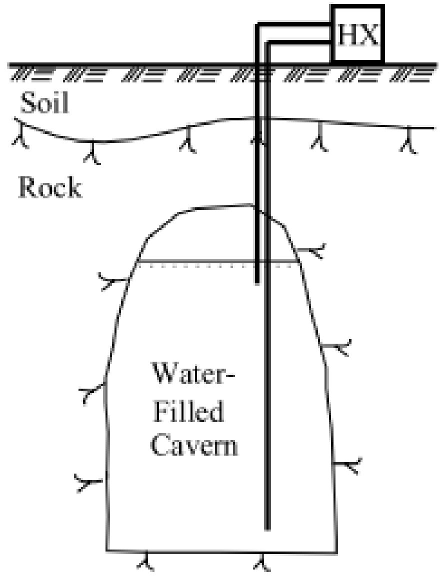


Figure 51 CTES-Rock Cavern hot water storage (Gustafson, 1985)

There are two other types of UTES systems which are not widely used in practice. They are ducts in soils and pit storage. A conceptual diagram of five different types of UTES systems is shown in Figure 52. The concept of "ducts in soils" has found extensive use in connection with ground-coupled heat pumps, where the duct can be placed in shallow trenches horizontally or in vertical boreholes. The vertical boreholes are also suitable for geothermal storage, as discussed previously (i.e., BTES). As reported, approximately ten installations of soil storage with vertical ducts in soils and clays have been built in Sweden. The active storage volumes vary between 10,000 and 100,000 m^3. An insulation cover is needed at the top of the ducts. This type of storage is best suited for low temperatures of around 25 to 30^{o}C and will need heat pumps to raise the temperature of the water used for space heating and tap water to a suitable level (Nordell, 2000). The low temperature in the store means that it can be combined with solar collectors working at low-to-medium temperatures. Such collectors are simpler and cheaper than high temperature collectors, and also increase efficiency and practical operating hours (Andren, 2001).

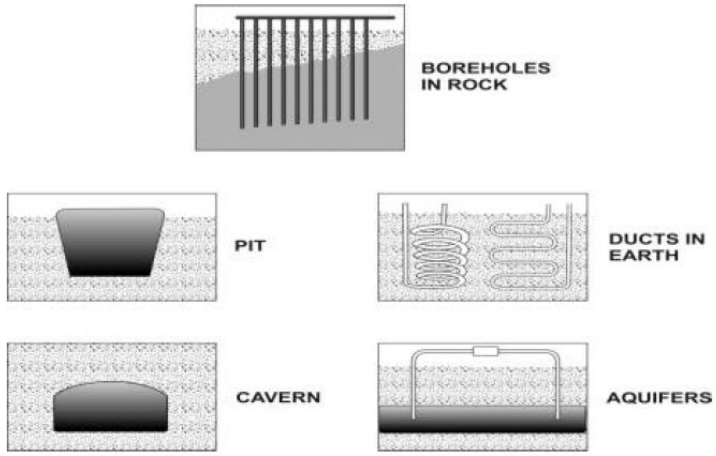


Figure 52 Conceptual diagram of five different types of UTES systems (Nielsen, 2003)

There are a number of seasonal pit storage installations in Denmark, Sweden, and Germany. Their volumes vary from 1 to 3000 m^3 for a multi-family dwelling up to more than 10,000 m^3 for housing complexes and commercial buildings. The largest installation in Europe is, at present, a 12,000 m^3 concrete pit with a stainless-steel liner in Friedrichshaven, Germany. It is used to store solar energy from a collector system, has an area of 5600 m^2, and a maximum temperature of 95^{o}C (Lottner and Mangold, 2000).

Figure 53 shows the basic conceptual design of a pit storage facility in soil. The store is usually placed close to the surface in order to reduce excavation costs, but it needs to be insulated both on the top and along the inclined walls. The top is usually covered with a load-carrying construction, so that the surface area can be used for something else. The pit also needs to be waterproofed, and this is usually done by installing a liner of plastic or rubber. The storage temperature can be up to a maximum of 95^{o}C.

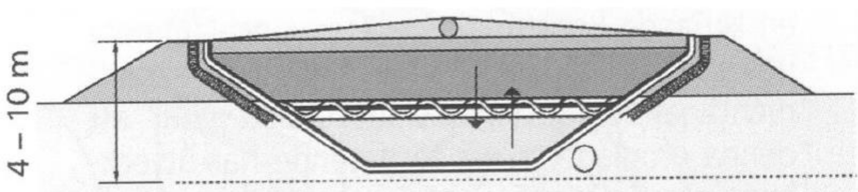


Figure 53 Pit storage facility in soil (Nielsen, 2003)

Pit storage is normally filled with water, but there are also examples where the pit is filled with both rock and water, using pipe heat exchangers placed in sand between layers of rock. Most pit storage facilities in Europe are built in connection with solar collector systems for district heating; however, the snow storage used for summer cooling at the Sundsvall hospital in Sweden is an exception. The storage is a shallow pit lined with waterproof asphalt, and it has the capacity to store 60,000 m^3 (40,000 tons) of snow. The stored snow is covered with a 0.2 m thick layer of wood chips that insulates the snow and reduces the natural melting rates so that some snow remains in storage during the entire cooling season. Melted water from the storage is pumped to the hospital, where it is used for cooling, and afterwards returned to the snow storage. When all the snow has melted, the wood chips are dried and burned in a local heating plant (Skogsberg and Nordell, 2001). According to published literature, although all the various pit storage installations are different, two common problems are water leakage and heat loss because the pit storage facility is not usually placed deep in the ground due to the relatively high costs.

In summary, ATES systems are feasible when the geological conditions are favorable. ATES is for large-scale cooling or heating. In addition, it is used for short-term and seasonal cold and heat storage. ATES is a standard option in some countries, but BTES is the most general type of UTES system. It is feasible in a very small scale and also in large scale; however, the soil cover should not be too deep. BTES is the most efficient when the task is to load and unload a base load of thermal energy. BTES relies on installed pipes and therefore it is possible to operate at below-freezing temperatures. A combination of CTES and phase-change material (PCM), seasonal storage of ice and snow in a rock cavern for district cooling seems to be a very promising application. The most important external factor for efficient UTES systems is that the temperature requirement for space heating is low, about 35^{o}C and that the temperature requirement for cooling is about 15^{o}C, i.e., a temperature difference of 10^{o}C. The most favorable UTES applications are high-temperature storage with low-temperature applications, without heat pumps. The realization of the long-term goal of storing solar heat from the summer for space heating during the winter does not seem to be far away. The Anneberg project was the first Swedish solar energy-seasonal storage project that showed similar costs for both the solar system and the best conventional alternative.

2.2.4. Working Principle of UTES System

For the ATES system, a pair of well is usually pumped constantly in one direction or from one well to the other for heating and cooling. These two operation principles are called continuous regime and cyclic regime, respectively (Nielsen, 2003). The continuous regime is only feasible for plants where the load can be met with temperatures close to natural ground temperatures, and the storage part is more an enhanced recovery of natural ground temperatures. With a continuous flow, design and control of the system are much simpler and easier. Only one well or group of wells needs to be equipped with pumps. The limited temperature range is a shortcoming for this system, but the cyclic flow creates a definite cold and heat reservoir around each well or group of wells, making it possible to maintain a ground volume above or below the natural ground temperature all the time. The drawback is the need for a more complicated well design and control system, with each well being able to both produce and inject groundwater.

The BTES system has two functions heat extraction to warm the buildings and heat injection to cool the buildings. Thus, this system is considered as a heating system in the winter or a cooling system in the summer. In addition, the heat pump is installed to supply extra thermal energy in extremely cold areas where the geothermal energy is not sufficient for heating. Similarly, a cooling tower might be used in order to balance the heat injected into the ground and extracted from the ground (as shown in Figure 54). Typically, the system consists of a high efficiency screw water source heat pump with a new counter-flow gas-liquid heat exchanger and borehole heat exchanger. The schematic of a borehole heat exchanger with a polyethylene double U-pipe is shown in Figure 55.

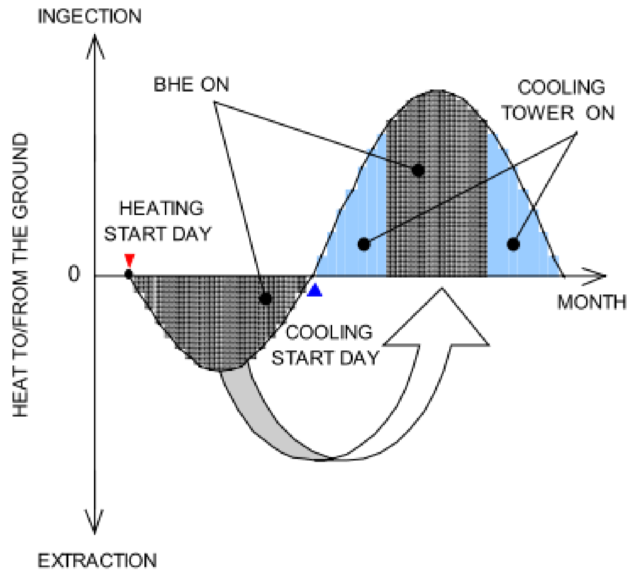


Figure 54 Annual heat balance (Lee, 2010)

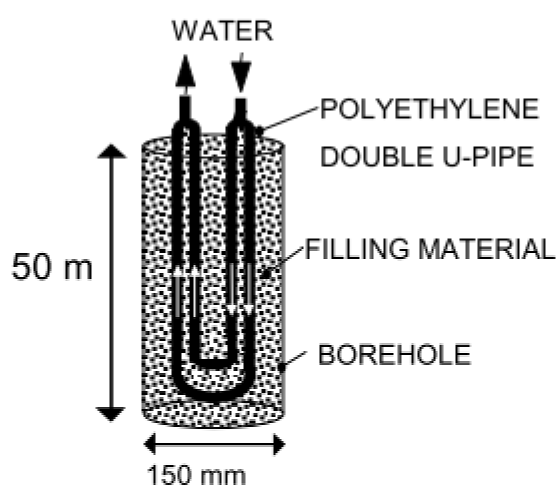


Figure 55 Schematic of borehole heat exchanger (Ohga, 2001)

The CTES system, which has the potential to save substantial operating costs, is most likely to be cost effective under some specific situations, such as when a facility's maximum cooling load much greater than the average load, the utility rate structure has higher demand charges for peak demand periods, or an existing cooling system is being expanded. Some CTES systems generate ice during off-peak hours and store it for use in daytime cooling. Until recently, decreasing electricity costs and an abundance of reliable cooling equipment had slowed the development of this technology, which has existed for more than half a century. However, the increase in maximum power demands, major changes in electric rate structures, and the emergence of utility-sponsored incentive programs have inspired a renewed interest in CTES.

2.2.5. Heat Storage Materials

Heat storage material is a key issue for underground thermal storage. Many different materials can be used for thermal storage, as shown by Table 8. The most common storage medium is water. The classical example of PCMs is the Glauber salt (sodium sulphate). Metal hydrides are well-known hydrogen stores in which hydrogen is absorbed into the metallic structure with the help of heat, or turning it around; adding hydrogen would release heat and removing hydrogen would absorb heat. In this way, metal hydrides also work as thermo-chemical heat storage.

Table 8 Examples of materials suitable for thermal storage (Ohga, 2001)

Sensible Heat	
Water, ground, rock, ceramics T=60^{o}C -400^{o}C	
Phase-Change	
Inorganic salts, inorganic and organic compounds; classical example:	
$Na_2SO_4 \times 10\ H_2O$ + heat (24^{o}C) – $Na_2SO_4 + 10H_2O$	
$CaCl_2 \times 6\ H_2O$ (30^{o}C)	
Paraffin (melting at 20^{o}C – 60^{o}C)	
Chemicals Reactions	
S × nG + heat – S × mG + (n-m) × G; G(g) – G(liqu)	
G=working fluid/gas	S=sorption material
Water	Hydroxides, hydrates
Ammonia	Ammoniates
Hydrogen	Metal hydrides
Carbon dioxide	Carbonates
Alcohols	Alcoholates

One of the most interesting physical parameters of thermal storage is its storage capacity and temperature range. These two parameters determine the size and suitability of the storage to an application. Table 9 gives a summary of the storage capacity and temperature range for some important potential storage materials.

Table 9 Storage capacity (Faninger, 1998)

Medium	Temperature[C-deg.]	Capacity[kWh/m^3]
Water	DT=50 ^oC	60
Rock		40
$Na_2SO_4 \times 10H_2O$	24	70
$CaCl_2 \times 6H_2O$	30	47
Paraffin	20–60	56
Lauric acid	46	50
Stearic acid	58	45
Pentaglycerine	81	59
Butyl stearate	19	39
Propyl palmiate	19	52
Silica gel N+H_2O	60–80	250
Zeolite 13 X+ H_2O	100–180	180
Zeolite + methanol	100	300
$CaCl_2$ + ammonia	100	1000
$M_eH_x + H_2$	50–400	200–1500
$Na_2S + H_2O$	50–100	500

Sensible heat energy storage has the advantage of being relatively cheap, but the energy density is low and there is a gliding discharging temperature. To overcome these disadvantages, PCMs can be used for thermal energy storage. The change of phase can be a melting or a vaporization process. Melting processes have energy densities in the order of 100 kWh/m^3 compared to 25 kWh/m^3 for sensible heat storage. Vaporization processes are combined with a sorption process. Energy has to be withdrawn at a low temperature when charging and be delivered at a high temperature when discharging the storage. Energy densities of around 300 kWh/m^3 can be achieved. As shown in Table 9, it is found that the storage capacity of water in a typical house-heating application is about 60 kWh/m^3. In comparison, the storage capacity of oil is about 10 MWh/m^3. PCMs based on hydrates or fatty acids have a phase change heat of the same order as the whole storage capacity of water. If the sensible heat of the PCM is added, then the storage capacity of the PCM would be doubled. Moreover, PCM can be incorporated into building materials and thus contribute to lower energy consumption and power demands by storing solar energy during the day and storing cold at night.

As the PCM has a sharp change in the storage capacity at a single temperature point i.e., phase change temperature, it can be used for temperature regulation. For example, mixing PCM into the building material could increase the thermal capacity of a wall manifold. A wall has typically an effective ΔT of around 10–15^oC, which gives a storage capacity of 10 kWh/m^3, which is about 1/5 of that of paraffin wax. Mixing two different PCM's in a suitable proportion makes it possible to match the phase-change temperature exactly with the temperature of the application.

Thermo-chemical storage materials have the highest storage capacity of all storage media. Some of the materials may even approach the storage density of biomass. Solid silica gel has a storage capacity which is almost four times that of water. However, water storage is the main commercially-available thermal storage system. Small PCM storage units have been sold mainly for special applications. Both PCM and thermo-chemical storage need further research and development efforts to be practical.

Storage is a critical component of systems, providing both space heating and hot water production. In order to achieve high efficiency and be a significant breakthrough, both at an acceptable cost and in a marketable volume, a suitable material for high-density thermal storage should achieve at least triple the storage capacity of water. Such a material has not been found yet. Fundamental related research is still needed to find a material which can meet those requirements.

Zizzo (2009) reviewed some commonly-used thermal storage materials and their thermal properties, as shown in Table 10. Water has the highest volumetric thermal capacity, while gravel-rich earth has the third highest value. Both of them are, therefore, excellent thermal storage media. Based on this data, it is concluded that the ideal storage medium is water alone, and although water is abundant and cheap, containing and storing large volumes in underground tanks is extremely expensive. Underground areas containing naturally-occurring water and gravel-rich earth, where large material volumes can be obtained for relatively low cost, are an ideal storage medium from both an economic and thermal efficiency perspective.

BTES systems make use of long boreholes from 20–400 m deep, dug into the ground. Each borehole contains a U-tube that links together with a central piping system at the surface. This technology can be applied to almost any ground condition, from clay to bedrock. Warm water, or a water-glycol mixture, is pumped through the U-tubes, travelling down, then back up each borehole. The heat is transferred from the heat carrier fluid to the ground by conduction. Over the course of a season, the borehole field is continuously heated. When the winter arrives, the flow is reversed, and heat is extracted from the field and delivered to the building or roadway.

Due to the significant cost associated with drilling multiple deep boreholes, BTES is the most expensive of the natural UTES options (Zizzo 2009). While double U-tubes are common in central Europe, most BTES systems today use single U-tubes. Systems in northern Europe are basically saturated with groundwater up to a few meters below the ground surface. In North America, it is common to fill the boreholes with a backfill material such as bentonite, concrete, quartz sand, or grouts that have been thermally enhanced. Table 11 provides thermal conductivity values for some common backfill materials. The heat transfer capacity of the system depends on the material properties of the tubes, grout, and surrounding soil, as well as the arrangement and flow characteristics of the field.

Table 10 Thermal properties of common UTES materials at 20°C (Zizzo, 2009)

Material	Density kg/m^3	Specific heat (J/kg K)	Volumetric thermal capacity (10^6 J/m^3 K)
Clay	1458	879	1.28
Brick	1800	837	1.51
Sandstone	2200	712	1.57
Wood	700	2390	1.67
Concrete	2000	880	1.76
Glass	2710	837	2.27
Aluminum	2710	896	2.43
Iron	7900	452	3.57
Steel	7840	465	3.68
Gravel-rich earth	2050	1840	3.77
Magnetite	5177	752	3.89
Water	988	4182	4.17

Table 11 Thermal conductivity of common borehole backfill materials

(Nordell and Hellstrom, 2000)

Backfill Material	Thermal Conductivity, W $m^{-1}K^{-1}$
Stagnant water	0.6
Bentonite	0.8–1.0
Thermal enhanced grouts with quartz	1.0–1.5
Water-saturated quartz sand	1.5–2.0
Ice	2.3

Hasnain (1998) reviewed heat storage materials for sustainable thermal energy storage technologies. Conventionally, the heat is stored in the form of sensible heat (typically by raising the temperature of water, rocks, etc.) for future use. Water is the most widely used storage medium in most of the applications. Latent heat storage is a new and developing technology that is of considerable interest because of the advantages of smaller temperature fluctuations, smaller size, and low weight per unit of storage capacity. Table 12 shows the comparison of various heat storage materials (Hasnain, 1998).

Table 12 Comparison of various heat storage media (stored energy =106 kJ=300 kWh; ΔT=15 K)

(Hasnain 1998)

Property	Heat Storage Material			
	Sensible Heat Storage		Phase Change Materials	
	Rock	Water	Organic	Inorganic
Latent heat of fusion (kJ/kg)	*	*	190	230
Specific heat (kJ/kg)	1.0	4.2	2.0	2.0
Density (kg/m^3)	2240	1000	800	1600
Storage mass for storing 10^6 kJ (kg)	67000	16000	5300	4350
Relative mass	15	4	1.25	1.0
Storage volume for storing 10^6 kJ (m^3)	30	16	6.6	2.7
Relative volume	11	6	2.5	1.0

2.2.6. Case Studies

This section will review some successful applications of UTES systems including ATES, BTES, and CTES. Basically, applications of ATES in large-scale projects started in the 1980s, when 492 cold storage wells supplied cold thermal energy to the industries to cool down their machines. Their use has recently begun to wane, however. The first large-scale application of BTES was in Sweden. The system had 120 holes that were 60 m deep each. It was used to store warm thermal energy at about 70^{o}C to warm the local university. At the moment, the largest BTES is in Fort Polk, Louisiana. There are 8,000 holes, which supply both cold and warm thermal energy to the residents. BTES are also used to deice frozen roads in Japan, Switzerland, and the United States.

In the U.S., the University of Texas at Austin added more than 2 million square feet for a thermal energy facility in 2013. Obviously, the larger area created a need for additional utility infrastructure to serve the new space. To meet these needs, UT Austin's Utilities and Energy Management Department took on the large project and constructed a thermal energy storage facility (Figure 56).

The facility allows the university to add cooling capacity at about a third of the cost of another chilling station. This facility consists of an insulated four-million-gallon water tank that stores chilled water produced at night, when the demand for cooling is less.

Figure 56 Thermal energy facility at UT Austin

New 42-inch diameter pipes installed between this tank and the central part of the campus, using trench-less technology called micro tunneling. Two 52-inch diameter tunnels measuring 1,500 feet in length were bored 40 feet below ground. The 42-inch steel pipes were slipped inside the tunnels. The boring route actually goes under the nearby Waller Creek and carefully avoids existing building foundations, as shown in Figure 57.

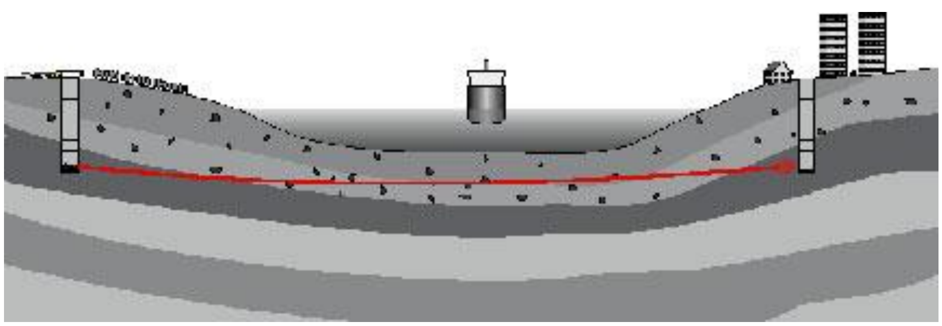


Figure 57 Graphical representation of the thermal energy facility

The advantages of this thermal energy facility allow the university to avoid the construction of another chilling station, and thus avoid the use of refrigerant, a source of environment hazard. Moreover, it is more efficient than a new chilling station because pumps move the cold water produced by the existing chilling stations, eliminating the need to power large chillers. It creates a new cost-effective and innovative supply and energy pathway to meet the needs of the campus and reduces greenhouse gases.

In Turkey, a system was designed using solar energy in combination with ATES that will conserve a major part of the oil and electricity used for heating or cooling the Cukurova University's Balcali Hospital in Adana. The general objective of the system is to provide heating and cooling to the hospital by storing solar heat underground in the summer and cold in the winter. Ventilation air in the hospital and surface water from the nearby Seyhan Lake is used as the main source of cold energy, (Hasnain, 1998). A supermarket, Yonca, was constructed in Mersin, Turkey, using the ATES system (Figure 58). The system has two wells with a depth of 330 ft. (100 m) and distance of 266 ft. (81 m); the type of aquifer is sandstone; the flow rate is 64 gallon/minute (14.4 m^3/h); and the cooling load is 2401.5 kWh/day.

Figure 58 Yonca Supermarket at Mersin (Paksoy et al., 2000)

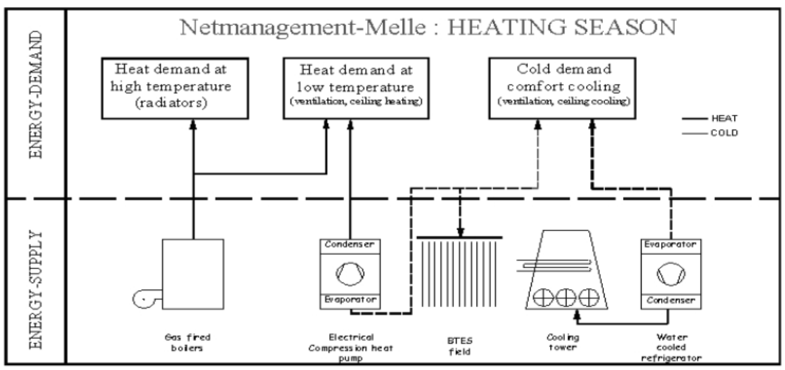
Two UTES concepts, ATES and BTES, are commercially available in Belgium. The geological structure in Belgium is characterized by a tabular area with a large number of accumulated sand layers separated by clay layers. This accumulation of layers leads to many different aquifers, each with its own characteristics. The capacity of the aquifers varies from 25 to 100 m^3/h. Table 13 presents updated statistics of the ATES plants in Flanders, Belgium.

The BTES application is another alternative technology for some other regions where ATES cannot be applied. Flemish Institute for Technological Research conducted several feasibility studies, in the health and commercial building sector, on GSHPs in combination with vertical borehole heat changers (Desmedt et al. 2006). BTES applications are proven technology that work without leaking or collapsing, and are most suitable for seasonal thermal energy storage, such as solar heat, heat from cogeneration units, etc. It can also be used for direct cooling in summer, without the need for a chiller that consumes a lot of electricity. Figures 59 and 60 depict the schematic view of BTES in the winter and summer periods, respectively.

Table 13 Updated statistics of ATES plants in Belgium at the end of 2005

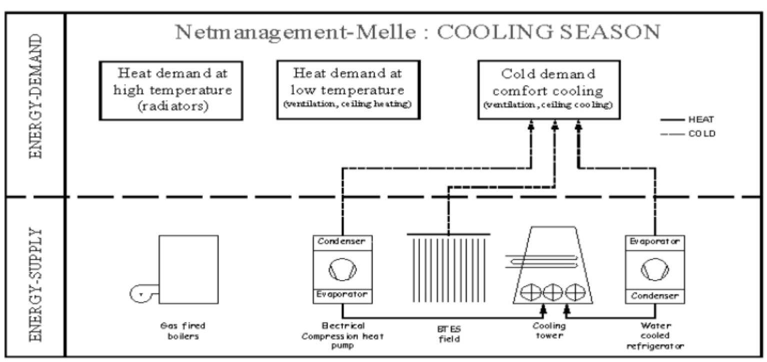
(Desmedt et al., 2006)

Location	Year operation	Building	Capacity kWt	Flow rate m^3/h	Number of wells	Distance wells (m)	Depth (m)
Leuven	1998	Bank	1,000	50	2W, 2C	150	65
Brasschaat	2002	Hospital	1,000	100	1W, 1C	100	65
Malle	2002	Office	600	90	1W, 1C	85	67
Turnhout	2002	Office	600	66	1W, 1C	110	100
Geel	2003	Office	500	50	1W, 1C	100	75
Geel	2002	Hospital	1,050	100	1W, 1C	100	100
Meer	2005	Greenhouse	800	80	1W, 1C	200	140
Mol	2001	Laser	600	80	1W, 1C	90	92
Turnhout	2003	Hospital	690	74	1W, 1C	175	100
Overpelt	2005	Hospital	1,500	185	2W, 2C	110	80



(Desmedt et al., 2006)

Figure 59 Schematic view of a common BTES application in winter period



(Desmedt et al., 2006)

Figure 60 Schematic view of a common BTES application in summer period

China has GSHP systems installed, but research on UTES or BTES are still limited, as compared to Europe, U.S., and Japan. A few reported studies include Tianjin University (Desmedt et al., 2006), Shandong Institute of architecture & Engineering, Tongji University (Yu et al., 2004), Chongqing University (Zhou and Chen, 2001), Harbin Institute of Technology (Cheng et al., 2005), Jilin University (Yu and Ma, 2005), etc.

Wong et al. (2006) indicated that Canada receives a significant amount of solar radiation compared to other International Energy Agency (IEA) nations. Due to geographic and climatic conditions, however, it is more sufficient in the summer than in the winter.

Four ATES systems were installed in Canada as early as in the mid-1980s. These projects included the Scarborough Canada Centre in 1986, which employed the application of ATES to cooling office buildings. The main challenge encountered was balancing the loads for cooling and heating. More recently, the BTES system was installed, with 384 boreholes, at the University of Ontario Institute of Technology.

In addition, there is a solar BTES residential development located in the Drake Landing community, as shown in Figure 61. The overview of the project is shown in Figure 62. The cost of the ATES system is relatively lower than the BTES system. The City of Medicine Hat in Canada is situated above a long-documented body of aquifer known as the Buried Valley Aquifer, and a commercial building in the city had been identified as a potential building for ATES implementation. The schematic of the ATES system beneath the building is shown in Figure 63.

Figure 61 Computer-generated image showing the solar BTES sub-division (2006)

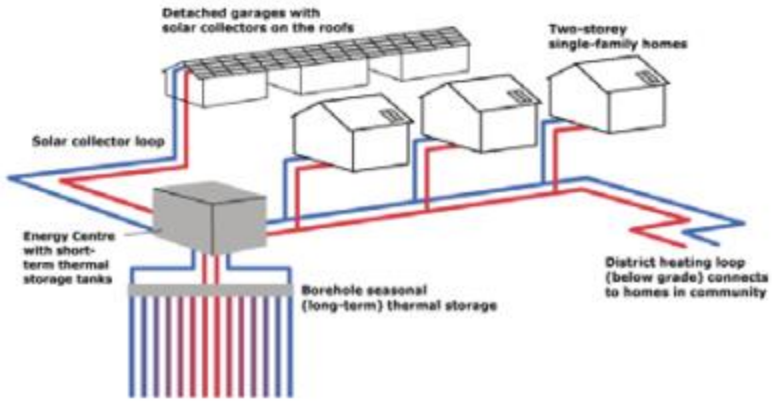


Figure 62 Overview of BTES in Drake Landing community (Wong, 2006)

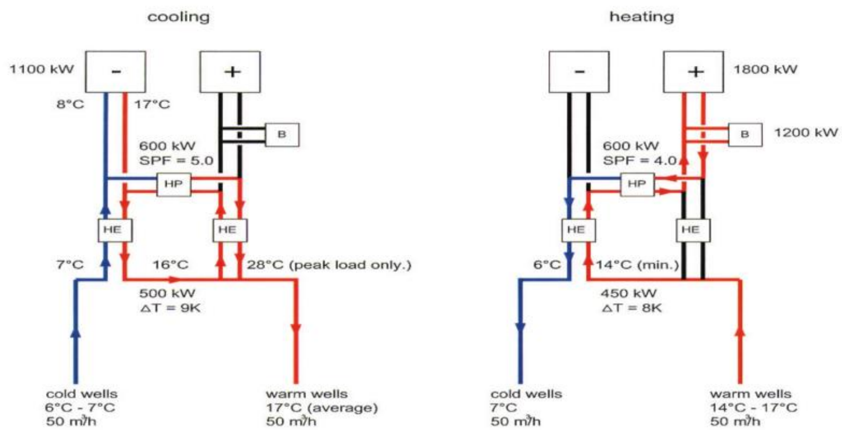


Figure 63 Schematic of ATES system (Wong, 2006)

In Germany, storage of solar or waste heat in the summer is used for heating in the winter. Major plants in Germany are in Neckarsulm, where a BTES system is charged with heat from solar collectors and heats a housing district; and in Berlin, where waste heat from heat-and-power co-generation in summer is stored in an ATES system for heating in winter, as shown in Figure 64 (Wong, 2006). The Berlin plant supplies heat and cold to the German parliament buildings, the first time that two ATES systems at different levels were incorporated. The upper level is used for cold storage, and the lower for heat storage (up to 70^{o}C). All the excess heat from power generation is stored in the lower ATES system, and a big part of the cooling is provided from the upper ATES. The two aquifers are in different geological layers, at different depths. In the Quarternary sands in California, an aquifer, at a 60 m depth, is used for storage of cold to cover summer cooling loads, and two sets of five wells each access that aquifer. At another aquifer in Lower Jurassic, sediments about 320 m deep serve as storage of excess heat from CHP in the summertime to assist heating during the winter. Only two wells are required, and temperatures may reach up to 70°C (Sanner, 2001).

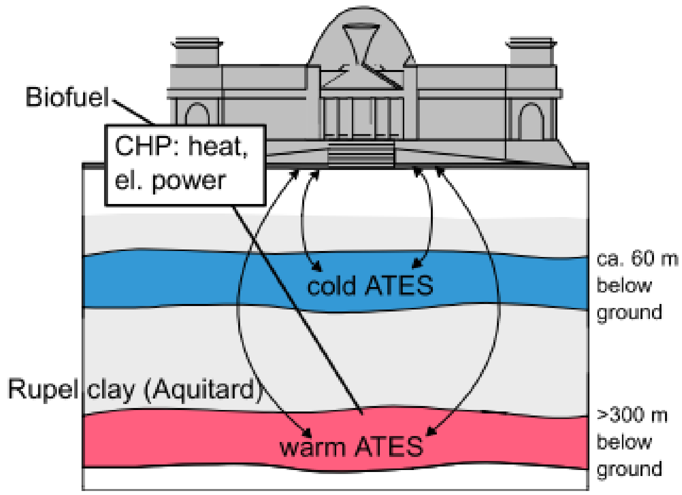


Figure 64 Schematic of Berlin Reichstagsgebaude ATES system (not to scale) (Sanner et al., 2005)

Bonte et al. (2011) presented an overview of the risks that UTES can impose on groundwater systems, drinking water production, and the subsurface environment in general. The map showing the locations of ATES systems and groundwater protection zones for public supply well fields in the province of Noord-Brabant is presented in Figure 65.

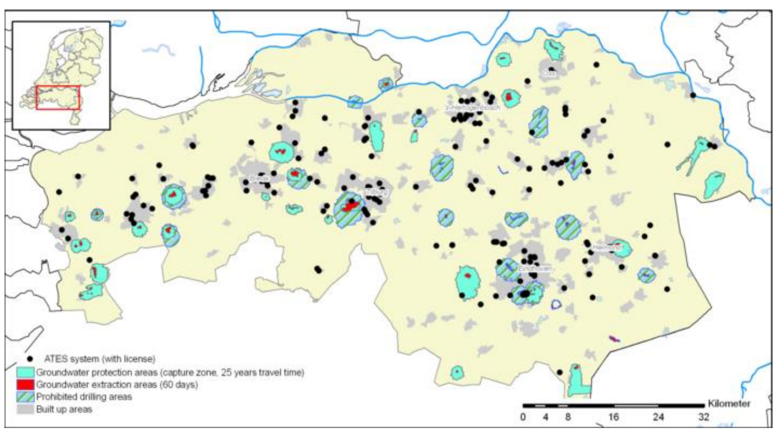


Figure 65 Map showing the locations of ATES systems and groundwater protection zones for public supply well fields in the province of Noord-Brabant, in the Netherlands (Bonte et al. 2011)

An office building located in the southwest part of the Netherlands, which has a two-well ATES system, has been operational for 5 years. The site plan of the building is shown in Figure 66. The building is fronted with a three-story office block, with some manufacturing capability in a warehouse to the rear of the building. The total treated floor area is 4800 m^2, and the entire heating and cooling load is provided by the ATES system. A cold well is located in the southwest part of the site, and a warm well in the northeast, at a distance of 119 m away from the cold well, as shown in Figure 66. The schematic of the ATES system is shown in Figure 67. In the cold season, the water is extracted from the warm well at around 14ºC and discharged to the cold well by the heat exchanger at around 6ºC. Conversely, in the hot season, the groundwater is abstracted from the cold well at approximately 7–9ºC and discharged to the warm well at around 13–14ºC.

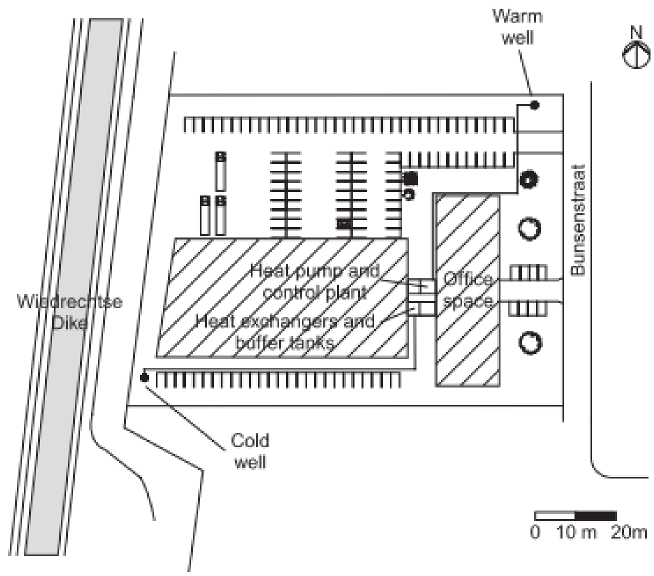


Figure 66 Site plan (Bonte et al., 2011)

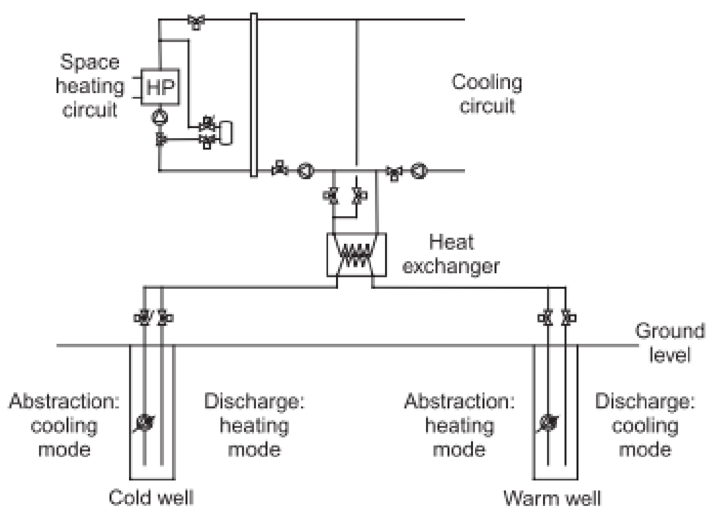


Figure 67 Schematic of ATES system (Dickinson et al., 2009)

Andersson et al. (2013) presented an overview of the UTES systems applied in Sweden together with statistics on efficiency and market development. The principle of ATES is shown in Figure 68. Typically, the temperature is often 12 to 16ºC on the warm side of the aquifer, and 4 to 8ºC on the cold side. The system can cover the total cooling load, but in some applications the heat pumps are used for peak heating. In the design of such system, the thermal balance between the warm side and cold side has to be considered through numerical simulation based on site investigation.

The principle of BTES is illustrated in Figure 69. The system can be regarded as huge tube heat exchangers, where a large number of densely-spaced boreholes represent the tubes. Geothermal energy is exchanged with the mass of soils and rock by circulating the heat carried fluid through the boreholes. Swedish BTES boreholes usually have a dimension of 115–140 mm and are commonly 150 to 200 m deep. The borehole heat exchanger is primarily single or double U-pipes, and tubes are filled with a fluid consisting of water and bio-ethanol.

Figure 68 The principle of ATES, an open loop concept, where heat and cold are seasonally stored in an aquifer (2013)

(Andersson et al., 2013)

Figure 69 The principle of BTES, a closed loop concept, where heat and cold are seasonally stored in a solid rock mass through a large number of densely-spaced boreholes

The CTES system has the advantage of very high injection and extraction powers, but the disadvantage is the high construction cost. There are some examples of how old rock caverns, previously used for oil storage, have been converted for high temperature water storage. The first large-scale high-temperature CTES was constructed in 1983 in Uppsala, Sweden, as shown in Figure 70. The storage volume of 115,000 m^3 had maximum water temperature of 90ºC, and 5500 MWh of heat was stored between the seasons. This storage, which was connected to the district heating net of Uppsala, was used for both short term and seasonal storage of heat. It was partially heated by solar collectors and used to meet the power peaks in the mornings and evenings (Andersson et al., 2013).

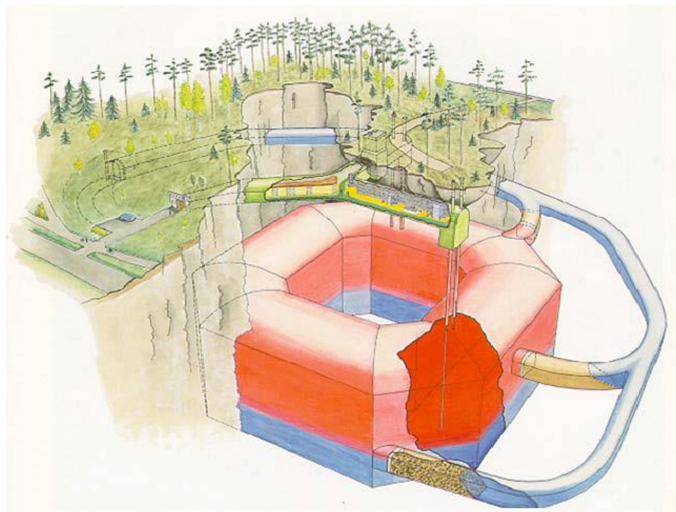


Figure 70 Uppsala rock cavern heat storage (CTES) (Nordell et al., 2007)

In Japan, there are hundreds of snow-cooling systems in the north, with several different types, most of which are for cooling root vegetables, fruits, and vegetables. There are also some applications of snow/ice storage rooms built close to residential buildings that are cooled during the summer season (Nordell et al., 2007). Other examples are of recently-built, large-scale snow cooling systems that are used for cooling commercial buildings. The large snow storage plant in Sundsvall utilizes 75,000 m^3 of snow in supplying cooling for the Sundsvall regional hospital from May to September. Both of these plants are working very well and deliver cold considerably cheaper than a conventional cooling system (Nordell, 2012; Skogsberg, 2005; Yukie and Masayoshi, 2009). In addition, there is another successful application of snow storage which began operating in 2010 at the New Chitose Airport in Sapporo, Japan, as shown in Figure 71. This system, which was inspired by the Sundsvall snow storage, was made for 120,000 to 240,000 m^3 of snow, corresponding to 5 to 10 GWh of cold.

Figure 71 Snow storage (L: 200 m, W: 100 m, D: 2 m) is filled up and covered with thermal insulation at the New Chitose Airport in Japan

Approximately 100 snow storage systems in buildings are in operation in Japan (Nordell et al., 2007). In Sweden, one pit storage has been in operation since 2000 for cooling the Sundsvall regional hospital from May to September. This snow storage contains 40,000 m^3 of snow and covers about 2000 MWh of cooling with cooling peaks of 2000 kW. Figure 72 shows trucks unloading snow at the Sundsvall snow storage. The very successful storage system delivers cooling at considerably lower cost than conventional cooling systems, several new plants are presently planned. The best method for snow storage would be to use snow caverns.

Figure 72 Trucks unloading snow at the Sundsvall snow storage, in Sweden (Skogsberg, 2005)

Another successful snow storage case is located at Bibai City, Hokkaido, Japan, which is located near the center of Hokkaido. They have as much as 8 to 11 m of snow during a winter, and the area has been specified by Japan as a “special heavy snow zone.” The locals intended to utilize the snow resources by store it and use it in the summer. For this purpose, they established the “Bibai Natural Energy Society” as an industrial-government-academic complex in 1997.

The first snow air-conditioned apartment house attempted in the world (Figures 73 and 74) was built by the technology of the Bibai Natural Energy Society. The operation of this apartment house demonstrated that snow air-conditioning is easy and not prohibitively expensive. There are currently ten facilities using snow that have been built by the citizens in Bibai an office, a nursing facility, a hot spring facility, and storage houses for vegetables and rice (Nordell et al., 2007).

Figure 73 Snow air-conditioning apartment house (Yukie and Masayoshi, 2009)

Figure 74 Throwing snow into a storage room (Yukie and Masayoshi, 2009)

A tank thermal energy storage is built of steel or reinforced and pre-stressed concrete and, as a rule, is partially built into the ground and is filled with water. The first pilot storages have been in operation in Hamburg and Friedrichshafen since 1996. These storages were built as reinforced and pre-stressed concrete tanks. They are heat insulated only on the roof and at the side walls and are lined with 1.2 mm stainless steel sheets. The cost analysis of these two storages shows that the stainless steel liners are quite expensive (Yukie and Masayoshi, 2009).

The storage in Munich goes one step further in cost and energy efficiency, as shown in Figure 75. The following is a short sequence of the construction of the storage. The frustum at the bottom was built on-site, while the side walls and the roof were built of prefabricated concrete elements that had a stainless-steel liner at the inner surface. The wall elements were pre-stressed by steel cables after their installation, and the stainless-steel plates were welded together to ensure water-vapor -tightness. The storage is heat insulated at the side walls and on the top by expanded glass granules, with a minimum thickness of 30 cm at the bottom and a maximum thickness of 70 cm on top of the storage. A vertical drainage protects the insulation from moisture. The bottom of the storage is heat insulated by a 20 cm layer of foam glass gravel because of its higher stability against static pressure. The storage is equipped with a stratification device to enhance temperature stratification and thereby the usability of the accumulated heat. The specific investment cost of this storage construction is significantly lower than those of the tank storages in the Friedrichshafen, Hamburg and Hannover projects, even though it has an improved heat insulation and a stratification device. The cost reduction can be attributed mainly to material savings in the concrete construction and the cost-effective mounting on-site by using prefabricated elements.

(Mangold and Schmidt, 2007)

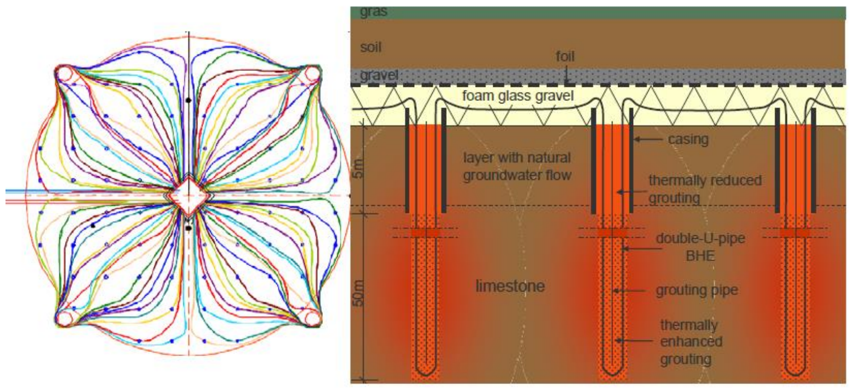
Figure 75 Construction of the tank thermal energy storage in Munich, 2006

Another interesting case study deals with pit thermal energy storage (PTES). The usually naturally-tilted walls of a pit are heat insulated and lined with a watertight plastic foil. The storage is filled with water, and a heat insulated roof closes the pit. The roof can be floating on the water like those in Denmark, or built like a self-support structure, as a rugged roof. The design of the heat insulation system of the bottom, the walls, and the roof; possible materials for the watertight plastic foils; and construction technologies for the roof were investigated in a separate research project at the University of Stuttgart, Germany. Due to the fact that the construction of the roof is difficult and might be quite costly, the first storages were filled with a gravel-water mixture. Heat was fed into and out of the storage by direct water exchange, or indirectly via plastic pipes. Based on the satisfactory results of the first 1,000 m³ pilot plant, which was built at ITW of Stuttgart University in 1984, the storage concept was applied for the construction of an 8,000 m^3 demonstration plant in the Solaris project in Chemnitz, Germany. The storage was completed in 1996; however, the heating plant was not ready for operation until 540 m^2 of solar collectors (vacuum tubes) were installed in 1999. Another 1,500 m^3 of storage was constructed with a modified concept for the solar-assisted district heating system of a new housing project in Steinfurt Borghorst. The storage was tightened with a doubled plastic liner. The space between the two layers was evacuated to allow permanent control of the water-tightness during construction and operation. As heat insulation material expanded, glass granules were used for seasonal storages for the first time. The most recent pit storage was built in Eggenstein in 2007, as shown in Figure 76.

(Mangold and Schmidt, 2007)

Figure 76 Construction of the pit energy storage in Eggenstein, 2007

In the ducts in the soils thermal storage system, the heat is directly stored in the soil. U-pipes, called ducts, are inserted into vertical boreholes to build a large heat exchanger. While water is running in the U-pipes, heat is fed into or out of the ground. The upper surface of the storage is heat insulated. A pilot BTES facility has been in operation in Neckarsulm, Germany since 1997. The feasibility of this storage concept was proven with the installation of a 5,000 m^3 research storage at the site of the plant. The ducts were double-U-pipes made of polybutene, placed at a depth of 30 m. The design data of the model calculations were validated by the experimental results of the monitoring program. In 1999, the storage was enlarged to a storage volume of 20,000 m^3. The next phase of the solar-assisted district heating project began in 2002, when the borehole storage was enlarged to 63,300 m^3, reaching half of the planned volume. A next-generation BTES was built in Crailsheim, Germany in 2008. In the first construction stage, the storage consists of 80 boreholes, with a depth of 55 m. The storage volume (37,500 m^3) is in a cylinder, with the boreholes situated in a 3 x 3 m square pattern (shown in Figure 77). The ground heat exchangers were double-U-pipes made from cross-linked polyethylene (PEX). The storage volume will be doubled when the second part of the connected residential area will be built. The hydro-geological investigation showed an intermittent water movement in the upper part (5 m) of the storage volume. For this reason, the boreholes were drilled with a bigger diameter in this part. After the installation of the ground heat exchangers, the lower part was filled with a thermally-enhanced grouting material (thermal conductivity=2.0 W/m·K), and the upper part was filled with a thermally-reduced grouting material to reduce the heat transfer into this layer as well as the thermal losses due to the water movement in this region. The horizontal piping on top of the storage was embedded into an insulation layer of foam glass gravel, protective foil, and drainage layer were installed below a 2 m layer of soil, on top of the insulation area.



(Mangold and Schmidt, 2007)

Figure 77 Top view with horizontal piping (left) and vertical cross-section (right) of BTES in Crailsheim, 2008

2.2.7. Cost Analysis

Basically, the UTES system is more cost effective when storing energy from one time to another, than it is to produce it later when needed. This implies that the storage energy is cheaper when injected than the value of energy when it is recovered. The price difference must be big enough to cover the cost of investment, maintenance, operation, and energy losses because there are many other economically feasible storage applications (Mangold and Schmidt, 2007).

Investment costs for an UTES system depends on several characteristics. Storage volume is a major aspect that affects the total investment cost. An optimal volume for inter-seasonal UTES systems varies between 2,000 and 20,000 m^3. Within this range, the investment costs are estimated to be between \$45 and \$280 for each cubic meter. Beside the costs related to the storage volume, the thermal performance of the storage itself and the connected network are equally important when considering the economics of a UTES system. Consequently, each system has to be examined separately. To determine the economy of storage, the investment, maintenance, and operational costs of the storage have to be related to its thermal performance. Considering the above, the costs involved with implementing ATES and BTES systems are lower than a tank thermal energy storage or PTES system; however, ATES and BTES systems often require supplementary equipment for operation, like buffer storages or water treatment. Furthermore, many countries have stringent requirements concerning local ground conditions that might increase the costs of ATES systems.

Nordell studied the cost of the largest economic burden of UTES systems occurring at the time of installation (Nordell, 2000). Building these systems, with the required ground condition studies and drilling, accounts for the vast majority of the costs. Since these studies must be undertaken regardless of the size of the system, it has been found that larger systems are more economical since a greater output is achieved for marginally increased capital expenditures. Figure 78 illustrates that as system size increases, the investment output per unit decreases.

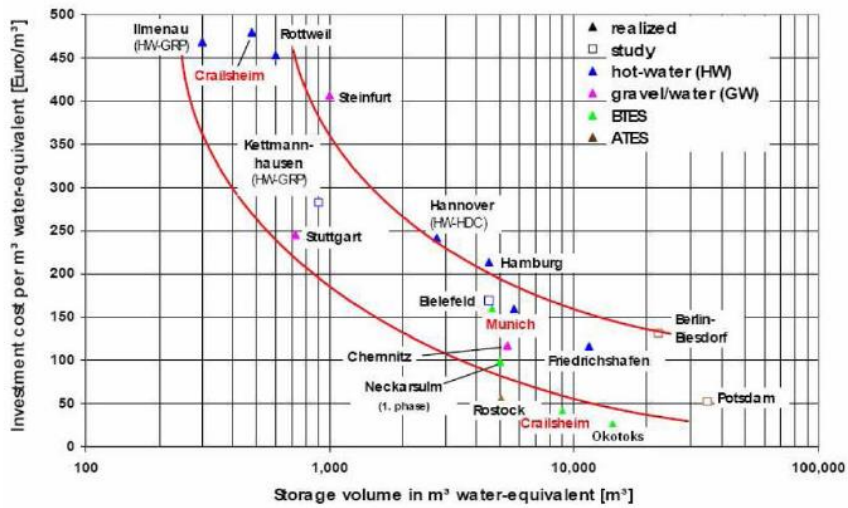


Figure 78 Decreasing marginal cost of UTES systems (Zizzo 2009)

Nordell and Hellström (2000) performed a detailed energy simulation for a solar-heated BTES system. The system was designed to serve 90 building units of 100 m^2, each using a 3,000 m^{2}roof-mounted solar collection system and a 99-borehole BTES system of 65 m depth for a storage volume of 60,000 m^3. It was estimated that 60% of total heat demand would be met by the system. The construction cost, including heat exchanger installations in buildings (which can range from $1,000 to $10,000), and annual operation expenses were then compared with two conventional alternate systems: a small-scale, biomass pellet and oil district energy (DE) system, and a GSHP system. A summary of findings can be seen in Table 14, showing that the DE system has the lowest construction cost, but also the highest annual cost. The solar-heated BTES has the highest initial cost, but has an annual cost only 8% higher than the least expensive annual option of GSHP. Annual DE costs are 20% above GSHP. This illustrates that although UTES systems do cost more than some alternatives, they provide long-term stability of energy pricing and should be considered for future projects.

Table 14 Solar-heated BTES cost comparison with alternate systems (Zizzo 2009))

System	Construction costs (millions $ CAD)	Annual costs (millions $ CAD)
Solar-heated BTES	1.377	0.161
Small-scale district heating	0.878	0.179
GSHP for each building	0.945	0.149

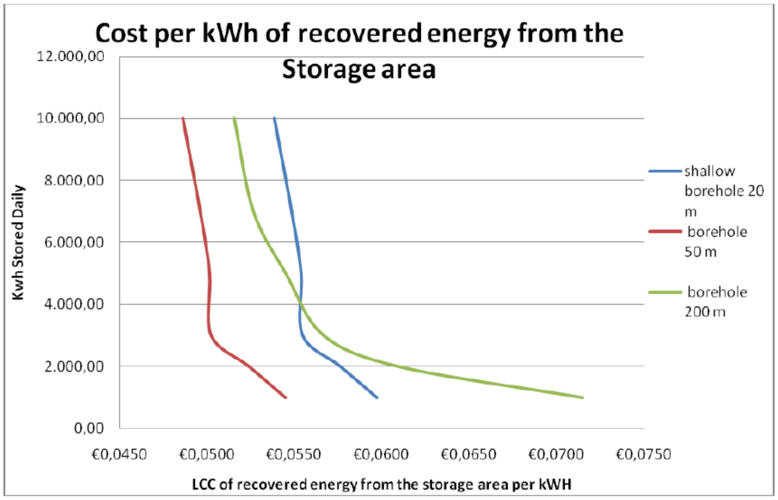
Note: Prices exclude sales tax; based on conversion of 1 SEK=0.15 CAD (April, 2009)

Gaine and Duffy (2010) conducted life-cycle cost analyses of a project which was used to determine whether future operational savings justify the initial capital costs. The capital and operating costs of a number of different BTES systems were estimated for a large-scale mixed development. Cash flows were estimated, and net present values were determined. Cost data was gathered from Irish boring and groundwork contractors for the installation.

Capital costs are incurred at the initial stages of the project. They are the highest and biggest barrier to almost any small-scale energy-efficient system. For a BTES, the capital costs include some of the following: site investigation and testing, design, site preparation and set up, drilling pipe work installation, backfilling the borehole, connecting the header and piping to the energy supply center, and commissioning. These add up to the capital costs associated with the BTES system. Industry quotations, rates, and estimates were obtained and were applied to each system analyzed. Piping from the borehole headers to the energy center was accounted for based on an average pipe length of 75 meters.

Running costs are associated with the day-to-day operation of the plant. For the BTES system, electrical energy is needed for pumping power to deliver and recover energy from the storage area. The pumping power required was calculated by obtaining the total equivalent length of pipe and calculating the pressure drops in each system. An average industrial tariff for electricity of €0.12 per kWh in Ireland was used to calculate the total running costs for the pumps. The fixed costs for maintaining the system include repairs, cleaning, and controls. The controls of these systems are the highest cost associated with maintenance as they can vary on a daily basis.

Figure 79 depicts three different cost curves (€/kWh of stored energy) recovered from the storage area. It shows that for low quantities of energy stored, deep borehole systems are considerably more expensive than shallow systems. This is due to the thermal performance. The system is not able to reach the needed ground temperature, resulting in additional heating costs. However, above 4,000 kWh, 200 m becomes preferable to the shallow system. Due to economies of scale, the capital costs are a higher percentage of the life-cycle cost analyses for smaller size systems. As Figure 79 demonstrates, as the curve increases in cost, the quantity of energy stored decreases.

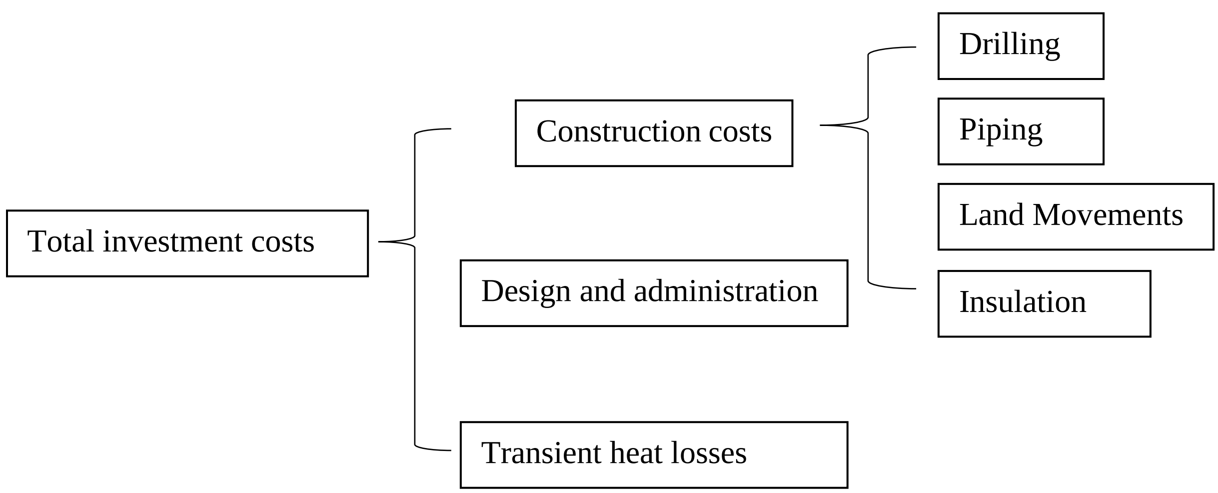


(Gaine and Duffy 2010)

Figure 79 LCC of 20-year period per kWh of recovered energy from the storage area

Economics is the decisive factor that sets one project ahead of others (Gaine and Duffy 2010), and the annuity factor method is used to decide which of the different BTES models is optimal. The calculation includes the different costs, divided into groups. Some of the groups are greatly dependent on the storage parameters such as depth, volume, and spacing, while others are common to all of the models. Moreover, some costs are estimated as a percentage of the construction costs. Table 15 presents the total investment cost summary, and equations show how the costs were calculated.

Table 15 Total investment cost summary (Manonelles, 2014)



$$C_{cons} = C_{drill} + C_{pipe} + C_{land} + C_{insu} + C_{indoor}$$

$$C_{Tot\,inv} = C_{cons} + C_{design} + HL_{transient}$$

Where C means costs and the subscripts mean cost group. For example, C_{cons} means cost of construction.

The annuity method is a reliable means of comparing the economic viability of various investment options. The annuity factor is calculated over the mortgage time (in years) at the given capital interest rate. It assumes an interest rate of 5% and a mortgage time of ten years, which means the total investment cost of the storage, considering the interest rate, will be paid off in 10 years. Using the annuity factor, the annual storage cost is calculated, which is used to choose the optimum storage.

The cost of annual storage represents the amount of money, including the interest rate, that it costs each year to pay off the investment cost. Energy or heat loss is a significant factor, depending on the energy price, but although it has to be considered, it is not a constant value. Heat loss is higher at the beginning, when the surroundings are warming up and after a few years becomes an almost constant value.

Therefore, a criterion to differentiate the costs in transient heat losses and steady-state heat losses is assumed. The heat loss in the tenth year is considered as the steady-state, and all the losses higher than this value during the previous years are considered transient losses. In this way, the costs for the transient heat losses are included as an investment cost, while the steady-state losses are included in the annual costs.

The single most important cost in BTES construction is the cost of drilling and piping. For that reason, the drilling costs are detailed below as a function of the storage model parameters. The price to drill the soil layer is at least twice the price of drilling rock, and it highlights the importance of choosing a location with a thinner soil layer. It is more expensive to drill in soil because of the different header used, which moves rotationally. The soil drilling includes the casing, which is a pipe that covers the area around the borehole to prevent particles from falling into it. A fracturing system is used in bedrock. For example, in a large-scale BTES with 200 boreholes, each meter of soil layer reduced represents savings of 44,000 SEK. It is remarkable that the price of drilling deeper than 200 meters is just 5% higher, which means that for the same storage volume, it’s more advantageous to drill deeper boreholes than it is to increase the number of them.

The largest cost in a BTES, after drilling, is the piping. It includes the cost of the entire network: the connecting pipes between boreholes, the collector pipes for injection and extraction, and the culvert which connects with the energy operation center. The prices obtained from the drilling company include the borehole U-pipes found in the Manonelles’ 2014 study. In order to calculate the piping cost for the different models, the pipes’ lengths have been assumed based on the number of boreholes, the spacing between them, and a distance of 50 m from the storage to the heat exchanger. This latter distance is used as a culvert length and is a fixed cost for all of the storage models.

In Table 15, the cost of acquiring land is not counted as no purchase was required. But the cost to prepare the land to build the storage was counted. The indoor costs include all of the operation control systems, measurement devices, heat exchangers, valves, frequency converters, pumps, and accessories. In addition, the design and administration costs include the tests, calculations, and drawings of the BTES, normally made by a consultancy office, and the legal procedures to carry out the project. During the BTES operation, there are constant costs for the maintenance and work processes. These costs include the electricity for the pumps and other electronic devices, employees, and continual maintenance for the proper operation.

2.2.8. Summary

This section mainly reviewed the current status and development UTES systems from the aspects of the type of system, working principles, and heat storage material. Three types of UTES systems, including ATES, BTES, and CTES, were introduced. Ducts in soils and pit storage were briefly described as well. An overview of various successful applications of UTES systems from all around the world were presented, followed by a brief discussion of the cost of implementing this system. It was demonstrated that the UTES system has a great potential for utilizing natural energy (e.g., solar radiation, geothermal energy, etc.) efficiently through balancing the energy supply and demand and partially replacing the traditional energy sources such as fossil fuels and natural gas.

Chapter 3. FINITE ELEMENT ANALYSIS OF BRIDGE DECK DEICING

3.1. Introduction

Bridges are an important part of the highway infrastructure and are critical to a nation's economy and security. Deterioration of the aging bridge infrastructure is a major concern that presents significant economic and engineering challenges. There are about 600,000 bridges in the United States, of which about 60% were built either with traditional reinforced concrete or prestressed concrete (FHWA 2008). The same report classifies a quarter of the bridges in the U.S., including their substructures, as structurally deficient or functionally obsolete (Bowers and Olgun, 2014).

The icing of bridge decks in winter is a major problem which creates dangerous driving conditions for motorists. Several current deicing methods for bridge decks are either energy intensive, corrosive to the bridge, or dangerous to the environment. For example, salts and other chemicals commonly used to deice concrete bridge decks leads to accelerated corrosion of the bridge structure, threatening its structural integrity and impacting the long-term life of the bridge due to increased maintenance and repair costs. One major factor that leads to accelerated deterioration of bridge infrastructure is the attack of chloride from the deicing salts.

Ground-source heating has been used recently to deice bridge decks and pavement slabs, and results in a significant reduction in the use of salts and chemicals. The constant temperature of the ground and its thermal storage capacity can be utilized as a renewable heat source that can be exploited for heating bridge decks in winter. Technology can also potentially drastically reduce the need for chemical deicing agents and can be used to decrease the temperature of the bridge deck during concrete curing and help minimize early age cracking. Similarly, the temperature of bridge decks can be regulated to reduce the severity of the heating/cooling cycles between day and night in summer.

This report presents the results of a series of numerical analyses performed in COMSOL Multiphysics to investigate the effect of geothermal heating system-related parameters on heated bridge decks. These parameters include tube spacing, concrete-cover thickness, fluid flow rate, and some environmental factors such as inlet fluid temperature, ambient temperature, and wind speed. The results are presented and discussed to serve as a benchmark to gauge the operational conditions and the energy requirements for designing a ground-source bridge deck deicing system.

3.2. Research Background

Several numerical studies have considered both the transient and two-dimensional components of a hydronic heating system. Rees et al. (2002) developed a two-dimensional numerical model, accounting for the transient effect of the snow melting process on the performance of a pavement snow-melting system. They modeled a cross section of the slab that included one-half of the heating elements and extended to a distance directly between the two heating elements. The slab was situated on soil, and the surface boundary condition was controlled by a surface boundary model that was developed to account for seven possible surface conditions. The study included a parametric analysis of pipe configuration, the system's geographical location, and the storm. Results were analyzed by observing the heat flux required to maintain a given snow-free area ratio, where the required heat flux could be used to determine the required inlet fluid temperature. One conclusion from this study is that idling is likely required to achieve a snow-free area ratio system.

Liu et al. (2003) improved upon the model found in Rees et al. (2002) to simulate hydronic heating of a bridge deck over its lifetime, as opposed to singular storm events, as well as to incorporate a GSHP. The entire model consisted of four sub-models: a hydronically-heated bridge deck model, a ground-loop heat-exchanger model, a water-to-water heat pump model, and a system control model. The model was then experimentally validated with a hydronic ground-source bridge deck deicing system installed in an experimental bridge at Oklahoma State University. The deck is 18.3 m long by 6.1 m wide, with 19 mm hydronic tubing installed on 0.3 m centers at a depth of 89 mm. The system is designed to control the bridge deck temperature in the range of 40–42^{o}F (4.4–5.6^{o}C) when there is a risk of snowfall. The model did a good job of predicting the average bridge surface temperatures and fluid exiting temperature, but slightly over-predicted the surface temperatures. The authors highlight the difficulty of numerically accounting for the long-wave radiation and convective heat fluxes.

Liu and Spitler (2004) utilized the simulation from Liu et al. (2003) and performed a parametric study to investigate the effects of idling time, pipe spacing, slab insulation, and control strategies on system performance. Their findings included that preemptive heating is required to achieve the expected snow-melting performance when using the tabulated ASHRAE surface heat flux value. Furthermore, preheating the slab to full-heating capacity before snowfall can significantly improve the system's performance. This model has been further refined (Liu et al., 2007a) and validated (Liu et al., 2007b).

The focus of the Wang et al. (2014) study was to determine the temperature distribution within a hot mix asphaltic layer when using a hydronic system to collect the solar heat energy. Their two-dimensional finite element model accounted for several hot mix asphaltic layers on top of a soil base. The geometry was such that it accounted for several hydronic tubing elements, as opposed to just one, as the previous models have done. The authors varied several parameters in the model, including thermal conductivity of the hot mix asphaltic pavement, distance between the pipes, and the pipes' diameters. They then reported the temperature changes that took place in the slab.

Chen et al. (2011) used the model created by Wang et al. (2014) to study deicing in order to design a pavement hydronic deicing system. Snow melting was substituted by ice melting, and it was assumed that whenever the temperature of the ice reached 0^{o}C, part of the ice had melted. The chosen inlet fluid temperature for this model was 25^{o}C, which is the assumed temperature of the 'thermal bank' that provides the heat energy. They varied the thermal conductivity of the hot mix asphalt, as well as the pipe depth, and then reported the time of initiation of ice-melting. The results were then used to design an experimental system. However, the results from the experiment were not used to validate the model.

3.3. Model Development

A series of three-dimensional numerical analyses were performed to model the bridge-deck heating process, using the finite element software COMSOL Multiphysics. The bridge deck slab modeled in the analyses is shown in Figure 80. The dimensions of the slab are 3.5 m x 2s m x 0.25 m; “s” denotes the tube spacing. Warm fluid was circulated through the circulation tube at a constant flow rate, and the temperature progression within the deck was evaluated. Water was used as the heat carrier fluid. The temperature of the inlet fluid is a reflection of the in-situ ground temperature, as these analyses considered the use of a circulation pump rather than a heat pump. Inlet fluid temperature was kept constant throughout the analyses, even though it is likely to vary slightly as a result of colder fluid being injected into the ground.

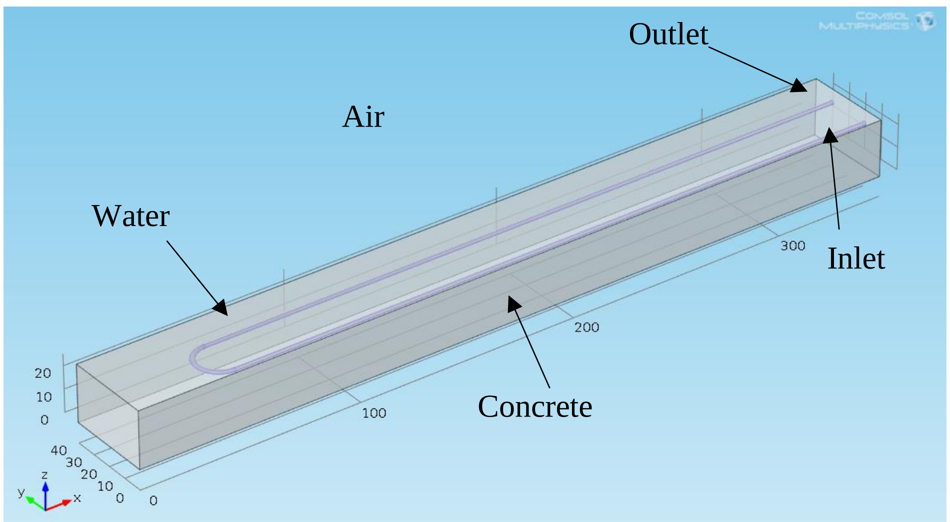


Figure 80 The configuration of bridge deck in 3D

The analyses considered a variety of tube spacings, inlet fluid temperatures, flow rates, wind speeds, ambient temperatures, inlet fluid temperatures, and thicknesses of concrete cover over the circulation tubes. The ambient temperature was kept constant throughout the analyses. A parametric study was also performed to evaluate the effects of different factors on the bridge deck heating process. In addition, the rebar was not modeled in the analyses because its volumetric mass and heat capacity is small, and its thermal conductivity is much higher compared to the concrete. The diameter of the rebar is also very small and would require an extremely fine mesh, significantly increasing computation time. Bowers and Olgun (2014) indicated that the effect of rebar was negligible, based on their preliminary numerical analyses in COMSOL.

It is noted that the analyses were limited to the heating process of the bridge deck, while the ambient temperature was kept constant and the melting of the snow was not included. The main purpose of these assumptions was to maintain simplicity in the computations and also to develop a guideline for the design of the geothermal heating system. It was assumed that the bridge deck was preemptively heated to above-freezing temperatures before the snowfall. It was concluded that the bridge deck will remain snow-free after precipitation if the heat injection can compensate for the latent and evaporative heat demands from snow melting after the start of precipitation.

Properties of the materials used in the analyses are summarized in Table 16. A total of 27 models were analyzed, with different model parameters systematically varied, as presented in Table 17. The center-to-center spacing of the circulation tubes for the base was set at 20 cm, and the centerline of the tubes was 6.0 cm below the deck surface. Heat carrier fluid with 12°C inlet temperature was circulated at a flow rate of 0.6 m/s. The initial temperatures of the bridge deck and the air were -2°C, and wind was not considered.

Table 16 Property of materials used in the numerical analyses

Property	Material	Value	Unit
Density	Concrete	2300	kg/m^3
	Water	1000	kg/m^3
	Air	1.23	kg/m^3
Heat capacity	Concrete	880	J/kg⋆K
	Water	3691	J/kg⋆K
	Air	1006	J/kg⋆K
Thermal conductivity	Concrete	1.88	W/m⋆K
	Water	0.61	W/m⋆K
	Air	0.0239	W/m⋆K
Surface emissivity	Concrete	0.91	
Dynamic viscosity	Water	0.00273	kg/m⋆s
Kinematic viscosity	Air	1.315×10^{-5}	m^2/s

Table 17 Results of the numerical analyses

Tube spacing (cm)	Wind speed (m/s)	Concrete cover (cm)	Inlet fluid temperature (°C)	Ambient temperature (°C)	Flow rate (m/s)	Number of runs
20	0	6	12	-2.0	0.6	1 (Base)
20	0	6	12	-2.0	0.3, 0.9, 1.2, 1.5	4
20	0	6	12	-10, -8, -6, -4	0.6	4
20	0	6	6, 8, 10, 14, 16, 18, 20	-2.0	0.6	7
20	1, 2, 4, 6	6	12	-2.0	0.6	4
15, 25, 30, 35	0	6	12	-2.0	0.6	4
20	0	4, 8, 10, 12	12	-2.0	0.6	4

Figure 81 shows the mesh of the bridge deck and the circulation fluid in 3D. The specification of interaction between the fluid and the concrete was very important to the heat transfer process, a free triangular element, with size of extra fine, was utilized as the mesh above the interface. The free tetrahedral element, with size of fine, was adopted as the mesh for both the concrete and the fluid. The total number of elements generated in this model was 408,772 for the base case. This number will change slightly for different thicknesses of concrete cover and tube spacing because of the changes in configuration of the bridge deck and the fluid.

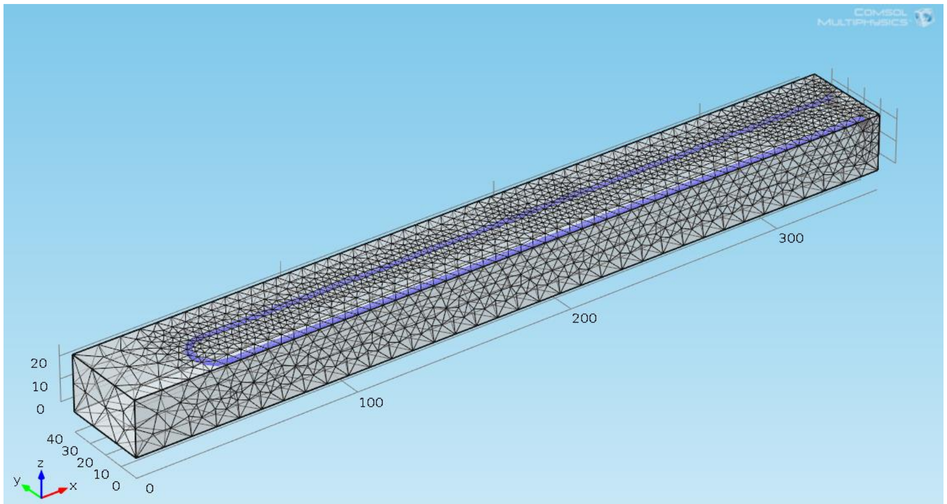
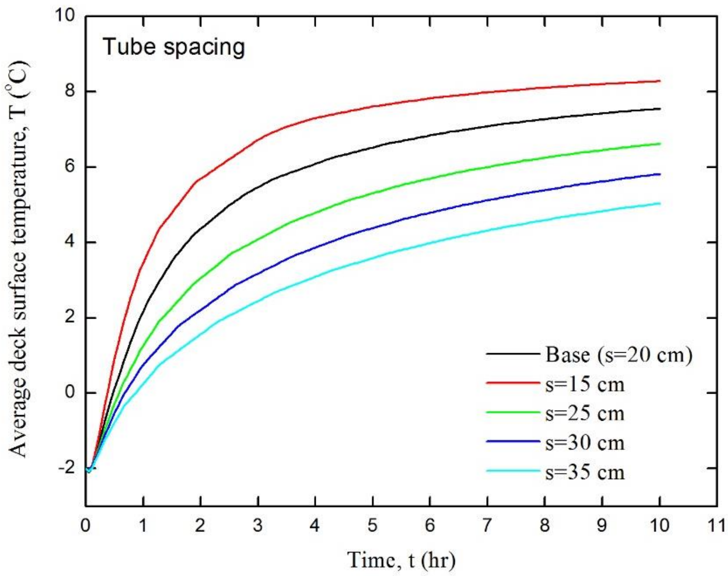


Figure 81 Mesh of bridge deck and fluid in 3D

3.4. Results

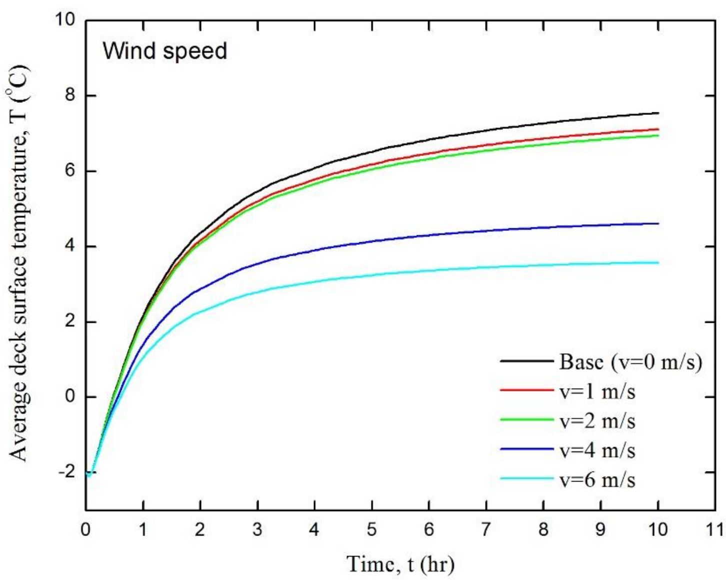
3.4.1. Average Temperature at Top Surface of Bridge Deck

Figure 82 presents the average temperature at the top surface of the bridge deck and how it is affected by (a) tube spacing, (b) wind speed, (c) concrete cover, (d) inlet fluid temperature, (e) ambient temperature, and (f) flow rate. The average temperature increased rapidly at the beginning of the simulation and became more gradual after three hours. Moreover, the temperature increased with decreased tube spacing. The effect of wind speed on the surface temperature of the bridge deck was found to be considerable when it exceeded 2 m/s, as shown in Figure 82(b); however, it did not affect the heated bridge deck at low levels. The concrete cover affected the heat transfer distance from the heat source, i.e., heat carrier fluid, to the surface of the bridge deck. The time required to reach the same temperature at the surface was increased with an increase in the thickness of the concrete cover. Figure 82(d) shows that the effect of the inlet temperature followed the same pattern as of that of tube spacing. The increase of the inlet fluid temperature resulted in an increase of the surface temperature. Figure 82(e) shows the effect of ambient temperature on the heated bridge deck. The ambient temperature provided an initial temperature value for further calculations, but it did not affect the evolution of the surface temperature of the bridge deck. The effect of flow rate was found to be negligible compared with other factors, as shown in Figure 82(f).



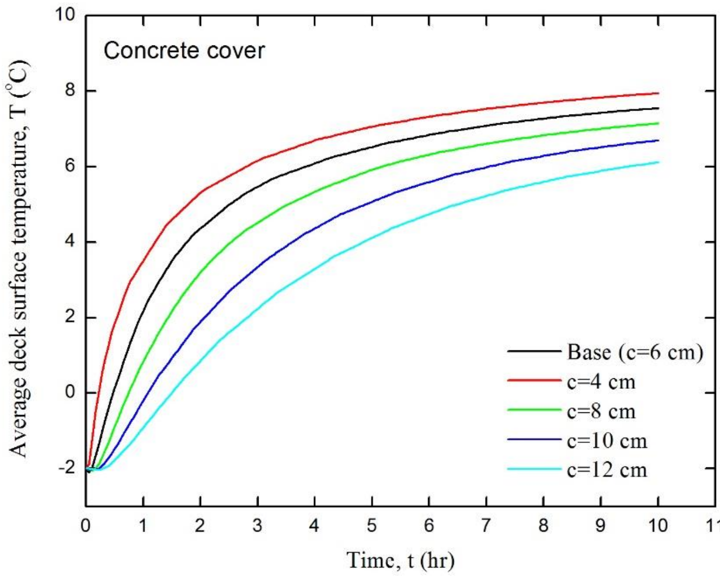
Tube spacing
Average deck surface temperature, T (°C)
Time, t (hr)
Base (s=20 cm)
s=15 cm
s=25 cm
s=30 cm
s=35 cm

(a)

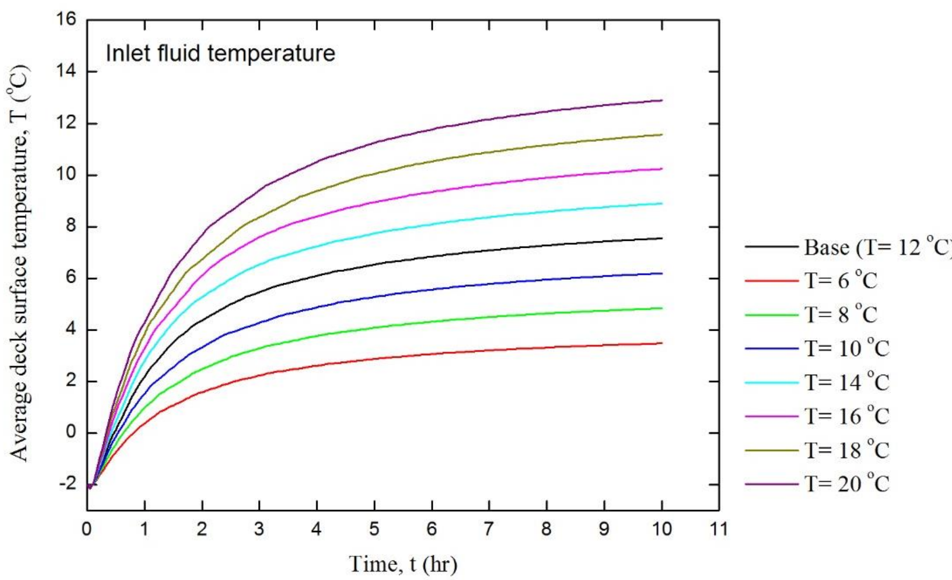


Wind speed
Average deck surface temperature, T (°C)
Time, t (hr)
Base (v=0 m/s)
v=1 m/s
v=2 m/s
v=4 m/s
v=6 m/s

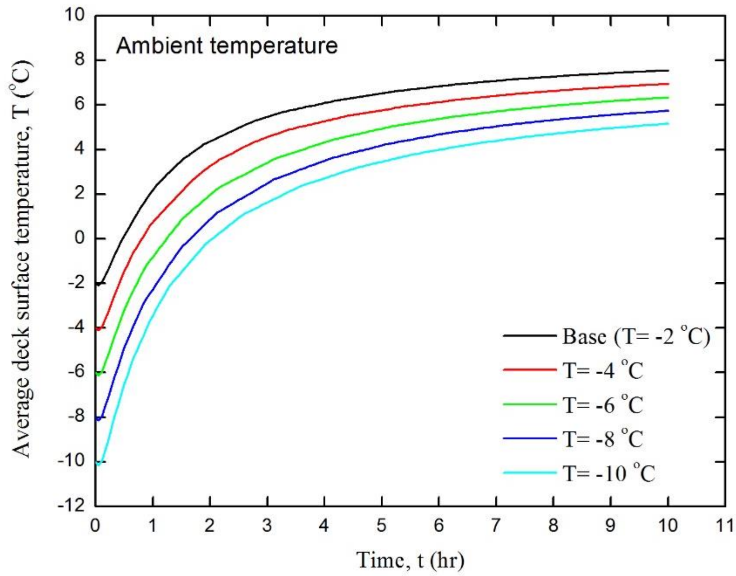
(b)


Concrete cover
Average deck surface temperature, T (°C)
Time, t (hr)
Base (c=6 cm)
c=4 cm
c=8 cm
c=10 cm
c=12 cm

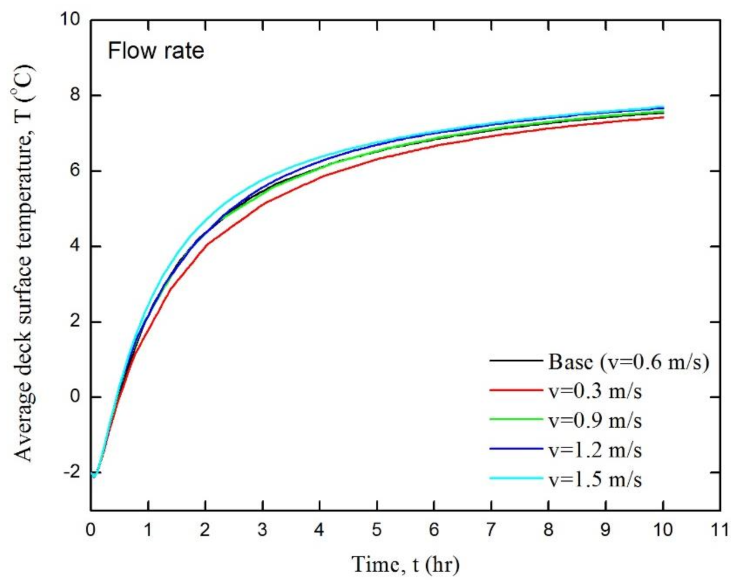
(c)


Inlet fluid temperature
Average deck surface temperature, T (°C)
Time, t (hr)
Base (T= 12 °C)
T= 6 °C
T= 8 °C
T= 10 °C
T= 14 °C
T= 16 °C
T= 18 °C
T= 20 °C

(d)



(e)

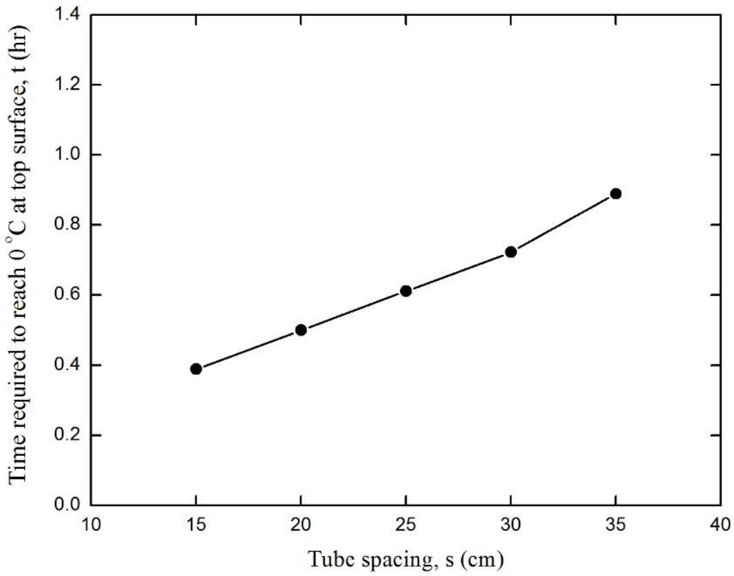


(f)

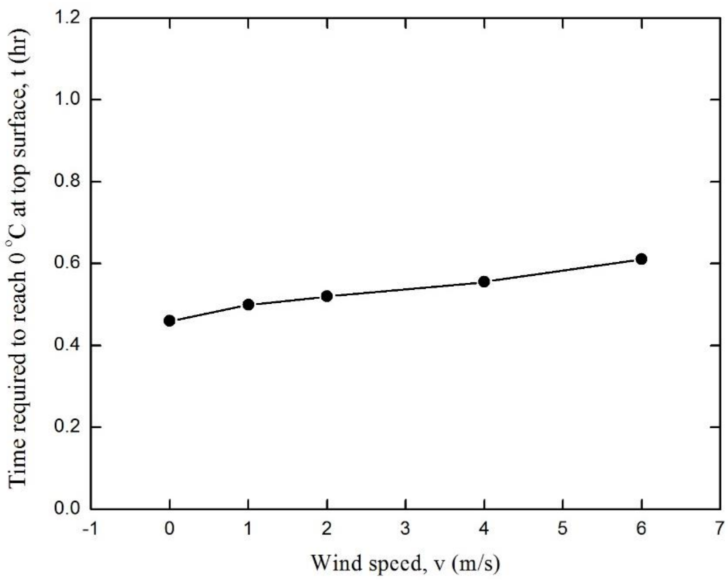
Figure 82 Average temperature at top surface of bridge deck: (a) tube spacing; (b) wind speed; (c) concrete cover; (d) inlet fluid temperature; (e) ambient temperature; (f) flow rate

3.4.2. Time Required to Reach 0^{o}C at the Bridge Deck Surface

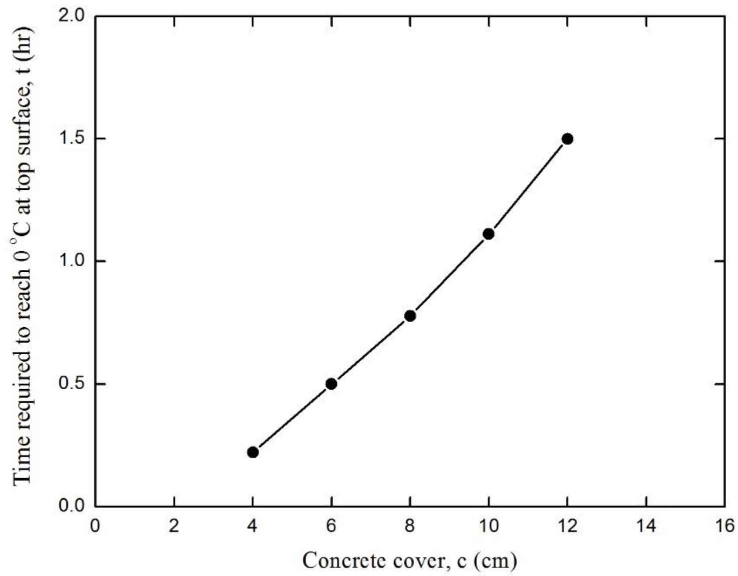
Figure 83 shows how the time required to reach 0^{o}C at the top surface of the bridge deck is affected by (a) tube spacing, (b) wind speed, (c) concrete cover, (d) inlet fluid temperature, (e) ambient temperature, and (f) flow rate. It is evident that the time required to reach 0^{o}C at the top of the bridge deck surface was increased with an increase in tube spacing, wind speed, and concrete cover; while it decreased with an increase in inlet fluid temperature, ambient temperature, and flow rate. The effects of flow rate on the required time were not as significant as the other factors. As a result, concrete cover thickness, inlet fluid temperature, ambient temperature, wind speed, and tube spacing are critical parameters in the design of geothermal heated bridge deck systems.



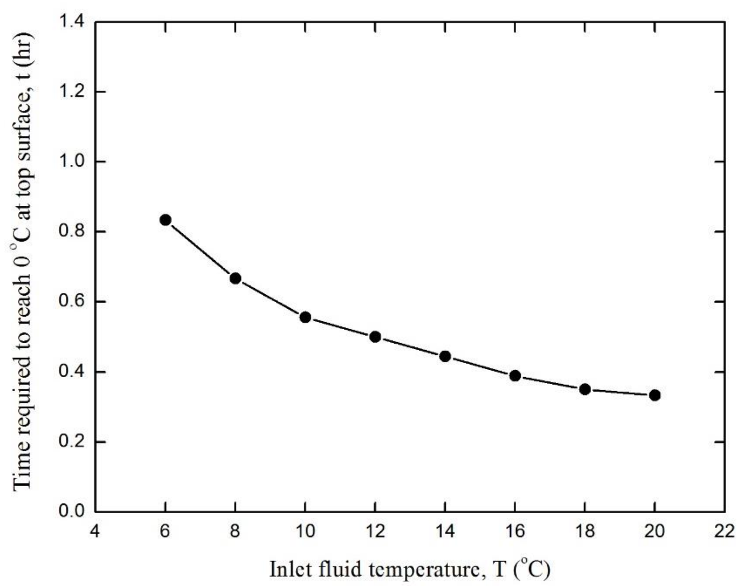
(a)



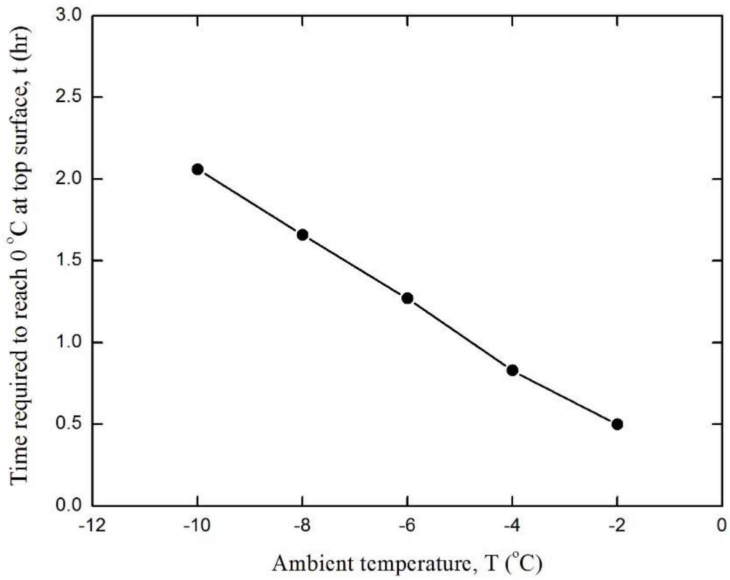
(b)


Time required to reach 0 °C at top surface, t (hr)
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
14
16
Concrete cover, c (cm)

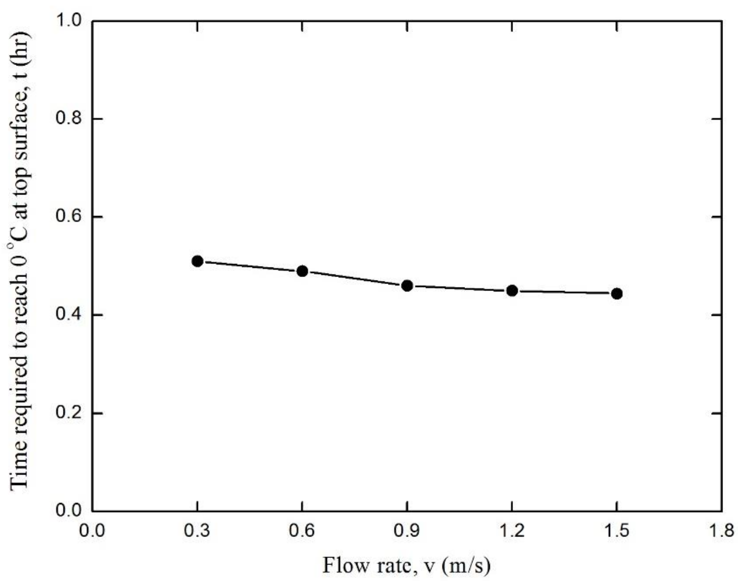
(c)


Time required to reach 0 °C at top surface, t (hr)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
4
6
8
10
12
14
16
18
20
22
Inlet fluid temperature, T (°C)

(d)



(e)

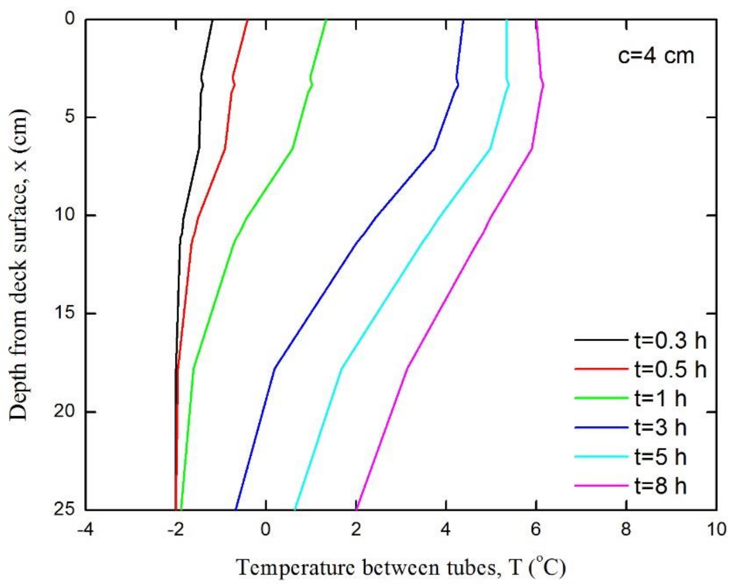


(f)

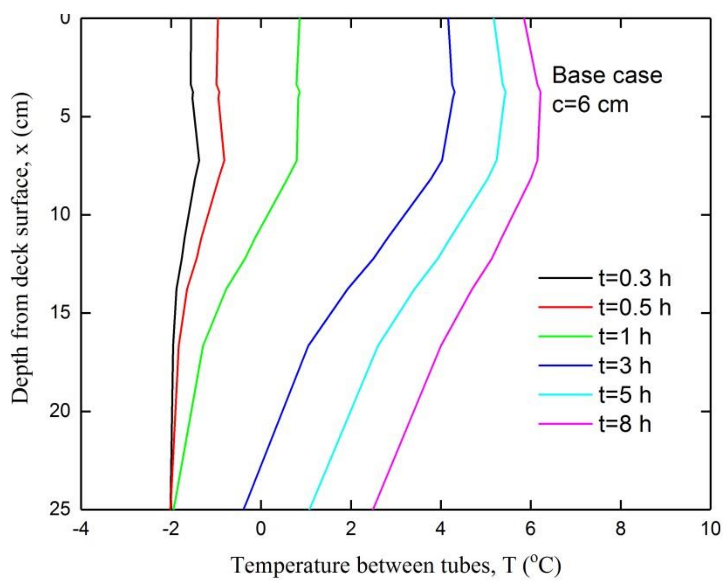
Figure 83 Time required to reach 0^{o}C at top surface of bridge deck: (a) tube spacing; (b) wind speed; (c) concrete cover; (d) inlet fluid temperature; (e) ambient temperature; (f) flow rate

3.4.3. Temperature Distribution along a Vertical Section

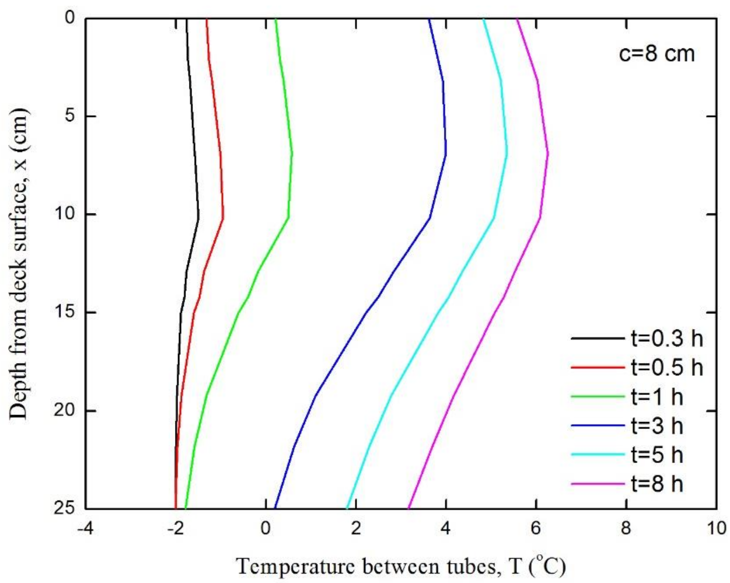
Figure 84 shows the temperature along the vertical section, between circulation tubes for different thicknesses of concrete cover: (a) c=4 cm, (b) c=6 cm (base case), (c) c=8 cm, (d) c=10 cm, and (e) c=12 cm. This centerline section represents the most distant point from each tube in the horizontal direction. It was found that the temperature rises fastest near the tube elevation within the deck, and the bridge deck gets progressively warmer, with temperatures higher at the surface than at the deck base. In this analysis, the top 7.5 cm of the deck slab was greater than 0°C at the end of one hour of heating, with 12°C circulation fluid. In addition, the observed temperature contour was shown in different patterns, with different thicknesses of concrete cover. The maximum temperature was always located at the same depth of the circulation fluid. As the thickness of concrete cover increased, the temperature dropped at the top of the bridge deck surface, and the temperature at the deck base increased, because of the change of the distance between the heat source and the two surfaces.



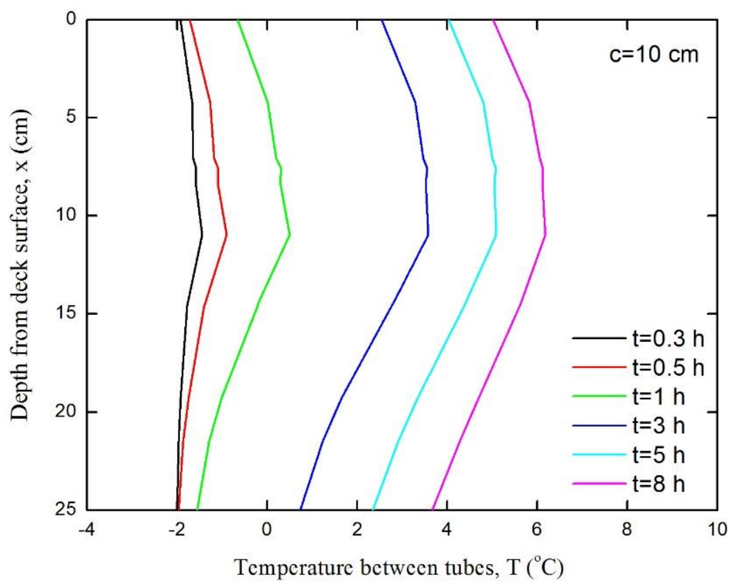
(a)



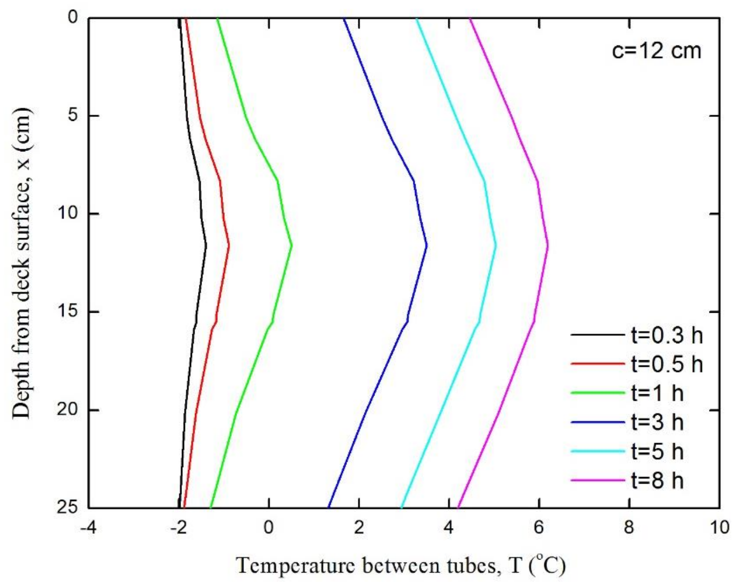
(b)


c=8 cm
Depth from deck surface, x (cm)
Temperature between tubes, T (°C)
t=0.3 h
t=0.5 h
t=1 h
t=3 h
t=5 h
t=8 h

(c)


c=10 cm
Depth from deck surface, x (cm)
Temperature between tubes, T (°C)
t=0.3 h
t=0.5 h
t=1 h
t=3 h
t=5 h
t=8 h

(d)



(e)

(a) c=4 cm, (b) c=6 cm (Base case), (c) c=8 cm, (d) c=10 cm, and (e) c=12 cm.

Figure 84 Temperature along the vertical section in between circulation tubes

3.5. Summary and Conclusions

FEM simulation of a hydronically-heated bridged decks was performed in this study. The effects of system parameters were investigated, including tube spacing, concrete cover, fluid flow rate, inlet fluid temperature, ambient temperature, and wind speed. It was demonstrated that the wind speed and flow rate have a quite small effect on the heating efficiency of the system, but the other factors should be considered in the design of a hydronically geothermal heating system. The new findings in this report can serve as a benchmark to gauge the operational conditions and the energy requirements for designing ground-source bridge deck deicing systems.

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