
A few minor revisions have been made from the paper as it appeared in the conference preprints.
A Modeling Approach To Design Of A Ground-Source Heat Pump Bridge Deck Heating System

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Abstract

This paper describes the approach taken to design a hydronic snow melting system for a bridge deck on an interstate highway in Oklahoma where a vertical borehole, closed-loop ground-source heat pump system is to be used as an energy efficient means to provide the heating requirement. It is proposed to use the bridge deck as a solar collector in the summer months so that the ground can be thermally “recharged” by circulating fluid from the bridge deck to the ground. This option can significantly reduce the size of the ground-loop heat exchanger (GLHE), thus resulting in a significant reduction in the system first cost. A design of this type involves the determination of a number of inter-dependent variables that are difficult or impossible to accurately quantify by conventional design practices. It was therefore decided to use a detailed system simulation to examine various system configurations and select the best design.

Mathematical models were developed to describe the performance of a hydronically-heated pavement slab and a water-to-water heat pump unit. The slab model uses a finite difference method to solve the transient two-dimensional heat conduction equation with the appropriate boundary conditions. The heat pump model uses a multi-variable optimization method to determine characteristic parameters for a particular heat pump unit and then predicts its performance as a function of entering fluid temperatures and flow rates.

In order to determine the bridge heating loads for subsequent sizing of the GLHE, it was necessary to determine the required heat flux to the bridge. The heat flux was computed by coupling the heat pump model to the slab model and fixing the weather factors at design conditions. Design parameters such as minimum heat pump entering fluid temperature, number of heat pumps and flow rate were then varied and several potential designs were selected that kept the bridge surface temperature above freezing. The slab model was then used to estimate the hourly heating loads by using ten years of actual weather data acquired from a nearby monitoring station as inputs to the model. The hourly heating loads determined by the model were then used to estimate the required size of the GLHE for each of the above configurations.

There is a trade-off between the number of boreholes that make up the GLHE and the number of heat pumps required. Of the configurations examined, a system with 16 heat pumps of nominal 30-ton capacity and 250 boreholes, each 250 feet deep, was selected.
INTRODUCTION

Engineered heating systems for the melting of snow and ice from paved surfaces have been used for several decades. Some of the first documented systems are described by Adlam (1). Their advantages are that they provide “on-demand” performance and eliminate the use of chemicals, which may be deleterious to the pavement material or harmful to the environment.

Snow melting systems may be grouped into one of three categories according to ASHRAE (3): (1) hydronic systems, where a hot fluid is circulated through embedded pipes, (2) electric systems, where heat is generated by embedded electric cables, and (3) infrared systems, where heat is generated by overhead high intensity radiant panels. Because of the relatively large power consumption required by electric and infrared systems, hydronic systems are perhaps the most practical type for large applications such as roadways. In typical hydronic system applications, a gas-fired or electric boiler is generally used to heat the working fluid. For the work described here, we plan to use a ground-source heat pump (GSHP) system as an energy efficient means to provide the heating requirement.

The design of GSHP systems, as compared to conventional heating and cooling systems, presents a unique challenge because of the thermal storage properties of the earth. A designer cannot simply select equipment based on some extreme condition because heat transfer within the earth is not instantaneous; present responses of the ground to a thermal load depend upon previous loading conditions. Thermal loads imposed on the ground are seldom balanced on an annual basis since heating and cooling demands are rarely equal. The designer, therefore, needs to consider thermal responses of the ground throughout the life of the project (i.e. 20 to 30 years) on a monthly or an hourly basis. This requires calculation of the heating and cooling loads.

The design of a GSHP snow-melting system presents some further challenges since the demand is solely for heating purposes. The system will continually extract heat from the ground during the winter season thereby depleting the potentially available heating energy in the ground each year. As a result, the ground-loop heat exchanger (GLHE) needs to be excessively large to be able to accommodate the heating load some 20 to 30 years in the future. To offset the imbalance in thermal loads to the ground, we can take advantage of the thermal storage properties of the earth and the large surface area of the bridge deck and use it as a solar energy collector. Fluid can be circulated from the bridge deck to the ground in the summer months to thermally “recharge” the ground for the next winter heating season and therefore reduce the required size of the GLHE.

Given the complexities of heat transfer in the ground and in the bridge deck itself, the design of a GSHP snow-melting system for a bridge deck involves determining a number of inter-dependent variables that are difficult or impossible to accurately quantify by conventional design practices. In this paper, we describe a system simulation approach that was used to design such a system for a bridge deck on an interstate highway in Oklahoma. The paper is organized into three sections. First, some background information is presented regarding GSHP systems, hydronic pavement heating systems, and the mathematical models used to describe the performance of these systems. Second an overview of the design and system simulation procedure is presented, and the third section discusses the results of the design effort. The goal of this project was to improve the design of future GSHP bridge deck heating systems.

BACKGROUND

This section presents a brief description of the subject site and a brief overview of ground-source heat pump (GSHP) systems. Each component of a GSHP system as related to hydronic bridge deck de-icing is discussed and relevant heat transfer mechanisms are outlined. The mathematical models used to describe the performance of each of the system components is also briefly outlined.

Site Description

The bridge deck described in this paper is a section of Interstate Highway 40 (I-40), located just east of Weatherford, Oklahoma. This particular section of I-40 consists of eastbound and westbound bridges that span over a county road, a creek, and a railroad. The highway bridges are scheduled to be
replaced by new bridges approximately 700 feet long by 40 feet wide. Only the westbound bridge is to be heated by the GSHP system.

Ground-Source Heat Pump (GSHP) Systems

GSHP systems (also referred to as geothermal heat pump systems, earth energy systems, and GeoExchange systems) have received considerable attention in recent decades as an alternative energy source for heating and cooling applications. GSHP applications are one of three categories of geothermal energy resources as defined by ASHRAE (2). These categories are: (1) high-temperature (>302°F) electric power production, (2) intermediate- and low-temperature (<302°F) direct-use applications, and (3) GSHP applications (generally <90°F). The GSHP applications are distinguished from the others by the fact that they operate at relatively low temperatures. A heat pump is needed to move heat from a lower temperature source to a higher temperature sink.

The term “ground-source heat pump” has become an all-inclusive term to describe a heat pump system that uses the earth, ground water, or surface water as a heat source and/or sink. In our application, the heat pump extracts heat from the ground for use in the winter. Energy is stored in the summer by directly circulating fluid from the bridge deck to the ground loop heat exchanger. (The heat pump is not operated during the summer.)

The Hydronic Snow-Melting Component

The heat demanded by the snow-melting system represents the thermal load. The serpentine pipe configuration is that commonly used in snow-melting systems as shown in Figure 1.

![Figure 1. Typical construction of a hydronic snow-melting system in (a) plan view and (b) cross-sectional view.](image)

The typical construction consists of high-density plastic pipes embedded in the pavement material on even centers and connected with U-shaped tubing. Typical pipe spacings range from 6 to 12 in. with a burial depth of 2 to 3 in. Nominal pipe diameters are commonly ¾ or 1 in.
Pertinent concepts of heat transfer in pavement slabs have been addressed for snow melting applications by many sources including Adlam (3), Chapman (4), Kilkis (5), ASHRAE (2), and Ramsey et al. (6). Heat transfer mechanisms acting upon the pavement slab are shown schematically in Figure 2.

Heat transfer within the slab itself is by conduction. Internal sources of heat are due to convection from flow of the heat transfer fluid through the pipes. Heat fluxes at the pavement surface are due to a number of environmental interactions and include convection, solar radiation, thermal (long-wave) radiation, sensible heat transfer from precipitation, and latent heat transfer from melting snow and evaporating water. In the case of a bridge deck where the slab bottom is exposed, heat transfer from the bottom surface is by convection and radiation to the surroundings.

![Figure 2. Heat transfer mechanisms in a hydronically-heated bridge deck](image)

A computer model has been developed for use in component-based system simulation environments such as TRNSYS (7) and HVACSim+ (8) to describe the heat transfer in hydronically-heated slabs. Details of the model are described by Chiasson. (9). Transient heat transfer in the slab is represented in the model in two-dimensional (2-D) cross-section using the Cartesian coordinate system. Each of the heat transfer mechanisms shown in Figure 2 is represented in the model.

**The Heat Pump Component**

A heat pump consists of four basic components: (1) a reciprocating compressor, (2) an evaporator, (3) a condenser, and (4) an expansion device. Heat is absorbed from a lower temperature source on the evaporator side and rejected to a higher temperature sink on the condenser side. The heat pump coefficient of performance (COP) is much greater than the thermodynamic efficiency of fossil fuel combustion. The typical COP of a water-source heat pump is 2 to 4, while conventional natural gas systems can only attain
efficiencies of about 0.8. The much greater efficiency attainable by a GSHP system is makes them attractive as an alternative to conventional heating equipment.

A computer model has been developed for use in component-based system simulation environments such as TRNSYS (7) and HVACSim+ (8) to describe the performance of a water-to-water heat pump. Details of the model are described by Jin and Spitler (10). This model makes use of the manufacturers’ catalog data and a multi-variable optimization routine to calculate the optimal values of parameters that describe the overall performance of the heat pump. The objective function in the optimization routine is formulated from the basic thermodynamic laws of the conservation of mass, energy, and momentum that describe the behavior of the compressor, the evaporator, the condenser, and the refrigerant. Once the optimal values of the performance parameters have been determined, the model can accurately simulate the performance of the heat pump over its full operating range.

The Ground-Loop Heat Exchanger (GLHE) Component

Several types of GLHE configurations can be installed at a particular site, depending on the site conditions. In this work, we selected the vertical closed-loop ground-coupled type, which can be installed at any location where drilling and earth trenching are feasible.

In vertical closed-loop ground-coupled type systems, heat rejection/extraction is accomplished by circulating a heat exchange fluid through high-density polyethylene (HDPE) pipe installed in vertical boreholes. GLHE arrangements typically consist of one to hundreds of boreholes each containing a U-shaped pipe through which the heat exchange fluid is circulated. A number of borehole-to-borehole plumbing arrangements is possible. Typical U-tubes have a diameter in the range of ⅜ in. to 1 ½ in. and each borehole is typically 100 ft to 300 ft deep with a diameter ranging from 3 in. to 5 in. The borehole annulus is generally backfilled with a grout or other material that prevents contamination of ground water.

One of the fundamental tasks in the design of a reliable GSHP system is properly sizing the GLHE (i.e. depth and number of boreholes). The higher first cost of these systems relative to conventional heating/cooling systems often makes short-term economics unattractive. Therefore, particularly for large systems, an extensive effort is made to design the GLHE so that it is not too large, resulting in too high of a first cost. If the system is too small, the thermal load will not be met at some time in the future. Extensive research throughout the past 20 years has produced several methods and commercially available design software tools for sizing GLHEs. We used design software developed by Spitler, et al. (11) for this task.

The GLHE design software developed by Spitler et al. (11) uses the results of Eskilson (12), who used a finite difference model to solve for the temperature distribution in borehole fields of various configurations in response to a step heat extraction or rejection rate. The temperature distribution over time was then converted to a series of non-dimensional response factors known as “g-functions”. It is the g-functions that are used by Spitler et al. (11) to size GLHEs and simulate their performance.

THE SYSTEM DESIGN PROCESS

The system design was completed in four phases: (1) establish the required heat flux to the bridge surface, (2) estimate the bridge heating loads, (3) estimate the energy available for thermal recharge of the ground, and (4) size the GLHE. None of these phases are completely independent; the final design decisions were the result of iterations of the four phases, each of which are described in the following subsections. A flow chart summarizing the design process is shown in Figure 3.
The Heat Flux to the Bridge

The heating requirement of a snow-melting system is commonly described in terms of a heat flux. The heat flux required for successful operation of the system depends upon many factors including: (1)
environmental heat transfer mechanisms (as shown in Figure 2), (2) bridge deck construction (materials, thickness, area, and orientation), (3) hydronic tubing construction (material, diameter, spacing, and burial depth), (4) system flow rates, (5) heat transfer fluid properties (density and thermal properties), and (6) the fluid supply temperature. The following design conditions were chosen:

**Weather Conditions:**
- air temperature = 15°F
- wind speed = 14 mph
- snowfall rate = 10 in./day

**Bridge Deck and Piping System Design:**
- pipe diameter = ¾-in. nominal
- pipe depth = 3 in. below road surface
- pipe center spacing = 12 in.
- deck thickness = 8 in.
- deck area = 26,649 ft
- heat transfer fluid = 42% propylene glycol @ a flow rate of 350 gpm
- heat pump model = Water Furnace, Spectra SXW 360

The objective of the design heat flux was to keep the average bridge surface temperature above freezing under the weather conditions listed above. These design weather conditions were selected based on a compromise between system feasibility and a realistic winter storm scenario. Determination of the design heat flux required quantification of the heat transfer mechanisms shown in Figure 2. However, this depended upon knowledge of the heat pump performance, which at this stage of the design process could not be reliably determined by conventional means. The conventional practice is to estimate the heating load and use manufacturers’ catalog data to estimate load-side and source-side entering fluid temperatures to the heat pump by assuming the temperature decrease across the load is the same as listed in the catalog. In this case, none of the input parameters (entering fluid temperatures and flow rates) match any of the catalog data, making even interpolation of the catalog data difficult. Therefore, it was decided that it would be ideal to be able to predict the heat pump performance in response to a dynamic heating load, and hence the need for a system modeling approach.

To determine the heat flux, the heat pump model was coupled to the slab model and the design conditions described above were used as inputs to the models. Design parameters such as minimum heat pump entering fluid temperature, number of heat pumps, and flow rate were varied with the models and several potential designs were considered. It became evident that it would be necessary to arrange the heat pumps in pairs in parallel on the source side and in series on the load side in order to produce the required entering fluid temperature to the bridge. This allowed only a fraction of the bridge deck be modeled, corresponding to the fraction served by a single heat pump pair. Bridge deck average surface temperatures and the corresponding heat flux are plotted versus source-side heat pump entering fluid temperature for 8 heat pump pairs in Figure 4.
The performance of 9 pairs and 10 pairs of heat pumps was also simulated, but these arrangements were rejected from consideration because the model results showed that the entering fluid temperature to the second heat pump in each pair exceeded the manufacturer’s rating.

The Bridge Heating Loads

The design heat flux only represents the maximum potential output of the system. It yields no information regarding the actual energy use of the system over the course of a heating season, since the heat flux is determined for extreme weather conditions only. As previously stated, the performance of the GLHE depends upon the short-term loads on the heat pump. It is therefore necessary to estimate the hourly heating loads on the heat pump in order to design a reliable and cost-effective GLHE. Such estimates of the heating loads require the use of reliable weather data.

The heating loads on the heat pump for the various cases were estimated using the design heat fluxes shown in Figure 4 and actual hourly climatic data for Oklahoma City for the years 1982 through 1992. Actual hourly weather data are desirable to properly simulate storm events. Included in the data sets are the hours when rain or snow was falling along with the quantity of precipitation in equivalent inches of water.

For each year from 1982 to 1992, the numerical bridge deck model was used to predict the bridge surface temperature under the actual climatic conditions for the given year. Inputs to the model were weather data only. The modeled bridge deck surface temperature, the air temperature, and amount of precipitation for 1983 are shown graphically in Figure 5.
Figure 5. Air temperature, precipitation, and modeled bridge deck surface temperature corresponding to actual 1983 winter weather data for Oklahoma City.

One of the advantages of the system simulation approach can be inferred from Figure 5. The bridge surface temperature is frequently much warmer than the air temperature during the day because of solar radiation effects. During the night hours, the opposite is generally true and the bridge deck surface is colder than the air because of thermal radiation and convection effects. The system simulation allows for proper accounting of these effects, so that the actual coincidence between precipitation and sub-freezing bridge deck temperatures can be determined.

The hourly heating loads were then determined for each year based on an assumed control strategy that the bridge will call for heating 12 hours before and 12 hours after a freezing precipitation event. This conservative control strategy was adopted primarily because more advanced forecasting-based control strategies are not yet available. The bridge heating load was then assumed to be linearly proportional to its surface temperature: heating load = 0% of the design flux at 35°F and heating load = 100% of the design flux at 20°F. When more advanced control strategies are available, which include forecasting and variable rate heating, a better prediction of the bridge deck heating loads may be made. The year 1983 was chosen as the “design year” since that year exhibited the highest heating requirement. Monthly bridge heating loads for 1983 are summarized graphically in Figure 6 for the four design cases shown in Figure 4.
Ground Thermal Recharge

Thermal recharge of the ground is necessary to effectively balance the thermal loading to the ground over the annual cycle, and hence reduce the size and therefore the cost of the GLHE. Thermal recharge is analogous to the cooling load of a building since heat is rejected to the ground in both cases. Therefore, as with the heating load, thermal recharge loads need to be estimated on an hourly basis in order to design a reliable and cost-effective GLHE.

Potentially available energy for recharging the ground was estimated using the numerical bridge deck model and “typical” weather data for Oklahoma City. The weather data were of the Typical Meteorological Year (TMY) format, produced by the National Climatic Data Center. A TMY record for a particular location represents a long-term statistical average of various weather parameters. TMY data were used for estimating the recharge loads rather than actual weather data because the TMY data are more representative of the long-term weather conditions over the life cycle of the bridge.

Modeled bridge surface temperatures during the months of April through October for a typical year are shown graphically in Figure 7.
A review of this figure demonstrates the potential for using the bridge deck as a solar energy collector. Daily surface temperatures of the deck frequently exceed 120°F, with a maximum of 140°F.

The recharge strategies investigated with the model included circulating fluid from the bridge deck to the ground loop when the bridge surface exceeds some specified temperature. A surface temperature of 90°F was found to be adequate. The hourly thermal recharge rates were computed by the slab model using an overall energy balance on the heat transfer fluid. The monthly thermal recharge rates are shown graphically in Figure 8. The advantage of summer recharge is seen in the next subsection.
The Ground-Loop Heat Exchanger (GLHE)

The GLHE was sized using design software developed by Spitler et al. (11). Inputs to the model included the heating loads, the thermal recharge loads, a description of the ground thermal properties, a description of the borehole geometry, the fluid physical and thermal properties, and a description of the heat pump. A 42% propylene glycol solution was specified as the heat transfer fluid with a total flow rate of 900 gpm. A borehole diameter of 5 in., HDPE U-tubes with a nominal diameter of ¾ in., and thermally enhanced grout were also specified.

All borehole fields considered in the design process were rectangular-shaped with 250-feet deep bores on 15-feet spacings and were sized for 25 years of operation. Figure 9 shows the relationship between the design minimum entering fluid temperature to the heat pump and the required number of boreholes for cases with and without summer recharge. The impact of the entering fluid temperature as well as using summer recharge on the borehole field size are evident.
The Final Design

The final design is shown schematically in Figure 10. The system consists of 16 heat pumps arranged in 8 pairs such that the fluid flow is in parallel on the source side and in series on the load side. The heat pumps will supply fluid to the bridge deck at approximately 122°F with a total flow rate of 350 gpm. The borehole field configuration selected consists of 250 boreholes, each 250 ft deep, that uses summer recharge. The borehole field will supply fluid to the heat pumps at a minimum temperature of 44°F with a total flow rate of 900 gpm.

DISCUSSION OF RESULTS

With the system modeling and simulation approach, key design parameters could be easily varied and the performance of several possible designs could be examined in order to obtain a workable solution. There is a trade-off between the number of boreholes that make up the GLHE and the number of heat pumps required to provide the heating load. In other words, fewer heat pumps could have been chosen, but the GLHE length would approach an extremely large value. Therefore, the size of the GLHE is traded off against the size and number of heat pumps required. The modeling approach allows a suitable combination to be found.

The advantages of the modeling effort can be summarized by conducting a simple cost analysis. Given that a typical cost for drilling, grouting, and installing pipe in a borehole is approximately $1,000 per borehole, a borehole field with no summer recharge supplying 50°F fluid to 16 heat pumps (Figure 9) would cost about $490,000. A borehole field taking advantage of summer recharge supplying 44°F fluid to 16 heat pumps (Figure 9) would cost about $250,000.
**Figure 10.** The final design showing the bridge deck heat transfer details for 1/8 span (design weather conditions and bridge-loop design details are described in the text).

**SUMMARY AND CONCLUSIONS**

This paper has described the modeling approach taken to design a hydronic snow melting system for a bridge deck on an interstate highway in Oklahoma. The heating requirement is to be provided by a vertical borehole, closed-loop GSHP system. It is proposed to use the bridge deck as a solar collector in the summer months so that the ground can be thermally “recharged” by circulating fluid from the bridge deck to the ground, thereby significantly reducing the size, and therefore the cost, of the GLHE.

Computer models were developed to describe the performance of a hydraulically-heated pavement slab and a water-to-water heat pump unit. The models were formulated for use in a component-based system simulation environment such as TRNSYS or HVACSim+. The heat flux necessary to keep the average bridge surface temperature above freezing was computed by coupling the heat pump model to the slab model and fixing the weather factors at design conditions. The design parameters such as minimum heat pump entering fluid temperature, number of heat pumps and flow rate could then be easily varied in order to examine several possible design scenarios. To determine the required size of the GLHE, the slab
model was used to estimate the hourly heating loads on the heat pump and the hourly summer recharge loads on the ground. Actual weather data were used to determine the heating loads and “typical” weather data were used to determine the summer recharge loads.

The modeling approach demonstrated the advantage of design through system simulation. There is a trade-off between the number of boreholes that make up the GLHE and the number of heat pumps required. The system cost is dominated by the GLHE cost and the modeling approach allowed a practical solution to be found. Of the configurations examined, a system with 16 heat pumps of nominal 30-ton capacity and 250 boreholes, each 250 ft deep, was finally selected.

ACKNOWLEDGEMENTS

This material is based upon work supported by the Federal Highway Administration under Grant No. DTFH61-99-X-00067. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the Authors and do not necessarily reflect the view of the Federal Highway Administration. Earlier funding that helped establish the basis of this work by the Oklahoma Department of Transportation and the U.S. Department of Energy is gratefully acknowledged.

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