BoFiSi

A fast C++ program for the simulation of bore fields

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BoFiSi (Bore Field Simulator) is a C++ program that can simulate the thermal response any field of Borehole Heat Exchangers (BHEs) having the same length, fed in parallel with an equal inlet fluid temperature, and buried at the same depth in a homogeneous ground. It is based on the semi-analytical model illustrated in Ref. [1], which is a conceptually simpler and equally precise alternative to the excellent model proposed by Massimo Cimmino [2].

Description of the program

BoFiSi computes both the *g-function* of a bore field, namely the time evolution of the mean temperature of the external surface of the BHEs, and the fluid-to-ground function (*ftg-function*), namely the time evolution of the mean temperature of the fluid inside the BHEs.
For convenience, time and temperature are expressed in dimensionless form. The dimensionless time is defined as:

$$t^* = t\frac{9\alpha_\mathrm{g}}{{H_\mathrm{b}}^2},$$

where t is the dimensional time, α_g is the thermal diffusivity of the ground, and H_b is the length of each BHE. The dimensionless temperature is defined as:

$$T^* = \frac{k_\mathrm{g}}{\dot{q}_{l0}}\left(T - T_g\right),$$

where T is the dimensional temperature, T_g is the undisturbed ground temperature and $\dot{q}_{l0}$ is the mean heat rate per unit length supplied to the bore field, which is assumed to be constant.
The BHEs are divided into segments, each subjected to a uniform and time dependent heat load per unit length. The interaction between the segments is calculated by applying the finite line-source solutions for BHE segments determined by Cimmino and Bernier [3] and the superposition of the effects in space and time. The heat load of each segment is determined by solving a system of linear equations that impose the conditions of uniform fluid temperature in the bore field and constant total heat load.
The finite line-source solutions are computed by numerical integrals with the trapezoidal rule, and the linear systems of equations are solved by the Gaussian elimination method. Thanks to the optimizations introduced in the computations of the finite line-source solutions and in the solution of the linear systems, the runtime of the program is very low.
The relation between the temperature of the fluid and the mean temperature of the external surface of the BHEs is set by introducing a 3D borehole thermal resistance, R_b3D, that considers the thermal short-circuiting between the descending and the ascending flow. This way, the condition of uniform fluid temperature yields the same *g-function* and *ftg-function* as a model involving the energy balance along the flow.
The program can be run in two different options: it can either estimate a constant value of R_b3D based on the characteristics of the BHEs and on the properties of the fluid, or it can read the values of R_b3D as a function of t^* from an input file supplied by the user. The latter can be obtained, for instance, through a suitable numerical simulation of a single BHE, by the relation:

$$R_\mathrm{b3D}(t^*) = \frac{T_\mathrm{f}(t^*) - T_\mathrm{b}(t^*)}{\dot{q}_l},$$

where T_f is the mean temperature of the fluid, T_b is the average temperature of the external surface of the BHE, and $\dot{q}_l$ is the mean heat rate per unit length supplied to the BHE.
In the first option, the program yields a very accurate *g-function* in a time range from a few minutes to thousands of years, and a reasonably accurate *ftg-function* from a few hours to thousands of years.
In the second option, if the supplied values of R_b3D are precise, the program yields both an accurate *g-function* and an accurate *ftg-function* from a few seconds to thousands of years.
The program also yields the dimensionless heat load of each BHE segment for every value of t^*, defined as:

$$a_n(t^*) = \frac{\dot{q}_{l,n}(t^*)}{\dot{q}_{l0}},$$

where $\dot{q}_{l,n}(t^*)$ is the heat load per unit length of the n-th segment at the instant t^*.
The program has been validated by comparison with a Python code provided by Massimo Cimmino using pygfunction [4], obtaining an excellent agreement.

Instructions for users

BoFiSi can be run on any Linux PC, as it only requires the standard GCC compiler for C++.
To use BoFiSi, download the homonymous program folder, unzip it, and move it to your Desktop. Inside the folder, you will find the main file of the program, BoFiSi.cpp, together with five text files:

- settings.txt
- rectangular_field.txt
- custom_field.txt
- borehole_specifics.txt
- borehole_resistance.txt

These are all input files, containing the parameters that need to be set to run the simulations.

Setting the input data

Only three of the five input files are required to run the program. The file settings.txt is strictly necessary. The files rectangular_field.txt and custom_field.txt are mutually exclusive, and so are the files borehole_specifics.txt and borehole_resistance.txt.

1. settings.txt

The first input file you need to open to start setting the input data is settings.txt. The file requires ten parameters. The first five parameters are some general characteristics of the bore field:

- the thermal conductivity of the ground
- the length of the BHEs
- the radius of the BHEs
- the buried depth, namely the distance between the BHEs top and the surface of the ground
- the number of segments in which each BHE should be divided

The latter has a default value of 100, which is more than enough to ensure good accuracy. Lower values give shorter computation times, but also lower precision.
The next three parameters describe the time mesh used by the program for the simulations. The program considers equally spaced values of $\ln(t^*)$, and it requires:

- the natural logarithm of the initial instant, namely $\ln(t^*_\mathrm{initial})$
- the natural logarithm of the final instant, namely $\ln(t^*_\mathrm{final})$
- the logarithmic time step, namely $\Delta\ln(t^*)$

For instance, if the three parameters are set, respectively, to -16, 6 and 0.25, the program computes the *g-function* and the *ftg-function* of the bore field for $\ln(t^*) = -16, -15.75, \dots, 5.75, 6$. Note that, if the initial instant is chosen too early, or if the time mesh contains too many instants, the program may have trouble running the simulation.
The last two parameters are:

- the maximum number of simultaneous processes run by the program
- the number of decimal digits that will be printed in the output files

The maximum number of simultaneous processes is asked because some parts of the program make use of multithreading. A higher number of simultaneous threads usually results in a shorter computation time, although the optimal value for this parameter depends on the hardware on which the program runs. The number of decimal digits to print in the output files can be chosen arbitrarily.

2. **rectangular_field.txt or custom_field.txt**

If your bore field is rectangular, namely it is a 2D array of BHEs with m rows and n columns, open the file rectangular_field.txt and set the required parameters. These are:

- the number of rows of BHEs
- the number of columns of BHEs
- the distance between the rows
- the distance between the columns

If your bore field is not rectangular, open the file custom_field.txt instead, and write, for each BHE, its x and y coordinates, separated by a space.
The program will ask you which of the two files you want to use at the execution.

3. **borehole_specifics.txt or borehole_resistance.txt**

The program also needs the 3D borehole thermal resistance, R_{b3D}, to run the simulations.
If you want the program to estimate a constant value of R_{b3D} based on the characteristics of the BHEs and on the properties of the fluid, open the file borehole_specifics.txt. The file requires eleven parameters. The first seven parameters are some properties of the BHEs:

- the type of the BHEs (type 1 for single U-tube or 2 for double U-tube)
- the internal radius of the pipes
- the external radius of the pipes
- the half shank spacing, namely the distance between the BHE axis and the pipes axis
- the thermal conductivity of the pipes
- the thermal conductivity of the grout
- the volume flow rate per pipe

The remaining four parameters are the properties of the fluid inside the BHEs:

- the density of the fluid
- the dynamic viscosity of the fluid
- the thermal conductivity of the fluid
- the specific heat capacity at constant pressure

Alternatively, the program offers the possibility to supply the values of R_{b3D} as a function of time. If you wish to do so, open the file borehole_resistance.txt and write, for every instant of the time mesh, the value of $\ln(t^*)$ and the corresponding value of R_{b3D}, separated by a space.
The program will ask you which of the two files you want to use at the execution.

Compiling and running

If you have already set the parameters for the simulation (and you have saved the changes), you are ready to compile and run the program.
Open a terminal and type the following command line to access the program folder:

```
cd Desktop/BoFiSi
```

Next, type the following command line to compile:

```
g++ -pthread -O4 -o BoFiSi.out BoFiSi.cpp
```

(you will need to compile the program only once).
Finally, type the following command line to run the program:

```
./BoFiSi.out
```

At the execution, the program will ask you if you want to use the data from the file rectangular_field.txt or custom_field.txt. Type 1 in the first case; type 0 in the latter.
The program will also ask you if you want to use the data from the file borehole_specifics.txt or borehole_resistance.txt. As before, type 1 in the first case; type 0 in the latter.
After that, you will need to wait for the program to complete the simulation. The computation time depends on many factors, but, normally, it should not exceed a few minutes.

Checking the results

At the end of the execution, the program creates a folder named output_data with the results of the simulation. The folder contains:

- a text file named g-function_&_ftg-function.txt, which reports the *g-function* and of the *ftg-funtion* of the bore field
- a text file named average_heat_loads.txt, which reports the time evolution of the dimensionless heat load averaged along each BHE (if two BHEs are located symmetrically with respect to a symmetry plane, the average dimensionless heat load is reported only for one of them, since it would be the same for both)
- a series of text files named heat_loads_#.txt (one for each time instant), which report the dimensionless heat load of each BHE segment for every value of $\ln(t^*)$

The output files are overwritten every time the program is executed. If the files were already open before the program execution, you may need to refresh them to view the latest results.

References

1. E. Zanchini, F. Zanchini, A fast and accurate semi-analytical method to determine the thermal response of bore fields, arXiv:2412.07557 [physics.app-ph], https://doi.org/10.48550/arXiv.2412.07557
2. M. Cimmino, The effects of borehole thermal resistances and fluid flow rate on the *g-functions* of geothermal bore fields, Int J Heat Mass Tran 91 (2015) 1119–1127, https://doi.org/10.1016/j.ijheatmasstransfer.2015.08.041
3. M. Cimmino, M. Bernier, A semi-analytical method to generate g-functions for geothermal bore fields, Int J Heat Mass Tran 70 (2014) 641–650, https://doi.org/10.1016/j.ijheatmasstransfer.2013.11.037
4. M. Cimmino, J.C. Cook, pygfunction 2.2: New features and improvements in accuracy and computational efficiency. In Research Conference Proceedings, IGSHPA Annual Conference 2022, International Ground Source Heat Pump Association, 2022, pp. 45–52, https://doi.org/10.22488/okstate.22.000015