Bulletin d'Hydrogéologie No 17 (1999)
Centre d'Hydrogéologie, Université de Neuchâtel
EDITIONS PETER LANG

PILESIM: a simulation tool for pile and borehole heat exchanger systems

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ABSTRACT

PILESIM is a user-friendly programme devised for the thermal simulation of heat exchanger pile systems. A heat exchanger pile system is a system which uses foundation piles for heating and cooling purposes. Borehole heat exchangers may also he simulated with PILESIM. PILESIM is based on the development of simulation tools with the TRNSYS system simulation programme, in which the non-standard TRNVDST component was adapted for the simulation of heat exchanger piles. A short description of the PILESIM programme is presented.

KEYWORDS

Heat exchanger piles, borehole heat exchangers, ground coupled system, dynamic system simulation, thermal simulation tool

1. Introduction

A pile foundation is used when the upper layers of soil are too soft and compressible to support the loads of a superstructure, normally a building. A heat exchanger pile is a pile foundation equipped with a pipe system, in which a heat carrier fluid can he circulated so as to exchange heat with the surrounding ground. The two main functions of a heat exchanger pile are thus to support the loads of a superstructure and to serve as a heat exchanger with the ground. A heat exchanger pile system is comprised of a set of heat exchanger piles which are connected together hydraulically, and normally are coupled to a heat pump. Such a system is usually used for heating andor cooling purposes.

The principal constraint on the system is that the thermal solicitations withstood by the piles must not deteriorate their mechanical properties, i.e., their ability to support the loads of the building. In particular, freezing of the piles must be avoided. In a safely sized heat exchanger pile system, the fluid temperature in the piles never drops below 0 "C for a long period of time. This temperature constraint influences the size of the heat pump, which in turn affects the heating potential provided by the heat exchanger piles. When direct cooling is performed, i.e. when the pile flow circuit is connected to the cold distribution without a cooling machine in between, the cooling potential also depends directly on the temperature level of the fluid in the cooling system. The annual extracted and injected thermal energy through the piles determines the evolution of the ground temperature year after year, which in turn may affect the thermal performances of the system. An accurate assessment of the heating and cooling potential offered by a heat exchanger pile system requests a dynamic simulation of the system, which takes into account both short-term and long-term thermal performances. It requires good knowledge of the systemís thermal characteristics, the local ground conditions and the use of an accurate system simulation tool.

Simulation tools of heat exchanger pile systems have been developed in the Laboratory of Energy Systems (LASEN), at the Swiss Federal Institute of Technology in Lausanne (EPFL) (see FROMENTIN et al. 1997). Their development has been carried out with the help of measurements from existing systems for comparison and validation purposes. The well-known transient system simulation programme TRNSYS (IUEIN et al. 1998) was used. A non-standard simulation model, devised for heat storage in the ground with borehole heat exchangers (PAHUD et al. 1996a), has been adapted for heat exchanger piles (PAHUD et al. 1996b) and used to build up the simulation tools. However, the required level of knowledge limits their use to few experts in the field. Simple design rules were also established with the help of these simulation tools (FROMENTIN et al. 1997), but they are limited to special cases only. There is a need for a design simulation tool for such systems which can be used by people who are not necessarily experts in system simulation, and which still provides sufficient flexibility for a large variety of system concepts.

In the framework of a research project relative to the simulation of a heat exchanger pile system at Ziirich airport (HUBBUCH 1998), the experience gained in the simulation of such systems was used to create PILESIM (PAHUD 1999). The development of the simulation tools that were validated with measurements from existing systems (FROMENTIN et al. 1997) forms the basis of PILESIM. This programme offers easy use and relatively fast calculations. PILESIM may also be used for the simulation of ground coupled systems with a relatively large number of borehole heat exchangers. A borehole heat exchanger is a borehole equipped with a pipe system (for example with U-shape pipes) to exchange heat between the heat carrier fluid and the ground.

2. The PILESIM simulation tool

PILESIM has been developed with TRNSYS (KLEIN et al. 1998) and then adapted to the TRNSED format. Thanks to the TRNSED application, a stand alone programme can be created. In addition, the TRNSYS simulation tool is embedded in a user-friendly interface which provides online help and allows a non-specialist TRNSYS user to use the programme.

2.1 What does PILESIM simulate ?

In Fig. 1, a schematic view of the type of systems simulated by PILESIM is shown. **A** great flexibility has been given to PILESIM in order to provide a large variety of systems that can be simulated.

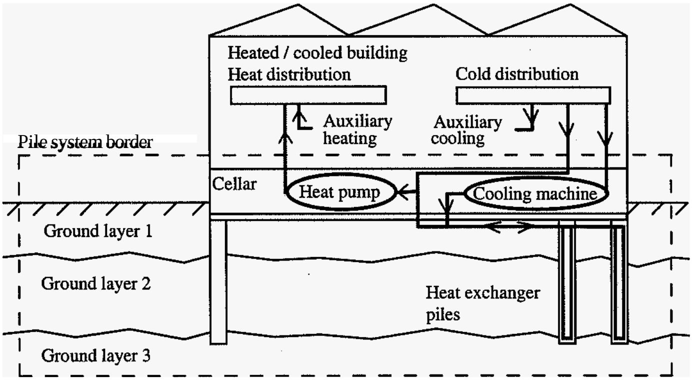

Figure 1: Schematic view of a heat exchanger pile system. The part of the system which is simulated by the PILESIM programme is delimited by the pile system border shown with the dashed line.

The pile system border shown in Fig. 1 indicates the limits of the thermal simulations. The heat transfers are calculated from the ground to the thermal energy distributed in the building (heating and cooling). In particular, the heat transferred by the piles, by the horizontal connecting pipes under the concrete plate of the cellar, through the floor and ceiling of the cellar are assessed. The cellar, assumed to be unheated, has a temperature which depends on the indoor building temperature, the outside air temperature and the ground temperature below the building. The cellar can he given the temperature of the outside air by an appropriate setting of heat transfer coefficients.

The loading conditions, determined by the heat demand, the cold demand and their corresponding temperature levels, are contained in a text file and read by the programme. Predefined values are stored in files for several locations and can readily he used **for** a simulation. These predefined loading conditions are established on the basis **of** simple models which determine the space heating and space cooling requirements. The user also has the possibility to use his own loading conditions with PILESIM, in order to make them correspond to his particular problem. A temporal evolution of the hourly loading conditions is required for a whole year.

Four different types of system can be simulated. Heating can either be combined with a thermal recharge of the ground during the summer, or with cooling which can be performed in three different manners: a cooling machine, direct cooling, or a combination of the two.

2.2 How may PILESIM be used ?

PILESIM can be used in different ways, depending on the degree of knowledge of a project. At an early stage, a pre-simulation can be performed by using a predefined file for the loading conditions, a constant performance coefficient for the heat pump and a constant efficiency for the cooling machine. Later in the project, more will obviously be known about the building. The pile system's parameters will also be better known and more accurate loading conditions can be established with the help of another programme. They can be used to create an input data file for PILESIM, and a more precise simulation of the pile system can be performed, which may include the temperature-dependent heat pump performance coefficient and cooling machine efficiency.

2.3 What does PILESIM calculate ?

The energies transferred between the different components of the systems are calculated and integrated on a monthly or a yearly basis. A global heat balance of the system can be made month by month or year by year. The Sankey diagram shown in Fig. 2 can be established with PILESIM.

Temperature levels, the heat pump performance coefficient and cooling machine efficiency, etc. are also calculated. The influence of long terms effects on the results can be assessed for up to 25 years. The temporal evolution of some energy rates and temperatures are printed in a file for the last simulated year. They can be then plotted thanks to a functionality of TRNSED.

2.4 How does PILESIM calculate?

Once the loading conditions are chosen and all the system parameters fixed, a simulation can be started. The undisturbed ground temperature is chosen for the initial conditions of the ground. The thermal simulation is performed with a time-step set to one hour. At each time-step, the operational mode of the system is determined, depending on the system type chosen, the current loading conditions and the system component's thermal performances (heat pump, cooling machine, heat exchanger piles, etc.). Three basic operational modes are possible (cf. Fig. **3).**

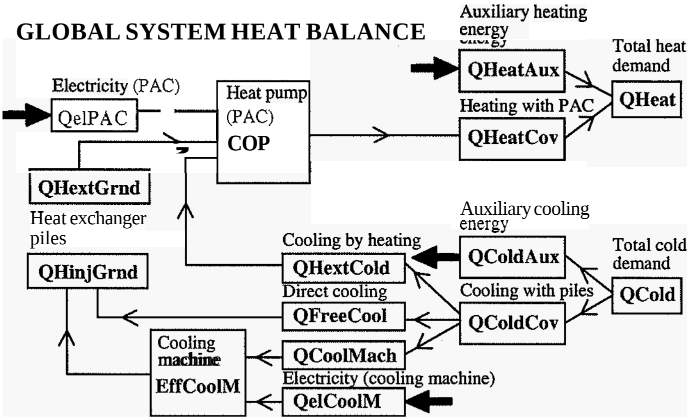

Figure 2: Sankey diagram which can be established with the quantities calculated with PILESIM

Heating and cooling can be simultaneously satisfied with each of these three operational modes. The mode that satisfies the greatest part of the heating and cooling demands is chosen. If there is no cooling requirement when heating is needed or vice versa, the three basic operational modes are reduced to three simple situations:

- heating with the heat pump connected to the piles;
- direct cooling with the piles connected to the cold distribution;
- cooling with the cooling machine connected to the piles.

The heat pump performance coefficient and the cooling machine efficiency may depend on the temperature levels of the heat carrier fluid in the condenser and evaporator. The performance coefficient determines the heating power, with the help of the design electric power of the heat pump, set to a constant value. If the heating requirement is smaller, the heating power is decreased to match the heating requirement. **As** a result, the electric power consumed by the heat pump and the heat rate extracted at the evaporator are recalculated with the help of the performance coefficient. The heating power of the heat pump may also be reduced by the temperature constraint associated with the heat carrier fluid which circulates in the piles. This constraint requires that the fluid temperature in the piles never drops below a user given value, normally fixed at 0 °C. If this is not the case, the heat rate extracted by the heat pump is decreased until the fluid temperature satisfies the criterion. As a result, the heating power delivered by the heat pump is reduced. In consequence, an oversized heat pump will not yield much more heating energy per year than a correctly sized one. A temperature constraint is also given for the highest allowed fluid temperature in the pile flow circuit. The same kind of considerations apply for the cooling machine.

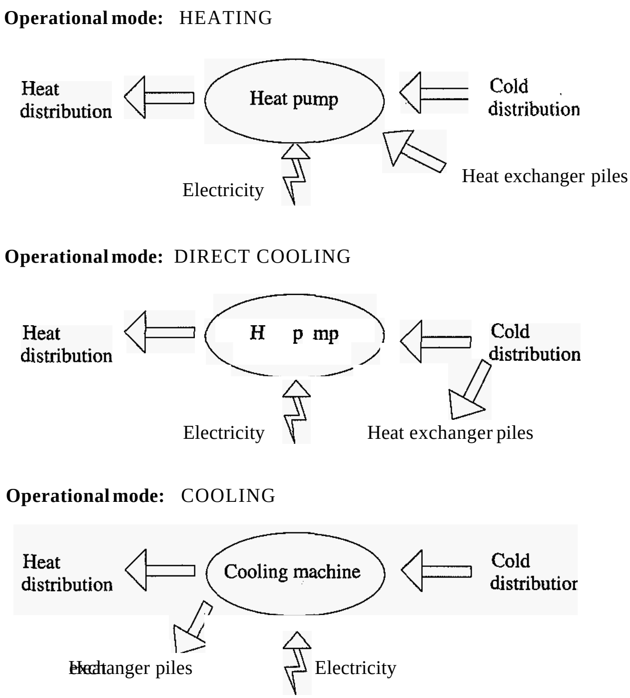

Figure 3: The three drawings illustrate the three basic operational modes of the heat exchanger pile system. The arrows indicate the direction of the (positive) energy fluxes

PILESIM assumes an optimal system control the best operational mode is selected; the heating and cooling powers are adjusted to the heating and cooling demands if necessary, while the temperature constraints on the heat carrier fluid in the piles are satisfied. The influence of frequent starts and stops of the heat pump and cooling machine is not taken into account, although a penalty value can be specified on the performance coefficient and efficiency.

2.5 Main assumptions of the PILESIM simulation tool

As previously mentioned, the system control in PILESIM is optimal. Other assumptions are related to the specificity of the simulation model used. The heat pump model is based on the model used in the MINSUN programme (MINSUN 1985). The heat exchanger piles are simulated with TRNVDSTP (PAHUD et al. 1996b). This model assumes a uniform arrangement of the heat exchanger piles in a ground volume, called store volume, which has the shape of a vertical cylinder. The thermal process in the ground is treated as a superposition of a global and a local problem. The global problem handles the large-scale heat flows in the store volume and the surrounding ground, whereas the local problem takes into account the heat transfer between the heat carrier fluid and the store. The global and local problems are solved for pure heat conduction with the use of the explicit finite difference method (FDM). The model, not suited for the computation of a ground water flow, uses approximations instead. They are based on the beat transfer induced by forced convection on a cylinder imbedded in a porous media (NIELD & BEJAN 1992). The main assumptions of PILESIM are:

- the number of heat exchanger piles is relatively large;
- the spatial arrangement of the heat exchanger piles is more or less regular;
- the ground area occupied by the heat exchanger piles bas a shape which is more or less the shape of a circle or a square;
- the heat exchanger piles have about the same active length. (The active length of a heat exchanger pile is the length along which a radial heat transfer takes place.)

These assumptions imply that most of the beat exchanger piles are surrounded by other heat exchanger piles. In other terms, PILESIM is not suited to the simulation of a single heat exchanger pile or several heat exchanger piles arranged in a line. When the shape of the ground area occupied by the heat exchanger piles is far from being a circle or a square, or the pile arrangement is highly irregular, the average pile spacing; which is a input parameter to PILESIM, can be calibrated with another programme. (For example with TRNSBM (ESKILSON 1986; PAHUD et al. 1996c)).

3. Conclusion

PILESIM is a new simulation tool for beat exchanger pile systems developed with TRNSYS. People involved in the planning of a heat exchanger pile system should be able to use PILESIM, although they are not necessarily accustomed to **TRNSYS.** System thermal performances, utilisation potential of heat exchanger piles and a large variety of system designs can be assessed with PILESIM.

Acknowledgements

The authors would like to acknowledge the Swiss Federal Office of Energy for its financial support.

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