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Modelling of Thermosyphons Foundation System Using Plaxis 2D

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1 INTRODUCTION

Thermosyphon systems are passive refrigeration devices, helping to protect the permafrost to support buildings, pipelines, railroad embankments and highways (Wagner (2014)). They are charged with a working fluid circulating between an evaporator and a condenser/radiator due to the natural convection. A schema operation example of a thermosyphon system is in Figure 1.1. In the winter, the ground temperature is higher than the air temperature, so the fluid at the base of the thermosyphon warms up, vaporises and moves upward to the radiator where the liquid cools down by colder air, condenses and moves downward again. This loop transfers heat from the ground to the air as long as the appropriate temperature difference prevails; otherwise, the system stops working. Therefore, the cycle ceases in the summer, and the cold is stored in the ground.

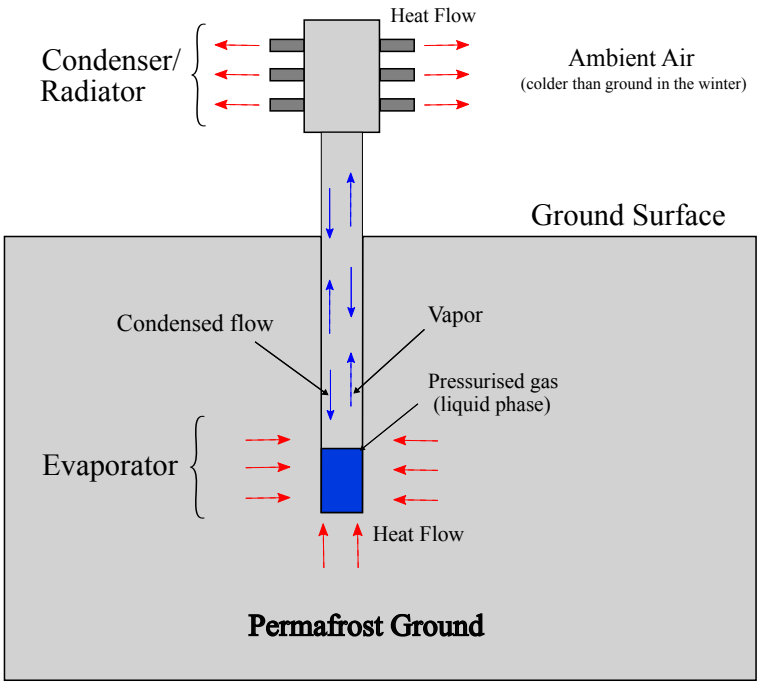


Figure 1.1 Thermosyphon operation (after Wagner (2014))

This document presents an example illustrating how to model thermosyphon applications in geotechnical engineering using PLAXIS 2D. This example shows a flat thermosyphon foundation system model in a 2D geometry where the end view of horizontal evaporator pipes is described in the plane of the model. This analysis aims at showing the usefulness of thermosyphons in permafrost protection under the effects of a heated building and air temperature variation.

2 THEORETICAL BACKGROUND

The heat transfer performance of a thermosyphon can be described by the following equation (Long & Zarling (2004)):

$$Q = P(T_s - T_a) \tag{2.1}$$

Where Q is the overall heat transfer rate of a thermosyphon (kW), P is the overall thermal conductance ($kW/^\circ C$), T_s and T_a are soil and ambient air temperature.

The thermal conductance P (inverse of total thermal resistance) depends principally on the thermal conductance of the soil and the radiator. The latter depends not only on the radiator size and wind speed but also the emplacement of the thermosyphon next to a building (Long & Zarling (2004)). As aforementioned, the thermal conductance becomes zero when the air temperature $T_a > T_{fluid\ max}$ or $T_s - T_a < \Delta T$ so that the thermosyphon stops working in the summer (heat is only extracted but never supplied to the ground).

Apart from the above factors, the evaporator size also influences the heat transfer process (Long & Zarling (2004)). To summarise, the following factors should be considered in the analysis of thermosyphon performance:

- Thermal conductance of the radiator
- Soil thermal properties
- Air temperature
- Size of the evaporator pipe

3 MODEL GEOMETRY AND MESH GENERATION

The geometry of the model comprises of a permafrost layer with 10.5 m thickness beneath the house which is 10 m wide. The thermosyphon system includes five heat pipes installed in the permafrost under the house. Due to the symmetry of this geometry, the numerical model consists of only its right half, which extends to 16 m in the $x-$axis (Figure 3.1. In PLAXIS, the real geometry of the evaporators (cross section of the pipes in this 2D model) must be explicitly modelled. Comparing methods which simplify the modelling of a pipe cross section as a free point boundary condition, the present method is more realistic, and it considers the effect of evaporator size explicitly and avoids possible singularities.

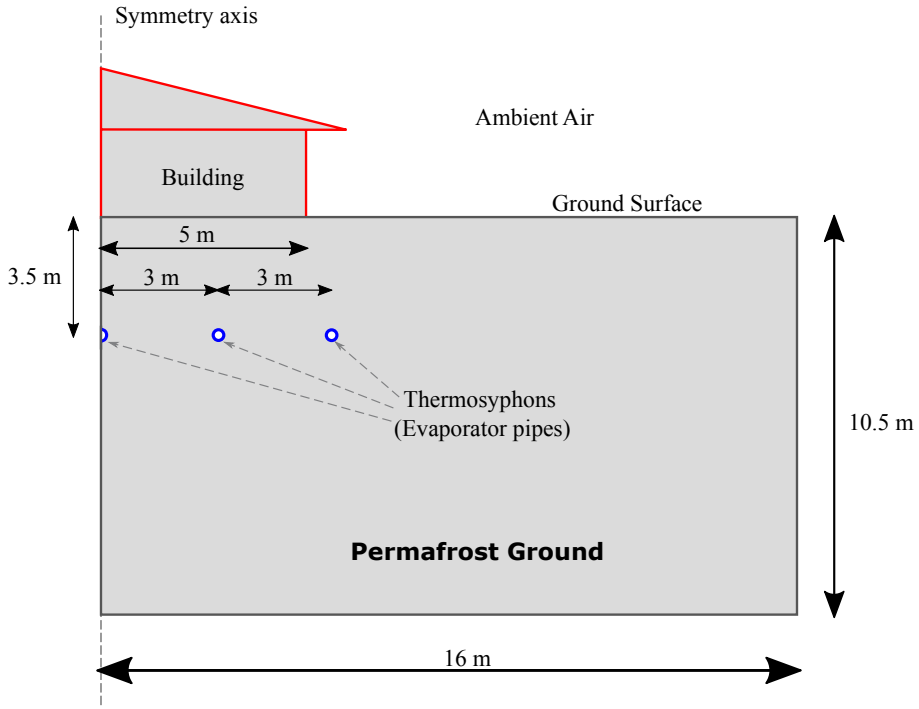


Figure 3.1 Model geometry

In this example, the evaporators are modelled by circles (or half-circle for the thermosyphon located at the symmetry axis) with a diameter of 2 cm, which is a realistic pipe size in flat thermosyphon foundation system application (see NSC (2013)). In this model, triangular 15 node-elements are in use. Due to a small size of the pipes when compared with the entire model, it was necessary to use mesh refinement around them by setting a coarseness factor of 0.1. To increase mesh quality, a *Fine mesh* option is used (Figure 3.2).

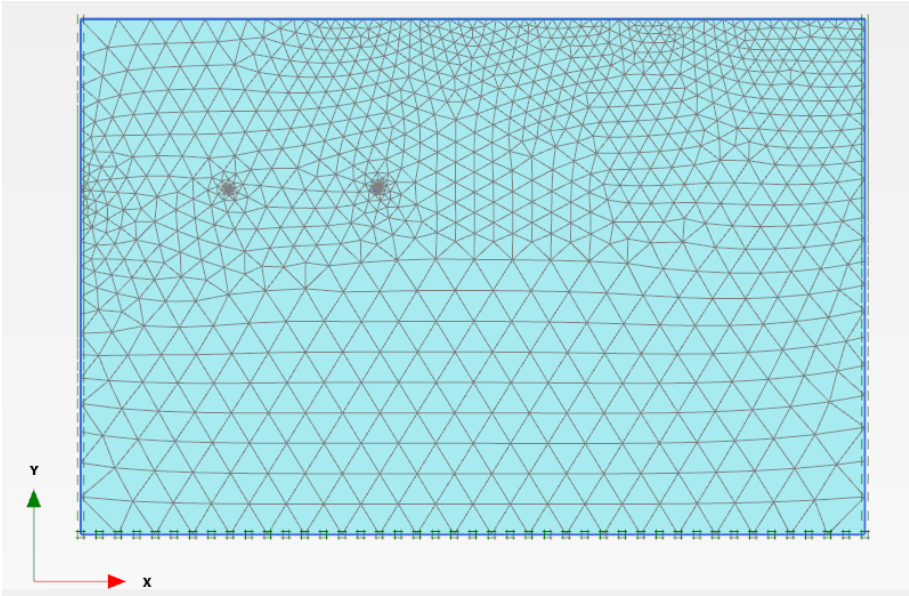


Figure 3.2 Model Mesh

4 MATERIAL PARAMETERS

This example emphasises thermal flow analysis; thus no deformation parameters are involved in the calculation. A simple drained linear elastic model is used for the soil (a silty sand) constitutive behaviour. The void ratio is 0.538, corresponding to a porosity of 0.35.

The unfrozen water characteristic curve (relation between unfrozen water content w_u and temperature) is in Figure 4.1.:

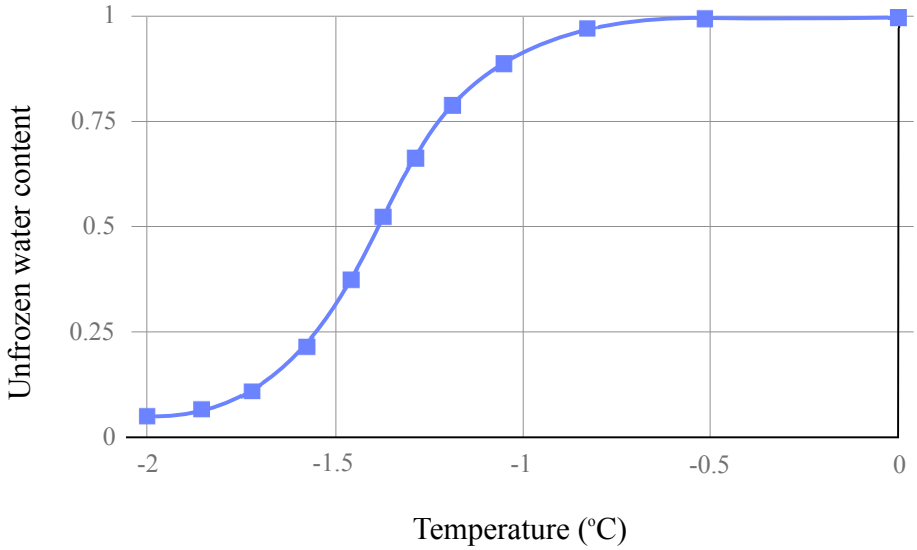


Figure 4.1 Unfrozen water content

The thermal properties of liquid water and ice (*Project properties* toolbox) and solid grains (*Material* toolbox) are needed (Table 4.1).

Table 4.1 Thermal properties of liquid water, ice and soil grains

	Density (kG/m^3)	Specific heat capacity ($kJ/t/°C$)	Thermal conductivity ($kW/m/°C$)
Water	ρ_w = 1000	C_w = 4185	$\lambda_w = 0.56E-3$
Ice	ρ_i = 920	C_i = 2275	$\lambda_i = 5.47E-3$
Soil grains	ρ_s = 2500	C_s = 1034	$\lambda_s = 3.97E-3$

Note that the ice density value is not required as input, but assigned internally in PLAXIS. PLAXIS considers saturated frozen soil as a porous medium consisting of solid grains, ice and liquid water. From the values above, the equivalent thermal properties of the soil (heat capacity and thermal conductivity) can be calculated as follows (see Eq 2.35 and 2.36 in the THM Report):

$$\rho C = (1-n)\rho_s C_s + n w_u \rho_w C_w + n(1-w_u) n w_u \rho_i C_i + nL\frac{dw_u}{dT} \tag{4.1}$$

$$\lambda = (1-n)\lambda_s + n w_u \lambda_w + n(1-w_u)\lambda_i \tag{4.2}$$

where n is the porosity, $L = 334E3\ kJ/t$ is the latent heat of fusion, ρ is the soil density and C is the soil specific heat capacity.

From the above input values, the equivalent frozen and unfrozen volumetric heat capacity of the soil (ρC) can be deduced: 2413 $kJ/m3/°C$ and 3145 $kJ/m3/°C$, respectively.

Another important fact is that in thermal flow analysis, only thermal properties of the porous medium (soil) are essential for problem-solving. The soil input parameters in table 4.1 are similar to original data for later comparison. These values are discussed later in Section 6).

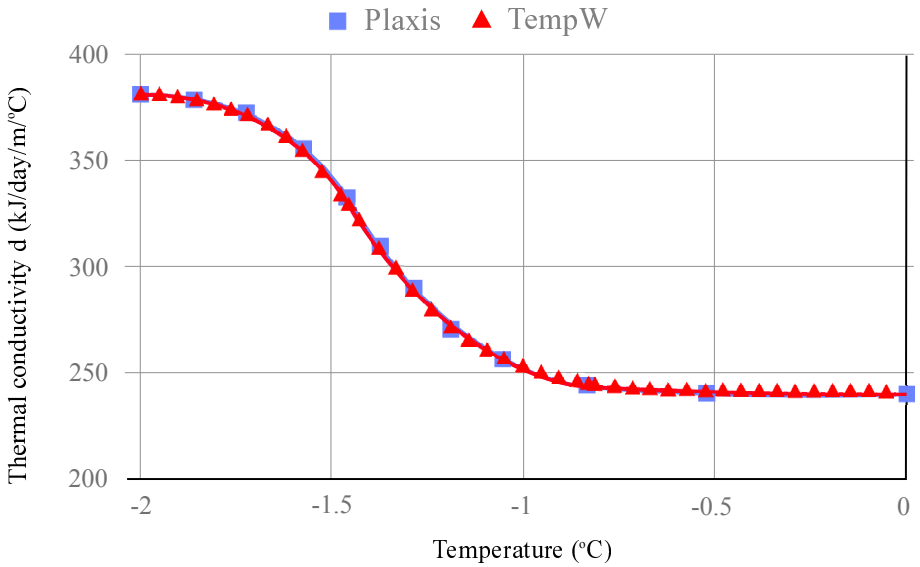


Figure 4.2 Soil thermal conductivity (data deduced by PLAXIS compared with original data)

5 INITIAL AND BOUNDARY CONDITIONS

The initial material activation temperature is set to $0°C$.

Both left (symmetry line) and right boundary (far field) are assumed to be insulated. A constant geothermal heat flow (inflow boundary condition) of $0.9259 W/m^2$, corresponding to $8\ kJ/day/m$, is prescribed to the base of the model. The temperature at the base of the building is constant at $15°C$ (upper boundary of the model from $X = 0$ to $X = 5m$).

At the ground surface outside the building, some options are available for users. A climate boundary condition may apply to calculate heat exchange at the ground surface using air temperature data during a year. In this example, for later comparison, the same ground surface temperature data as original input data (derived from the calculation of the other simulator TempW from the air temperature data) apply directly on this boundary via the time-dependent option of temperature function (Figure 5.1). The yearly air temperature and resulted ground surface temperature can be downloaded from the PLAXIS knowledge base website (air temperature datum, ground surface temperature datum). Note that the analysis will be performed for four years and these provided data (available for one year) should be correspondingly repeated four times in PLAXIS Input (Figure 5.2).

The *Thermosyphon boundary condition* is applied on the evaporator pipe locations. This requires the threshold values $T_{fluid\ max} = -0.5°C$ and $T = 1°C$, as well as the air temperature data Figure 4.2. Other necessary values are the heat transfer coefficient $h(kW/m^2/°C)$ which is calculated in this 2D example as follows:

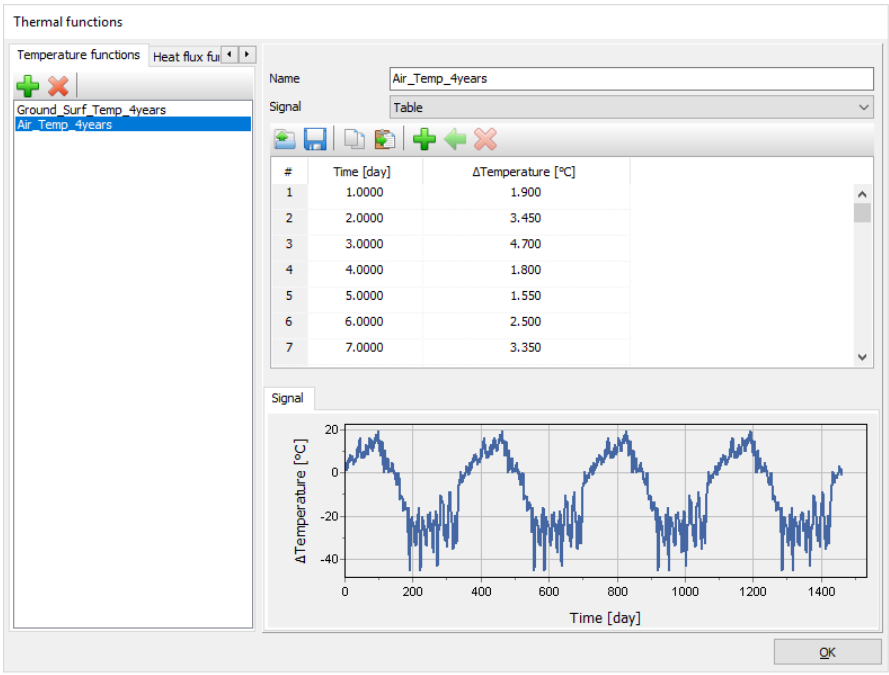
$$h = P/A \tag{5.1}$$

where $A\,[m^2]$ is the surface of the pipe:

$$A = \pi D \cdot L \tag{5.2}$$

where D is the diameter (2 cm in this example), and L is the length of the evaporator pipes.

The overall conductance P, as discussed in Section 2, can be computed based on different factors (wind speed, emplacement of the thermosyphon next to the building) and by various empirical formulae (see Wagner (2014)). In PLAXIS, users are free to choose the method and data to compute the values of P and h, depending on each heat exchanger product and application situation. Then, the value of h can be assigned directly to the transfer function in PLAXIS via the time-dependent table option (Figure 5.2). In this example, this transfer function h is calculated in the same way as Geo-slope (2016) for comparison. Its yearly value can be downloaded from PLAXIS website. All the boundary conditions are illustrated in Figure 5.3.



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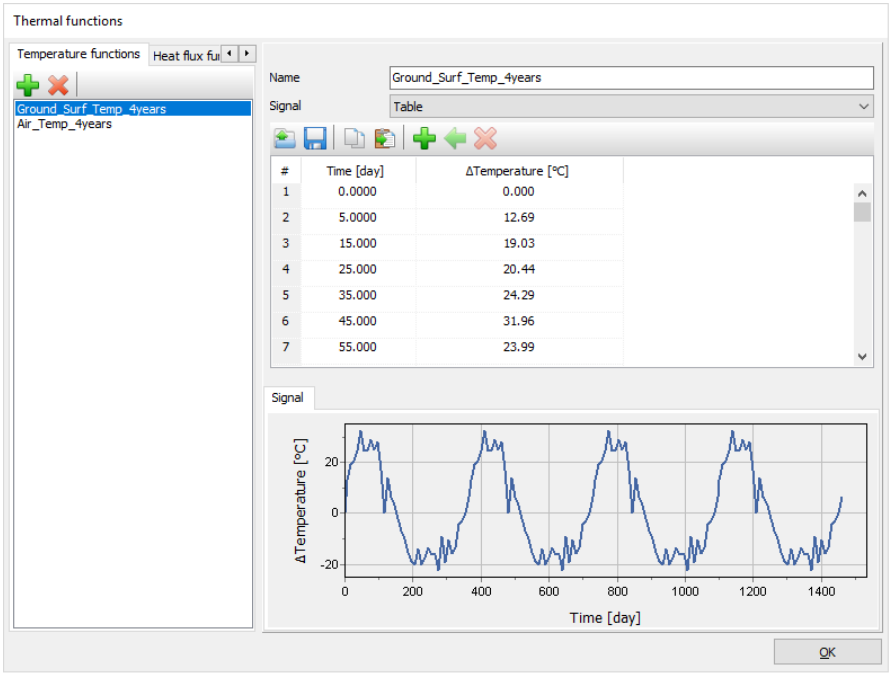


b.

Figure 5.1 (a) Air and (b) Ground surface temperature table functions for 4 years

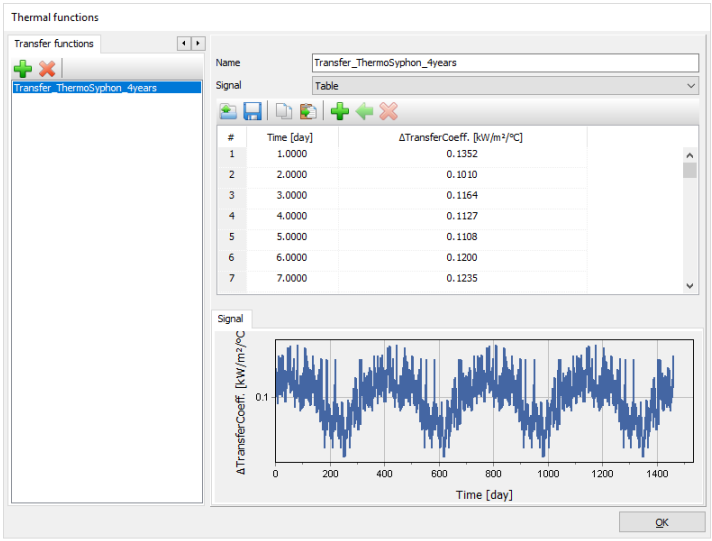


Figure 5.2 Transfer coefficient function for 4 years

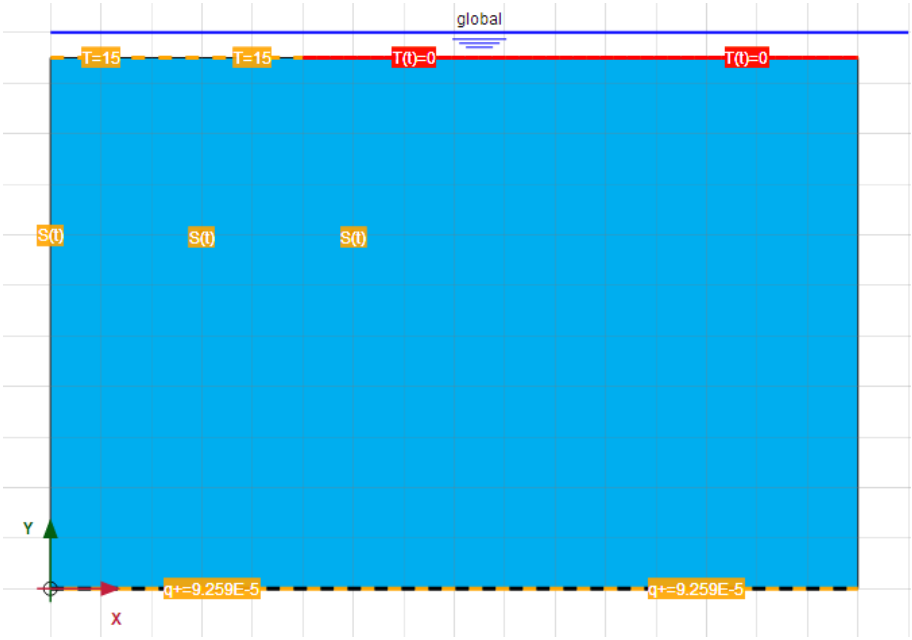


Figure 5.3 Boundary conditions of the model with ground temperature functions $T(t)$ around a reference value of $0^{\circ}C$, building temperature $T = 15^{\circ}C$, inflow imposed flux $q = 0.9259 W/m^2$, thermosyphon $S(t)$ with a time-dependent transfer function $S(t)$ at pipe boundary.

6 CALCULATIONS AND RESULTS

The calculations are carried out during an initial phase, then a succeeding phase (phase 1), both are in the Flow only mode for Calculation Type. The thermal calculation type is an earth gradient during the initial phase and transient thermal flow during the phase 1. A small time step (max 0.25 day) is chosen to facilitate convergence, and consequently, the max number of steps is set to be 10000 steps (see Figure 6.1) to cover four years (1460 days) analysis. The calculation log information is also available here.

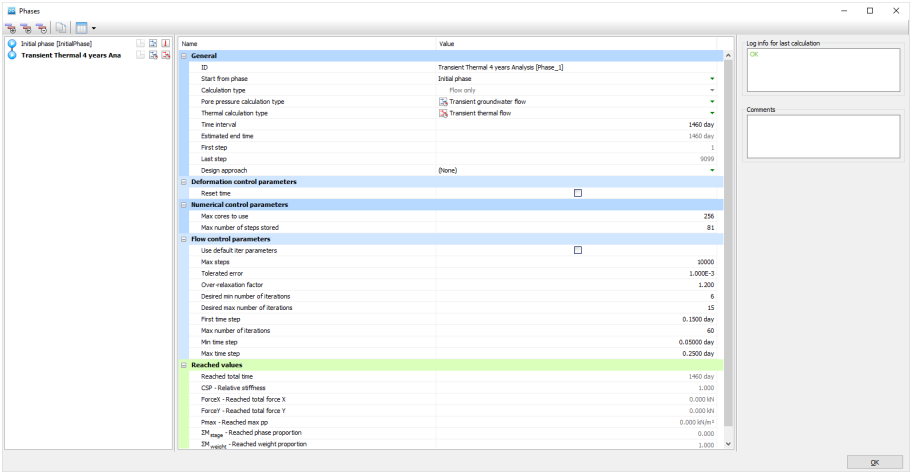
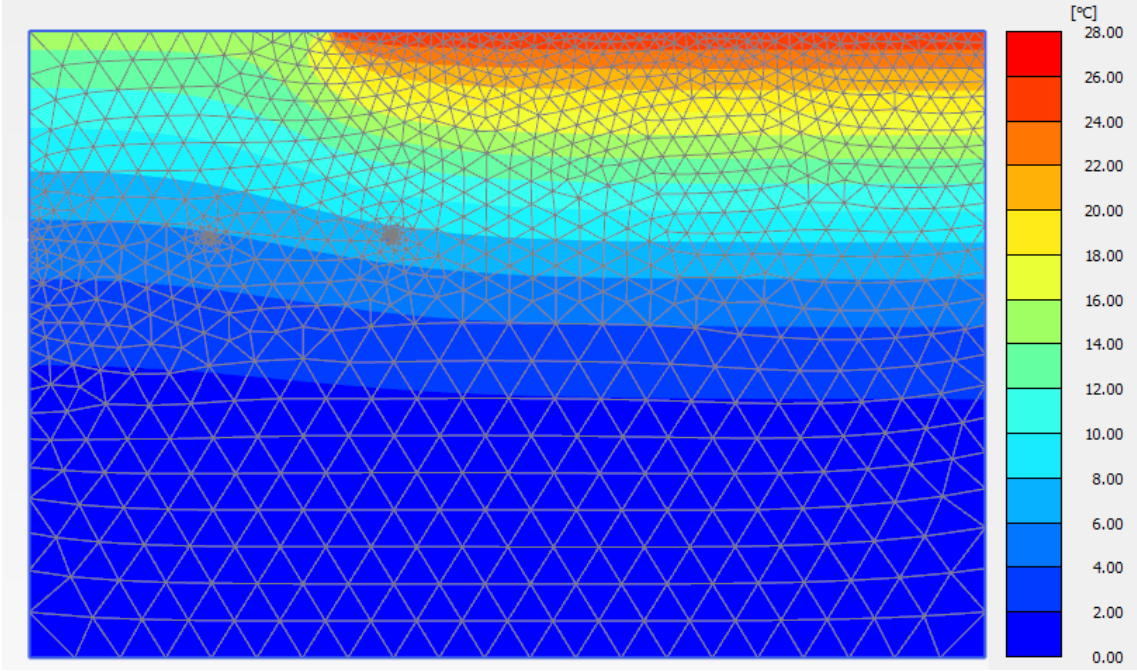


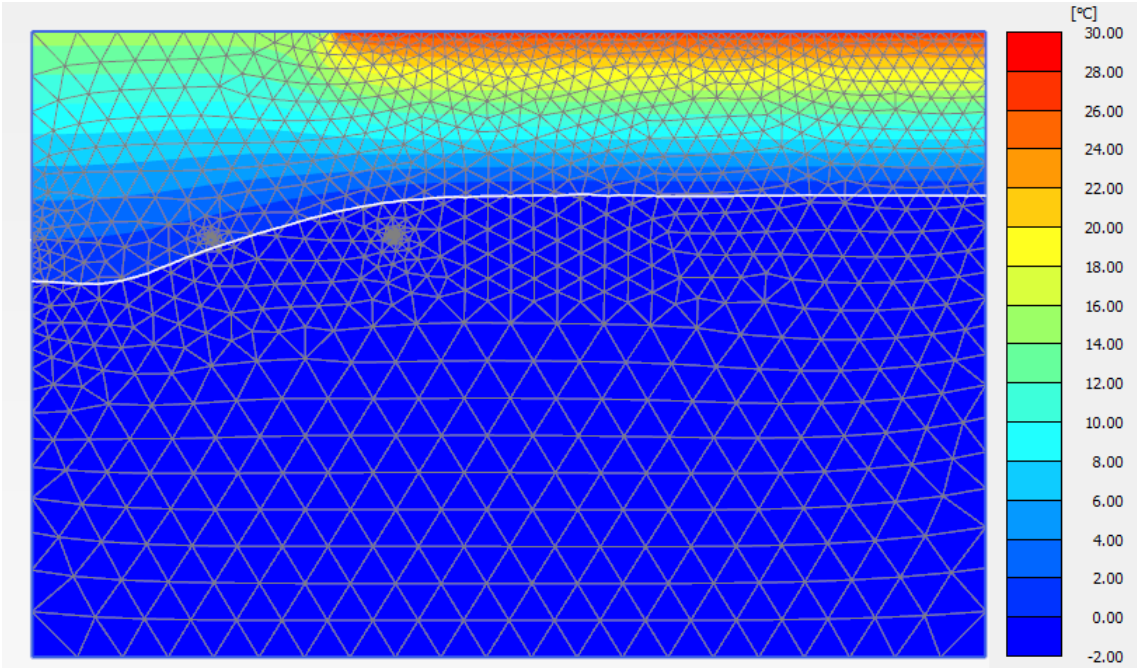
Figure 6.1 Calculation parameters in Phases box

Figure 6.2 shows the temperature profile in the middle of summer of the first year (90th day) and the same period of the fourth year (1190th day). The whole ground is hotter than $0^{\circ}C$ during the first summer due to the effect of air and building temperature, so no frost line is observed (Figure 6.2a). The ground becomes much colder at the same period of the fourth year since heat is extracted during each winter. The position of the frost line (display option available in *Geometry* menu of the PLAXIS output program) indicates that a large region of the ground (below this line) is maintained in a frozen state despite summertime Figure 6.2b. This illustrates the permafrost protection by thermosyphons that helps to stabilize the ground.

Figure 6.3 shows the temporal evolution of the temperature at different locations at the symmetry axis of the model A(0,0), B(0,3.2) and C(0,6.06). It is observed that far from the surface, air temperature variation influences the ground temperature less. The temperatures at all the points decrease year by year, what shows that thermosyphons help to preserve the cold in the permafrost. The PLAXIS results are also very close to the results published by the other simulator with the same model input (as explained in sections 3 and 4). A small difference between the results may emanate from the fact that PLAXIS considers the real geometry of evaporator pipes, while the other simulator models these pipes by free points, which is a simplifying assumption. It is also expected that the bigger the pipes are, the larger the difference between these two methods is. Note that in other applications, pipe size may be much higher than that used in this example (Wagner (2014), Abdalla, Fan, Mckinnon & Gaffard (2015)).



a.



b.

Figure 6.2 Temperature profile of the ground at the 90th day (a) and the 1190th day (b)

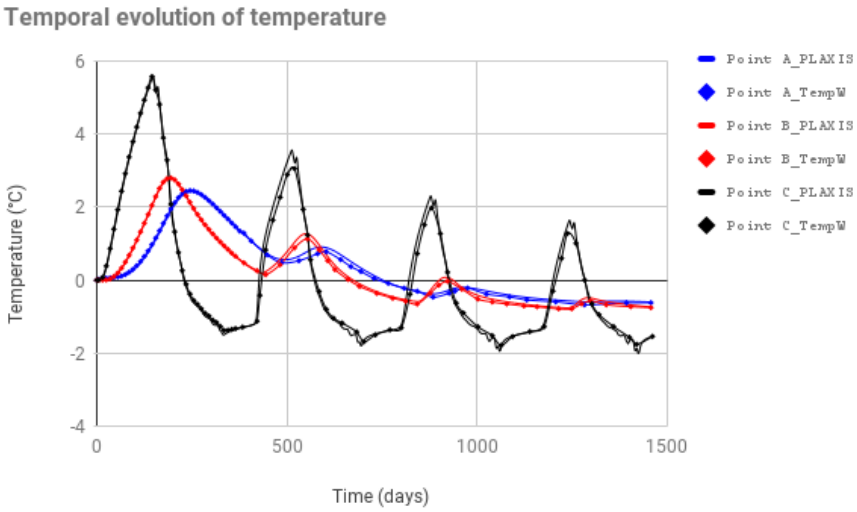


Figure 6.3 Temporal evolution of temperature at different locations at the line of symmetry

7 CONCLUSIONS

This report illustrates the thermal analysis of thermosyphon-ground systems in Geotechnical engineering using PLAXIS 2D finite element software. A typical engineering application of thermosyphon foundation subjected to yearly air temperature variation and a permanent heated building is presented. A theoretical background of thermosyphon is briefly introduced. The key factors influencing the ground response are performance characteristics (thermal conductance) of thermosyphon, air temperature, soil thermal properties and evaporator pipe size. All these factors can be modelled by different flexible functionalities in PLAXIS, including time-dependent temperature and heat transfer functions and especially Thermosyphon boundary condition. The obtained results are consistent with physically-expected ground responses, showing the permafrost protection by a thermosyphon system.

8 REFERENCES

[1] Abdalla, B., Fan, C., Mckinnon, C., Gaffard, V. (2015). Numerical study of thermosyphon protection for frost heave. In Numerical study of thermosyphon protection for frost heave. St. John's, Canada.

[2] Geo-slope (2016). Thermosyphon in end view. Technical report, Geo-slope International Ltd.

[3] Long, E.L., Zarling, J.P. (2004). Thermal Analysis, Construction, and Monitoring Methods for Frozen Ground. University of Belfast.

[4] NSC (2013). Thermosyphon foundations for buildings in permafrost regions. In Thermosyphon foundations for buildings in permafrost regions. Canada.

[5] Wagner, A.M. (2014). Review of thermosyphon applications. Technical report, US Army Corps of Engineers.