6 HEAT EXPLOITMENT FROM THE GROUND

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6.1 General Considerations

The need to reduce carbon dioxide emissions and to significantly increase energy production from renewable sources in response to climate change has led to an emerging interest in geothermal resources, especially shallow ones. Their use is independent of geographical location, since they are accessible all over the world, making them a local, reliable, and economically competitive energy source. Recent research developments show how, in addition to conventional open-loop and closed-loop geothermal systems, it is also possible to use geotechnical structures in contact with the ground as heat exchangers, so-called energy geostructures (EGS). They consist of equipping underground structures with closed-loop ground source heat pump systems, hence serving the dual purpose of (1) supporting soil and/or the overlying building and (2) exchanging heat with the surrounding ground (Brandl, 2006). EGS have been shown to represent a viable alternative to more traditional borehole heat exchanger (BHE) systems, since they remove the need (and cost) for special purpose excavations, whilst benefitting from a larger efficiency (e.g., as represented by the COP) compared to other (non-geothermal) space heating/cooling systems.

The fluid flowing in the tube heat exchangers embedded in the geostructure allows heat transfer from the ground to the buildings or vice versa, through ground source heat pumps. These pumps absorb heat from a low temperature fluid and transfer it, at a higher temperature, to another fluid. In heating mode, the heat pump transfers heat from the subsoil to the building. In cooling mode, the process is reversed, and heat is removed from the building and transferred to the subsoil, through a reversible valve that changes the fluid direction in the pump. From the same equipment it is therefore possible to obtain a heating system for the winter and a cooling system for the summer. The main elements of a heat pump are the evaporator, the compressor, the condenser, and the expansion valve (Fig. 6). In the evaporator the heat is transferred from the subsurface to the refrigerant fluid characterized by a low boiling point (working fluid) flowing within the heat pump. As its temperature rises, the fluid evaporates and flows into the compressor, which, by compressing it, increases its temperature. Subsequently, the hot vapor transfers its heat to the fluid in the distribution system. Then in the condenser the vapor falls in temperature and returns to its liquid state. It then passes through an expansion valve and is cooled further to start the process again.

This chapter will address the possible use of EGS to exploit heat from the ground surrounding an underground excavation such as a tunnel. While Section 6.2 below will provide a glimpse of the different types of EGS, Section 6.3 will describe the main phases of thermal design, which is the primary interest of these Guidelines, with particular reference to energy tunnels

6.2 Energy geostructure types

Several EGS types exist that are currently being developed and experimented by both academics and professionals worldwide. While the basic construction principle is similar for all EGS (namely, embedding pipe heat exchanger loops within the geostructure, typically attaching them to the reinforcement cage prior to concreting), every EGS must be considered on its own with respect to both thermal and (thermo-)mechanical analysis and design criteria, since they are characterized by different loading, geometry and boundary conditions. In this section, an overview is provided of the main EGS types, including energy tunnels (Section 6.2.1), energy piles and micropiles (Section 6.2.2), energy walls (Section 6.2.3).

6.2.1 Energy tunnels

Tunnel linings can be adapted to become an energy geo-structure, by fixing the geothermal coil circuit between the primary and secondary lining in tunnels excavated

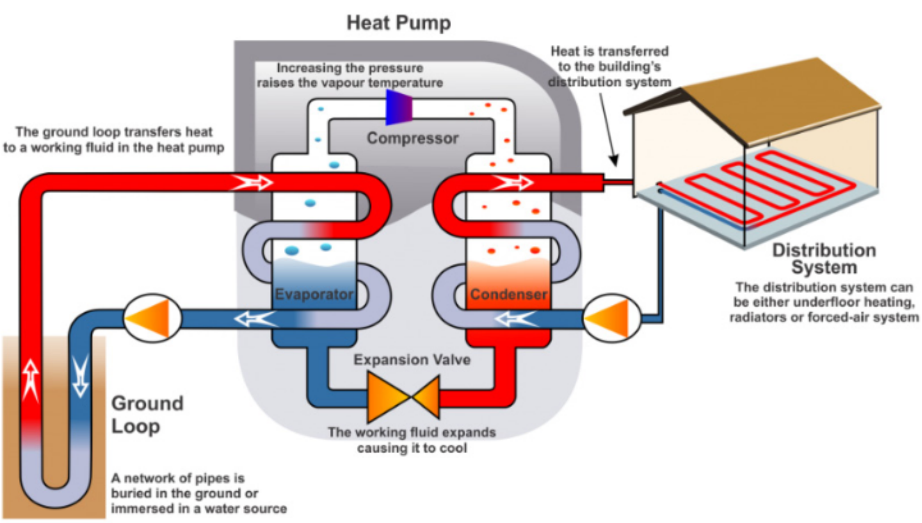

Fig. 6 - Schematic representation of a ground source heat pump installation (from EECA y GNS 2013).

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by conventional methods, or by incorporating it in the prefabricated segments, for tunnels excavated using a mechanized technique (Adam & Markiewicz 2009, Barla et al. 2016, Barla et al. 2019). The thermal energy extracted can have various uses, including air conditioning for underground/subway stations and buildings, the heating of the lining itself, and de-icing tunnel portals, bridge decks and road surfaces in general.

The design process that leads to the construction of an energy tunnel goes beyond specific regulatory references and cannot be reduced to a series of verifications, whether structural and/or geotechnical. It necessarily involves a wide range of issues, including planning the energy supply and distribution in the area. Therefore, as in the case of the recovery of water drained by the tunnel described in Chapter 4, the possibility to build an energy tunnel should necessarily be planned from the feasibility study phase of an infrastructure. Only in this way is it possible to ensure that the infrastructure can contribute to sustainable development, by being integrated into the energy planning of the territory.

More specifically, the thermal activation of tunnel linings involves at least two technical aspects, to be considered during the design phases: 1) structural design, which includes the mechanical effects induced by temperature variations on structural elements to ensure their long-term integrity, and 2) analysis of energy optimization to maximize efficiency at the same cost, i.e. thermal design. If the structural project can reasonably be further developed in the more advanced design phases, the thermal project must be implemented since the conception of the infrastructure.

6.2.2 Energy piles and micropiles

Energy piles (EPs) were among the first type of EGS to be historically developed. Pile types that are most commonly equipped with heat exchangers are rotary bored and continuous flight auger (CFA) ones. The former are the easiest to construct, in that (1) one or more sets of plastic heat exchanger U-loops can be attached to the reinforcement cage before lowering it, then (2) the cage is lowered and finally (3) concrete is poured, while the geothermal circuit is kept full of fluid and pressurized to contrast fluid concrete pressure. CFA piles, on the other hand, usually require a slightly more complex procedure to introduce the geothermal circuit. In fact, in this case the reinforcement cage is introduced after concreting while the concrete is still fluid. An account of the most relevant construction challenges for cast-in-situ EPs can be found in Loveridge et al. (2013).

In addition to the above, other types of EPs have gained some popularity in recent years, including precast thermoactive driven piles (Alberdi-Pagola & Poulsen 2015, Alberdi-Pagola et al. 2019) and micropiles (Salciarini & Cecinato, 2021).

Despite EPs can be considered the most similar shallow geothermal installation to BHEs, due to their similar (axisymmetric) geometry and boundary conditions, important differences exist and bespoke analyses are required (Loveridge & Powrie 2013).

6.2.3 Energy walls

So-called energy walls (EWs) include cast in situ thermo-active diaphragm walls, made of reinforced concrete vertical slabs, sheet pile walls and different types of earth retaining structures made of adjacent piles. In spite of the relatively straightforward construction procedures, involving the attachment of the U-loops to the reinforcement cages prior to concreting, EWs pose significant challenges regarding their thermal performance and operation. In fact, their geometry and boundary conditions are very different to those of EPs. The large surfaces available suggest a high energy exchange potential, but the presence of air on the excavation side exerts a major influence on their thermal performance. Depending on the use of the excavation space, the air temperature boundary condition can exhibit diverse variation patterns with time. For example, for EWs installed as the perimeter walls of an underground car park, the boundary air temperature is likely to follow (with some attenuation) the seasonally changing outdoor one. For EWs used in a metro tunnel, on the other hand, the air temperature is likely to be quite 'hot' regardless of the season, due to the heat rejected by trains' passage (especially due to breaking) and underground station heated spaces in winter.

From the EW thermal performance point of view, Sterpi et al. (2020) identified as key factors the layout of heat exchanger pipes and the embedment depth, concluding that the energy performance can be improved by limiting the thermal interference between different pipe branches. Di Donna et al. (2017) identified the most influential factors to maximise thermal output of EWs, suggesting that increasing the number of pipes is the primary route to increasing energy efficiency in the short term. However, the thermal properties of the wall concrete and the temperature excess within the excavation space are also important, with the latter becoming the most significant in the long term. This confirms the benefits of exploiting, for winter use, EWs in railway tunnels and metro stations where additional sources of heat are available.

In addition to the energy performance, the mechanical one is of paramount importance for EWs due to their primary geotechnical/structural function. In particular, it is essential to account for any additional thermally induced internal actions in the structural design, and make sure that thermo-mechanical displacements lie within acceptable limits.

6.3 The thermal project for energy tunnels

The objective of the thermal project is the quantification of the heat exchange with the ground according to the specific conditions of the site, to assess the real energy efficiency of the installation, indicating its economic viability and environmental sustainability. Determining the efficiency of the system essentially involves the quantification of the heat extracted or transferred to the geothermal reservoir by means of the tunnel lining. Environmental sustainability, on the other hand, refers to the evaluation of the effects of the thermal project on the surrounding environment, in order to

limit their impact.
Since thermal projects in tunnels are a recently introduced technology, there are no clear methodological or normative indications to follow. A procedure for thermal energy tunnel design is proposed and schematized in the flow chart shown in Figure 7.

First, it is necessary to conduct an additional investigation whose accuracy will depend on the design phase considered. The objective is to determine the hydrogeological characteristics of the geological formations hosting the tunnel, since they influence the heat exchange processes. The useful parameters to determine are shown in Table 1. In situ testing techniques include Thermal Response Tests (TRT), widely used for BHEs and EPs, that are useful to assess the thermal conductivity of the soil, the thermal resistance of the heat exchanger, and the undisturbed temperature of the soil. Laboratory testing is divided into stationary methods (e.g. hot plate) and transient methods (e.g. needle probe, transient plane source) to evaluate thermal conductivity, thermal diffusivity, and volumetric heat capacity.

6.3.1 Measurement of thermal and hydraulic properties

When dealing with energy tunnels, additional investigations need to be carried out. Indeed, routine investigations do not provide any information about soil/rock thermal properties, groundwater temperature and, sometimes, about permeability. Both laboratory and in situ tests can be carried out to this aim (Table 2). The most common available techniques will be briefly described in the following.

Laboratory measurements do not account for site-specific conditions such as the presence of groundwater flow, spatial heterogeneity, and scale effects that directly impact actual thermal properties (Vieira et al. 2017). However, these analyses are relatively cheap and can be a suitable method to provide a first estimation of soils and rock thermal properties. Several tools can be employed to measure thermal properties (Raymond et al. 2017). Both steady state and transient methods exist.

In steady state methods (e.g. guarded hot plate, divided cut-bar, thermal cell) a constant thermal flow is applied through the specimen to obtain a thermal gradient, the measurement is taken when temperature does not vary with time and interpretation is done through the Fourier's law. The duration of such tests is long, hence moisture migration and heat losses may affect the result. A heat flow meter can be used to quantify the thermal conductivity of plugs, which can be obtained from rock samples collected at outcrops or from drilled cores. The measurement can be done at a controlled temperature, from both dry and water saturated samples, to represent the temperature-dependency of thermal conductivity.

Transient methods are shorter, therefore with no moisture migration issues, and are performed at a smaller scale compared to steady state methods. A thermal conductivity scanner with an infrared heat source can be applied for transient thermal conductivity and diffusivity analysis of hand specimens and core samples at room temperature. The transient heat transfer analysis achieved with this tool has a small depth of penetration and allows a local evaluation along the scan line, being useful to identify potential heterogeneity in the rock sample. A needle probe can be used as well for transient thermal conductivity and diffusivity analysis at room temperature. A narrow hole must be drilled in the sample where a temperature sensor is inserted and then the thermal conductivity is calculated from the transient temperature perturbation. The heat pulse transmitted to the sample has a limited depth of penetration, such that this analysis reveals point values that are representative of the homogenous samples.

It is highlighted that in the case of coarse soils the appropriate density and moisture content need to be reconstituted before performing the test.

The Thermal Response Test (TRT) is an in-situ technique that allows to evaluate ground thermal properties, i.e. undisturbed temperature, effective soil/rock thermal conductivity and thermal resistance, accounting for groundwater and other disturbances. It can be conducted using the conventional method or recently developed methods.

In the conventional method a constant heat power is injected into a borehole heat exchanger, 150-200 mm in diameter, via circulating fluid and the temperature response in measured. In a first stage undisturbed ground temperature is measured, then a constant thermal power is injected for 2-3 days, inlet and outlet temperature, flow rate, ambient temperature and electrical power are measured every 1-10 minutes and a recovery phase is then performed. As ground heat flow is radial, it can be represented as a line source. Hence, thermal conductivity and thermal resistance can be interpreted by

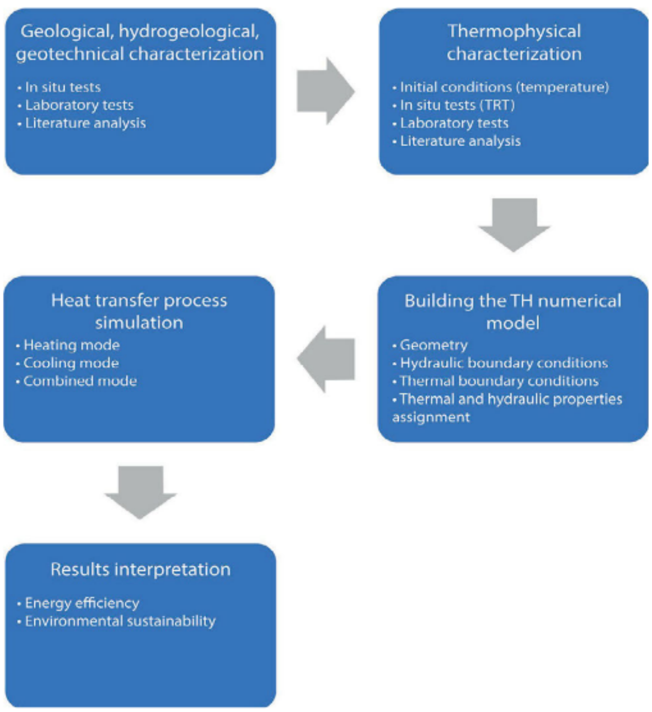

Fig. 7 - Thermal design procedure for an energy tunnel (Barla 2020; Insana 2020).

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means of the Infinite Line Source (ILS) mathematical model of heat transfer.

More recent methods are focused on reducing cost using heating cables that do not require water circulating in the BHE: this new approach permits the use of a smaller power source and simpler test execution (Raymond et al. 2020). Two main cable installations can be used: continuous and interchanging sections of heating and non-heating cable. Heating cables are located in the water column of the BHE, together with submersible temperature sensors or with fiber optic distributed temperature sensing technology. The analysis of the temperature data collected during the test to estimate the thermal conductivity of the lithological formation is similar to that of a conventional TRT, based on the infinite line source solution (Stauffer et al. 2014). A finite heat source solution must be used when a TRT with heating cable sections is conducted, to reproduce the measured temperatures along the heating sections, which are usually 1–2 m long. Both solutions assume only conductive heat transfer. However, water movements due to free convection that can occur at the interface between heating and non-heating sections make the test analysis more complex. Perforated rubber discs have been installed at the boundary between heating and non-heating sections to reduce free convection effect. Field tests have shown that the continuous heating cable is more accurate than the heating sections TRT (Vélez et al. 2018). Additionally, a method to infer groundwater flow direction and magnitude with temperature sensors surrounding the heating cable has been proposed (Raymond et al. 2020).

Undisturbed ground temperature can also be evaluated at different depths in a piezometer by means of a phreatimeter with thermocouple or can be monitored continuously and remotely.

As regards the hydraulic properties, pumping tests or slug tests can be used for the measurement of hydraulic conductivity. In the former, a well is pumped at a controlled flow rate and water-level response is measured in one or more surrounding observation wells and optionally in the pumped well itself. In the latter, water is quickly added or removed from a groundwater well and the change in hydraulic head is monitored with time. Additionally, a laboratory or portable permeameter can be used to quantify the permeability of the formation in core samples or in the field, respectively.

Laboratory measurements can then be compared with those conducted in the field to analyze the scale effect and obtain a more detailed quantification of the thermal and hydraulic values to be used in the numerical models, as described in the next section.

6.3.2 Thermo-hydraulic numerical modeling

The amount of exchangeable heat depends on several factors. To obtain a first approximate assessment, it is possible to use the nomograms suggested by Insana and Barla (2020) where the amount of exchangeable heat is evaluated as a function of several parameters, such as subsurface temperature, groundwater flow, soil thermal conductivity, orientation of the groundwater direction, and the inlet temperature of the heat transfer fluid.

For a more complete quantification, a 3D thermo-hydraulic numerical model reproducing a portion of a thermally activated lining must be created. For example, in the case of energy segments, it is possible to reproduce a limited number of tunnel rings equipped for heat exchange (see Alvi et al., 2022). In general, finite element or finite difference methods specifically coded to solve THM (Thermo-Hydro-Mechanical) or TH (Thermo-Hydraulic) mathematical formulations, are used, depending on the physical phenomena to be simulated. Typically, the analyses are performed by reproducing the operation of the lining for a certain number of years to analyze not only the short-term effects, but also and above all the long-term ones. To build a numerical model, it is necessary to reproduce the correct geometry of the tunnel faithfully, including the layout and geometry of the geothermal installation; moreover, the hydrogeological and thermal conditions of the subsurface must be incorporated in the model as boundary and initial conditions. For example, groundwater flow can be reproduced by applying a hydraulic head difference on the boundaries of the model as a boundary condition to reproduce the flow direction observed in situ, with a magnitude depending on the hydraulic conductivity of the existing geological formations. In a transient simulation, the initial conditions must describe the initial value of the hydraulic head and temperature in the whole model. Next, the analysis is conducted by imposing the temperature at the inlet and the flow velocity at the inlet and outlet of the tube heat exchanger and calculating the temperature at the outlet, which will depend on the heat transfer mechanism that is numerically reproduced during the simulation. By varying the inlet temperature, the analysis can permit simulation of the average behavior in the different periods of activation of the geothermal installation. For example, by applying an inlet temperature of between 24° and 28°C, it is possible to simulate summer operation, when excess heat is injected and allowed to disperse back into the ground. On the contrary, by imposing an inlet temperature of between 3° and 6°C, it is possible to simulate winter operation, when heat is extracted from the ground.

Finally, by varying the inlet temperature cyclically, in accordance with the annual operating mode, it is possible to simulate the seasonal behavior of the installation and evaluate the long-term effects.

The thermal power exchanged in winter and summer can be calculated from the temperature difference between the inlet and outlet of the tube heat exchangers and used to determine the geothermal potential of the tunnel section of interest. This assessment is necessary in order to select the ground source heat pump size most appropriate to each project.

As regards the environmental sustainability analysis, the objective is to verify the impact of the energy tunnel lining on the surrounding environment and possible positive and negative interferences with other existing plants (open-loop, closed-loop, ecc.). A thermo-hydraulic numerical model can also be used for this purpose, to reproduce the groundwater flow and assess the magnitude of the thermal variations induced in the aquifer and in the subsoil for the real operating conditions of the energy geostructure (Barla et al., 2018).

Finally, one of the peculiarities of energy tunnels that can significantly affect their performance is the air temperature inside the tunnel, as shown in several studies (Bourne-Webb et al. 2016; Insana and Barla 2020; Ma et al., 2021).

Tab. 2 - Key properties and parameters required for the thermal design of an energy tunnel.

Propriety or parameter	Symbol	Unit	Material	Testing method
Thermal conductivity	λ	W/mK	Soil/Rock, concrete	TRT, needle probe, transient plane source
Specific heat capacity	S_c	J/kgK	Soil/Rock, concrete	Transient plane source
Undisturbed temperature	T_0	°C	Soil/Rock	TRT, measurement at different depths with phreatimeter with thermocouple in piezometer
Effective porosity	n_e	-	Soil/Rock	Tests with artificial tracers
Horizontal and vertical hydraulic conductivity	K_h, K_v	m/s	Soil/Rock	Pumping tests, slug tests, laboratory and portable permeameters
Groundwater velocity	v	m/s		Piezometric surveys (phreatimeter measurements), test with artificial tracers
Depth of piezometric level	f	m		Piezometric surveys (phreatimeter measurements)
Groundwater flow direction	df	°		Piezometric surveys (phreatimeter measurements)