GROUND-SOURCE HEAT PIPE SNOW-MELTING SYSTEMS IN JAPAN

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ABSTRACT

Many types of ground thermal energy systems have been used in Japan to melt snow on pavement. Such systems include direct circulating pipes (DCP), ground-source heat pumps (GSHP) and heat pipes (HP). This paper focuses on application of HP systems to road heating.

DCP use direct thermal conduction of ground thermal energy through heat radiating pipes laid beneath the pavement and circulate a medium through a borehole or a well. DCP and GSHP use ground thermal energy, but they also need electric power to drive the heat pump and the water circulation pump and to control the units. In contrast, HP needs no electricity at all. HP systems consist of a vertical borehole and heat pipes. The borehole diameter is about 150 mm. The depth ranges from 15 to 20 m. The heat pipe diameter is 27 mm. The length varies from 20 to 25 m. The system is capable of melting a snow-covered area of 2 to 5 m^2.

HP systems feature automatic control, no operating costs and low maintenance requirements. However, the initial cost is higher than that of any other system. There are many challenges, such as reducing the drilling cost, controlling the heat radiation and determining the effective area of snow-melting.

1. ROAD SNOW-MELTING SYSTEMS IN JAPAN

1.1 Heat sources and snow-melting method

The heat sources used for snow-melting systems in Japan include renewable energy sources, waste energy sources and fossil fuels (Figure 1). Of the renewables, groundwater, ambient air, river water and ground heat have been applied to many projects. Less commonly used have been hot spring water, seawater, solar energy and lake water. There are not many application examples of waste energy sources; however, sewage water and exhaust heat from buildings in urbanized areas have been used. As for fossil energy sources, kerosene, petroleum, gas and electricity have been commonly applied for snow-melting systems. Table 1 summarizes snow-melting systems and their heat sources.

Groundwater snow-melting systems utilize the abundant groundwater that is found in snowy regions. The methods can be divided into two types: 1) those that sprinkle water directly on the road, and 2) those that melt snow by transferring groundwater heat to the road surface. The sprinkler type was first introduced in 1961[1]. The method is widely used in regions where the ambient air temperature is above the freezing point and there is little risk of the sprinkled water freezing (Figure 2). The groundwater heat transfer type was first introduced in 1980[2]. The groundwater is transported through pipes installed in the pavement. The heat of the groundwater is conduced to the pavement to melt snow. This type is widely used at high latitudes and at high altitudes, where the air temperature drops below the freezing point (Figure 3).

Table 1 - Major road snow-melting systems and their installation records in Japan

Heat source		Type	Snow-melting method	Installation frequency
Renewable energy	Groundwater	Sprinkler	Direct sprinkling of groundwater on the road surface	Very common
		Groundwater heat conduction (water circulation)	Piping of groundwater through the pavement	Very common
		Heat pump	Circulation of medium heated by water-source heat pump through pipes in the pavement	Common
	Ground thermal	Direct circulation	Circulation of medium through ground heat exchanger and radiator installed in the pavement	Common
		Heat pump	Circulation of medium heated by ground-source heat pump through pipes in the pavement	Common
		Heat pipe	Conduction of ground heat to the pavement by heat pipes installed in the ground	Common
	Ambient air	Heat pump	Circulation of medium heated by air-source heat pump through the pavement	Very common
	Hot spring water	Heat exchanger	Circulation of medium heated by heat exchanger through the pavement	Limited, only at hot spring area
		Heat pump	Circulation of medium heated by water-source heat pump through the pipes in the pavement	Uncommon
	River water	Sprinkler	Direct sprinkling of river water on road surface	Common
	Seawater	Sprinkler	Direct sprinkling of seawater on road surface	Uncommon
		Heat pump	Circulation of medium heated by water-source heat pump through pipes in the pavement	Uncommon
	Lake water	Heat pump	Circulation of medium heated by water-source heat pump through pipes in the pavement	Uncommon
	Solar thermal	Shallow ground thermal	Circulation of medium through pipes between the ground and the pavement; use of solar heat stored in the ground in summer to melt snow in winter	Uncommon
		Aquifer thermal storage	Circulation of groundwater through pipes between aquifer and pavement to store solar heat in the aquifer in summer for use in winter for snow melting	Uncommon
		Photovoltaic	Heating of an electric heater buried in the pavement	Limited
Waste energy	Sewage water	Circulation	Circulation of medium through the heat exchanger in sewage pipes and radiator installed in the pavement	Limited
		Heat pipe	Circulation of medium heated by water-source heat pump through pipes in the pavement	Under experiment
	Exhaust heat	Air circulation	Transport of hot exhaust air from buildings to the pavement	Uncommon
Fossil energy	Petroleum	Boiler	Piping of medium heated by petroleum boiler through the pavement	Common
	Gas	Boiler	Piping of medium heated by gas boiler through the pavement	Very common
	Electricity	Heater	Heating of an electric heater buried in the pavement	Very common

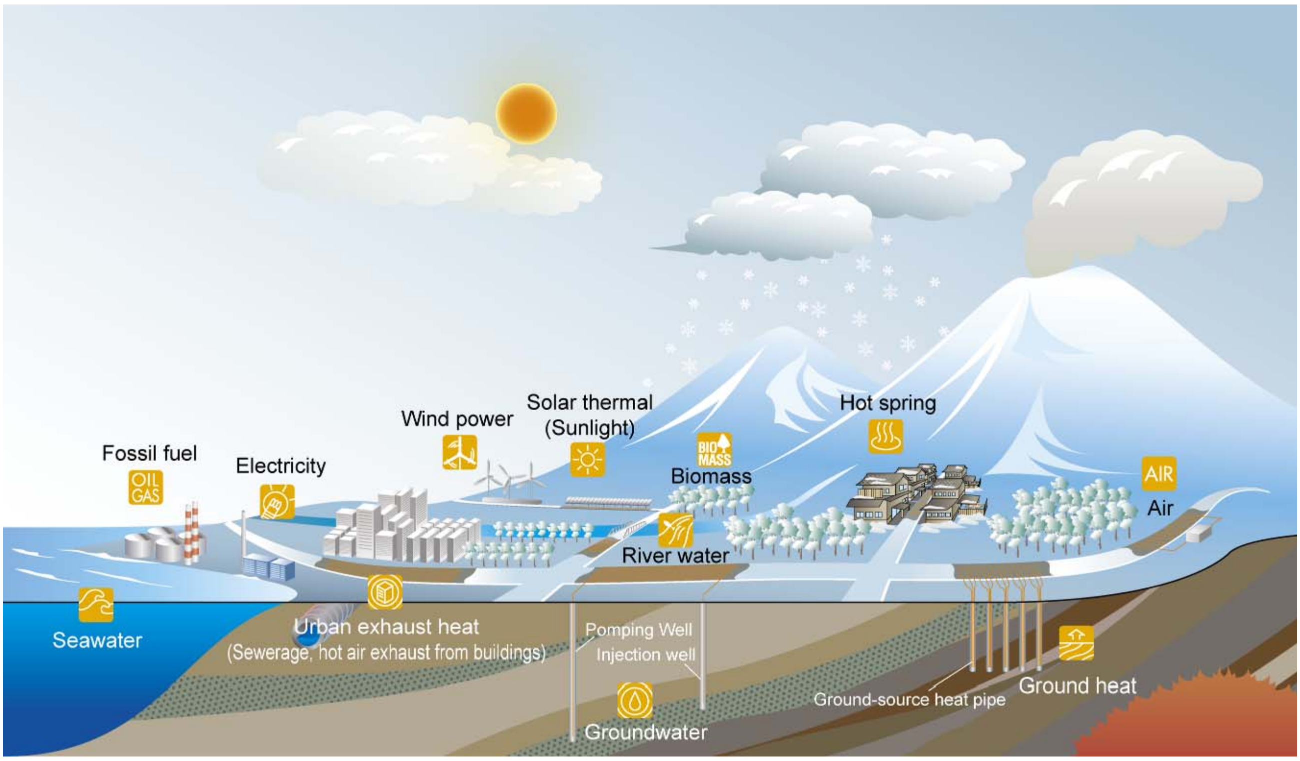


Figure 1 - Types of thermal energy used for snow-melting systems



Well screen pipes | Sprinkler pipes | Sprinkling water

Groundwater is sprinkled from nozzles installed in the pavement surface.
Figure 2 - Groundwater sprinkler snow-melting system



Pumping test | Radiation pipes | Melting snow

Groundwater pumped up from the well (left) is circulated through the heat radiation pipe (center) to melt snow (right).
Figure 3 - Groundwater heat conduction snow-melting system

To use the heat of ambient air, a heat pump raises the temperature of water circulating through pipes in the pavement. The method was first applied in 1994. It is widely used in regions where groundwater cannot be used for reasons of geology or groundwater pumping bans (Figure 4).

Air-source heat pump

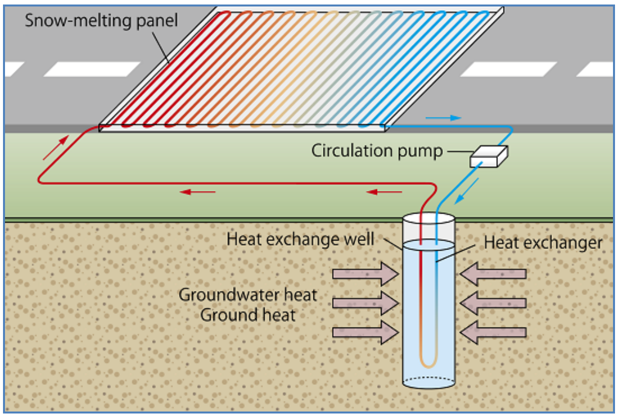
Radiation pipes

Melting snow

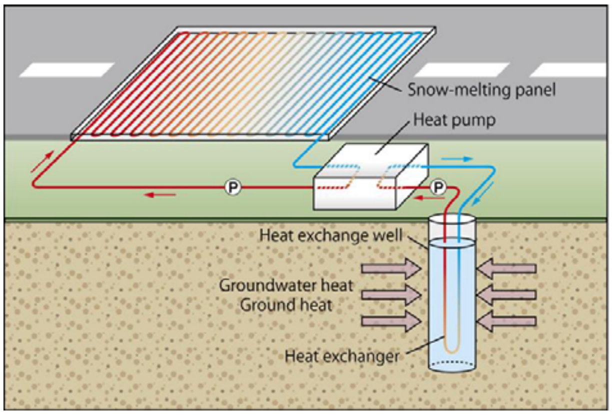
Water heated in the air-source heat pump (right) is circulated through radiation pipes (center) to melt snow (right).
Figure 4 - Air-source heat pump snow-melting system

1.2 Road snow-melting systems using ground heat

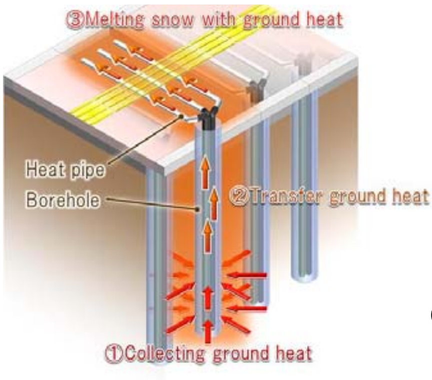
Ground thermal heat is defined as the heat stored in the ground within a depth of 200 m from the ground surface. The temperature of the ground within that depth is often nearly the same as, or higher than, the annual average air temperature of the region and is generally 10 to 17 °C in the snowy cold regions of Japan, other than in Hokkaido (the northernmost island). The snow-melting systems that use ground heat energy are 1) direct-circulating pipe (DCP) systems, 2) ground-source heat pump (GSHP) systems, and 3) heat pipe (HP) systems (Table 1 and Figure 5).



Direct circulating pipe (DCP) system



Ground-source heat pump (GSHP) system



Ground-source heat pipe (HP) system

Figure 5 - Ground-source snow-melting systems

The DCP and GSHP systems collect heat from the ground from wells drilled to a depth of about 100 m; heat exchangers are inserted into the wells, and a medium is circulated through those exchangers. To melt snow with a DCP system, the medium is circulated through radiation pipes installed in the pavement. This type of system is widely used in regions where snowfall is scant and, thus, the heat required for snow-melting systems is less than in regions where the snowfall is heavy. The GSHP system uses ground heat and a heat pump to heat medium that is circulated in the pavement. Such a system can be installed in regions where the snowfall is heavy and the temperatures are low. GSHP systems need less electricity and fuel than air-source heat pumps or petroleum boiler snow-melting systems; thus, GSHP systems have lower operating costs and carbon dioxide emissions.

HP systems collect heat from the ground from boreholes drilled to depths of 15 to 20 m; heat pipes are inserted into the holes, and ground heat is conducted to the pavement. Such systems are widely used in Japan, other than in Hokkaido, the coldest region.

2. FEATURES OF THE GROUND-SOURCE HEAT PIPE SNOW-MELTING SYSTEM

2.1 System configuration

The heat source of the ground-source HP snow-melting system is ground heat. The system uses heat pipes for heat conduction.

Figure 6 shows the heat conduction mechanism of a heat pipe. A heat pipe is a closed stainless pipe filled with a medium. When the medium is heated in the heated section (the evaporator) of the pipe, it evaporates. The vapor moves to the heat-release section (the condensation section) of the pipe, where it releases latent heat and condensates into liquid state. When a heat pipe is installed such that the liquid medium returns to the heated section of the pipe, the cycle of evaporation and condensation is repeated continuously and heat is continuously transferred from the heated section to the heat-release section. When there is no temperature difference between the heated section and the heat-release section, heat transfer does not occur. The amount of heat released from the pipe increases with increases in the temperature differential between the heated section and the heat-release section.

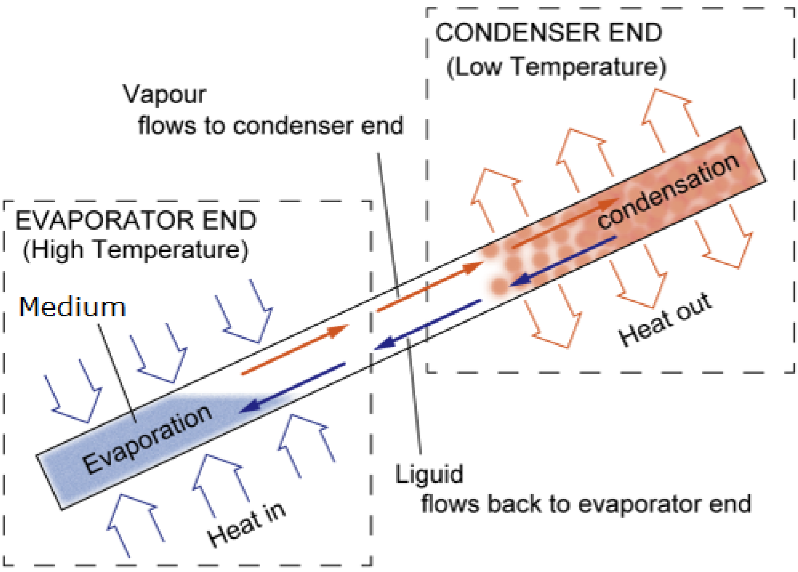


Figure 6 - Heat transfer mechanism of heat pipes

The medium of heat pipes differs depending on the environmental temperature where the heat pipe system is adopted. Generally, HFC-134a, a CFC alternative, is used for the heat pipes of ground-source heat pipe snow-melting systems.

Figure 7 outlines a ground-source heat pipe snow-melting system. Three to five heat pipes are combined and inserted into a borehole of 150 mm in diameter and 15 to 20 m in depth. The heated section is installed in the ground and the heat-release section is installed in the pavement. The heat pipe is 27 mm in diameter and 20 to 25 m in length. The heat release sections of heat pipes are placed in the pavement body at a regular interval of 15 to 25 cm so that the pavement is uniformly heated. The length of the heat-release section is between 2 and 5 m. One borehole is used to melt snow in an area of 2 to 5 m^2.

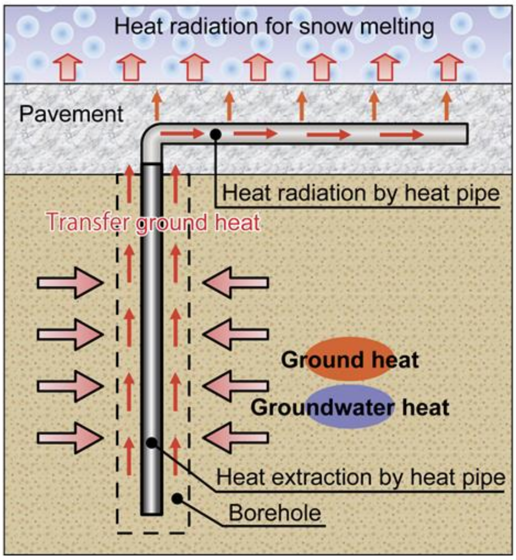


Figure 7 - Heat transfer mechanism of heat pipes (left), and the heat pipes (right)

Because the ground-source heat pipe snow-melting system has no machinery, its construction is much easier than those of other snow-melting systems. The construction procedure is as follows: 1) Make a borehole with a diameter of about 150 mm with a boring machine (Figure 8a); 2) Protect the borehole from collapse with a steel pipe with a diameter of about 100 mm; 3) Insert a few heat pipes in the steel pipe; 4) Fill the gaps between the steel pipe and the heat pipes with silica gravel (Figure 8b); 5) Fix the heat-release section of the heat pipes to spacers laid on the base course of a road at a uniform interval (Figure 8c); and 6) Pave the road with concrete (Figure 8d).

2.2 Snow melting mechanism

The mechanism of heat pipe heat transfer is applied to ground-source heat pipe snow-melting systems, without additional equipment. When the pavement temperature falls below the ground temperature, the heat pipes start to transfer ground heat to the pavement in order to warm it. When the air temperature drops or snow falls, the temperature differential between the pavement and the ground becomes large and the heat pipes increase the amount of heat transferred and released to the pavement. The transferred heat melts snow and prevents ice from forming on the pavement surface. When there is no snowfall or the air temperature is above the freezing point, the temperature differential between the pavement and the ground is small and heat release from heat pipe is also small. When the pavement temperature is higher than the ground temperature, the heat pipes do not release any heat. In this way, the heat pipes automatically activate and deactivate. The ground-source heat pipe snow-melting system only operates when the weather conditions require snow melting and/or ice prevention. The system efficiently uses ground heat.

a: Drilling

b: Heat pipe installation

c: Heat pipe installation and fixation

d: Completed for snow melting

Figure 8 - Procedures for installation of the ground-source heat pipe snow-melting system

The system's heat flux is calculated from the thermal resistivity of soils at the heated section (evaporator) of the heat pipes, the thermal resistivity of the heat pipes themselves, the thermal resistivity of pavement between the base course and the pavement surface, and the ground temperature. The thermal resistivity of soil varies depending on the geological and groundwater conditions. However, in general, the thermal resistivity of soil is 0.2 to 0.3 °Cm/W per meter depth of borehole and the thermal resistivity of heat pipe is 0.01 °C/W per borehole. The thermal resistivity between the pavement surface and the base course depends on the pavement materials and thickness. In general, pavement is installed to have a thermal resistivity of 0.05 to 0.08 °Cm^2/W per square meter of road surface. When the ground temperature increases, the heat flux increases. The ground temperature of regions with the system tends to be between 10 and 16 °C. The heat flux of the ground-source heat pipe snow-melting system is between 100 and 180 W/m^2. This heat flux can melt snow up to a snowfall intensity of 1 to 3 cm/h where the road surface temperature rarely falls below the freezing point.

Figure 9 shows examples of observed ground temperature, road surface temperature and heat flux when snow falls. The heat flux (the red line in the figure) increases when snow starts to fall, and the system maintains the heat flux while snow accumulates on the pavement. When snow stops falling and the system has completely melted the snow on the pavement, the system's heat flux decreases and a high enough pavement temperature is maintained to prevent ice from forming on it.

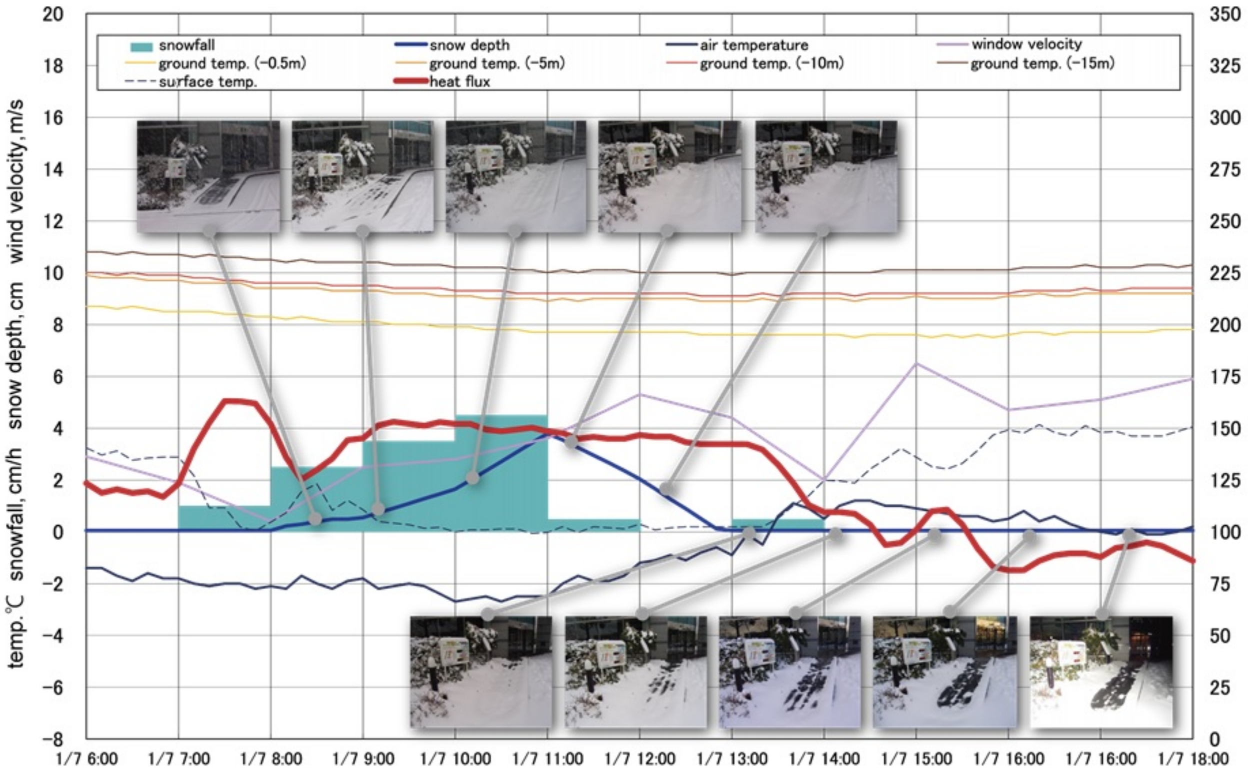


Figure 9 - Examples of observation data of temperatures and heat flux under snowfall

2.3 Installation conditions

2.3.1 Cumulative number of installations and total installation area

Experiments on ground-source heat pipe snow-melting systems in Japan started in 1978. The first field installation on a road was in 1980[3]. Since then, a variety of research and improvements, such as corrosion protection of the heat pipes and system control, have been made toward commercial introduction. In 2002, the current installation method was established. Since then, installations of the system have gradually increased. There was a particularly great increase from 2005 to 2006. As of 2011, the system had been introduced at a cumulative total of 40 locations for a total installation area of more than 7,800 m^2 (Figure 10).

The system tends to be introduced at sites with a small installation area. 60% of installations have an installation area of less than 50 m^2. Installations with a snow-melting area exceeding 1,000 m^2 number only three (Figure 11). The reason for the predominance of small-area installations is that the borehole can melt snow only in a small area of 2 to 5 m^2, and a large-area snow-melting project needs to have many boreholes and, thus, construction costs increase.

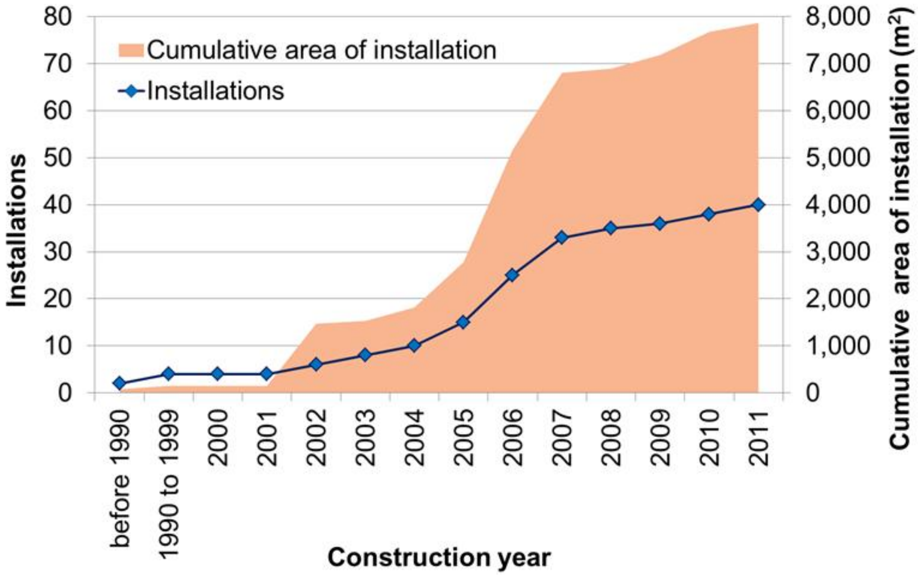


Figure 10 - Installations of ground-source heat pipe snow-melting systems by year

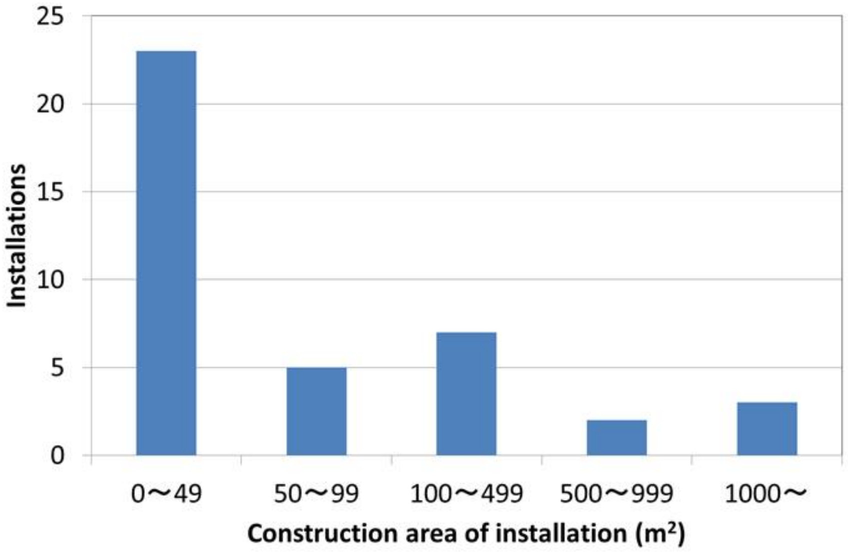


Figure 11 - Installations of ground-source heat pipe snow-melting systems
by area of snow melting

2.3.2 Regions

Figure 12 shows that the system has been widely introduced in the northern part of Japan's main island but not on Hokkaido, Japan's northernmost major island. The regions where the system has been introduced are those where ground temperatures exceed 10ºC but groundwater sprinkler may cause icy roads. This is why the system has been selected for these regions. It is difficult for Hokkaido to introduce the system, because the ground temperatures are not high enough to supply sufficient heat for snow melting.

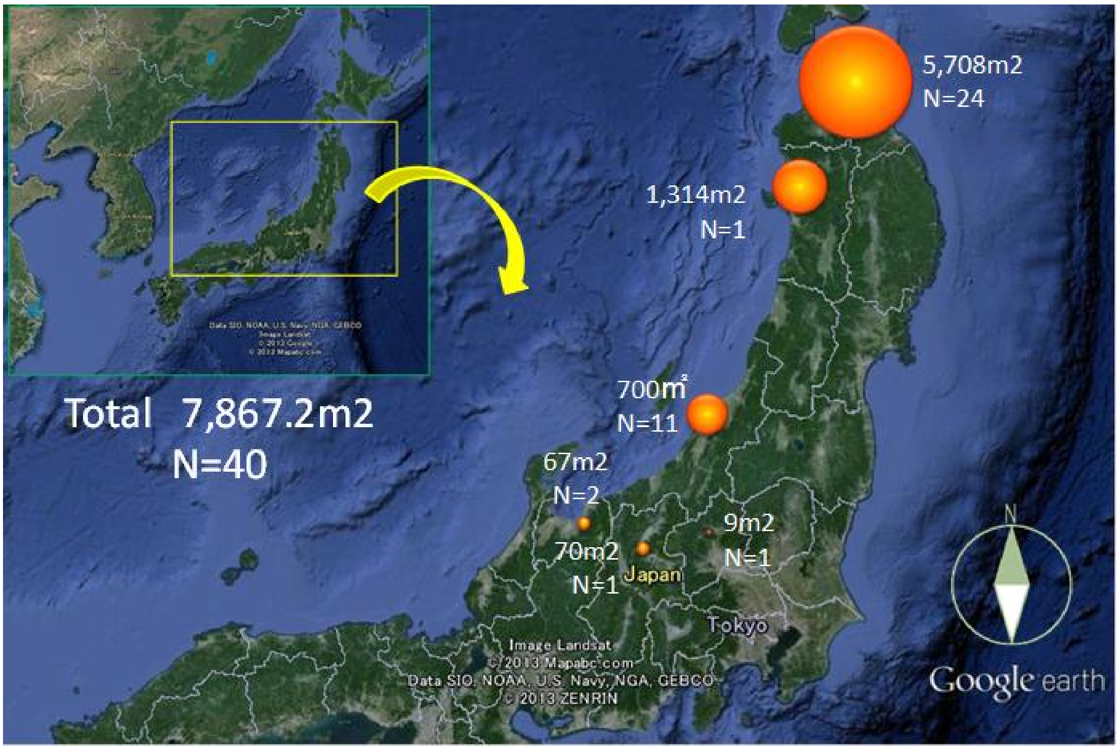


Figure 12 - Installation locations of ground-source heat pipe snow-melting systems (as of 2011)

2.3.3 Locations

The breakdown of installation locations shows that, in terms of the total area of system installations, sidewalks have the largest share, followed by carriageways; in terms of the number of installation locations, sidewalks also have the largest share, followed by parking lots (Figure 13). The area of carriageway per installations is larger than any other types of installations, even though there are not many installations on carriageways. In contrast, there are many installations at parking lots, although the area per installation is small. At each installation site, the system has achieved good snow melting regardless of location or installation area (Figure 14).

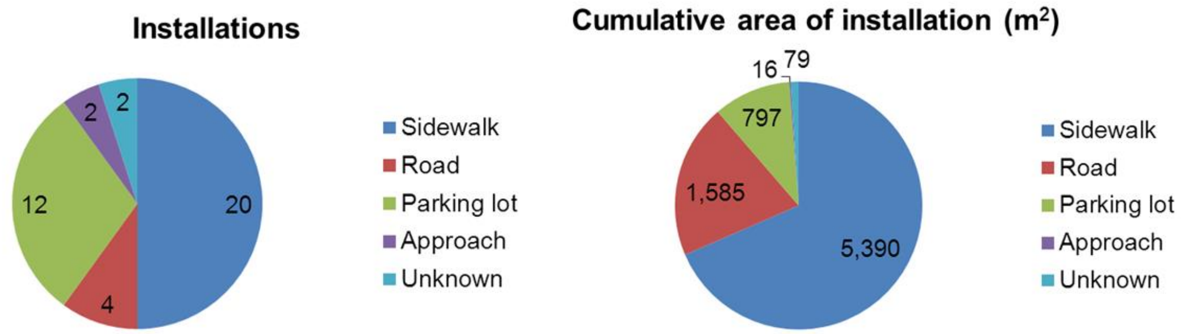


Figure 13 - Number of installations and cumulative area of installation of ground-source heat pipe snow-melting systems by installation location (as of 2011)

a: Sidewalk (station square)

b: Sidewalk (bus stop)

c: Carriageway (steep slope/curve)

d: Carriageway (interchange ramp/curve)

e: Parking lot (social welfare building)

f: Parking lot (residence)

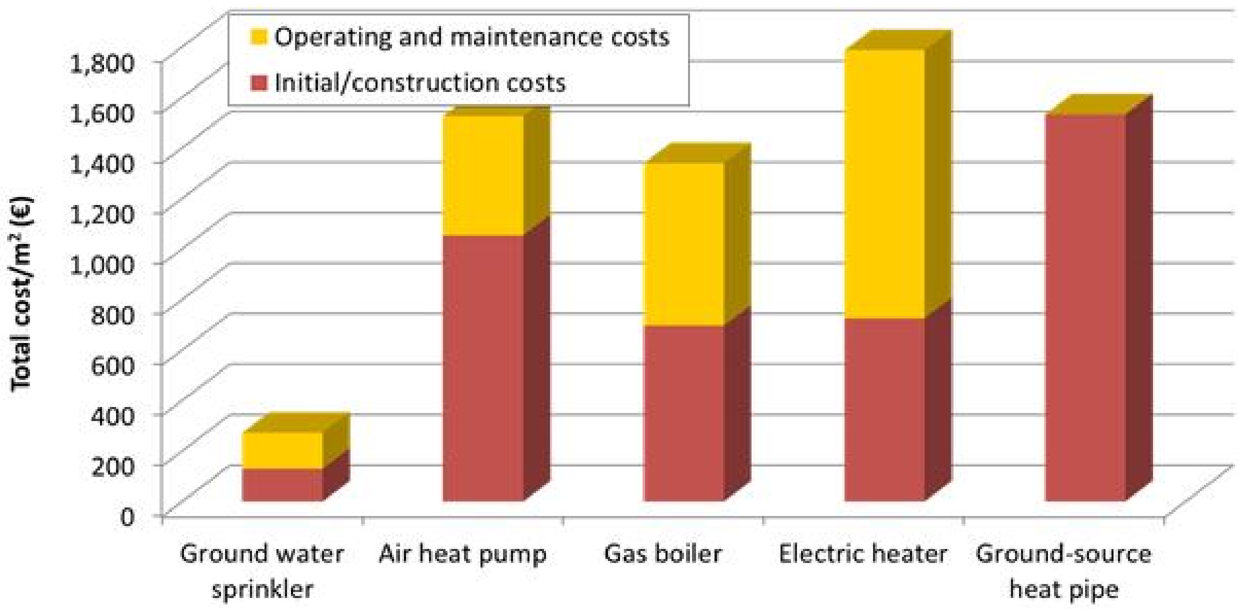
Figure 14 - Installation examples

3. COST OF THE GROUND-SOURCE HEAT PIPE SNOW-MELTING SYSTEM

3.1 Current installation costs and issues

Figure 15 shows a cost comparison between the ground-source heat pipe snow-melting system and other common snow-melting systems (gas boiler, air space heat pump, electric heater). In general, these systems have been adopted in areas where groundwater is not available. The data of the cost of groundwater sprinkler system, the most economical alternative, is also shown for reference.

The construction/initial cost of the ground-source heat pipe snow-melting system is about 1.5 to 2 times that of other systems. The main reason for the high constriction cost is the high cost of drilling boreholes to collect ground thermal heat. However, because ground-source heat pipe snow-melting systems do not incur operating costs, the long-term cost (construction / initial cost and operating cost for 30 years) is almost the same as those of the other systems.



Comparison is made assuming 1) 2,400 m^2 installation area 2) lifetime: 30 years; 1 EUR = 130 yen

Figure 15 - Cost comparison:
ground-source heat pipe snow-melting system vs. other systems

3.2 Undertakings to reduce costs

The construction/initial cost of ground-source heat pipe snow-melting systems greatly increases with large increases in the required heat flux. Because the system does not incur operating costs, long hours of operation do not increase its operating costs at all. By allowing for a longer time for snow melting, the system can be designed to have a reduced heat flux that can be constructed at lower cost. Also, by limiting snow-melting areas instead of melting snow on the entire area, the system installation area can be reduced and, thus, the construction costs can be reduced.

Figure 16 is an example of a system installed on a steep slope to prevent vehicle skidding. The heat flux was set at 70% of the climate requirement for the site because mechanized snow removal is provided for the road. The total installation area was reduced using a few zebra-like transverse installations. The system has performed sufficiently for the 5 winters since its installation. In designing future installations, we will work to reduce the construction costs while maintaining customer satisfaction with the snow-melting performance.

Figure 16 - Partial installation at a steep slope to prevent skidding accidents

4. HEAT PIPE MEDIUM

The ground-source heat pipe snow-melting system is an environmentally superior alternative, because its operation does not use any electricity or fossil fuel; thus, it does not emit any carbon dioxide. However, the medium in the tube is HFC-134a, a CFC alternative. Although HFC-134a is commonly used today for motor vehicle air conditioning systems and the like, it is designated as a greenhouse gas under the Kyoto Protocol and its use will be regulated. Because heat pipes are protected firmly with concrete, we can assume that the medium will not be released by the system. However, we studied the feasibility of using other mediums.

Since 2007, we have been testing heat pipes whose medium is isobutane (R600a) or dimethylether (DME). These mediums have small Global Warming Potential (GWP). We tested these mediums for snow-melting performance and persistence of effectiveness (Table 2, Figure 17). However, because these mediums are inflammable gasses, we are looking for the development of an inexpensive new medium that is non-flammable or non-flammable when combined with air, and that has with a minimum GWP and an Ozone Depletion Potential (ODP) of zero.

Table 2 - Characteristics of Refrigerants

Refrigerant number, etc.	ODP	GWP	Flammable?	Note
HFC-134a	0	1430	No	In use
Isobutene R600a	0	3	Yes	In trial production
Dimethyl ether	0	0.2	Yes	In testing

ODP: Ozone Depletion Potential; GWP: Global Warming Potential

Figure 17 - DME heat pipes and snow melting

5. CONCLUSION

Ground-source heat pipe snow-melting systems melt snow on pavement by the insertion of heat pipes into boreholes to transfer the ground heat to the pavement. When the pavement is cooled by snowfall, a temperature difference is generated between the ground and the pavement, and the heat pipe medium works automatically. The system does not require activation or deactivation. No electricity or petroleum is used for the operation; thus, no greenhouse gasses are emitted and no operating costs are incurred. Consequently, the system contributes to winter road trafficability and mitigates global warming. Expanded use of the system is expected to contribute to society.

Toward expanded use, issues such as reduction in drilling costs and reduction in the GWP of the medium need to be addressed by continuous efforts.

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