



Master Project : Numerical simulation of deck de-icing using energy pile systems

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Introduction

Geothermal energy is heat energy generated and stored in the Earth. With the awareness of the society about environmental issues, geothermal power is developing worldwide. It is cost-effective, reliable, sustainable, and environmentally friendly but has historically been extracted from the depth of the earth. Recent technological advances permits to use this energy from the shallow depth of the earth. Thanks to infrastructure foundations combined with heat pump technology, we are able to use this geothermal shallow energy. It have dramatically expanded the range and size of viable resources especially for applications such as home heating, cooling thus opening a potential for widespread exploitation. The renewable soil energy can be also used in transportation infrastructures such as the de-icing of bridges. Indeed, the icing of bridge decks in the winter is a real problem that potentially creates vehicules accidents. For example, in United states, more than 5'500'000 vehicle crashes occur per year and 23% of them are weather-related (data derived from Federal Highway Administration website).

Instead of performing a mechanical de-icing combined with spraying de-icing salt, we can use geothermal energy to proceed to the de-icing by heating the bridge slab. This energy is extracted thanks to the foundations (piles) of the bridge. These foundations are used as heat exchangers to extract the heat from the ground. Snow melting system based on energy piles is a technology that combines the structural function as a foundation with geothermal energy extraction. This technology was already proposed in 1990s in Japan [35] but it is actually nearly applied. The concept is simple: during snowfall periods, hot fluid is injected inside the bridge's deck through the pipes placed in the bridge's slab. The heat is transmitted to the pavement and the ice melts down. The hot fluid is obtained thanks to the mechanical work of heat pumps which enhances the power extracted from the energy piles.

This method overcomes the problems of prevalent methods (mechanical de-icing combined with spraying de-icing salt) which are associated with extensive corrosion of transportation infrastructure, huge amount of material consumption, and negative environmental impacts.

In this technical report, we will see why such a melting system could be a good alternative to traditional de-icing methods? How can we define the applicability and performance of such a snow melting system? How this system could be designed and implemented in a real case? What is the structural behaviour of a bridge deck when the system operates ?

In the first chapter, we will explain the different methods used for bridge de-icing and we will focus in particular on the concept of deck de-icing using energy piles system explaining

the physical phenomena of heat transfer involved in this system. In chapter 2, we will define a methodology that could determine the energy demand of a bridge deck to remove the ice in different weather conditions. Furthermore, we will investigate to what corresponds this required energy in terms of the fluid temperature injected below the pavement and in terms of the required number of energy piles. We will study the feasability of such a system through verifying whether the heat provided by energy piles will be sufficient to satisfy the energy demand.

In the chapter 3, we will study a real case bridge located in the city of Jiangyin (China) where Hohai University geotechnical group is supervising the project. We will decribe first the main features of the project. Since I had the opportunity to assist to the construction phases of the bridge, we will explain in details the construction phases of the project (bridge+de-icing system). Then we will determine the thermal needs of the bridge deck considering the project data. We will conclude this report by dedicating a chapter for numerical simulations done using Comsol Multiphysics software. As a first part, a parametric analysis was performed considering the main elements forming the melting system of the bridge deck in order to understand more its thermal performance. In the next part of this chapter, a set of numerical simulations were done to compare different possible pipe layouts that can be installed on Jiangyin bridge deck. Finally, based on this real case bridge deck, we will concentrate on its structural behaviour during the de-icing process. Since the bridge was in construction during this study, iterative operations were done to optimise the efficiency of the system and predict the thermal and structural response of the bridge deck.

Chapter 1

Concepts of deck de-icing

1.1 Deck interaction with atmosphere and ice formation

In contact with atmosphere, the bridge deck is exposed to different weather conditions: air temperature, wind, moisture content, deck solar effect. During cold periods, snowfall can occur leading to snow accumulation on the deck pavement. When the air and the slab temperature are below 0°C, a thin layer of ice could be formed. When these natural phenomena occur, the frequency of accidents increase because roads are slippery. For the safety of the users and the decrease of fuel comsumption, the de-icing must be carried out. The most common methods are simply the mechanical remove of snow from roads and salt spraying preventing the ice formation. Nowadays, more and more bridges integrate below their pavements heating systems in order to melt the snow without performing any external actions. The numerous advantages of those melting systems lead authorites to study their feasibility during the project phase.

1.2 Methods used for de-icing

1.2.1 Mechanical method

The mechanical method is the oldest and most commun method for de-icing. It could be applied directly while there is snow accumulation or in addition of spraying salt when there is strong precipitation. The concept is simply to pick up the snow that is fresh and not bonded to the pavement surface from the road, shearing it from the road or removing it to a storage area off the road. The mechanical method includes plowing and brooming. Snow plowing, in either de-icing or antiicing operations, is to remove the maximum quantity of loose ice before eventually spraying salt. Brooming is a complement to the plowing, it consists on brushing and sweeping residual snow to give the surface a groomed appearance. This method is safer for the deck membrane, better for the environment and more cost effective. It can also significantly reduce the need for chemical methods in roads. However, in urban areas, large volumes of snow cleared from roads can exceed the available space along roadways for snow storage: it could requires some specific disposals for the snow, moreover, it can take much more time to remove the snow due to availability of trucks and the fact that the removal will significantly slow the traffic.

1.2.2 Chemical method

It consists on application of chemicals on pavements for melting ice and preventing its accumulation. Salting is one of the most common chemical methods used world wide. This is due to its cost efficiency as well as its availability. From a scientific point of view, we know that the snow melts at 0°C, but when salt is sparyed on the snow, the water freezing point will drop off to very low temperatures and the snow will melt at lower temperature than 0°C. When we spary salt on the snow, it dissolves with the water it contains. The pure water of the snow then becomes salty water. The melting temperature is thus lower and it does not freeze at 0°C. If the air temperature stays the same, the snow will melt. When the water contains 10% of salt, it is transformed to ice in less than -7 ° C. If it contains a little more salt, around 23%, it freezes when it is even colder (-21 ° C)[41].

Hence, the salt can be used to melt the snow and to prevent ice formation on walkways and roads.

The salt spread is done by snowplows or dump trucks, and it is often mixed with sand and gravel. Those abrasives are mainly used to improve friction between roads and tires specially when pavement temperatures are too low for chemical treatments to be effective. The salting application rate depends on the level of service required, weather conditions, application time, traffic density, as well as topography and the type of road surface [10]. It implies having an efficient logistic but also important human and financial ressources. Indeed, the local authorities should allocate spaces for salt stocks and parking for trucks. In addition, it should ensure having the necessary human ressources to drive the trucks and transfer the salt from the stock to the trucks during the snow events, to pay for oil consumption and maintenance of the trucks. During huge snow events, a strategy should be implemented and many questions are raised. For instance:

- What are the major public roads to de-ice in priority ?
- What are the roads we can neglect ?
- How many times the spraying should be done to keep roads clear of ice (weather is sometimes not predicable)
- How to avoid the spraying during rush hours ?

In addition to the logistical issues, the salt spraying has other drawbacks such as negative influence on infrastructure, vehicles and the environment in general. The main problems of the salting are the infrastructure corrosion, the vehicle corrosion (rusting the body sills) and the negative effects on the natural environment near by the roads (vegetation and animals). Spraying salt and chemicals in high concentration can be toxic for animals and vegetation: the sodium chloride can infiltrate in the soil, groundwater and crossed rivers (in case of bridges de-icing) by splashing, spraying, or plowing with an impact on drinking water salinity, on permeability and fertility of soils and could affect globally the nature ecosystem [28].

The infrastructures corrosion leads to the most notable and expensive damages in short and medium term. Applying salt on roads will initiate corrosion of rebars in the bridges, tunnels or retaining walls along the roads. Their structural integrity is directly affected because the oxidation of the reinforcement will reduce the cross sectional area of the rebars which can lead to the collapse of structures. In the United States, there is approximately 583,000 bridges, 200,000 are constructed using steel, 235,000 are reinforced concrete bridges and 108,000 are constructed using prestressed concrete. 15% of these bridges are structurally deficient because of corroded steel and steel reinforcement. This induces an annual direct cost of \$8.3 billion, including \$3.8 billion to replace deficient bridges over the next 10 years, \$2 billion for maintenance and capital costs for concrete bridge decks and \$2 billion for their concrete substructures, \$0.5 billion for maintenance painting of steel bridges. Indirect costs to the motorists, such as traffic delays and productivity losses were estimated to be as high as 10 times the direct corrosion costs [27].

The life cycle of the salt should also be taken into account. A life cycle of the deicing salt is done in [25] to know in details it's environmental impact. In brief, in the life cycle, we should also consider the raw material extraction and preparation which is in general located far away from the snowing zones. Then the salt is transported to the salt manifacturer where it is treated and stored. After manufacturing, it is stored and transported again before being spread on the bridge deck. The extraction needs energy, the treatment operation involve the use of chemicals, the storage and transport needs energy too which imply critical air pollution.

1.2.3 Heating methods

Alternative methods to chemical and mechanical de-icing exist such as heating the bridge deck using electrical, boiler-powered or geothermal source systems.

Electrical method

It consists on incorporating in the bridge deck mineral insulated electric wires while passing through them an electric power when we need to de ice. Electrical current flows through the wires and heat is generated by their electrical resistance. The heat produced is governed by the voltage applied through the conductors and the composition of the wires that offers resistance to flow [29]. One of the largest project using electrical wires for the de-icing is a

two lane interchange bridge located in USA (Oregon State) where 1182 m^2 are heated by mineral insulated cables providing more than 300 W/m^2 to the slab [8].

Another technology is to use a conductive concrete as a bridge slab material [30]. A conductive concrete can be defined as a cement-based composite that contains electronically conductive components (such as carbon fiber or graphite) which allow to reach a high electrical conductivity. Due to its electrical resistance and impedance, concrete slab generates heat to prevent ice formation on a bridge deck when it is connected to a power source. The most common power source for heating the conductive concrete overlay is the DC power. Such power supplies will employ a transformer to convert the input voltage to the required AC voltage. This voltage also depends on the resistance of the concrete. The voltage should not exceed 48 volts, which is the safe threshold of a human being. Several bridges use this technology for the de-icing. One of the most important bridges constructed using this technology is the Roca Spur Bridge located on Nebraska state (USA) which is a three-span highway bridge generating an average power of 500 W/m² by the conductive concrete to raise the slab temperature about 9°C above the ambient temperature [32].

Hydronic method usage for de-icing

Boiler-powered method is one method for heating the bridge by simply heating water in underground tanks and injecting it into the slab thanks to water pumps. In the case study done in Japan by I. Yoshitake &al [31], the subject bridge is a part of a mountain road and ice prevention is done on 116.4 m in length. The author explain all the steps of the construction: how the watertank is designed to insure the required heat, the layout of the pipes on the slab, a cost performance comparing costs of construction and maintenance of watertank system to a geothermal ground source system, then he concludes by showing the experimental results when the system is running.

Ground source heating is a more sustainable method preventing bridge from ice. The ground source heating uses geothermal energy thanks to ground source probes, shallow tranches or energy foundations. Keeping a constant temperature, the soil can be used as thermal storage and its heat can be utilized for the de-icing when the fluid circulation is performed using a geothermal heat pump. One of the most well-known geothermal snow melting system is the project SERSO in Switzerland realized in 1994 [33] and is still in service nowadays. The objective of the project was more for ice prevention (anti-icing) rather than snow melting. During cold periods, "the surface temperature is stabilised just above 0°C, thus hindering ice formation and the freezing of compacted snow". The heated area is about 1300 m². The system is extracting heat from the ground thanks to 91 ground source boreholes with a depth of 65 m each. Each year, the system runs less than 1000 hours in winter and 1000 hours for thermal recharge in summer. The hydronic pipes embedded below the pavement provide a average power of 100 W/m^2 .

The several benefits of the heating melting systems can lead to the substitution of the prevalents methods: First a better safety for motorists and walkers because it eliminates the overall snow and ice present on the slab, keeping surfaces clear during snowfall events and preventing freeze because the water present on the slab evaporates. A lowered maintenance costs because traditional snow removal is expensive and requires an efficient organization upstream. A minimized environmental impact because run-off of deicing chemicals into conduits and drains is eliminated and moreover Co2 emissions are reduced.

1.2.4 Operational Control for de-icing using hydronic method

The heating system using hydronic pipes has 2 principal objectives: First it is to maintain the slab temperature above the freezing point to avoid the formation of an ice layer on the pavement. The second objective is to melt the snow when there is snowfall. To ensure those goals, an operational control is highly recommended in order to optimize the supply energy and to be cost effective. The probable occurence of the deck freezing or the probable occurrence of a snowfall precipitation are known thanks to instruments and sensors which allow to anticipate the heating response of the bridge based on an analysis of environmental and in slab conditions. Some sensors are embedded in the pavement and other instruments are measuring the local weather data. The 2 main sensors are thermistors (embedded in the slab) which provide the pavement surface temperature and thermometers to measure the air temperature. For a better control and optimization of the heating system, it is possible to add wind speed and direction sensors, relative humidity and solar irradiance sensors.

The operation control can be accomplished either manually or automatically. Manual control will require human observation: an operator will activate the system when snow falls or when either the pavement temperature or the air temperature become below 0°C. He will turn off the system after the snow melts and evaporates.

The automatic control is more sophisticated and more instrumentation will be needed. Automatic control requires the addition of another type of sensors that detects either a wet pavement or snow precipitation. The system will be also energized when the slab is nearfreezing temperature or a precipitation is detected. Two types of precipitation detectors are commercially available: one that detects falling precipitation by the interruption of a light beam, and another that senses water or ice on the pavement itself.

Used on Oregon, Nebraska, West Virginia bridges, the conductivity unit (made by Delta-Therm) measures the electrical resistance between closely spaced mutually insulated conductors. "When dry, no leakage current flows between the conductors. When wet, a small leakage current is detected by the control circuitry" [8]. In Virginia bridge, a pneumatic ice detector (made by Aanderaa) is used. It incorporates a porous membrane that is permeable to air when dry or wet but impermeable when it is covered with ice; " a small blower delivers a low volume of low pressure air to the device" [8].

In the paper "Smart Control of a Geothermally Heated Bridge Deck" written by Jenks & al.[9], an additional feature is added: the controller implements feed forward action using principles of model predictive control (MPC). The idea behind MPC is that the forecast weather conditions are known (ambient air temperature, snowfall rate, windspeed, solar irradiance..). So at any instant, "the controller uses the model to predict the future response of the bridge deck temperature assuming the manipulated inputs (supply temperature of the

fluid circulating through the bridge loop heat exchanger) are held constant". The operational control becomes a proactive control and preheat the bridge prior to an expected icing event (we call it idling). This is why we call it a smart control.

The idling will eliminate the transient effect of the bridge deck heating in order to keep the surface clear from snow since the begining of the snowfall event. However, continuous idling of the system will consume too much energy to be practical. Implementing the weather forecasts and local weather data in the smart control will predict snow events several hours in advance. The idling time will be reduced but may also require higher power requirement than that calculated from the steady-state heat fluxes (given in the Ashrae guidelines). Thus, "the relationship between the idling duration and the snow melting performance is important to reach the optimal balance between the system heating capacity and the operating costs" [37].

1.3 General concept of de-icing design using energy piles system

The deck de-icing using the hydronic pipes was used in several projects in USA since already 20 years. The source of the heated fluid in the deck was from a water tank heated or geothermal ground probes associated with a heat pump for a better efficiency. The deck de-icing using energy piles is a new concept used only in few bridges in the world. Snow melting system based on energy piles is a new technology that combines the structural function as a foundation with geothermal energy. As shown in figure 1.1, the system is working in winter for the de-icing and in summer for a thermal recharge of soil.



Figure 1.1: How the system works during winter (right) and during sumer (left)

During the de-icing, a cold fluid is injected in the energy piles. This fluid will be heated

thanks to soil temperature (Constant during the year). This fluid is directly injected on the bridge slab or a heat pump is used to enhance the fluid temperature which is then injected in the slab.

Thermal recharge of the ground

To keep the energy balance in equilibrum. The energy used from the ground to heat the deck should be reseted to the soil during hot periods. It will allow the system to work in a sustainable way.

During summer, solar irradiation phenomenon occur under the bridge deck, therefore the deck is heated. The solar energy is then stored into the soil from bridge deck to energy piles thanks to the water circulating in the pipes. The recharge will be done from the bridge deck to the ground loops when the bridge surface exceeds some specified temperature. A surface temperature of 32.2°C was found to be adequate in [11].

Energy behaviour of energy piles for different design solutions

The energy obtained from the energy piles is depending from a project to another. Indeed, numerous researches (including the prestudy project [13]) about energy performance of the piles have shown the influence of the following parameters on the extracted thermal power:

- Number of pipes in the pile (highest influence)
- Pile length (highest influence)
- Solid and fluid thermal conductivity
- Solid and fluid specific heat
- Presence of groundwater flow (depends on flow velocity)
- Pile diameter
- Pipes layout
- Velocity of the fluid circulating in the pipes (lower influence)
- Pipe diameter (lower influence)

1.4 Physical phenomena involved

De-icing based on energy pile system is composed by two main parts. First, the bridge deck, which is subjected to weather conditions. Second the energy piles buried in the soil. The system is complexed and three heat transfer phenomema are involved: conduction, convection and radiation.

For the bridge deck, external phenomena like the solar radiation, the forced wind convection and the conduction due to the snow layer. We can add to them the thermal convection between the fluid and the pipe wall and thermal conduction in the concrete. For the energy piles, three principal components of a ground heat exchanger are the heat exchanger fluid within the pipes, the concrete surrounding the pipes and the soil. The corresponding three main heat transfer mechanisms are thermal convection between the fluid and the pipe wall, thermal conduction in the concrete and thermal conduction in the ground.

1.4.1 How the snow melts in contact with a heated pavement ?

When the snow is in contact with a hot pavement, heat transfer occur between the snow layer and the slab. Since the snow is considered as a solid material, this heat transfer is mainly done through conduction. The melting process starts by a formation of a thin layer of water (slush) between the slab and the snow. Its temperature doesnt exceed in general 0.56°C [44]. Then, the temperature of all the snow pack increase to the freezing point temperature (0°C) and keeps constant without melting instantanously. Indeed, even if the snow pack reaches the melting temperature, the phase change doesn't occur. To be melted, the snow should also absorb a huge amount of energy called the latent heat which depends mainly of the heat of fusion of the snow. During this phase, the snow melts gradually from the bottom to the top of the snow layer.

1.4.2 Heat transfers in the energy piles

In energy geostructures, two main modes of heat transfer govern the heat exchanges between the different parts involved: conduction and convection. Conduction is the mode of heat transfer that occurs at the molecular and atomic levels between particles of a medium at different temperatures. This process is governed by Fourier's law:

$$\dot{q} = -\lambda \nabla T \tag{1.1}$$

where \dot{q} is the heat power flux [W/m], λ is the thermal conductivity of material [W/mK] and ∇T is the temperature gradient [K]. Heat transfer will occur from the higher temperature region to the lower temperature region.

Convection is also playing a role in the system. In general, the forced convection is the most relevant for ground energy systems. It is when a flowing fluid passes over a surface of a different temperature. It mainly occurs due to the temperature difference between the

circulated heat exchange fluid and the closed loop pipe walls. It can also occur due to the movement of flowing groundwater. The heat power flux $q_{conv,i}$ [W/m] generated by convection of flowing ground water is:

$$q_{conv,i} = \rho_w c_{pw} v_{rw,i} (T - T_0) \tag{1.2}$$

where ρ_w is the water density $[kg/m^3]$, c_{pw} the specific heat capacity of the water [J/kgK], $v_{rw,i}$ the relative velocity of water with respect to the solid skeleton (calculated thanks to darcy law) [m/s] and T_0 the reference temperature [K].

Applying energy conservation equation to the heat exchanger fluid (considering convective heat transfer between the fluid and the pipe wall), we can write:

$$\rho_f c_f A_p \frac{\partial T_{bulk,f}}{\partial t} - \nabla \cdot \left[A_p \lambda_f \nabla(T_{bulk,f})\right] + \rho_f c_f A_p u_f \nabla(T_{bulk,f}) = \dot{q}_p \tag{1.3}$$

where $\rho_f, c_f, A_p, T_{bulk,f}, u_f, \lambda_f$ are respectively the fluid density $[kg/m^3]$, the fluid specific heat capacity [J/kgK], the pipe cross sectional area $[m^2]$, the bulk temperature [K], the longitudinal velocity of the fluid [m/s] and thermal conductivity of the fluid [W/mK]. The first term on the left hand side represents the time rate of change of temperature, the second term represents heat diffusion in the circulating fluid along the pipe, and the third term is linked to the convective spatial temperature change due to fluid circulation. \dot{q}_p represents the convective heat flux per unit length through the pipe wall and is given by:

$$\dot{q}_p = UP_p(T_s - T_f) \tag{1.4}$$

where U is the effective value of the pipe heat transfert coefficient, $P_p = 2\pi r_{int}$ is the wetted lateral surface of the pipe segment and $(T_s - T_f)$ is the temperature difference between the pipe wall and the fluid. The heat transfer coefficient U, including the internal film resistance and the wall resistance, can be obtained as follows:

$$U = \frac{1}{\frac{1}{h_{int}} + \frac{r_{int}}{\lambda_p} ln(\frac{r_{ext}}{r_{int}})}$$
(1.5)

where λ_p is pipe thermal conductivity, $\frac{r_{ext}}{r_{int}}$ is the ratio between external and internal radius of the pipe, $d_h = \frac{4A_p}{P_p}$ is the hydraulic diameter and $h_{int} = \frac{Nu\lambda_f}{d_h}$ is the convective heat transfer coefficient inside the pipe where Nu is the Nusselt number which depends on Reynolds and Prandtl numbers. The Nusselt number is a non-dimensional number used to characterize the thermal transfers between a fluid and a wall, called convective transfer. A larger nusselt number corresponds to more active convection and so to heat transfer. The nusselt number for turbulant flow in rough tubes is given by the Dittus-Boelter equation (McAdams, 1942):

$$Nu = 0.023 * Re^{4/5} * Pr^{0.4}$$
(1.6)

where Re is the Reynlods number and Pr is the Prandtl number (Pr = 7 for water).

Basically this convective heat transfer coefficient depends on fluid velocity, fluid density, specific heat, thermal conductivity and kinematic viscosity of the fluid ν .

The flow condition plays an important role in convective heat transfer. Internal flow in the pipe can be either laminar flow or turbulent flow. In laminar flow, the streamlines of fluid movement are smooth, largely linear and highly ordered. In turbulent flow, the streamlines are chaotic and the velocity is subject to significant fluctuations. The intense mixing of fluids in turbulent flow causes them to enhance heat transfer compared to laminar flow.

The Reynolds number is equal to

$$Re = \frac{2u_f r_{int}}{\nu} \tag{1.7}$$

where u_f is the fluid velocity [m/s], r_{int} is the internal diameter [m] and ν is the kinematic viscosity $[m/s^2]$.

When its value reaches 2300, the flow is turbulent. Moreover, according to equation (1.3), exchanged power increase with fluid velocity. Thus, the value of velocity has to be suffisiently high to assure turbulent flow but not too high otherwise, the outflow temperature will not be suffisiently high to provide the maximum energy. In fact, "the circulating water has not the time to be heated inside the loop".

In the pile, the pipe loops are in contact with concrete which is itself in contact with the ground. The heat transfer through the concrete and the ground is governed by the standard transient heat conduction process. Globally, the heat transfer in the energy pile system + ground may vary throughout the body or over time. If we assume that there is groundwater flow in the soil and if the thermal conductivity of the medium is constant, the heat transfer process is governed by the energy conservation equation:

$$\lambda \nabla^2 T - \rho c_p \frac{\partial T}{\partial t} - \rho_w c_{pw} v_{rw,i} (T - T_0) = 0$$
(1.8)

where c_p is the specific heat capacity [J/kgK]; t the time; ρ the solid density. The first term represents the heat transferred by conduction, the second term represents the transient component of the internal energy stored in the medium and the third term represents the convective heat flux density.

1.4.3 Heat transfers in the bridge deck

The bridge deck is subject to external interactions between the slab and the atmosphere. Heat transfers by solar radiation, forced convection due to the wind, and with a lower frequency, heat conduction due to snow precipitations are involved.

The heat transfer by forced convection $q_{forced,conv}[W/m^2]$ is the main phenomena who govern the surface temperature. It is the heat transfer between the ambient air and the exposed surface. It depends of the air temperature, the wind velocity, the air propreties, the absolute pressure and the surface geometry. The equation governing this phenomona is as follow:

$$q_{forced,conv} = h_c (T_{surf} - T_{air}) \tag{1.9}$$

where h_c the convection heat transfer coefficient $[W/m^2K]$, T_{surf} is surface temperature and T_{air} is the ambient air temperature [K]. This convection coefficient is calculated as follow (Incropera and DeWitt 1996):

$$h_c = 0.037 (\frac{k_{air}}{L}) R e_L^{0.8} P r^{1/3}$$
(1.10)

where k_{air} is the thermal conductivity of the air, L is the plate length, $Pr = \frac{c_p * \mu}{k}$ is the Prandtl number and Re_L is the Reynolds number.

Radiation is also affecting the top surface temperature of the deck. This heat transfer correspond to the emission or transmission of energy in the form of waves or particles through space or through a material medium. This heat transfer is governed by the following equation:

$$q_{rad} = \varepsilon \sigma (T_{surf}^4 - T_{air}^4) \tag{1.11}$$

where ε is the emissivity of the surface (0.85-0.95 for concrete), σ is the Stefan-Boltzmann's constant ($\sigma = 5.68 * 10^{-8} [W/m^2 K^4]$). Each object emits or absobs thermal energy depending of it's temperature. The exposed surfaces of the bridge are submitted to two types of thermal radiation: long wave thermal radiation which occurs between the exposed surface and the surroundings and short wave radiation which is a direct exchange between the sun and the exposed surface (we call it thermal irradiation). During the day, the sun emits shortwaves to the exposed surface: its temperature will raise. One part of this energy is then transmitted to the atmosphere through longwaves radiation. The atmosphere will be then heated. The following figure presents all the interactions between the atmosphere and the bridge deck.



Figure 1.2: Heat transfer interactions between the atmosphere and the bridge

Since we are also inserting hydronic pipes in the bridge slab. The same phenomena of heat conduction in the concrete and forced convection in the pipes of the heat exchanger fluid occur in the bridge deck. The equations 1.1 and 1.3 are valid for the conduction and convection in the bridge deck.

Chapter 2

Energy requirement for the de-icing and energy piles thermal potential

As stated previously, our study focuses on the deck de-icing using the heating method. This system consist on injecting a hot fluid into hydronic pipes below the pavement when needed. By forced convection and conduction heat transfer mechanisms, the slab surface will be heated.

In this chapter, we will first explain what are the input energy requirements below the slab surface in order to de ice a bridge deck and how can we calculate them. Knowing the energy needed per surface unit, we will see from 2 different point of view to what corresponds those heat requirements. In one hand, we will determine, using an analytical solution, the fluid temperature which should be injected in the deck to provide the required heat. In the other hand, we will study the system as a whole, that means in terms of power extracted from the soil corresponding to a number of energy piles required.

2.1 ASHRAE Criterias

The chapter 51 of ASHRAE handbook provides guidelines [18] to calculate the amount of energy required to melt the snow from a surface in function of the rate of snowfall per hour and the local weather conditions. This rate of snowfall corresponds actually to the melting rate desired. To have an efficient snow melting system, we take in general the melting rate equal to the average snowfall rate at the bridge location.

The obtained powers, if they are inputed to the pavement, can ensure either that the slab remains free of snow during all the snowfall period or that the snow will melt at the same rate of that snowfall (or desired melting rate) whenever the slab is already covered by a layer of snow. We can also use the guidelines to know what is the required power to keep the slab temperature greater than 0°C, thus avoiding any freeze layer on the slab.

The heat required for snow melting depends on 5 main factors:

- Hourly rate of snowfall (in water equivalent)
- Air temperature
- Relative humidity
- Wind velocity
- Geometry of the heated slab

The heat requirement is given per W/m^2 and corresponds to the power to be injected per hour to the slab to melt the hourly snowfall amount falling on the slab.

To determine the heat requirement for melting the snow on any surface, the Ashrae guidelines consider all the snow melting phenomenon. When the snow falls in the bridge slab, this snow must first be warmed up to 0°C before the melting process: the heat needed for warming up the snow is called the sensible heat flux. Warming the snow until the melting temperature is not sufficient for the melting, the snow need also to absorb a huge amount of energy while keeping it's temperature equal to 0°C. This amount of energy is called the latent heat and depends of the heat of fusion of the snow. This energy is the predominant energy we should supply to the slab surface to ensure the snow melting.

In addition to the energy needed for the melting, the Ashrae takes also into account the energy losses of the bridge deck due to weather conditions (by convection and radiation heat losses) as well as the energy needed to evaporate the water after the snow melts in order to avoid the slab freezing.

The following equation provides the total heat flux required $q_0 [W/m^2]$ at the upper surface of the slab when the slab reaches the steady-flux state (Chapman and Katunich 1956):

$$q_0 = q_s + q_m + A_r(q_h + q_e)$$
(2.1)

where q_s is the sensible heat flux $[W/m^2]$, q_m is the latent heat flux $[W/m^2]$, q_h is the convective and radiative heat flux from the snow free surface $[W/m^2]$, and q_e is the heat required for the water evaporation $[W/m^2]$. A_r is snow free area ratio (A_r ranges from 0 to 1 and is the ratio between the equivalent snow free area and the total area). The steady-flux state is the state in which the temperature difference between the fluid and the top surface of the pavement is constant.

In the equation 2.1, all the terms could not be involved in the same time. Indeed, the sensible heat flux and the latent heat flux are taken into account whether there is snowfall at the time considered. In case there is no snowfall, we could only consider the convective and radiative heat flux from the snow free surface. The power injected corresponds to the power to keep the slab temperature greater than the freezing temperature avoiding the formation of an ice layer. This condition can be used to define the heat requirement for the idling. The idling is the time before a snowfall precipitation when the slab is heated to keep the slab temperature above 0°C activating directly the snow melting process without waiting more time until the slab surface reached the melting temperature.

When snowfall occurs, we should automatically take into account the sensible and the latent heat flux but we can more or less consider the convective and radiative losses together with the evaporation heat flux depending of the level of service desired. This is why Chapman in 1952 [18], indicates that sufficient snowmelting system design is obtained by considering 3 values of the snowfree area ratio A_r : 0,0.5 and 1.

To satisfy that the system will melt the snow quickly enough that the slab stay completely free of snow during the snowfall event, the heat required should be calculated with an equivalent snow free area ratio $A_r = 1$. In this case, all the terms of the equation 2.1 must be considered. If the slab is already completely covered by the snow and we start the system, the heat required is calculated with an equivalent snow free area ratio $A_r = 0$. In this case, the snow at the bottom of the layer melts at the same rate of snow accumulation rate. We notice also that the convective and radiative heat flux and the evaporation heat flux are cancelled: the snow acts as a insulator so there is no radiative and convective losses and no water evaporation in contact with the slab.

If the heat required is calculated using an equivalent snow free area ratio of $A_r = 0.5$, it means that we allow that all the pavement is covered by a thin layer of snow or we make the hypothesis that only one half of the pavement area is covered by snow. For the design of the system, using an equivalent snow free area ratio of $A_r = 0.5$ would be "reasonable for most traffic conditions [22]."

The sensible heat flux q_s and the latent heat flux q_m are function of the rate of snowfall water equivalent in [mm/h]. The snow water equivalent is a common snowfall measurement. The Natural Ressources Conservation Service (of the United states department of agriculture) defines it as the amount of water contained within the snowpack. In other words, it is the depth of water that would theoretically result if the entire snowpack melts instantaneously.

The sensible heat flux q_s is the heat flux required to raise the snow directly in contact with the slab to the melting temperature. A liquid film will be formed.

$$q_s = \rho_{water} s[c_{p,ice}(t_s - t_a) + c_{p,water}(t_f - t_s)]/c_1$$
(2.2)

The latent heat flux q_m is the heat flux required to melt the snow which is above this liquid film.

$$q_m = \rho_{water} sh_{if}/c_1 \tag{2.3}$$

where

ρ_{water}	density of water, kg/m^3
s	snowfall rate water equivalent mm/h
$c_{p,ice}$	specific heat of ice $J/(kg.K)$
t_s	melting temperature $^{\circ}C$
t_a	ambient temperature coincident with snowfall $^\circ C$
$c_{p,water}$	specific heat of water $J/(kg.K)$
t_f	liquid film temperature $^\circ C$
c_1	$3.6 * 10^{6}$
h_{if}	heat of fusion of snow J/kg

The rate of snow water equivalent is function of the snow water density and the effective snowfall rate. This density of fresh snow ranges from about 5% when the air temperature is -10° C, to about 20% when the temperature is 0° C. The density of snow increases until 30% when it is settled snow [42]. The formula to find about the snowfall water equivalent is :

Snow water equivalent =
$$Density_{snow} * Effective Depth_{snow}$$
 (2.4)

As we said previously, the bridge deck is subject to the weather conditions and heat losses occuring by radiation of the slab to the atmosphere and by convection due to the wind velocity. To compensate the heat losses due to these phenomena, the ASHRAE guidelines take it into account in the calculation of the de-icing power requirement.

The convective and radiative heat flux losses from a Snow-free area q_h are function of the snow free area ratio A_r . (When $A_r = 0$, the convective and radiative heat flux losses are not considered because the snow insulates the slab from atmosphere)

$$q_h = h_c(t_s - t_a) + \sigma \varepsilon_s(T_f^4 - T_a^4) \tag{2.5}$$

where h_c is the convection heat transfer coefficient for turbulant flow $[W/(m^2K)]$ (given in equation 1.10), ε_s is the emissivity of the surface (0.85-0.95 for concrete), σ is the Stefan-Boltzmann's constant ($\sigma = 5.68 * 10^{-8} [W/m^2K^4]$), T_f is liquid film temperature in [K] and T_a is the temperature of the surroundings [K].

Once the snow is melted, the liquid film should also be evaporated to keep the slab dry. The heat required for the water evaporation q_e is equal to (extrated from [17], chapter 5):

$$q_e = \rho_{dryair} h_m (W_f - W_a) h_{fg} \tag{2.6}$$

where h_m is the mass transfer coefficient [m/s], ρ_{dryair} is the density of dry air $[kg/m^3]$, W_f is the humidity ratio of saturated air at film surface temperature, W_a is the humidity ratio of ambient air. The humidity ratios are given in the tables of Ashrae Handbook of

Fundamentals[17], as function of the local atmospheric pressure and the dew temperature of the air.

The mass transfer coefficient is defined as (Kuehn &al 1998):

$$h_m = \left(\frac{Pr}{Sc}\right)^{2/3} \frac{h_c}{\rho_{dryair} c_{p,air}} \tag{2.7}$$

where Sc = 0.6 is the Schmidt number and Pr = 0.7 is the Prandtl number, $\rho_{dryair} = 1.33 [kg/m^3]$ is the density of dry air and $c_{p,air} = 1005 [J/(kg.K)]$ is the specific heat of air.

All the terms are now known to calculate the heat required q_0 for the slab for de-icing purpose. In chapter 3, using the local conditions of the real bridge case of Jiangyin city (China), those equations will be applied to determine the thermal needs.

However, some remarks should be noted and precautions should be taken when calculating the total required heat flux:

- All the results are given based on steady state analysis. Since the bridge deck has a thermal mass, transcient effects could be significant because the slab can take time to be heated before to operate to any melting process. A transcient analysis done by Spitler & al [20] showed that if a snowfall event starts and the system starts to operate in the same time, to keep slab surface free from snow during the 1st hour, the required heat flux can be up to 5 times the required heat flux given by steadystate condition.
- Back and edge losses of the slab are not taken into account. According to Spitler & al [20], heat losses, can reach 30 % of the surface heat flux.
- Heat gains such as solar irradiation are not taken into account in the computations.
- The evaporation heat flux q_e could be neglected if the slab has a good drainage system. The melted ice could run off directly into the conduits.
- The Ashrae guideline provide expressly the power required to apply to below slab in W/m^2 . Based on a specific slab case, they gives a simple empirical equation giving a relationship between the temperature injected in the slab and the resultant power. In the next sections, we will investigate more this issue and give more details about how this relationship is founded

Computation of different energy requirement terms based on the Ashrae equations

Depending on the weather conditions, the energy requirements for the de-icing can be more or less important. In the tables below, we provide the different energy requirement terms as function of the weather parameters (Snowfall rate, wind speed, air temeprature). The sensible heat flux q_s depends on the snowfall rate and the air temperature while the latent heat flux q_m depends only on the snowfall rate.

	Air te	mperatu	re [°C]
Effective Snow depth [mm/h]	-2	-5	-10
5	1.8	3.6	6.5
10	3.7	7.2	13
20	7.3	14.3	26

Table 2.1: Possible values of the sensible heat flux $q_s [W/m^2]$

Table 2.2: Possible values of the latent heat flux $q_m [W/m^2]$

Effective Snow depth [mm/h]	Latent heat flux $q_m \; [W/m^2]$
5	93
10	185
15	278
20	371
25	464

Thanks to the table above, we can see that a huge energy is needed to melt the snow (latent heat flux). The sensible heat flux which correspond to the raise off the snow temperature to the melting temperature (sensible heat) is negligeable comparing to the huge energy that should be absorbed for the melting (latent heat). During heating, the ice temperature stabilises at 0°C during the heating until all of the snow melts. So, since the latent flux depends exclusively on the snowfall rate, the predominent parameter to determine the heat flux needed to melt the snow is the snowfall rate and not the ambient air temperature.

The convective and radiative heat flux q_h depends mainly on the air temperature, the wind velocity and the geometry of the slab. The next table gives an estimation of the possible values that this convective and radiative heat flux can take (The characteristic length to calculate the convection coefficient is taken equal to 13 m):

Wind velocity [km/h]	-2	-5	-10
5	25	54	101
10	36	77	145
20	54	117	221

Table 2.3: Possible values of the convective and radiative heat flux $q_h [W/m^2]$

Air temperature [°C]

We can see that the heat losses due to convection and radiation can be also extremely high for severe weather conditions. A significative energy is needed to compensate those losses especially when the snowfree area ratio is choosen equal to 1.

The values of the heat required to evaporate the water q_e are function of the relative humidity of the air, the local atmospheric pressure and the dew temperature of the air. The possible values are around 40 $[W/m^2]$ which is neglegtable comparing to the latent flux.

We can see that the main terms composing the total de-icing requirements are :

- The latent heat flux q_m which is function of the snowfall rate s is the predominant term in terms of power requirements. We can see that the highest the snow fall rate (or desired melting rate) is, the higher is the energy required for the de-icing.
- The power needed to compensate the radiative and convective heat flux q_h (but only when the wind velocity is high and the air temperature are very low). However, this heat flux q_h can be more or less neglected because this term is function of snow free area ratio. For the design of a melting system in a standard bridge, this ratio is in general taken to be 0 or 0.5.

We observed in the tables above that the different energy requirement terms can be considerable especially when the de-icing should be done in zones where the weather conditions are severe. Depending on the choosen level of service, the latent heat flux and the sensible heat flux can be added to the convective and radiative heat flux q_h plus the evaporation heat flux q_e . The total heat requirements for the de-icing can be therefore very high.

We will see in section 2.3 and in section 2.4 what does represent those energy requirements in terms of injected fluid temperature in the hydronic pipes and in terms of required energy piles.

2.2 Determination of the slab temperature with analytical method and comparison with numerical results

In this section, the aim is to determine what is the relationship between the power injected in W/m^2 and the fluid temperature as function of the geometry and the material composing the system (slab + hydronic pipes). For this purpose, we will use the equivalent heat resistance method to determine the slab temperature analytically. Then we will check the accuracy of this method comparing the results obtained with the numerical results given by Comsol and we will discuss the accuracy of the equivalent heat resistance method.

In order to solve our problem by the analytical way, we studied our problem like a 2 dimensional problem in steady state condition, the slab temperature will be determined using an equivalent heat resistance method. With this method, the average heat flux of slab surface $q_l [W/m^2]$ can be expressed mathematically as

$$q_l = \frac{T_{fluid} - T_{slab}}{R_T} \tag{2.8}$$

where T_{fluid} is the fluid temperature in [K], T_{slab} is the average slab temperature in [K]and $R_T [m^2 K/W]$ is the total thermal resistance of the slab. The equation 2.8 is only valid when we reached the steady state condition time. In figure 2.1, the problem is modelized graphically.



Figure 2.1: Cross section in the slab

The total thermal resistance of the slab R_T is function of the geometry and the material composing the system (slab + hydronic pipes). It is equal the sum of the thermal resistance of tube wall, the thermal resistance of the concrete slab and the thermal resistance of the ice layer or the thermal resistance due to the wind convection if there is no snow.

The thermal resistance of tube wall R_w is given by [19] and equal to

$$R_w = \frac{\ln(D_0/D_i) * s}{2\pi * \lambda_{pipe}}$$
(2.9)

where D_0 is the external diameter [m] of the pipe, D_i is the internal diameter [m] of the pipe, λ_{pipe} is the thermal conductivity of the pipe [W/mK] and s the pipe spacing [m].

The thermal resistance due to the concrete slab R_s is given by

$$R_s = \frac{s}{\lambda_{concrete} * S} \tag{2.10}$$

This thermal resistance is function of the shape factor S:

$$S = \frac{\pi}{\ln[\frac{1.22s}{\pi 0.75D_i} * \sinh(\frac{\pi h}{s})]}$$
(2.11)

where $\lambda_{concrete}$ is the thermal conductivity of the concrete [W/mK]. This shape factor is derived from a study on heat transfer process for in-slab heating floor done by Liu, Y & al [36]. In their publication, they showed that the shape factor for a periodic array of pipes embedded in a slab which is insulated at it's bottom has the formulation above. In their study, they compare the heat transfer with an equivalent heat resistance model (using the shape factor) with a numerical simulation and they proved that the equivalent heat resistance model would give errors less than 10 % when compared with the numerical simulation results. Since the influence of the hydronic pipes is very low in the bottom of the deck, we will calculate the thermal resistance of our slab based on this shape factor and make the hypothesis that the pipes are buried in a slab where the bottom is insulated.

The thermal resistance of the ice layer R_i given by [19] is equal

$$R_i = \frac{x_{snow}}{\lambda_{ice}} \tag{2.12}$$

where x_{snow} is the thickness of the snow λ_{ice} is the thermal conductivity of the snow. This term is in general very small comparing to the other thermal resistances.

The thermal resistance due to the wind convection R_w is equal to

$$R_w = \frac{1}{h_c} \tag{2.13}$$

where h_c is the convection heat transfer coefficient in $[W/m^2K]$.

The total thermal resistance of the slab R_T is equal to

$$R_T = R_w + R_s + R_i + R_w \quad [m^2 K/W]$$
(2.14)

whether there is a snow layer. If there is no snow layer, the term R_i is ignored.

Thanks to the shape factor method, we are now able to determine the temperature of the slab when a fluid is injected. It is mainly depending of :

- The average heat flux at the slab surface
- The pipe location (distance from the top of the slab).
- The thermal conductivity of the material composing the slab.
- The pipe spacing.
- The pipe diameter and thickness aas well as it's thermal conductivity.

To compare analytical and numerical solutions, we will use a same simple 2 dimensional slab where the caracteristics are listed below:

Slab thickness H [m]	0.76
Pipe spacing s [m]	0.25
Pipe internal diameter [cm]	2
Pipe external diameter [cm]	2.2
Pipe position (below the slab surface) h [cm]	10
Pipe thermal conductive $[W/mK]$	0.42
Concrete conductivity $[W/mK]$	1.8

Table 2.4:	Slab	parameters
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The conditions applied on the slab are:

- The ambient air temperature at the top and the bottom of the slab is -2 [°C]
- A convection heat flux at the top and the bottom of the slab: The convection heat transfer coefficient of the wind is: $h_c = 10.5 [W/m^2 K]$
- The injected fluid (water) temperature in the pipes is constant and equal to 8 [°C]
- The water velocity is 0.5 [m/s] which is providing a turbulent flow regime.

The cross section of the slab is presented in the next figure.



Figure 2.2: Simple 2 dimensional slab

Analytical solution

Using the parameters in the table 2.4, the total thermal resistance of the slab is R_{T1} . The heat flux rate per unit area is equal to

$$q_{l1} = \frac{T_{fluid} - T_{slab}}{R_{T1}} = \frac{281 - 271}{R_{w1} + R_{s1} + R_{w1}} = \frac{10}{\frac{ln(2.2/2)*0.25}{2\pi*0.42} + \frac{0.25}{1.8*1.33} + \frac{1}{10.5}} = \frac{10}{0.216} = 46.23 \left[W/m^2 \right]$$

To know the surface temperature of the slab, we use the same equation by considering the temperature difference between the slab and the air and the convection heat transfer coefficient as thermal resistance:

$$q_{l1} = \frac{T_{slab} - T_{air}}{\frac{1}{h_c}}$$

$$T_{slab} = T_{air} + q_{l1} * \frac{1}{h_c * s} = 271 + 46.23 * \frac{1}{10.5} = 275.38 \ [K] = 2.40 \ [^{\circ}C]$$

The slab temperature using the shape factor method is equal to 2.40 °C.

This computation was performed following the solution of the solved problems in the book "Solving Direct and Inverse Heat Conduction Problems" written by Jan Taler and Piotr Duda [16]

Numerical solution

The numerical Comsol software is using finite elements method to determine the slab temperature. A brief description of how the software computes the simulation is given here: The first step of the numerical simulation is to mesh the geometry into elements and each element is composed by nodes. The second step is to choose a temperature function within each element using its nodal value . Then we should define the heat flux/temperature or the temperature gradient/temperature relationship in the elements. We derive the conduction matrix for each element and we assemble the element equations to obtain the global equations by introducing the boundary conditions. Finally, we find the temperature for each node of the elements and the element temperature gradients.

Using the slab presented in figure 2.2, we will apply the same convection heat flux due to the wind on the top and the bottom of the slab with a fluid injected at constant temperature. The figure 2.3 shows the numerical results of the slab temperature on the top of the slab in a stationary state.



Figure 2.3: Top slab temperature

The average temperature of the slab surface is equal to 2.35°C. The average surface temperature using the shape factor method is equal to 2.40 °C. Hence, we can say that the analytical method provides a good approximation of the slab temperature, which is confirming the results found in [36].

Now, after the validation of the equivalent heat resistance method allowing to know the slab temperature, in the next section, we will use the same method to determine the relationship between the power injected in W/m^2 and the fluid temperature as function of the geometry and the material composing the system (slab + hydronic pipes).

2.3 Analytical determination of the input fluid temperature for a given heat requirement on the slab

We will use now the Ashrae equations in order to determine the heat requirements for the de-icing function of the snowfall rate. We will choose the lowest level of service given by the Ashrae which correspond a snowfree area ratio A_r of 0. It means that we accept that the slab is covered by the snow during the precipitation event, however the melting rate will be the same than the snowfall rate. The wind and the radiation losses are so not considered in the heat requirements because the slab is thermally insulated by the snow. We saw in the section 2.1 that the air temperature doesnt influence a lot the heat required especially when the convection and radiation losses are not considered. We choose an arbitry air temperature equal to -2° C.

In a second phase, using those heat requirements, we will determine analytically the input fluid temperature required to provide the power calculated (see this section) and in the next section, we will see how we can calculate the required number of energy piles to provide this heat and we will conclude on how we can know more about the feasibility of such a melting system.

The heat required to melt the snow is the sum of the sensible heat flux q_s and the latent heat flux q_m , which are function of the rate of snowfall and the ambient temperature. The sensible heat flux is the heat flux required to raise off the snow directly in contact with the slab to the melting temperature. A liquid film between the slab and the snow layer will be formed at a temperature of 0.56°C ([18, 40]).

$$q_s = \rho_{water} s[c_{p,ice}(t_s - t_a) + c_{p,water}(t_f - t_s)]/c_1$$
(2.15)

The latent heat flux is the heat flux required to melt the snow which is above this liquid film.

$$q_m = \rho_{water} sh_{if} / c_1 \tag{2.16}$$

where
ρ_{water}	density of water, kg/m^3
s	snowfall rate water equivalent mm/h
	(taken as 20 $\%$ of the effective snowfall
	rate)
$c_{p,ice}$	specific heat of ice $J/(kg.K)$
t_s	melting temperature $^{\circ}C$
t_a	ambient temperature coincident with
	snowfall $^{\circ}C$
$c_{p,water}$	specific heat of water $J/(kg.K)$
t_f	liquid film temperature $^{\circ}C$
c_1	$3.6 * 10^6$
h_{if}	heat of fusion of snow J/kg

The table 2.5 present the heat flux required to increase the ice temperature to 0° C as function of snowfall rate for an ambient air temperature of -2° C.

Effective Snow depth [mm/h]	Snowfall rate water equivalent [mm/h]	Sensible heat flux $q_s \; [W/m^2]$
5	1	1,8
10	2	3,7
15	3	5,5
20	4	7,3
25	5	9,2

Table 2.5: Sensible heat flux needed in function of snowfall rate

The table 2.6 present the latent heat flux required in function of snowfall rate.

Effective Snow depth [mm/h]	Snowfall rate water equivalent [mm/h]	Latent heat flux $q_m \; [W/m^2]$
5	1	93
10	2	186
15	3	278
20	4	371
25	5	464

Table 2.6: Latent heat flux needed in function of snowfall rate

The heat requirements as function of the snowfall rate are the sum of the latent and sensible heat flux (see tables above).

To determine the required fluid temperature to ensure the heat required to melt the ice, we will base our calculations on the same slab case of the last section. The geometrical parameters are listed in the table 2.4.

Thanks to equation 2.8, the thermal resistance R_{T2} is equal to

$$R_{T2} = R_w + R_s + R_i = \frac{\ln(2.2/2) * 0.25}{2\pi * 0.42} + \frac{0.25}{1.8 * 1.33} + \frac{x_c}{2.1} \approx 0.009 + 0.104 = 0.113 \left[m^2 K/W\right]$$

The term R_i is very small and so it is ignored.

$$(q_m + q_s) = \frac{T_{fluid} - T_{slab}}{R_{T2}}$$

$$T_{fluid} = (q_m + q_s) * R_{T2} + T_{slab}$$

When there is a snow layer, we will consider that T_{slab} is equal to the liquid film temperature which is equal to 0.56 °C.

The fluid temperature required to de ice the snow is:

Snow depth [mm/h]	$q_m + q_s \; [W/m^2]$	Average fluid temperature to inject [°C]
5	94	11
10	189	22
15	284	33
20	378	43
25	473	57

Table 2.7: Required fluid temperature for a snow depth and required heat flux

The average temperature of the fluid gives an indication about the energy needed for the deicing. For heavy snows such as 2 or 2.5 cm/h, we need to inject very high fluid temperatures below the slab. If the heated slab is large, the energy needed to inject those fluid temperature could be very important and require a huge heat source (see next section).

Those fluid temperature can be used to design other melting system such as boiler-powered system if the a geothermal system doesn't fulfill the thermal needs.

Moreover, those temperatures can be also used to simulate the induced thermal stresses in the slab when the system operates. In the chapter 4, we will study more in details the thermal stresses induced.

In the next section, we will see how we can provide this energy from the energy piles and its feasibility. For this purpose, we will see how many energy piles (combined with a heat pump) are needed to provide this energy.

2.4 Determination of the required pile number and feasibility of bridge deck snow melting system based on energy piles

In the paper, "Feasibility of geothermal heat exchanger pile-based bridge deck snow melting system: A simulation based analysis from Han, C., & Yu, X. (Bill)" [21], the authors gives a gross estimation of how to evaluate the feasibility of a snow melting system using energy piles. The feasibility is depending directly of the number of energy piles supporting the bridge and their propreties and the local weather conditions of the bridge as well as the performance of the used heat pump. For one bridge deck case, they show what are the energy requirements at 10 different locations in the USA (with different weather conditions), then, they conclude by giving the required pile number (as function of different energy pile type and different

injected velocites) to ensure the de-icing and so the feasibility of bridge deck snow melting system in 10 different locations.

First, they provide the heat requirements Q_{heat} for each location based on the Ashrae criterias, then they determine the required heat extracted from the soil Q_{source} when a heat pump is used. Indeed, the heat directly extracted from the soil is in general not enough to provide the required heat. A higher fluid temperature should be injected in the slab. For this purpose, a heat pump is combined to the geothermal system.

A heat pump is a thermal machine allowing the use of mechanical energy (compressor pumps) to extract heat at low temperature from a medium (e.g. soil) says "cold source" and to restore it to a higher temperature. The principle of the heat pump is simple, it is composed by a circuit where a fluid circulates on a cycle of 4 main components: an evaporator, a condenser, a compressor, and a expansion valve.

The fluid coming at low temperature from the cold source (energy pile buried in the soil) is in contact with the refrigerant fluid of the heat pump. This refrigirent fluid evaporates at the low temperature and then circulates through a compressor that compresses the gas, the phenomena of the compression will heat the gas at high temperature. This gas will be in contact with the fluid going to the slab and the heat is transfered to this fluid in the condenser. After the heat transfer, the gas becomes a warm liquid and then it is relaxed in the expansion valve and it's temperature drops by adiabatic decompression. This fluid now is colder than the fluid of the cold source and so can be evaporate again in the evaporator. This cycle is called the Carnot cycle. To ensure the work of the heat pump , we should provide an energy to the heat pump and this energy is less than the energy generated by the heat pump itself.

The performance of heat pump is indicated by its coefficient of performance (COP), which is defined as the ratio of the power supplied by the heat pump Q_{heat} to heat pump input work W (electricity consumption). The power supplied is the sum of the heat pump input work W and heat extracted from the soil Q_{source} .

$$COP = \frac{Q_{heat}}{W} = \frac{Q_{source} + W}{W} = 1 + \frac{Q_{source}}{W}$$
(2.17)

we can also write that

$$Q_{source} = \frac{COP - 1}{COP} * Q_{heat} \tag{2.18}$$

The overal supplied power needed for the de-icing Q_{heat} is:

$$Q_{heat} = q_0 * A \tag{2.19}$$

where q_0 is the heat required in $[W/m^2]$ (determined thanks to the Ashrae guidelines) and A in $[m^2]$ is equal to the heated slab area. We will calculate q_0 as:

$$q_0 = q_s + q_m + A_r(q_h + q_e)$$

where A_r is the equivalent snow free area ratio (A_r can take the value 0, 0.5 or 1), q_s is the sensible heat flux $[W/m^2]$, q_m is the latent heat flux $[W/m^2]$, q_h is the convective and radiative heat flux from the snow free surface $[W/m^2]$, and q_e is the heat required for the water evaporation $[W/m^2]$.

Once we calculate the value of Q_{heat} , we can calculate the heat extracted from the soil Q_{source} with equation 2.18.

To determine the required number of piles N, we can simply divide the heat extracted from the soil Q_{source} by the maximum power extracted by a single pile q.

$$N = \frac{Q_{source}}{q} \tag{2.20}$$

We will notice that the heat losses during the energy transfer are not considered. Those losses occur mainly in the heat pump (losses in the compression and decompression phases). and during the transfer of the fluids between the piles, the heat pump(s) and the slab.

In the prestudy done in 2017 "Development of charts for energy design of energy piles" [13], it has been demonstrated that the power extracted by a single pile q is depending on several parameters such as:

- Number of pipes in the pile (highest influence)
- Pile length (highest influence)
- Solid and fluid thermal conductivity
- Solid and fluid specific heat
- Presence of groundwater flow (depends on flow velocity)
- Pile diameter
- Pipes layout
- Velocity of fluid circulating in the pipes (lower influence)
- Pipe diameter (lower influence)

We have shown in the prestudy that the power extracted per meter of pile ranges between the values of 30 W/m and 70 W/m. The values of 30 W/m correspond to energy pile composed by a single U loop in a soil with a low thermal conductivity 1.5 [W/mK] and the values of 70 W/m correspond to an energy pile composed by a 5U loop in a soil with a high thermal conductivity 3 [W/mK].

Let's take an example: A bridge of 36 m length and 26 m width (heated area : 936 m^2) supported by energy piles (length: 20 m / diameter: 1.2 m) should be heated for de-icing

purpose. The slab parameters are listed in the table 2.4. We will make the hypothesis that the piles are buried in a soil with a high conductivity of 3 [W/mK] and so the heat extracted per meter of pile is about 70 W/m. Considering a geothermal heat pump with a COP of 3, the heat extracted per pile is 2100 W.

For the heat requirements, we will refer to the same requirements found in section 2.3; they are given in table 2.7. The level of service is considering an equivalent snow free area ratio A_r of 0.

Snow depth [mm/h]	$q_m + q_s$ $[W/m^2]$	Power needed for the de-icing Q_{heat} [kW]	Meter of energy pile needed to de ice 1 m^2	Heat extracted from the soil Q_{source} [kW]	Required number of energy piles	Average fluid tem- perature to inject [°C]
5	94	88	0.89	59	43	11
10	189	176	1.8	117	84	22
15	284	265	2.7	177	127	33
20	378	353	3.6	235	167	43
25	473	442	4.5	295	210	57

Table 2.8: Required number of piles for different snowfall rates and corresponding injected fluid temperature

In the table above, we can see what represent the energy requirements Q_{heat} to heat the bridge deck in terms of average fluid temperature injected in the slab (calculated in the last section) and in terms of required number of energy piles as function of the rate of snowfall (or desired melting rate). The numbers of meter of energy pile needed to de ice 1 m² are also presented.

We can notice that even with the lowest level of service (equivalent snow free area ratio A_r equal to 0) and a high heat extraction rate from the energy piles, a huge amount of piles is needed to de ice a bridge deck with a surface of 936 m^2 . Indeed, to melt, 5 mm of fallen snow per hour, we need 43 energy piles with a length of 20 m and a diameter of 1.2 m providing a important extracting rate of 70 W/m. In terms of fluid temperature, it represent an average fluid temperature below the pavement equal to 11°C. The feasibility of deck de-icing using energy piles can be discussed.

In the paper "Feasibility of geothermal heat exchanger pile-based bridge deck snow melting system: A simulation based analysis from Han, C., & Yu, X. (Bill)"[21], it has been founded also huge number of energy piles for the majority of the studied cases which is coherent with the our results.

We will add few comments about the results:

- The powers needed for the de-icing even for small snowfall rates are huge comparing to the potential heat extracted from the soil which implies a important number of energy piles.
- If the number of energy piles fixed by the structural bridge needs is lower than the required energy piles, the power injected to the bridge will be automatically less than the heat requirements for the de-icing. The de-icing will be done but will take more time.
- If the local administration accepts that the deicing can last more time (5 or 10 hours after the snowfall event), in this way, the de-icing will be insured in more time and we will only avoid large traffic interruptions.
- In order to decrease the overall energy requirements and so reduce the number of energy piles, we can reduce the heated area of the bridge deck (by optimising the heated zones see section 4.2), we can adapt the best configuration during the fluid injection in the hydronic pipes (see sensitivity analysis 4.1.3), we can also do a combined system including geothermal source and other type of source such as boiler-powered source (by gas, oil, or solar if possible).

Nevertheless, considering the small amount of energy extracted from energy piles compared to the energy requirements for the de-icing, we can conclude that the thermal potential of the energy piles is more suitable to ice prevention (anti-icing) than quick snow melting.

Feasibility of bridge deck snow melting system based on energy piles

In order to conclude on the feasibility to implement a de-icing system using energy piles for other projects, it is important to know:

- What is the power requirements we need: principally at which melting rate we want to design the system (this melting rate is in general equal to the average snowfall rate at the project location)? and at which level of service (equivalent snow free area ratio)?
- The deck surface to be heated
- The power and COP of the heat pump used.
- The potential heat extracted per meter of pile (which is function of several parameters listed above) and their length.

Those data should be known at the begining of the project thanks to a close collaboration with the engineering firm responsable of the project. A gross evaluation of the feasibility of such a system is known by simply calculating the required number of piles following the method explained above and compare the founded result with the planned number of piles decided by the engineering firm.

Chapter 3

Real scale bridge in Jiangyin, China

During my master thesis, I had the chance to work on a real scale project in China (Jiangyin City). The objective of this project was to equip one part of the bridge deck with hydronic pipes in connection with few energy piles and then to see the thermal and the structural behaviour of the bridge deck and the energy piles when the melting system operates. Since my arrival was coincident with the beginning of the construction of the bridge, I had the chance to assist to the construction of the main elements of the bridge (foundations and bridge deck) and work directly on the installation of the pipes inside the structure.

In this chapter, we will decribe the bridge project and it's main features, then we will explain the experimentation project on the bridge and the different steps of the hydronic pipes installation. We will finish this chapter by determining the thermal needs for the de-icing considering the local weather conditions of Jiangyin and compare them to the potential of heat extraction from the bridge energy piles.

3.1 Description of the bridge

The construction of this bridge in Jiangyin was decided by the local authorites in order to respond to the fast extension of the city. This bridge crosses a small river of 28 m width facilitating the vehicules circulation.

It is a 3 span prestressed bridge of 32 m length, 26 m width with 0.76 m deck thickness (see figure 3.1). The bridge deck is supported axially by 4 row of 5 piles. The piles of each row are connected thanks to transversal beams.



Figure 3.1: Longitudinal view of the bridge

We can see in figure 3.2 a transversal view of each set of piles. The piles are spaced by 4.5 m each and are connected to transversal beams which have 1.1 m thickness and 1.3 m width.

The bridge deck, composed by prestressed concrete panels with a thickness of 0.66 m are simply laid on the transversal beams by the intermediary of elastic joints (figure 3.7). Those joints permit a free displacement in the longitudinal and transversal way. A concrete reinforced slab with a thin asphalt layer is placed on the bridge deck and will be in direct contact with the vehicules.



Figure 3.2: Transversal view of the bridge

The concrete panels composing the bridge deck are "pre-stressed" by being placed under compression before to support any loads. This compression is produced by the tensioning of high tensile steel wires located within the panels. This operation of pretensionning is made in the concrete factory before bringing the panels to the construction site.

The aim of the prestressing is to improve the performance of the structure during its service (structural capacity and serviceability) compared to the classical reinforced concrete. Since the strength of the concrete in compression is by far larger than it's strength in tension, the prestessing process is advantageous because it keep the concrete deck completely in compression initially. When the bridge is under an important load, the compression in the lower part of the panels will be canceled by the tensional stresses created by the load whereas the compression in the upper part of the panel will be greater than the compression in a normal reinforced panel. The in-service panel deflection will also be less than a standard reinforced panel (see figure 3.8 for the prestressed slab).

The piles are semi floating piles with a diameter of 1 m and a length of 20 m. Two sets of piles are driven deep below the river bed and the 2 others are placed directly on the ground. The soil layers crossed by the piles are globally composed by clay and silt: the soils characterisitcs are given in the section 3.2.3. The piles are constructed as drilled piles. When drilling through weak soils (such as silt and soft clays), drill holes require temporary support. This support can be a temporary metallic casing or can be done by the injection of a fluid under pressure that retains the borehole wall (for example bentonite injection).

In Jiangyin project, the borehole wall was supported by the injection (under pressure) of mud with water. Firstly, the borehole is drilled a little larger than the requested diameter. The liquid mud+water is injected in the hole maintaining the borehole wall. Then, the reinforcement cage of the pile is put in the hole and the concreting was done from the bottom to the top of the pile. Since the density of the mud is lower than the density of the concrete, the concrete will take the place of the mud. The slurry will come out from the hole (see figure 3.5).

Two kinds of concrete were used for the bridge deck and for the piles. For the bridge deck, the concrete used is C40/50 and for the piles the concrete used is C30/37.

During my stay in China, the bridge was under construction. The first phase of the construction was to drill and set up the 4 set of piles and connecting each set by transversal reinforced concrete beams. Afterwards, the bridge deck composed by prestressed panels was placed over the beams. The last phase was to build the ramp between the bridge and the road and to finish the asphalt layer on the bridge. The next photos are showing the main steps of the construction of the bridge.



Figure 3.3: General view of the site in the beginning of the construction



Figure 3.4: Piles drilling 1



Figure 3.5: Injection of the mud+water to support the borehole wall



Figure 3.6: Construction of the transversal beams



Figure 3.7: Laying of the prestressed slab on the beams

The next picture shows the prestressed panels laying on the beams. They are brought from the factory in slices of 1 meter width and a length of 10 m or 16 m depending if they are in the central span or in the side spans of the bridge. A thin layer of concrete is put in between each panel to join them.



Figure 3.8: Prestressed slab

3.2 Project introduction

3.2.1 Deck de-icing project

The bridge de-icing experimentation was done for a small part of the bridge: only 1 set of piles are used as energy piles and the deicing system is installed on the first span slab of the bridge (length of the span 10 m) and will cover only the half of it transversely. It corresponds to 81 m² of slab equiped with hydronic pipes (see figure 3.1). The slab thickness is 0.76 m.

The next figure present a top view of the bridge deck. We can see that the bridge is a 2 way bridge where for each way, 2 lanes are dedicated for cars and one lane for the 2 wheels vehicules. The heated slab is as indicated in figure 3.1.



Figure 3.9: Top view of the bridge

The layout of the pipes in the heated slab zone with the exact measurements is given in the drawing below (Values are in cm). The choice of this layout is discussed in section 4.2. The total length needed for the pipes is about 300 meters. The heated slab is composed by 4 heated panels (4 inlet/outlet). Two panels are composing the bike lane, and for the car lanes, one panel is used by lane. The objective to seperate the heated zone into several heated panels was to have the possiblity to test each part of the heated slab separetely in the experiment or to concentrate all the heat in a small zone in order to have a higher deicing efficiency. Moreover, the choice to divide the heated zone in several panels is to obtain homogenously heated zones. (we will see further in this report the importance of the pipe length)

PE-RT tubes with 20 mm as an internal diameter and 2.0 mm thickness were used. The distance between each tube is 25 cm and the loops are done by hand with a bending radius of 25 cm. The pipes are buried 10 cm below the surface.

The PE RT are used for the slab because they allow a higher temperature fluid inside the tube, they are also more easy to bend by hand and more resistant to oxidation. They are communly used for the radiant slabs. The diameter of 20 mm was chosen because the suppliers in Nanjing have only this type of diameter. Since, we have a small heated zone, it was not possible to order another type of tubes.



Figure 3.10: Layout of the pipes in the heated slab

For the numerical simulations done in chapter 4, (sections 4.2 and 4.3), we will concentrate only on the deck part that interests us. The geometric propreties of this slab are:

Slab length [m]	10
Slab width [m]	26
Slab thickness [cm]	76
Distance of the pipes from the top of the slab [cm]	10

Table 3.1: Geometric propreties of the slab for the numerical simulations

The 5 energy piles are equipped with different types of layout. Three of them are equipped with 5 U loop pipes in series, 1 with 3 U loop in series, and the last one with spiral layout. The pipes are then connected to the pump passing through the beam below the bridge deck. The aim of equipping the system with 3 kinds of layout is to test their thermal efficiency and the thermo-mechanical behaviour of each kind of pile.

The concrete cover of the piles is 75 mm. The pipe loops are located at 50 cm from the base of the pile and at 60 cm from the top of the pile in order to avoid problems due to the concreting. For the 5 U loop pile, the distance between each pipe is equal to 26 cm while for the 3 U loop pile, this distance is equal to 42 cm. The location of the loops is showed in the figure 3.11.



Figure 3.11: Location of the pipes in the piles

For the spiral loop pile, the distance between each tube is equal to 20 cm. A schematic draw is also presented.



Figure 3.12: Schematic representation on the spiral energy pile

For the piles, PE-XA tube with 25 mm as internal diameter and 2.3 mm thickness were used. The loops are bended thanks to connectors and not by hand because the required bending radius of the tubes was too small comparing to the minimum bending radius acceptable for this kind of tubes.

3.2.2 Climatic conditions

The climatic conditions in Jiangyin are not very suitable to test the efficiency of the system for snow melting in the winter because the total average snowfall amount is about 6 cm a year and the snowfall precipitations occur only few days a year [14]. The air temperature in Jiangyin often drops below 0°C up to -4°C through midnight and the early morning hours, and an ice formation on roads could happen. Thus, the ice prevention will be more problematic rather than snow melting. Icy roads could be dangerous for the trafic because the car tires are not suitable for very cold condition.

The table below resumes the weather conditions in Jiangyin for the coldest months (average values calculated on the last 5 years):

	December	January	February
Average temperature	6 [°C]	$5 \ [^{\circ}C]$	6 [°C]
Lowest temperature	-4 [°C]	-4 [°C]	-4 [°C]
Average wind velocity		12 km/h	
Maximum wind velocity		20 km/h	
Average air humidy		$75 \ \%$	
Average snow amount per year		$6 \mathrm{~cm}$	

Figure 3.13: Weather conditions in Jiangyin for the coldest months

3.2.3 Soil propreties

The soil in Jiangyin is mainly a fine soil (Clay and silt). A geological investigation was done to determine the soil nature and its propreties. Several drillings were done on 65 meters depth. Three main soil layers are recognized along the pile depth. The soil layers are resumed in the table 3.2. The level 0 refers to the top level of the piles. The water table level is mesured at the same level than the river (i.e 1.5 m below the ground surface) and no groundwater flow is measured in the soil. The water level in the river raises during the summer (rain season) and

drops during the winter which keep the clay surrounding the river fully saturated (Saturation >95%) during summer and partially saturated during winter.

To know the soil properties, some samples from each layer were taken from the site to the laboratory. For the mechanical propreties, a non consolidated direct shear test with "fast shearing" was done to know the apparent cohesion and the apparent friction angle. Oedometric tests were also performed to have an idea about the compressibility of the soil and the degree of consolidation of the soils.

The consolidated direct shear test with "quick shearing" provides the apparent cohesion c_{cu} and the apparent friction angle φ_{cu} . The sample is first consolidated thanks to increments of normal stress allowing water seepage. The sample becomes then partially saturated. The aim of this test is to justify the stability of the foundations at the end of the construction. Indeed, in presence of low permeable soils, the construction time will be greater than the soil drainage, so the soil will not have the time to be drained. This theory is taken from the book "Fondations et ouvrages en terre" of Gérard Philipponnat[24].

An oedometric test is a laboratory test that measures a soil's consolidation properties. Oedometer tests are performed by applying different loads to a soil sample and measuring the deformation response. The output of these tests are used to predict how a soil in the field will deform in response to a change in effective stress. We can obtain from this test the precondolitation stress (giving an idea about the history of the sample), the compression index, the swell index and the oedometric modulus. One curve is in general plotted to know thoses values: the curve void ratio in function of the vertical stress applied (in log scale).



Figure 3.14: Void ratio curve

The void ratio e is calculated from the measured deformation as

$$\frac{\Delta H}{H_0} = \frac{\Delta e}{1+e_0} \tag{3.1}$$

where ΔH is the deformation of the sample, H_0 is the initial thickness of the sample, e_0 is the initial void ratio index (calculated from the porosity of the sample).

The compression index C_c is defined as the slope of the curve 3.14 when we are in the virgin line:

$$C_c = \frac{\Delta e}{\log(\frac{p_1 + \Delta p}{p_1})} \tag{3.2}$$

where Δe is the variation of the void ratio index between 2 loads, and Δp is the variation of the load, p_1 is an arbitrary point on the virgin line. This index provides information about the compressibility of the soil.

The compression index α_C is similar to C_c but the curve obtained from has as abscissa the vertical stress and not the logarithm of the stress:

$$\alpha_C = -\frac{\Delta e}{\Delta p} \tag{3.3}$$

where Δe is the variation of the void ratio index between 2 loads, and Δp is the variation of the load (without applying the logscale to the stress). This index is given in the geological survey of the project. This index provides us also with information about the compressibility of the soil:

- if $\alpha_C < 0.1 M pa^{-1}$, the soil is lowly compressible,
- if $0.1 M pa^{-1} \leq \alpha_C < 0.5 M pa^{-1}$, the soil is moderately compressible,
- if $\alpha_C \ge 0.5 M p a^{-1}$, the soil is highly compressible

The oedometric modulus E_{oed} is equal to

$$E_{oed} = \frac{1 + e_1}{\alpha_C} = -\frac{\Delta p}{\Delta e} (1 + e_1)$$
(3.4)

where e_1 is a value of the void ratio index when the sample is in the consolidation phase (at the virgin line).

The preconsolidation stress σ_p is the first value of stress obtained when the virgin line begins. With this value, we can distinguish between different type of soils:

• If the vertical stress applied on the sample before it's extraction $\sigma_z < \sigma_p$, the soil is overconsolidated

- If $\sigma_z = \sigma_p$, the soil is normaly consolidated
- If $\sigma_z > \sigma_p$, the soil is under consolidated

In the geological survey of the site of Jiangyin, only the value of the oedometric modulus E_{oed} and the compression index α_C are given.

The table 3.2 resumes the soil propreties for the different layers:

For the 3 layers, a consolidated direct shear test with "quick shearing" was carried out. We can see in the results that the apparent friction angle is not equal to 0 but in the same time, the soils are fully saturated (Sr > 95%). Indeed, during the laboratory tests, the degree of saturation decreases because the samples are consolidated before applying the shear stress. Moreover, some water is evaporating with time. That's why we are measuring values of friction angle greater than 0.

An apparent cohesion was measured for the 3 layers. According to the theory explained in the book "Soil mechanics, work team at Hohai university" [26], this means that our soil is overconsolidated. Indeed the failure envelope for normally consolidated soils under consolidated-undrained condition is a line through origin and the angle of the line is φ_{cu} (the cohesion is equal to 0). However if the specimens are overconsolidated, there is less void ratio before shear than in normal consolidation. The effective stress at failure is larger than in normal consolidation and the shear stress is higher: An apparent cohesion is then measured. The curve deviatoric stress versus deformation of overconsolidation clay is similar to that of a dense sand with peak value and it decreases with the increase of axial strain. So the values measured for the 3 layers are peak values.

The pile crosses a first layer moderately compressible (Compression index = 0.23 [1/[MPa]]) then a more compressible layer where the soil is more like a viscous liquid (Its compression index = 0.5 1/[MPa] and the water content of this layer exceeds it's liquidity limit [%]: 44.7 % > 40.7%). Then the pile is embedded along 13 m in a lower compressible layer (Compression index = 0.20 1/[MPa] with an apparent cohesion of 35 KPa. Therefore, we can say that the piles are mostly embedded in a stiff soil, we can consider them as semi floating piles.



Figure 3.15: Layer location

Porosity [%]		44.3	55.7	39.6	Compression index α_C [1/[MPa]]		0.230	0.5	0.2
Water content [%]		28	44.4	23.4	Oedometric modulus E_{oed} [MPa]		×	ŋ	11.5
Apparent friction angle φ_{cu} [°]	I	12.6	8.6	15.3	Plasticiy limit [%]	I	19.9	27.4	20.6
Apparent cohesion c_{cu} $[KPa]$		29	9.3	35	Liquidity limit [%]		33.8	40.7	35
Density (saturated) [g/cm ³]		1.94	1.73	2.03	Saturation ratio [%]		96.5	95	97
Soil type	Backfill material	Moderately plastic Silty clay	Low plastic Clay	Moderately plastic Silty clay	Soil type	Backfill material	Moderately plastic Silty clay	Low plastic Clay	Moderately plastic Silty clay
Level [m]	0-0.5	0.5 - 1.5	1.5-7	7-	Level [m]	0-0.5	0.5 - 1.5	1.5-7	7-
	Layer 0	Layer 1	Layer 2	Layer 3		Layer 0	Layer 1	Layer 2	Layer 3

Table 3.2: Layer propreties

Concerning the thermal properties, they were not yet measured in Jiangyin site during the redaction of this report. The results presented below are from another site where the soil has the same nature than in Jiangyin site (Silty clay) and were obtained thanks to a KD2 sensor. The latter consists on a dual-needle sensor inserted into the soil which indicates the thermal conductivity and its volumetric specific heat capacity. The thermal conductivity is $1.52 \ [W/mK]$ and the specific heat capacity is $3.2 \ [MJ/m^3K]$. Those values are coherent with the thermal propreties of saturated clay measured in others projects [38]. Unfortenutely, a soil with these thermal propreties will induce a low heat exchange between the soil and the energy piles, this will limit the heat power injected to the bridge deck for de-icing purpose.

Nevetherless, the soil temperature was measured on site thanks to the thermistors burried in the soil. The soil temperature is increasing lineary from the ambiant temperature at the ground surface (2°C) to 20°C at 5 m depth. This ground temperature is constant from 5 meter till the piles end.

For our numerical simulations, we will admit those values.

Table 3.3: Soil thermal propreties

Specific heat capacity (MJ/m^3K)	3.2
Thermal conductivity (W/mK)	1.52

3.3 Experimental works on Jiangyin site

3.3.1 Construction of energy piles

As mentionned before, only one set of piles were used as energy piles. The main reasons why the experimentation was limited to only 5 energy piles was that the local adminstration of Jiangyin city limited the scale of the project. Moreover the budget allocated to this real scale experiment was limited. The next figure shows a view from the top to see where are placed the piles.



Figure 3.16: Top view of the bridge (piles location)

In order to measure the thermo mechanical behaviour of the energy piles, several sensors were introduced in the piles. The figure 3.17 shows the location and the type of sensors embeddedin and surrounding the 5 energy piles. The piles are principally equipped with sensors which have 2 functions: they mesure at the same time the strain and the temperature at the pile shaft (strain gages and thermistors). Those sensors are attached to the reinforced cage. The pile B (5U loop) and the pile D (spiral) will be the 2 main test piles: they are equipped with those sensors each 2 meters while the remaining 3 piles are equiped with those sensors each 5 meter. The aim of using those sensors is to measure the pile temperature during the deicing or during the thermal recharge and to see how the thermal strain is evolving by temperature difference.

In addition to those sensors, 3 small boreholes of 15 cm are drilled next to the pile B and spaced from one to another by 1 m. Those boreholes contain also thermistors (in order to measure the soil temperature) and pore water transducers to measure the pore water pressure surrounding the pile. One borehole is drilled to the level of the pile base and is equipped with sensors at 5 m and 15 m while the 2 other boreholes are drilled up to 10 meters below the surface and are equiped with the 2 sensors each 5 m. The objective is to investigate the influence of the energy piles (during the cooling and the heating) on the soil temperature at different distances from the pile and see how the porewater pressure is evolving when there is a temperature gradient.

We notice that the sensors were the most expensive features in all the experimentation: the combined strain and thermistor sensor cost 400 rmb/piece (60 CHF/piece), the thermistors cost 40 rmb/piece (6 CHF/piece) and the pore water transducers cost 600 rmb/piece (90 CHF/piece). The total cost of the sensors for the energy piles is about 21840 rmb (3275 CHF).



Figure 3.17: Sensors in piles

However, the cost of the material needed to equip the piles with the tubes is less significant compared to the sensors. About 1000 meters of PE X tubes were necessary to equip the piles. The price of the PE X is 3 RMB/meter (0.44 CHF/m). 200 meters of tubes were necessary for each 5 Uloop pile and spiral pile while the 3 Uloop pile needed 120 meters of tubes. Moreover 35 connectors (3.41 RMB/piece (0.90 CHF/piece)) were bought in order to connect the tubes when we needed to bend the pipes. The tubes are connected to the reinforced cage thanks to metallic and plastic small wires. A fusion welder was also needed to stick the connectors and the tubes: The fusion welder is simply a heater for the PE tube, which allows to stick the tube with the connector. The total cost for the pipes and connectors for the energy pile is about 3120 RMB (470 CHF).

In terms of installation time, we spent 4 to 5 hours for each 5Uloop pile as well as for the spiral pile. Three hours were enough for the 3U loop pile. For the sensors, about 2 hours by pile were necessary to install them.

I had the chance to work directly on the installation of the tubes in the piles. We enumerate below the different steps of the construction of the energy piles (5Uloop and 3U loop):

• Phase 1: The pipes PE XA were delivered to the site wrapped from the manufacturer and fitted with protective caps to prevent debris from entering the pipe. The first step was to straighten the pipe roll and cut it on slices of 22 m or 19 m (depending if it is the outlet/inlet pipes or the connecting pipes).

- Phase 2: We insert the inlet tube and fix it to the reinforcement cage thanks to the plastic connecting wires.
- Phase 3: Following the drawings of the energy piles (see figure 3.11), we assemblate the next tube with the previous one using a connector. A fusion welder is needed to connect the pipes with the connector.
- Phase 4: We repeat phase 3 for all the tubes until reaching the outlet pipe.
- Phase 5: Knowing the location of the sensors in the drawing 3.17, we fix them to the reinforcement cage with the metallic wires and we insert the electric wires into PE tube to protect them.
- Phase 6: We inject water in the tubes to see if there is no damage occured during the construction and no leakage observed in the tubes.
- Phase 7: The pile is driven into the ground with all the tubes and the sensors and the concreting is done.
- Phase 8: We checked all the sensors with an ampermeter to see if they are still working. We proceed to a flow test into the tubes to see if there is no broken tubes after the concreting.

Some pictures representing the different phases of the construction are given below:





Fixation of the tubes on the reinforcement cage

Connection of the tubes



fixing of the sensors



Pile lifting





Driving off the pile inside the borehole

Pile after concreting

For the Spiral loop pile, the connectors were not needed, one continuous tube was bended by hand following the drawings. The spiral loop pile was more challenging because the tube was first rolled-up to reach the bottom and then rolled-up until reaching again the top of the pile. One student was inside the reinforcement cage during all the installation to bend the tube following the spiral shape and then to fix it to the reinforcement cage. The spiral loop is more adapted to big diameters. For small diameters, this layout becomes hard to do.



Spiral loop pile

5U loop pile

As it is recommended by the GSHP Association [6], during the concreting of the piles, the thermal loops should be filled up with water and subjected to pressure in order to prevent the pipe from being crushed by the concrete shrinkage. Unfortunately, this procedure was not done in site (absence of water pump). Hopefully, all the energy piles were tested after the concreting and no particular reporting had been notified.

The problems encountred to build those energy piles were mainly during the introduction of the pile inside the ground. Since the reiforcement cage is inserted in the ground all at once, the reinforcement cage should be well tighted to the truck crane. The challenge was to find the place to tight the cage without damaging the tubes and the sensors.

Another issue was to keep the sensors fare from the pile wall in order to avoid damaging them. Hence, during the introduction of the pile, the pile should be inserted straight and slowly to control whether every thing is going well.

The row of piles is connected to a transveral beam at the top, thus the tubes of each pile were put in the beam and driven out to one side of the beam thanks to special connectors (connecting the pipes going in the axis of the beam and the pipes of the energy piles). The pipes were also here connected to the reinforcement cage of the beam before it's concreting. The next photo presents the beam with all the tubes inside.



Figure 3.18: Pipes within the beam

3.3.2 Construction of the hydronic pipes in the bridge deck

Two months after the construction of the energy piles, we installed the hydronic pipes in the bridge deck. The concrete prestressed panels were placed and connected to each other. Above the prestressed panels, a thin reinforced concrete slab was constructed to which we fixed the hydronic pipes into its reinforced cage. The bending of the tubes were done in this case by hand keeping a spacing of 25 cm between the tubes. A particular attention was needed in order to not brake the tubes during the bending. The bike lane was clearly more difficult to set up than the 2 car lanes because of the numerous curves of the pipes trajectory. Another challenge was to respect the drawings with precision and to define external markers in order to heat the right zone. Since the deck width is 26 meters, the visual markers were difficult to find.

The final layout for the hydonic pipes is presented below:



Figure 3.19: Layout of the pipes in the heated slab

To install the tubes, we spent 1 hour for the preparation of the slab, 2 hours for each car lane (the 2 lanes on the right) and 3 hours for the bike lane (lane on the left). For the sensors, about 3 hours were necessary to install them. The different phases of the construction of the hydronic pipes are listed below:

- Phase 1: Preparation: outline the layout of the pipes directly on the slab surface thanks to spray print cans. Textile yarns fixed at the boundaries of the deck were also used as visual markers.
- Phase 2: For each heated panel (panel means a continuous tube with an inlet and outlet), we fix our pipes on the reinforcement cage thanks to the plastic connecting wires. We will pay great attention when we bend the tubes.
- Phase 3: Knowing the location of the sensors, we fix them to the reinforcement cage using metallic wires and then we insert the electric wires of the sensors into PE tube to protect them.
- Phase 4: We inject water in the tubes to see if there is no leakage in the tubes.
- Phase 5: We proceed to the concreting of the slab.
- Phase 6: We check all the sensors with an ampermeter to see if they are still working, we also inject water into the tubes to see if there is no broken tubes after the concreting.

Before the installation of the tubes, we realized that the timber formwork placed by the workers (for concreting the slab) was crossing in certain locations the trajectory of the tubes.

A small offset of all the pipes was necessary to overcome this problem. We could avoid such inconvinences by means of a better communication between the construction firm and the engineers.

No important problems were notified during the installation of tubes except difficulties to bend the tubes: the manufacturer annnounced that the minimum bending radius of the tubes is 11.5 cm, but in reality the bending radius was higher. This problem leads us to to bend the loops with a higher radius and then to come back to the right spacing along the straight lines.

The next photos are showing the pipes fixed to the reinforced cage.



Figure 3.20: Hydronic pipes before concreting

The location of the sensors embedded in the slab is showed in the figure 3.19. The sensors are

also combined sensors (strain gages with thermistors). Three sensors measure the strain and temperature in the transversal direction of the slab and 3 others measure the strain following the bridge axial direction. For each layout (bike lane and track lanes), 2 sensors will measure the strain and temperature in the 2 directions (axial and transveral direction). One other sensor will measure the axial strain between the 2 heated lines (car lane) and another one placed 1.2 m far from the heated zone will measure transveral deformation between in the middle of the slab (between the heated and the non heated part). The goal of those sensors was to measure the thermal and strutural response of the bridge in the heated zones and to see the influence of this heating in the non heated zones.

3.3.3 De-icing test

A huge snowfall occured the 24th and 25th of january 2018. The depth of the snow accumulated was about 5 cm. We decided to carry out in a hurry a pre test to check if the hydronic pipes on the slab are working. We implemented a simple system where we heat only one panel (for car lane panel). This basic system consisted of:

- A water tank
- A water heater is submerged inside the water tank
- A water pump injecting the water at flow rate of $0.9 \text{ m}^3/\text{h}$ (velocity of 0.8 m/s)
- A pipe insulation film for the pipes in contact with the air

A heater submerged is heating a small water tank. The inlet pipe is pumping the water from the water tank and the outlet pipe rejects directly the water in the same tank. We started the system few hours before the end of the snowfall. 12 hours were necessary to melt the snow above the hydronic pipes.



Figure 3.21: Snow depth



Figure 3.22: Melted snow in the slab

3.4 Thermal Needs

3.4.1 Determination of the heat requirements for the de-icing for Jiangyin bridge

Using the ashrae guidelines and based on the weather conditions in Jiangyin, we can determine the heat requirements needed in this city. In winter, the coldest months are from december to february. The weather data given in the table below are taken from the weather office of Nanjing and from the website "worldweatheronline.com"[14]. These average values are taken from the last 5 years.

	December	January	February
Average temperature	$6 [^{\circ}C]$	$5 \ [^{\circ}C]$	6 [°C]
Lowest temperature	-4 [°C]	-4 [°C]	-4 [°C]
Average wind velocity		12 km/h	
Maximum wind velocity		20 km/h	
Average air humidy		75~%	
Annual snow amount in the overall period		$6 \mathrm{cm}$	

Figure 3.23: Weather conditions in Jiangyin

During the 5 last years, the average snow amount per year was about 6 cm and the snow precipitation occur 4 days to one week per year. However in 2011 and 2013, the snow amount reached 15 cm per year. In 2011, the snow precipitation lasted 10 days while in 2013, it lasted only 3 days. The specificity of this area is that the snow precipitations are not frequent but condensed in few days. These snow days are quite heavy.

To design our system, we should know what is the heat requirements to satisfy a certain level of customer satisfaction. For this purpose, we should know, when there is a snowfall event, the hourly values of the precipitation amount in this zone, the ambient temperature, the wind speed and the dew point temperature. We should also define the equivalent snow free area ratio accepted.

Unfortunately, we don't have all the data concerning Jiangyin weather. Especially, we don't have the hourly snowfall rate but only the total amount of snow accumulated and the number of snow days. To solve this issue, we will design our de-icing system in such a way that it is able to melt a middle-heavy snow with a snowfall rate of 1.5 cm/h, an air temperature of $-4^{\circ}C$ and a wind velocity of 12 km/h.
The bridge deck in Jiangyin is 26 m width and 32 m length with a thickness of 76 cm. The pipes are embedded 10 cm below the slab surface. The concrete emissivity is equal to 0.94.

Using the equations given by the ashrae guidelines (see section 2), we calculate the heat required for de-icing:

The sensible heat flux q_s :

$$q_s = \rho_{water} s[c_{p,ice}(t_s - t_a) + c_{p,water}(t_f - t_s)]/c_1$$

= 1000 * (15 * 0.2) * (2100(0 + 4) + 4290(0.56 - 0)/(3.6 * 10⁶))
= 3 W/m²

The latent heat flux q_m :

$$q_m = \rho_{water} sh_{if}/c_1 = 1000 * (15 * 0.2) * 334000/(3.6 * 10^6) = 278 W/m^2$$

The convective and radiative heat flux from a snow free surface q_h :

$$q_h = h_c(t_s - t_a) + \sigma \varepsilon_s(T_f^4 - T_a^4) = 9.8(0.56 + 4) + (5.67 \times 10^{-8}) \times 0.94 \times (273.7^4 - 269.15^4) = 64 W/m^2$$

with the convection heat transfer for the wind h_c :

$$h_c = 0.037 (\frac{k_{air}}{L}) Re_L^{0.8} Pr^{1/3} = 0.037 * (\frac{0.027}{26}) * (6.67 * 10^6)^{0.8} * 0.7^{1/3} = 9.8 \ W/(m^2 * K)$$

$$Re_L = \frac{12 * 26 * 0.278}{1.3 * 10^{-5}} = 6.67 * 10^6$$

The length of 26 m was chosen as a characteristic length of the slab in direction of the wind. Since the convection heat transfer is function of $L^{-0.2}$, we chose the shortest dimension of the slab for the design.

The evaporation heat flux q_e is the heat needed to evaporate the melted ice (water) from the slab:

$$q_e = \rho_{dryair} h_m (W_f - W_a) h_{fg} = 1.33 * 0.0814 * (0.0039 - 0.0031) * 2499 * 10^3 = 23 W/m^2$$

with the mass transfer coefficient h_m :

$$h_m = \left(\frac{Pr}{Sc}\right)^{2/3} \frac{h_c}{\rho_{dryair} c_{p,air}} = \left(\frac{0.7}{0.6}\right)^{2/3} * \frac{9.8}{1.33 * 1005} = 0.0814 \ m/s$$

Regarding the above calculations, the greatest heat requirement corresponds to the latent heat flux (which is the heat to melt the snow). In contrast, the sensible heat flux and the evaporation heat flux are very small. As the latent heat flux depends mainly on the snowfall rate, the latter is the predominant parameter for the de-icing power requirement.

Depending on the choosen value of the equivalent snow free area ratio A_r , a corresponding level of service is guaranteed. The heat required q_0 for the melting is depending on this value:

$$q_0 = q_s + q_m + A_r(q_h + q_e)$$

To satisfy that the system will melt rapidely enough the snow that the slab stays completely free of snow even during the snowfall event, the heat required should be calculated with an equivalent snow free area ratio $A_r = 1$ and all the terms of the equation are involved. If we accept that the slab will be completely covered by the snow during the precipitation and few hours after, the heat required is calculated with an equivalent snow free area ratio $A_r = 0$. In this case, the convective and radiative heat flux and the evaporation heat flux are not taken into account: (the snow acts as an insulator so there is no radiative and convective losses and no water evaporation in contact with the slab). In this case, the melting process is activated in such a way that the snow at the bottom of the layer melts at the same rate as snow accumulates.

If we choose an equivalent snow free area ratio of $A_r = 0.5$, it means that all the pavement is covered by a thin layer of snow or that only one half of the pavement area is insulated by a snow layer. Usually, for the design of such a system, using an equivalent snow free area ratio of $A_r = 0.5$ would be "reasonable for most traffic conditions [22]."

We can also derive the heat required to keep the slab above the freezing point when there is no snowfall. This value should compensate the convective and radiative heat losses q_h . Keeping the slab above the freezing temperature will prevent the creation of a thin ice layer which can be very dangerous for the vehicules. Moreover, keeping the slab surface above 0.5°C before a snow precipitation occurs, the process of deicing can directly start without considering the transient effect of the slab heating.

When we consider also the evaporation heat flux q_e in the calculations, we provide also the energy needed to evaporate the melted ice (water) from the slab. It will prevent the re icing of the melted snow keeping the slab dry.

The total heat requirements for the corresponding level of service are given in the table below. Those presented values are valid for steady state condition and not for the transient phasis. To adress this issue, the slab should be heated before the snowfall precipitation to attain the steady state condition. The time of this pre heating is called the idling time.

Provided level of service	Terms involved	Values in W/m^2	Fluid temperature needed in °C
Heat requirement for $A_r = 1$ (to keep the slab totally free of snow)	$q_s + q_m + q_h + q_e$	368	42
Heat requirement for $A_r = 0$ (if the slab is totally covered by the snow)	$q_s + q_m$	281	32
Heat requirement for $A_r = 0.5$ (if the slab is totally covered by a thin layer of snow)	$q_s + q_m + 0.5(q_h + q_e)$	324	37
Heat requirement to keep the slab above 0°C	q_h	64	8
Heat requirement to keep the slab above 0°C and dry the slab (evaporate of the liquid film)	$q_h + q_e$	87	10

Table 3.5: Heat requirements

The fluid temperature needed to provide the heat requirements are also given in the table above. Those fluid temperature are derived analytically from the equivalent heat resistance method (considering the shape factor of the deck). This method was explained in chapter 3 (section 2.3); the case of the slab studied in this chapter was similar to the slab of Jiangyin bridge.

The fluid temperature is calculated as

$$T_{fluid} = q_{required} * R_T + T_{slab}$$

with $R_T = 0.113 \ [m^2 K/W]$ is the total thermal resistance of the slab and T_{slab} the slab temperature during melting which is taken equal to the liquid film temperature: 273.71 [K]= 0.56 [°C]. We recall that this liquid film appears between the snow and the slab during the melting process.

3.4.2 Determination of the required pile number and heat pump properties

To determine the required pile number, we will do the same method explained in section 2.4. The performance of a heat pump is indicated by its coefficient of performance (COP), which

is defined as the ratio of the power supplied by the heat pump Q_{heat} to heat pump input work W (electricity consumption). The power supplied is the sum of the heat pump input work W and heat extracted from the soil Q_{source} .

$$COP = \frac{Q_{heat}}{W} = \frac{Q_{source} + W}{W} = 1 + \frac{Q_{source}}{W}$$
(3.5)

we can also write that

$$Q_{source} = \frac{COP - 1}{COP} * Q_{heat} \tag{3.6}$$

The overal supplied power needed for the de-icing Q_{heat} :

$$Q_{heat} = q_0 * A \tag{3.7}$$

where q_0 is the heat required in $[W/m^2]$ presented in table 3.5. For the design of the system, we will calculate q_0 using an equivalent snow free area ratio of $A_r = 0.5$. For our case, this value is equal to

$$q_0 = q_s + q_m + 0.5(q_h + q_e) = 324 W/m^2$$

and A in $[m^2]$ is equal to the heated slab area. In terms of fluid temperature inside the pipes, it represents an average fluid temperature of 37° C.

Once we calculate the value of Q_{heat} , we can calculate the heat extracted from the soil Q_{source} with equation 3.6.

To determine the required number of piles N, we can simply divide the heat extracted from the soil Q_{source} by the maximum power extracted by a single pile q.

$$N = \frac{Q_{source}}{q} \tag{3.8}$$

In Jiangyin bridge case, the main features in relation with the energy piles are listed below:

Pile length $[m]$	20
Pile diameter $[m]$	1
Pipe layout	5 U loop
Soil conductivity $[W/mK]$	1.5
Presence of groundwater flow	No
Pipe diameter [cm]	2.5
Fluid velocity inside the pipes $[m/s]$	0.5

Table 3.6: Energy piles propreties

Based on the prestudy report [13] (see figure 3.24), the power extracted from a 5U loop pile with a diameter of 1 m is about 40 [W/m] which corresponds in terms of total power

extracted to 800 [W] per single pile. This result is conservative and should be used with precaution because this simulation was done with a uniform soil temperature of 15 °C and with a uniform soil conductivity of 1.5 [W/mK].

In reality, the temperature of the soil is equal to 20° C from the depth of 5 m and the thermal conductivity is a simple interpolation from one site to another. The low value of 1.5 [W/mK] is taken from another site which have similar soil propreties than Jiangyin site. A TRT test in Jiangyin field will be performed in the next weeks. Moreover, we didn't consider differences in terms of power extracted between the piles directly buried in the soil and the those which are buried in the river bed. The water flow of the river could enhance the thermal exchange.



Soil thermal conductivity $\lambda = 1.5 [W/mK]$

Figure 3.24: Thermal power extracted as function of diameter, length, number of loops for soil thermal conductivity of 1,5 [W/mK] (Source: Prestudy of Aymen Achich [13])

The COP of a geothermal heat pump ranges between 3 and 5. If we consider a heat pump with a COP of 3, it means in terms of energy efficiency that the heat pump can provide to the de-icing system a power Q_{heat} which is 3 times more than the heat pump input work W. Therefore, if we negleget the heat losses, each energy pile can provide 1200 [W].

Knowing that the heat requirement for the de-icing is $324 W/m^2$, it means that 5.4 m of energy pile are needed to de ice 1 m² on the bridge deck.

We will now determine the required number of piles for 2 cases:

- Case 1: required number of piles if all the bridge is equipped with the deicing system
- Case 2: required number of piles if we consider only the heated slab portion of the experimentation.

According to the slab pipe layout and the bridge dimensions (see section 3.2.1), the heated areas and the overal supplied power needed for the de-icing Q_{heat} for the 2 cases are

	Bike lanes $[m^2]$	Car lanes $[m^2]$	Total area $[m^2]$	$Q_{heat} \; [kW]$
Case 1	$(2.5 \times 2) \times 2 = 160$	$(0.75 \times 2 \times 32) \times 4 = 192$	352	$324 \times 352 = 114$
Case 2	$2.5 \times 10 = 25$	$(0.75 \times 2 \times 10) \times 2 = 30$	55	$324 \times 55 = 17.82$

Table 3.7: Heated area and ower needed for the de-icing

Using equation 3.6, we can determine the needed heat extracted from the soil Q_{source} and the number of pile required from equation 3.8.

Table 3.8: Heat extracted from the soil and required number of piles

Case 1	76	95
Case 2	11.88	16

 $Q_{source} [kW^{"}]$ Required Number of piles N

If we design our system in such a way that the snow melting will be efficient for the following conditions:

- snowfall rate of 1.5 cm/h
- an air temperature of -4°C
- wind velocity of 12 km/h
- level of service corresponding to an equivalent snow free area ratio of $A_r = 0.5$

the required number of piles is much more higher than the piles needed to insure the structural stability of the bridge. We need 95 piles to de ice all the bridge whereas the total number of piles in the bridge of Jiangyin is 20. Even if we want to do deice only the small part of the slab done for the experimentation (case 2), we need 16 piles.

This analysis provides us with an idea about the feasibility of such a melting system. In order to reduce the number of required piles, we should automatically reduce our level of satisfaction in terms of de-icing efficiency and do the calculations above iteratively. For example, we can choose a level of service corresponding to an equivalent snow free area ratio of $A_r = 0$ or we can also design our system for a smaller snowfall rate (which is equivalent to the melting rate) and see how much the required number of piles decreases.

In the next section, we will analyse this situation from a different point of view: knowing the planed number of piles for Jiangyin bridge, we will see how much energy we can provide to the bridge deck per unit surface. This calculation will allow to determine the maximal depth of snow which can be melted per hour of heating during a snowfall event.

3.4.3 Extracted power using the available energy piles and time for de-icing

In the case 1, we make the hypothesis that all the bridge is fully equipped with the de-icing system. The maximum number of energy piles can not exceed the total number of piles of the bridge. The bridge is composed by 20 piles, we know that we can extract from them $Q_{source} = 800 * 20 = 16000 W$. The ratio of the pavement heating area to total pile length for the case 1 is equal to 0.55. The energy piles combined with a heat pump (COP of 3) could provide to the deck a total heat equal to:

$$Q_{heat} = \frac{COP}{COP - 1} * Q_{source} = \frac{3}{3 - 1} * 16000 = 24 \, kW$$

The heat provided q_0 in $[W/m^2]$ provided thanks to the heat pump is equal to

$$q_0 = \frac{Q_{heat}}{A} = \frac{24000}{352} = 68 \ W/m^2$$

This value is by far smaller than the value of 352 $[W/m^2]$ required to melt the snow in the conditions listed in the previous section. If we refer to table 3.5, the heat provided allows to keep the slab above 0°C. If the bridge is subjected to those weather conditions, during the snowfall, the snow will accumulate and it will melt at a rate much slower than the snowfall rate (1.5 cm/h). To determine at which rate the snow will be melted comparing to the snowfall rate of 1.5 cm/h, we will use the ashrae equation considering an equivalent snow free area ratio of $A_r = 0$ because the slab will be totally covered by the snow during the melting.

$$q_0 = q_s + q_m = \rho_{water} s[c_{p,ice}(t_s - t_a) + c_{p,water}(t_f - t_s)]/c_1 + \rho_{water} sh_{if}/c_1$$

$$s = \frac{q_0}{\rho_{water}[c_{p,ice}(t_s - t_a) + c_{p,water}(t_f - t_s)]/c_1 + \rho_{water}h_{if}/c_1} = \frac{68}{92.1 + 1} = 0.73 \, mm/h_{ef}/c_1$$

This value of s is the snowfall rate in water equivalent. To know the depth of the snow melted per hour. We should divide this value by 0.2 for a fresh snow. So the depth of snow melted

per hour is equal to 3.6 mm/h which corresponds to a soft snowfall precipitation. So to melt the snowfall amount of one hour (eg 1.5 cm/h), it needs 4 hours.

For the experimentation (case 2), we equiped only 5 piles with hydronic pipes. We can extract from them $Q_{source} = 800 * 5 = 4000 W$. The ratio of pavement heating area to total pile length for the case 2 is equal to 0.88. Thanks to a heat pump with COP of 3, we can provide heat equal to $Q_{heat} = 6000 W$.

The heat provided is equal to

$$q_0 = \frac{Q_{heat}}{A} = \frac{6000}{55} = 109 \ W/m^2$$

The snow melted in water equivalent is equal to 1.17 mm/h which is equivalent to melt 5.86 mm/h of snow depth. To melt the snowfall amount of one hour (eg 1.5 cm/h), it needs 2.5 hours.

Even if the heat extracted from the energy piles can not insure the deicing according to the ashrae requirements, the de-icing will still be possible but assured in more time. Thus, the long traffic interruptions are avoided.

The Jiangyin case bridge study demonstrates that deck de-icing using energy piles is possible but not at high level of service. The power extracted from the soil is not enough. Some remarks about this system:

- The results showed that the thermal potential of the energy piles is more suitable to ice prevention (anti-icing) than snow melting.
- The thermal conductivity of the soil taken here is low $(1.5 \ [W/mK])$ which is limiting the heat extraction from the soil. With a higher soil thermal conductivity, we can almost double the heat extracted from the soil. However, it is still not enough to insure the heat requirements given by the Ashrae (for a snowfall rate of 1.5 cm/h).
- The ratio of pavement heating area to total pile length is important (0.55 for case 1 and 0.88 for case 2). This ratio will decrease if the surface heated is reduced or if we add more energy piles or increase their length. Changing the structural mechanism of the bridge could be a solution to add more energy pile length.
- To have more power, we can also add to the energy piles geothermal probes around the bridge.
- We can also increase the electricity consumption of the heat pump (with a lower COP) to enhance the heating of the fluid injected. This method could be a mix of boiler-powered system and geothermal energy. The technical feasibility of such a system is not investigated.

Direct heating

In direct heating, we will use simply a water pump to circulate the water from the energy piles to the bridge deck. The energy injected in the slab is directly extracted from the soil (energy piles).

Case 1:

We know that we can extract from them $Q_{source} = 800 * 20 = 16000 W$. The heat provided q_0 in $[W/m^2]$ provided by direct equal to

$$q_0 = \frac{Q_{heat}}{A} = \frac{16000}{352} = 46 \ W/m^2$$

Considering the table 3.5, the direct heating is not enough to keep the slab temperature of all the bridge above 0°C when the air temperature is -4°C and the wind speed is 12 km/h. However, when the slab is covered by the snow, the rate of melting is equal to 2.4 mm/h of snow depth. To melt the snowfall amount of one hour (eg 1.5 cm/h), it needs 6.25 hours which is quite slow.

Case 2:

We know that we can extract from them $Q_{source} = 800 * 5 = 4000 W$. The heat provided q_0 in $[W/m^2]$ provided by direct equal to

$$q_0 = \frac{Q_{heat}}{A} = \frac{4000}{55} = 73 \ W/m^2$$

Considering the table 3.5, the energy provided directly by the energy piles is enough to keep the slab temperature above 0° C when the air temperature is -4° C and the wind speed is 12 km/h. When the slab is covered by the snow, the rate of melting is equal to 3.92 mm/h of snow depth. To melt the snowfall amount of one hour (eg 1.5 cm/h), it require 3.8 hours.

In both cases, we didn't consider any energy losses during the heat transfer between the energy piles and the bridge deck. In reality, the rate of melting is lower. The further experimentations on the real case bridge deck will allow us to confront the obtained results with the measured results on site.

3.4.4 Synthesis

Based on the weather conditions in Jiangyin, we have determined, using the Ashrae guidelines, the heat requirements to de ice the bridge. We have seen that the heat requirements are mainly depending on the desired melting rate (which corresponds to the snowfall rate in the ashrae guidelines). The winters in this area are not severe and the snowfall amounts not very heavy. Nevertheless, the energy requirements are still important compared to the geothermal energy which can be extracted for the energy piles. This problem is, for our case, more pronounced because of the bad thermal propreties of the soil and the small number of the (possible) energy piles compared to the heated area. Indeed, for a reasonable de-icing rate (1.5 cm/h), 5.4 m of energy pile are needed to de ice 1 m² on the bridge deck. This leads us to have a huge number of energy piles and the feasibility of such a system is questionnable for this melting rate.

Thus, we tried to know what could be the maximum melting rate using the available energy piles. If we suppose that the snowfall rate is 1.5 cm/h, when the system operates, the melting rate is lower than the snowfall rate, which induces snow accumulation during the precipitation: if all the bridge is equiped with hydronic pipes, it takes 4 hours to melt 1.5 cm of fresh snow knowing that this result is calculated without considering any heat losses of the heat pump and during the transfer of heat between the deck and the energy piles. However, the energy extracted by the (possible) energy piles permits to keep the slab temperature above 0°C preventing the pavement from the formation of an ice layer which is positive for the users security. As a conclusion, we can say that, concerning Jiangyin bridge, the melting system using geothermal energy from energy piles is more suitable to ice prevention (anti-icing) rather than snow melting.

Chapter 4

Numerical analyses on Comsol Multiphysics

This chapter summarizes in it's first part a series of numerical simulations (performed with Comsol Multiphysics) providing analyses on the thermal response of a bridge deck. The objective was to investigate the effect of several parameters composing the hydronic system of the bridge deck (pipe diameter, pipe spacing, fluid velocity flowing inside the slab) as well as the effect of external factors as the inlet fluid temperature and the wind velocity applied on the slab surface. In second part, we run simulations in order to compare different pipe layouts possible to set up in the bridge deck of Jiangyin. Then, we simulate the structural response on the bridge deck during the de-icing considering the choosen layout.

4.1 Parametric analysis

The goal of the parametric analysis is to know the influence of several parameters in the heat transfer process on the bridge deck. The parameters analyzed are the pipe diameter, the pipe spacing, the fluid velocity as well as external factors as the fluid temperature and the wind influence. Varying these parameters, will allows us to evaluate the effect of different factors on the bridge deck heating process.

To do this study, a 3 dimensional numerical analysis modeling the bridge deck heating process is performed. The area of the heated slab is 18.75 m^2 where the initial characteristics are listed in the table 4.1. The analyses were limited to the idling process (heating before the snowfall event) and the melting process of the snow is not included to maintain simplicity in the calculations.

The objective of the idling process is to heat the bridge before the start of precipitation. This is done in order to maintain the pavement free of snow after precipitation because the heat injection will compensates the latent heat from the snow melting.

For each analysis, we will study the slab surface temperature along the cross section (represented by normalized distance from 0 to 1) (indicated in the figure 4.1) and the fluid

temperature as function of it's normalized length inside the pipes. This crossection was choosen since it is passing through the input and the output of the panel which is providing a representive overall slab temperature. The results are given after 20 hours of heating, the time when the steady state condition is reached.

Slab parameters	Values
Slab thickness [m]	0.76
Pipe position below the slab surface [cm]	10
Slab area $[m^2]$	18.75
Pipe spacing [m]	0.25
Initial slab temperature and ambient temperature [°C]	-2
Injected fluid temperature [°C]	8
Pipe internal diameter [cm]	2
Pipe thickness [mm]	2
Wind velocity [km/h]	8
Fluid velocity $[m/s]$	0.5

Table 4.1: Base case slab parameters and values



Figure 4.1: Analysed slab



Figure 4.2: Transversal view of the studied zone

Material propreties

Material	Thermal conductivity [W/mK]	Specific heat capacity $[J/kgK]$	Density $[kg/m^3]$	Radiation emissivity
Slab : Concrete	1,8	950	2500	0.94
Pipe : PE RT	0.42	-	-	_
Fluid injected : Water	depends of the temperature	4200 but also depends of the temperature	1000	-

 Table 4.2: Material propreties

Boundary conditions

In order to be the more close to the reality, Convection and radiation heat flux are applied at the top and the bottom of the slab. The convection heat flux imposed at the surfaces is calculated based on equation 2.1. The characteristic length of the slab taken to calculate the convection heat flux is equal to 13 m and could be representative of a bridge deck width. The radiation heat flux imposed at the surfaces is calculated based on equation 1.11. The ambient air temperature imposed is -2°C and the initial temperature of the slab is also equal to -2 °C. The fluid circulating inside the pipes is water.

4.1.1 Influence of the fluid flow rate

The thermal behaviour of the bridge deck characterised by different fluid flow rates circulating in the tubes is investigated in the present section. The flow rate can change both by a variation of the tube diameter and by the fluid velocity. Therefore, we will run numerical analyses to see the influence of both options. First, the response of the bridge deck equipped with pipes where the water is flowing at a constant velocity but the diameter is varying. Then, considering the same diameter (nominal one referring to the base case), the variation of the flow rate will be characterised by different velocities of the circulating fluid.

Pipe diameter influence

For snow melt applications, it is in general recommended to install tubes with values of diameter comprised in a range between 1.5 cm to 2.5 cm. Thus, we decided to compare 3 values of pipe diameter (1.5 cm, 2 cm and 2.5 cm) to see the size influence in the heat transfer process. The values correspond to the internal diameters of the pipes. The hydraulic characteristics for the 3 cases are given in the table below:

	$d=1.5~\mathrm{cm}$	d=2~cm	$d=2.5~\mathrm{cm}$
Fluid velocity [m/s]		0.5	
Reynolds number (see equation 1.7)	7500	10000	12500
Nusselt number (see equation 1.6)	55	69	83
Flow rate [l/min]	5.3	9.43	14.72

Table 4.3: Hydraulic characteristics for the two pipe diameter

For the diameter 2.5 cm, the flow is the most turbulant (higher Reynolds number) and the Nusselt number is also higher. We recall that the Nusselt number corresponds to the ratio of convective to conductive heat transfer across the pipe wall. The higher this number, the more enhanced is the heat transfer to the pipe.



Figure 4.3: Fluid temperature along the pipe for different pipe diamter (Top) Slab surface temperature for different pipe diameter (Down)

In the figure above, we can see in the top diagram the evolution of the fluid temperature along the pipes for the 3 cases. The fluid temperature is decreasing with 3 different slope: The slope of the temperature drop (given in $^{\circ}C/10$ m of pipe length) for 1.5 cm, 2 cm and 2.5 cm are respectively 0.51, 0.27 and 0.19. When the diameter passes from 1.5 cm to 2 cm, the drop slope is decreased by almost 47% and from 2 cm to 2.5 cm the decrease is about 30%. This phenomenon can be explained considering the energy balance calculation. Indeed,

the variation of temperature along a pipe circuit is equal to :

$$T(x) = T_{in} + \frac{q}{\rho_f u_f A_p c_f} x \tag{4.1}$$

where T(x) is the fluid temperature at a distance x around the pipe circuit, ρ_f is the fluid density, u_f is the fluid density, A_p is the pipe cross sectional area, c_f is the fluid specific heat capacity, T_{in} is the inlet temperature and q is the heat transfer rate per metre length of the pipe (in W/m). For a constant pipe wall heat flux, when the cross sectional area is bigger, the slope of the temperature variation is smaller.

The slab surface is also presented along the crossed line. The position along this line is represented from 0 to 1. The line begins near by the input and finishes near by the output point. The average surface temperature for the 2.5 cm pipe is 20 % larger (1.44°C) than the temperature for the 2 cm pipe (1.13°C) and 54% greater than the case with 1.5 cm diameter (0.66°C). Near by the input, the slab temperature difference between the different pipe's diameters is about 12 % whereas at the end of the slab, the difference increase and reach 43 %. The slab temperature is directly resulting from the fluid temperature drop slope.

The energy injected in the slab as well as the ratio average slab temperature by injected power are presented in the table below. The energy Q in [W] is calculated following this equation:

$$Q = \rho_f u_f A_p c_f [T_{out} - T_{in}] \tag{4.2}$$

We define also a parameter to qualify the efficiency of the heated panel. It is the ratio of the average surface temperature by the power injected in the slab. The more this ratio is high, the better is the heating efficiency of the panel. We will call it the TP ratio. This ratio will allow us further to find which is the best combination of parameters (the pipe diameter, the pipe spacing, the fluid velocity) to heat the same slab surface.

Table 4.4: Power injected for the different pipe diameter

	Power injected in the slab $[W]$	Average slab temperature [°C]	$\frac{\text{TP Ratio}:}{\frac{Average \ slab \ temperature}{Injected \ power}} \\ \begin{bmatrix} \circ C/kW \end{bmatrix}$
d = 1.5 cm	1356	0.66	0.48
d = 2 cm	1558	1.13	0.72
d = 2.5 cm	1690	1.44	0.85

We can see that the more the diameter is big, the more we are injecting power. In terms of TP ratio, the larger diameter also have the higher TP ratio.

The most important points to hold from this analysis are:

- Keeping the same fluid velocity, a bigger diameter permits a better heat transfer exchange and an enhanced slab temperature which is profitable to the deicing process.
- The heat losses in the fluid when the diameter is bigger are less important, the slab surface temperature is therefore higher and more homogeneous.
- With a bigger diameter, we need more energy to inject with the same fluid velocity (19% more energy from 1.5 to 2.5 cm). However, in terms of ratio between the average temperature and injected power, the bigger diameter has the higher value.
- The flow rate is multiplied by 3 from the smaller to the higher diameter, however the energy needed by the water pump is very small compared to the electrical energy used by a heat pump.
- Having a bigger diameter have also drawbacks: the cost price of a higher pipe diameter is more important. In addition, during the construction of the hydronic slab, a pipe with a higher diameter will be less convenient to install because of it's large bending radius. The pipe spacing will be therefore affected. A smaller diameter have a smaller bending radius. Hence, the pipe spacing can be smaller and the energy efficiency is greater (see pipe spacing parametric analysis).

Fluid velocity influence

We inject now the fluid with different velocities within the nominal pipe diameter (2 cm) in order to see the thermal response of bridge deck.

	$v=0.1~\mathrm{m/s}$	$v=0.2~\mathrm{m/s}$	$v=0.5~\mathrm{m/s}$	$v=1~\mathrm{m/s}$	$v=1.5\;\mathrm{m/s}$
Reynolds number	2000	4000	10000	20000	30000
Hydraulic Regime	Laminar	Laminar to turbulent	turbulent	turbulent	turbulent
Nusselt number	4.36	19	69	121	168
Flow rate [l/min]	1.88	3.76	9.43	18.84	28.27

Table 4.5: Fluid velocity and hydraulic regime

The fluid temperature distributions along the pipe obtained by varying the water velocities are shown in the top of figure 4.4. The corresponding surface temperature in the same figure (bottom diagram). We can see that the variation of temperature for the small velocities (0.1 m/s and 0.2 m/s) decreases significantly along the pipe circuit and this is mainly due to the small mass flowrate of the fluid. The smallest the mass flowrate, the highest is the drop of the slope of fluid temperature (see equation 4.1).

This decrease can be also seen in terms of surface temperature: the average surface temperature for the fluid with velocity 0.1 m/s and 0.2 m/s are respectively -0.36 °C and 0.4°C. Those values are due first to the lower fluid temperature and because of the hydraulic regime of the fluid. When the velocity of the fluid is small, the flow regime is laminar and the streamlines of fluid movement are smooth and highly ordered. Thus, the heat transfer between the fluid and the pipe wall will be limited.



Figure 4.4: Fluid temperature along the pipe for different water velocites (Top) Slab surface temperature for different water velocites (Down)

A significant increase of the temperature at the surface was observed when the fluid velocity

was increased from 0.1 m/s to 0.5 m/s. The flow becomes fully turbulent, the intense mixing of the fluid in turbulent flow causes an enhancement of the heat transfer compared with laminar flow. The temperature of the fluid along the pipe is also more constant giving a higher and more homogeneous slab temperature.

However, from a velocity of 0.5 m/s to a velocity of 1.5 m/s, variations of temperature are noticed in the fluid along the pipes and hence at the slab surface. The temperature drop inside the tube passes respectively from 28 % to 10 % along the pipe. This variation involve a gain in the slab surface temperature of 24 % when the fluid velocity passes from 0.5 to 1.5 m/s (1.13°C to 1.49°C). In terms of energy (see table below), we need 6 % more power when we inject with a velocity of 1.5 m/s compared to 0.5 m/s. Between a water velocity of 1 m/s and 1.5 m/s, the slab temperature and the injected power are almost the same. However, the water pressure drop when the velocity is equal to 1.5 m/s is higher than 1 m/s.

The average slab temperature, the power injected in the slab as well as the TP ratio are presented in the table below:

	Average slab temperature [°C]	Power injected in the slab $[W]$	$\begin{array}{c} \text{TP ratio} \\ \underline{Average \ slab \ temperature} \\ \underline{Injected \ power} \\ [^{\circ}C/kW] \end{array}$
v = 0.1 m/s	-0.36	881	-0.4
v = 0.2 m/s	0.4	1271	0.31
v = 0.5 m/s	1.13	1558	0.72
v = 1 m/s	1.39	1655	0.84
v = 1.5 m/s	1.49	1656	0.90

Table 4.6: Power injected for the different fluid velocities

The key points to hold from this analysis are:

- The higher the velocity, the more constant the fluid temperature stays along the pipe circuit providing more energy to the slab surface. The slab temperature is then higher. The bigger ratio slab temperature/injected power is when the velocity is equal to 1.5 m/s.
- Injecting the fluid with very high velocity will induce head losses characterised by pressure drops. When the water pressure drops too much (in the case of a longer pipe length), a cavitation phenomenon will be created which is problematic for the pump. The cavitation phenomenon is when a fluid passes to water vapor due to its low pressure.
- Moreover, a direct heating (using a standard water pump) from the energy piles to the deck will be probably performed. A higher fluid velocity in the energy piles will

decrease the output temperature from the energy piles. A velocity optimisation should be done to know the flow rate permitting the best thermal efficiency on the bridge deck.

4.1.2 Pipe spacing influence

In this section, keeping the same heated area, we vary the pipe spacing between 3 values : 20 cm, 25 cm and 30 cm. The total length of the pipes is respectively equal to 106 m, 85 m and 76 m. We can see first the evolution of the fluid temperature along the pipes for the 3 cases. The fluid temperature is decreasing from the initial input temperature of 8°C to 5.4 °C (for the case with 20 cm spacing), to 5.65° C (for the case with 25 cm spacing) and 5.75° C (for the case with 30 cm spacing).



Figure 4.5: Fluid temperature along the pipe for different pipe spacing (Top) Slab surface temperature for different pipe spacing (Down)

The fluid temperature differences are small. Those differences are due to the pipe length, indeed more the distance traveled by the fluid is important more the fluid is loosing its heat. The most notable differences are along the slab surface. In fact, due to the distance between

the pipes, a thermal interaction for small spacing may enhance the slab temperature. The average deck surface temperature, the temperature difference between the locations: directly above the tubes (A) and in between the tubes (B), the injected power and the TP ratio are given in the table below:

	Average slab temperature [°C]	Temperature difference between A and B [°C]	Energy injected [W]	$\begin{array}{c} \text{TP Ratio}:\\ \underline{Average\ slab\ temperature}\\ Injected\ power\\ [^{\circ}C/kW] \end{array}$
Spacing : 20 cm	1.42	0.2	1705	0.83
Spacing : 25 cm	1.13	0.45	1558	0.72
Spacing : 30 cm	0.78	0.65	1493	0.52

Table 4.7: Slab temperatures for the 3 spacings

The pipe spacing is notably influencing the slab surface temperature. With a spacing of 20 cm, the slab surface temperature increases by 20 % comparing to the 25 cm spacing slab and by 45 % comparing to the 30 cm spacing slab. Moreover, the temperature difference between the locations: directly above the tubes (A) and in between the tubes (B) are different: : 0.2 °C difference between A and B when the spacing is equal 20 cm while for a larger spacing, the temperature difference reach 0.65°C. However, those variations are very small and the deicing will be quite uniform for the 3 spacing.

In terms of energy injected, the power injected for the slab with 20 cm spacing is only 12.5% more than for the slab with 30 cm spacing.

The most important points to hold from this analysis are:

- A smaller tube spacing is increasing the slab temperature and will improve the efficiency of the de-icing.
- More energy is needed to inject for the smaller the tube spacing because the length of tubes is higher. However the ratio slab temperature/injected power is the highest for the smallest spacing.
- A smaller spacing is more convenient to construct only when we have a smaller pipe diameter (because of the bending radius constraint).

4.1.3 Sensitivity analysis

The analysis done for the flow rate and the pipe spacing showed us that slab temperature is the highest for the highest fluid velocity, the highest pipe diameter and the smallest pipe spacing. However, for each analysis, we vary only one parameter (fluid velocity, pipe diameter, pipe spacing) to show the thermal response of the bridge deck. In this sensitivity analysis, we will try to find the best combination to have the highest slab temperature and the best energy efficiency.

For this purpose, we only combine the parameters giving high TP ratios:

- $\bullet\,$ The diameters 2 cm and 2.5 cm
- The pipe spacings 20 and 20 cm
- The fluid velocities 0.5, 1 and 1.5 m/s

The simulations are done keeping the same heated panel area.

Pipe diameter [cm]		2		2.5	
Pipe spacing [cm]	20	25	20	25
Fluid velocity [m/s]	0.5	1.42	1.13	1.81	1.44
	1	1.79	1.39	2.05	1.63
	1.5	1.9	1.43	2.13	1.7

Table 4.8: Average slab temperature $[^{\circ}C]$

The table 4.8 presents the average surface temperature of the slab for the different parameters. The highest temperature (2.13 °C) is obtained for a spacing 20 cm, a pipe diameter of 2.5 cm and a velocity of 1.5 m/s. The lowest temperature (1.13°C) is provided by the configuration: spacing 25 cm, pipe diameter 2 cm and velocity 0.5 m/s. This result is logical and expected. One degree of temperature difference between the best configuration and the worst one. However, we are just injecting a fluid of 8°C. If we inject a higher temperature, the difference will be more pronounced (see next section).

We can see also that 3 configurations give approximately the same slab temperature (between 1.42°C and 1.44°C). Thanks to the TP ratio, we can know which one is the most efficient (see the following analysis).

Table 4.9 :	Injected	power	[W]	
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Pipe diameter [cm]		2		2.5	
Pipe spacing [cm]		20	25	20	25
	0.5	1705	1558	1855	1690
Fluid velocity [m/s]	1	1807	1655	1917	1752
	1.5	1821	1656	1886	1732

The table above presents the power injected in the slab. We can see here that the highest power to inject is not corresponding to the configuration giving the highest temperature. This configuration corresponds to spacing 20 cm, pipe diameter 2.5 cm and velocity 1 m/s. Although, the lowest injected power correspond to the configuration giving the lowest temperature.

Pipe diameter [cm]		2		2.5	
Pipe spacing [cm]		20	25	20	25
	0.5	0.83	0.72	0.97	0.85
Fluid velocity [m/s]	1	0.99	0.84	1.07	0.93
	1.5	1.04	0.90	1.13	0.98

Table 4.10: TP Ratio : Average slab temperature / Injected power $[^{\circ}C/kW]$

The TP ratio permits to know better the energy efficiency for each configuration (see above table). Indeed, since the power injected to the slab is provided from the energy piles (for example), but in the same time, we know that this source of energy is low comparing to de-icing requirements. So the aim is to minimize the injected energy and maximize the slab temperature. Thus a configuration with a better TP ratio will provide a better energy efficiency.

The highest TP ratio (1.13 [°C/kW]) is obtained for a spacing 20 cm, a pipe diameter of 2.5 cm and a velocity of 1.5 m/s. The lowest temperature (0.72 [°C/kW]) is provided by the configuration: spacing 25 cm, pipe diameter 2 cm and velocity 0.5 m/s. To obtain the same slab temperature, the power injected in the configuration with a TP ratio of 1.13 [°C/kW]) should be 64% of the power injected in the configuration with TP ratio equal to 0.73. To reduce the power injected in the slab, we can inject a fluid with a lower temperature.

For example, we can see in the table showing the surface temperature that 3 configurations have approximately the same slab temperature (between 1.42°C and 1.44°C). However, their TP ratio is not the same. The latter is variying between 0.83 and 0.9. The injected power to have this same slab temperature is not the same. Regarding the 3 configurations, the best one is spacing 25 cm, pipe diameter 2 cm and velocity 1.5 m/s.

The TP ratio permits also to compare the different configurations:

- If we compare the case A (velocity = 1 m/s, d = 2cm, s = 25 cm) and the case B (velocity = 0.5 m/s, d= 2.5cm, s = 25 cm), the case A has a higher flow rate (18.84 l/min) than the case B (14.72 l/min) but the case B has a higher ratio average slab temperature/power injected (0.85 [°C/kW] > 0.83 [°C/kW]).
- If we compare the case A (velocity = 1 m/s, d = 2cm, s = 20 cm) and the case B (velocity = 1 m/s, d = 2.5cm, s = 25 cm), The TP ratio of case A is higher than case B (0.99 [°C/kW] > 0.93 [°C/kW]). Thus, for the design of the layout, an optimisation should be done between the pipe spacing and the pipe diameter considering the cost of the pipes (diameter and length), the TP ratio and the pratical constraints (bending radius of tubes).

Thus, the TP ratio can be a good tool to get an idea about thermal efficiency of the different configurations. To design the pipe layout, we should also consider the construction constraints (bending radius of tubes), the technical constraints (pump performance and pressure drops) and not to forget the cost constraints.

For the 2 next sections, we will discuss the influence of external factors such as injected fluid temperature and the wind influence.

4.1.4 Injected fluid temperature influence

For a more efficient and quick deck de-icing during heavy snowfall events, we may inject in the slab fluid at higher temperatures. As we see previously, those temperatures can reach 50°C. In this section, the injected fluid temperature is investigated: we will compare the nominal value of the fluid temperature 8°C with fluid at 20°C and 30°C.

As shown in the diagram below, the rate of fluid temperature drop along the pipes is linear but different. The higher is the inlet temperature, the higher is the slope of the temperature drop. For a fluid injected at 8° C, this rate is equal to a loss of 0.29° C / 10 m of pipes. For a fluid injected at 20° C, this rate is equal to 0.65° C / 10 m of pipes and for a fluid injected at 30° C, this rate is equal to 0.94° C / 10 m of pipes. Those difference could be explained by the variation of the specific heat capacity of the water at different temperatures. Based on equation 4.1, the lower is the specific heat capacity, the larger is the temperature drop. The table below presents the heat capacity of the water at the studied temperature.

Table 4.11: Specific heat capacity of water at different temperatures

	Water at $8^{\circ}C$	Water at $20^{\circ}C$	Water at 30°C
Specific heat capacity $[J/kgK]$	4202	4187	4179.5



Figure 4.6: Fluid temperature along the pipe for different injected fluid temperature (Top) Slab surface temperature for different injected fluid temperature (Down)

The observed phenomenon has of course an impact on the slab surface temperature. We can see that the lower is the fluid temperature the more homogeneous is the slab temperature. The temperature variation along the slab is equal to 0.75°C, 1.5°C and 2.5 °C when the temperature of the fluid is respectively equal to 8°C, 20°C and 30°C.

The key points to hold from this analysis are:

- The higher is the inlet temperature, the higher is the slope of the temperature drop along the pipe circuit
- This phenomenon implies a less uniform slab surface temperature at higher temperature, hence the de-icing will be also less uniform from a zone to another of the slab. Some zones of the slab will be de iced and others not yet, which induce more energy waste.

- Significant thermal stresses on the deck could be developped if the temperature variation is important.
- During the design of the heated bridge deck (for example, the size of the heated panels), the future inputed temperatures should be considered in order to determine the pipe length (see section 4.2.1)

4.1.5 Wind convection influence

The bridge deck is subjected to the weather conditions at the boundaries. During the de-icing process, heat losses by convection occur at the deck surface due to the wind and by radiation due to the atmosphere. In this section, we will focus mainly on the influence of the wind convection. We will compare the case when the slab is not subjected to the wind to 3 others cases when the wind speed is equal to 5, 10 and 20 km/h. The heat flux due to the radiation heat losses is not considered for all the cases.

The convective heat fluxes corresponding to the different wind speed are presented in the table below. The characteristic length of the slab taken to calculate the convection heat flux is equal to 13 m (could be representative of a bridge deck width). The corresponding heat fluxes are calculated based on equation 2.1.

Table 4.12: Convective heat fluxes corresponding to the different wind speed

Wind speed [km/h]	0	5	10	20
Corresponding heat flux $[W/m^2K]$	0	5.6	9.75	16.98

The surface temperature when there is no convection losses (no wind) reach almost the initial fluid temperature (7°C in average) from its initial temperature which is -2°C. The losses due to the wind are observeable on the slab surface temperature. When the slab is subjected to a wind velocity of 5 km/h, the slab temperature losses 3.8 °C (42% losses from the case when there is no wind). If the wind speed is equal to 10 km/h, the slab temperature losses 5° C (55% losses). For a wind speed of 20 km/h, the slab temperature losses reach 6°C (68% of losses). The heat losses due to the wind are huge when the slab temperature is higher compared to the air temperature. The heat losses between the case when there is no wind to the case where the wind speed is 5 km/h are much higher than the losses when the wind passes from 10 km/h to 20 km/h. For example, the surface temperature drop, when the wind velocity passes from 10 km/h, the surface temperature drop by 50%, which is 25 % drop for each additional 5 km/h of wind.

The wind influence should be particularly taken into account during the idling period (period of heating before the snow precipitation) and when the level of service of the de-icing is very

high (snow melts instanously when it is in contact with the slab). In order to avoid loosing a lot of energy during the idling, we can inject the energy sufficient to maintain the slab temperature above 0°C. When the snow starts to fall and the slab is covered by a thin layer of snow, we can increase the power injected without suffering heat losses due to the wind because the snow will thermally insulate the slab.



Figure 4.7: Fluid temperature along the pipe for different wind velocities (Top) Slab surface temperature for different wind velocities (Down)

4.2 Choice of the hydronic pipe deck layout for the Jiangyin bridge slab

This study was done before the construction of the hydronic pipes of the bridge deck.

One of the main features of a heated pavement is the layout of the pipes, the total length of the pipes, the pipe propreties (diameter, thickness,quality, durability, thermal conductivity, minimum bending radius), the spacing between pipes, and the number of heated panels in the slab (Number of inlet/outlet for the total heated slab). For the Jiangyin bridge demonstration project, one of the challenges was to choose the hydronic pipe layout considering the construction and financial constraints. The pipe type was for example imposed by its availability in the local market in Jiangsu province. The pipe propreties are listed in the table below:

Figure 4.	8: Pip	be pro	preties
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Pipe type	PERT
Pipe diameter [cm]	2
Pipe thickness [mm]	2
Thermal conductivity $[W/mK]$	0.42
Minimum bending radius [cm]	25

However, we were more flexible concerning the choice of the pipe layout and the number of heated panels. In this section, we will show the reflection process which allows us to choose the layout of the bridge deck.

4.2.1 Pipe length

The first study was to know what pipe length is accepted by heated panel ? How the fluid temperature will evolve in function of the length of the pipes and what is the slab temperature induced. To answer to these questions, we did numerical simulations on Comsol multiphysics. Using the deck geometric propreties of Jiangyin bridge (see table 3.1), we set up a pipe serpentine covering 83 m² of the slab with a length of 355 m which is embedded 10 cm below the slab surface. Considering the local weather conditions of Jiangyin and the geometric propreties of the slab, we impose a convective heat flux corresponding to a wind velocity of 10 km/h on the top and the bottom of the slab. We add also a radiation heat flux to take into acount the radiative losses. The ambient air temperature is $-2^{\circ}C$.

We inject a fluid into the serpentine at 3 different temperature: 8°C, 15°C and 20°C during 20 hours (time when we already reached steady state condition). We choose as a lower fluid temperature 8°C in order to reproduce the case when the system is working in direct heating

(without using a heat pump). When a heat pump is used, the injected temperature is higher: a fluid injected with an initial temperature of 15° C or 20° C are simulated to reproduce this case.

The fluid is injected with a velocity of 0.5 m/s. The hydraulic regime of the flow is turbulant. This velocity was choosen in order to be closer to the practical situation: the pump used in the field may be not very performant. Moreover, a direct heating (using a standard water pump) from the energy piles to the deck will be probably performed. The paper "Energy and geotechnical behaviour of energy piles for different design solutions" of N. Batini & al showed that a higher injected fluid velocity in the energy piles will induce a decrease of the output temperature from the energy piles [2]. Thus, the bridge deck will be less efficiently heated.



The slab with the pipes inside is presented in the figure below:

Figure 4.9: Slab with the pipes

The fluid and the slab temperature (average temperature along the slab from the input to the output zone) are given in the next diagram.100 m of pipes represents 23 m^2 .



Figure 4.10: Fluid temperature (top) and slab temperature (down)

As we saw in the parametric analysis, the fluid temperature decreases the more it flows into the pipes (top plot) but the slope of decrease is not anymore linear as the pipe circuit studied in the parametric analysis. Along the pipe circuit, this slope is less and less pronounced. This is due to the specific heat of the fluid which is increasing when the temperature of the fluid is decreasing (see subsection 4.1.4 for more explanations). Since the fluid temperature is linearly correlated to the slab surface temperature, the slab temperature is also decreasing with the same slope along the length L of the heated area (see figure 4.9).

The table 4.13 shows the fluid temperature drop along the pipe length (for 100 m, 200 m and 300 m). When the fluid flows on the first 200 m, the fluid losses more or less (depending of it's initial temperature) 35% of it's initial temperature each 100 m: for the first 100 m of the pipe circuit, the fluid injected at 8°C loses 3°C, the fluid injected at 15°C loses 5°C and the fluid injected at 20°C loses 7°C. After 300 m of flow inside the pipes, the fluid temperature

drops by 70% of it's original temperature. This phenomenon could be more marked when we inject with a larger input temperature (see subsection 4.1.4) especially for the de-icing: As an example, if we inject 30°C as an input fluid temperature, the fluid temperature after 100 m is only 20.5°C.

Since the slab surface temperature is linearly correlated to the fluid temperature, we obtain slab temperature differential from one side to another side of the slab and a lower slab surface temperature average. The average slab temperature (at its surface) along the line L (Value of L is 0 represents the side near by the input and L=9.75 m represents the side near by the output) is presented in the table 4.14. For example, for a 46 m² heated panel (100 m of pipes represents 23 m²), the slab temperature differential is about 4°C when we inject a fluid with a temperature of 20°C and it's average temperature is equal to 3.7°C. Whereas, for a 23 m² heated panel, the slab temperature differential is 2.3°C and the average temperature is equal to 4.65° C (20% more than the 46 m² panel).

Table 4.13: Fluid temperature drop function of length of pipe

	Pipe length			
	$100 \mathrm{m}$	$200 \mathrm{m}$	300 m	
Temperature fluid : 8°C	3°C	$5^{\circ}\mathrm{C}$	$6,5^{\circ}\mathrm{C}$	
Temperature fluid : 15°C	5°C	9°C	11°C	
Temperature fluid : 20° C	$7^{\circ}\mathrm{C}$	11°C	14°C	

Table 4.14: Average slab temperature along the heated panel

Distance L (Area of the panel)	$3 \text{ m} (23 \text{ m}^2)$	$5.6 \text{ m} (46 \text{ m}^2)$	$9.75 \ (83 \ {\rm m}^2)$
Temperature fluid : 8° C	1	0.65	0.25
Temperature fluid : $15^{\circ}C$	3.1	2.45	1.8
Temperature fluid : 20° C	4.65	3.7	2.9

These results demonstrate the importance of the pipe length and so the panel area for the design of a melting ice system. To provide the heat requirements for deicing given by the Ashrae guidelines along all the surface of the heated panel, the input temperature in the panel should also be choosen as a function of the panel length in order to provide at the end of the panel the power required. The bigger the area of the panel, the more reduced is the temperature of the fluid injected in the end of the panel compared to its initial value. This point is not analysed by the ashrae guidelines since they provide relashionship only between the heat requirement and fluid temperature directly below the slab (2D analysis). In reality , the problem is more complex because the fluid temperature changes when the fluid is flowing.

To conclude, the maximum length of the pipes should not be important in order to :

- Have an homogeneous heating and a higher average surface temperature.
- If the slab temperature differential along the panel is important, the thermal stress inside the heated slab will increase.
- Limit the heat losses: if the pipe length is too big, in order to provide the heat requirement in all the slab, the slab part near by the input temperature will be heated more than required while the area near by the output will be sub heated. Hence, the energy efficiency of the system is affected.
- In terms of water pressure, long pipes will induce very high head losses and could lead to a water cavitation which damage the water pump or the heat pump. In our study, we analyse the length of the pipes only in terms of fluid temperature. However, the pipe length is also controlled by pressure losses of the fluid. In the tables given by the pipe supplier REHAU, we have the pressure loss tables per 100 feet of length (linear losses) as a function of the flowrate and the fluid temperature [39].
- A threshold of 8°C differential in the fluid temperature along the pipe could be admitted, thus a maximum pipe length of 125 m per panel should be admitted to design the hydronic pipe layout.

4.2.2 Layout comparison

The layout of the pipes inside the deck is one of the main part of the design for a deck deicing system. The challenge is to have the best thermal efficiency during the heating considering the practical constraints (on site) and the cost constraints. The thermal efficiency of the system in terms of geometry depends on the shape of the layout, the distance of the pipes from the slab surface, the pipe spacing, and the pipe length per heated panel.

In order to protect the pipes during the construction, they should be fixed on the reinforcement cage of the slab. The distance between the pipes to the slab surface is fixed by this constraint: this distance is about 10 cm. The pipe spacing is also controlled by the minimum bending radius of the PERT pipes which is 25 cm. The layout options are thus limited to the pipe length per panel, the number of heated panels and the geometrical shape of the pipes.

Most of the previous deck deicing projects are using standard serpentine layout (similar to figure 4.9). We tried to compare this standard layout to a new layout. Our aproach was to concentrate the heat in the most important areas in order to limit the length of the pipes and the total area heated. Indeed, limiting the length of the pipes per panel will provide a more homegenous and a higher heating. Moreover, we know that the overal supplied power needed for the de-icing Q_{heat} (see equation 2.19) is depending of the heated area. Thus, reducing the heated area will reduce the required heat extraction from the soil and so the required number of energy piles for the same required de-icing energy. From another point of view, for

the same heat extraction, reducing the overall heated area will improve the thermal power per unit surface inputed on the deck so the de-icing efficiency.

The idea was to superpose the heated area to the vehicules trajectories in the bridge. The bridge in Jiangyin is composed by 3 tracks per direction (see figure 3.9): One track for the bikes and 2 for the cars. For the 2 wheels vehicules, their trajectory is random on their track, hence all the lane area should be heated in the same way in order to preserve it from the snow. A serpentine shape covering all the track (with 2 heated panels) is used as layout (see figure 3.10) so the layout optimisation is limited.

In contrast, the cars have all the same trajectory on the track. This trajectory is governed by their width (precisely by their axle width) and the track width. Thus, for the car lanes, instead of using a standard serpentine layout where all the track is heated, we can reduce the heated area superposing the heated area to the tires trajectory area. So we can improve the efficiency of the system and save pipe length.

First, we saw how large the axle width of the vehicules can be: the majority of the vehicules (4 wheels) have an axle width ranging between 1.25 m for the smallest vehicules to 2.5 m for the widest trucks. The hydronic pipes should then cover this width range. The figure below shows schematically where the heated zone should be for one car track. The design of the new layout is based on this figure.



Figure 4.11: Heated zone for car track

In order to see the thermal efficiency of such a layout, we will compare it to the standard

serpentine layout.

The analysis done in the previous section showed that the pipe length per heated panel can not be indefinetely long. A threshold of 125 m per heated panel is choosen as a maximum limit. Taking account of this constraint, we decide to compare 4 types of layouts (for the car lanes) where we vary the pipe length and the geometric layout.

The 4 versions are presented in the figure 4.12. The pipe spacing is taken to be 25 cm for all the versions. The versions A and B are using the serpentine layout covering all the road area (2.5 m width). The only difference is that version A is composed by 2 heated panels per lane and the version B is composed by only 1 heated panel per lane. The versions C and D are using the new layout. The pipe gap in the midle of each line is equal 1.25 m and each heated zone is composed by 4 longitudinal pipes covering 0.75 m from the 1st line to the 4th line. The version C is composed by 1 heated panel per lane and the version D is composed by 2 heated panels by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by 1 heated panel per lane and the version D is composed by 2 heated panels by



Figure 4.12: Layout versions

We compared these layouts in the following conditions:

- Ambient temperature : -2°C (on the top and bottom of the slab)
- Wind velocity : 10 km/h (applied on the top and bottom of the slab)
- Without consideration of radiation losses
- Inlet fluid : 8°C with a fluid velocity of 0.5 m/s.
- Pipe Spacing : 25 cm

• Duration of the simulation: 20 hours (steady state condition reached)

For each version, the fluid and the surface slab temperature are presented. For the versions A and B, the surface slab temperature is represented as a function of a line crossing axially the middle of the right track (see the dashed line in the figures). For the versions C and D, the surface slab temperature is represented as a function of a line crossing transversally of the middle of the right track (see the dashed line in the figures). These studied lines were choosen in order to have the closest representation of the surface temperature of the track. The surface temperatures given are the the temperature of the slab just above the tubes (since the spacing is the same for the 4 versions, we didn't consider the slab temperature between the pipes).


Figure 4.13: Version A: fluid temperature in °C (up) (image from Comsol); slab temperature in °C (axial cross section in the middle of the right lane) (down)



Figure 4.14: Version B: fluid temperature in $^{\circ}C$ (up) (image from Comsol); slab temperature in $^{\circ}C$ (axial cross section in the middle of the right lane) (down)

For version A, the heated slab is composed by for 4 heated panels of 68 m each (average value). For version B, the heated slab is composed by 2 heated panels of 121 m each (average value). In the plots showing the slab temperature of the versions A and B, we can see that the slab temperature is heterogeneous along the track lane. This heterogeneity is due to the disposition of the pipes and the fluid temperature flowing inside. In the layout of the version A, the temperature difference is 0.6°C. In the version B, this difference is about 1°C. Those temperature difference are not considerable but as we said in the parametric analysis, if we inject with higher temperature, the fluid temperature will decrease more quick along the pipe circuit. This phenomenon can cause an important temperature differential on the heated slab.



Figure 4.15: Version C: fluid temperature in °C (up) (image from Comsol); slab temperature in °C (transversal cross section in the middle of the right lane) (down)



Figure 4.16: Version D: fluid temperature in °C (up) (image from Comsol); slab temperature in °C (transversal cross section in the middle of the right lane) (down

For version C, the heated slab is composed by for 2 heated panels of 91 m each (average value). For version D, the heated slab is composed by 4 heated panels of 54 m each (average value). In the versions C and D, the temperature is more homogenous along the lane track. However, the slab temperature in the boundaries on the heated panels is low comparing to the zone where the pipes are inside the circuit: the temperature difference can reach 1.5° C between the boundaries and inside the heated zone for version D. We will notice also that the influence of the boundaries pipes on the non heated area doesn't exceed 25 cm.

In order to compare the 4 versions, some criterias are listed in the table below.

Table 4.15: Comparison table

	Version A	Version B	Version C	Version D
Total length of the pipes for the 2 lanes [m]	273	243	183	215
Number of panels	4	2	2	4
Area of heated zone $[m^2]$	54,6	54,6	31,5	31.5
Average output fluid temperature [°C]	5,8	4,3	4,9	6,25
Injected power per lane [kW]	$2 \times 1,45 = 2,9$	2,4	2	$2 \times 1,15 = 2,3$
Average temperature on the heated zone (just above the pipes) [°C]	2	1,72	1,83	2.18
$\begin{array}{c} \text{TP Ratio}:\\ \frac{Average\ slab\ temperature}{Injected\ power\ per\ lane}\\ [^{\circ}C/kW] \end{array}$	0.68	0.71	0.89	0.94
Pressure drop per heated panel [kPa] (tables given in [39]: 6894 Pa/30 m)	15.6	27.8	20.9	12.4
Construction difficulty (time spended, number of bending) (1 most difficult one / 4 easiest one)	1	2	4	3
Cost price $(3,4 \text{ rmb/m} = 0,51 \text{ chf/m})$ [CHF]	139,23	123,93	93,33	109,65

First we can see clearly that the version A and D, composed by 2 heated panels per lane have the highest average temperature (2°C and 2.18°C). This is due to their small pipe length per panel (68 m and 54 m) which permit to limit the fluid temperature drop. However, we should inject more power per lane when we have 2 heated panels instead of 1 per lane. The versions composed by 2 panels per lane (version A and D) have also higher total length compared to the versions composed by 1 panel per lane. The total cost price is also higher.

If we compare now the 2 different layouts composed by 1 heated panel per lane (versions B and C). We can see that the total pipe length of version B is 25 % higher than the version C. In terms of heated area, the version B covers 42 % more area than the version C. In terms of average slab temperature, the version C is 6% higher than version B. In terms of power injected, if we compare the output fluid temperature, we can see that we are injecting in the panels of version B 16% more power than in the panel of version C.

The pressure drops per heated panels are also given in the table above. Those pressure drops are due to the head losses along the pipes. Two type of head losses exist in piping, the linear head losses and the local head losses which occur when the fluid is changing direction in case of encountering an obstacle. The pressure drops given are considering only the linear head losses. We can see that the more the pipe is long, the more the pressure is droping. The more the pressure drops, the more the pump should provide energy to provide the same flow rate. The new layout (versions C and D) have the advantage to have few bending of the tubes in contrast to the versions A and B. If we consider the local head losses, the versions C and D will be significantly less affected by those losses unlike to the serpentine layout (version A and B).

The choice of the pipe layout was discussed for Jiangyin bridge deck, based on this analysis and considering the future experimentations for the de-icing. It was decided to install the 2 types of layout. The serpentine layout (version A) was choosen for the bike lane with 2 heated panels. the choice to divide the lane into 2 heated panels is to test each part of the heated slab separetely and to have the possibility to concentrate all the heat in a small zone in order to have a higher de-icing efficiency.

For the car lanes, the version C was choosen as a pipe layout. Indeed, this layout has several advantages:

- The heated area is reduced by 42~% compared to the serpentine layout, which reduce the total required injected power for de-icing purpose.
- The pipe length is the lowest one. This version is the cheapest version.
- The injected power per lane is the lowest one.
- In terms of TP ratio (average temperature/injected power): this layout gives a higher value than the serpentine layout.
- It is also the easiest layout to construct.
- This layout have the smallest pipe length and only few bending of the tubes, the linear and local head losses are thus limited which induce a lower pressure drop. Less energy will be consumed by the pump.

Moreover, this layout was not constructed in any previous deck deicing project. Since the bike lane was constructed with the serpentine layout, we will have the possibility to compare the efficiency of the 2 layouts in reality. The final layout is showed in figure 3.19.

4.3 Structural response of the bridge deck

The bridge is exposed during it's life time to weather conditions. The bridge temperature vary during a day and during the seasons. During the day and in summer period, it is heated

and during the night and winter periods, the temperature drops and the bridge is cooled. This temperature variation will cause expansion when the bridge is heated, and contraction when it is cooled inducing thermal stresses. Adding the de-icing system in the bridge, the temperature of the bridge deck will be directly affected which can induce additional thermal stresses. We will see in this section how the bridge deck will react when the system is active for the Jiangyin bridge case.

For this purpose, we will use the software Comsol to determine the thermal stresses induced during the de-icing for the bridge deck of Jiangyin. In order to be more confident with the simulation results, we will investigate first analytically the thermal stresses for a simple beam subjected to a variation of temperature whitin its cross section. Then, we will compare the obtained results with the numerical results given by Comsol for the same beam. Finally, we will extand the numerical simulation to the real bridge deck case of Jiangyin.

4.3.1 Analytical solution to determine vertical displacement and thermal stresses and comparison with numerical results

The analytical solutions for the thermal stresses in beams and slabs are based on the Euler-Bernoulli hypothesis: The plane which is perpendicular to the neutral axis before deformation remains plane and perpendicular to the neutral axis after deformation. According to this hypothesis the elastic strain ϵ is given by:

$$\epsilon = \epsilon_0 + \frac{y}{r_y} + \frac{y}{r_y} \epsilon_0 \approx \epsilon_0 + \frac{y}{r_y}$$
(4.3)

where y is the vertical coordinate ϵ_0 is the axial strain at the neutral plane and r_y is the radius of curvature.



Figure 4.17: Deflection of an element of beam

If we consider a rectangular beam with thermal gradients along the y and z-directions (see figure 4.18), in accordance with Euler-Bernoulli assumption, the axial strain ϵ_{xx} is

$$\epsilon_{xx} = \epsilon_0 + \frac{y}{r_y} + \frac{z}{r_z} \tag{4.4}$$

The axial stress σ_{xx} including the thermal stress is given by:

$$\sigma_{xx} = E(\epsilon_{xx} - \alpha\theta) = E(\epsilon_0 + \frac{y}{r_y} + \frac{z}{r_z} - \alpha\theta)$$
(4.5)

where E is the Young modulus, α is the thermal expansion coefficient, $\theta = T - T_0$ is the variation of temperature along the cross section of the beam.



Figure 4.18: Rectangular beam

For a simply supported beam, it is in static equilibrium, the axial force and bending moments in y and z directions are nul. These conditions in terms of the axial stress in the beam yield the following relations:

$$\int_{A} \sigma_{xx} dA = 0 \quad \int_{A} \sigma_{xx} y dA = 0 \quad \int_{A} \sigma_{xx} z dA = 0 \tag{4.6}$$

where dA = dydz.

Substituting equation 4.5 in equations 4.6, we obtain $\epsilon_0,\,r_y$ and $r_z :$

$$\epsilon_0 = \frac{P_T}{EA} \qquad r_z = \frac{EI_y}{M_{Ty}} \qquad r_z = \frac{EI_y}{M_{Ty}} \tag{4.7}$$

where

$$P_T = \int_A E\alpha\theta dA$$
$$M_{Ty} = \int_A E\alpha\theta z dA$$
$$M_{Tz} = \int_A E\alpha\theta y dA$$

Those values are valid only if we are assuming thermal loading only. To find the strains, radii of curvature and thermal stresses due to the combined mechanical and thermal loads we should add to P_T the axial load due to the external forces applied on the beam and the reaction forces at the boundary. Besides, we should add to M_{Ty} and M_{Tz} the possible mechanical moments due to the action of the external forces.

The moments of inertia I_y and I_z on axis y and z are by definition equal to

$$I_y = \int_A y^2 dA \quad \& \quad I_z = \int_A z^2 dA \tag{4.8}$$

Using the equation 4.5, we obtain the axial thermal stress σ_{xx} in a beam subjected to thermal loading (without considering gravity loads) when the temperature distribution is a function of y and z as:

$$\sigma_{xx} = -E\alpha\theta + \frac{P_T}{A} + \frac{M_{Tz}y}{I_z} + \frac{M_{Ty}z}{I_y}$$
(4.9)

Since the temperature gradient (in the cross section) along the axis of the beam is constant, the axial stress is also constant along the axis of the beam.

We can also determine the deflection v in the slab as function of it's length. By definition

$$-\frac{dv^2}{dx^2} = \frac{1}{r_y} = -\frac{M_z}{EI_z}$$
(4.10)

We integrate 2 times over the x axis to obtain

$$v = -\int (\int \frac{M_z}{EI_z} dx) dx + C_1 x + C_2$$
(4.11)

 C_1 et C_2 are obtained from the boundary conditions v(0) = 0 and v(L) = 0.

This analytical method to determine thermal stress and vertical deflection is taken from the book "Theory of Elasticity and Thermal Stresses" of R.Eslami & al[23].

Let's consider now a simply supported beam subjected to a temperature gradient along its cross section (the mechanical boundary conditions are shown in the next figure). The beam length is 10.5 m, 1 m width and a thickness of 76 cm. The initial temperature of the beam is equal to 0°C (the strain reference temperature is equal to 0°C). Then we apply a sudden change of temperature. The temperature at the top surface of the beam is 1.3°C. The temperature at 10 cm below the top surface is 2.2 °C. The temperature at the bottom surface of the beam is -2°C. The values taken for the Young modulus and the coefficient of thermal expansion of the concrete are respectively 25 GPa and $1 * 10^{-5} °C^{-1}$.



Figure 4.19: Simply supported beam

To apply the equations written above, we should first approximate the temperature gradient θ along the thickness of the beam according to the y direction. We can do this using a polynomial function of order 5. We called this function $\theta(y)$ (see figure 4.20) :

$$\theta(y) = -272,95 * y^5 - 90,055 * y^4 + 29,505 * y^3 + 7,8666 * y^2 + 5,6403 * y + 0,341$$

The temperature difference between the polynomial and the real temperature gradient doesn't exceed 0.15°C.



Figure 4.20: Temperature gradient and polynomial approximation along the beam thickness

Using this polynomial function of the temperature and the beam propreties, we can calculate analytically the axial thermal stress using equation 4.9 and the vertical deflection using equation 4.11.

On Comsol, we built the same beam case without considering the gravity loads and by imposing the same temperatures. The boundary conditions on the edges of the beam (given in figure 4.19) are also applied on our model. Then we run a simulation using the solid mechanics module coupled to the heat transfer module to obtain thermal stresses and displacements.

In the next diagram, the axial stress obtained numerically and analytically are showed.



Figure 4.21: Thermal axial stress of the beam (numerical and analytical solutions)

The results given by the numerical and the analytical solution are very close. The variation in terms of stress between the analytical and the numerical solution doesn't exceed 0.025 Mpa.

The next plot presents the vertical deflection obtained numerically and analytically.



Figure 4.22: Vertical deflection of the beam (numerical and analytical solutions)

The variation in terms of vertical displacement between the analytical and the numerical solution doesn't exceed 0.026 mm.

Thus we can see for this simple case that the numerical and the analytical way give roughly the same solution for the stress and the deflection induced by the thermal loadings. However, to study more complex cases, the numerical resolution is more convenient. Thanks to this comparison, we are now more confident to use Comsol in order to study the structural response of the bridge deck of Jiangyin.

4.3.2 Study case of the bridge deck in Jiangyin: Geometry and boundary conditions

In this part, we want to study the thermal stresses induced by the melting system in the bridge deck of Jiangyin. As we showed previously, the real case experimentation is covering a small part of the bridge deck (see figure 3.9). The hydronic pipes are only located above the side span of the bridge and covering half of the deck width. The layout of the pipes is showed in figure 3.10.

The deck in Jiangyin bridge is composed by independant prestressed panels simply layed on the transversal beams which are linking each row of piles (elastic joints are used for the interface). Those panels can have 2 different lengths: 10 m if they are covering the side spans or 16 m when they are forming the central span. The panels are linked longitudinally (at the transversal beams) by rubber expansion joints which allow a free axial displacement. Transversally, the displacement is also totally free. With this manner, the bridge deck can expand or shrink during hot and cold periods without inducing additional stresses at the boundaries.

Therefore we can consider that our bridge deck is composed by 3 independant prestressed slabs simply supported axially at the transversal beams.

Since each slab is free to displace without impacting the displacement of the surrounding slabs when it is subjected to thermal loadings, we will simplify our study considering only the slab in which the hydronic pipes are inserted.

Using Comsol, we built the geometry of our slab following the same hydronic pipes layout installed in reality. The tubes are embedded 10 cm below the slab surface. The slab has the following features:

Slab length [m]	
Slab width [m]	
Slab thickness [cm]	76
Distance of the pipes from the top of the slab [cm]	
Pipe internal diameter [cm]	
Pipe thickness [mm]	
Injected water velocity $[m/s]$	0.5

Table 4.16: Geometric propreties of the studied slab and pipes propreties

For simplification reasons, we did not consider the pretension of the slab, neither the steel bars within the slab or the thin asphalt layer at the upper boundary. The slab is taken as an homogenous concrete element with a high Young modulus (E = 35 GPa) and the coefficient of thermal expansion of the concrete is $1 * 10^{-5} °C^{-1}$. The thermal propreties of the fluid, the pipes and the concrete are given in table 4.2.

Mechanical and thermal boundary conditions

As we said previously, the heated bridge deck behave mechanically as a simply supported slab. On Comsol, it is equivalent to constrain the vertical displacement on the 2 lower edges perpendicular to the bridge axis. Those supports are at the location of the transversal beams. The mechanical load (gravity) is not considered.

In order to represent the thermal conditions during the de-icing operation, we will consider that all the slab is covered by snow and when the melting process is in progress. Thus, we will consider that the slab is already heated when the snow precipitation occur in a way that the heat transfer between the slab and the fluid injected reaches the steady state condition. The obtained thermal stresses and the vertical deflection are given for this condition. The thermal boundary conditions are:

- The air temperature applied at the top and bottom surface of the slab is -2°C
- The strain reference temperature is -2°C. It means that no thermal stresses and deflection occur when the slab temperature is equal to -2°C. (corresponding to the beginning of the simulation)
- The bottom surface of the slab is subjected to a convection heat flux representing the wind (the convection heat transfer coefficient is taken equal to $0.5 \ [W/m^2 K]$)
- We make the hypothesis that the snow covering the slab has a temperature of -2°C. However, in the heated zones, since we are in the snow melting process, a thin film of

water is formed between the snow and the slab surface. This water film keeps a constant temperature of 0.56° C ([18, 40]) during the melting process as long as there is snow above it. So for our model, we imposed at the top surface of the slab a temperature of 0.56° C above the heated areas and a temperature of -2° C where there is no hydronic pipes below. This temperature is corresponding to the snow temperature.

The numerical model is presented in the next figure:



Figure 4.23: Numerical model including the boundary conditions

4.3.3 Numerical analysis to determine vertical displacement and stress during de-icing

To analyse the thermal stress during the de-icing process, we decide to study 2 cases. A first case where we inject a fluid temperature of 8°C. This could be the case where we use directly the heat extracted from the energy piles without using a heat pump. The second case represents the case when we are using a heat pump which enhance the power injected in the bridge deck. A fluid temperature of 25°C is injected.

We will present for the 2 cases, the vertical displacement, the axial stress (stress in the direction the bridge axis) and the transversal stress (stress in the direction perpendicular to the bridge axis). The stresses are given at the pipe location and for the top and bottom boundaries of the slab. Those variables will be given along the studied cross section (see the figure below).



Figure 4.24: Slab cross section

Case 1: Injected temperature: 8°C



Figure 4.25: Vertical deflection along the section (case 1)

By injecting hot fluid close to the upper part of the cold slab, the concrete will expand and induce vertical displacement upwards. When we inject a fluid temerature at 8°C, the value of this deflection reaches a maximum of 0.8 mm above the lane 1. This deflection decreases

the closer we are to the non heated zone. It drops to a value of 0.4 mm at the lane 3 then return to negligible values 5 m from the last heated zone.



Figure 4.26: Axial stress (case 1)

The figure 4.26 presents the axial thermal stresses (parallel to the axis of the bridge). By convention, the negative stress values means compression and positive values tension. We can see first that the thermal stress at bottom boundary of the slab is almost 0 along all the crossed section. Indeed, the hydronic pipes are 66 cm far from the bottom boundary and their thermal influence is very small at this zone except at the left of the lane 1. The stress at this location can be explained by the fact that in the numerical model we make the hypothesis that the slab is insulated at its lateral boundaries.

Since the vertical deformation in the global heated zone is upwards, the top boundary of the slab is in tension. The values are comprised globally between 0.5 and 1 MPa. In the non heated zones, the stresses tends to decrease except between the lane 1 and 2 where an increase of the tensional stress (1.3 MPa) is observed. This could be explained by the lateral expansion of the 2 heated lanes which induce lateral compression (see next figure) and may cause in this zone an enhanced tension on the bridge axis. The stress at the pipe locations is mainly compression. The values are around -1 MPa in the heated zones.

2 MPa of variation of stress occur between the tubes zone and the top surface (the distance between them is equal to 10 cm).

When there is no heat, the stress values at the pipe zone tend to 0 MPa except between the lane 1 and 2 and near by the lane 3 where there is tension stresses. We can see that those zones have the same behaviour observed at the top boundary.



Figure 4.27: Transversal stress (case 1)

In the figure above, the transversal stresses (in the direction perpendicular to the bridge axis) are presented. The peak values observed between the heated zones and non heated zones are due to the low quality of the meshing at the interfaces. First, we can observe that in this direction, thermal stresses at the bottom boundary are also very low. At the left of the lane 1, thermal stresses are nul because the slab is free to displace in this direction.

The top boundary in the heated zones is in tension: the values are roughly higher than the axial stresses (1 to 1.5 MPa). However in the non heated zones, the top boundaries are in compression (about -0.5 MPa). The expansion phenomenon above the heated zones induces this compression as a reaction. The stress at the pipe locations is also compression. The values for the lane 2 and 3 are around -1 MPa but in the lane 1, it is about -0.25 MPa and this is due to the fact that lane 1 is near by the free boundary

We can see here also that, when the area is not heated, the pipe zone and the top boundaries have almost the same stress. In this direction, 2 MPa of variation of stress are observed between the tubes zone and the top surface (the distance between them is equal to 10 cm).

Vertical displacement heated zone 1,8 1,6 Vertical displacement [mm] 1,4 1,2 1 0,8 0,6 1 0,4 I I 0,2 0 5 0 10 15 20 25 Distance [m]

Case 2: Injected temperature: 25°C

Figure 4.28: Vertical deflection along the section (case 2)

When we inject the fluid at 25°C, the value of the deflection is doubled and reaches a maximum of 1.7 mm above the lane 1. This deflection decreases the closer we are to the non heated zone. It drops to a value of 0.8 mm in lane 3 then returns to neglegteable values 5 m from the last heated zone.



Figure 4.29: Axial stress (case 2)

The figure above presents the axial stresses for the case 2. Even if the injected temperature increased, thermal stress at bottom boundary of the slab doens't evolve a lot except the zone near by the lane 1 since the slab is thermally insulated laterally. For the top boundary and pipe zone, we observe the same structural response than the case 1 but with higher stresses. The top boundary of the slab (in tension) has stress values ranging globally between 3 and 4 MPa. Those values become quite important and should be taken into account when designing the bridge deck. In reality the bridge deck is subjected to his load and the service loads, which attenuates those tensional stresses.

The stress at the pipe locations is mainly compression. The values are ranging between -2 and -3 MPa. In the non heated zones, we obtain tensional thermal stresses almost equal to the stress at the top boundary.

7 MPa of stress variation are observed between the tubes zone and the top surface which is quite high.



Figure 4.30: Transversal stress (case 2)

The figure above presents the transversal stresses for the case 2. In this direction, we observe the same behaviour than case 1 but higher stress values. In the heated zones, we can observe at the top boundary (in the heated zones) that the values passes from 1-1.5 MPa in case 1 to 4.5-5 MPa in case 2. In the pipe zone, the stress difference between the 2 cases is 2 MPa. This stress increase induces a larger variation of stress between the top surface and the pipe zone (9 MPa).

Through this numerical analysis, we investigated the structural behaviour of the slab of Jiangyin bridge during the de-icing process. The stresses are concentrated globally in the upper part of the slab. High variation of stresses was observed especially between the top surface (tension) and near by the tubes zone (compression). The higher the injected fluid temperature is, the higher are the stresses.

The obtained results give only an idea about the structural behaviour of the bridge deck and don't target to be used for a precise design. The main reasons are: the bridge deck was considered as a homogenous structure and totally free to displace on the lateral and axial direction which is not the case in reality. In order to keep the bridge under the servicialibility limit state, it is important to investigate more in details those thermal stresses. This can be done through comparing thermal stresses with the maximal stresses that can be handled by the bridge deck and its pavement in order to define a maximal injected temperature to avoid damaging the structure.

Conclusion

Throughout the master thesis, the applicability, the performance and the behaviour of the bridge deck de-icing system based on energy piles were analyzed. Besides, a real scale bridge experimentation in the city of Jiangyin (China) was studied as a practical example giving to the project a global vision of the considered de-icing system.

In the first part of the report, the emphasis was given on the general concept of the deck de-icing. The different methods of de icing used worldwide were enumerated and described with few examples with a special focus on the heating method using the energy pile systems where the physical phenomena involved in the melting phase (on the bridge deck) and the heat extraction (from energy piles) are explained in details.

To design such a melting system, the first thing to do is to determine the thermal needs which allow the remove of the snow in a efficient and effective way. That's why, in the second chapter, we define a methodology that could determine the energy demand for de-icing purpose. We based our research on the Ashrae (American Society of Heating, Refrigerating and Air-Conditioning Engineers) guidelines in order to know those energy requirements. The guidelines provide a way to find the heat flux to impose below the pavement in order to compensate the energy absorbed by the snow during the melting, the convective and radiative heat losses along the deck and the energy needed to evaporate the water after the melting phase. The energy requirements can be also calculated as function of different levels of service choosen by the designer engineer. Thus, the weather conditions at the bridge location (snowfall rate, air temperature, wind speed) are the main parameters to find the de-icing requirements.

Then, we tried to understand to what corresponds the energy requirements given by the Ashrae in 2 different ways. First, in terms of fluid temperature injected: an analytical method (equivalent heat resistance method) considering the geometric propreties of a slab was done to determine the fluid temperature to inject as function of the energy requirements. Second, from a global manner where we consider the whole system, e.g in terms of required number of energy piles. The required number of piles allowed us to discuss the applicability of such a system in function of the weather conditions imposed. In this study, we realized that the energy requirements for the de icing are very important comparing to the potential extracted heat from the energy piles (for a snowfall rate of 1.5 cm/h, a 2.7 m of energy pile with a high heat extraction rate is needed to de ice 1 m² of bridge deck). We concluded this chapter saying that the thermal potential of the energy piles is more suitable to ice prevention

(where the bridge deck keeps a temperature above 0°C) than quick snow melting.

Since I had the opportunity to assist to the construction of a real scale bridge in China which include for a small part of it, the melting system based on energy piles, the third chapter was dedicated to my stay there. A descriptive part was done to explain the project and the different phases of the melting system construction where I personally participated on-site: the implementation of the PE pipes in the piles and on the bridge deck, as well as the set up of a pretest for the melting system. We concluded this chapter by defining the energy requirements for the deicing considering the weather conditions of Jiangyin. Then, we determine the required number of piles for the case where all the bridge deck surface covered by the hydronic pipes and for the case of the experimentation where 55 m^2 of the bridge deck is covered. It has been found, for the 2 cases, that the required number of energy piles is higher than the available piles of the bridge. Thus, we decided to know at which melting rate the system operates for the cases considering the available energy piles. For the experimentation case, since we have only 5 energy piles to de ice 55 m^2 , 5.86 mm of snow can be melted in one hour and so 2.5 hours are needed to de ice 1.5 cm of snow depth which is less than the average snow fall rate in Jiagyin zone. However, since the hydronic pipes in the bridge deck are divided in 4 independent panels, for the future experimentations, it is still possible to connect the 5 energy piles on one heated panel to concentrate the heat in a smaller zone allowing to test an efficient de icing.

The performance and the structural behaviour of the bridge deck during the heating phase were investigated in the last chapter through performing numerical simulations using Comsol Multiphysics. A parametric analysis was performed in order to investigate the effect of several parameters composing the hydronic system of the bridge deck (pipe diameter, pipe spacing, fluid velocity flowing inside the slab) as well as the effect of external factors as the inlet fluid temperature and the wind velocity applied on the slab surface. Moreover, concerning the internal parameters such as pipe diameter, pipe spacing and fluid velocity flowing inside the slab, we define a ratio called TP ratio (ratio of the average slab temperature by the injected power inside the slab) which allows us to qualify the thermal efficiency of the heating. The higher this ratio is, the more efficient is the heating. Hence, a sensitivity analysis (where we combine the 3 mentionned parameters) were done to determine the best configuration in order to have the highest thermal efficiency. According to this sensitivity analysis, the best thermal efficiency is obtained for a pipe spacing of 20 cm, a pipe diameter of 2.5 cm and a fluid velocity of 1.5 m/s .

This chapter included also a section where numerical simulations were done to compare different layouts in the bridge deck. Indeed, since the construction of the bridge deck pipe layout was done a long time after my arrival in China, we tried to optimise the layout by decreasing the heated area in order to improve the thermal efficiency during the heating. The simulations have shown that the optimised layout can be a good alternative to the standard serpentine layout. Therefore, it was decided to test this new layout on the real case bridge deck.

We finished this chapter by forecasting the structural behaviour of the bridge deck (only the part where the hydronic pipes are installed) of Jiangyin during the de-icing process. We

observed that stresses are concentrated globally in the upper part of the slab with high variation of stresses between the top surface (tension) and near by the tubes zone (compression). Since we performed the simulations using two different fluid temperature, we observed that the higher the injected fluid temperature, the higher are the stresses. Those thermal stresses could induce damages on the bridge deck. Hence, it is important to investigate more in detail this issue before injecting very high fluid temperatures.

As a conclusion, we can say that a project including a deck de icing system using energy piles can be an alternative to traditional de icing methods. However, it is important to know in the early phases of such a project the energy requirements for the de-icing and the level of acceptance for the local authorities in terms of de-icing speed and efficiency. In fact, the limited number of (energy) piles supporting a bridge compared to the potentially heated deck surface reduce the thermal power of the system to ice prevention (keeping the bridge deck at a temperature above 0°C) rather than a quick snow melting. Nevertheless, we have seen in this report few methods allowing to improve the heating efficiency such as reducing the heated area of the bridge deck (by optimising the heated zones) or/and adapting a good configuration concerning the deck hydronic pipes (limit pipe spacing, increase the pipe diameter, limit the pipe length, increase the fluid velocity). We can also design a bivalent system including geothermal source and other type of energy source such as boiler-powered source (by gas, oil, or solar if possible). The structural behaviour of the bridge deck is also challenging. The latter requires a close collaboration between the mandated consultancy firms which are managing this type of project.

To make a de-icing project more reliable, a cost evaluation including construction costs, operation costs and environmental costs should be performed for the different de-icing methods considering the local constraints. This evaluation constitute together with the technical specifications the main arguments in the choice of the de-icing method and should be deeply investigated.

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