Thermal behaviour of borefields (part 2): G-function

Author: Wouter Peere – Date: 1/04/2025

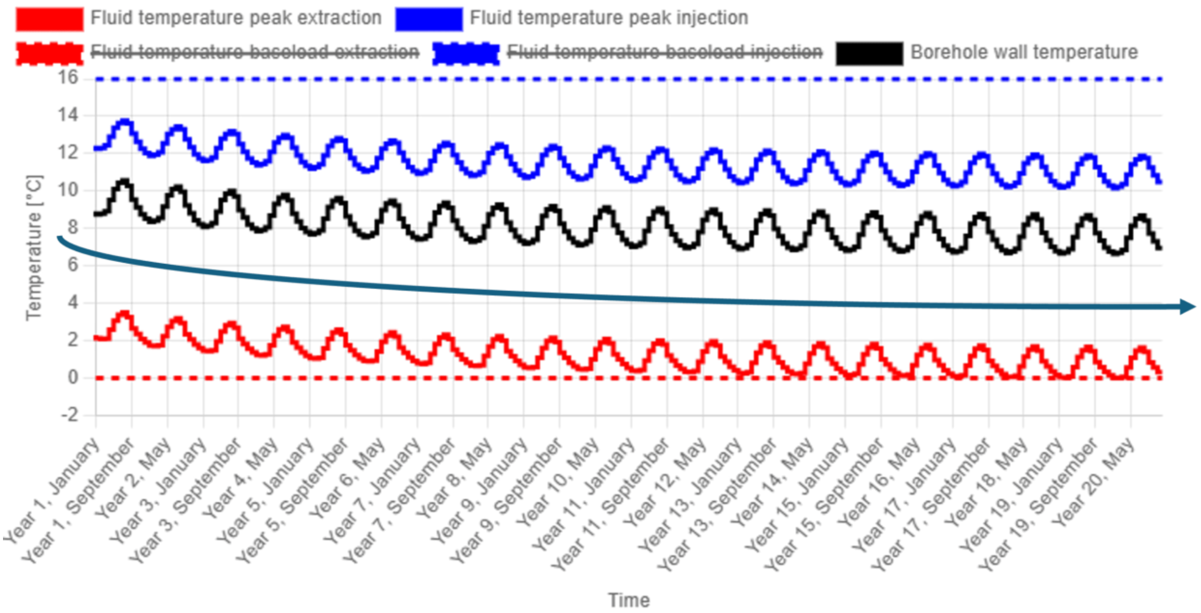
The thermal behaviour of borefields is rather complex, extending over timescales ranging from hourly to yearly. This article describes the concept of g-functions, which are used to model the long-term (seasonal and yearly) behaviour of borefields.

Thermal behaviour of borefields

The thermal behaviour of borefields becomes apparent when we examine the ground temperature profile (if you have not read our article specifically on this topic, you can find it here). Two distinct timescales can be observed on this graph:

- The short-term response, in the order of hours. This is the difference between the fluid temperatures and the ground temperature, and was discussed in our previous article on the effective borehole thermal resistance, which you can find here. At these short timescales, the ground temperature (and therefore the borehole wall temperature) is assumed to be constant.
- On a longer timescale of months to years, the ground temperature does vary due to energy exchange. This is seen seasonally, where the ground heats up in summer due to heat injection and cools down again in winter during heat extraction. Additionally, the borehole wall temperature gradually changes over time due to imbalance (the net heating or cooling of the ground).

This article focuses on this medium to long-term timescale and explains how the borehole wall temperature changes over time, and how designers can adjust their design to account for this effect.



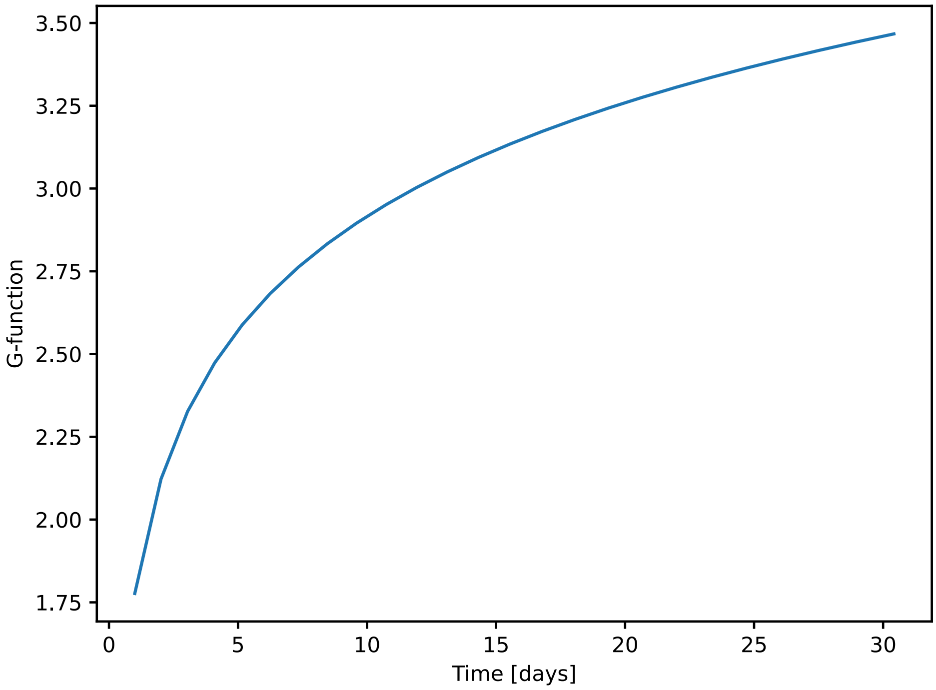
Temperature plot of the borefield.

G-functions

The physics behind a borefield is quite complex, as it involves a three-dimensional transient heat diffusion problem. Although a detailed explanation of the physics is beyond the scope of this article, we can identify a number of effects that play a role:

- There is thermal interaction between the different boreholes in the borefield.
- There is interaction between the borefield and the surrounding ‘infinite’ ground, since heat transfer does not stop at the edge of the project site.

To model these two effects, Eskilson developed the concept of a *g-function* in his PhD thesis in 1987: a dimensionless function that describes how the borehole wall temperature evolves when a constant load is applied. Each borefield design has its own characteristic g-function, which can be seen as the thermal fingerprint of the system’s long-term behaviour. An example is shown below.



Example of a g-function.

In the graph above, a constant heat injection of 1 kW was applied to a certain borefield. You can see that the temperature increases but, over time, the rate of increase becomes smaller. This can be understood as follows: in the beginning, when heat is injected into a borehole, it affects only its immediate surroundings. Since this ‘region of influence’ is initially quite small, the temperature increase is relatively high. Over time, more of the heat is dissipated further into the ground, and the region of influence expands. The borehole now has more volume through which it can dissipate heat, so the temperature increase becomes smaller.

> ***!Note***
> *Strictly speaking, this effect is also influenced by the temperature gradient in the ground, but a detailed mathematical derivation of the g-functions is beyond the scope of this article.*

This ever-increasing (or decreasing, in the case of heat extraction) but less-than-linear trend describes the long-term behaviour of the borefield, where the imbalance causes the ground to heat up or cool down over the years at a decreasing rate. Understanding how your design influences the characteristic g-function will help you manage imbalance more effectively.

Important parameters

There are three important parameters that influence the g-functions: ground thermal conductivity, borehole spacing, and borefield configuration. Each of them is briefly described below.

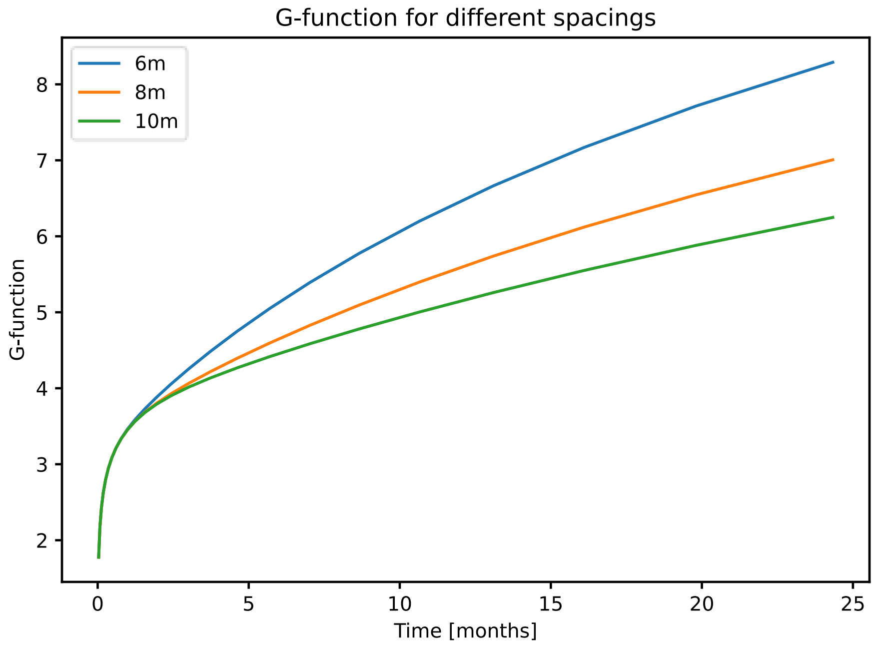
Ground thermal conductivity

Ground thermal conductivity affects how quickly heat is dissipated into the ground. If the ground has a higher thermal conductivity, your borefield can more rapidly utilise a larger region around the borehole to exchange heat. This lowers the g-function and therefore reduces the impact of the imbalance.

> ***!Note***
> *Although you cannot change the ground thermal conductivity at your location—since it is determined by the geology—you can choose how deep to drill. If your subsoil consists of layers with varying conductivity, you can adapt your design to optimise the thermal conductivity for your specific situation. Check out our article on the ground properties to learn more.*

Borehole spacing

As mentioned earlier, one of the effects captured in the g-function is the thermal interaction between boreholes. The further apart your boreholes are, the less they will influence each other and the more energy can be exchanged with the surrounding ground. This effect is shown in the figure below.



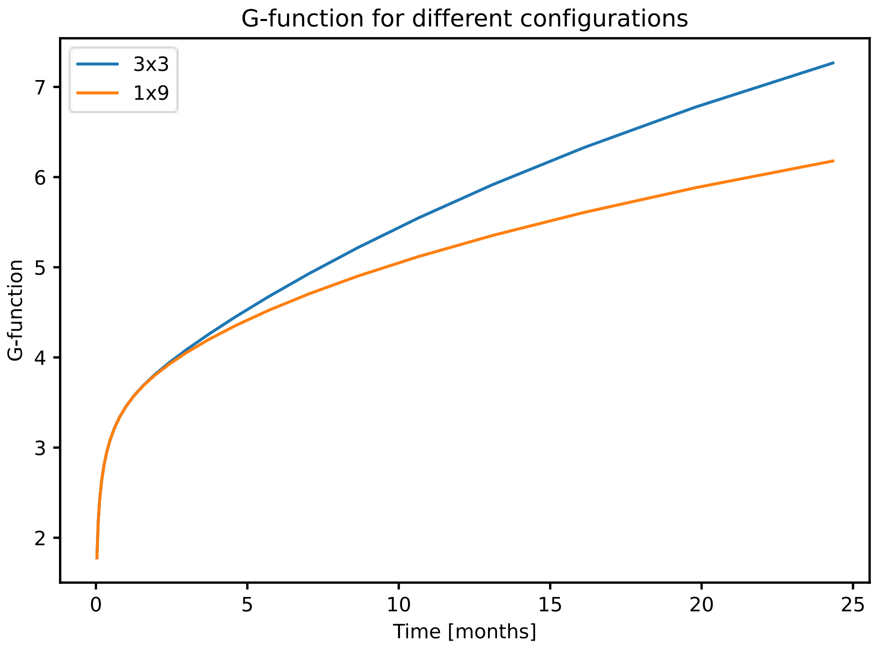
G-functions for three different borehole spacings.

When the boreholes are spaced further apart (for example, 10 m), the g-function is clearly lower. This is because the greater spacing allows heat to be transferred more easily to the surrounding ground, reducing the g-function and therefore the impact of ground imbalance on the design.

You can also observe that all the different spacings converge at shorter timescales. This is because, initially, the boreholes do not interact and only exchange energy with their immediate surroundings. After a certain time, these regions of influence begin to overlap and the curves diverge due to the thermal interaction between the boreholes. This divergence happens first with the 6 m spacing, as the boreholes interact with each other sooner than those separated by 8 or 10 metres.

Borefield configuration

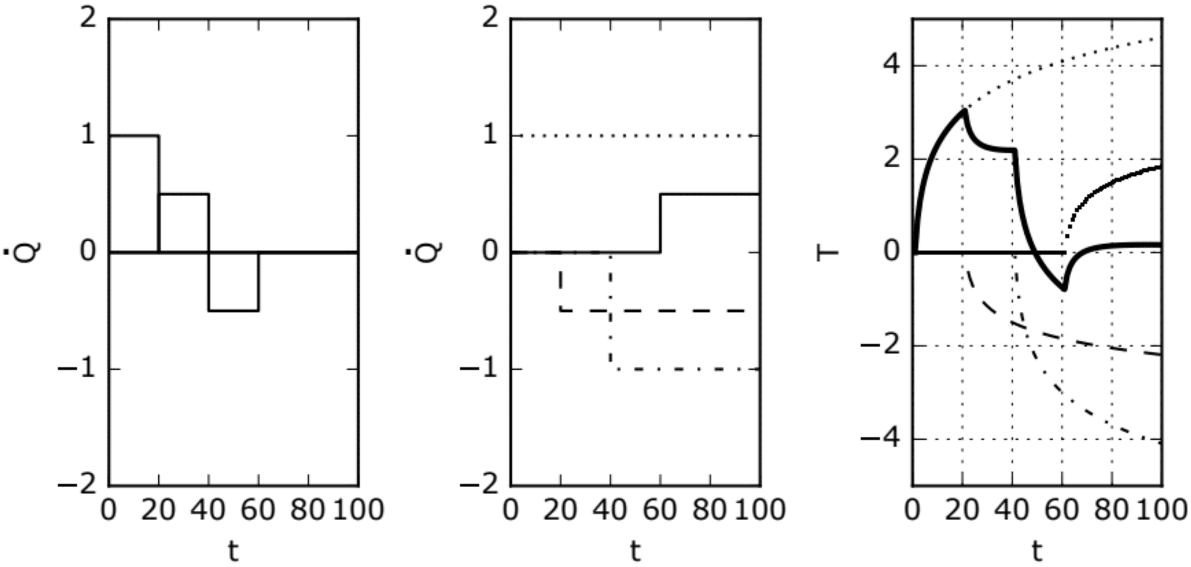
A final effect that influences the g-functions is the configuration of the borefield. If the boreholes are placed close together in a rectangular (or dense) grid, the boreholes in the centre have a harder time transferring heat to the surrounding ground. This results in a faster increase in the borehole wall temperature, which is reflected by a steeper g-function. However, if the boreholes are arranged in a single line, they can more easily exchange heat with the surrounding ground. This leads to a lower g-function and, therefore, a reduced impact of imbalance on the final design.



Influence of the borefield configuration on the g-functions.

Temporal superposition

Up until now, we have only discussed the constant injection or extraction of heat into or from the ground. However, in reality, the geothermal load varies over time. To account for this, we can use a method called temporal superposition to transition from a constant load to a varying one. This is done in three steps, illustrated in the image below.



The concept of thermal superposition of the g-functions. (Picard D., 2017)

1. **Load decomposition**

   First, the real geothermal load (on a monthly or even hourly timescale) is broken down into a series of constant loads. For example, if we have a load of 1, 0.5, -0.5, and 0 as shown in the graph on the left, we can decompose this into constant loads of 1, -0.5, -1, and 0.5, as shown in the middle graph, each starting at different times.

   What we do is the following: we begin with a constant load of 1 starting at t=0. At t=20, the original load drops from 1 to 0.5 (a change of -0.5), so we add a constant load of -0.5 starting at t=20. If we sum the original 1 and the new -0.5 from t>20, we end up with 0.5, as intended. This continues: at t=40, the load drops to -0.5 (a change of -1), so we add a load of -1 starting at t=40. The result, 1−0.5−1=−0.5, matches the original data. This process continues for every step in the load profile.

2. **Applying the g-function to each constant load**

   Now that the load is decomposed into different constant components, we can apply the g-function to each one individually. This is shown in the transition from the middle figure to the one on the right. Each time a new constant load starts, a corresponding g-function is initiated. For example, at t=0, we apply a g-function multiplied by the load of 1. At t=20, we apply a new g-function multiplied by -0.5, and so on. All the g-functions are the same, since they only depend on the borefield design, but they are scaled according to the magnitude of the load.

3. **Summing the g-functions**

   Finally, to determine the resulting ground temperature over time, we sum all the active g-functions vertically. From t=0 to t=20, only one g-function is contributing. From t=20 to t=40, we sum two g-functions, and from t=40 to t=60, three, and so on. The final result is the black line in the graph, which describes the borehole wall temperature over time.

By using this method of temporal superposition, both the seasonal variation in the ground and the long-term thermal behaviour can be calculated using constant and elegant g-functions.

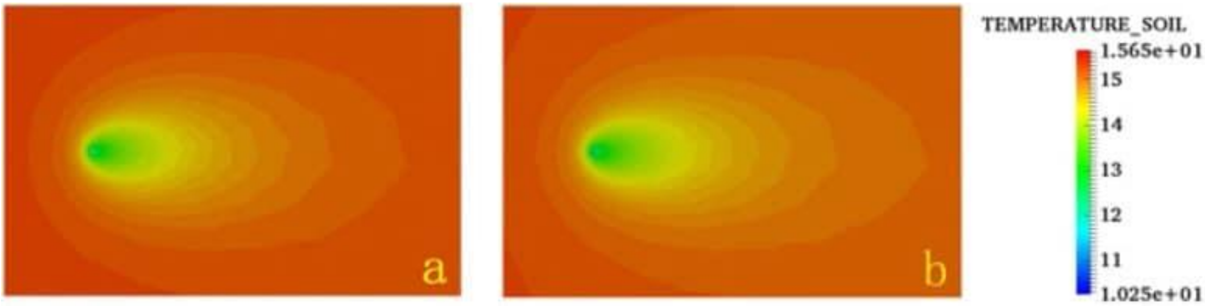
Final remarks

There are two important aspects related to g-functions that have not yet been covered: groundwater flow and the concept of thermal interference through cross-g-functions.

Groundwater flow

The g-functions described above consider only conductive heat transfer in the ground. This simplification allows for fast ground response calculations but neglects a factor that can significantly influence some projects: groundwater flow.

When groundwater flows through the borefield, it carries heat or cold downstream via a process known as advective heat transfer, resulting in a temperature plume, as illustrated in the figure below.



Effect of the groundwater flow on the temperature of the ground. (Goa Z. et al., 2022)

This advective heat transfer can play a major role in the long-term thermal evolution of the borefield. Since groundwater transports part of the imbalance away from the field, the borehole wall temperature tends to remain much more stable over time. This can allow for a smaller borefield size, especially in systems with high imbalance. However, in the case of seasonal thermal energy storage (STES), this effect can be disadvantageous, as some of the stored energy may be carried away by the groundwater, reducing system efficiency.

If groundwater flow is known and your borefield suffers from long-term imbalance, it's best to orient the longest dimension of the borefield perpendicular to the groundwater flow. This orientation maximises the positive influence of advective heat transfer. Conversely, placing the borefield parallel to the groundwater flow increases the risk of losing heat to the environment.

Accounting for groundwater flow is challenging. It is a parameter that is both difficult to estimate and highly influential in simulation results. If you want to model these effects specifically, you can use dedicated software such as Modflow or Feflow. However, in general practice, assuming only conductive heat transfer will likely result in a conservative estimate, as groundwater flow often improves performance in reality.

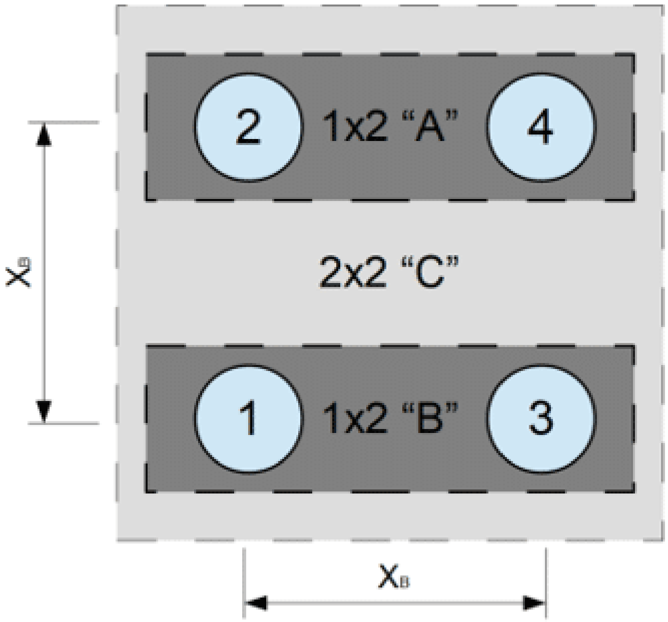
> ***!Note***
> *The g-function formulation used in GHEtool Cloud is based on the implementation in pygfunction which includes only conductive heat transfer. Although alternative methods such as the moving line source approximation (Molina-Giraldo N. et al., 2011) exist, they have not yet been implemented due to their slower computation speeds.*

Cross-g-functions

At the start of this article, we mentioned that g-functions describe the thermal interaction between boreholes within a single borefield. However, because thermal effects do not stop at the project boundary, adjacent borefields can influence one another. This is known as thermal interference.

> ***!Stay tuned***
> *Thermal interference is an important topic in borefield design, especially in densely populated urban areas. It deserves a full article of its own, which will be published later this year.*

This interference between borefields can also be described using g-functions, specifically cross-g-functions, which represent the thermal interaction between different borefields. The figure below shows the relation between traditional and cross-g-functions.



Concept of cross-g-functions. (Michell M. et al., 2020)

Imagine we have four boreholes. These could be viewed as a single borefield "C", allowing us to model the system using traditional g-functions. However, if they actually belong to two separate borefields, "A" and "B", each with two boreholes, we would describe each borefield with its own g-functions.

The final result depends on how the borefields are defined, which introduces an arbitrary boundary. To avoid this discrepancy, the design should consider the thermal influence of borefield B on A and vice versa, accounting properly for thermal interference.

> ***!Note***
> *The mathematical formulation of cross-g-functions is not straightforward and is potentially more complex than the traditional g-functions described above. One of the key differences lies in the boundary condition used during calculation. GHEtool Cloud currently calculates g-functions using the uniform borehole wall temperature boundary condition, while most methods for computing cross-g-functions are based on the constant heat flux boundary condition. The impact of this difference on accuracy is still under investigation, which is why cross-g-functions are not yet implemented in GHEtool Cloud.*

Conclusion

Understanding how the borehole wall temperature evolves over the seasons and in the long term is essential for good borefield design, especially when there is significant imbalance. This article introduced the concept of g-functions to describe how the borehole wall temperature changes over time. It was shown that a higher ground thermal conductivity, increased distance between boreholes, and a more open configuration (such as a line configuration) result in a lower g-function, and thus reduce the impact of imbalance on the geothermal design.

As with all models, there are aspects that are not (yet) included. Advective heat transfer due to groundwater flow can have a major influence on long-term behaviour, but is currently not taken into account. However, designing without this effect introduces an inherent safety margin, reducing the risk involved in assuming no advective heat transfer.

Finally, we mentioned that the concept of g-functions can be extended to cross-g-functions, which account not only for interactions between boreholes within the same borefield, but also between different borefields. This relates to the topic of thermal interference, which will be covered in a future article.

References

- Watch our video explanation over on our YouTube page by clicking here.

Check out GHEtool today at:
https://ghetool.eu