Design of Geothermal Heat Source Systems for Heating and Cooling Applications

- Introduction: Mechanisms of thermal transport, thermal properties of rock
- Thermal response test
- Design calculation methods, using
  …numerical simulation (FE, FD)
  …resistance methods (FE?)
  …response functions
- Calculation example
- Conclusions

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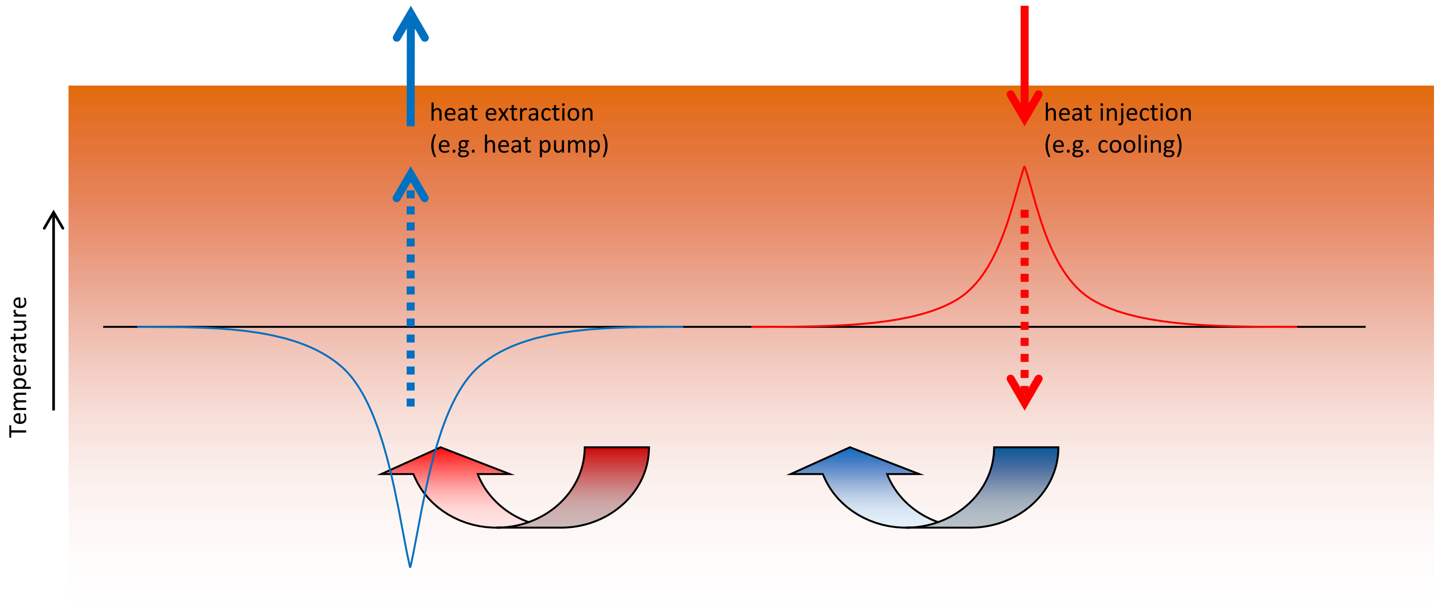
Mechanisms of thermal transport



Geothermal flux from inside the earth is usually negligible, thus surface near effects dominate:

- Heat conduction from farer regions of the surface layer of the earth (powered by the energy flux from the sun and the environment)
- Convection by ground water flow

Heat conduction

Equation of heat conduction

$$a \cdot \left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2} \right) + \frac{1}{\rho c_P} \dot{Q}_V = \frac{\partial \vartheta}{\partial t}$$

General Solution (Fourier):

$$\Delta\vartheta(x,y,z,t) = \frac{1}{8\rho c_P (\pi a)^{3/2}} \int_0^t d\tau \int_{-\infty}^{\infty} d\xi \int_{-\infty}^{\infty} d\psi \int_{-\infty}^{\infty} d\zeta \cdot$$

$$\cdot \frac{\dot{Q}_V(x-\xi, y-\psi, z-\zeta, t-\tau)}{(t-\tau)^{3/2}} \cdot e^{-\frac{(x-\xi)^2+(y-\psi)^2+(z-\zeta)^2}{4 \cdot a \cdot (t-\tau)}}$$

Cylindrical geometry of heat source/sink (dimesionless):

$$\frac{\partial^2 \vartheta'}{\partial r'^2} + \frac{1}{r'} \frac{\partial \vartheta'}{\partial r'} + \left(\frac{R}{H}\right) \frac{\partial^2 \vartheta'}{\partial z^2} + \left\{ \begin{matrix} 1 \text{ if } r' = 1 \text{ and } |z'| \le 1 \\ 0 \text{ otherwise} \end{matrix} \right\} = \frac{\partial \vartheta'}{\partial t'}$$

Scale invariancy yields

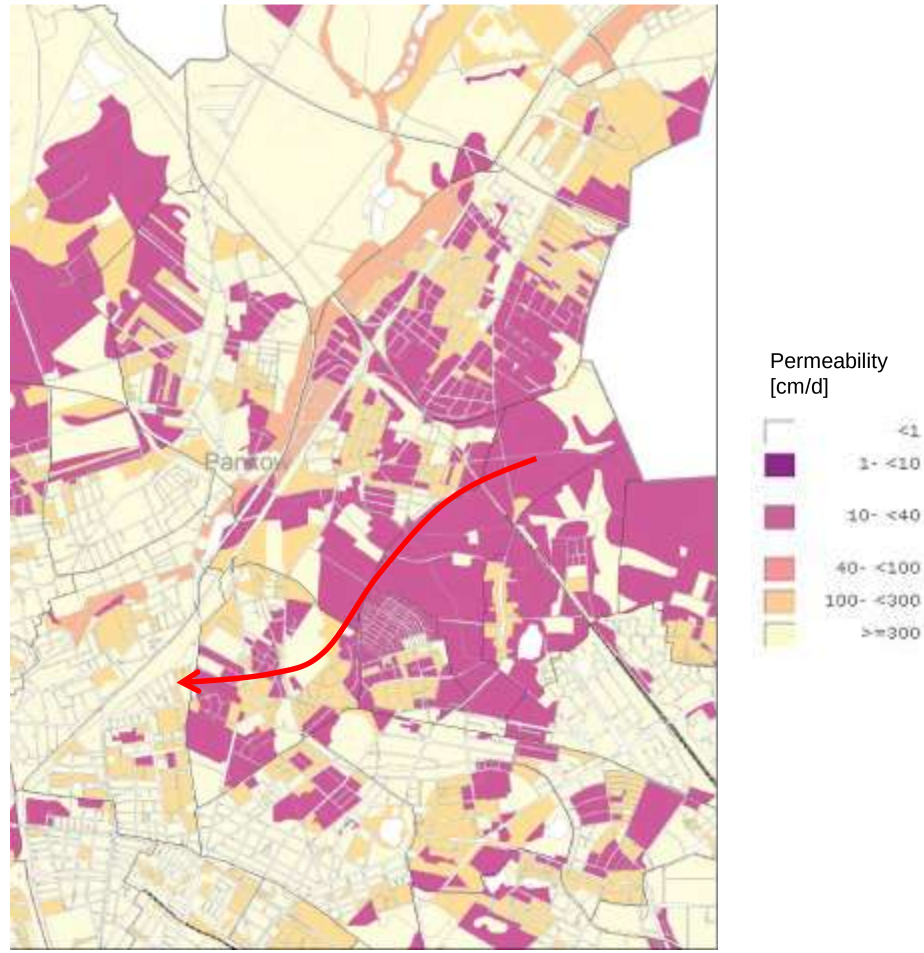
$$\dot{Q} = \lambda \cdot \frac{2\pi H}{\vartheta'} \cdot \Delta\vartheta$$

with ϑ' = response function (time dependent)

Convection by ground water

(example: part of Berlin-Pankow, left isohypses, right water permeability of the ground)

$$\dot{Q} = \rho c_P \dot{V}(\vartheta_0 - \vartheta_m) \quad \text{with} \quad \dot{V} = A \cdot w_{GW} \quad \text{and} \quad w_{GW} = m \cdot k_f$$



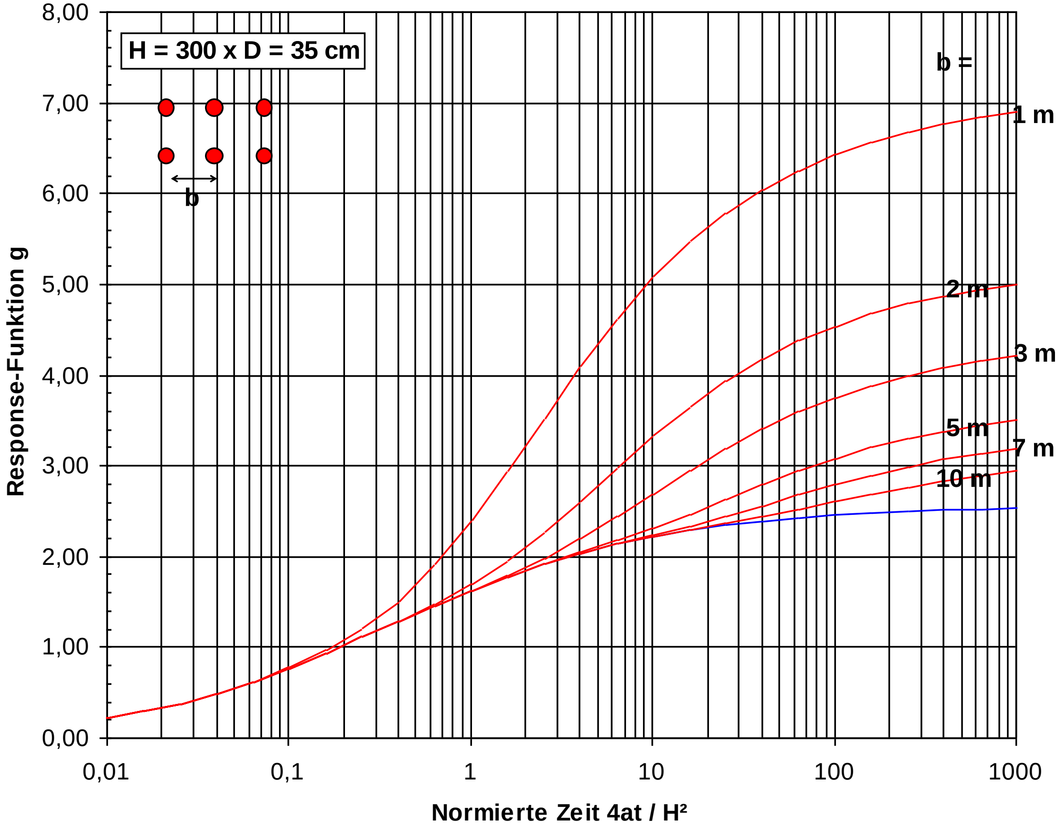
Usually A and w_{GW} are very small, so that convection may be neglected (has to be verified in each individual case!)

Thermal properties of rock

Most important conductivity λ.

As well important response function, depending on $a \cdot t / L^2$ (a: thermal diffusity, t: time, L: characteristic length) and shape of heat extraction/injection probe and geometrical arrangement of probe field.

Example:



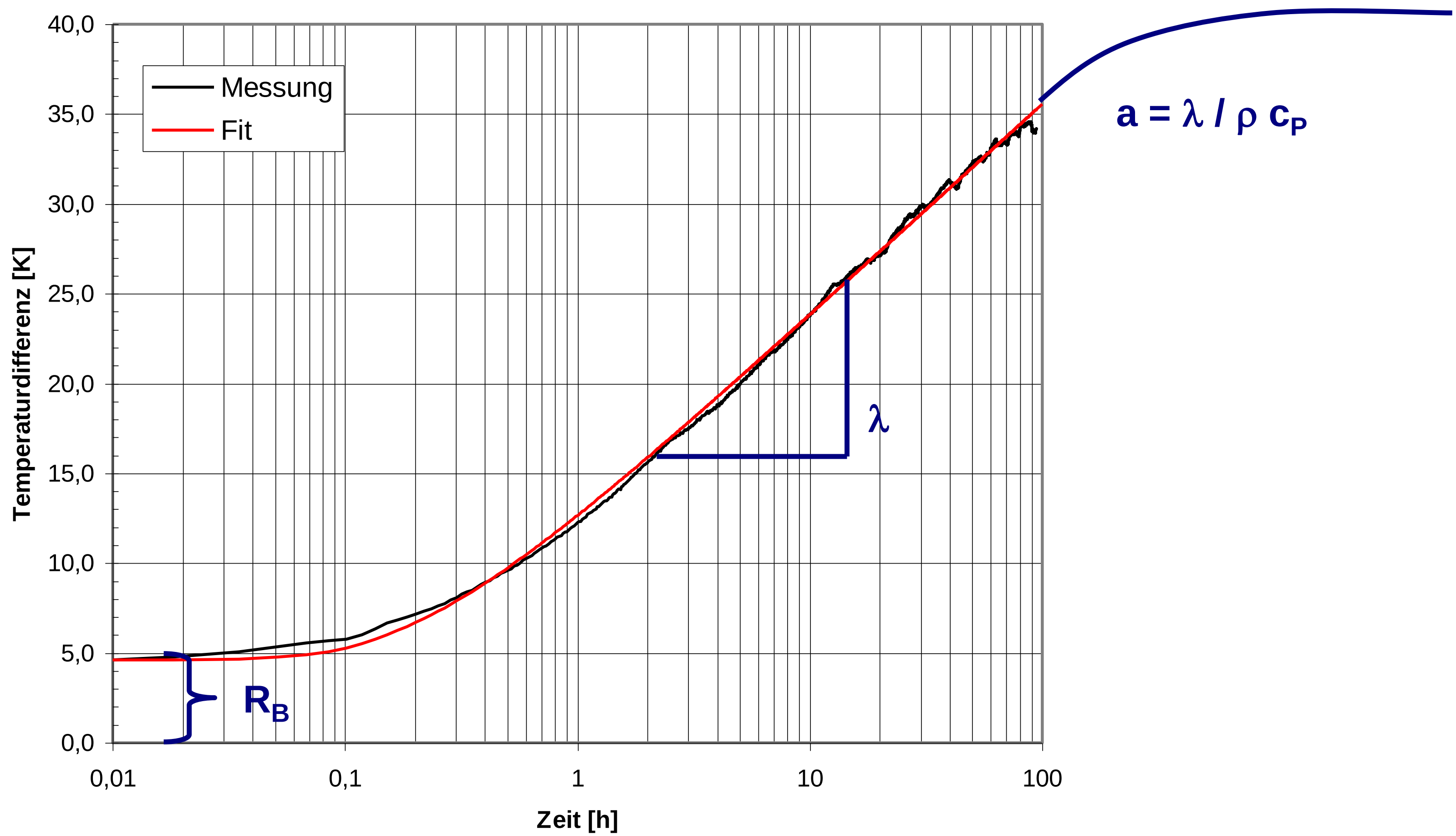
Thermal response test…

…is a method to measure λ, a (resp. $\rho\ c_P$) and thermal resistance R_B between the probe fluid and the rock:

Injection of a constant heat power into a test probe yields a time dependent temperature rise of test probe, which should be recorded and evaluated with respect to the expected analytical form of the response function.

Mobile thermal response apparatus of the Hochschule Lausitz (without insulation)

Evaluation of a thermal response test, example



Typical thermal properties of some types of rock

	λ	$\rho\ c_P$	$\dot{Q}_H$
	W / m K	kJ / m³ K	W / m
Loose rock			
Gravel, dry	0.4	1,500	20
Gravel, wet	1.8	2,400	70
Sand, dry	0.4	1,500	20
Sand, wet	2.4	2,500	70
Slit, clay, dry	0.5	1,500	20
Slit, clay, wet	1.7	2,500	50
Sedimentary rock			
Limestone	3.0	2,200	70
Sandstone	2.3	2,000	70
Marl	2.2	2,200	50
Metamorphic rock			
Gneiss	3.0	2,100	80
Schist	2.2	2,300	60
Magmatic rock			
Granite	3.2	2,500	80
Basalt	1.8	2,500	60
Strong ground water flow			100

Design calculation methods: numerical simulation

FD: finite differences method solves the heat conduction differential equation numerically by replacing the differentials $\frac{\partial \ldots}{\partial x}$ by the difference quotients $\frac{\Delta \ldots}{\Delta x}$

Problem: costly method, in most cases unreasonable, long computation time, definition of an “intelligent” grid for computation difficult

Most popular: FEFlow (ANSYS)

Application: Mainly ground water flow, flow of ground water contaminations…

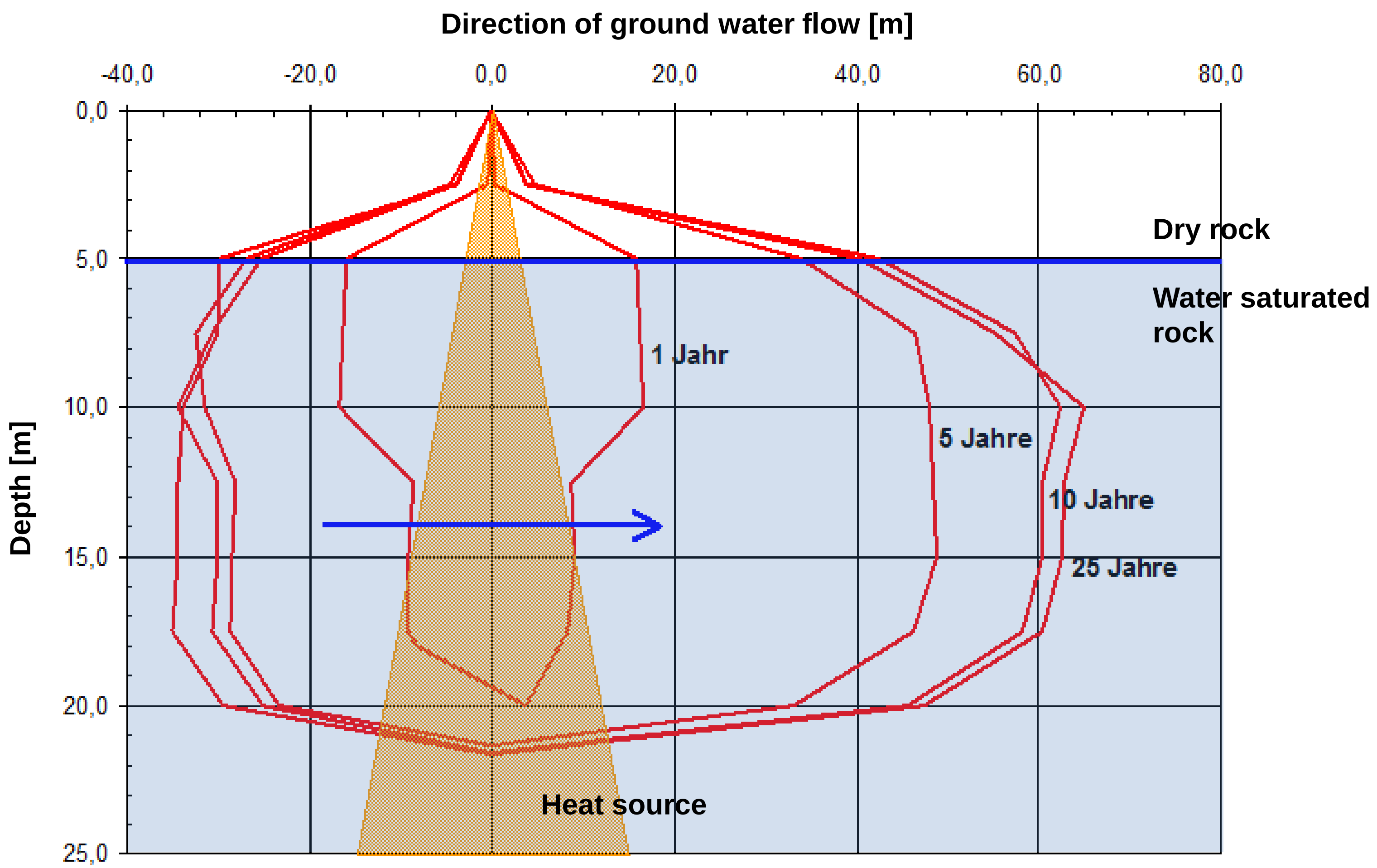
FE: finite elements method solves the stationary heat conduction equations for finite elements with the state of the neighboring elements as boundary conditions

Problem: convergence, definition of an “intelligent” grid of elements

Useful approximation: “Resistance” methods, where networks of thermal resistances represent the heat flow between larger elements

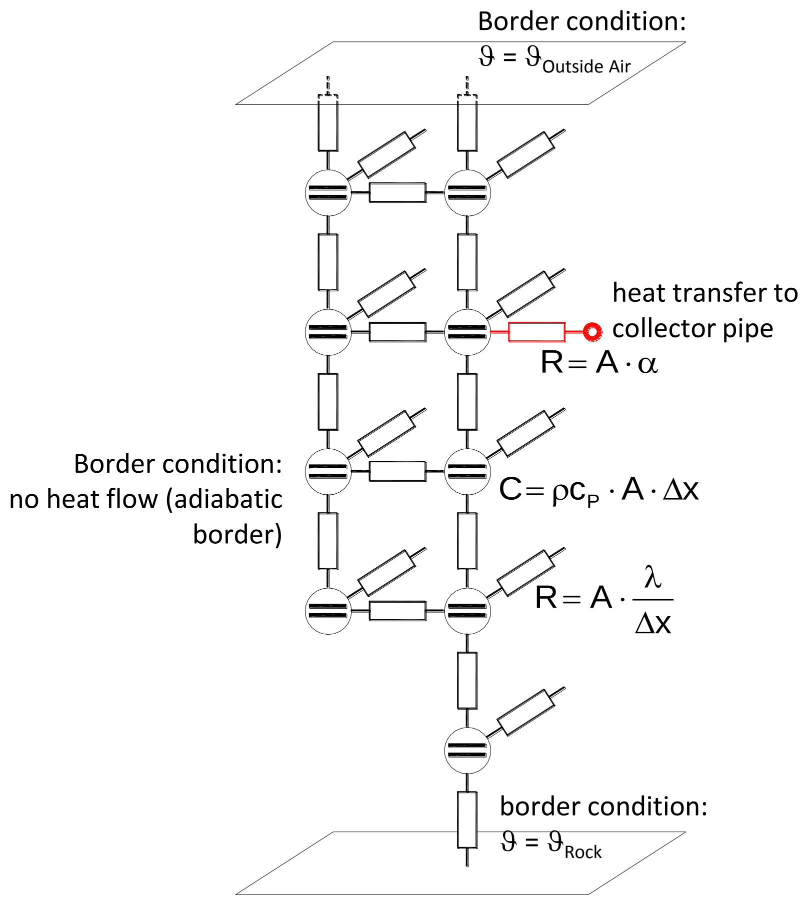
Most popular: TRNSYS/TESS-Types, EED (Earth Energy Designer)

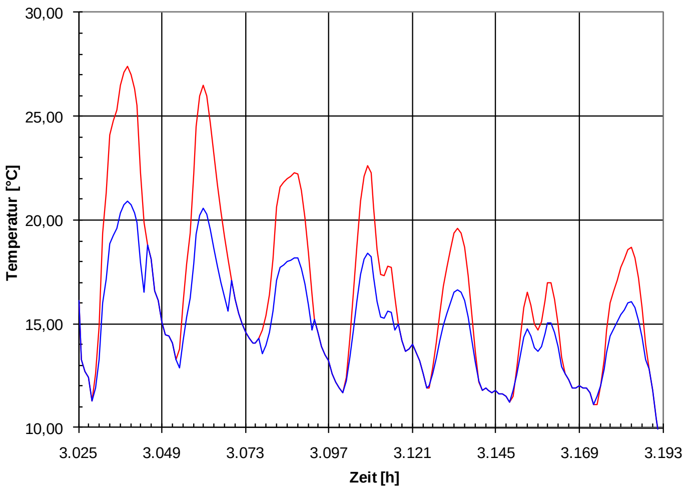
Example FE-calculation-result

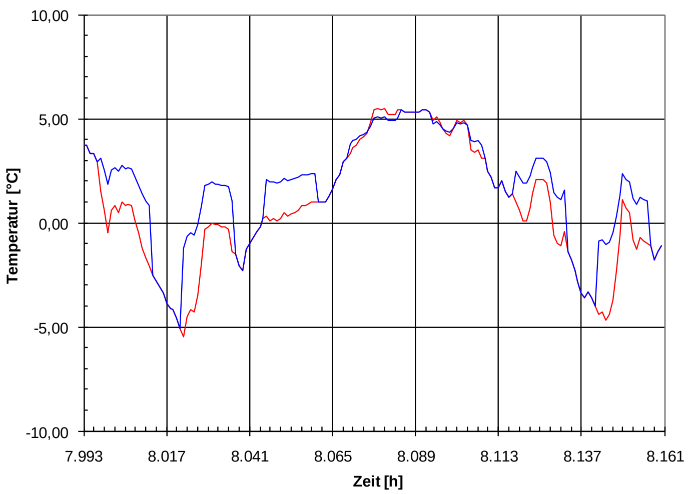


3 K temperature change isotherms (very inaccurate due to large finite elements, balance without consideration of water storage effects)

Example resistance method







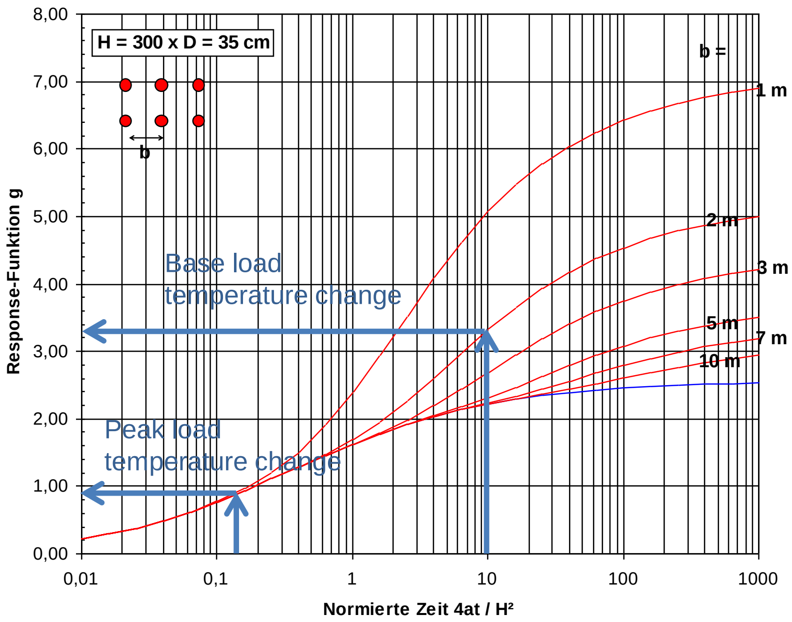
Simple resistance model for buried air pipes for conditioning air and result of calculation

Response function method (example cylindrical probes)

From the long term average load a temperature change near the probe (resp. probe field) is calculated due to

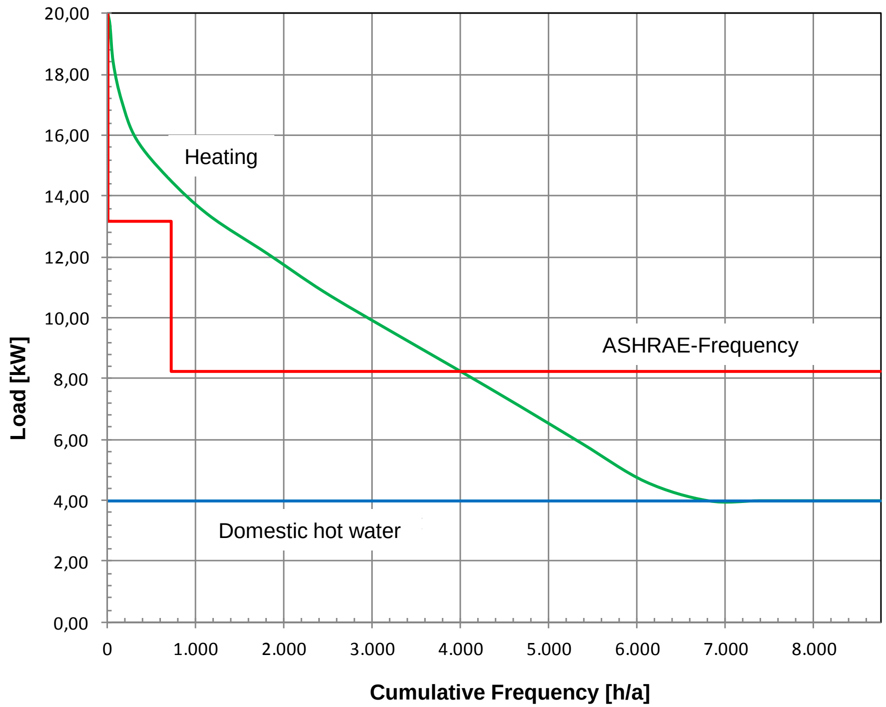
$$\dot{Q}_H = 2\pi\lambda \frac{\Delta\vartheta}{g(t)}$$

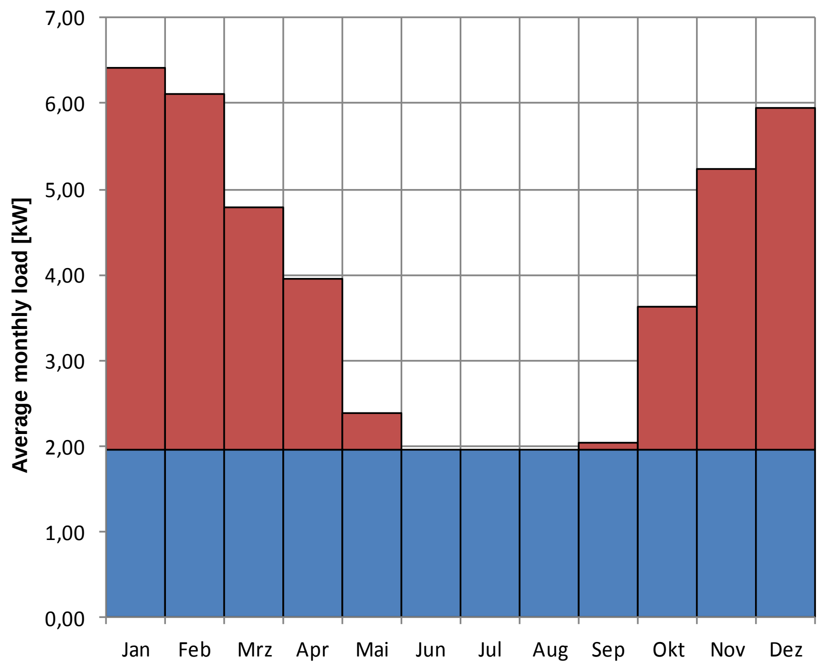
According to the same equation the temperature difference during a peak load period is calculated. The overlay of both temperature differences is used for design.



Calculation example (heating, domestic hot water)

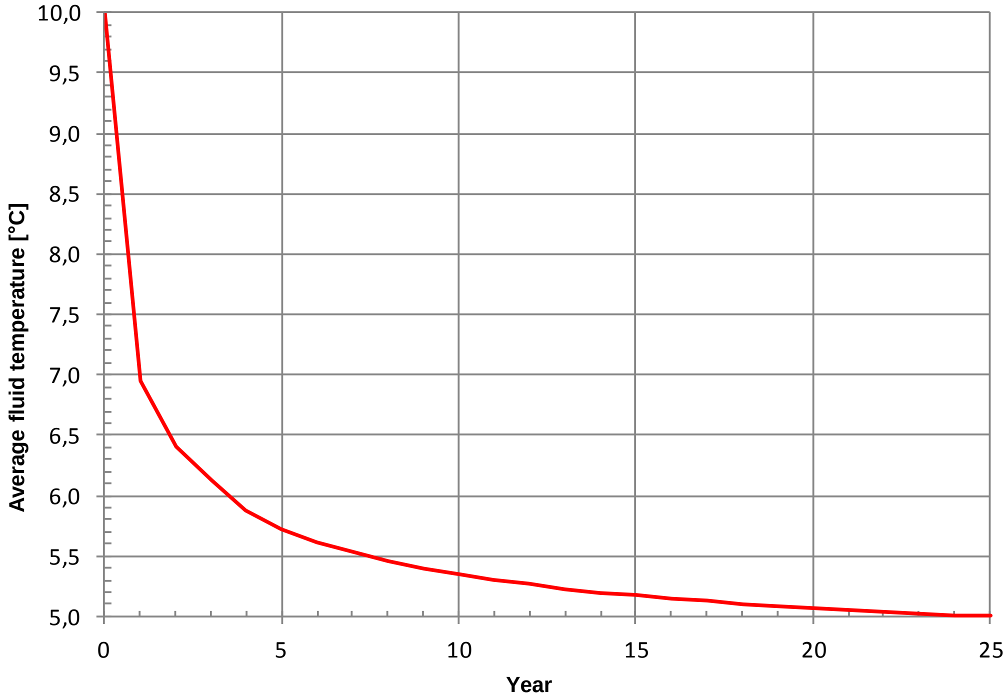
Cumulative frequency of load and average monthly load



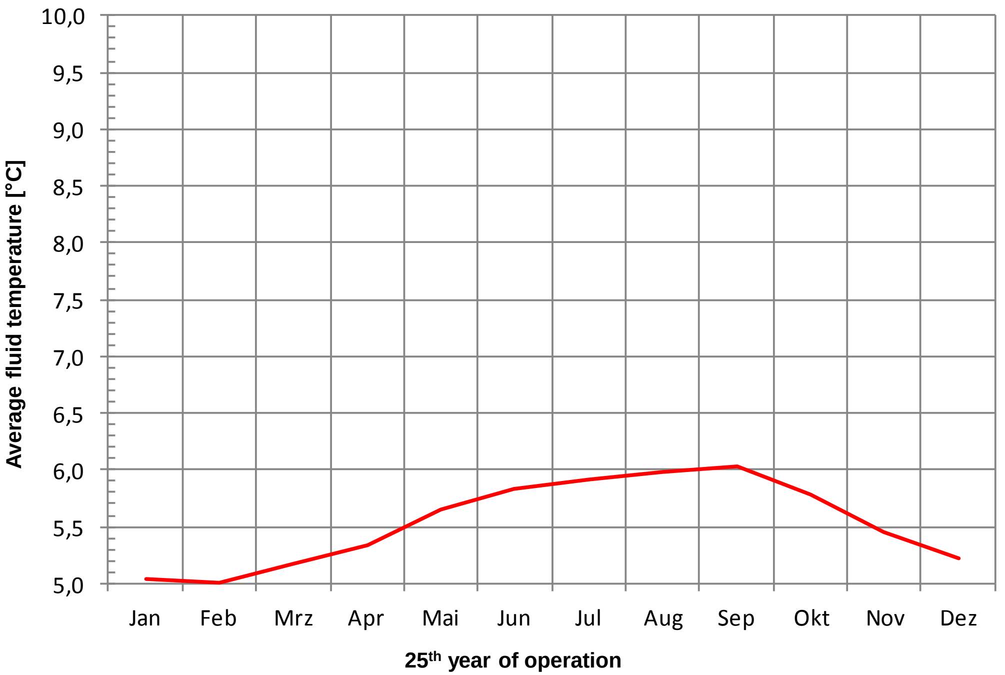


Border conditions for all calculations: U-shaped probes, distance 5 m, max. depth 100 m, min. fluid temperature 5 °C, same thermal properties of the ground, same inner heat transfer resistance…

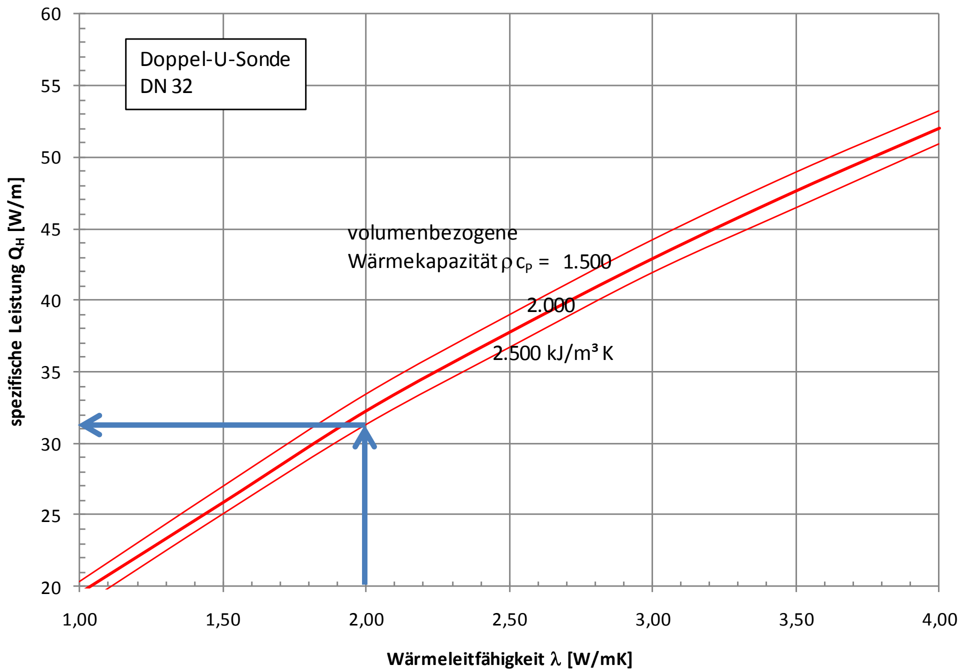
Calculation example, result EED (FE-Method)

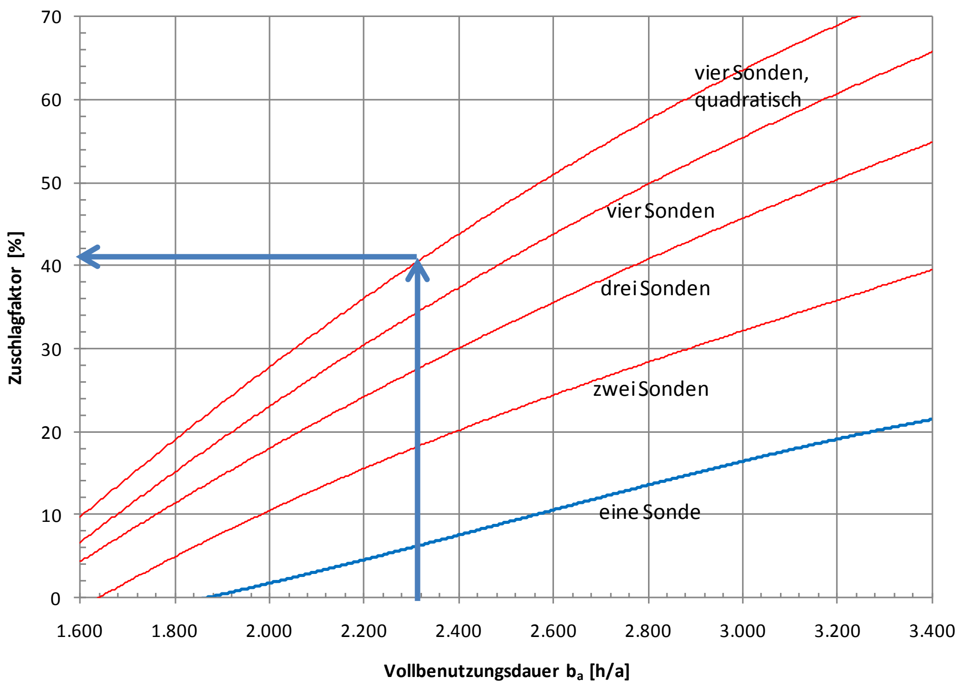


Fluid temperature after 25 years of operation



Calculation example, procedure and result SIA-Method (response function method)





Determination of principle power capacity (heat conductivity, volumetric heat capacity, upper figure)

Correction according to load (i.e. full power operation hours, lower figure)

Correction according to fluid temperature difference to the rock compared to standard conditions (not shown)

IBL

INGENIEURBÜRO PROF. DR. LOOSE GMBH

Gebäude- und Energietechnik - Fernwärme

Calculation example, ASHRAE-Method (response function method)

Excel-workbook using numerical fits of the response functions, overlay of three temperature differen-ces according to peak, medium, and long term load (cf. previous slide)

		UNITS	Single borehole	Multiple boreholes
1st SET OF INPUTS				
Ground loads				
peak hourly ground load	q_h	W	12000	-392250
monthly ground load	q_m	W	6000	-100000
yearly average ground load	q_y	W	1500	-1762
Ground properties				
thermal conductivity	k	$W.m^{-1}K^{-1}$	2	2,25
thermal diffusivity	α	$m^2.day^{-1}$	0,086	0,068
Undisturbed ground temperature	T_g	°C	15	12,41
Fluid properties				
thermal heat capacity	Cp	$J.kg^{-1}.K^{-1}$	4200	4000
total mass flow rate per kW of peak hourly ground load	m_{fls}	$kg.s^{-1}.kW^{-1}$	0,050	0,074
max/min heat pump inlet temperature	T_{inHP}	°C	40,2	4,44
Borehole characteristics				
borehole radius	r_{bore}	m	0,060	0,054
pipe inner radius	r_{pin}	m	0,0137	0,0137
pipe outer radius	r_{pext}	m	0,0167	0,0167
grout thermal conductivity	k_{grout}	$W.m^{-1}.K^{-1}$	1,50	1,73
pipe thermal conductivity	k_{pipe}	$W.m^{-1}.K^{-1}$	0,42	0,45
center-to-center distance between pipes	L_U	m	0,0511	0,0471
internal convection coefficient	h_{conv}	$W.m^{-2}.K^{-1}$	1000	1000
1st SET OF RESULTS				
Calculation of the effective borehole thermal resistance				
convective resistance	R_{conv}	$m.K.W^{-1}$	0,012	0,012
pipe resistance	R_p	$m.K.W^{-1}$	0,076	0,071
grout resistance	R_g	$m.K.W^{-1}$	0,076	0,060
effective borehole thermal resistance	R_b	$m.K.W^{-1}$	0,120	0,102
Calculation of the effective ground thermal resistances				
short term (6 hours pulse)	R_{6h}	$m.K.W^{-1}$	0,114	0,101
medium term (1 month pulse)	R_{1m}	$m.K.W^{-1}$	0,180	0,160
long term (10 years pulse)	R_{10y}	$m.K.W^{-1}$	0,191	0,170
Total length calculation assuming no borehole thermal interference				
heat pump outlet temperature	T_{outHP}	°C	45,0	1,1
average fluid temperature in the borehole	T_m	°C	42,6	2,8
total length	L	m	151,7	9899,3
2nd SET OF INPUTS				
Borefield characteristics				
distance between boreholes	B	m		6,1
number of boreholes	NB	-		120
borefield aspect ratio	A	-		1,2
FINAL RESULTS				
Total length calculation (with Tp)				
1st iteration				
distance-depth ratio	B/H	-		0,074
logarithm of dimensionless time	$\ln(t_{10y}/t_s)$	-		-1,120
temperature penalty	T_p	°C		-0,240
total borefield length	L	m		10151,5
2nd iteration				
distance-depth ratio	B/H	-		0,072
logarithm of dimensionless time	$\ln(t_{10y}/t_s)$	-		-1,170
temperature penalty	T_p	°C		-0,238
total borefield length	L	m		10149,7
3rd iteration				
distance-depth ratio	B/H	-		0,072
logarithm of dimensionless time	$\ln(t_{10y}/t_s)$	-		-1,170
temperature penalty	T_p	°C		-0,238
total borefield length	L	m		10149,7
4th iteration				
distance-depth ratio	B/H	-		0,072
logarithm of dimensionless time	$\ln(t_{10y}/t_s)$	-		-1,170
temperature penalty	T_p	°C		-0,238
total borefield length	L	m		10149,7
5th iteration				
distance-depth ratio	B/H	-		0,072
logarithm of dimensionless time	$\ln(t_{10y}/t_s)$	-		-1,170
temperature penalty	T_p	°C		-0,238
total borefield length	L	m		10149,7
Final results				
total borefield length	L	m		10149,7
borehole depth	H	m		84,6

Sign convention:
+: heat injection to the ground
-: heat extraction from the ground

<- Warning: α must be in the range between 0.025 and 0.2 m²/day

<- Mass flow rate in kg/s divided by the absolute value of the peak hourly ground load in kW

<- Design criterion for the operation of the heat pump

<- Warning: r_{bore} must be in the range between 0.05 and 0.1 m

<- Warning: NB must be in the range between 4 and 144

<- Number of boreholes in the longest direction over the number of borehole in the other direction, A must be in the range between 1 and 9

Important note on the evaluation of T_p:
The correlation for Tp is based on 1485 simulations covering the following range of borefield configurations:

$$-2 \le \ln(t/t_s) \le 3$$
$$4 \le NB \le 144$$
$$1 \le A \le 9$$
$$0.05 \le B/H \le 0.1$$

When used within these ranges, T_p is typically accurate to within +/- 10%.
However, in certain cases, when Tp is near zero, values of Tp are less accurate
This inaccuracy combined with small values of (T_m, T_g) can lead to inaccurate borehole depths

Calculation example, comparison of the results of different methods

Method	Type of probe field	Depth of single borehole [m]	Total borelength [m]
EED	2 x 2	78	312
ASHRAE	2 x 3	89	534
SIA	2 x 2	99	398

Conclusions:

- The results of different design methods differ considerably. We could only verify FE-calculations by measurements.
- Further research (measurements) to verify calculation methods is necessary.
- At the moment the SIA-method seems to be the best approach for practical design purposes.

Thank you for your attention

Спасибо за внимание!

Merci beaucoup pour votre attention!

谢谢大家!

Herzlichen Dank für Ihre Aufmerksamkeit!