

Energy Pile Performance and Preventing Ground Freezing

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ABSTRACT

The increasing use of energy piles – structural foundation piles also used as heat exchangers in a ground energy system – has led to some concerns that excessive temperature changes may occur within the ground, thus affecting the pile capacity. As a consequence, operational temperature limits for the thermal fluid circulating in the piles are usually specified. At the lower end of the operational range the aim is to prevent the temperature at the pile-ground interface from falling below zero degrees Celcius and hence remove the risk of ground freezing. However, as the ground temperature is rarely measured, this aim is typically achieved by specifying that the thermal fluid temperature must remain positive. A margin for error of up to two degrees is sometimes also applied. Given that the pile concrete acts as a thermal buffer and that there can be up to ten degrees temperature difference between the fluid and the ground, this approach is very conservative and will lead to a failure to maximise the thermal capacity of the energy pile system. This paper uses typical heating and cooling demand profiles applied to numerical models of pile heat exchangers to examine the likely temperature differences between the thermal fluid and the ground during heat pulses of different magnitudes and durations. This demonstrates that a less conservative approach to fluid temperature limits could be adopted.

1. INTRODUCTION

Dual use of pile foundations as heat exchangers as part of a ground energy system can lead to significant energy and carbon savings for building projects. However, it is essential that the systems are operated within agreed temperature limits. These are usually applied to the thermal fluid which is circulated through pipes cast into the pile foundations (Fig. 1). While there is no universally recommended upper temperature

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limit, practically the circulating fluid is usually kept below 40°C (SIA, 2005). For lower temperatures the aim is to prevent the ground surrounding the pile from freezing as this could potentially cause significant heave and reduction in the shaft capacity of the pile. The lower temperature limit is usually set as the minimum value for the fluid as it either leaves or enters the heat pump. For winter operation when heat is being extracted from the ground, the temperature of the fluid as it leaves the heat pump will be the lowest temperature in the fluid circuit and hence to use this as a control temperature is a more conservative approach.

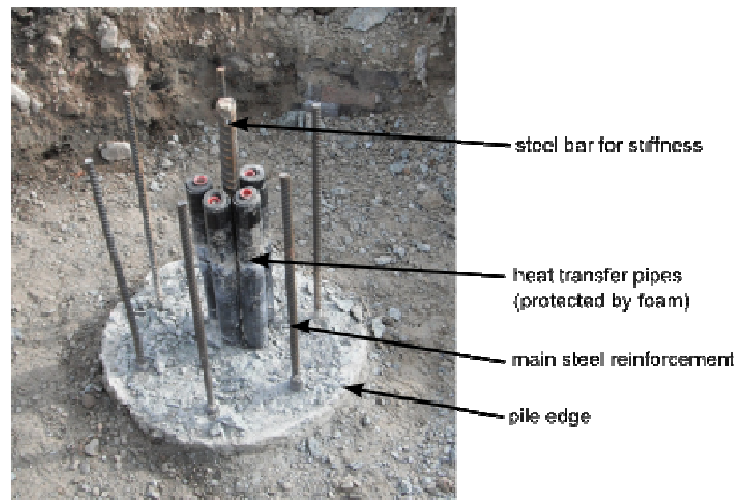


Fig. 1 Pile heat exchanger

1.1. Existing Guidance

A number of publications (eg Brandl, 1998, 2006) highlight the need to prevent freezing of the ground and in particular the soil-pile interface. However, there are few sources of guidance with respect to the limits on fluid temperature needed to prevent this occurring.

The Swiss Society for Engineers and Architects (SIA, 2005) recommends that “*In all cases, except with special permission from the civil engineer, the temperatures imposed on the geotechnical structures must remain positive, with a margin of 2°C.*” The guidance then goes on to refer to the “*operational returning (ie heat pump entering) temperature*” which is to be maintained with the 2°C safety margin. However, this would mean that the temperature of the fluid could fall below 0°C if the difference between the fluid temperature leaving and entering the heat pump is more than 2°C. This would contradict the requirement for the imposed temperatures to remain positive. Nonetheless the guidance is clear that the most important factor is the temperature at the soil-pile boundary, stating that “*a lower return temperature is eventually possible, if a control system can guarantee that at all times the pile soil boundary does not fall below 0°C.*”

In the UK, the National House Building Council guidance for “Efficient design of piled foundations for low-rise housing” (NHBC, 2010) also gives recommendations for fluid temperatures for pile heat exchangers. The guidance says that *“if the coolant is circulated at temperatures below freezing point, then it will be necessary to demonstrate that the freezing front does not reach the soil interface. It is recommended that geothermal pile fluid circulation temperatures range from ambient ground temperatures down to no less than 2 °C.”*

The German Institute for Engineers (VDI, 1998) document on the “Thermal use of the underground” does not discuss extensively the use of pile foundations as heat exchangers. It highlights that freezing temperatures should never be reached, but no more specific guidance is given. Thus while all existing guidance is specific that the soil-pile interface should not be subjected to temperatures below 0°C, there is no consensus on the approach to achieving this.

1.2. Case studies

Brandl (1998) presents the only published case study where ground freezing was caused by the operation of a pile heat exchanger. In this case, an early example of this technology, too much heat was extracted during a test run. *“Operational temperatures”* were between -2°C and -3°C (and for shorter periods as low as -5°C) and this caused the formation of ice lenses and up to 150mm of heave adjacent to the pile head. While details of the duration of operation and the position of the pipes relative to the ground were not provided, Brandl does describe the test as *“improper operation”*. However, Brandl also recognised that limiting operational temperature to be above freezing reduced the efficiency of the system. Thus in his Rankine lecture Brandl, (2006) recommends that the core of pile heat exchangers (ie the fluid rather than the surrounding soil temperature) could be permitted to fall to -1°C.

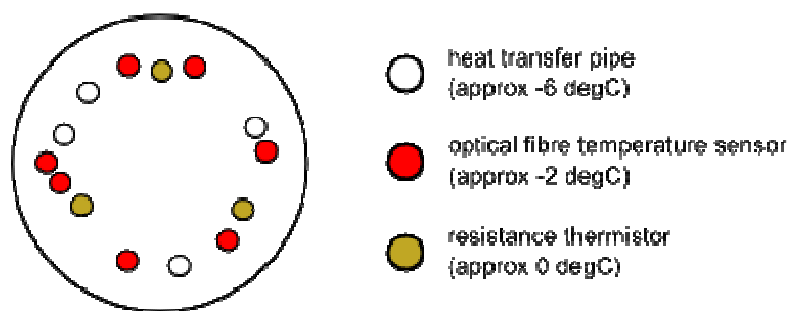


Fig. 2 Minimum temperatures recorded in the Lambeth College test (after Bourne-Webb et al, 2009).

Further support for the idea of lower minimum temperature limits comes from the Lambeth College test pile in the UK (Bourne-Webb et al, 2009). Here a 600mm

diameter test pile was subject to a working load of 1200kN while extreme and sustained temperatures were applied. Fluid temperatures went down to about -6°C for a period of one month, yet temperatures within the pile itself were typically between 0°C and -2°C (Fig. 2). There was no evidence that the ground or the pile-soil interface reached temperatures below 0°C even with such low temperatures applied for a prolonged period. It is important to note that for a well designed ground energy system, normal operational conditions would not approach the kind of temperatures or vary as dramatically as was applied in this test.

2. TYPICAL FLUID TEMPERATURE PROFILES

Fig. 3 shows typical variation of the fluid entering and leaving temperatures to a heat pump for a pile heat exchanger system installed in a London college. The data covers one year from February 2011 to February 2012, the first winter of which was unusually cold for the UK. From a low point of a leaving temperature of around 1°C the fluid temperatures rise to a maximum of around 34°C at the end of the summer. The leaving temperature then falls to a minimum of around 2°C at the end of the seasonal cycle. The leaving temperature is lower than the entering temperature in the winter and the situation is reversed in the summer. The magnitude of the difference between the two values is typically up to around 5°C during heat extraction in winter and up to around 8°C in summer when heat is being injected into the ground. The measured fluid temperatures can be compared to typical ground temperatures of 12°C to 16°C in this part of the UK.

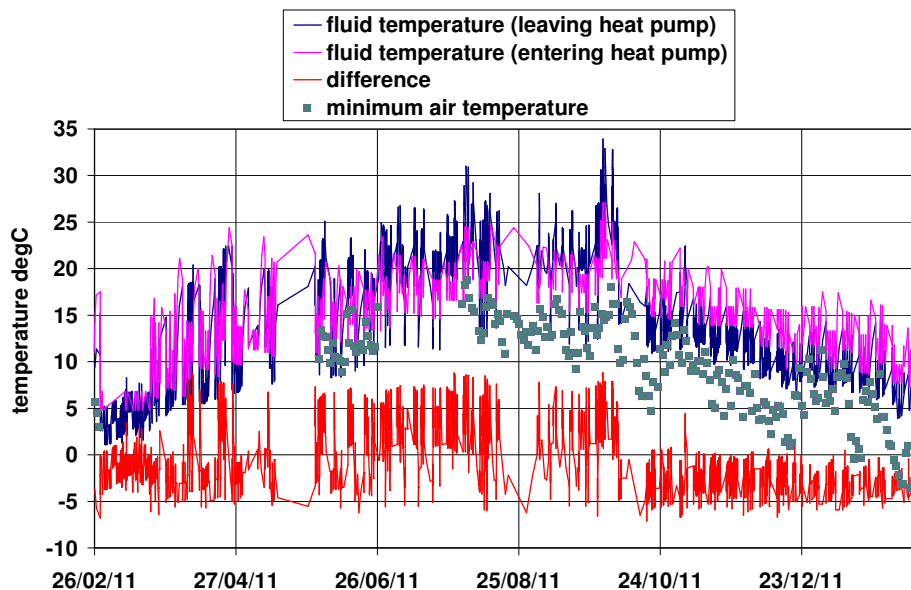


Fig. 3 Typical fluid temperatures over one season

Despite the first winter being colder than the long term average (Meteorological Office, 2012) and the end of the second winter also reaching subzero temperatures (Fig. 3), it is interesting to note that the fluid temperature never fell below 0°C. The significant difference between the entering and leaving temperatures also means that if the fluid temperature is used as a control point to prevent freezing at the soil-pile interface, it is important to understand at which point (ie entering or leaving the heat pump) the temperature limits are specified.

3. IMPACT ON GROUND TEMPERATURES

Specifying that the fluid temperatures should not fall below 0°C will always be a conservative approach due to the temperature gradient that will exist across the pile. SIA (2005) report that the temperature difference between the fluid and the edge of the pile can be as great as 10°C, although it would more typically be expected to be a less than this. The temperature difference depends on the applied heat flux and the properties of the pile. These include the number and location of the pipes and the concrete thermal conductivity and diffusivity. If the pile concrete is at a thermal steady state then the temperature difference will be:

$$\Delta T = qR_b \quad (1)$$

where q is the applied heat flux (in Watts per metre length of the pile) and R_b is the thermal resistance of the pile (mK/W). Guidance for choosing values of R_b , which typically fall between 0.05 and 0.25 mK/W, is given in Loveridge (2012). For a typical pile exchanging heat at 25 to 35 W/m (SIA, 2005) this gives a temperature difference between approximately 1°C and 9°C.

Depending on the size and thermal properties of the pile it can take several days for a pile to reach thermal steady state. This means that high magnitude but short duration heat pulses are not transferred to the edge of the pile. In this way the ground is protected against the lowest temperatures due to the thermal buffering capacity of the pile concrete.

3.1. Model

To illustrate this behaviour a simple two dimensional heat transfer model of a pile heat exchanger was set up (Fig. 4). Using symmetry, one quarter of a 600mm diameter pile heat exchanger was modelled using the software ABAQUS. The pile has four heat transfer pipes of 25mm outer diameter, placed symmetrically and set 75mm from the outside edge of the pile. This type of arrangement is common, with the pipes typically fixed to the steel reinforcement cage. Especially in contiguous flight auger piles, pipes are sometimes installed in the centre of the pile (e.g. as shown in Fig. 1). This latter arrangement would tend to have larger temperature differences between the fluid and the ground and hence has not been the subject of numerical simulation in this study.

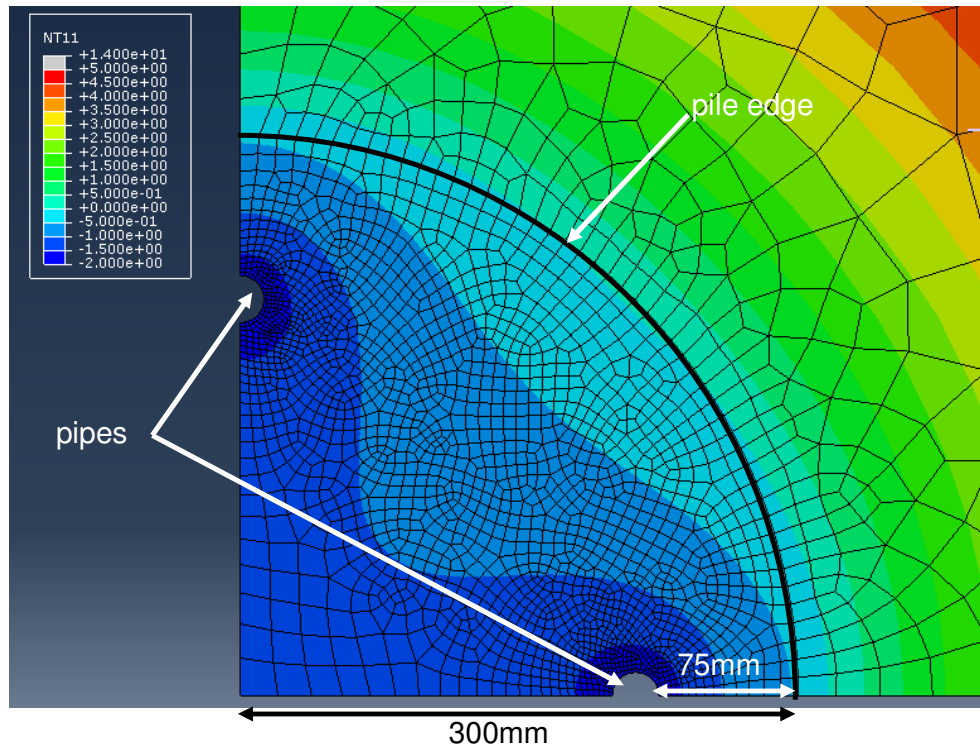


Fig. 4 Extract from pile heat exchanger model showing temperature contours

The ground surrounding the pile, which is known to affect the heat transfer within the pile (Loveridge, 2012) was modelled to a radial distance of 25m. Therefore the overall model geometry comprises a quarter circle sector of 25m radius. The outer boundary condition was kept at constant temperature, set to the undisturbed ground temperature, throughout the analysis. Due to symmetry, the radial boundary conditions were insulated.

The model was meshed using linear quadrilateral heat transfer elements with a minimum size of 2mm at the pipes and 10mm at the pile edge. The mesh was refined and validated by applying constant temperatures at the pipes and outer boundary and using the resulting calculated temperature and heat flux at the pile edge to determine the thermal resistance. This was then compared to previous calculations of resistance made by Loveridge (2012). In the model, the pipes and the fluid were neglected. This is conservative as it omits the small temperature change that occurs between the fluid and the outside of the pipes, normally of the order of 0.5°C depending mainly on the number of pipes, their diameter and thickness and also the fluid Reynolds number.

The initial ground temperature was taken as 14°C, typical for an urban environment in the south of the UK. The profile of fluid leaving temperature from Fig. 3 was then applied to the pipe boundaries for the winter period of 2011/2012. To generate lower bound ground temperatures (closer to freezing), the profile was also offset by 4°C so

that in some cases the fluid leaving temperature fell below 0°C, representing an extreme operational scenario. Only a single winter period was modelled. This is considered appropriate as a well designed ground energy system should be balanced between heating and cooling loads and therefore not suffer degradation of temperature over the system lifespan.

The model was run for three cases corresponding to different combinations of thermal diffusivity of the ground and concrete based on the values given in Table 1. These represent the likely range of real values and hence bound the likely degree of thermal buffering to be expected in practice. Table 1 also gives the steady state resistance values for the concrete part of the pile (ie excluding the pipes and fluid) which is included in the model. The values have been calculated using the model by imposing steady state heat transfer and determining the temperature difference between the pipes and the pile edge.

Table 1 Model Parameters

| | Case 1 | | Case 2 | | Case 3 | |
|---------------------------|--|--|--|--|--|--|
| | Pile Concrete | Ground | Pile Concrete | Ground | Pile Concrete | Ground |
| Thermal conductivity | 3 W/mK | 3 W/mK | 1 W/mK | 3 W/mK | 3 W/mK | 1 W/mK |
| Thermal diffusivity | 1.5×10^{-6} m ² /s | 1.5×10^{-6} m ² /s | 0.5×10^{-6} m ² /s | 1.5×10^{-6} m ² /s | 1.5×10^{-6} m ² /s | 0.5×10^{-6} m ² /s |
| Pile thermal resistance * | 0.0375 mK/W | | 0.1092 mK/W | | 0.0371 mK/W | |

* concrete only, neglecting pipes and fluid resistance

3.2. Results: Case 1

The results from Case 1, where the thermal properties of the ground and concrete are equal, are taken as the base case. Thermal diffusivity of 1.5×10^{-6} m²/s represents a likely upper bound, where the temperature changes in the pile and the ground will happen most rapidly. The temperature change at the pile edge is dependent on the proximity to the pipes (see Fig. 4) with smaller temperature differences, which will increase the risk of ground freezing, calculated closer to the pipes.

Fig. 5 shows both the average and minimum temperatures at the pile edge. Also shown is the input temperature at the pipes and the difference between this and the average pile edge temperature. The magnitude of the difference between the temperature at the pipes and at the edge of the pile varies from near to zero to approximately 5°C. The temperature difference is greatest when the pipe temperature is decreasing (or at its lowest values); conversely the temperature difference is lowest when the pipe temperature is increasing (or is at its highest value). This means that at lower temperatures, when a larger temperature difference is beneficial to prevent ground freezing, a greater temperature gradient is available to help protect the ground.

Because of this effect, even though the pipe temperature falls below -1°C on several occasions the pile edge temperature never falls below approximately 2.5°C .

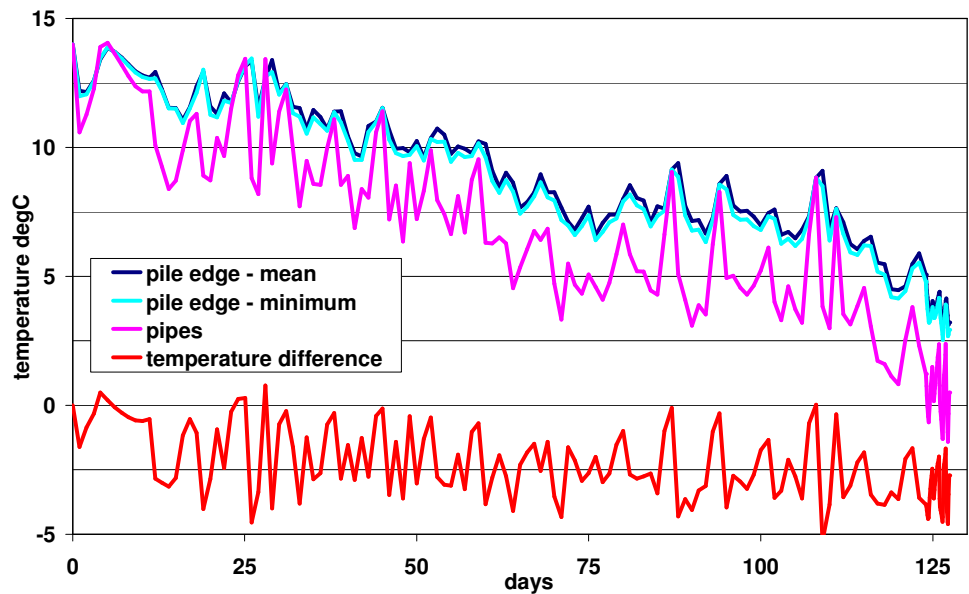


Fig. 5 Model temperature output, Case 1

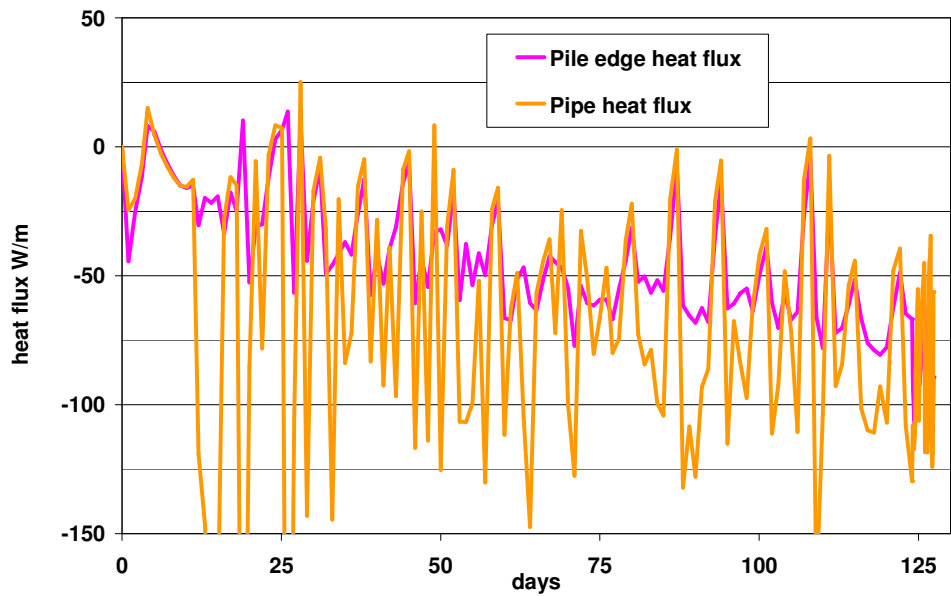


Fig. 6 Modelled heat flux, Case 1

Fig. 6 shows the average heat flux at the pipes and pile edge calculated by the model. Negative fluxes represent heat extraction from the ground. Generally the magnitude of heat extracted per metre length of the pile increases during the winter as the outside air temperatures decreases (Fig. 3). The pipes experience greater heat fluxes than the pile edge as the concrete insulates the pile-soil boundary from the larger, shorter duration heat pulses that occur at the pipes.

Fig. 7 shows the apparent thermal resistance of the pile calculated transiently from the modeled heat flux at the pile edge and the difference between the pipes and the average pile edge temperatures. This is compared with the steady state resistance given in Table 1. The transient resistance oscillates around the steady state resistance, but can show quite large variations. These are greatest when there are large peaks in the heat flux at the pipes which are not reflected in the temperature response at the pile edge. This illustrates both the transient nature of heat transfer and the importance of heat storage within the pile concrete during typical operation. Consequently there are significant limitations associated with using a constant value for the pile thermal resistance.

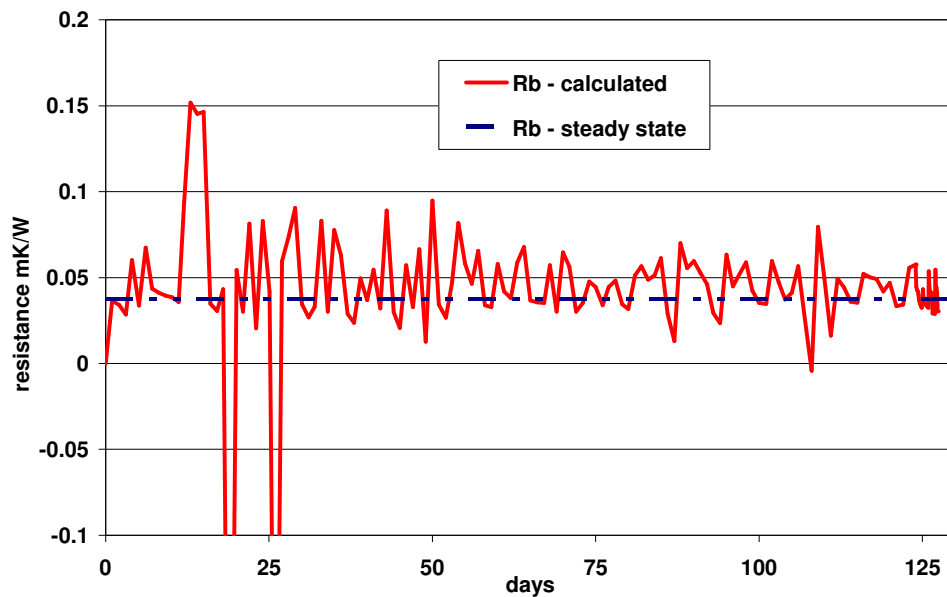


Fig. 7 Calculated thermal resistance, Case 1

3.3. Results: Cases 2 & 3

The calculated minimum temperatures at the edge of the pile for the three cases are shown in Fig. 8. Case 2, where the concrete conductivity is lower and hence the resistance higher, shows a larger temperature difference between the pipes and the

pile edge. Conversely, Case 3, where the resistance is slightly lower, shows a smaller temperature difference, typically up to about 3°C rather than 5°C, between the pipes and the pile edge. This means that for Case 3 the minimum pile edge temperature reaches a low point of about 1°C near the end of the winter period. However, the difference in resistance between Case 1 and Case 3 is relatively small, and this alone is not sufficient to explain the approximate 1.0 to 1.5°C difference between the pile edge temperatures for these two cases. Therefore reference must be made to the ground properties. Case 3 has lower ground thermal conductivity which results in reduced heat flux at the pile edge. Thus the combination of reduced resistance and reduced heat flux causes the lower temperature difference between the pipes and the pile edge. Therefore this scenario, with lower resistance (higher concrete conductivity) and lower ground conductivity, will be the critical case for the assessment of lower temperature limits.

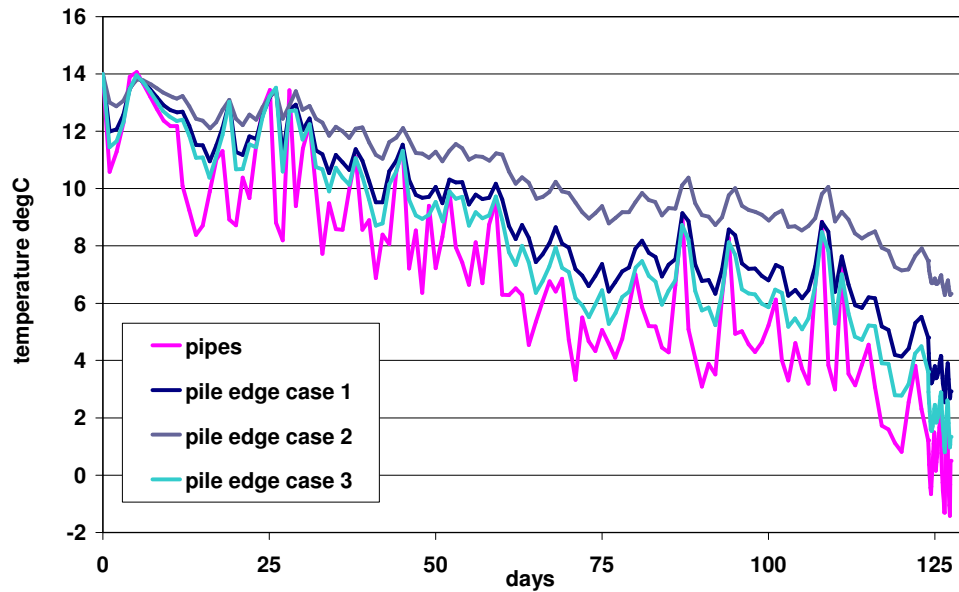


Fig. 8 Pile Edge Minimum Temperatures, All Cases

4. EXTREME TEMPERATURE PULSES

Section 3 shows that for lower bound normal operational conditions, and typical ground and concrete properties then even for fluid temperature at -1°C the edge of a 600mm pile remains at least 1°C above freezing. This is because the fluid only remains at this low temperature for short durations. These short term heat flux pulses do not reach all the way to the edge of the pile owing to the thermal inertia of the concrete surrounding the pipes.

To investigate the length of heat pulses which could be sustained by the pile heat exchanger without freezing the ground, a further step was added to the model described above in which a constant temperature boundary condition of -2°C was applied to the heat exchanger pipes for a period of 5 days. This extreme condition is exceptionally unlikely to occur in routine operation, but has been applied to investigate the behavior of the pile. The output from the analysis described in Section 3 was used as the initial conditions for the additional model step.

Fig. 9 shows the minimum temperatures at the pile edge for all three cases. The initial temperature differences between the pile edge and the pipe reflects the values of the pile resistance and the heat flux (controlled by the thermal conductivities) as described in Section 3. Within 1 to 2 days the pile effectively reaches a thermal steady state. Continued application of the -2°C boundary condition causes a reduction in heat transfer rate and thus the difference in temperature between the pipe and the pile edge starts to decrease. For case 3, with the lowest resistance and the lowest ground conductivity, this means that the pile edge temperature drops below 0°C after approximately 0.5 days with the pipe temperature held at -2°C . Case 1 and Case 2 maintain positive temperatures at the pile edge with margins of approximately 1.5 and 5 degrees respectively.

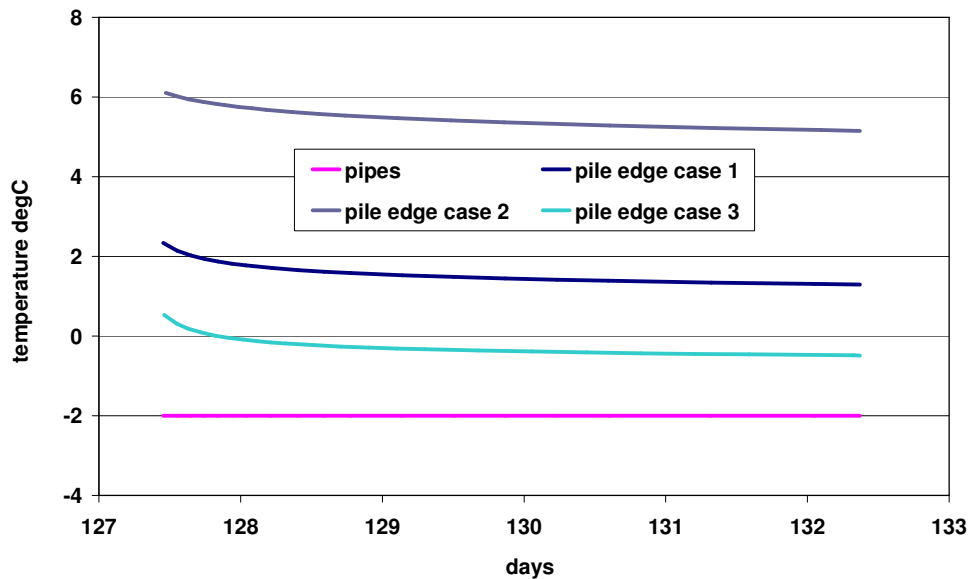


Fig. 9 Pile Edge Minimum Temperatures in Response to Extreme Pipe Temperature Pulse of -2°C

5. DISCUSSION

Simulation of lower bound operational conditions for a 600mm diameter pile heat exchanger, even allowing for negative fluid temperatures, has not led to freezing

conditions developing in the ground surrounding the pile. This is due to the thermal buffering effect of the concrete and the fact that low temperatures in the fluid persist for only relatively short durations. The magnitude of the effect depends on a number of factors:

1. The thermal resistance of the pile. This is in turn dependent on the concrete thermal properties, the number and arrangement of pipes and the fluid flow conditions. Piles with low thermal resistance will have the smallest temperature difference between the fluid and the pile edge. For the pile simulated, a concrete thermal resistance of 0.037mK/W is at the lower end of the typical range for pile heat exchangers, so the results presented will be conservative in comparison with most cases.
2. The thermal properties of the concrete. Thermal conductivity of the pile concrete will directly affect the pile steady state resistance. However, the thermal diffusivity will have an impact on the speed at which heat moves through the concrete and also the value of the transient heat flux within the pile. High rates of heat transfer will lead to reduced temperature differences between the fluid and the pile edge.
3. The thermal properties of the ground. The thermal conductivity of the ground also affects the steady state thermal resistance of the pile, albeit to a lesser extent than the concrete thermal conductivity. However, the thermal diffusivity of the ground also impacts on the heat transfer rate at the pile-ground interface. Low thermal diffusivity ground will reduce the heat flux at the pile edge and hence reduce the temperature difference between the fluid and the ground.
4. The size of the pile. Although not directly considered in this study, it is known that larger diameter piles, with a larger volume of concrete, will take longer to reach a thermal steady state (Loveridge, 2012). This means that longer duration pulses of low temperature can be tolerated in larger piles. Conversely, a more conservative approach to temperature limits should be adopted in smaller diameter piles.
5. The duration of the applied temperatures. Typically the lowest temperatures are applied only for a few hours and hence there is insufficient time for a steady state to develop in the pile.

The above factors indicate that the concrete used in piles can have a significant effect on the overall performance of a ground energy system. While there are still few schemes which specify thermally enhanced concrete for pile heat exchangers, this approach is starting to gain popularity. This study illustrates that there can be a trade-off between the effects of high thermal conductivity concrete. While heat transfer is enhanced, improving the thermal performance of the ground energy system, there is a reduction in the temperature differences between the fluid and the pile edge, hence increasing the risk of developing sub-zero ground temperatures. Therefore careful consideration of the concrete specification and its impacts on the overall system performance is required.

When the pile was subjected to an extreme pulse of low temperature (-2°C) fluid for a longer period (Fig. 9), it was possible for the ground temperature to reach 0°C or less,

but only for the most adverse combination of pile and ground properties and only after 12 hours of maintaining the fluid temperature at this level following more typical winter operation. As the likelihood of similar conditions occurring in operation is small, it is considered that for the pile heat exchanger simulated in this study allowing operational fluid temperatures to reach -1°C to -2°C will not cause negative temperatures to develop in the surrounding ground.

For larger diameter piles, similar fluid temperatures could easily be tolerated due to the larger volume of concrete within the pile. For smaller diameter piles, e.g. 300mm, the temperature gradient across the pile will be smaller and hence a smaller degree of buffering would occur. For such cases maintaining the fluid temperature at 0°C or higher would ensure that the surrounding ground does not fall to freezing temperatures.

In any calculations of acceptable lower temperature limits for pile heat exchangers it is also important to distinguish between factors of safety applied to temperature calculations and the accuracy of any measurements and control systems in place to prevent the temperature limits being breached. Current guidance (see Section 1) does not specify what sort of uncertainty the required 2°C “safety margin” is intended to account for. Based on the analysis in this paper, the greatest uncertainty is likely to arise due to lack of knowledge of the concrete thermal properties; ground thermal properties often being determined by in situ thermal response testing. This would suggest that factors of safety should be applied to the thermal properties prior to any calculation being carried out, rather than a lumped approach of applying 2°C to the fluid temperatures. The latter approach could lead to over-conservative design, as lower temperatures, applied for short durations would be sustainable in most cases.

It must be emphasised that these calculations are based on one season of heat extraction from the ground via the pile heat exchanger. The results are therefore valid for scenarios where there is a relative balance between the heat extracted from the ground in the winter and that injected (or naturally recovered) in the summer. Should a ground energy system not be balanced in this way, with excess heat extraction occurring, then the risk of ground freezing would be higher. However, this approach to ground energy system design should not be encouraged as it will also lead to reduced thermal capacity and threaten the long term sustainability of the system.

6. CONCLUSIONS AND RECOMMENDATIONS

For pile heat exchangers, existing guidance typically suggests that the thermal fluid temperatures should not fall below 0°C with a 2 degree safety margin. However, this approach is very conservative and calculations presented in this paper for typical operational patterns of temperature applied to a 600mm diameter piles show that, even for a fluid temperature of -1°C the edge of the pile remains at least 1°C above freezing. This is because:

1. There will always be a temperature gradient between the fluid and the pile edge;
2. Short term high magnitude heat fluxes do not reach the pile edge as the concrete is effectively insulating the ground from these variations.

The magnitude of the thermal buffering offered by the concrete depends on the arrangement of the pipes within the pile, the pile diameter and the concrete and ground thermal properties. When calculating acceptable temperature limits it would be conservative to assume higher concrete conductivity and diffusivity, but lower ground conductivity. The worst case, with a small temperature difference between the ground and the heat transfer fluid, would occur when high thermal diffusivity concrete allows rapid transfer of heat to the pile edge, but low ground conductivity limits the heat transfer rate in the ground, hence acting to further reduce the temperature difference between the ground and the fluid.

In the absence of calculations to determine the appropriate lower temperature limit for the heat exchanger fluid then it is recommended that for medium to large diameter piles ($\geq 600\text{mm}$ diameter), the fluid temperature is limited to a minimum of -1°C . Using the temperature of the fluid leaving the heat pump is the most conservative measure of temperature and would be appropriate in this case. For smaller diameter piles a limit of 0°C would be appropriate. No additional “safety margin” should be necessary unless the control system in place to prevent the limits being breached would require it.

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