Memo

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From	**Direct line**	**E-mail**
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Subject
Comparison of 1-dimensional heat transfer calculation between Calorics and Plaxis thermal

1 Background and introduction

In order to further validate the Plaxis thermal module to be used in the 2-dimensional heat transfer calculation, a study has been carried out to compare the 1-dimensional heat transfer calculation of Plaxis thermal en Calorics. The result of the comparison is described in this memo. Calorics is an 1-dimensional soil temperature model developed by KWR and has been tested and validated (up to 1.5 m below the soil surface). The validation of Calorics can be found in [1] and [2]. Plaxis thermal heat transfer is an extension module of 2D Plaxis and has been theoretically validated by comparing several 1-dimensional calculations with DG-Flow. DG-Flow and Plaxis thermal compared well up to a ground water flow of 7 mm/day. The results of the comparison between Plaxis thermal and DG-Flow can be found in [3].

The comparison between Plaxis thermal and Calorics was focused on the development of temperature in the soil of several depths due to the changes of temperature on the soil surface. Two basis cases were used in the calculation: TMVz (moist sand case) and TMK (clay soil case). The results of the transient heat transfer calculation of Plaxis thermal was compared to Calorics. The comparison focused on three periods: 1st of January to 1st of May 2016, 1st of May to 1st of September 2016 and 1st of September to 31st of December 2016.

Next to the comparison study, some sensitivity studies on 1-dimensional heat transfer calculations of Plaxis thermal were also conducted. This part covered the influence of elements number and the model length (vertical).

2 Calculation data from Calorics

The calculation data from Calorics used for the comparison study is described below. For the comparison study two cases (TMVz and TMK) were chosen.

The description of TMVz case is given below:

- Soil cover: tile.
- City type: average.
- Type of soil: moist sand.

The description of TMK case is as follows:

- Soil cover: tile.
- City type: average.
- Type of soil: clay.

The thermal properties are given in Table 2.1 for TMVz case and 2.2 for TMK case.

2.1 Temperature on the soil surface

Calorics calculated the temperature transferred from the atmosphere to the soil surface and from the soil surface into the soil. For this study, the temperature on the soil surface ranged from 1st of January 2016 until 1st of January 2017 for both the TMVz and TMK cases was calculated (see Figure 2.1).

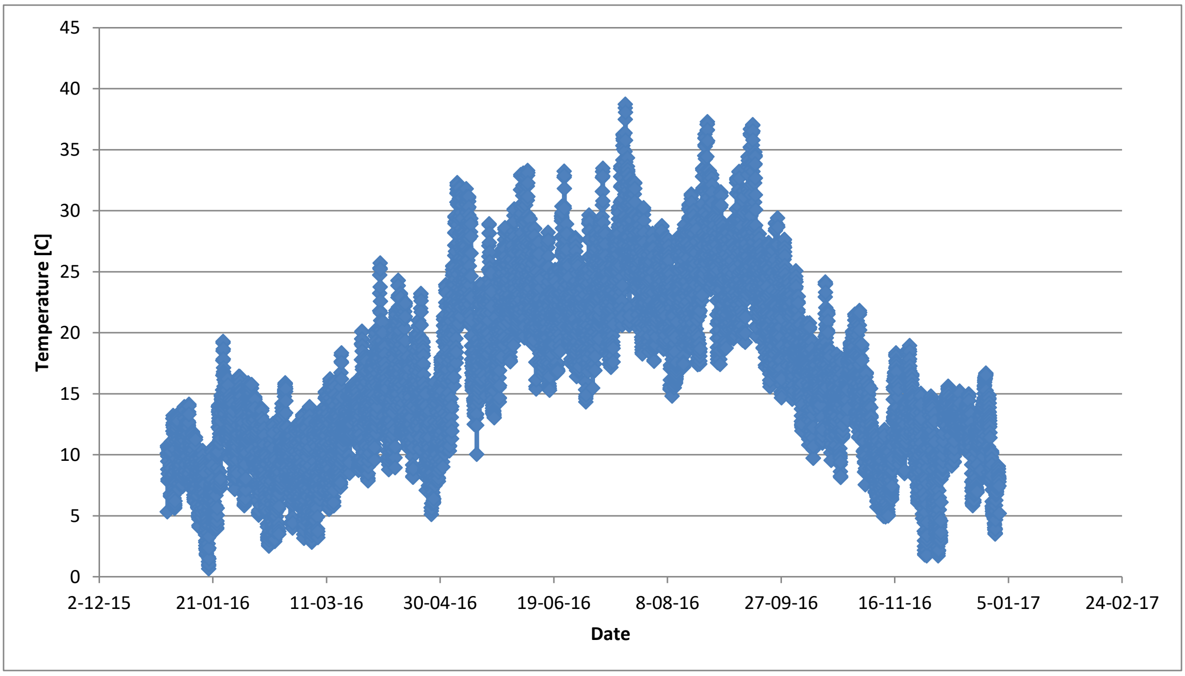

Figure 2.1 Temperature on the ground surface as function of time (hour) from 1st January 2016 until 1st January 2017 (soil cover: tile, city type: average).

2.2 Thermal properties of the soil

The thermal properties of the soil are given in Table 2.1 for TMVz case and Table 2.2 for TMK case.

Table 2.1 Thermal properties of the soil used in Calorics.(case TMVz: moist sand)

Parameter	Description	Value
λ	Thermal conductivity	1.4 W/m/K
C	Specific heat capacity	1000 J/kg/K
ρ	Bulk density of soil	1700 kg/m^3
α	Thermal diffusion coefficient	0.82 x 10^{-6} m^2/s
z_0	Roughness length	0.95 m
QF	Anthropogenic heat	100 W/m^2
a_1	empirical coefficient	0.8
a_2	empirical coefficient	30 s

a_3	empirical coefficient	-100 W/m^2

Table 2.2 Thermal properties of the soil used in Calorics.(case TMK: clay)

Parameter	Description	Value
λ	Thermal conductivity	1.35 W/m/K
C	Specific heat capacity	1350 J/kg/K
ρ	Bulk density of soil	1600 kg/m^3
α	Thermal diffusion coefficient	0.63 x 10^{-6} m^2/s
z_0	Roughness length	0.95 m
QF	Anthropogenic heat	100 W/m^2
a_1	empirical coefficient	0.8
a_2	empirical coefficient	0.3 s
a_3	empirical coefficient	-100 W/m^2

3 Input data for Plaxis thermal

3.1 Temperature on the soil surface

The temperature on the soil surface follows the time function calculated by Calorics (see Figure 2.1) for both cases (TMVz and TMK).

3.2 Thermal properties of the soil

Only λ (thermal conductivity), C (specific heat capacity) and ρ (bulk density of soil) were used in the Plaxis thermal calculation for each case.

3.3 Initial temperature profile

The initial temperature of the soil needs to be defined in Plaxis thermal. For this a temperature profile (with depth) on the 1st January 2016 (calculated with Calorics) was used. Figure 3.1 shows the initial temperature calculated by Calorics and the initial temperature idealization applied in Plaxis thermal for TMVz case. Figure 3.2 shows the initial temperature calculated by Calorics and the initial temperature idealization applied in Plaxis thermal for TMK case.

With Calorics the temperature was calculated up to 5.5 m depth. Starting from 5 m depth the temperature is almost constant. At the depth of 5.5m is the soil temperature 16.10^{o}C for TMVz case and 14.77^{o}C for TMK case. In Plaxis thermal the soil temperature from Calorics were modelled for different depths discretely up to 5.5 m under the soil surface. From 5.5 m below the surface the soil temperature was assumed to be constant and equals to the temperature at 5.5 m depth.

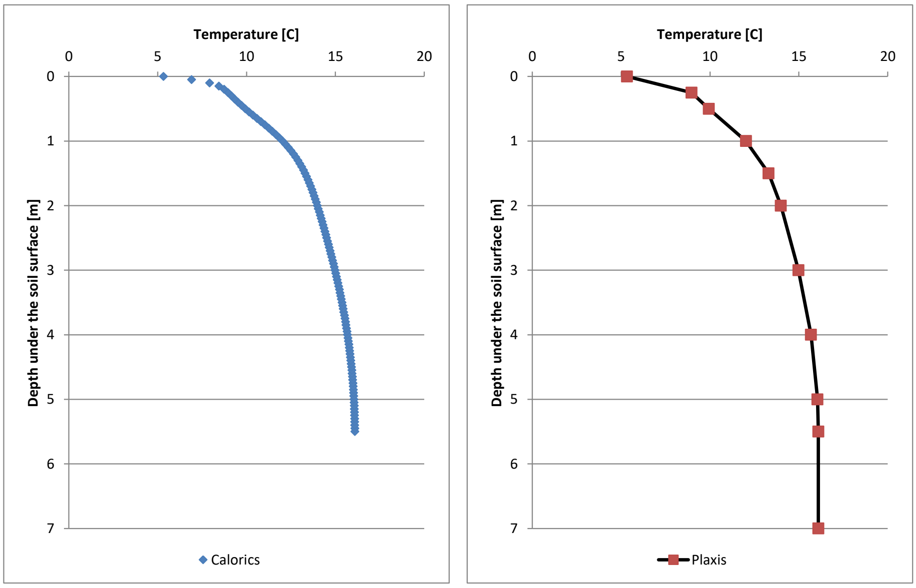

Figure 3.1 The temperature profile (with depth) on 1st January 2016 calculated with Calorics (left) and the idealization for Plaxis thermal (right) for TMVz case

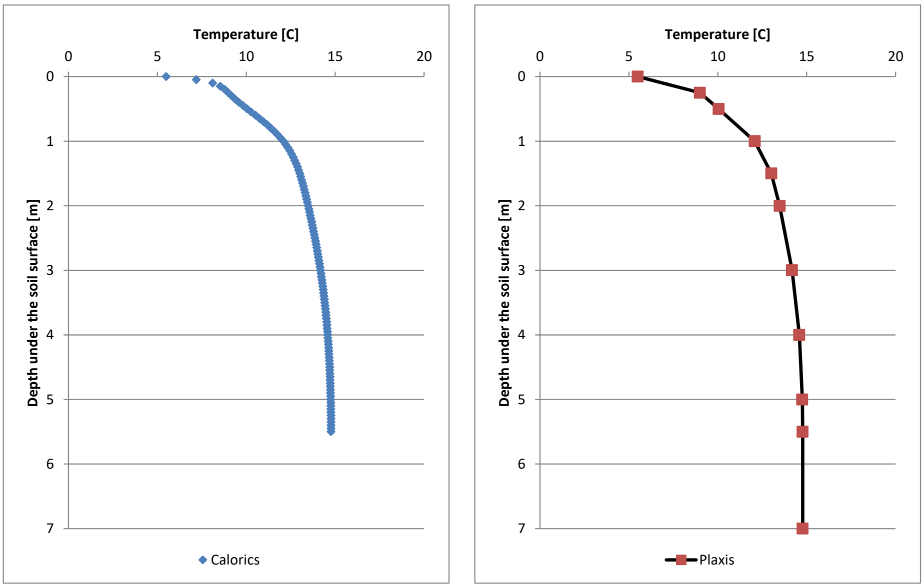

Figure 3.2 The temperature profile (with depth) on 1st January 2016 calculated with Calorics (left) and the idealization for Plaxis thermal (right) for TMK case

3.4 Finite element model

Figure 3.3 shows the finite element model used for the 1-dimensional heat transfer calculation in Plaxis thermal. The mesh was automatically generated and composed of 420 elements. The model was 1 m wide (horizontal) and 10 m long (vertical). The soil surface is at 0 m in the vertical direction.

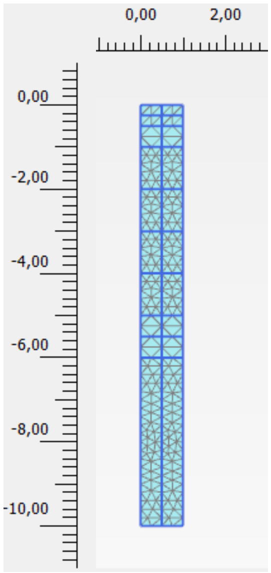

Figure 3.3 The finite element model in Plaxis thermal used for the 1-dimensional heat transfer calculation.

3.5 Calculation steps

The Plaxis thermal calculation consisted of two steps.

The first step is generation of initial soil temperature profile of 1^{st} of January 2016. This temperature profile was applied at different depths horizontally (on each horizontal blue line in the model, see Figure 3.3). The temperature boundary at the left and right sides of the model was not activated. This step was analysed using steady state calculation.

The second step is de transient analysis with the time dependent surface temperature from the Calorics (see Figure 3.4). The calculated temperature on the soil surface shown in Figure 2.1 was applied at the top of the model. During this step the left, right and bottom temperature boundaries were closed (1 dimensional analysis).

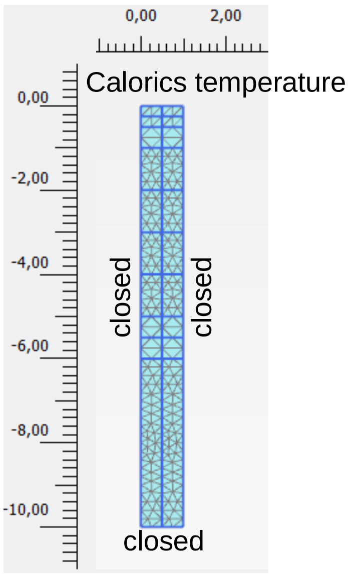

Figure 3.4 The finite element model in Plaxis thermal used for the 1-dimensional transient heat transfer calculation.

4 Comparison of 1D heat transfer calculation between Calorics and Plaxis thermal

The comparison of the calculated temperatures between Calorics and Plaxis thermal are presented below. The calculated temperatures located between 0 to 3 m depth below the soil surface are of interest since most of pipeline networks (gas, water, and electricity) are located within these depths.

4.1 Calculated temperatures at depth of 0 to 3 m below the soil surface

4.1.1 Period of 1st of January to 1st of May 2016

The calculated temperatures for the period of 1st of January to 1st of May 2016 in the soil as function of time at different depths (0 to 3m) for TMVz case are presented in Figure 4.1. For TMK case the calculated temperatures are presented in Figure 4.2.

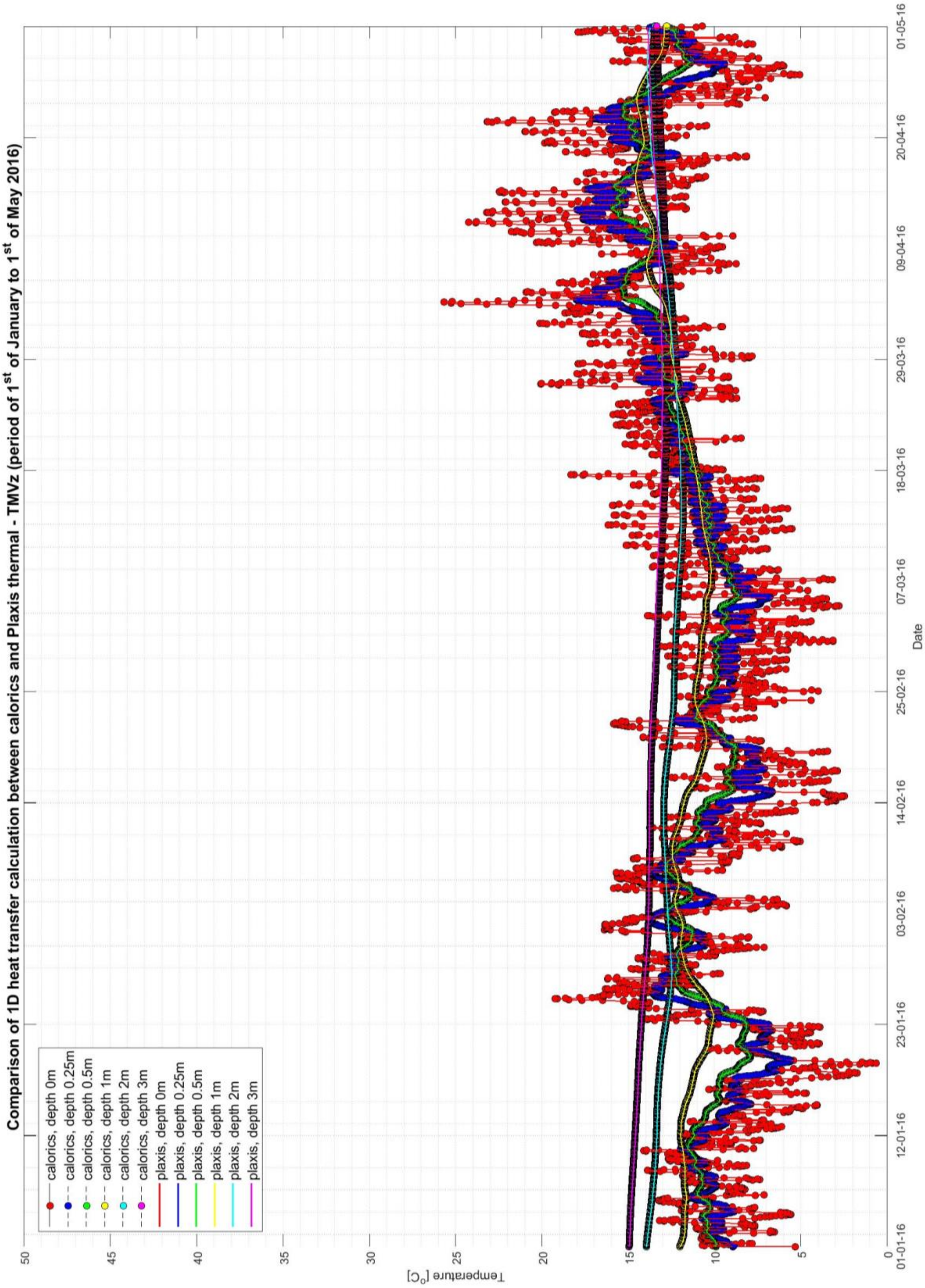

Figure 4.1 Calculated temperatures (Calorics and Plaxis thermal) from 1st of January 2016 until 1st of May 2016 at depth of 0 to 3 m (TMVz case).

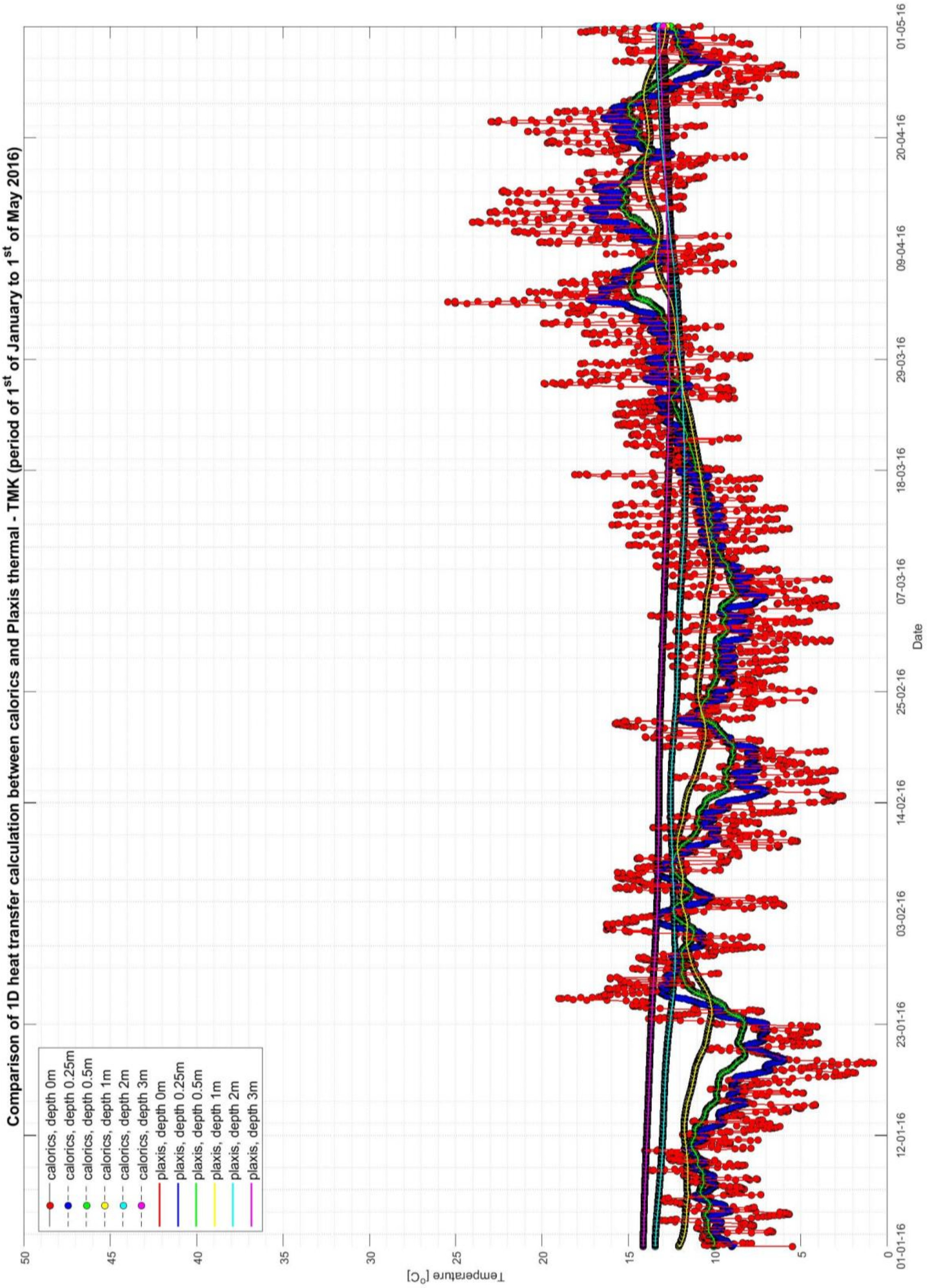

Figure 4.2 Calculated temperatures (Calorics and Plaxis thermal) from 1st of January 2016 until 1st of May 2016 at depth of 0 to 3 m (TMK case).

The temperature differences of both cases are shown in Figure 4.3 and 4.4. The quality of the comparison of the calculated temperatures between Plaxis thermal and Calorics is expressed by using R^2 value. Up to 3 m depth the minimum R^2 is 0.85 for TMVz case and 0.96 for TMK case.

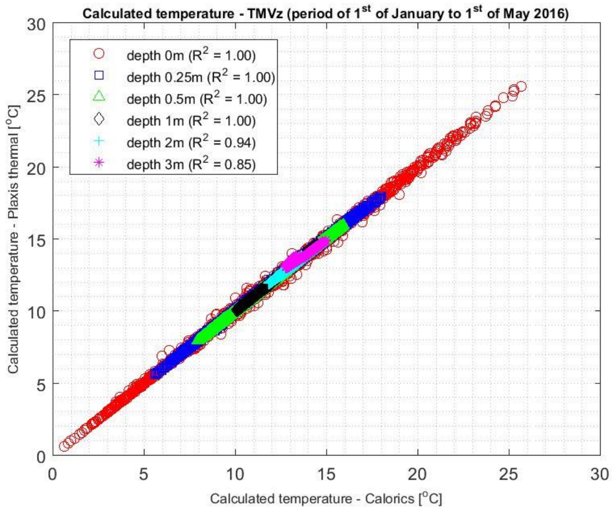

Figure 4.3 Comparison of calculated temperatures from 1st of January 2016 until 1st of May 2016 between Plaxis thermal and Calorics at depth of 0 to 3 m (TMVz case)

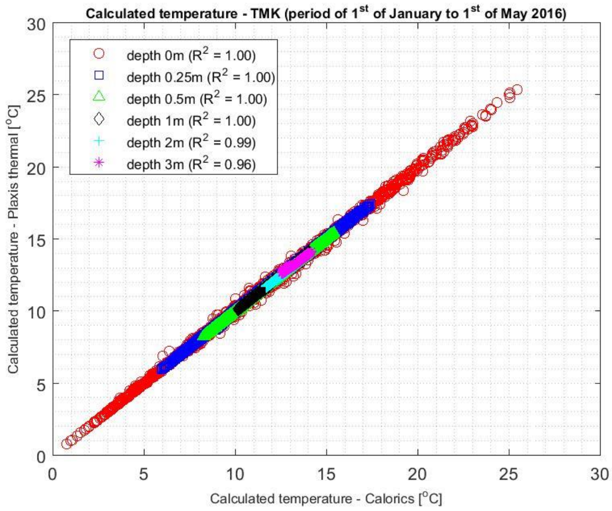

Figure 4.4 Comparison of calculated temperatures from 1st of January 2016 until 1st of May 2016 between Plaxis thermal and Calorics at depth of 0 to 3 m (TMK case)

4.1.2 Period of 1st of May to 1st of September 2016

The calculated temperatures for the period of 1st of May to 1st of September 2016 in the soil as function of time at different depths (0 to 3m) for TMVz case are presented in Figure 4.5. For TMK case the calculated temperatures are presented in Figure 4.6.

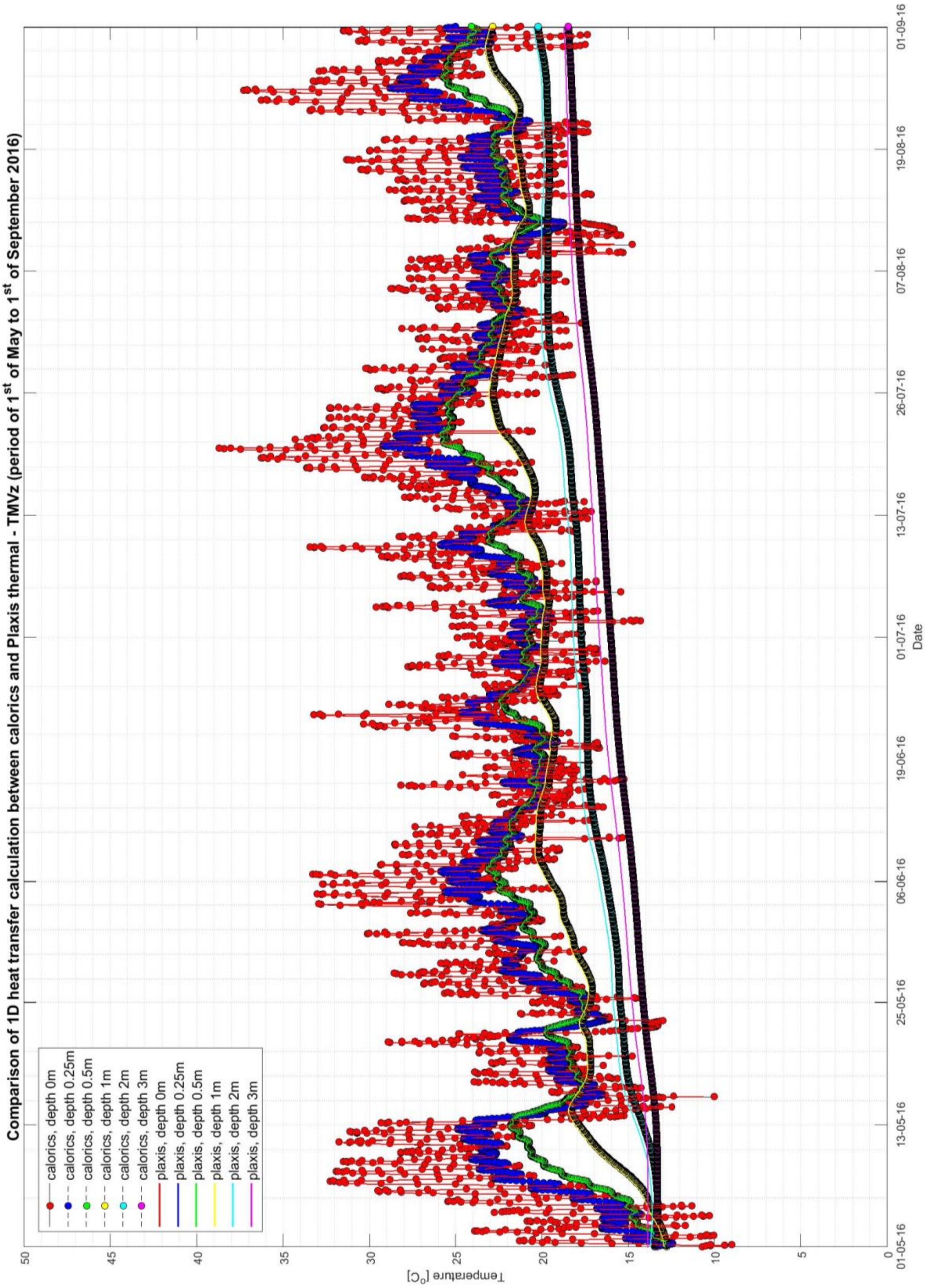

Figure 4.5 Calculated temperatures (Calorics and Plaxis thermal) from 1st of May 2016 until 1st of September 2016 at depth of 0 to 3 m (TMVz case).

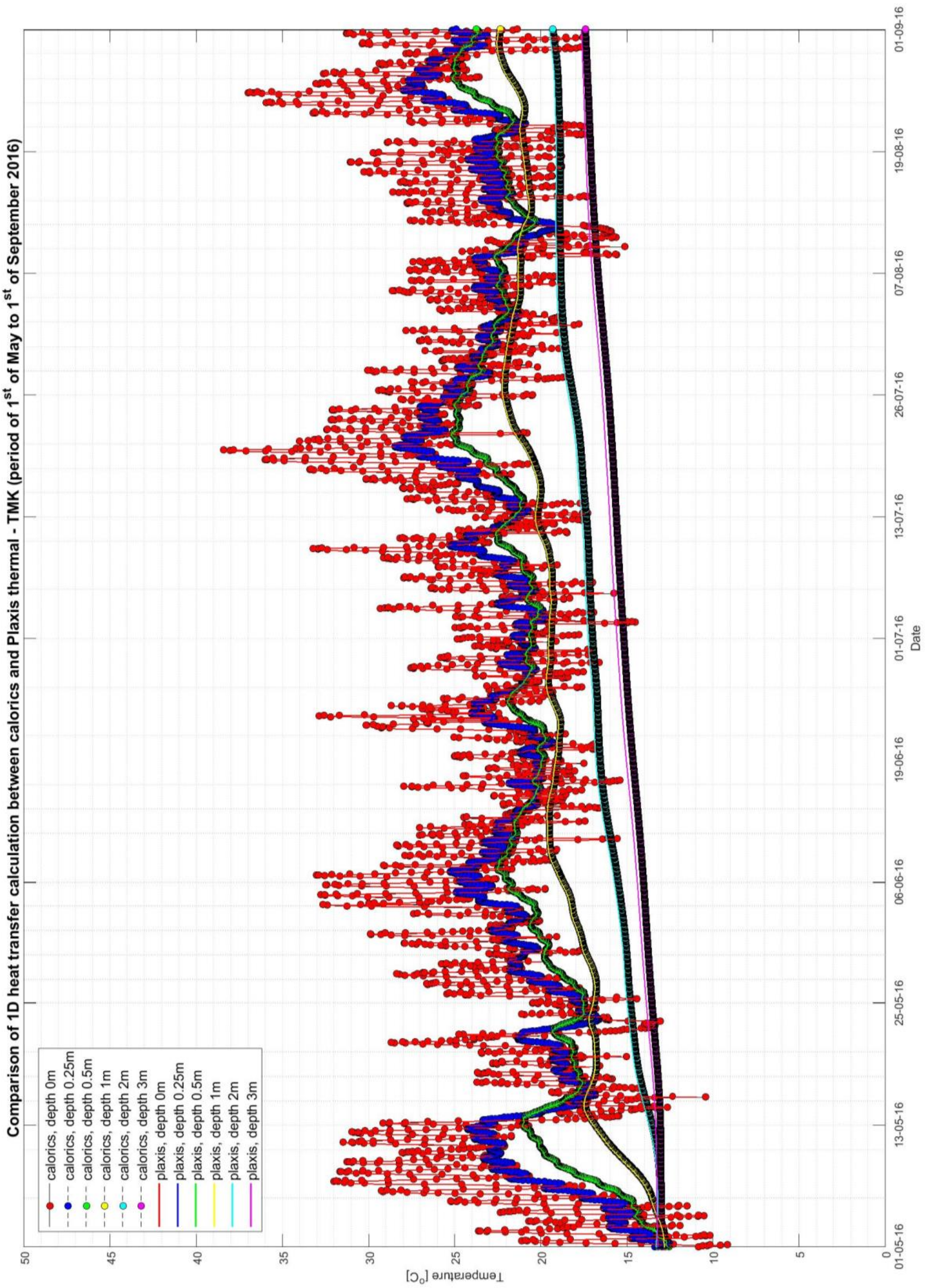

Figure 4.6 Calculated temperatures (Calorics and Plaxis thermal) from 1st of May 2016 until 1st of September 2016 at depth of 0 to 3 m (TMK case).

The temperature differences of both cases are shown in Figure 4.7 and 4.8. The quality of the comparison of the calculated temperatures between Plaxis thermal and Calorics is expressed by using R^2 value. Up to 3 m depth the minimum R^2 is 0.88 for TMVz case and 0.94 for TMK case.

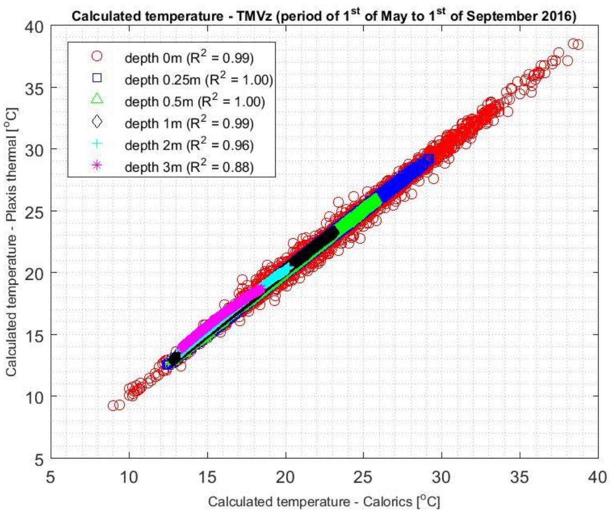

Figure 4.7 Comparison of calculated temperatures from 1st of May 2016 until 1st of September 2016 between Plaxis thermal and Calorics at depth of 0 to 3 m (TMVz case)

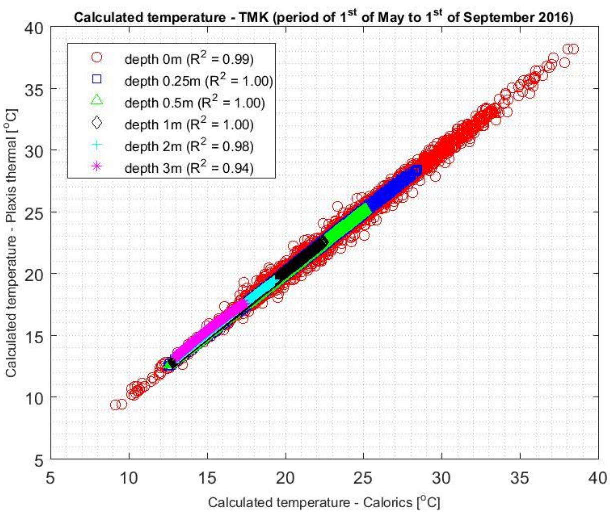

Figure 4.8 Comparison of calculated temperatures from 1st of May 2016 until 1st of September 2016 between Plaxis thermal and Calorics at depth of 0 to 3 m (TMK case)

4.1.3 Period of 1st of September to 31st of December 2016

The calculated temperatures for the period of 1st of September to 31st of December 2016 in the soil as function of time at different depths (0 to 3 m) for TMVz case are presented in Figure 4.9. For TMK case the calculated temperatures are presented in Figure 4.10.

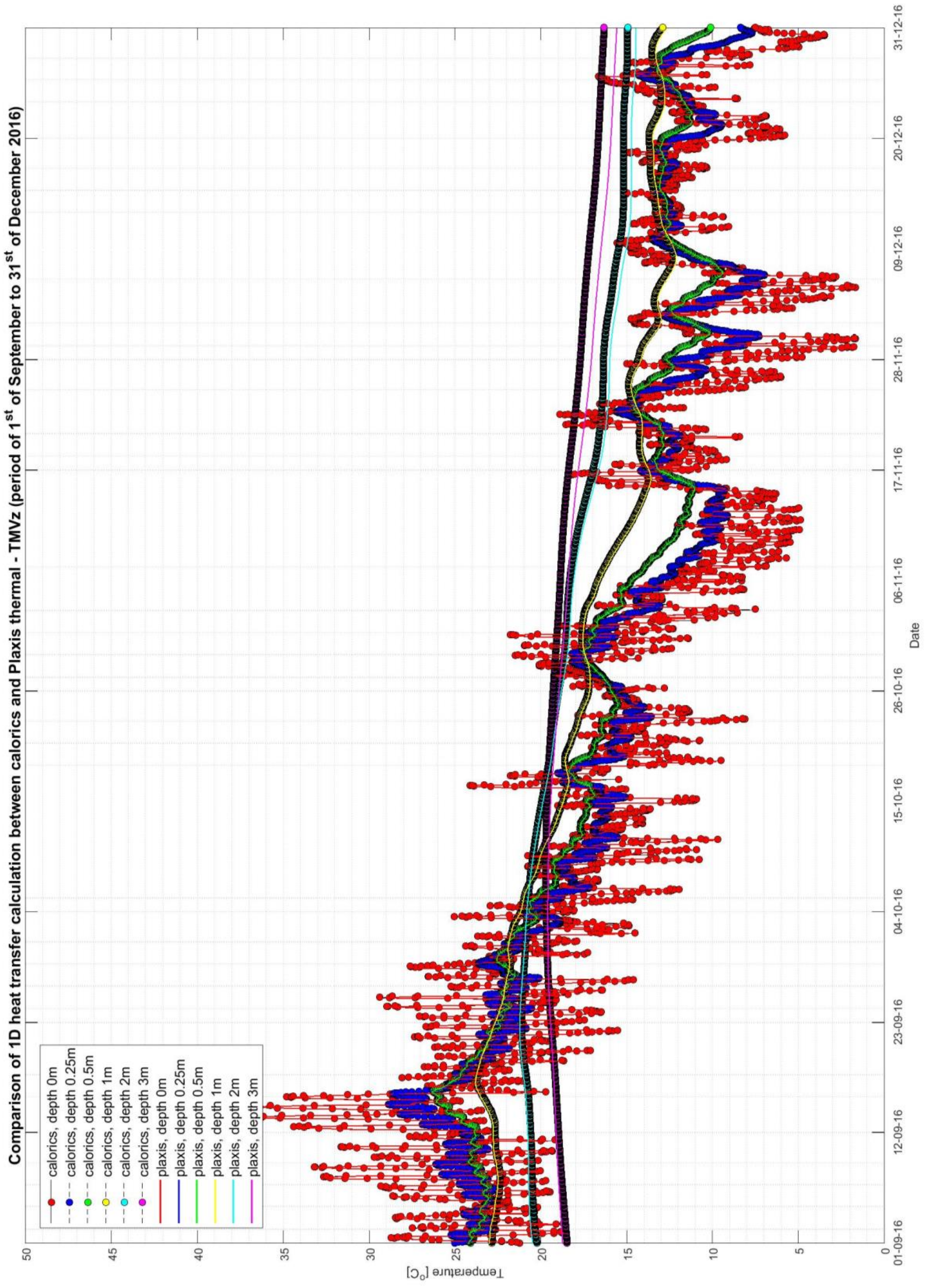

Figure 4.9 Calculated temperatures (Calorics and Plaxis thermal) from 1st of September 2016 until 31st of December 2016 at depth of 0 to 3 m (TMVz case).

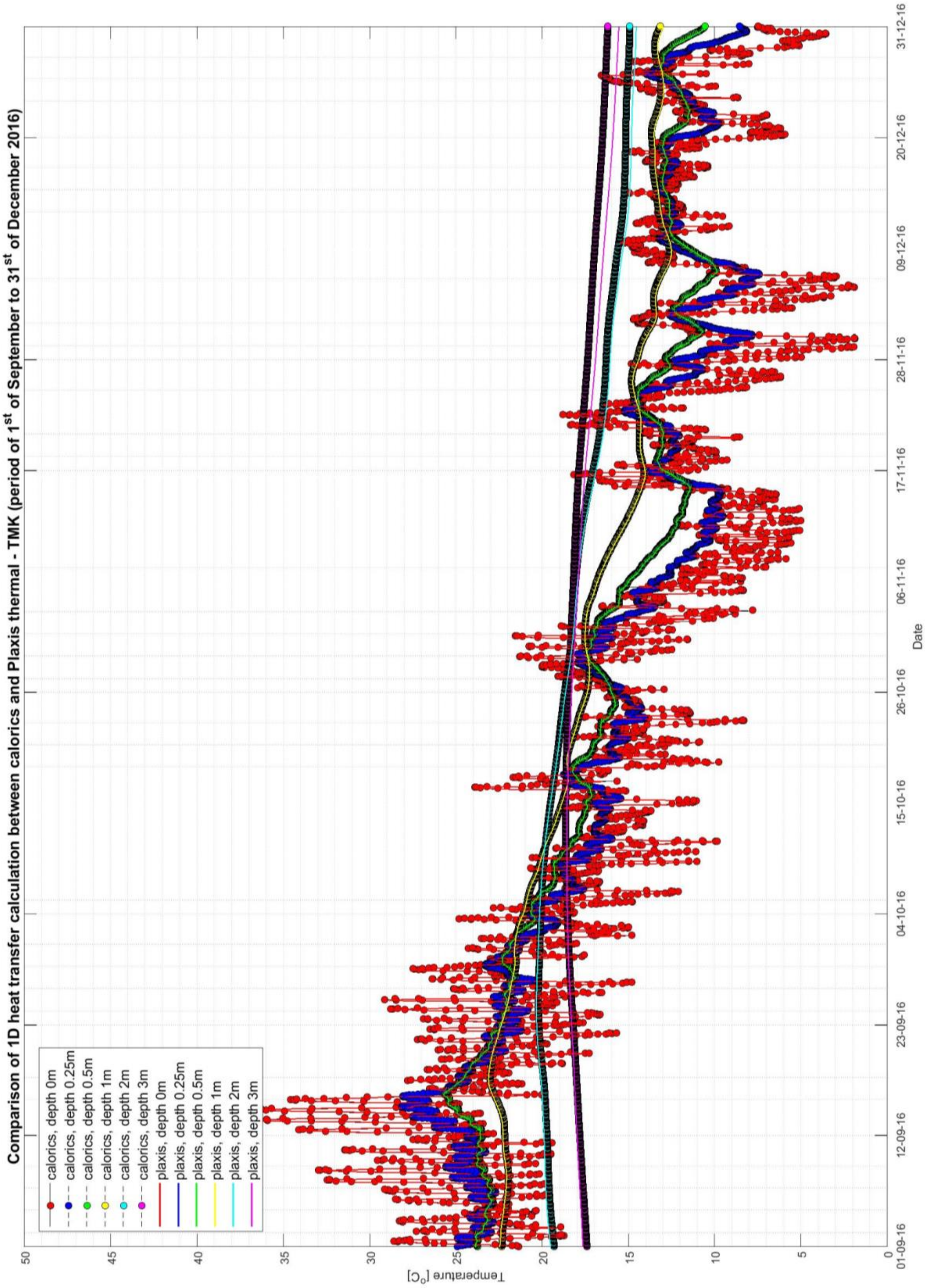

Figure 4.10 Calculated temperatures (Calorics and Plaxis thermal) from 1st of September 2016 until 31st of December 2016 at depth of 0 to 3 m (TMK case).

The temperature differences of both cases are shown in Figure 4.11 and 4.12. The quality of the comparison of the calculated temperatures between Plaxis thermal and Calorics is expressed by using R^2 value. Up to 3 m depth the minimum R^2 is 0.88 for TMVz case and 0.94 for TMK case.

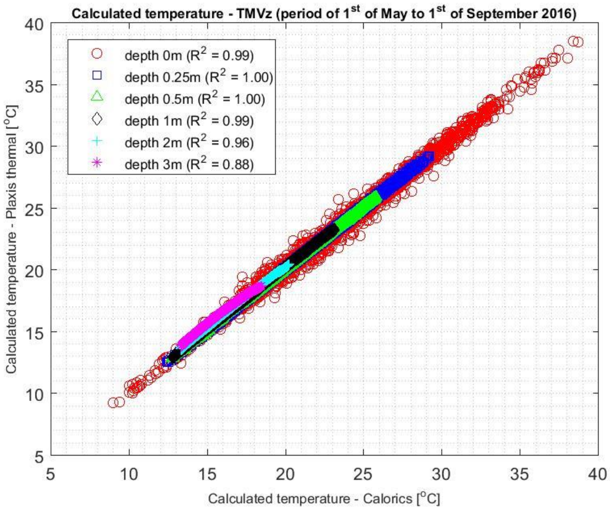

Figure 4.11 Comparison of calculated temperatures from 1st of September 2016 until 31st of December 2016 between Plaxis thermal and Calorics at depth of 0 to 3 m (TMVz case)

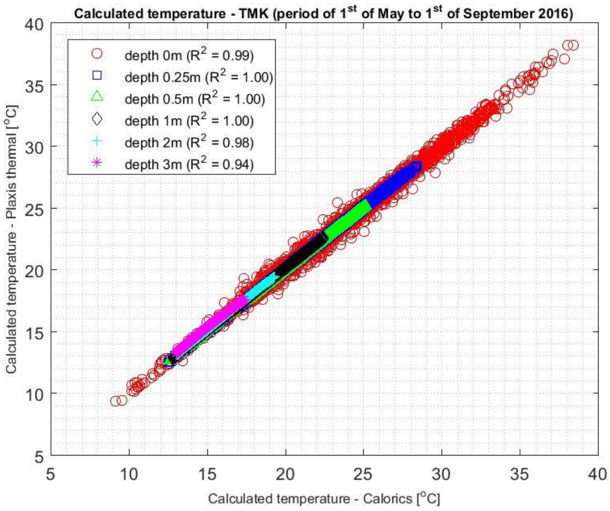

Figure 4.12 Comparison of calculated temperatures from 1st of September 2016 until 31st of December 2016 between Plaxis thermal and Calorics at depth of 0 to 3 m (TMK case)

4.2 Calculated temperatures at depth below 3 m from the soil surface

The calculated temperatures of Plaxis thermal at depth below 3m deviate from Calorics. The deviation ranges from 1° to 2°C. The maximum deviation found was approximately 2°C for both TMVz and TMK cases. The maximum deviation was observed between 6th and 17th of November 2016 at depth of 5.5m for TMVz case (see Figure 4.13). The deviation was caused the closed bottom boundary applied in Plaxis thermal. The accuracy of Plaxis thermal calculation can be improved by moving the closed bottom boundary of the model to greater depth.

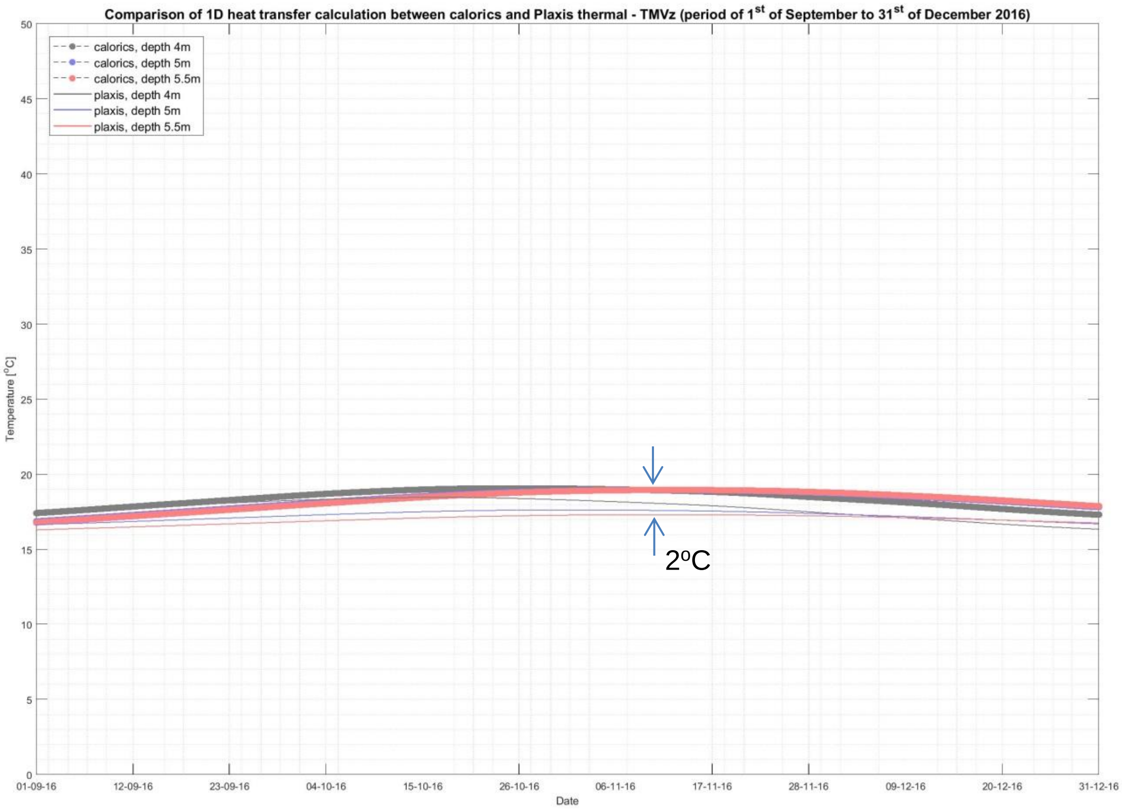

Figure 4.13 Calculated temperatures (Calorics and Plaxis thermal) from 1st of September 2016 until 31st of December 2016 at depth of 4, 5 and 5.5 m (case TMVz).

5 Sensitivity analysis on 1D heat transfer calculation with Plaxis thermal

The sensitivity analysis was carried out for TMVz case on the number of elements and model length. The result of the analysis has been summarized below.

5.1 Increase of number of finite elements

The maximum difference in calculated temperatures at different depths by using a 10 m long model with 420 elements (reference) and a 10 m long model with 1128 elements are indicated in Table 5.1. The maximum difference in the calculated temperature is 0.10°C at depth of 0.25 m.

Table 5.1 Maximum difference in calculated temperatures of different depths.

Depth from the soil surface [m]	Range of calculated temperatures [°C]*	Difference in calculated temperature [°C]
0	0 to 39	0
0.25	5 to 30	0.102
0.5	7 to 27	4.3×10^{-3}
1	10 to 24	2.83×10^{-4}
2	11 to 22	2.25×10^{-5}
3	13 to 20	1.85×10^{-5}
4	13 to 19	2.23×10^{-5}
5	14 to 18	7.5×10^{-6}
5.5	14 to 18	1.03×10^{-6}

*reference (calculation with 420 elements, 10 m long)

5.2 Increase of model length

The maximum difference in calculated temperatures at different depths by using 10 m long model with 420 elements (reference) and 20 m long model with 2264 elements are indicated in Table 5.2. The maximum difference in the calculated temperature is 0.15°C at depth of 5.5 m.

Table 5.2 Maximum difference in calculated temperatures of different depths.

Depth from the soil surface [m]	Range of calculated temperatures [°C]*	Difference in calculated temperature [°C]
0	0 to 39	0
0.25	5 to 30	0.102
0.5	7 to 27	0.015
1	10 to 24	0.025
2	11 to 22	0.050
3	13 to 20	0.075
4	13 to 19	0.102
5	14 to 18	0.133
5.5	14 to 18	0.150

*reference (calculation with 420 elements, 10 m long)

6 Conclusion

The 1-dimensional heat transfer calculation of Plaxis thermal and Calorics has been compared. For the comparison TMVz case (soil cover: tile, city type: average, soil type: moist sand) and TMK case (soil cover: tile, city type: average, soil type: clay) were used. The conclusions of this comparison study are summarized below:

- Below 3 m depth the calculated temperatures of Plaxis thermal deviate from Calorics. This was observed on both cases (TMVz and TMK). The maximum difference in the calculated temperature was approximately 2°C and observed at 5.5 m depth. The deviation was caused by the closed bottom boundary applied in Plaxis thermal. The accuracy of Plaxis thermal calculation can be improved by moving the closed bottom boundary of the model to greater depth.

- Despite the difference both programs (Calorics and Plaxis thermal) compared well for the calculated temperatures within 3 m from the ground surface. Since most of pipeline networks are located 1 to 2 m below soil surface, the comparison gives more confidentce to use Plaxis thermal for the 2-dimensional heat transfer calculation in the next phase.

- The influence of the increase of finite element numbers (in this case from 420 to 1128 elements) does not improve the calculated temperature of Plaxis thermal significantly. A small difference in the result was found (0.1ºC for the range of temperature between 0 and 39ºC). When increasing the model length form 10 m to 20 m (also increasing the element numbers from 420 to 2264) a small difference was also found (0.15ºC for the range of temperature between 14 and 18ºC). Based on this, it can be concluded that the model is not sensitive to the number of elements and the length above 10 m if the average element area is 0.024 m^2 ($10m^2$/420 elements). This will be validated further when assessing the model size prior to the 2-dimensional heat transfer calculations.

7 Reference

[1] Blokker, E.J.M and Pieterse-Quirijns, E.J. (2013). Modelling temperature in the drinking water distribution system. Journal - American Water Works Association.
[2] Agudelo-Vera, C. M. et al. (2017). Identifying (subsurface) anthropogenic heat sources that influence temperature in the drinking water distribution system. Drinking water engineering and science.
[3] Esch, J., Nugroho, D.S. (2018). Comparison of heat transfer calculation between Plaxis thermal and DgFlow. Deltares Memo 11201825-001-GEO-0002.

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