Numerical experimental design of a large field of neighboring single BHE-facilities with COMSOL Multiphysics and Feflow

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Federal Ministry for Economic Affairs and Climate Action

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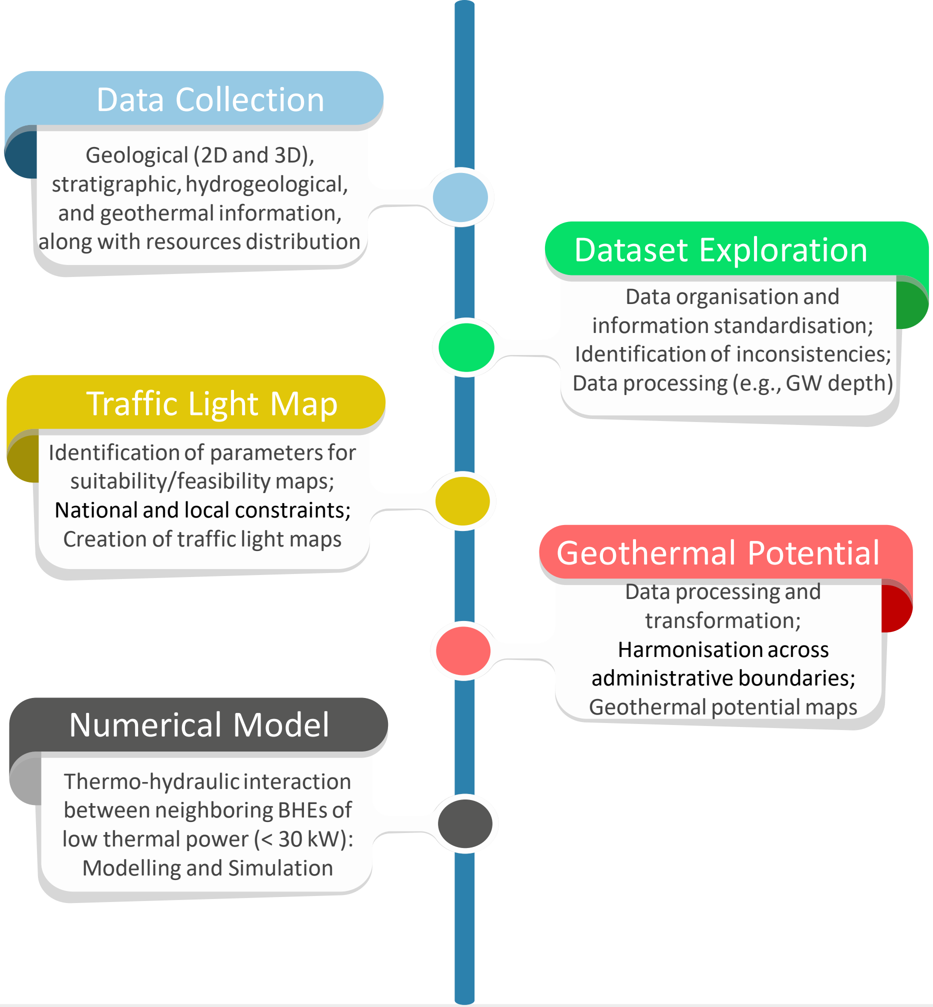
WärmeGut (UGOE)

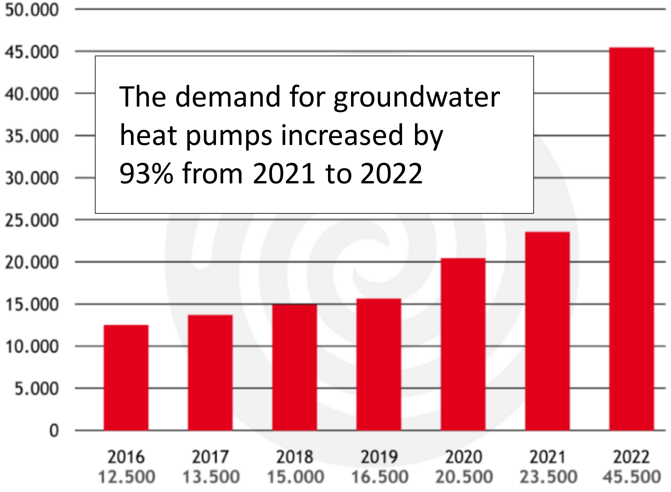
Today's talk

- ✓ Motivation & Problem definition
- ✓ Model setup (technical and geologic)
- ✓ Numerical experimental design
- ✓ Preliminary simulation results



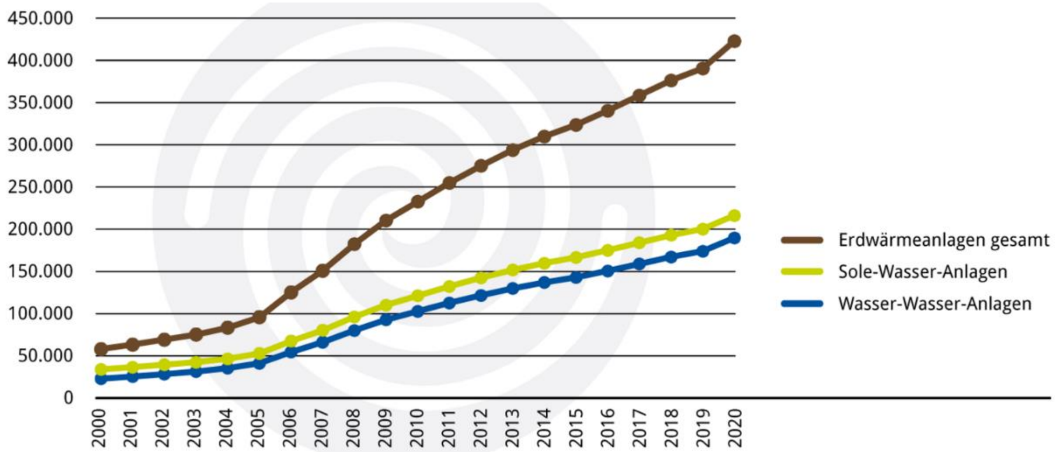
In the last decades, the utilization of shallow-geothermal energy in Germany has steadily risen

Geothermal heat pump sales from 2016 to 2022



The demand for groundwater heat pumps increased by 93% from 2021 to 2022

Near-surface geothermal energy projects in Germany (number of heat pumps 2000-2020)



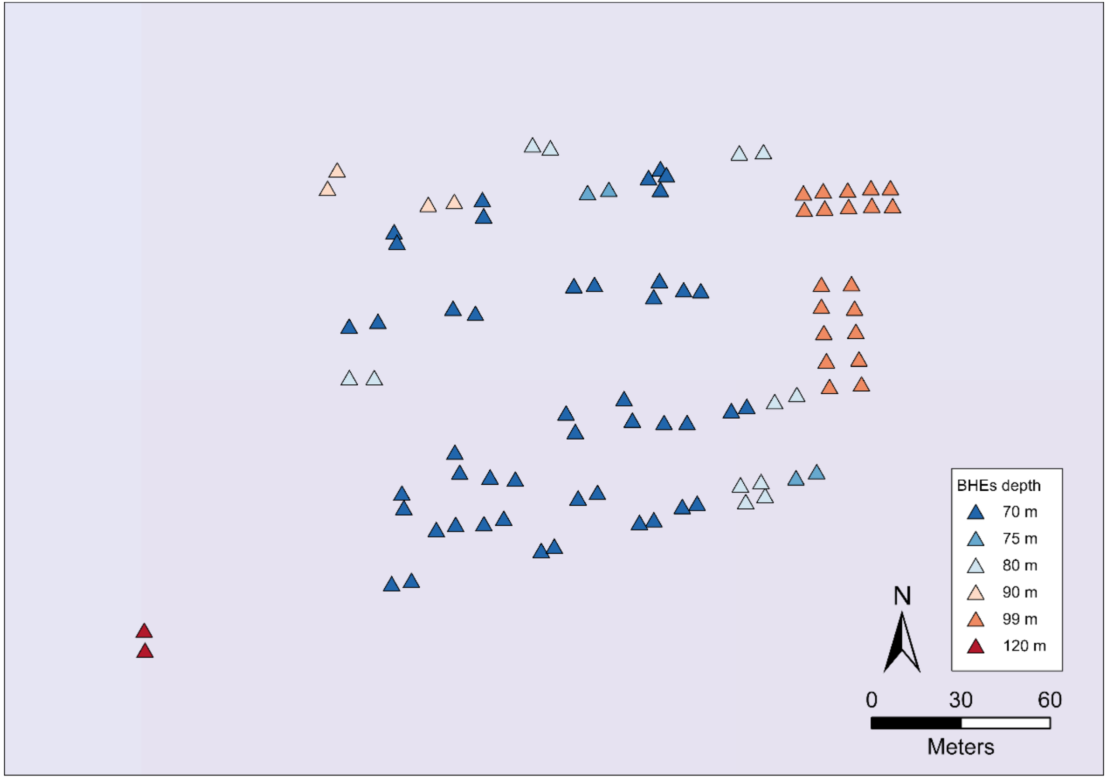
Bundesverband Wärmepumpe (BWP)

Motivation

Shallow geothermal installations of small thermal power (<30kW) for single houses and generally small-scale heating purposes do not require detailed thermal-hydraulic modelling by state geological surveys in Germany.

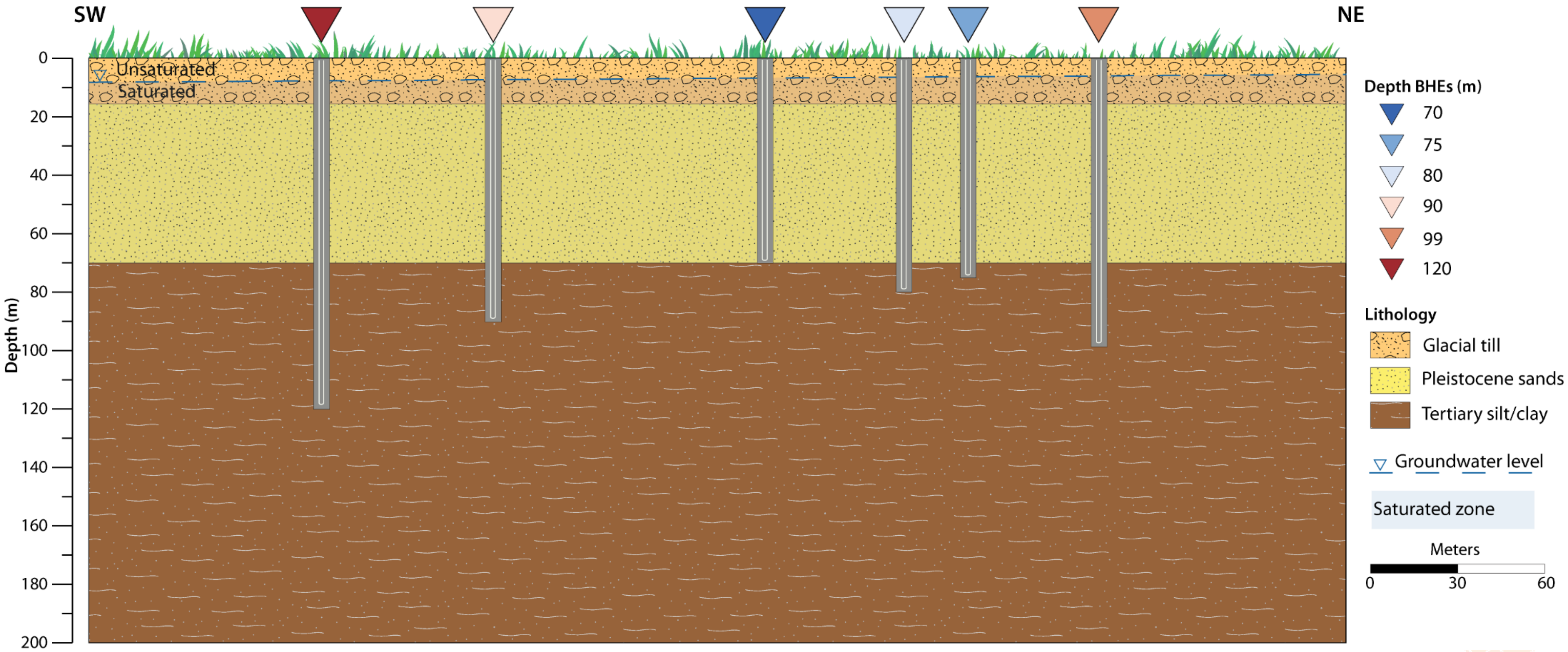
- What about the **long-term** thermo-hydraulic interaction between BHEs under different geothermal and hydrogeological conditions?
- What are the **controls on the long-term performance** of such field of individual, small-thermal-power BHE-units?
- Optimization?

FIELD OF BHEs OF SMALL THERMAL POWER (< 30kW) - IRREGULARLY DISTRIBUTED

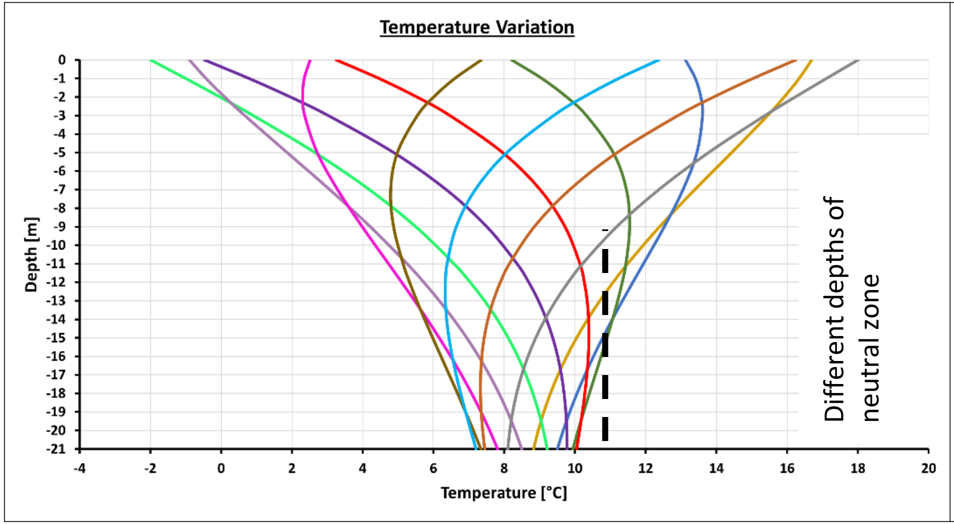


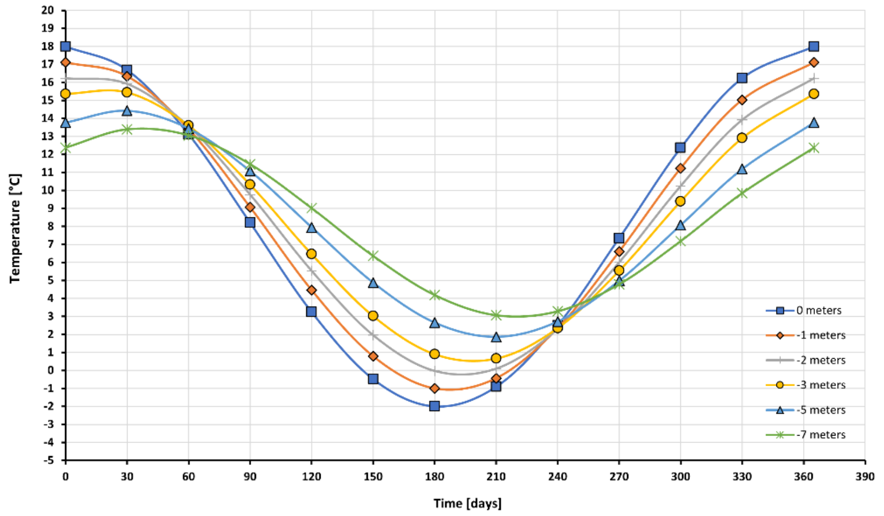
- **COLLABORATION WITH LBEG** (STATE AUTHORITY FOR MINING, ENERGY AND GEOLOGY) IN LOWER SAXONY
- REAL FIELD COMPRISING 88 BHEs

VERTICAL PROFILE – IMPACT ON HYDRAULIC AND **THERMAL PROPERTIES**



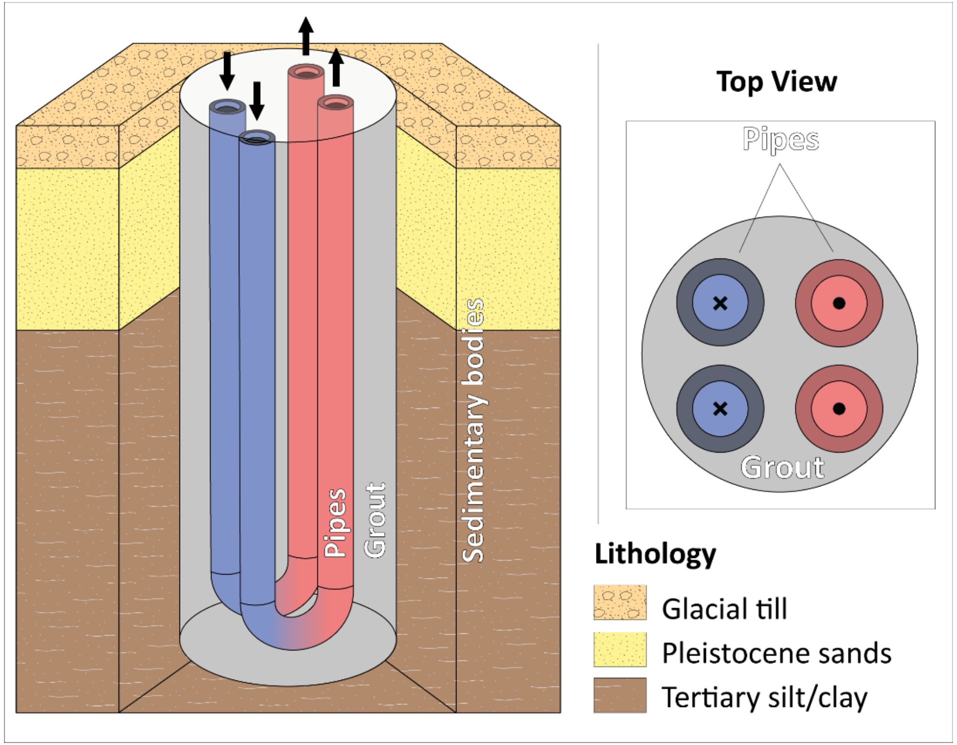
Geothermal – Theoretical Temperature distribution over depth and time





Different subsurface temperature scenarios

MODEL SETUP AND PHYSICAL PROCESSES



- DOUBLE U-TUBE PIPE ASSEMBLAGE, HIGH-DENSITY POLYTHYLENE PIPES
- WORKING FLUID (MIXTURE OF WATER AND 20-25% ANTIFREEZE) – PRESSURISED TO 2-3 BAR
- VERTICAL BOREHOLE (CYLINDER) – BENTONITE-CEMENT MIXTURE
- POROUS MATERIAL

MODEL PARAMETRISATION

	Heat Carrier Fluid	Pipes	Thermally-enhanced Grout	Porous Materials
Thermal conductivy	☑	☑	☑	☑
Specific Heat Capacity	☑	☑	☑	☑
Density	☑	☑	☑	☑
Thermal Capacity	☑	☑	☑	☑
Heat Resistence	☑	☑	☑	☑
Geometry		☑		
Wall Thickness		☑		
Viscosity	☑			☑
Porosity				☑
Dispersivity				☑
Roughness		☑		
Flow Rate	☑			
Freezing Point	☑			
Hydraulic Conductivity				☑
Saturation				☑

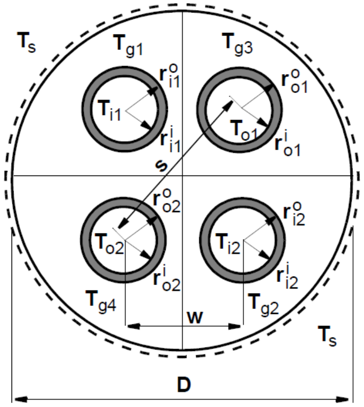
DIFFERENT FINITE-ELEMENT APPROACHES

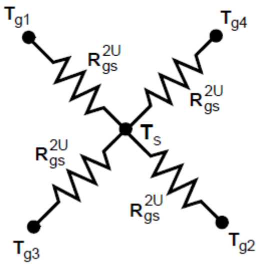
FEFLOW

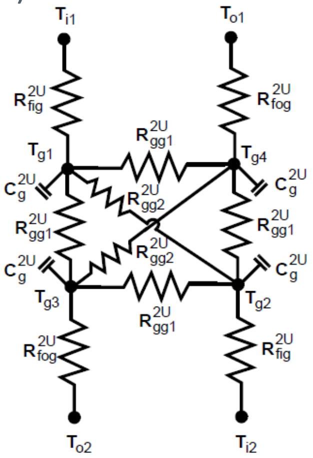
- Consideration of BHE-internal heat transfer
- Allows the detailed calculation of interaction between BHE
- Simplification of BHE-internal heat transfer calculation:

Resistance/capacity values depend on

- BHE geometry (diameters, pipe distances)
- Material properties (pipes/grout/fluid)







COMSOL MULTIPHYSICS

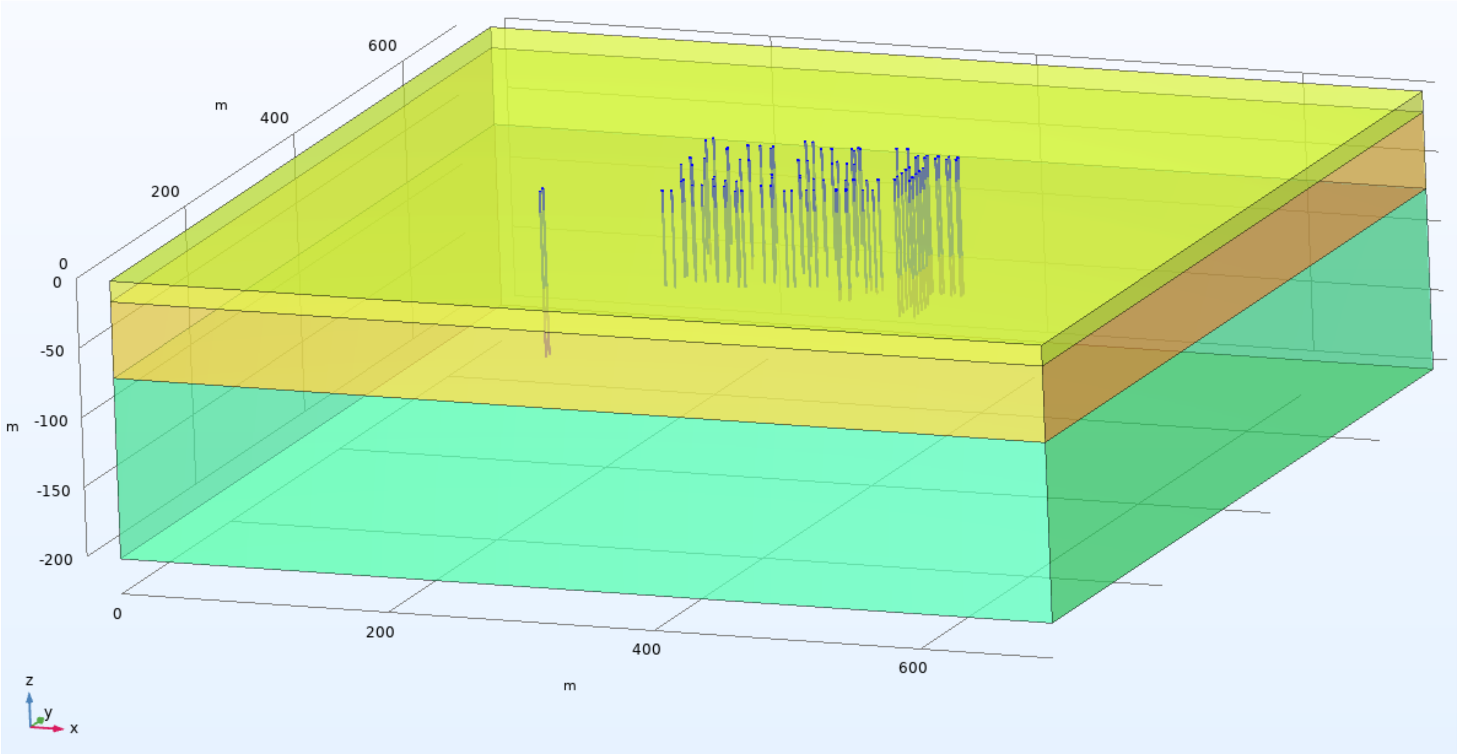
- Consideration of heat transfer in pipes
- Includes Wall heat transfer to the surroundings
- Heat loss 1-D element and couple to 3D model
- Additional term of pressure work
- Radial heat transfer from the surroundings into the pipe

$$\rho A C_p \frac{\partial T}{\partial t} + \rho A C_p \mathbf{u} \cdot \nabla T = \nabla \cdot Ak\nabla T + f_D \frac{\rho A}{2d_h} |\mathbf{u}|^3 + Q_{wall} + Q_p$$

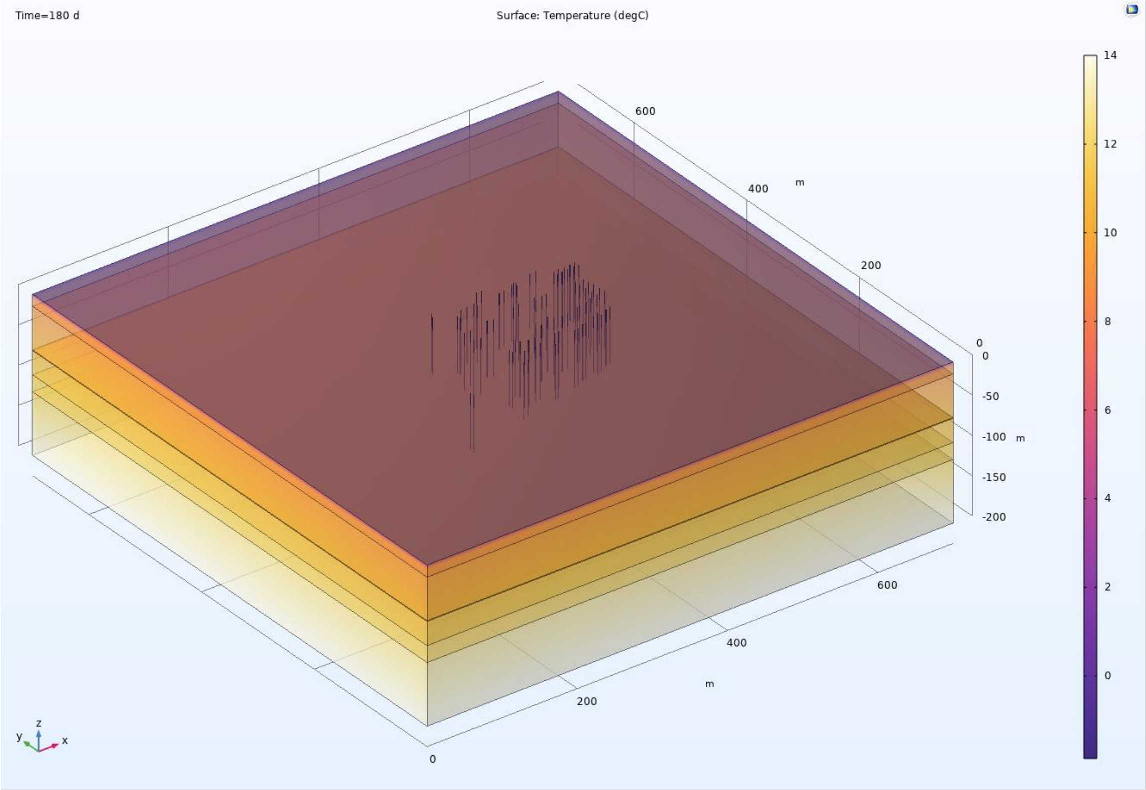
$$Q_p = -\frac{TA}{\rho}\left(\frac{\partial \rho}{\partial T}\right)\left(\frac{\partial p}{\partial T} + \mathbf{u} \cdot \nabla p\right)$$

$$Q_{wall} = (hZ)_{\text{eff}}(T_{\text{ext}} - T)$$

3-D IMPLEMENTATION IN COMSOL MULTIPHYSICS

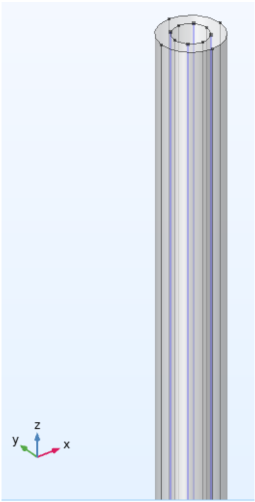


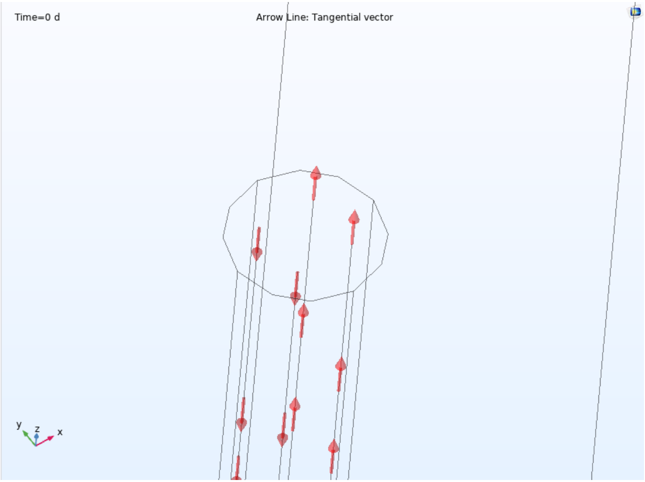
IMPLEMENTATION OF CYCLIC UNDISTURBED GROUND TEMPERATURE DISTRIBUTION



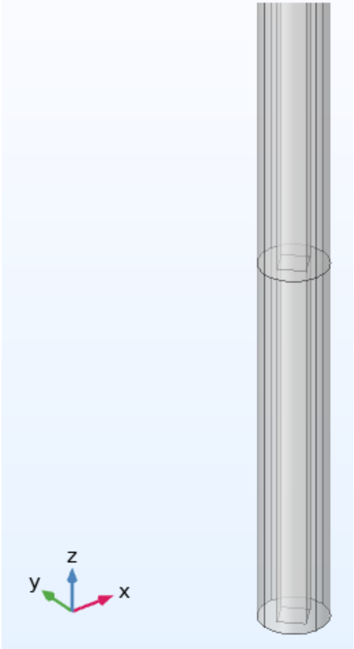
BUILDING THE BHEs- SELECTION OF INLET AND OUTLET TEMPERATURE IN COMSOL MULTIPHYSICS

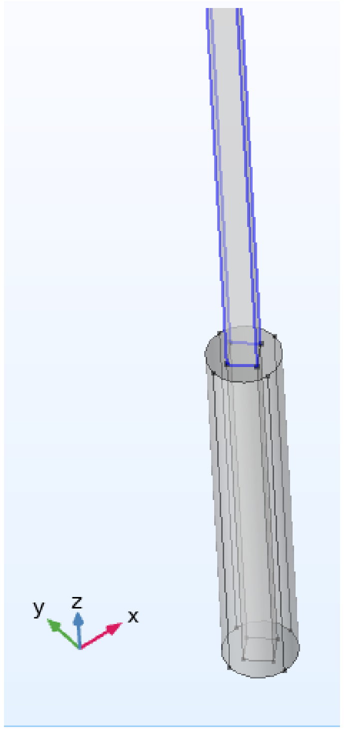
UPPER PART





LOWER PART





THERMAL LOAD – TIME SERIES - IMPLEMENTATION IN COMSOL MULTIPHYSICS

Definition

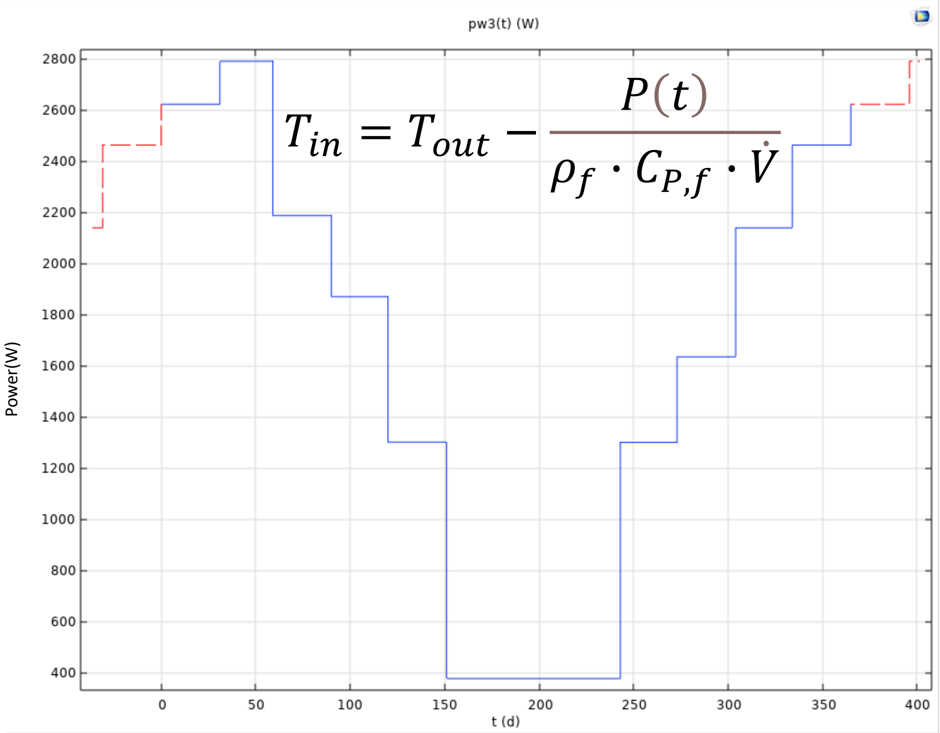
Argument: t

Extrapolation: Periodic

Smoothing: No smoothing

Intervals

Start	End	Function
0	31	1.952[MWh]/31[d]
31	31+28	1.876[MWh]/28[d]
31+28	2*31+28	1.628[MWh]/31[d]
2*31+28	2*31+28+30	1.347[MWh]/30[d]
2*31+2...	3*31+28+30	0.969[MWh]/31[d]
3*31+2...	5*31+28+2*30	0.834[MWh]/92[d]
5*31+2...	5*31+28+3*30	0.937[MWh]/30[d]
5*31+2...	6*31+28+3*30	1.217[MWh]/31[d]
6*31+2...	6*31+28+4*30	1.541[MWh]/30[d]
6*31+2...	7*31+28+4*30	1.833[MWh]/31[d]



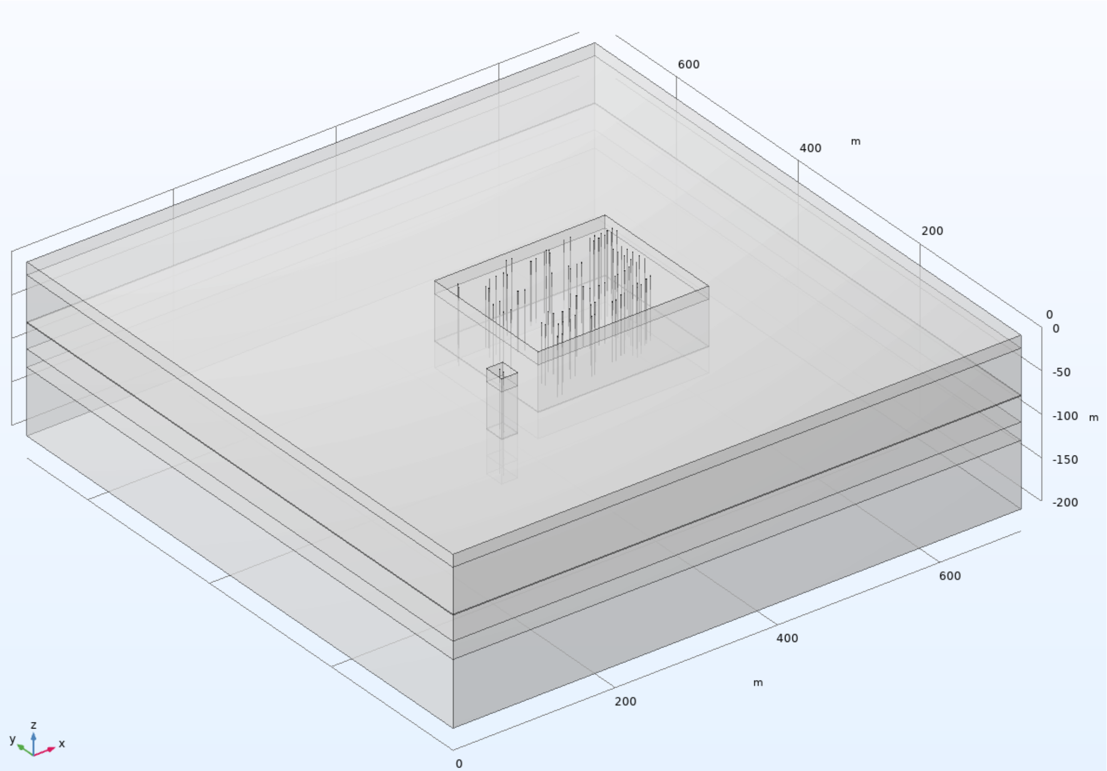
$$T_{in} = T_{out} - \frac{P(t)}{\rho_f \cdot C_{P,f} \cdot \dot{V}}$$

AUTOMATISATION OF BHE CONSTRUCTION AND SELECTIONS VIA CODING

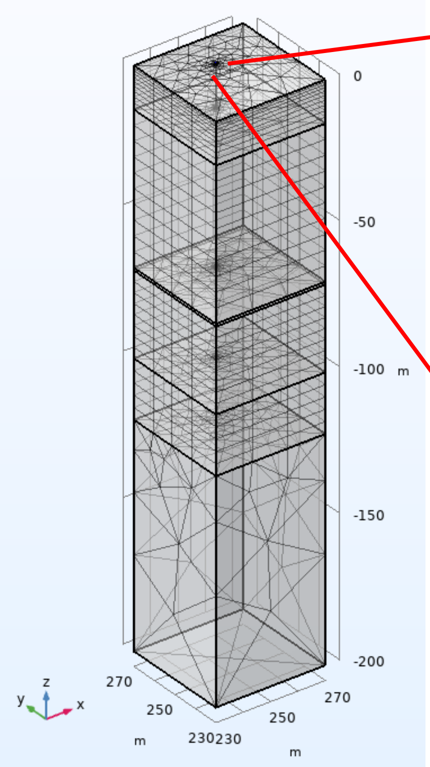
Preview | method2 | method3 | redefineSelections

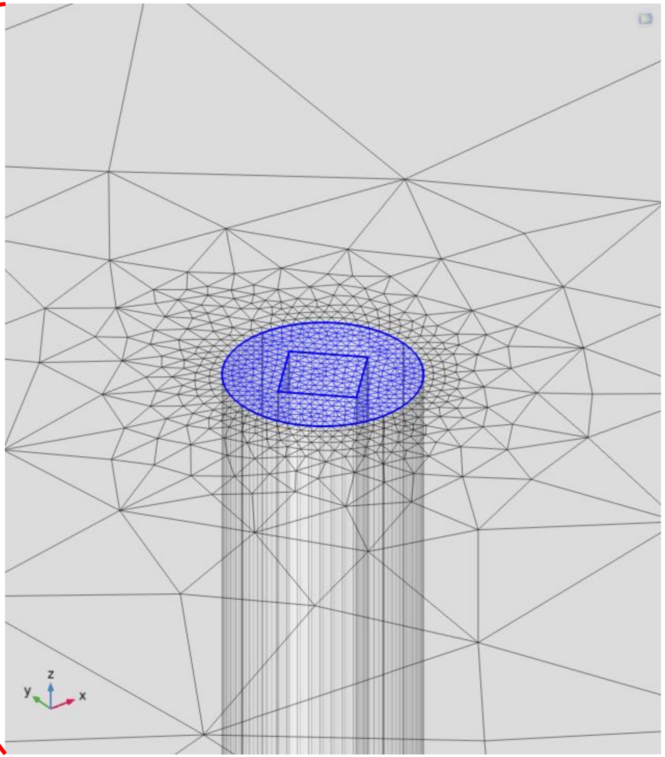
```java
double[][] coord = readMatrixFromFile("PositionenundTiefen.prn");
int[] size = matrixSize(coord);
int N = size[0];

for (int i = 0; i < N; ++i) {

  double x = coord[i][0];
  double y = coord[i][1];
  double depth = coord[i][2];
  model.component("comp1").geom("geom1").create("pi"+i, "PartInstance");
  model.component("comp1").geom("geom1").feature("pi"+i).set("part",
                                                              "part1");
  // Input Parameter setzen:
  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("inputexpr",
                                                                  "xPart", x);
  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("inputexpr",
                                                                  "yPart", y);
  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("inputexpr",
                                                                  "zPart", depth);

  //Selections einstellen
  model.component("comp1").geom("geom1").feature("pi"+i).set("selkeepnoncontr", false);
  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("selkeeppnt", "pi"+i+"_sel1", true); //Explicit Selections für In/Outlets einzeln behalten
  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("selkeeppnt", "pi"+i+"_sel2", true);

  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("selcontributetopnt", "pi"+i+"_sel1", "csel1"); //Explicit Selections aus PI in kumulative aus geom1 einfügen
  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("selcontributetopnt", "pi"+i+"_sel2", "csel2");
  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("selcontributetoedg", "pi"+i+"_sel3", "csel3");
  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("selcontributetodom", "pi"+i+"_sel4", "csel4");
  model.component("comp1").geom("geom1").feature("pi"+i).setEntry("selcontributetobnd", "pi"+i+"_sel5", "csel5");
  model.component("comp1").geom("geom1").feature("pi0").setEntry("selcontributetoedg", "pi"+i+"_sel6", "csel6");


  //Create Operators
  model.component("comp1").cpl().create("outlet"+i+"_avg", "Average");
  model.component("comp1").cpl("outlet"+i+"_avg").selection().named("geom1_pi"+i+"_sel2"); //Explicit Selection aus PI
  model.nodeGroup("grp2").add("cpl", "outlet"+i+"_avg");
  model.component("comp1").cpl().create("outlet"+i+"_int", "Integration");
  model.component("comp1").cpl("outlet"+i+"_int").selection().named("geom1_pi"+i+"_sel2"); //Explicit Selection aus PI
  model.nodeGroup("grp3").add("cpl", "outlet"+i+"_int");

  //Set Variables
  model.component("comp1").variable().create("variables"+i);
  model.component("comp1").variable("variables"+i).selection().named("geom1_pi"+i+"_sel1"); //Explicit Selection aus PI

  model.component("comp1").variable("variables"+i).set("T_out", "outlet"+i+"_avg(T2)");
  model.component("comp1").variable("variables"+i).descr("T_out", "");

  model.component("comp1").variable("variables"+i).set("dT", "P_local/htp.Cp/Q_local");
  model.component("comp1").variable("variables"+i).descr("dT", "");

  model.component("comp1").variable("variables"+i).set("P_local", "localPower("+i+",t)");
  model.component("comp1").variable("variables"+i).descr("P_local", "");

  model.component("comp1").variable("variables"+i).set("Q_local", "outlet"+i+"_int(htp.A*htp.u*htp.rho)");
  model.component("comp1").variable("variables"+i).descr("Q_local", "");

  model.component("comp1").variable("variables"+i).set("T_in", "T_out+dT");
  model.component("comp1").variable("variables"+i).descr("T_in", "");

  model.nodeGroup("grp4").add("variable", "variables"+i);

}
```

Optimizing mesh construction

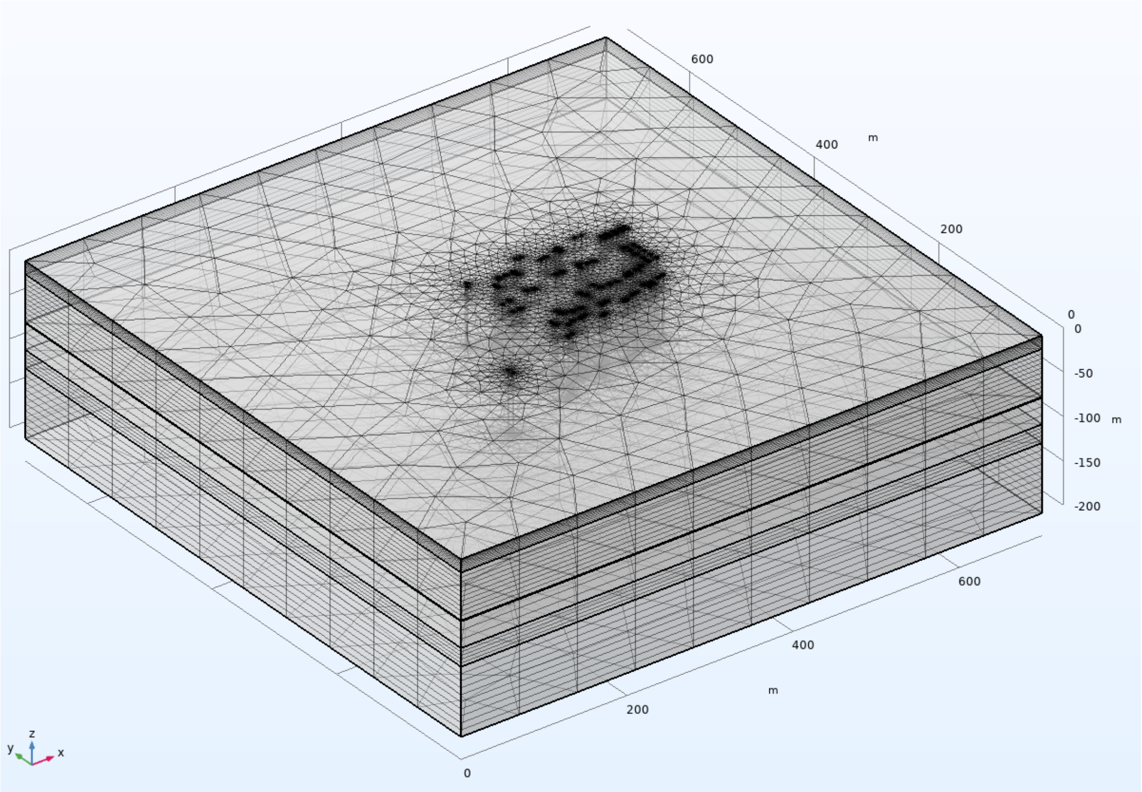


MESH STUDIES TO ADEQUATELY REPRESENT HEAT TRANSPORT MECHANISM





Final optimized mesh



Statistics

Complete mesh

Mesh vertices: 256491

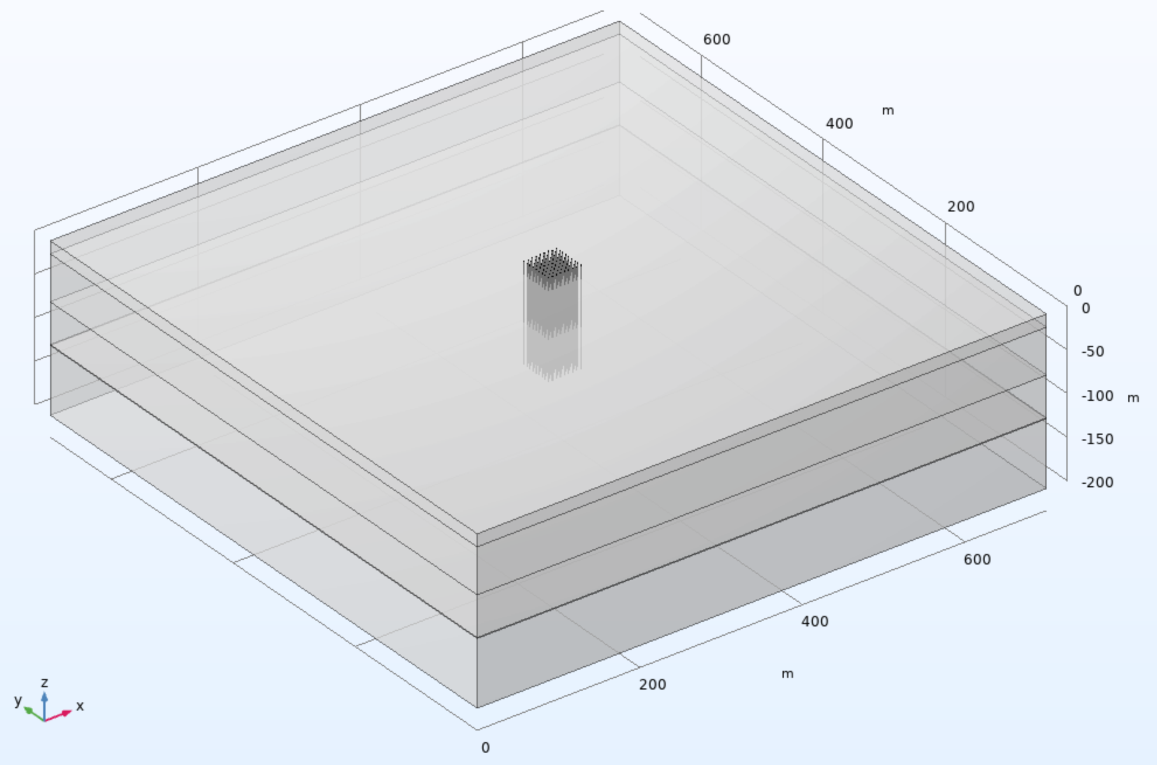
Element type: All elements

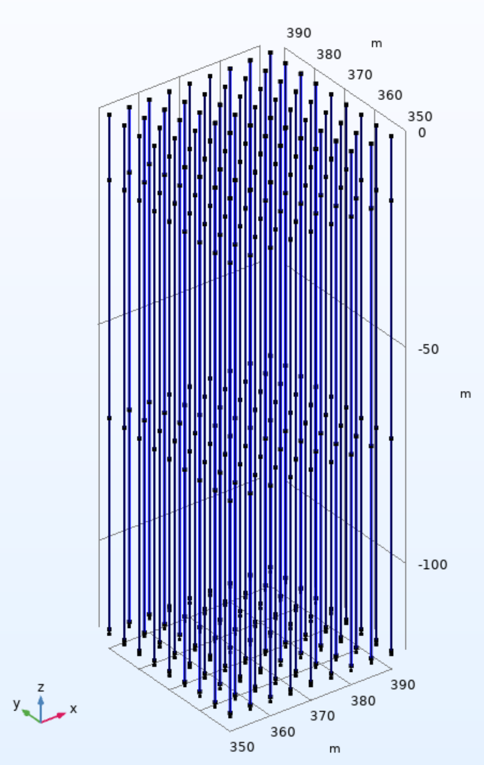
Tetrahedra:	250192
Pyramids:	3746
Prisms:	414440
Hexahedra:	120
Triangles:	77978
Quads:	23384
Edge elements:	25740
Vertex elements:	3532

Domain element statistics

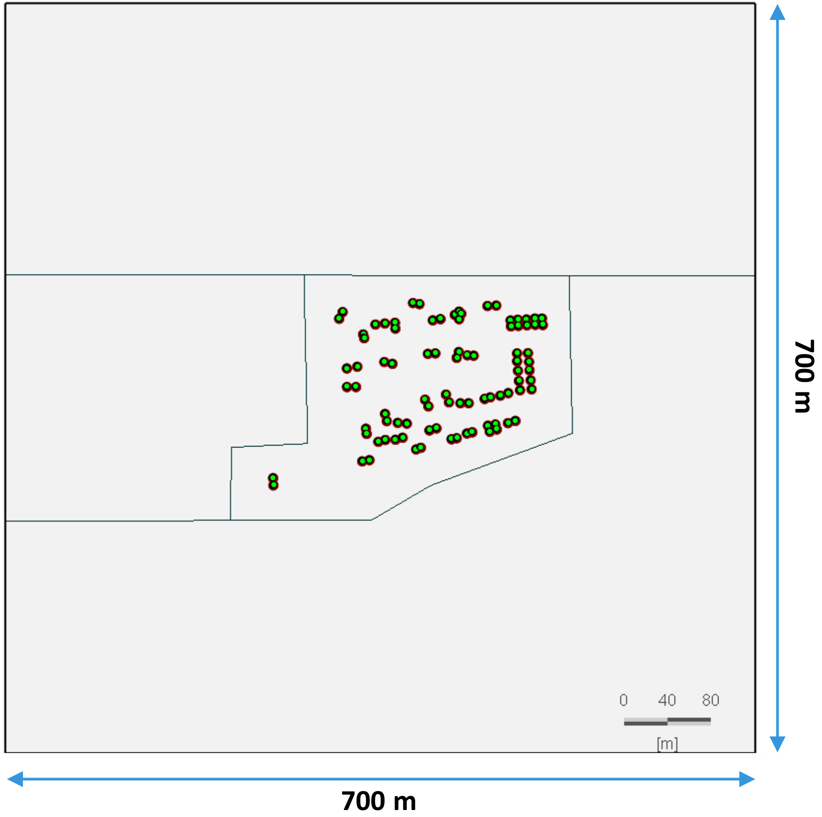
Number of elements:	668498
Minimum element quality:	0.001614
Average element quality:	0.6814
Element volume ratio:	3.866E-11
Mesh volume:	9.8E7 m^3

REGULARLY DISTRIBUTED BHE ARRAY FOR OPTIMIZATION PURPOSES



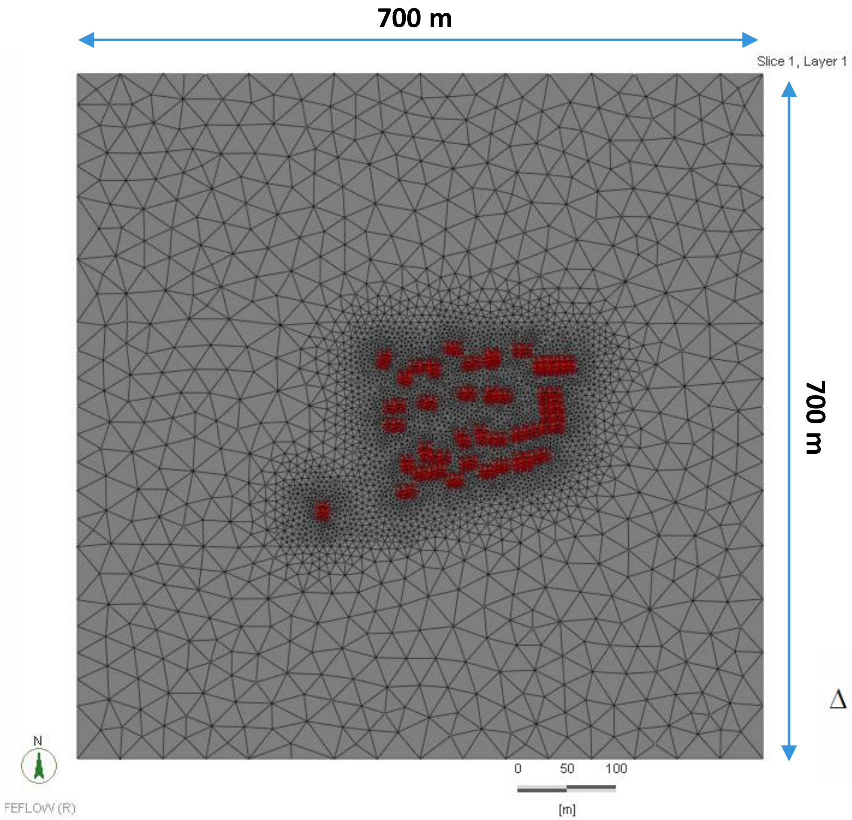


FEFLOW – Super mesh - Problem setting

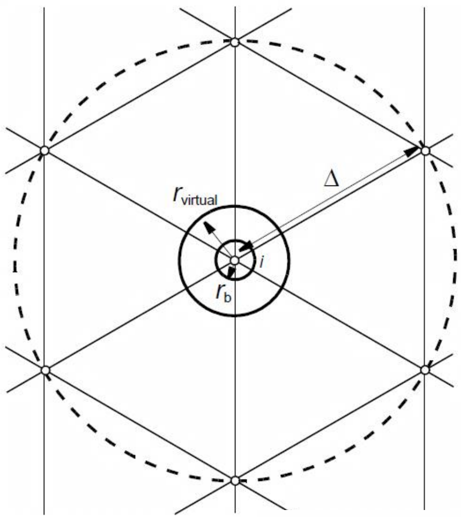


- Combined flow and heat processes
- 3-D unsaturated and saturated sediments
- Transient flow and heat transport

2-D MESH VIEW

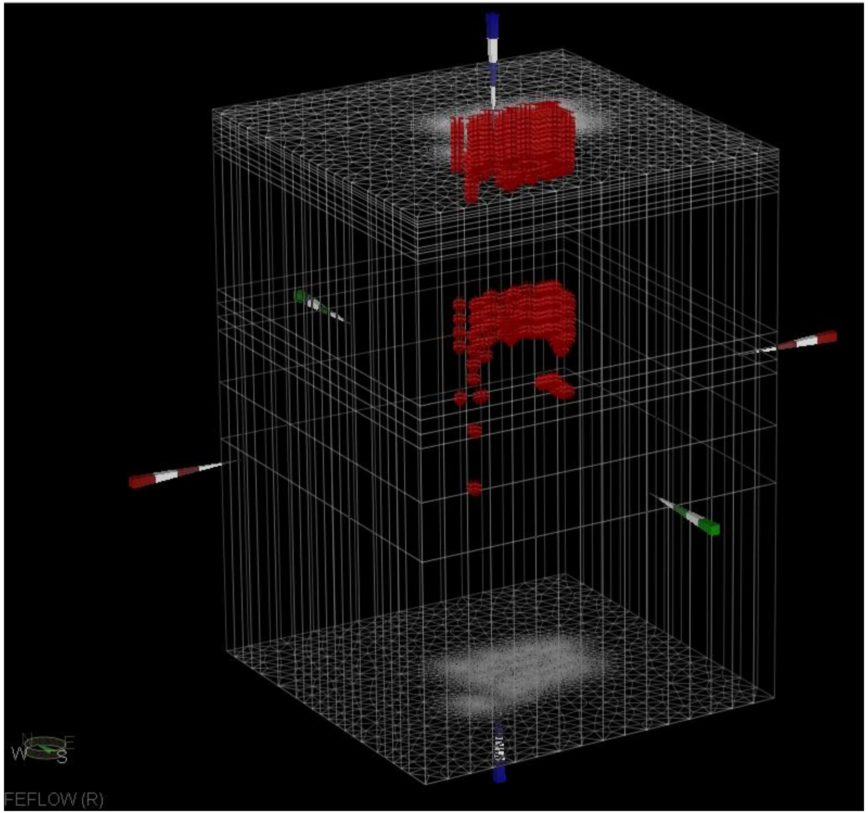


SPATIAL DISCRETIZATION AROUND A BHE



$$\Delta = \exp(\alpha)\, r_{virtual} \qquad \alpha = \frac{2\pi}{n \tan\left(\frac{\pi}{n}\right)} \qquad \Delta = a\, r_b \qquad a = \begin{cases} 4.81 & \text{for } n = 4 \\ 6.13 & \text{for } n = 6 \\ 6.66 & \text{for } n = 8 \end{cases}$$

3-D Mesh

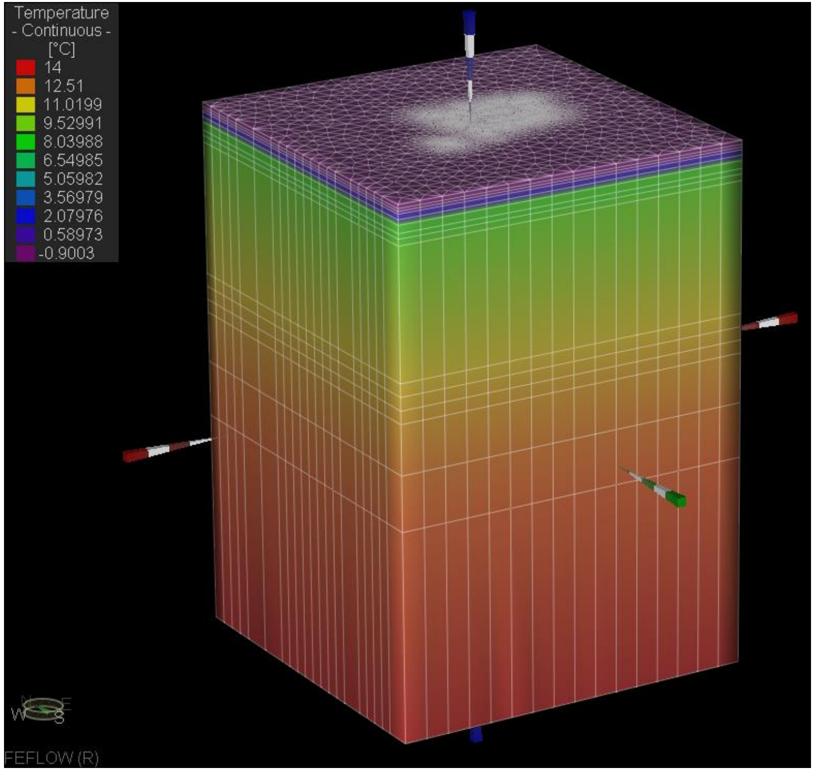


Mesh Optimization

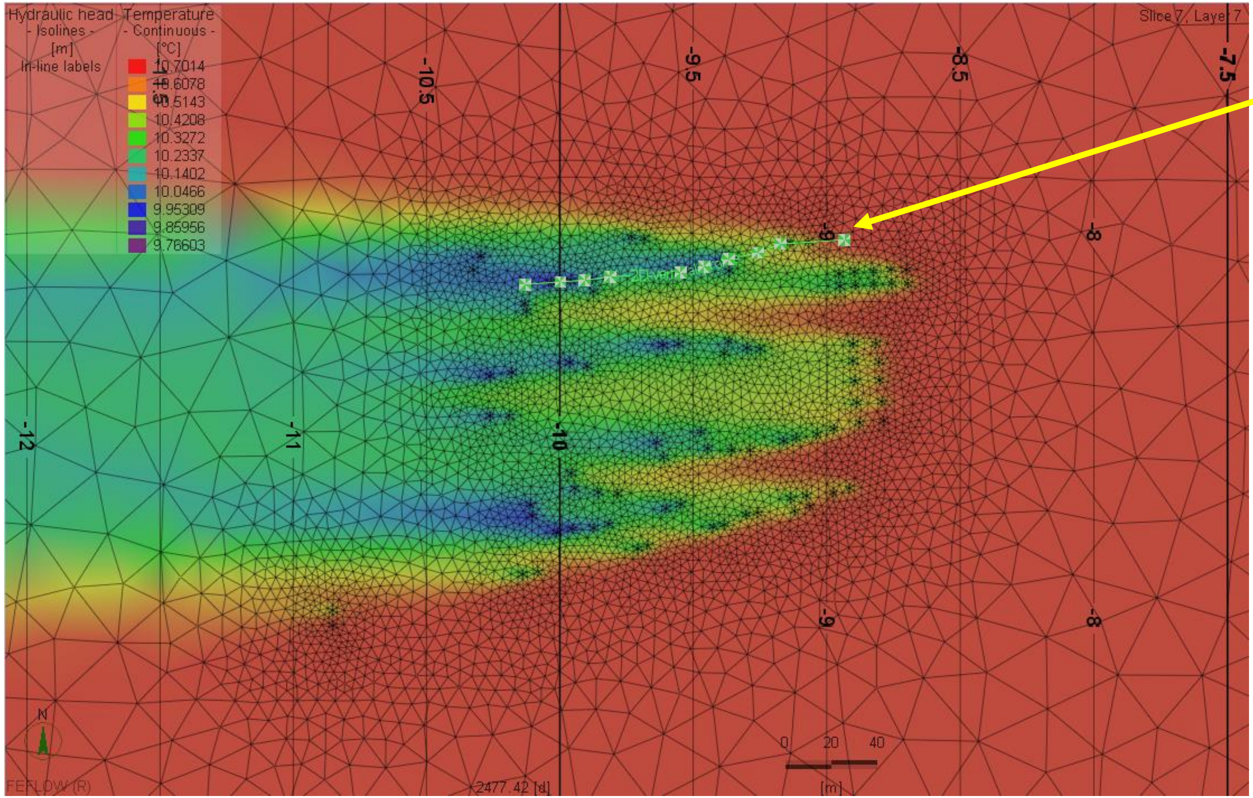
- Fine resolution in the zone of interest
- As many elements as necessary to adequately represent the heat transport mechanisms
- As few elements as possible to reduce computational load

- Triangular prism
- 167505 mesh elements
- 89920 mesh nodes

TIME-VARYING TEMPERATURE DISTRIBUTION

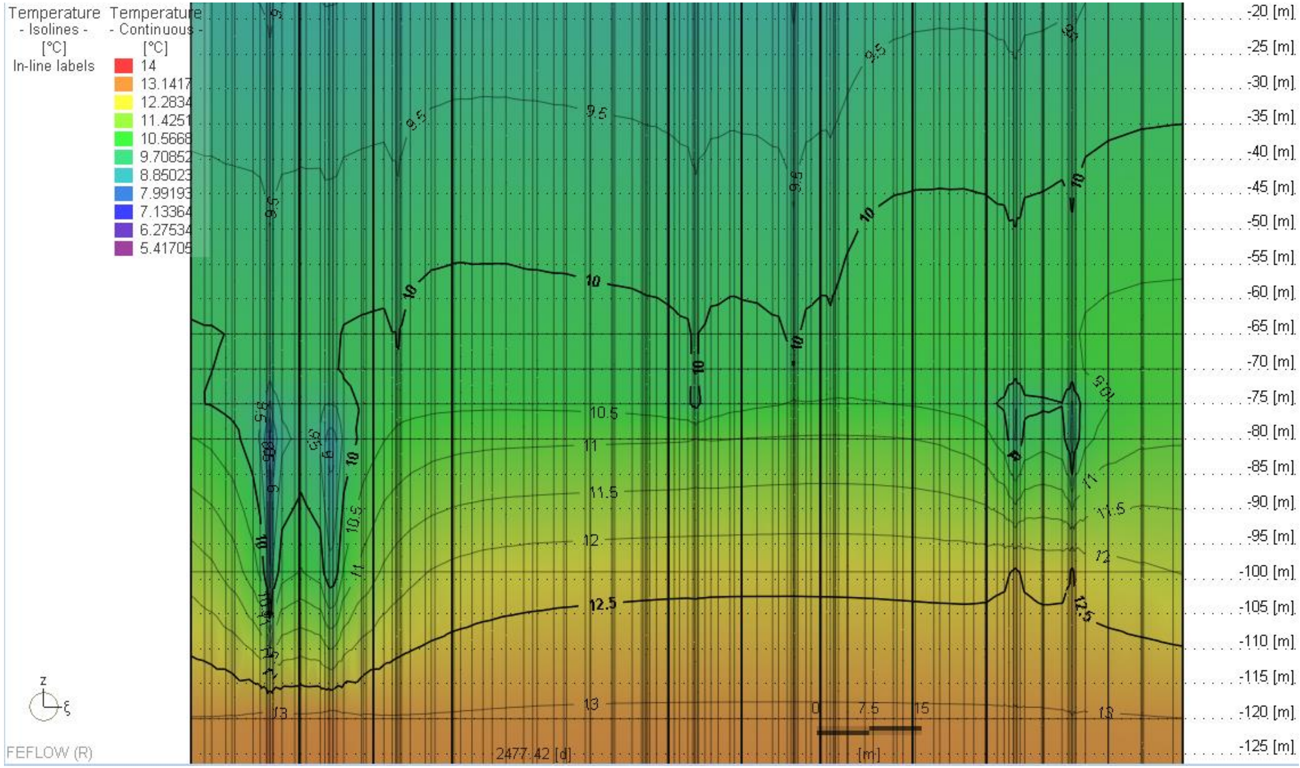


PRELIMINARY RESULTS – DEPTH 65 M

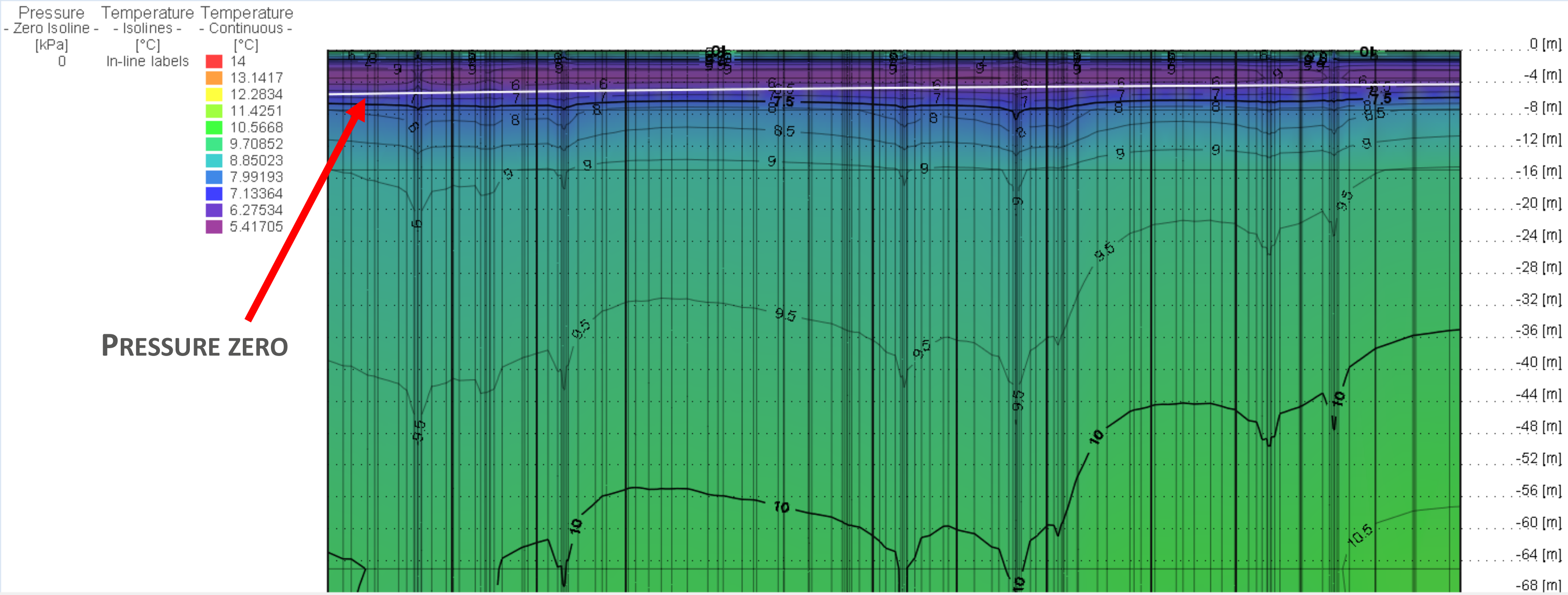


2-D VERTICAL PROFILE

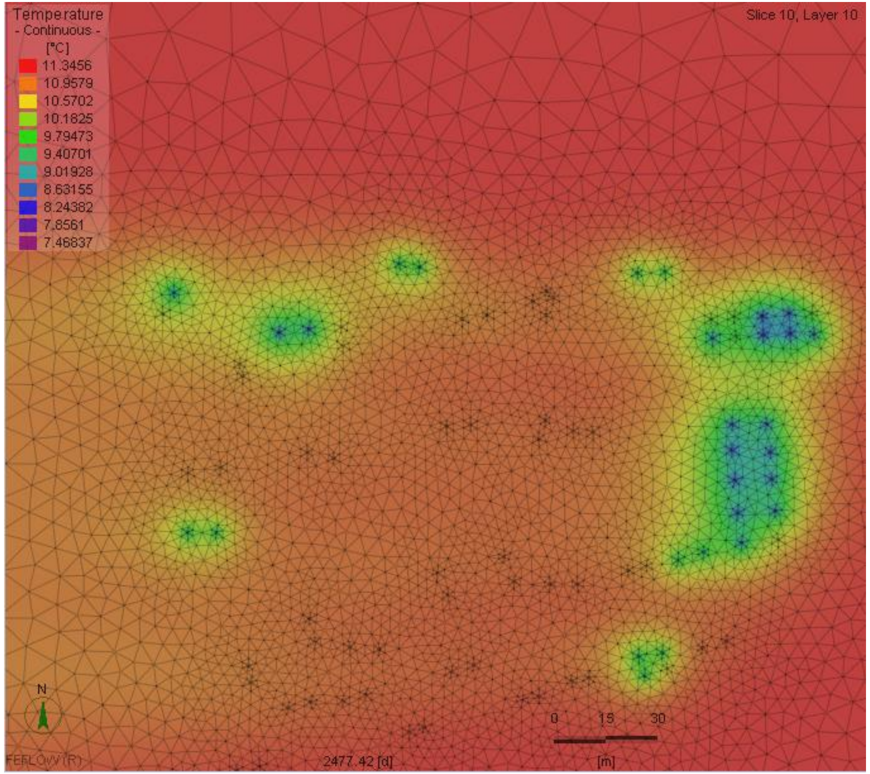
PRELIMINARY RESULTS – LOWER PART OF VERTICAL PROFILE



PRELIMINARY RESULTS – UPPER PART OF VERTICAL PROFILE



Preliminary results – Depth 80 m



Summarizing Remarks & Outlook

- Several numerical experimental designs have been considered
- Different finite-element approaches in COMSOL Multiphysics and FEFLOW have been used
- Detailed implementation of a complex, real field of individual BHEs under geothermal and hydrogeological conditions
- Field of regularly distributed BHEs has been setup for optimization and geothermal potential assessment
- Preliminary simulation results show long-term thermo-hydraulic performance of real field of low-thermal-power BHEs
- Future consideration of cyclic recharge and fluctuation of water table

Thank you for your attention!