Memo

Date	Our reference	Number of pages
November 11, 2018	11201825-000-HYE-0004	37
Contact person	**Direct number**	**E-mail**
David Nugroho	+31(0)88 335 7215	David.Nugroho@deltares.nl

Subject
Summary of the results of 2-dimensional heat transfer analysis

1 Background

The 2-dimensional heat transfer calculations were conducted to simulate heat transfer from the heat source (pipes and soil surface) to drinking water pipe. This will be used as an input to calculate the increase of temperature of drinking water due to the radial heat transfer through the soil and the drinking water pipe. The increase of temperature of drinking water due to the radial heat transfer will be implemented in Wanda Heat.

In the 2-dimensional heat transfer calculations the following parameters were varied: diameter of the heating pipe(s), diameter of the drinking water pipe, drinking water pipe material, distance between heating pipe(s) and the drinking water pipe, soil cover, temperature of heating pipe(s), configuration of heating pipe(s), temperature of soil surface and temperature of the drinking water. In the calculations, the weather conditions of the spring and summer in 2016 (between 1 May and 1 September) was taken into account.

The summary of the results of the 2-dimensional heat transfer calculations are presented in this memo.

2 Finite element model, calculation steps and boundary conditions

2.1 Finite element program

All the calculations were made in Plaxis thermal 2018.

2.2 Finite element model

For the cases with district heating pipes, up to 2 heating pipes were modelled. For the cases with the electricity cables only one casing pipe was modelled. Regardless the case, only one drinking water pipe was modelled in each calculation.

In order to reduce the boundary effect the model size was determined based on a sensitivity analysis. The required width and height of the model was normalized to the diameter of the heating pipe. The result of the sensitivity analysis can be found in Appendix A of this memo.

The general finite element model for the calculation with district heating pipe is shown in Figure 2.1. In Figure 2.1 the case with two district heating pipes is presented. The insulation (PUR and

PE casing) of the heating pipe was modelled around a steel pipe. One of the heating pipes acts as a supply pipe and the other one as a return pipe. The return pipe has generally larger temperature than the supply pipe. In the calculation scenarios (see section 4.2) both supply and return pipes have the same dimensions. For the calculation with one heating pipe, only the supply pipe was modelled.

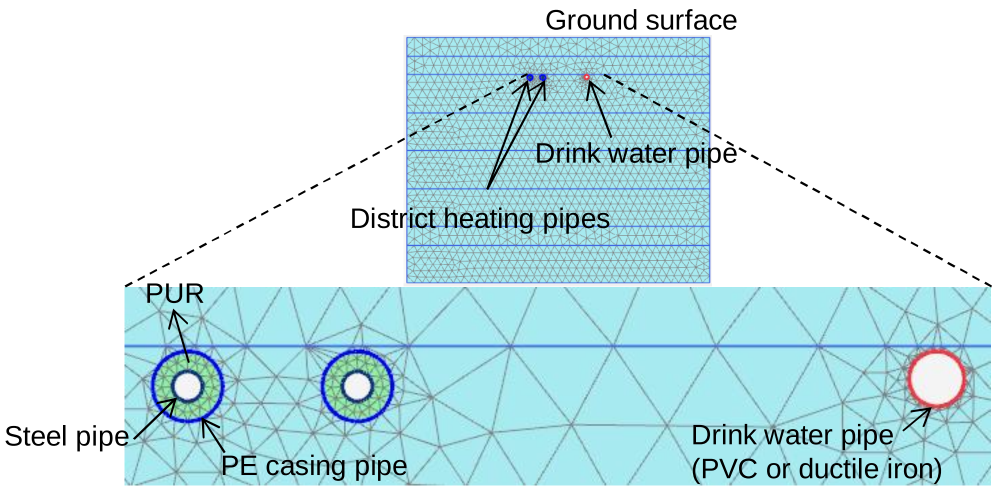


Figure 2.1 *Finite element model for the calculations with two district heating pipes*

The general finite element model for the calculation with electricity cables is shown in Figure 2.2. Only the casing pipe of the electricity cables was modelled. Unlike heating pipe, the casing of electricity cables has no external insulation.

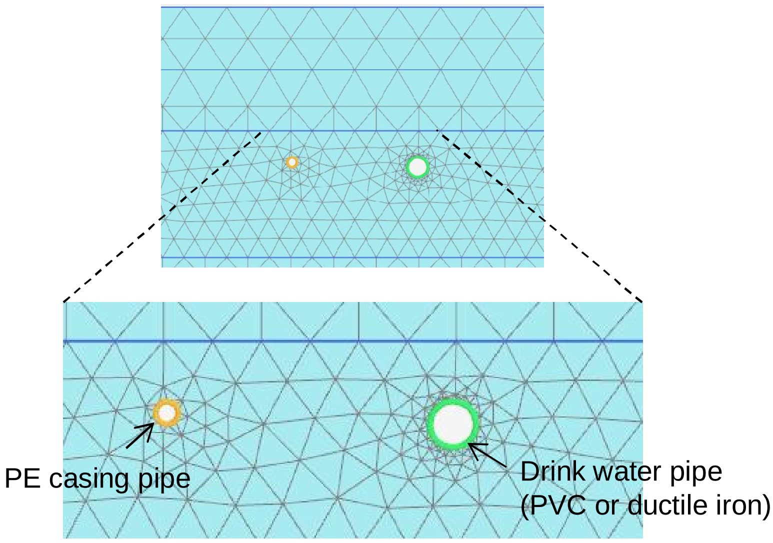


Figure 2.2 *Finite element model for the calculations with electricity cables*

2.3 Calculation steps and boundary conditions

To simulate the soil temperature in a warm environment, the period between 1 May (spring) and the 1 September in 2016 (end of summer) was selected. The calculation consisted of two steps:

- Steady state heat transfer
- Transient heat transfer

The first calculation step is a steady state heat transfer. The steady state heat transfer was used to simulate the initial temperature of the soil given the initial temperature of the heat sources (soil surface and the heating pipes) and the cold source (drink water) on 1 May 2016. From various calculations without the heating pipes and the drinking water pipe, the soil temperature on 1 May 2016 at 0.5 to 2 m depth was between 9^o to 12^{o}C and the surface temperature was approximately 20^{o}C [1]. This was considered sufficient for the heat development around the heating pipe(s) in which the soil was not extremely cold or warm.

The finite element boundaries for this step are shown in Figure 2.3. For the sake of describing the boundaries the finite element model with two districts heating pipes is used (see Figure 2.3). A temperature profile as a function of depth (z) was applied on left and right boundaries. From depth of 5.5 m the soil was kept constant. At the surface, a soil temperature at depth 0m (z = 0) was assigned. The spring temperatures were applied at the steel part of the heating pipes (denoted as $T_{hp1;spring}$ and $T_{hp2;spring}$) and inside the drinking water pipe (denoted as $T_{dw;spring}$). For the calculation with the electricity cables, a heat flux instead of temperature was applied at the casing pipe.

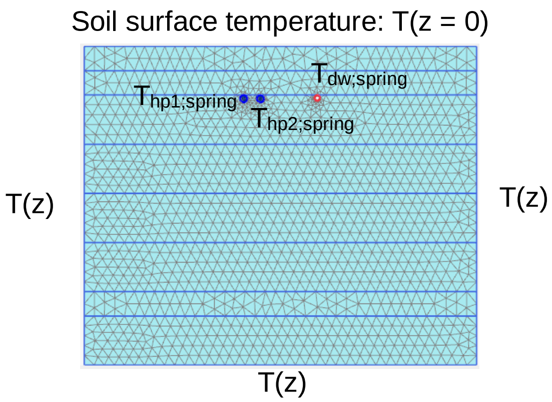


Figure 2.3 Boundary conditions at steady state calculation step

The next calculation step is transient heat transfer calculation. This calculation step was conducted between 1 May 2016 and 1 September 2016 with a time step of 1 hour. When the calculation time reached 1 June 2016 the temperature in the pipes were switched to summer temperature.

The boundary conditions of this calculation step are depicted in Figure 2.4. At the top, left and right boundaries a soil temperature as function of time (t) and depth (z) was applied denoted as T(t,z). The bottom boundary was set to closed (heat flux = 0). The summer temperatures inside the heating pipes were applied from 1 June 2016 at the steel pipe part of the heating pipes (denoted as $T_{hp1;summer}$ and $T_{hp2;summer}$) and inside the drinking water pipe (denoted as $T_{dw;summer}$).

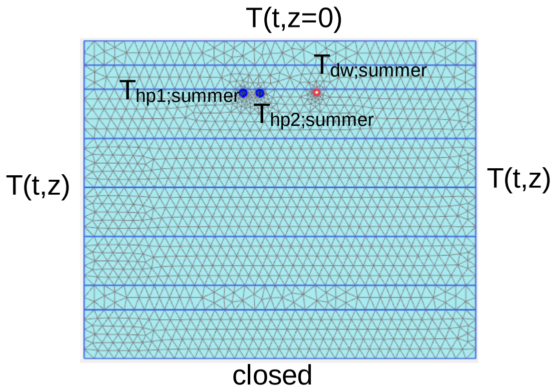


Figure 2.4 Boundary conditions at transient calculation step during summer period (from 1 June 2016)

2.4 Minimum distance between the pipe (heat source) and the boundaries

The distances between the pipe and each vertical boundary (left and right boundaries) and between the pipe and the bottom boundary must be sufficiently far from the pipe to minimalize the boundary effect. The distances from the pipe to each boundary were determined based on a sensitivity analysis on steady state calculations. More information about the sensitivity analysis can be found in Appendix A of this memo.

2.5 Number of finite element meshes

The minimum number of finite element meshes required was analysed in the sensitivity analyses on several steady state and transient calculations. More information can be found in Appendix A of this memo.

3 Input data for the calculation

3.1 Climate-soil model and thermal properties of soil

There were seven climate-soil models taken into account for the 2-dimenisonal heat transfer calculations: TMVz, TMDz, TMNz, GMVz, TLVz, TMK and TMZK. The first letter represents the type of cover material on the soil surface (T = tile, G = grass). The second letter represents the urbanity type (M = average urbanity, L = low urbanity). The last two letters represent the type of soil (Vz = moist sand, Dz = dry sand, Nz = wet sand, K = clay, ZK = sand-clay).

The soil thermal properties of each base scenario are in Table 2.1 presented and given as bulk properties.

Table 3.1 Thermal properties of soil of each climate-soil model [1]

Climate-soil model	C_ρ* [J/kg/K]	λ** [W/m/K]	ρ*** [kg/m^3]
TMVz (tile cover, average urbanity, moist sand soil)	1000	1.4	1700
TMDz (tile cover, average urbanity, dry sand soil)	800	1.6	1600
TMNz (tile cover, average urbanity, wet sand soil)	1200	1.2	1800
GMVz (grass cover, average urbanity, moist sand soil)	1000	1.4	1700
TLVz	1000	1.4	1700

(tile cover, low urbanity, moist sand soil)			
TMK (tile cover, average urbanity, clay soil)	1350	1.35	1600
TMZK (tile cover, average urbanity, sand-clay soil)	1175	1.375	1650

*Specific heat capacity
**Heat conductivity
***Density

3.2 Thermal properties of insulation materials of district heating pipe(s)

The district heating pipe consists of a steel pipe covered with PUR insulation and PE casing pipe. The thermal properties of PUR and PE materials are given in Table 3.2.

Table 3.2 Thermal properties of district heating pipe

Material	Thermal properties
PE	C = 1880 J/kg/K [11], λ = 0.47 W/m/K [11], ρ = 950 kg/m^3 [11]
PUR	C = 1470 J/kg/K [6], λ = 0.024 W/m/K [5], ρ = 90 kg/m^3 [5]

3.3 Thermal properties of the drinking water pipe

In the 2-dimensional heat transfer calculations the drinking water acts as a cold source which influences the temperature of the soil around the drinking water pipe proportional to the heat transfer coefficient of the drink water pipe wall (H_w). In the pipe wall of the drinking water pipe a temperature gradient caused by the difference between the drinking water temperature and soil temperature will develop and a heat flux through the pipe wall will occur.

The heat transfer coefficient of the pipe wall (H_w) can be calculated using the formula below and is a function of the effective thermal conductivity of the pipe material (λ_k), the outside diameter (D_o) and the wall thickness of the drinking water pipe (w) [13].

$$H_w = \frac{2\lambda_k}{D_i \times ln\left(\frac{D_o}{D_i}\right)}$$

Where:

- D_i is the inside diameter of the drink water pipe = $D_o - 2w$.

The thermal properties of the drink water pipes of various materials and diameters used in the calculations are presented in Table 3.3. The effective thermal conductivity was assumed to be the same as the thermal conductivity since the pipe wall has practically only one specific material.

Table 3.3 Heat transfer (H_w) coefficient of drink water pipes

D_o [mm]	w [mm]*	λ [W/m/K]*	Pipe material	H_w [W/m^2/K]
110	2.7	0.16	PVC	60.78
160	4	0.16	PVC	41.04
63	2**	0.16	PVC	82.68
63	2.4**	0.16	PVC	69.38
121.6	11.8	0.323	DI***	30.55
200	4.9	0.16	PVC	33.49

*source: [1].
**taken from the calculation scenarios with two heating pipes (see Table 4.4).
***lined ductile iron with cement.

4 Calculation scenarios

4.1 Calculation with one district heating pipe (supply pipe)

Table 4.1 and 4.2 give the calculations scenarios with one district supply heating pipe (SP) and one drinking water pipe (DWP). 7 various climate-soil models (TMVz, TMDz, TMNz, GMVz, TLVz, TMK and TMZK) were taken into account in the calculations. The description of each climate-soil model can be found in Table 3.1. Table 4.1 describes the configuration of the district heating supply pipe. Table 4.2 describes the configuration of the DWP.

Table 4.1 Configuration of the district heating supply pipe (D_o = outer diameter, w = wall thickness, T = temperature, H = soil cover, d = distance centre to centre between DWP and supply pipe)

Case	Supply	H [m]	d [m]
A	Type: DN 150 Steel pipe: D_o = 168.3 mm, w = 4 mm PE casing: Do = 280 mm, w = 3.9 mm PUR thickness = 55.85 mm T_{spring} = 100°C, T_{summer} = 90°C	1	0.5

Table 4.2 Configuration of the DWP (D_o = outer diameter, w = wall thickness, T = drinking water temperature, H = soil cover)

Case	D_o [mm]	w [mm]	Material	T_{spring} [°C]	T_{summer} [°C]	H [m]
A	200	4.9	PVC	18	18	1

4.2 Calculation with two district heating pipes (supply and return pipes)

Table 4.3 and 4.4 give the calculations scenarios with two district heating pipes and one drinking water pipe (DWP). There were 4 cases calculated (B = base calculations, C = primary network, D = DW tertiary). 4 various climate-soil models (TMVz, TMDz, TMNz and GMVz) were taken into account in the calculations. The information in these tables was summarized from [4]. Table 4.3 describes the configuration of the district heating pipes. Table 4.4 describes the configuration of the DWP.

Table 4.3 Configuration of the district heating pipes (D_o = outer diameter, w = wall thickness, T = temperature, s = centre to centre distance between supply and return pipe, H = soil cover, d = centre to centre distance between supply pipe and DWP)

Case	Supply	Return	s [m]	d [m]	H [m]
B	Type: DN 50 Steel pipe: D_o = 60.3 mm, w = 2.9 mm PE casing: D_o = 140 mm, w = 3 mm PUR thickness = 39.85 mm T_{spring} = 70°C T_{summer} = 70°C	Type: DN 50 Steel pipe: D_o = 60.3 mm, w = 2.9 mm PE casing: D_o = 140 mm, w = 3 mm PUR thickness = 39.85 mm T_{spring} = 40°C T_{summer} = 40°C	0.34	1	1
C1	Type: DN 150 Steel pipe: D_o = 168.3 mm,	Type: DN 150 Steel pipe: D_o = 168.3 mm,	0.5	1	1.2

	w = 4 mm PE casing: Do = 280 mm, w = 3.9 mm PUR thickness = 55.85 mm T_{spring} = 100°C T_{summer} = 65°C	w = 4 mm PE casing: Do = 280 mm, w = 3.9 mm PUR thickness = 55.85 mm T_{spring} = 90°C T_{summer} = 55°C			
C2	Type: DN 150 Steel pipe: D_o = 168.3 mm, w = 4 mm PE casing: Do = 280 mm, w = 3.9 mm PUR thickness = 55.85 mm T_{spring} = 100°C T_{summer} = 90°C	Type: DN 150 Steel pipe: D_o = 168.3 mm, w = 4 mm PE casing: Do = 280 mm, w = 3.9 mm PUR thickness = 55.85 mm T_{spring} = 55°C T_{summer} = 50°C	0.5	1	1.2
D	Type: DN 50 Steel pipe: D_o = 60.3 mm, w = 2.9 mm PE casing: D_o = 140 mm, w = 3 mm PUR thickness = 39.85 mm T_{spring} = 70°C T_{summer} = 70°C	Type: DN 50 Steel pipe: D_o = 60.3 mm, w = 2.9 mm PE casing: D_o = 140 mm, w = 3 mm PUR thickness = 39.85 mm T_{spring} = 40°C T_{summer} = 40°C	0.34	1	1

Table 4.4 Configuration of the drinking water pipe (D_o = outer diameter, w = wall thickness, T = drinking water temperature, H = soil cover)

Case	D_o [mm]	w [mm]	Material	T_{spring} [°C]	T_{summer} [°C]	H [m]
B	110	2.7	PVC	15	19	1
C1 and C2	160	4	PVC	12	15	1.2
D	63	2	PVC	17	22	1
	63	2.4	PVC	17	22	1
	121.6	11.8	Ductile iron	15	19	1

4.3 Calculation with electricity cables

Table 4.5 and 4.6 give the calculations scenarios with single pipe casing of electricity cables and one drinking water pipe (DWP). From the list given in [14] a single pipe casing of 4*240 VvMvKhsas/Alk 4*6 was chosen. Only TMVz climate-soil model was taken into account in the calculations. The configuration of the casing pipe is shown in Table 4.5. Table 4.6 shows the configuration of the DWP. In Plaxis thermal the heat loss was converted into heat flux by dividing the heat loss with the perimeter of the casing pipe.

Table 4.5 Configuration of the casing pipe for the electricity cables (D_o = outer diameter of casing pipe, d = centre to centre distance between casing pipe and DWP, H = soil cover)

Case	D_o [mm]	Heat loss [W/m']	Electricity cables	d [m]
E	80	4.5*	4*240 VvMvKhsas/Alk 4*6	1

*maximum heat loss 50 W/m' with 30% load of the summer period [14].

Table 4.6 Configuration of the drinking water pipe (D_o = outer diameter, w = wall thickness, T = drinking water temperature, H = soil cover)

#	D_o [mm]	w [mm]	Material	T_{spring} [°C]	T_{summer} [°C]	H [m]
E1	110	2.7	PVC	15	19	1
E2	160	4	PVC	12	15	1.2

5 Summary of the calculation results and discussion

The summary of the calculation results presented below focuses on the temperature distribution around the drinking water pipe. In this memo only the main results from 1 September 2016 (end of calculation step) are presented. The calculated temperature on 1 September 2016 sufficiently represents the average temperature between 26 August 2016 and 1 September 2016 to be used in the implementation of Wanda Heat. More information about this can be found in section 6.4.

In this section the following will be briefly discussed:
- Contour of calculated temperature (section 5.1).
- Calculated temperature around the drinking water pipe (section 5.2).
- Temperature difference around the drinking water pipe (section 5.3).
- Temperature difference of different time steps (section 5.4).

5.1 Contour of calculated temperature on 1 September 2016

The contour of the calculated temperatures around the heating pipe(s) and the drink water pipe are described below. Only the calculated temperature of TMVz climate-soil model is presented to give a general idea of the temperature distribution around the heating pipe(s) and the drink water pipe on different situations. The soil surface temperature on 1 September 2016 is approximately 29°C.

5.1.1 Calculation with one district supply heating pipe (case A)

The contours of calculated temperatures around the supply heating pipe (SP) and the drinking water pipe (DWP) for case A are presented in Figure 5.1 and 5.2. In Figure 5.1 the centre to centre distance between SP and DWP (d) is 0.5m. In Figure 5.2 the centre to centre distance between SP and DWP (d) is 1 m. The information regarding the calculation input data can be found in Table 4.1 and 4.2.

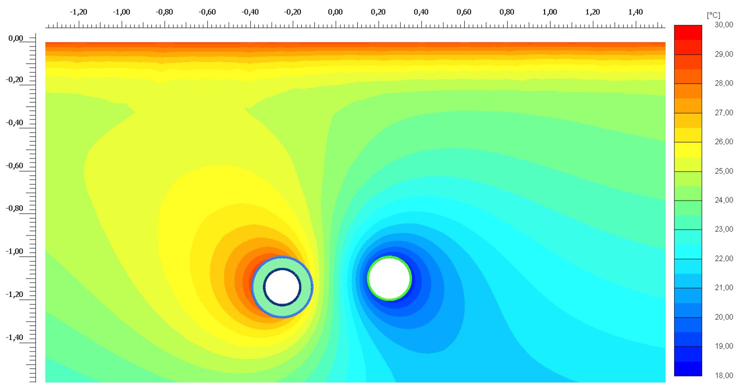


Figure 5.1 Contour of calculated temperature around the pipes for case A with TMVZ climate-soil model and d = 0.5 m.

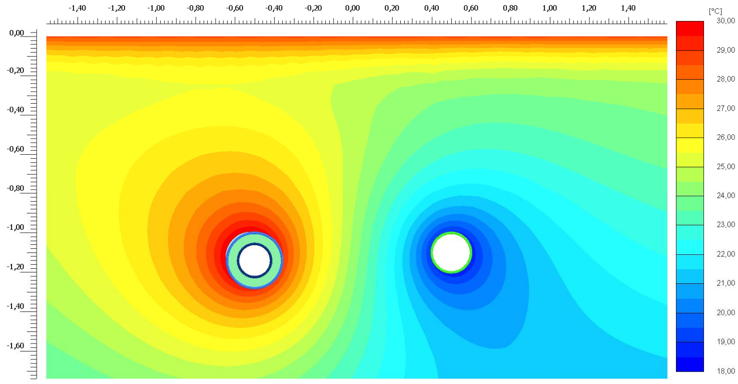


Figure 5.2 Contour of calculated temperature around the pipes for case A with TMVz climate-soil model and d = 1 m.

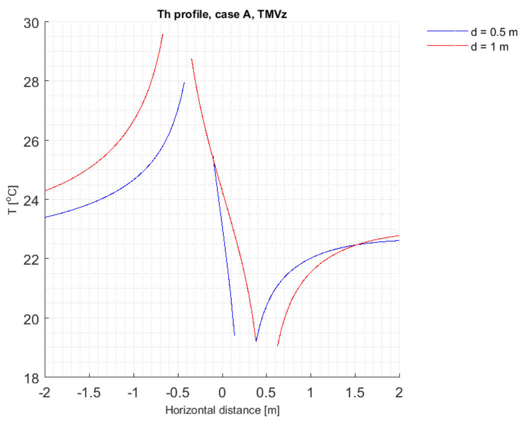


Figure 5.3 Temperature profile in horizontal direction through the centre of DWP

It is observed in Figure 5.3 that as the distance between SP and DWP (d) becomes greater, the temperature drop becomes more nonlinear. At distance d = 0.5m, the temperature drop is almost linear. The right side of the district heating pipe is approximately 3.5ºC cooler if the drinking water pipe is 0.5 m closer. It is surprising to note that even the left-side of the district heating pipe is 1.5ºC cooler with the drinking water pipe at 0.5 m distance. Hence the uninsulated drinking water pipe cools the complete surrounding of the district heating pipe.

5.1.2 Calculation with two district heating pipes (supply and return pipes)

The calculations with two district heating pipes are divided into 3 cases (see Table 4.3): case B (base scenarios), case C (primary network) and case D (DW tertiary). To give a general idea of the temperature contour with two district heating pipes, only case B with TMVz climate-soil model is presented. The calculation input data can be found in Table 4.3 and 4.4. The contours of calculated temperatures around the supply heating pipe and the drinking water pipe are presented in Figure 5.4 and 5.5 for different order of the district heating pipes.

In Figure 5.4, the supply pipe (SP) is located between the return pipe (RP) and the drinking water pipe (DWP), denoted further as RP-SP-DWP. In Figure 5.5 the return pipe (RP) is located between the supply pipe (SP) and the drinking water pipe (DWP), denoted further as SP-RP-DWP. In both figures (5.4 and 5.5), the centre to centre distance between RP and SP (s) is 0.34 m and the centre to centre distance between SP and DWP (d) is 1 m.

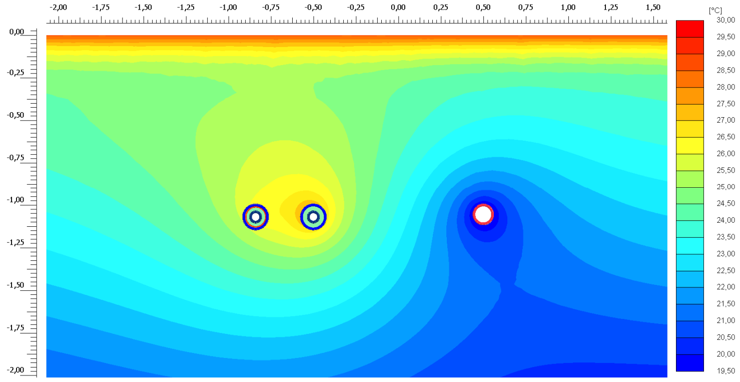


Figure 5.4 Contour of the calculated temperature around the pipes on 1 September 2016 of case B with TMVz climate-soil model (RP-SP-DWP, s = 0.34 m, d = 1 m).

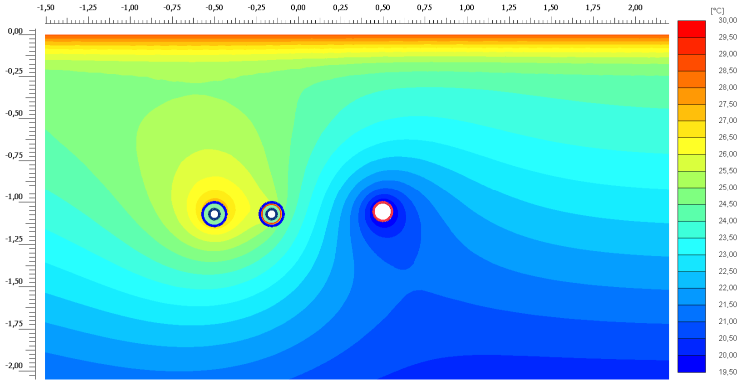


Figure 5.5 Contour of the calculated temperature around the pipes on 1 September 2016 of case B with TMVz climate-soil model (SP-RP-DWP, s = 0.34 m, d = 1 m)

The temperature profile in the horizontal direction through the centre of DWP of both configurations (SP-RP-DWP and RP-SP-DWP) is shown in Figure 5.6.

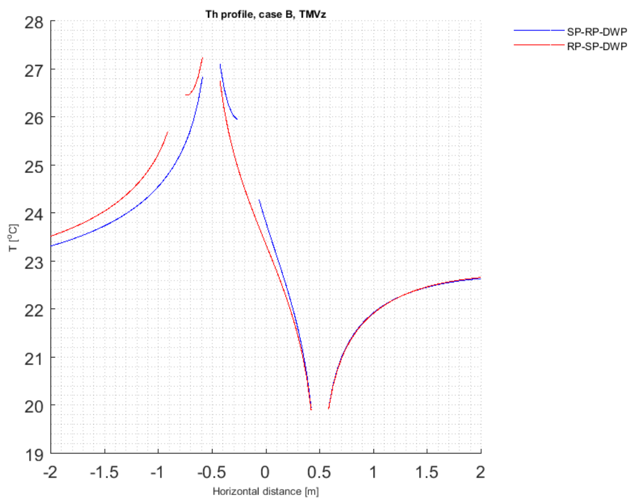


Figure 5.6 Temperature profile in horizontal direction through the centre of DWP.

It is observed in Figure 5.6 that the presence of RP influences the temperature drop between SP and DWP slightly with the current configurations. The temperature between SP and DWP is slightly higher when RP is placed in between SP and DWP than when RP is placed at the left hand side of SP. The temperature distribution around the DWP is not influenced location of RP with the current configurations.

5.1.3 Calculation with electricity casing pipes

The contour of calculated temperatures around the casing pipe of the electricity cables and the drinking water pipe (DWP) with TMVz climate-soil model are presented in Figure 5.7 and 5.8 for two different diameters of drinking water pipes. The centre to centre distance between the casing pipe and the DWP (d) is 1 m. The calculation input data can be found in Table 4.5 and 4.6.

The temperature propagated from the casing pipe is approximately 25ºC when the drinking water temperature is 19ºC (case E1, see Figure 5.7). When the drinking water temperature is 15ºC (case E2, see Figure 5.8) the temperature propagated from the casing pipe reduces to approximately 23ºC. It must be noted however that the drinking water pipe of case E2 has a lager diameter, a thicker pipe wall and greater soil cover. The temperature profile in the horizontal direction through the centre of DWP of both cases is shown in Figure 5.9.

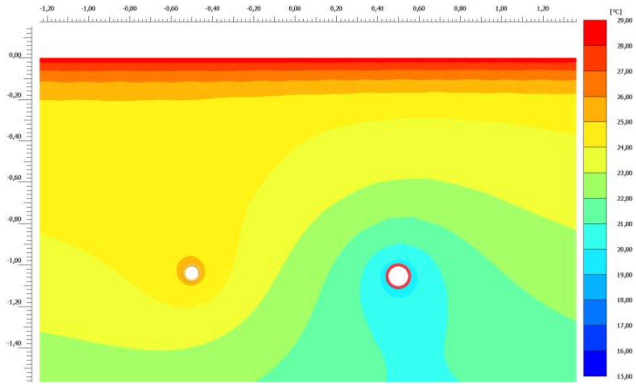


Figure 5.7 Contour of the calculated temperature around the pipes on 1 September 2016 for calculation with the electricity cables (case E1, d = 1 m)

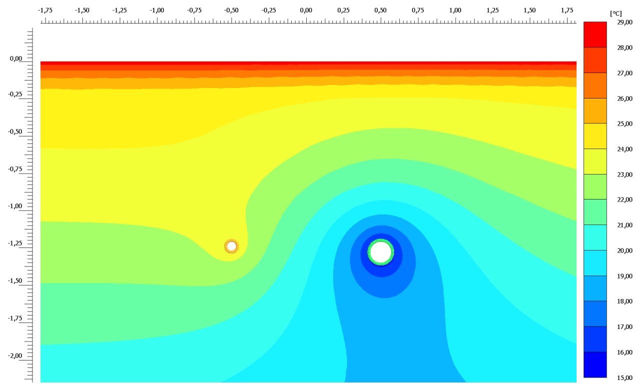


Figure 5.8 Contour of the calculated temperature around the pipes on 1 September 2016 for calculation with the electricity cables (case E2, d = 1 m)

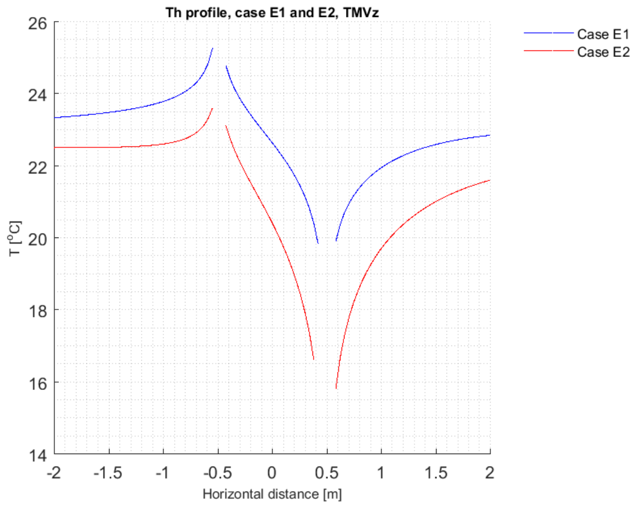
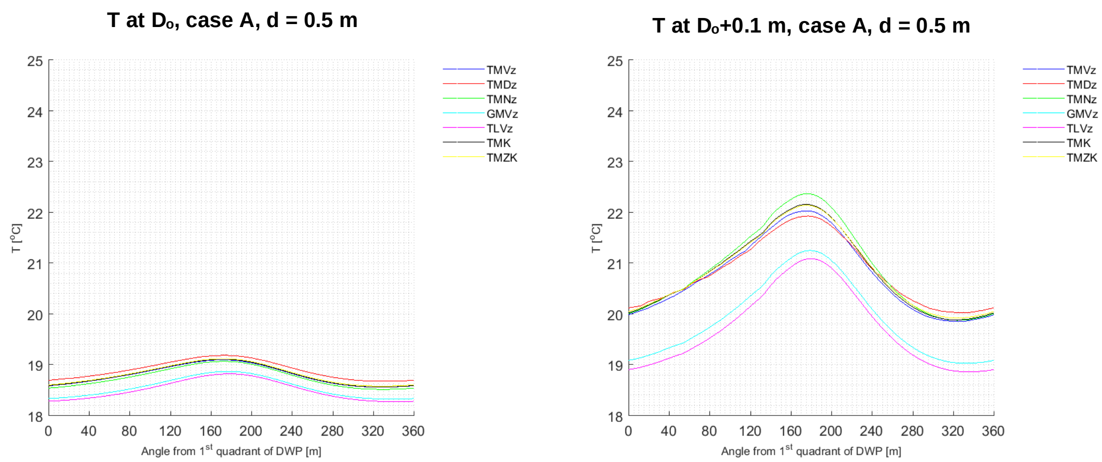


Figure 5.9 Temperature profile in horizontal direction through the centre of DWP (case E1 and E2).

5.2 Calculated temperature around the drinking water pipe on 1 September 2016

The calculated temperature around the drinking water pipe (DWP) on 1 September 2016 for the case with one district supply heating pipe SP (case A) is shown in Figure 5.10 for various distances from the outside diameter of DWP (at D_o, D_o+0.1 m and D_o+0.2 m) and for different climate-soil models. Figure 5.11 shows the influence of the centre to centre distance between SP and DWP (d) on the calculated temperature around DWP.



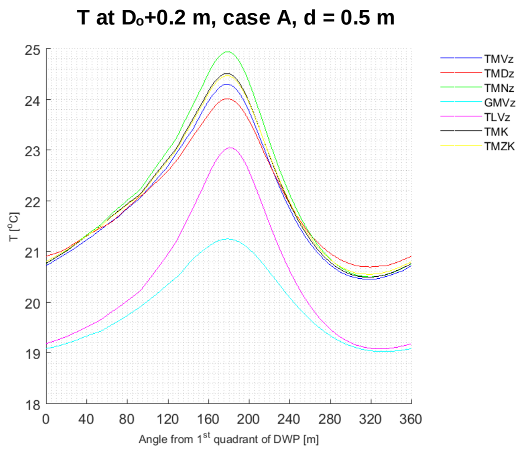


Figure 5.10 Temperature around DWP on various distances from DWP and climate-soil models (case A, d = centre to centre distance between SP and DWP)

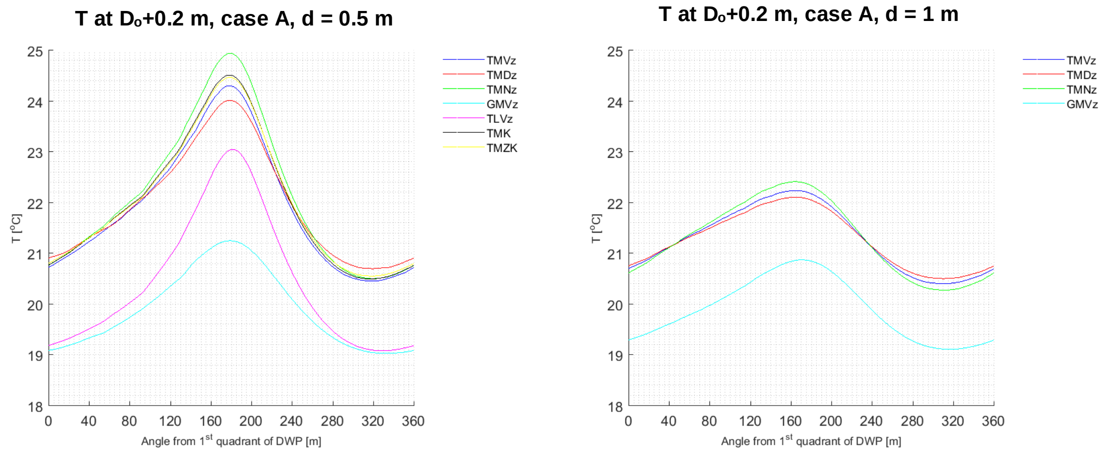


Figure 5.11 Temperature around DWP at distance D_o+0.2 m from DWP (case A, d = 0,5 m and 1 m)

It can be observed from Figure 5.10 that the temperature around drinking water pipe (DWP) at D_o is slightly higher than the drinking water temperature (for this case 18°C). As the distance from DWP becomes greater (at D_o+0.1 m and D_o+0.2 m) the temperature around DWP increases. It can be seen from Figure 5.11 that the temperature around DWP at the same distance from DWP (in this case at D_o+0.2 m) becomes lower as the centre to centre distance d becomes greater (from 0,5 m to 1 m). It can also be observed from Figure 5.10 and 5.11 that the temperature distribution around DWP calculated with TMVz, TMDz, TMNz, TMK and TMZK climate-soil models are comparable. This was also observed in the other cases (B, C, D and E).

Figure 5.12 presents a horizontal cross section through the centre of DWP to visualize the influence of different climate-soil models on the temperature distribution around the pipes. The comparable temperature profiles from the calculation with TMVz, TMDz, TMNz, TMK and TMZK can also be clearly seen in the horizontal cross section. The difference in temperature around the pipe wall of DWP and SP is influenced by the initial soil temperature. TLVz and GMVz have initially colder soil temperature than the other climate-soil models and hence a lower temperature at the pipe wall.

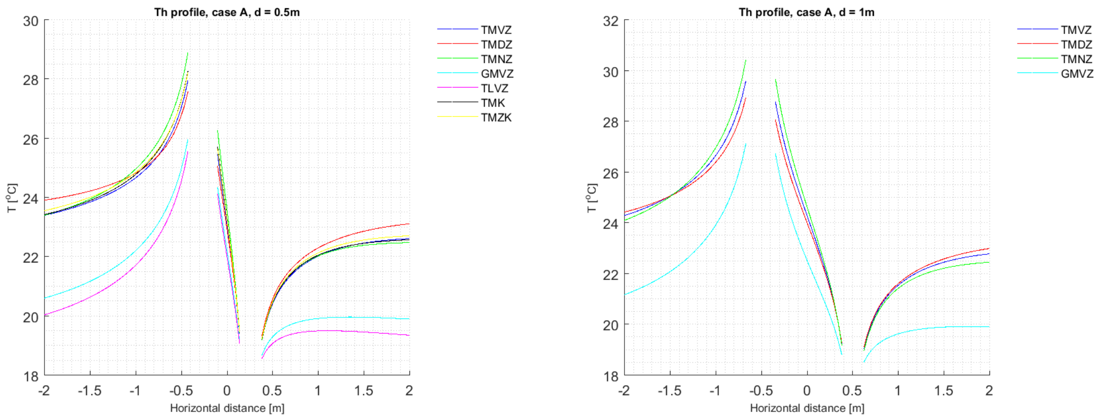


Figure 5.12 *Horizontal temperature profile through the centre of DWP (case A)*

The calculated temperatures around the drinking water pipe on 1 September 2016 for the case with two district heating pipes is shown in Figure 5.13 for different distances from the outside diameter of DWP (at D_o, D_o+0.1 m and D_o+0.2 m) and for TMVz climate-soil model. In this figure case B is presented to see the effect of the different pipe orders (SP-RP-DWP and RP-SP-DWP) and effect of inactive heating pipes (no SP-RP). The centre to centre distance between SP and DWP (d) is 1 m. The centre to centre distance between RP and SP is 0.34 m.

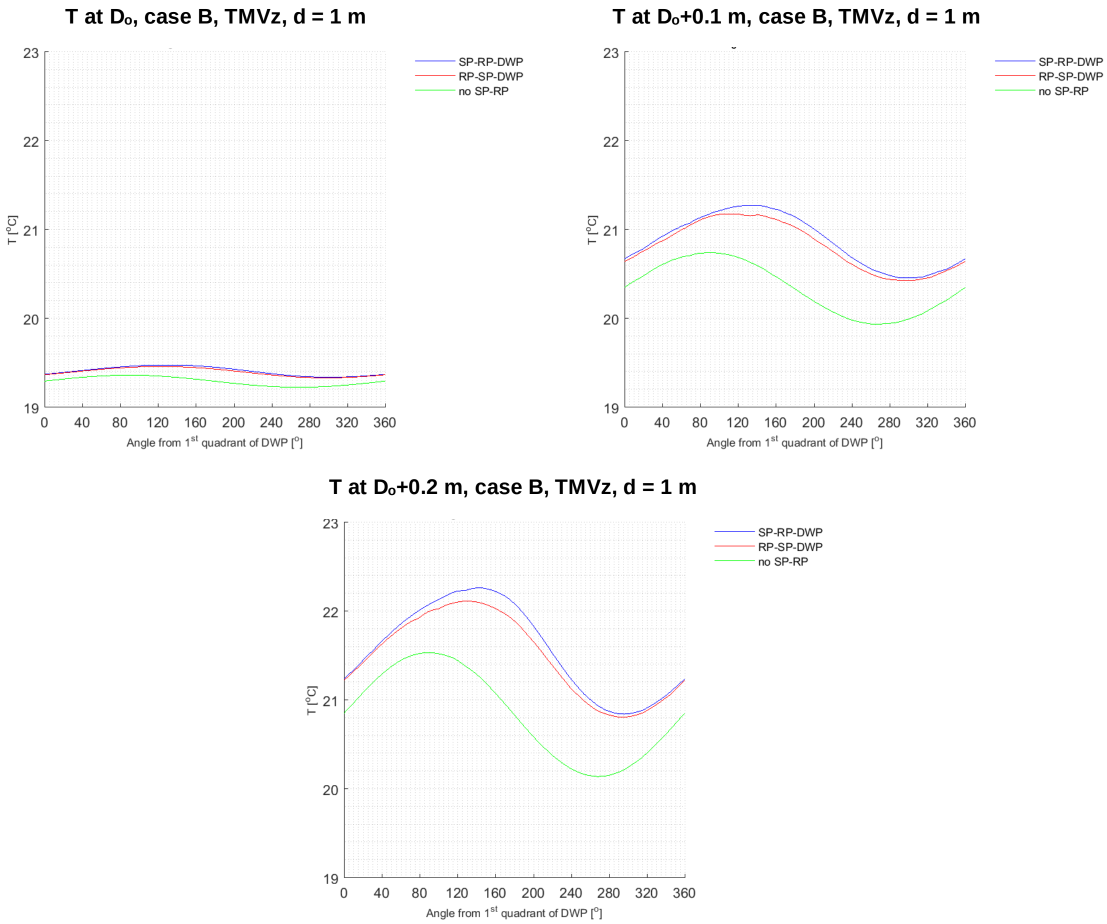


Figure 5.13 *Temperature around DWP on various distances from DWP (case B, TMVz, d = centre to centre distance between SP and DWP)*

It can be observed in the first graph in Figure 5.13 that the temperature around DWP at D_o, with a fixed distance d of 1 m, increases approximately 0.1ºC due to the heating pipes. At D_o+0.1m, it increases approximately 0.5ºC due to the heating pipes. At D_o+0.2m, the temperature around DWP, increases approximately 1ºC due to the heating pipes.

The calculated temperatures around the drinking water pipe (DWP) on 1 September 2016 at D_o and D_o+0.2m for the case with a single casing pipe for electricity cables and different configuration of drinking water pipe (DWP) is presented in Figure 5.14. The centre to centre distance between the casing pipe and the DWP (d) is 1 m.

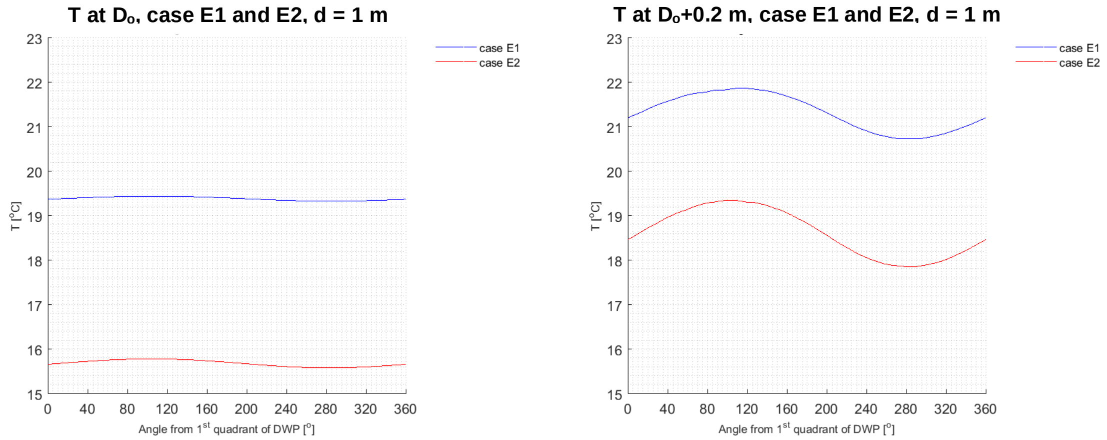


Figure 5.14 Temperature around DWP on various distances from Ro (case E1 and E2, TMVz, d = centre to centre distance between casing pipe and DWP)

The drinking water temperature of case E1 is 19ºC and case E2 15ºC. From the left hand side graph in Figure 5.14 the average temperature around the drinking water pipe (DWP) of case E1 is 19,4ºC. For case E2 this is 15,6ºC. The temperature difference to the drinking water temperature for case E1 and E2 is 0,4ºC and 0,6ºC respectively. Case E2 creates a lager temperature difference than case E1 because case E2 has a lager (diameter) and thicker DWP that case E1. In other words the DWP of case E2 has a lower heat transfer coefficient that of case E1. The same phenomenon can be seen at distance D_o+0,2m from the DWP (see the right hand side graph in Figure 5.14)

In the next section the calculated temperature around DWP is expressed as temperature difference to the temperature of drinking water. With this the influence of external aspects such as climate-soil model, distance between pipes and temperature of drinking water can be related to the change of the temperature.

5.3 Temperature difference (dT) around the drinking water pipe on 1 September 2016

In this section the temperature difference around the drinking water pipe is related to other variables such as climate-soil model, temperature of drinking water, pipe distances (normalized with pipe diameter and distance to DWP). The temperature difference is calculated as follows: the calculated temperature around DWP subtracted with the drinking water temperature.

5.3.1 Effect of climate-soil models on dT

The effect of climate-soil models on temperature difference (dT) around the drinking water pipe (DWP) of the case with one supply heating pipe (SP) or case A is presented in Figure 5.15. In

Figure 5.15 maximum, minimum and average temperature differences are given for various distances from drinking water pipe (DWP) and various distances between SP and DWP (d).

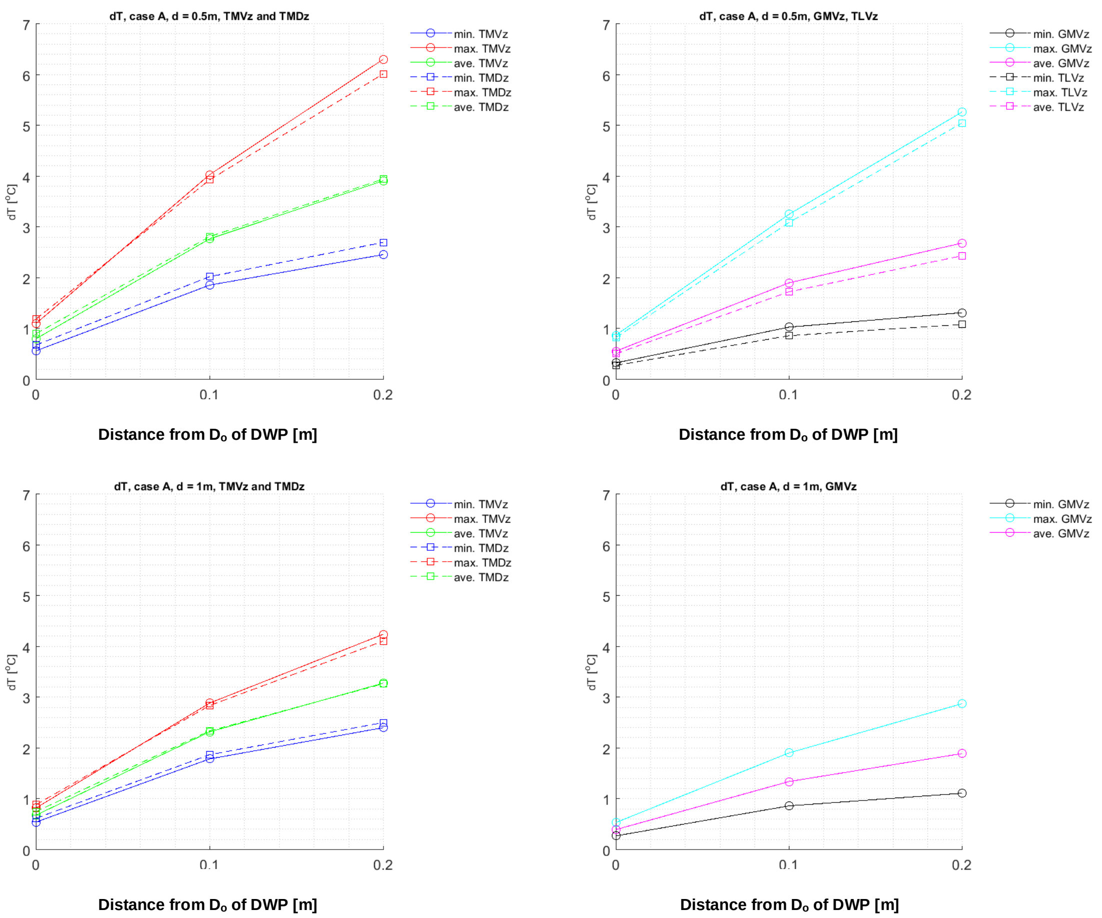


Figure 5.15 Effect of climate-soil models on temperature difference based on case A.

The average temperature differences shown in Figure 5.15 lay approximately in the middle between the maximum and minimum temperature differences up to distance D_o+0.2 m from DWP. This was also observed in the other cases (B, C, D, and E). The temperature difference from climate-soil model TMVz and TMDz are comparable which is also indicated previously in Figure 5.10 and 5.11.

5.3.2 Effect of order of heating pipes on dT

The effect of the order of heating pipes on temperature difference (dT) can be seen in the calculation for case B. The average temperature difference of case B with various climate-soil models (TMVz, TMDz and GMVz), order of pipes (SP-RP-DWP and RP-SP-DWP) and distance between SP and DWP (d) is presented in Figure 5.16. The centre to centre distance between RP and SP is kept constant of 0.34 m.

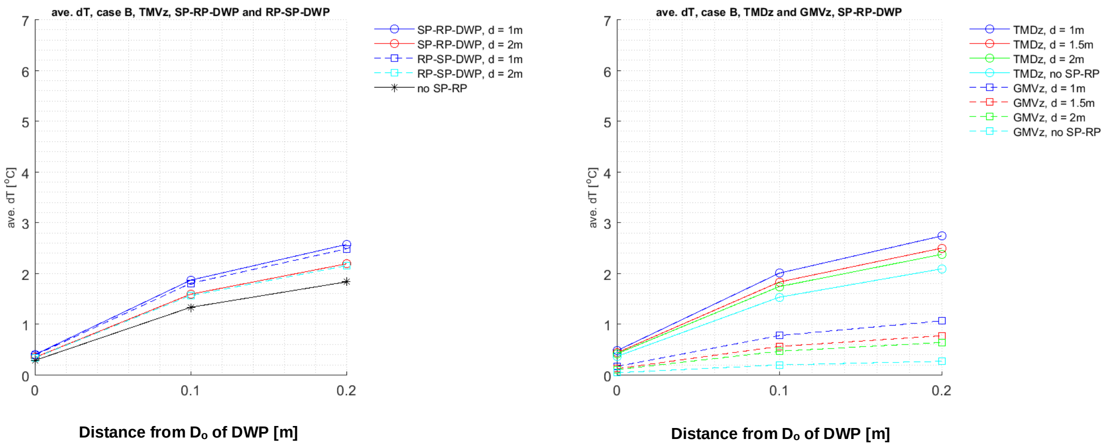


Figure 5.16 Effect of order of heating pipes on temperature difference based on case B.

It can be observed from the first (left side) graph of Figure 5.16 that the order of pipes, in this case, does not influence the average temperature difference significantly. As the distance d becomes greater, the average temperature difference becomes closer to the situation without heating pipes (no SP-RP).

From the left hand side graph of Figure 5.16, it can be observed at D_o+0.2m that when SP and RP are inactive (no SP-RP) the average temperature difference is approximately 1.8ºC. The average temperature difference when the distance between SP and DWP (d) 1 m and 2 m is 2.6ºC and 2.2ºC respectively. Using linear extrapolation on these data the distance needed between SP and DWP in which the influence of SP to DWP can be neglected is 3 m for both pipe orders (SP-RP-DWP and RP-SP-DWP) and the current configurations. This is approximately 27 times the outside diameter of DWP for case B. The same conclusion can be derived using the right hand side graph of Figure 5.16. This should be validated further with field measurement.

5.3.3 Effect of soil cover and temperature of supply pipe on dT

To see the influence of soil cover and temperature of supply pipe (SP) on average temperature difference around drinking water pipe (DWP), the calculation with two district heating pipes of the primary network (case C) with different climate-soil model (TMVz and GMVz), soil cover (h), heating pipe temperature, and distance between SP and DWP (d) is presented in Figure 5.17. The pipe order of case C is SP-RP-DWP. The centre to centre distance between return pipe (RP) and SP is kept constant of 0.5 m.

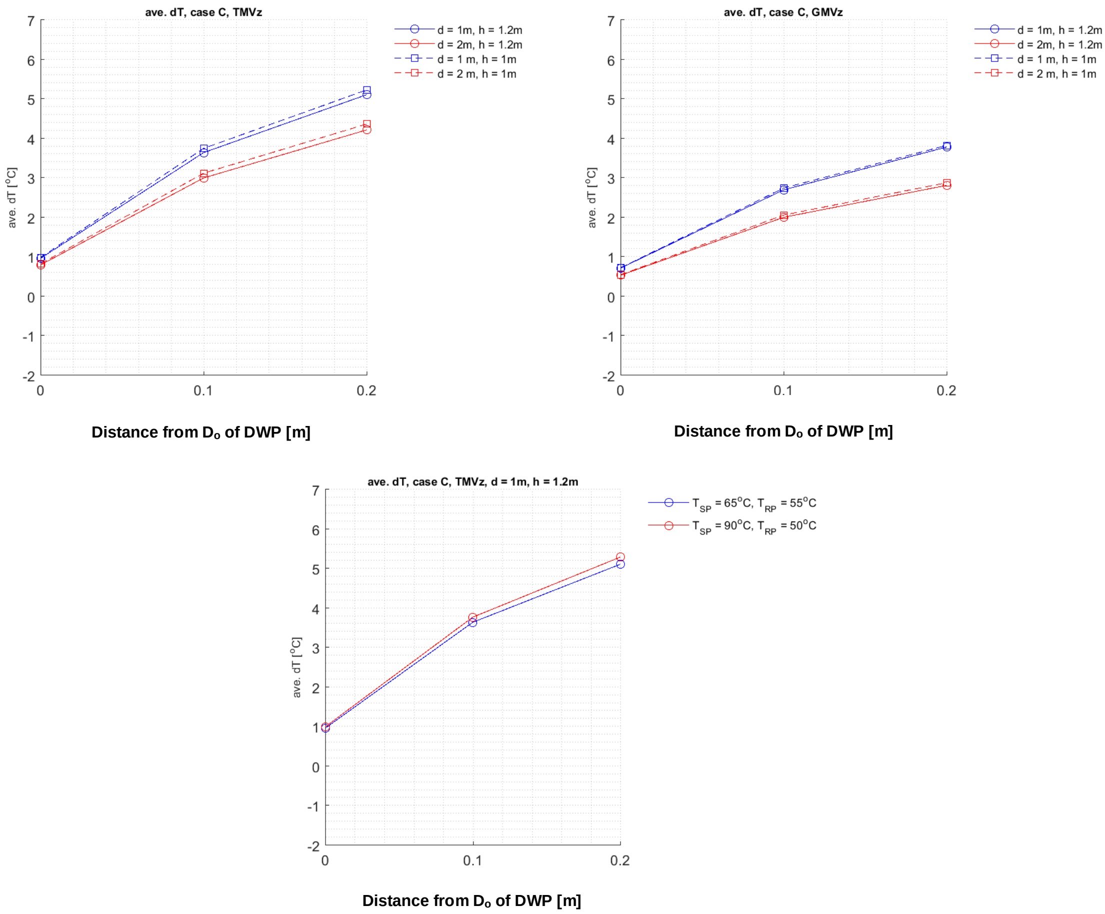


Figure 5.17 *Effect of soil cover and temperature of supply pipe on temperature difference based on case C.*

It can be observed in first two graphs of Figure 5.17 that the influence of soil cover from 1m to 1.2 m is small. The average temperature difference with the soil cover of 1 m is slightly higher than that with the soil cover of 1,2m. This can be expected since the calculations were derived from the same outside diameter of DWP (160 mm, see Table 4.4) and the same drinking water temperature (15°C, see Table 4.4).

From the third graph of Figure 5.17 it can be seen that the increase of temperature of supply pipe (SP) from 65°C to 90°C does not influence the average temperature difference significantly. The return pipe (RP) which is located between SP and DWP blocks the heat transfer from the “hot” supply pipe. This can be more clearly seen in a horizontal temperature cross section of the same case (see Figure 5.18).

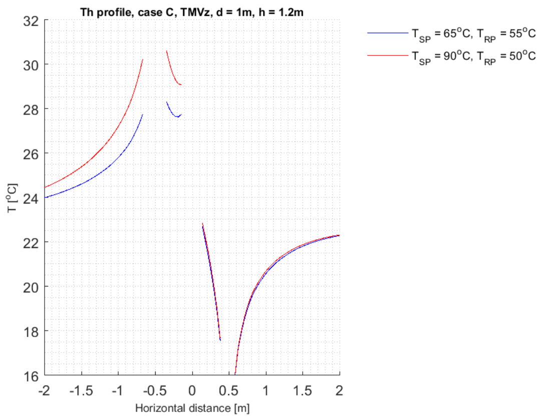


Figure 5.18 Horizontal temperature profile through the centre of DWP (case C)

The small effect of soil cover on the average temperature difference as described in case C is not valid when the drinking water temperature differs. It can be seen by comparing case E1 and E2 (see Figure 5.19). Case E1 has soil cover of 1 m and case E2 has soil cover of 1,2m. However the drinking water temperature for case E1 is 19ºC and for case E2 is 15ºC. The drinking water pipe (DWP) material of both cases is PVC.

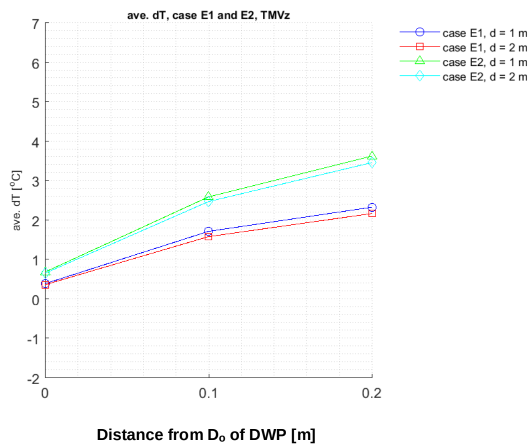


Figure 5.19 Effect of soil cover on temperature difference based on case E1 and E2.

It can be observed from Figure 5.19 that the average temperature difference of case E2 (with soil cover 1.2 m) is approximately 1ºC higher than case E1 at D_o+0.1m and approximately 1.5ºC higher than case E1 at D_o+0.2m. The difference drinking water temperature contributes mainly to the difference in average temperature difference.

5.3.4 Effect of drinking water pipe material on dT

The effect of drinking water pipe (DWP) material and wall thickness on temperature difference (dT) can be referred to case D (DW tertiary). The DWP material, diameter and wall thickness determine the heat transfer coefficient of the pipe wall of DWP which influences the temperature drop through the pipe wall of DWP. For case D, two materials were taken into account: PVC and DI (lines ductile iron with cement). The influence of the pipe material and wall thickness on the average temperature difference of case D is shown in Figure 5.20. The pipe order of case D is SP-RP-DWP. The centre to centre distance between return pipe (RP) and SP is kept constant of 0.34 m.

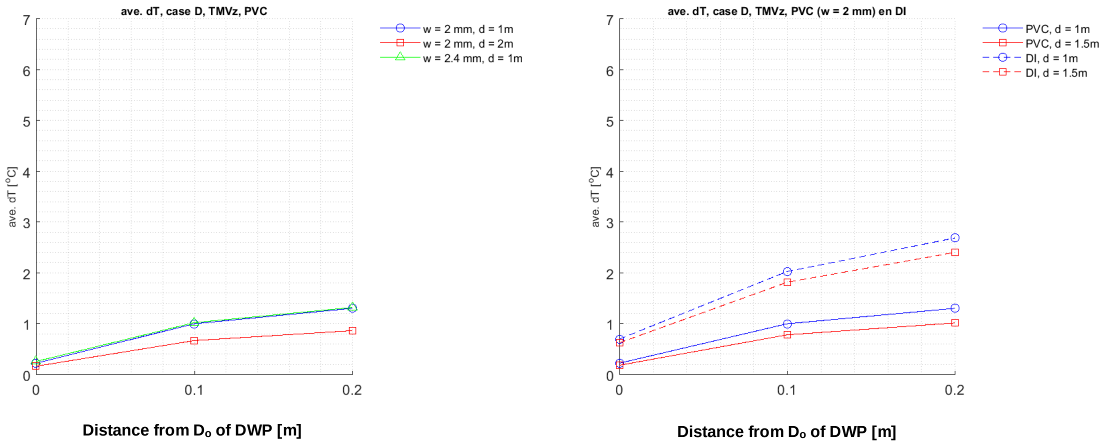


Figure 5.20 Effect of pipe material and wall thickness of DWP on temperature difference base on case D.

On the left hand side graph of Figure 5.20, the average temperature difference is calculated for DWP of PVC material with a wall thickness of 2 mm and 2.4 mm and for different centre to centre distance between SP and DWP (d). Due to small difference in wall thickness the average temperature difference around DWP is almost the same for the case with 2 mm and 2.4 mm thick of DWP. On the right hand side graph of Figure 5.20 the average temperature difference of around DWP of DI (line ductile iron with cement) and PVC materials is presented. With DI as DWP material, it can be observed that the average temperature difference at D_o of DWP jumps to 0.8ºC (see the right hand side graph of Figure 5.18). The reason for this is that DI material has lower heat transfer coefficient than PVC and allows less heat transfer through the DWP wall, hence greater average temperature difference. The cement part of DI has low heat conductivity and contributes to a lower heat transfer coefficient of DI DWP.

5.3.5 Effect of drinking water temperature on dT

The influence of drinking water temperature on different cases (A to E) is discussed below.

The influence of drinking water temperature on the temperature difference of the case with one supply heating pipe (case A) at distance D_o of DWP is shown in left hand side graph of Figure 6.21. The centre to centre distance between supply pipe and DWP (d) is 0.5 m. It can be observed that the maximum, minimum and average temperature differences decrease linearly and with the decrease of drinking water temperature. The reduction of temperature difference is approximately 0.5ºC (very small) for the range of drinking water temperature between 18ºC and 25ºC. This is expected since these are the temperature difference at D_o of DWP is small.

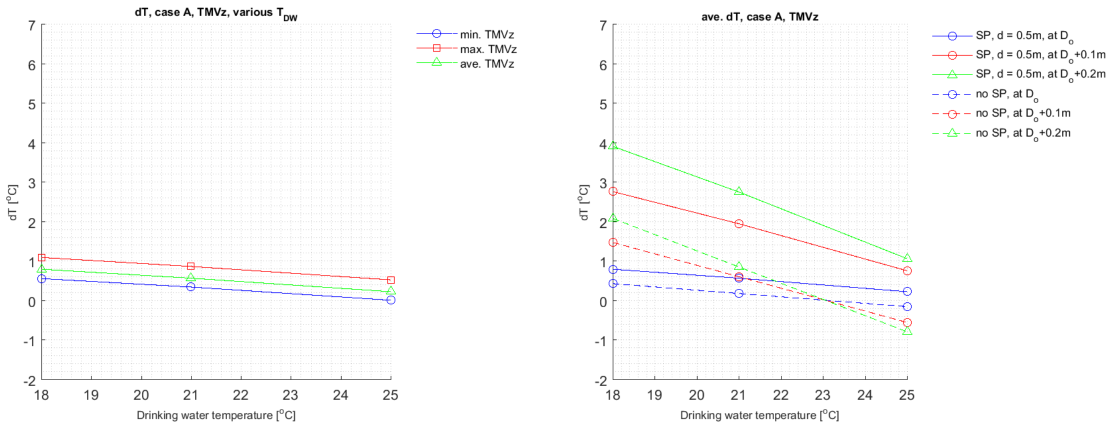


Figure 5.21 Influence of drinking water temperature (T_{DW}) on temperature difference based on case A.

On the right hand side graph of Figure 6.21, the influence of drinking water temperature on the average temperature difference for various distances from DWP (D_o, D_o+0.1m and D_o+0.2m) is shown. It can be observed that a linear reduce of average temperature also occurs. For the case with an inactive supply pipe (no SP) the average temperature difference for the drinking water temperature above 23°C becomes negative. It indicates that the drinking water temperature is higher that the soil temperature. In that case DWP becomes a heat source to the surrounding. In case SP is active, the drinking water temperature to cause a negative temperature difference is higher than 25°C.

The reduction of temperature difference with the increase of drinking water temperature of case with the casing pipe of electricity cables (case E1) for various distances from DWP (D_o, D_o+0.1m and D_o+0.2m) is presented in Figure 5.22. The drinking water temperature to cause a negative temperature difference is approximately 24°C.

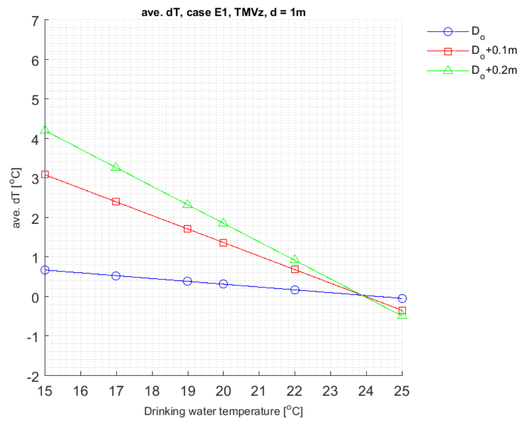


Figure 5.22 Influence of drinking water temperature on temperature difference based on case E1.

From the case with two heating pipes of case B (base calculation), the influence of drinking water temperature on the average temperature difference at distance D_o+0.2m from DWP for different pipe order (SP-RP-DWP and RP-SP-DWP) is shown in Figure 5.23. It can be observed that the average temperature difference also decreases as drinking water temperature increases. The pipe order does not significantly influence the change of average temperature difference with the change of drinking water temperature. The average temperature difference becomes negative when the drinking water temperature is approximately 25°C for the distance d 1 m. This is lower than that of case A (see Figure 5.21). The reason for this is the distance between the nearest heating pipe and DWP. The distance d of Case A presented Figure 5.21 is 1 m. When this distance d becomes smaller, the drinking water temperature required for DWP to act as heat source will be higher since the soil is warmer. When the distance between nearest heating pipe and DWP becomes larger, the drinking water temperature required for DWP to act as heat source will be lower since the soil is cooler.

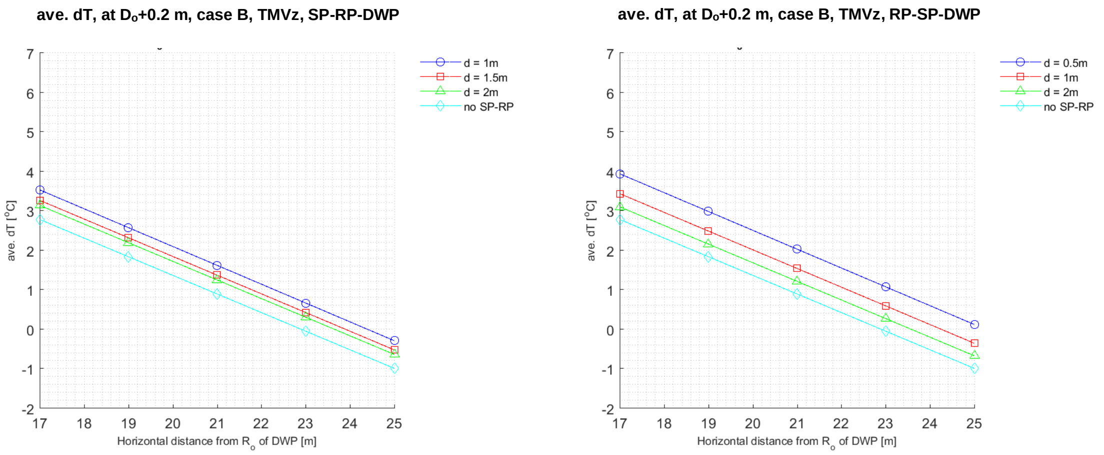


Figure 5.23 Influence of drinking water temperature on temperature difference based on case B (centre to centre distance between SP and RP is 0.34 m).

5.3.6 Effect of normalized pipe distance on dT

In this section the temperature difference is related to the normalized distance. The normalized pipe distance is calculated as the distance from outside diameter of DWP divided by the net distance between nearest heating pipe (SP or RP) and DWP. With this the diameter of the nearest heating pipe and the diameter of DWP are taken into account in normalized pipe distance.

The relation between the average temperature difference and the normalized distance on various scenarios of case A can be seen in Figure 5.24. It can be observed that the average temperature difference increases with the increase of normalized distance. The temperature difference for TMVz, TMDz, TMNz, TMK and TMZK climate-soil models at normalized distance 0.8 is approximately 4°C. For GMVz and TLVz climate-soil models this is approximately 2.5°C. The average temperature with climate-soil model GMVz and TLVz increases more gently than the other scenarios with the normalized distance because the soil temperature is of these climate-soil models are cooler.

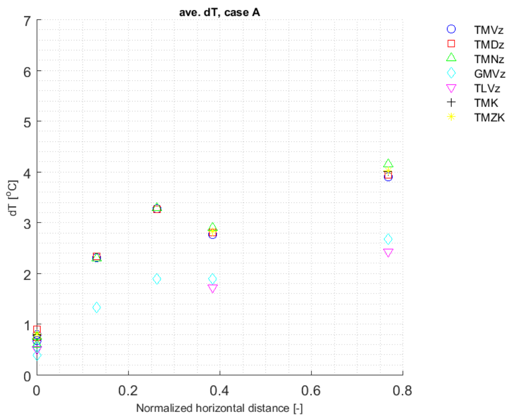


Figure 5.24 Temperature difference as function of normalized distance based on case A.

The relation between the average temperature difference and the normalized distance on various scenarios of case B can be seen in Figure 5.25. The average temperature difference for TMVz, TMDz and TMNz climate-soil models at normalized distance 0.38 is approximately 2.5^{o}C. For GMVz this is approximately 1^{o}C at normalized distance 0.38. Both values can be reasonably estimated with the graph of case A (Figure 5.24). Using the graph for case A (Figure 5.24), the temperature difference at normalized distance 0.38 for TMVz, TMDz and TMNz climate-soil models is approximately 2.9^{o}C. For GMVz this is approximately 1.9^{o}C at normalized distance 0.38.

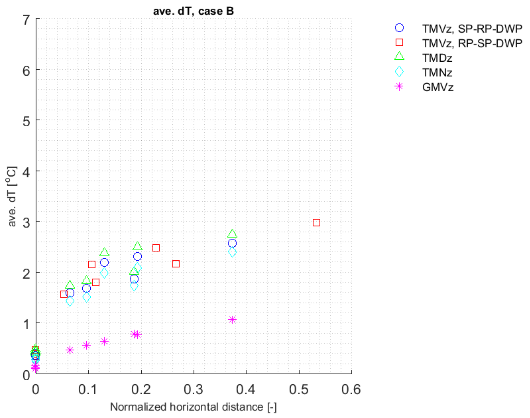


Figure 5.25 Temperature difference as function of normalized distance based on case B.

For case C and D, the relation between the average temperature difference and the normalized distance is shown in Figure 5.26. The increase of temperature difference with normalized distance of case C (see the left hand side graph of Figure 5.26) is steeper than that of case A (Figure 5.24). The reason for this is that case C was calculated with drinking water temperature of 15^{o}C. This is lower that case A which is 18^{o}C and allows a greater temperature gradient between heating pipe and DWP, hence greater temperature difference. The increase of temperature with the increase of normalized distance of case D (see the right hand side graph of Figure 5.26) is similar to case B (Figure 5.25).

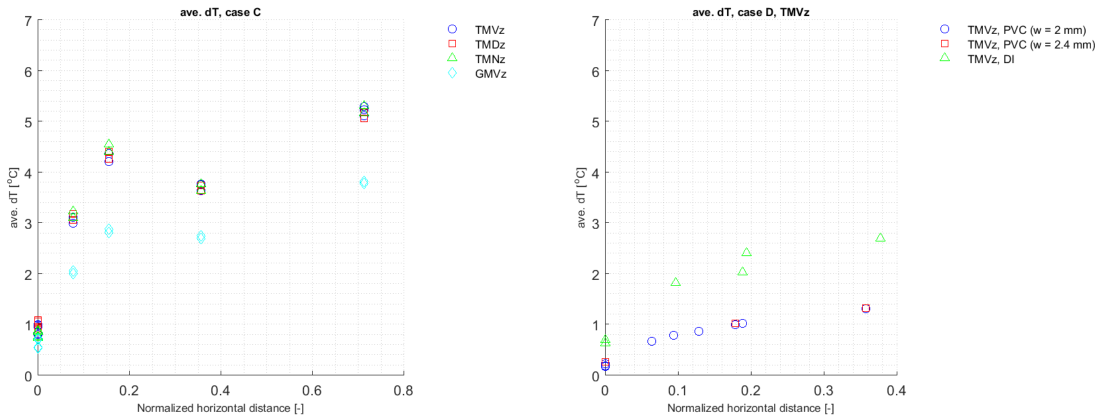


Figure 5.26 Temperature difference as function of normalized distance based on case C (left) and case D (right).

For case E1 and E2 (the cases with the casing pipe of electricity cables) the relation between the average temperature difference and the normalized distance is shown in Figure 5.27. The average temperature difference also increases with the increase of normalized distance like the other cases. The average temperature difference for case E2 is higher than that of case E1. The main reason for is that the drinking water pipe (DWP) of case E2 has a higher heat transfer coefficient than case E1 (greater diameter and thicker pipe wall).

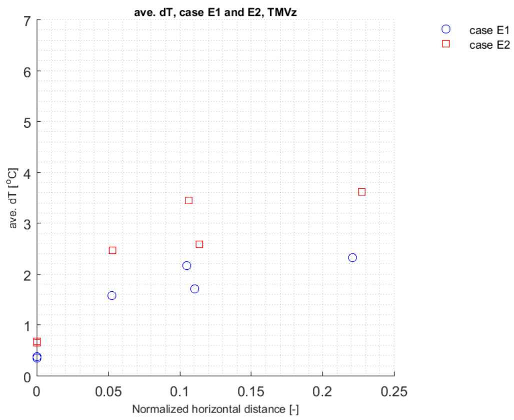


Figure 5.27 Temperature difference as function of normalized distance based on case E1 and E2.

5.4 Temperature difference (dT) of different time steps

The average temperature difference on various distances from drinking water pipe (DWP) at D_o, D_o+0.1 m and D_o+0.2 m for the period of 26 August 2016 to 1 September 2016 is shown in Figure 5.28. In Figure 5.28 case A with TMVz climate-soil model is presented.

It can be observed from Figure 5.28, that the temperature difference on 1 September is reasonably equal to the average temperature differences between 26 August 2016 and 1 September 2016. For this reason, the discussion above (section 5.3) has been focused on the calculated temperature on 1 September 2016. For the implementation of Wanda Heat, the temperature on 1 September 2016 can be used to get a quick impression of the increase of drink water temperature in DWP.

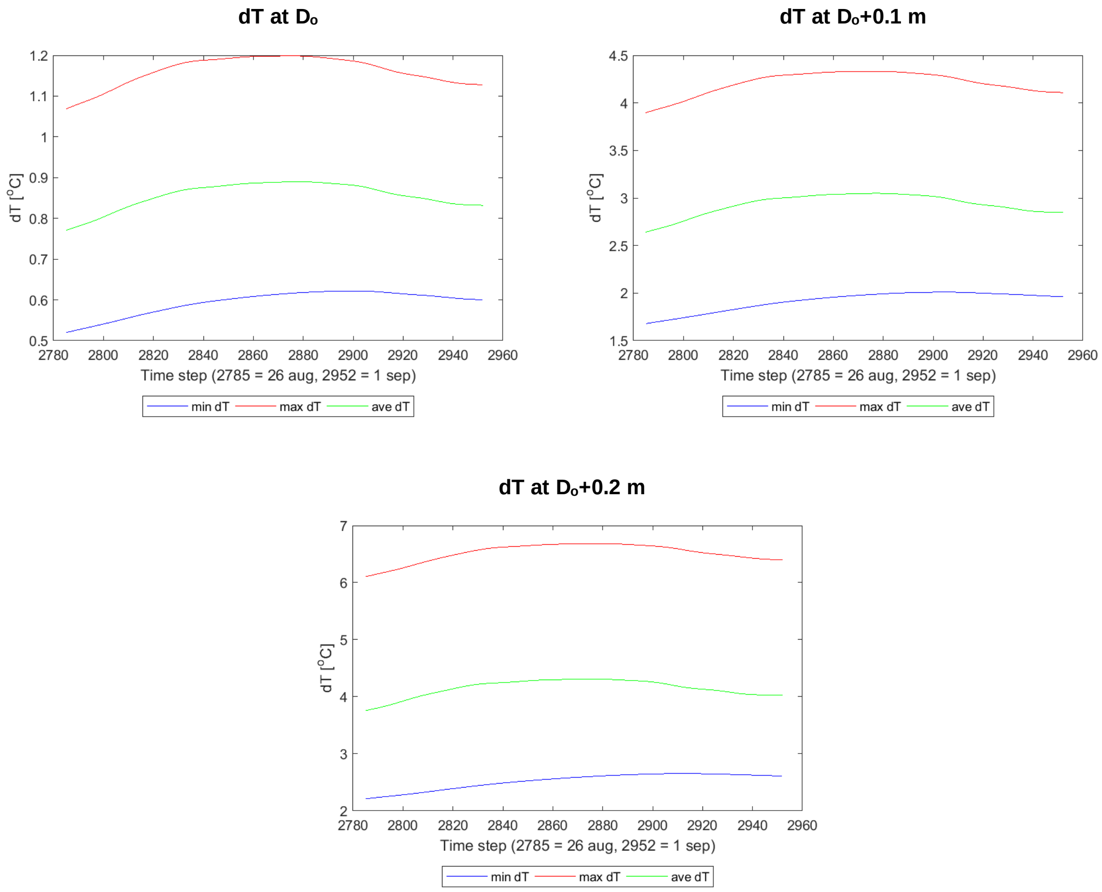


Figure 5.28 *Temperature difference of different time step and various distances from DWP (case A, TMVz)*

6 Conclusion

The calculated temperature between the heating pipes and the drinking water pipe are influenced by the temperature difference between the heating pipes and the drinking water pipe and the initial soil temperature. This is valid for both district heating pipes and electricity cables. The difference between the drinking water temperature and the temperature on the outer surface of the drinking water pipe varies between 0.5°C to 2°C depending on the heat transfer coefficient of the pipe wall. The higher the heat transfer coefficient the more easily heat is transferred through the pipe wall, causing a smaller temperature difference between both sides of the pipe wall.

The casing of the electricity cables, given the heat loss as indicated in Table 4.5, a lower temperature around the casing pipe than that of the district heating pipe. In the calculation it was observed that the temperature around the casing pipe of the electricity cables was between 23°C and 25°C, compared to that of the casing of the district heating pipe (between 26°C and 30°C).

The findings throughout the calculations are summarized below:

Effect of different base scenarios:
The heat transfer through the soil is influence by the volumetric heat capacity (*Cρ*) and the heat conductivity (λ). The greatest temperature gradient between the heating pipe and the drinking water pipe was observed in the soil with the lowest heat conductivity. It is observed in Figure 6.12 for TMNz case (green line). Among the cases with Vz (TMVz, GMVz and TLVz), the greatest temperature gradient was observed in TMVz. The combination of the soil cover and medium urbanity produces the greatest temperature gradient between the heating pipe and the drinking water pipe

Effect of return heating pipe:
For the case with two heating pipes with given configurations in case B, the temperature gradient between the supply heating pipe and the drinking water pipe will be limitedly influenced by the location and temperature of the return heating pipe.

Effect of sand or clay soil to the temperature around the drinking water pipe:
Based on given thermal properties, clay (K) allows in general more heat transfer than moist sand (Nz). There the temperature gradient between the heating pipe and the drinking water pipe in clay is lower than in moist sand.

With or without heating pipe:
The maximum temperature around the drinking water pipe shifts from quadrant I at 90^o to the quadrant II at approximately 160^o when the heating pipe is taken into account. This shows an effect of combined “loading” from heating pipe and soil surface. When the heating pipe is not present, the maximum temperature around the drinking water pipe will only be influenced by the temperature of the soil surface. The maximum temperature in that case is located on the top side of the drinking water pipe.

Effect of the drinking water temperature:
As the drinking water temperature goes up, the temperature difference between the soil and the drinking water pipe becomes smaller. So cooling due to drinking water pipe will decrease and even heating may occur. The decrease rate of temperature difference for every 1^{o}C increase of drinking water temperature is approximately 0.4^{o}C to 0.5^{o}C.

Effect of the distance between the heating pipe and the drinking water pipe:
As the drinking water pipe moves away from the heating pipe(s) the temperature around the drinking water pipe will be lower and will be more influenced by the ground surface temperature. From case B it can be estimated that the effect of heating pipe can be neglected if the distance to drinking water pipe 27 times outside diameter of drinking water pipe. This should be validated further with the field measurement.

Effect of the diameter, wall thickness and material of the drink water pipe:
Larger diameter of drinking water pipe (DWP), thicker pipe wall and material with lower heat conductivity generates higher temperature gradient at the pipe wall than the DWP with smaller diameter, thinner pipe wall and material of higher heat conductivity. This can be seen in case B and case D (with TMVz scenario, d = 1m and pipe order SP-RP-DWP) as shown in Figure 6.1. The outside diameter of DWP for cases B and D is 110 mm and 121.6 mm respectively. The pipe wall of DWP of case D is thicker than that of case B and the DWP material of case D (DI,

lined ductile iron with cement) has a lower heat conductivity that that of case B (PVC). This results in a DWP with a lower heat transfer coefficient for case D and for case B. With this a higher temperature gradient through the pipe wall of DWP of case D will be generated causing a higher temperature difference around the drinking water pipe.

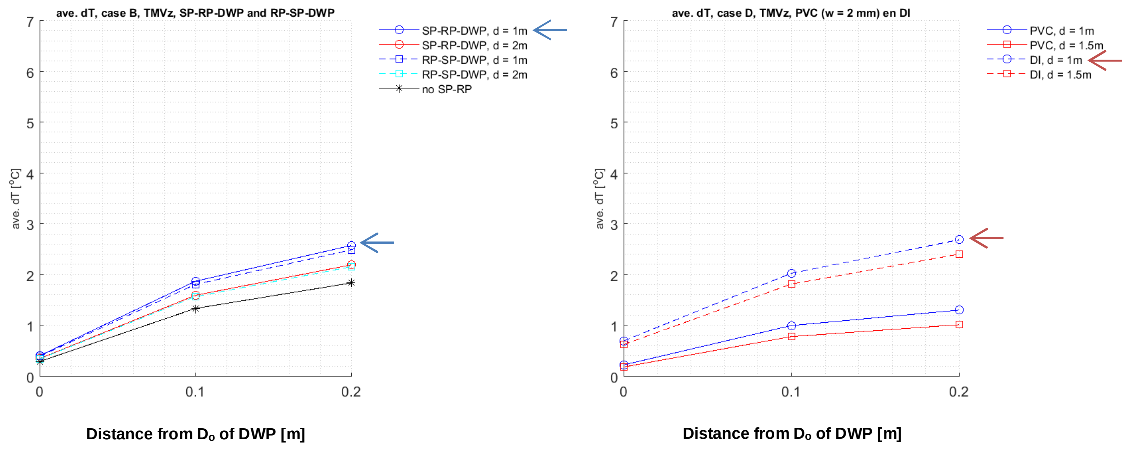


Figure 6.1 Comparison in temperature difference between case B (blue arrow shows the calculation of PVC DWP with D_o of 110 mm) and case D (red arrow shows the calculation of DI DWP with D_o of 160 mm).

Effect of the soil cover:
The greater the soil cover, the lower the temperature around the drink water pipe. The temperature difference from the calculation with soil cover between 1 m and 1.2 m is around 0.5°C to 1.5°C.

Consequence of assuming drinking water pipe as cold source:
It is not ideal to assume drinking water pipe as cold source. The temperature of drinking water pipe is influenced by the soil temperature, energy loss during transport (due to friction with pipe wall). In the current analysis, the temperature of drinking water has been kept constant in the calculation and acts as a cold source. Using the result of the current analysis to calculate the heat flux flowing through the drinking water pipe wall for a period of time will simplify the problem and may overestimate the increase of drinking water temperature.

7 References

[1] Email dated 28th of March 2018 from Claudia Agudelo-Vera (KWR) regarding the description of the base scenarios and the list of outer diameter and material for the drink water pipe.
[2] Email dated 25th of April 2018 from Jan Bozelie (Alliander) regarding the list of selected electricity cables with the amount heat released from the pipe casing.
[3] Email dated 16th of March 2018 from Marco den Burger (Rotterdam Engineering) regarding the list of district heating pipes.
[4] Email dated 17th of April 2018 from Mirjam Blokker (KWR) regarding the list of new 2D calculation scenarios.
[5] https://www.bouwenmetstaal.nl/themas/bouwfysica/warmteaccumulatie/

[6] Email dated 15th of March 2018 from Sam v.d. Zwan (Deltares) regarding the specific heat capacity of PUR.
[7] https://www.engineersedge.com/materials/specific_heat_capacity_of_metals_13259.html
[8] https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html
[9] https://www.engineeringtoolbox.com/thermal-conductivity-plastics-d_1786.html
[10] http://www.pvc.org/en/p/specific-gravity-density
[11]http://www.vbv.nl/download/pdf/technische_specificaties/Eigenschappen%20kunststoffen.pdf
[12] Email dated 1st of June 2018 from Jan Bozelie (Alliander) regarding the list of casing pipe diameters of electricity cables.
[13] https://www.fxsolver.com/browse/formulas/Heat+transfer+coefficient+of+pipe+wall

Copy for
dr. ir. Gert Greeuw;DELTARES, dr. ir. Ivo Pothof;DELTARES, ir. Sam van der Zwan;Deltares, dr. ir. John van Esch, dr. ir. Mirjam Blokker;KWR, dr. ir. Claudia Agudelo-Vera.

Appendix A: Determining minimum distance between the heating pipe and the model boundaries

Background

Before running different 2-dimensional heat transfer calculations, the sensitivity on the model sizes of the 2-dimensional finite element heat transfer calculations in Plaxis thermal needs to be verified. The sensitivity study mainly focused on the steady state heat transfer analysis rather than the transient analysis since the steady state analyse results in a larger influence area that the transient analysis.

Inventory of the input data

The list of input data for the sensitivity study is given in Table A.1. For the maximum heat transport, the largest district heating pipe from the calculation scenarios was selected. For the case with electricity cables, the temperature generated from the given heat loss is lower that the temperature propagated from the PE casing pipe of district heating pipe.

Table A.1. Inventory of the input data

Parameters/objects	Expected maximum value	Motivation
Temperature (in ^{o}C)	100^{o}C (for district heating pipe)	The maximum temperature in the district heating pipes (supply and return pipes) varies from 50^{o} to 100^{o}C [4].
Soil cover for the heating pipes and drink water pipe	1 m below the soil surface	The expected soil cover is between 1 to 2 m. For the sensitivity analysis 1 m is taken into account for the maximum influence of both heat sources (surface and heating pipe) to the soil.
Outer casing pipe diameter of the heating pipe	0.355 m	Based on [3] the outer diameter of casing pipe for district heating pipes is between 0.225 to 0.355 m. For the maximum heat transfer the largest diameter from the calculation scenarios was selected (0.355 m).
Thermal parameters of the insulation material	PE casing pipe with PUR (district heating pipe)	Based on [3]. The thermal parameters of PE casing pipe and PUR insulation are fixed values.
Temperature from the soil surface	$\pm$20^{o}C	A soil surface temperature of 20^{o}C of the base

		scenarios* is chosen to be included in the steady state calculation. This is the surface temperature from the last week of April 2016 first week of May 2016. Only TLVZ and TMVz are considered since these give the lower and upper bounds of soil temperature (see Figure A.1). This is considered as adequate start temperature for the transient heat transfer calculation.
Thermal properties of the soil	Heat conductivity (λ) 1.4 W/m/K. Volumetric heat capacity (Cρ) 1.2 x 10^6 J/m^3/K	From the climate-soil models*, the thermal conductivity ranges from 1.2 to 1.4 W/m/K and the volumetric heat capacity from 1.2 x 10^6 to 2.2 x 10^6 J/m^3/K. For the maximum heat transfer the lowest volumetric heat transfer (1.2 x 10^6 J/m^3/K) and the largest heat conductivity (1.4 W/m/K) are taken into account.

*GMVz, TLVz, TMDz, TMK, TMNz, TMVz en TMZK.

The casing of the heating pipe consists of different materials, thermal properties these materials are given in Table A.2.

Table A.2 Thermal properties of district heating pipe

Material	Thermal properties
Steel	C = 460.5 J/kg/K [7], λ = 28.5 W/m/K [8], ρ = 7850 kg/m^3
PE	C = 1880 J/kg/K [11], λ = 0.47 W/m/K [11], ρ = 950 kg/m^3 [11]
PUR	C = 1470 J/kg/K [6], λ = 0.024 W/m/K [5], ρ = 90 kg/m^3 [5]

The temperature vs. depth profile when the surface temperature is approximately 20^{o}C of each climate-soil model (GMVz, TLVz, TMDz, TMK, TMNz, TMVz en TMZK) is given in Figure A.1. These temperature profiles were calculated using 1-D Calorics. The lower and upper bounds of the temperature profiles are observed at TLVZ and TMVz models.

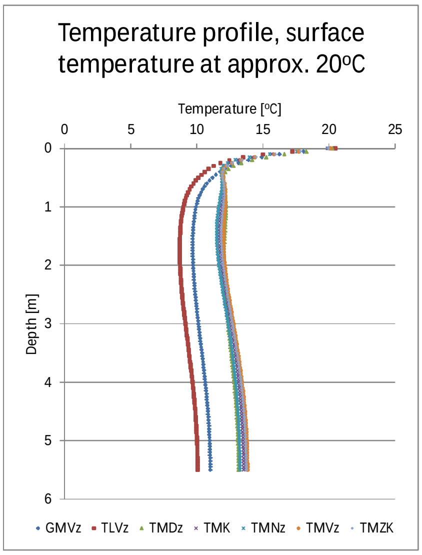


Figure A.1. Temperature profile (with depth) when the surface temperature reaches 20°C (average from all 7 climate-soil models), average temperature in the soil is 12°C

Finite element model for the sensitivity analyses
Figure A.2 shows the finite element model for the sensitivity analyses. Only half of the heating supply pipe is modelled. The minimum horizontal distance between the centre of the supply heating pipe and the left vertical boundary (B) and the minimum vertical distance between the centre of the supply pipe and the bottom boundary (z) were to be defined by increasing the model size gradually while conducting the steady state heat transfer analysis. Only two climate-soil models (TLVz and TMVz) were analysed.

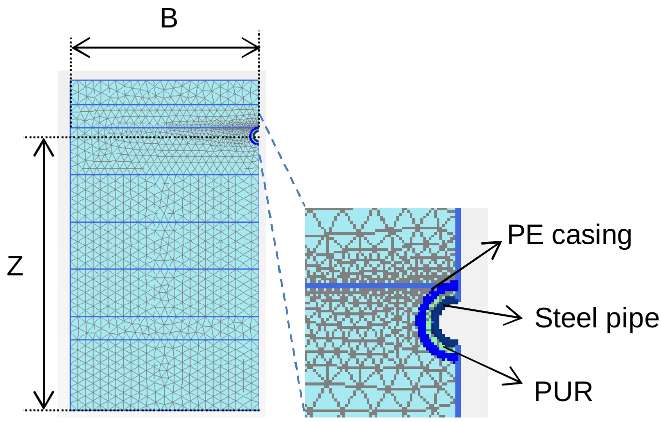


Figure A.2. Finite element model with a half of the supply heating pipe used to determine the minimum B and z through several steady state heat transfer analysis.

Calculation steps and boundary conditions
Two steady state calculations were executed in the sensitivity analysis. The first steady state was to simulate the initial temperature profile in the soil. The second steady state was to add the steady state heat transfer from the supply heating pipe.

The boundary conditions used during the first steady state analysis is shown in Figure A.3. From the depth deeper than 5.5 m the soil temperature was assumed to be equal to the one at 5.5 m depth.

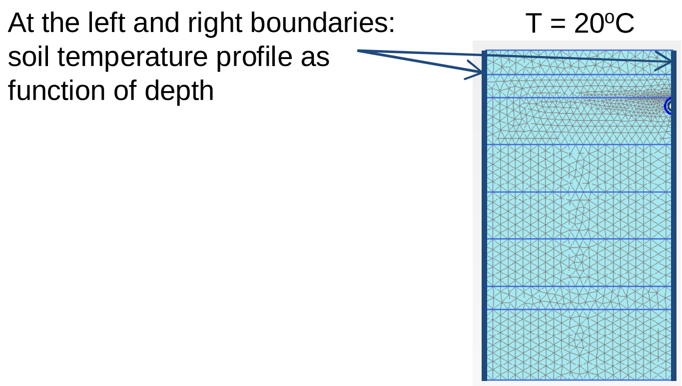


Figure A.3. Boundary conditions for the first step of the steady state heat transfer analysis.

The boundary conditions used for the second steady state step are shown in Figure A.4. In order to determine the minimum B and z values, the left and bottom boundary were set to closed boundary (no heat flux). The right boundary was also set to closed boundary since this is a symmetry model. The temperature of the supply heating pipe was activated at the steel pipe part.

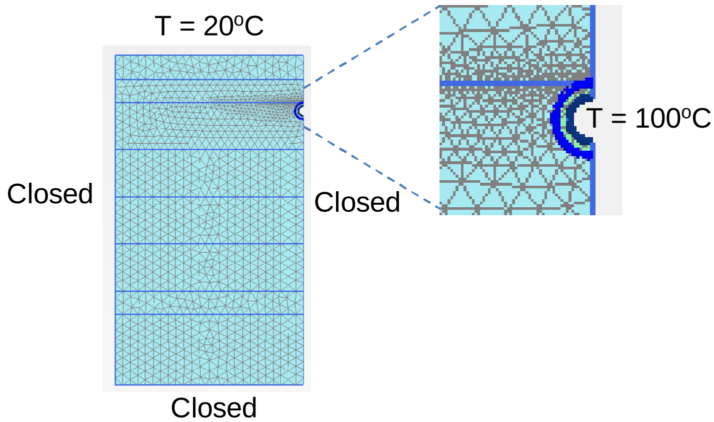


Figure A.4. Boundary conditions for the steady state heat transfer analysis.

Contour of the calculated temperature around the heating pipe

Figure A.5 shows the contour of the steady state calculated temperature around the heating pipe for TLVz and TMVz climate-soil model. It can be observed that the bottom boundary of the soil under the supply heating pipe with TLVz is approximately 1ºC warmer than that with TMVz. With TLVz the heat is transferred faster to the boundary due to the initial colder soil temperature profile than with TMVz case. Based on this, the subsequent sensitivity analyses were done only on TLVz case.

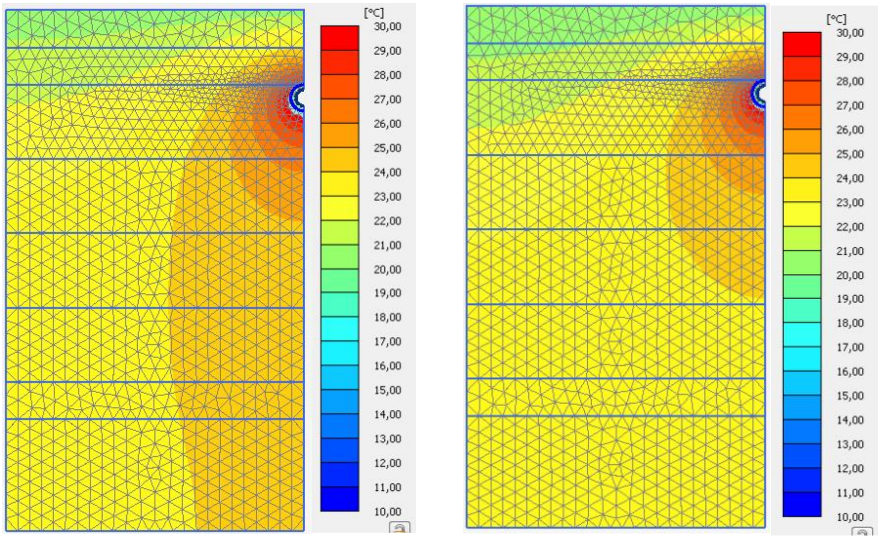


Figure A.5. Contour of the calculated steady state temperature in the soil of TLVz and TMVz climate-soil models (TLVz: left, TMVz: right)

Criteria to determine the minimum distance to the horizontal boundary (B)

The horizontal distance (L_h) between the centre of the supply heating pipe and the 25ºC calculated temperature contour line (see Figure A.6) is used as the criteria to determine the minimum B. As the model becomes lager, the distance L_h will reduce. A model size where the change of the distance is less than 3% determines the minimum B.

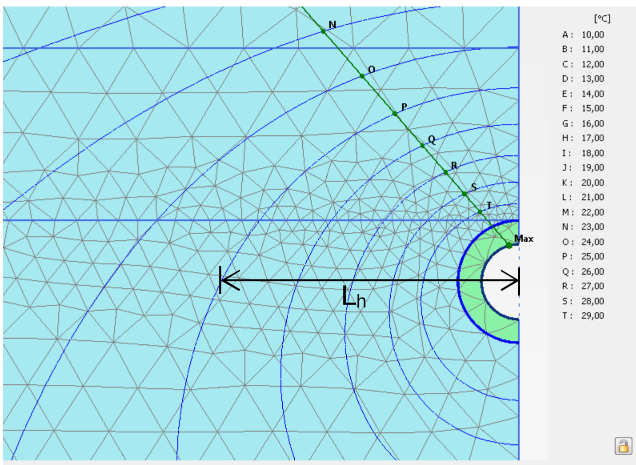


Figure A.6 Horizontal distance from the centre of the heating supply pipe to the 25ºC calculated temperature contour line (L_h)

Criteria to determine the minimum distance to the horizontal boundary (Z)

The vertical distance (L_v) between the centre of the supply heating pipe and the 25ºC calculated temperature line (see Figure A.7) is used as the criteria to determine the minimum Z. As the model became lager, the distance L_v will reduce. A model size where the change of the distance is less than 3% determines the minimum Z.

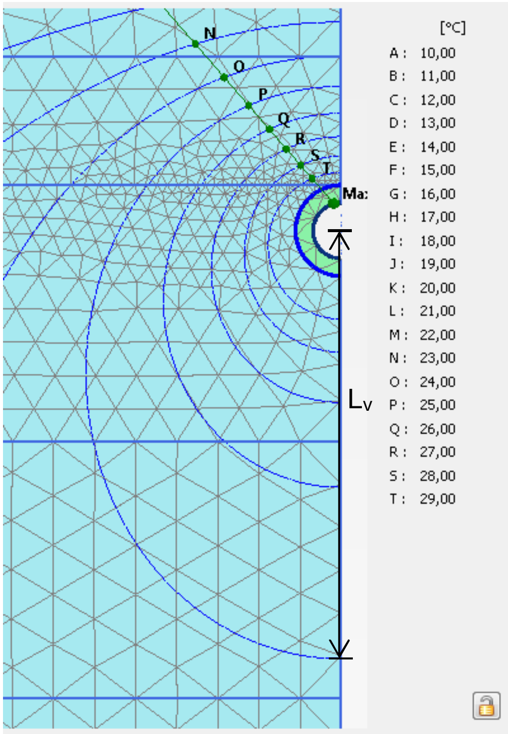


Figure A.7 Vertical distance from the centre of the heating supply pipe to the 25^{o}C calculated temperature contour line (L_v)

Minimum distance to the horizontal boundary (B)

The value of L_h for different sizes (width and length) of the model is given in Table A.3. The relative change in L_h to the largest model (26 m x 56 m) is given in the last column. To satisfy a maximum difference of 3% the minimum distance between the centre of the heating pipe and the left boundary must be 8.43 m, rounded up to 8.5 m. Normalizing the minimum distance with the outer diameter of the casing pipe (D_o) of 0.355 m gives about a distance of 24D_o from the centre of the heating pipe.

Table A.3. Analysis on the minimum value of B.

#	Width [m]	Length [m]	L_h [m]	Relative change in L_h to #6 [%]
1	4	7	0.8663	16.1176
2	6	10	0.7951	6.5729
3	8	14	0.7718	3.4532
4	10	21	0.7559	1.3275
5	16	28	0.7505	0.5948
6	26	56	0.7460	0

Minimum distance to the bottom boundary (Z)

The value of L_v for different sizes of the model is given in Table A.4. The relative change in L_v to the largest model (26 m x 56 m) is given in the last column. To satisfy a maximum difference of 3% the minimum distance between the centre of the heating pipe and the bottom boundary must be 16.21 m, rounded up to 16.5 m. Normalizing the minimum distance with the outer diameter of the casing pipe (D_o) of 0.355 m gives about a distance of 46.5D_o from the centre of the heating pipe.

Table A.4. Analysis on the minimum value of Z

#	Width [m]	Length [m]	L_v [m]	Relative change in L_v to #6 [%]
1	4	7	2.8448	28.1595
2	6	10	2.4167	8.8731
3	8	14	2.3150	4.2909
4	10	21	2.2558	1.6250
5	16	28	2.2357	0.7168
6	26	56	2.2198	0

Influence of the number of finite elements

To check the influence the number of finite elements on the calculated temperature in the soil, a soil model of 8.5m x 18 m was made (see Figure A.8). The distance to the left and bottom boundaries satisfy the required minimum distance as determined in the previous sections. With this the calculated temperatures from the steady state calculation along horizontal section (section 1-1, see Figure A.8) and along the right vertical boundary (section1-2, see Figure A.8) passing the centre of the heating pipe are compared for different number of elements.

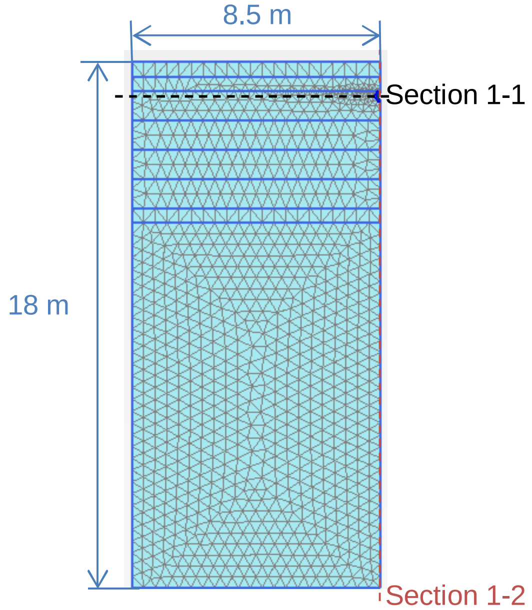


Figure A.8. Sensitivity analysis of the influence of number of finite elements on the calculated temperatures in the soil using a model of 8.5 m x 18 m.

The comparison of the calculated temperatures along section 1-1 for different number of finite elements is given in Figure A.9. The maximum absolute difference found is less than 0.5ºC. The comparison of the calculated temperatures along section 1-2 for different number of finite elements is given in Figure A.10. The maximum absolute difference found is also less than 0.5ºC. It can be concluded that the number of elements up to 2068 elements does not influence the calculated temperatures in the soil.

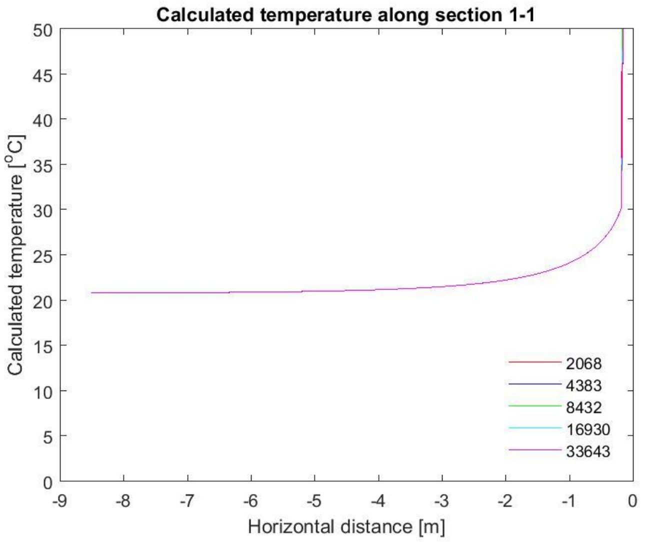


Figure A.9 Influence of the number of finite elements on the calculated temperatures along section 1-1 (Figure A.8)

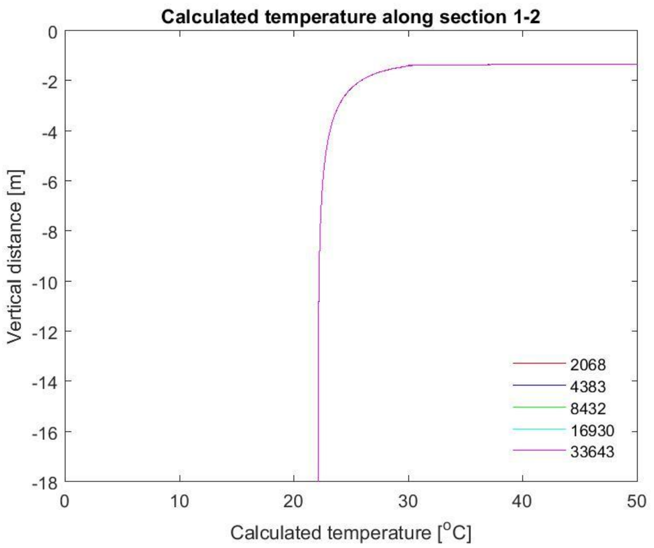


Figure A.10 Influence of the number of finite elements on the calculated temperatures along section 1-2 (Figure A.8)

Conclusion

Based on several steady state heat transfer analysis, it is concluded that the minimum distance from the centre of the heating pipe to the horizontal boundary to minimize the boundary effect must be at least $24D_o$ (D_o = outer diameter of heating pipe casing). For the same reason, the minimum distance from the centre of the heating pipe to the bottom boundary must be at least $46.5D_o$. With the current analysis, this conclusion is valid for the casing pipe diameter up to 355 mm.

For the electricity cables, the minimum distances from the casing pipe to the boundaries of the model follow the minimum distances of the district heating pipe.

Reference

(see section 8 of the memo)

Deltares

Enabling Delta Life

Copy to
DELTARES -> de heer dr. G. Greeuw

Attachment(s)
0