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Site characterization for the design of thermoactive geostructures

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Review Article

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Site thermal characterization
Undisturbed ground temperature
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Abstract

This paper addresses the topic of site characterization for the design of Shallow Geothermal Energy (SGE) systems, namely of thermoactive geostructures, which are geotechnical structures, such as piles, retaining walls and tunnel linings, also used as heat exchangers as part of closed-loop SGE systems. Such solutions, being increasingly adopted for buildings' and infrastructures' heating and/or cooling, are considered sustainable and cost effective. For the design of the primary circuit of the SGE system, which is embedded within the superficial soil layers, a comprehensive knowledge of the ground condition at the site is mandatory. This includes the evaluation of the energy features and whether the system can provide the required energy needs during the operational period, as well as the verification of the structural and geotechnical safety and functionality requirements. The site characterization for SGE systems involves different stages, from desk studies to detailed characterization, including in-situ trials, laboratory testing of undisturbed soil samples and the study of possible interferences. The specific aspects that will be addressed are: (i) the assessment of the site undisturbed ground temperature and its hydrogeological features; (ii) the thermal and thermomechanical characterization of the different soil layers; (iii) the investigation of the ground-heat exchanger thermal resistance; (iv) the collection of information related to the environmental constraints and to potential interferences among multiple users, which are related to the service life of the structure. The overall aim is to ensure a proper design of the SGE system for guaranteeing its sustainability in the long term.

1. Introduction

The need for adoption of renewable energy systems is increasing every year especially in the context of CO_2 emissions and climate change issues. Shallow Geothermal Energy (SGE) represent sustainable solutions for ensuring easy access to renewable energy for heating and cooling of buildings and infrastructure. Their performance is dependent on many factors, with site characterization being one of the most relevant. Proper use of piles and other buried concrete structures, such as retaining walls and tunnels, not only for geotechnical and structural purposes, but also for heat exchange, relies on an adequate and well-planned thermal characterization of the site. The use of the ground as a thermal reservoir is the conceptual basis of SGE functioning.

The design of the primary circuit of an SGE system involves both energy and geotechnical aspects (Figure 1). Adequate knowledge of the ground conditions for SGE systems allows determining whether the ground can fulfil the energy demand of the structure or infrastructure to be served (e.g.: Brandl, 2006; Barla & Di Donna, 2018; Loveridge et al., 2020) and if the structural and geotechnical integrity of the geostructure is affected due to the additional stresses and strains induced by the cyclic temperature changes (Laloui et al., 2014; Rotta Loria & Laloui, 2017; Insana, 2020; Insana et al., 2020). Also, the soil thermal

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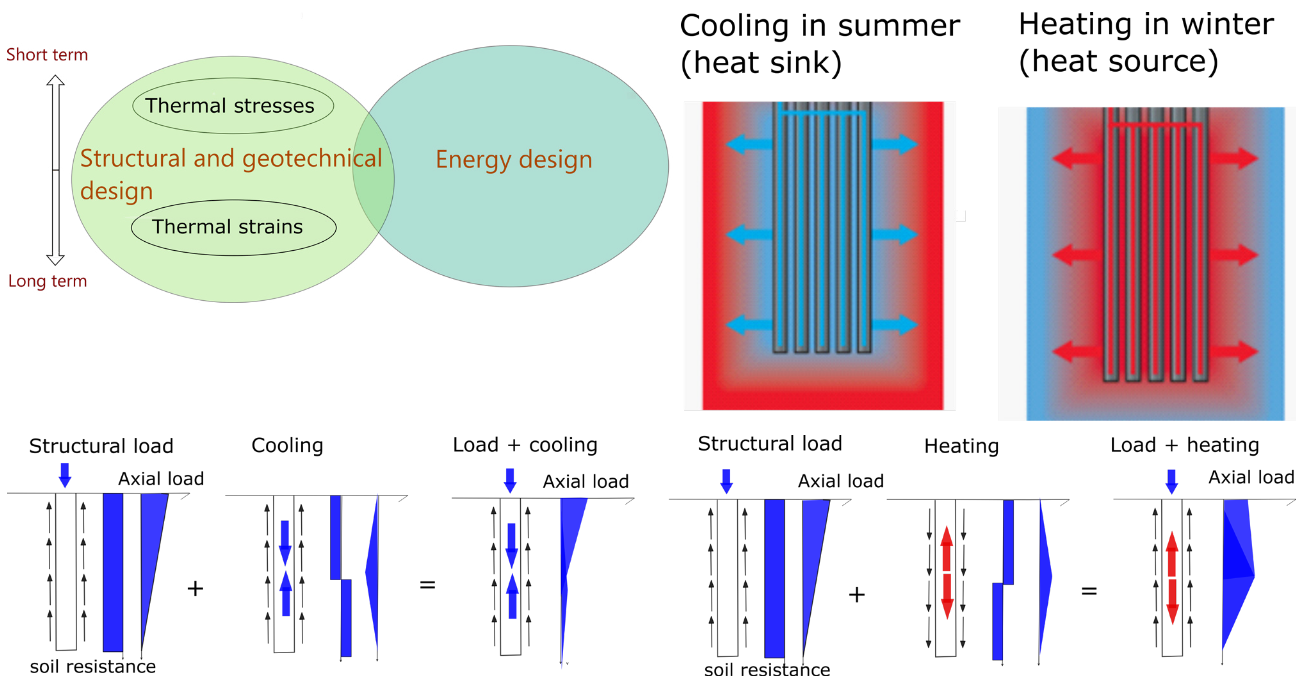

Figure 1. Main design aspects of a primary circuit of an SGE system (a); energy design (b); geotechnical and structural design (c) (Yang et al., 2017).

characteristics and the hydrogeological setting, are decisive factors in the generation of a permanent thermal plume which might affect the long-term energy efficiency of the system. An illustrative example of the consequences (over- or under-sizing a geothermal system) of an inappropriate subsurface characterization, based on a study of more than 1000 SGE systems installed in Germany, was provided by Blum et al. (2011). Hence, for the good performance and functioning of these systems, reliable parameters are needed in the design based on sufficient site investigation.

To reach the first objective of a SGE system proper design, i.e., to guarantee the energy needs, a detailed thermal characterization of the affected soil/ground layers is needed. Yet the evaluation of soil thermal properties is not generally considered during routine site investigation and, thus, additional characterization studies are necessary. Also, the thermal resistance of the thermoactive geostructure must be evaluated, as it affects its heat exchange with the surrounding ground and thus the entire system energy efficiency. The second objective, i.e., to guarantee structural and geotechnical integrity, depends on the geostructure and soil thermo-mechanical behaviour and on their interaction, with particular emphasis in their thermal expansion relative difference and the geostructure support conditions.

The level of detail of site characterization for SGE depends on the design stage and on the importance of the system. In general, two stages can be considered for site characterization: (i) a preliminary stage, which occurs at the planning phase (conceptual design), where the geological and hydrogeological conditions are investigated, and a first estimate of thermal parameters is provided, checking the feasibility of the system based on the expected building of infrastructure energy demand; (ii) a detailed characterization stage at the scale of the SGE, where the final ground design parameters are established.

The thermal efficiency of SGE (closed-loop) depends mainly on heat transfer by conduction, however, the groundwater flow can also have a significant impact on heat transfer by advection, particularly for coarse grained soil and high seepage velocities (Fan et al., 2007; Insana & Barla, 2020). For this latter case, an enhancement of the heat transfer process is generally achieved. Values of hydraulic conductivity of the soil greater than around 10^{-5} m.s^{-1} may induce significant effects in heat transfer (Hellström, 1991). Other less relevant thermal processes, dependent on soil granulometry and degree of saturation are heat radiation, thermal redistribution of moisture, and free convection in the air (Farouki, 1981).

Since 2000, some countries have published specific recommendations about the design and construction of energy geostructures, with a particular focus on energy piles, which also include site investigation specifications (GSHPA, 2012). Previous studies just related to the topic of ground characterization within the scope of SGE design were presented, for example, by Loveridge et al. (2017), Vieira et al. (2017) and Laloui & Rotta Loria (2020).

The current paper is based on an initial study developed by the authors between 2015 and 2019, in the framework of the COST Action TU1405 (GABI: European network for shallow geothermal energy applications in buildings and infrastructures), Working Group 1: Soil thermal characterization. It provides a review on the site characterization stages for the evaluation of thermal, hydrogeological and mechanical parameters and the involved methods in the context of SGE applications, from desk studies to laboratory and in-situ testing of soil samples. Also, a brief reference is made to environmental constraints and to the information needed to evaluate potential interferences among multiple users.

2. Preliminary design assessment

During the feasibility or planning stage of a SGE project, a preliminary estimation of the initial conditions and of the thermal properties of the soil on site should be carried out. As the main aim in the preliminary design assessment is to understand the feasibility and the economic convenience of the SGE system, the geotechnical aspect is not dealt with. The most significant aspects for the characterization of the ground thermal behaviour for SGE applications include: (i) the undisturbed ground temperature; (ii) the ground thermal conductivity; (iii) the ground volumetric heat capacity; (iv) the thermal resistance of the ground heat exchanger (GHE); and (v) the groundwater flow (Rees, 2016). At this initial stage, these aspects can be estimated based on geological mapping, analysis of relevant projects, expert judgement and qualified guesswork.

Undisturbed ground temperature T_0 [K] is the average temperature of the ground surrounding a GHE prior to its operation. It determines the initial condition of the geothermal system and its operating temperature limits. The heat transfer between the GHE and the surrounding ground is driven by their relative temperature difference. The thermal conductivity λ [$W.m^{-1}.K^{-1}$] is the ability of the ground to conduct heat, while the volumetric heat capacity $\rho.c_p$ [$J.m^{-3}.K^{-1}$] (being c_p [$J.kg^{-1}.K^{-1}$] the heat capacity and ρ [$J.kg.K^{-3}$] the density)is the capacity of the ground to store heat. The ratio between the last two properties yields the thermal diffusivity α [$m^2.s^{-1}$]. Ground with higher thermal conductivity yields larger heat transfer rates and recovers more rapidly from thermal depletions and thermal build-ups. The thermal resistance R_{GHE} [$K.m.W^{-1}$] of the GHE is the effective thermal resistance between the heat carrier fluid circulating in the pipes and the edge of the geostructure in contact with the surrounding ground. A low value of thermal resistance means enhanced heat transfer inside the GHE, which, in turn, means a GHE with a smaller size and lower installation costs.

A simple rule for the evaluation of the undisturbed ground temperature is that the average yearly temperature at bellow a depth of about 10 m is 1°C higher than the average yearly air temperature (SIA, 2005). Such information can be considered enough for a first sizing of the SGE system and can be further confirmed through specific in-situ measurements.

The ground thermal conductivity, which is the most important parameter in the evaluation of the energy efficiency of a SGE is affected by several factors, such as the water content, the solid particle composition and spatial arrangement and the porosity. λ increases with water content, due to the replacement of air, a poor heat conductor by, water which is a much better one (Figure 2). The values of this parameter vary in-depth through the different soil layers, however averaged values are initially estimated based on different approaches. Specific maps are available online and in the literature for several regions (e.g.: Ditlefsen et al., 2014; Ramstad et al., 2015; Geothermische Screeningstool, 2017). An example is the Thermomap project (ThermoMap, 2013) that provides 10-m average thermal conductivity values for Europe (Figure 3), based on an exhaustive compilation of available data. These maps provide a useful tool for planning, often integrating additional and relevant information, such as climatic data an protected zones. Still, the maps do not explicitly account for local site effects and specific conditions. In fact, they have been developed by assigning the available thermal property data to similar lithological units, thus extrapolating site-level information to whole regions. Alternatively, the initial estimate of the ground thermal conductivity and ground volumetric heat capacity can also be obtained from published data on thermal properties of soils, provided that the geological setting of the considered area is known. Ranges of values of thermal conductivity and volumetric heat capacity of soils and other materials can be found in the literature (Farouki, 1981; VDI, 2010). Some indicative values are shown in Table 1.

Another important parameter to consider when dealing with SGE systems is the thermal resistance of the GHE. R_{GHE} can be simply expressed as the ratio of the temperature difference between the heat carrier fluid and the ground and the applied heat flux. R_{GHE} depends on the number of pipes and their geometric arrangement and the physical properties of the GHE elements. A key factor in this regard is the thermal conductivity of the material between the heat exchanger pipes and the surrounding ground. As for borehole heat exchangers

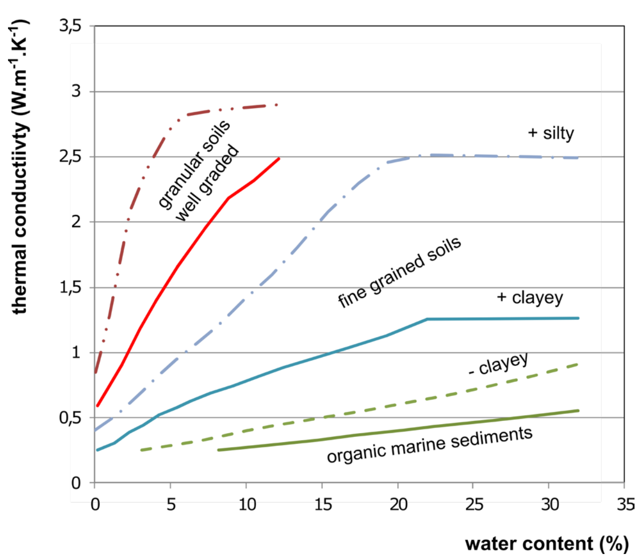

Figure 2. Relation between thermal conductivity and water content for different soils. Adapted from Reiffsteck et al. (2015).

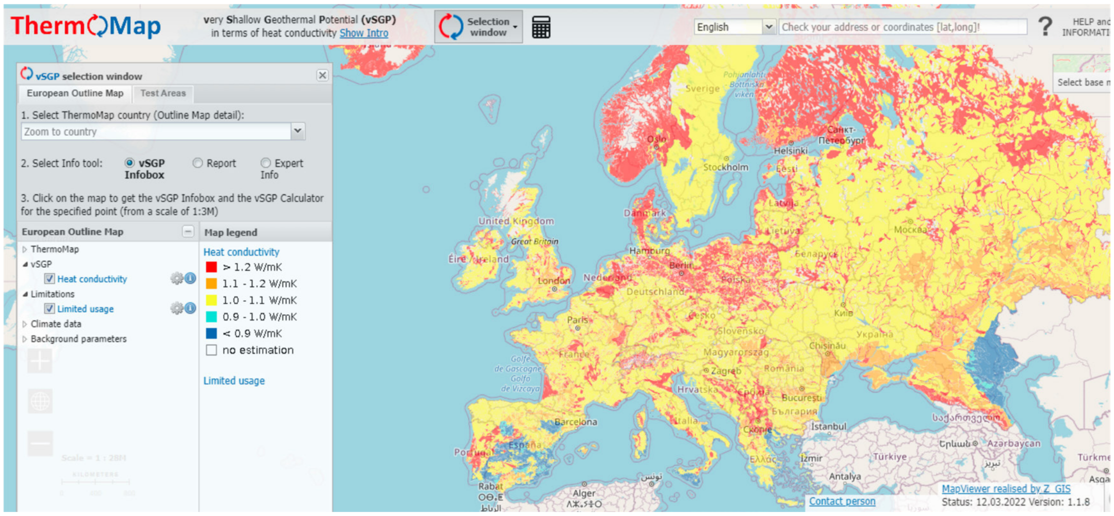

Figure 3. Very Shallow Geothermal Potential (vSGP) in terms of heat conductivity of unconsolidated underground up to 10 m depth (ThermoMap, 2013).

Table 1. Thermal properties of different types of soils and other materials, from (VDI, 2010).

Material	Thermal conductivity λ [W.m^{-1}.K^{-1}]		Volumetric heat capacity ρc_p [MJ.m^{-3}.K^{-1}]	
	Dry	Saturated	Dry	Saturated
Clay	0.4-1.0	1.1-3.1	1.5-1.6	2.0-2.8
Sand	0.3-0.9	2.0-3.0	1.3-1.6	2.2-2.8
Gravel	0.4-0.9	1.6-2.5	1.3-1.6	2.2-2.6
Air	0.02		0.0012	
Water	0.59		4.15	
Concrete	0.9-2.0		1.8	

(BHEs), there are several publications in the literature providing calculation formulas for the thermal resistance of different energy geostructures, such as energy piles (Loveridge & Powrie, 2014; Claesson & Javed, 2020), tunnel linings (Shafagh et al., 2020) and diaphragm walls (Shafagh & Rees, 2019).

Although for BHEs, Javed et al. (2019) suggested a method to design the whole system based on estimation approaches (without using any in-situ testing) and carried out a sensitivity analysis of the design if such an approach is used. A similar strategy could be implemented for other SGE systems including energy geostructures.

Flowing groundwater can provide significant additional heat transfer by advection in SGE systems (Claesson & Hellström, 2000; Rotta Loria et al., 2015; Di Donna & Barla, 2016; Di Donna et al., 2020), its impact on geothermal system performance differs, depending also on the ground use, i.e., on the thermal needs of the building. The groundwater flow can be beneficial for ground source systems that do not rely on seasonal storage, since it would recharge the heat faster or would remove the heat away (Laloui & François, 2009; Ma & Grabe, 2010; Suryatriyastuti, 2013; Loveridge et al., 2017; Epting et al., 2020; Insana & Barla, 2020). According to SIA (2005), the seasonal heat storage becomes unfeasible when Darcy's velocity exceeds 0.5-1 m/day. Hence, the geological and/or hydrogeological surveys of each region should be consulted to obtain meaningful information.

Finally, if no additional information is available, it may be acceptable to make an evaluation of the likely energy output based on "rules of thumb" and design charts to assess the feasibility and viability of the geothermal system. Heat extraction rates, expressed as power per meter or per square meter of heat exchanger have been proposed for piles (Brandl, 2006), for tunnels (Di Donna et al., 2020; Insana & Barla, 2020) and for diaphragm walls and slabs (Loveridge et al., 2017).

3. Detailed design characterization

3.1 Thermal parameters and initial conditions

For the final design, the undisturbed ground temperature should be determined in-situ, if possible. A comprehensive review of the available approaches is presented in Vieira et al. (2017). The measurements can be taken by either the downhole temperature logging or the fluid circulation method. In the downhole temperature logging method, the temperature distribution along the borehole depth can be measured by means of a downhole temperature sensing system. A simple or weighted average of the measured temperature values can then be used to approximate the undisturbed ground temperature. Various downhole temperature measurements systems, including wired temperature sensors, submersible wireless probes, and fiber optics, among others, can be used. Elsewise, the undisturbed ground temperature can be determined by circulating the fluid through a closed-loop GHE without heating or cooling the fluid and measuring the exit temperature of the fluid leaving the GHE.

In addition to undisturbed ground temperature, the thermal properties of the ground can be determined by means of semi-empirical models based on the relative proportions of soil phases and by in-situ or laboratory techniques. Based on the geotechnical characterization of the ground layers, thermal conductivity and specific heat can be estimated on the basis of the relative proportions and soil phases solid, liquid and gaseous phase. Several expressions can be found in the literature, assuming different distributions and geometric arrangements (e.g.: Dong et al., 2015), with the parallel and serial configurations providing, respectively, a lower and an upper bound for thermal conductivity. According to Rees et al. (2000), the weighted geometric mean configuration was found to be adequate by several researchers for a large variety of soils. According to it, soil thermal conductivity is:

$$\lambda = \lambda_s^{\chi_s} . \lambda_w^{\chi_w} . \lambda_a^{\chi_a} \tag{1}$$

where λ_s,λ_w λ_a are, respectively, the thermal conductivity of solid, water and air, and χ_s=1-n, $\chi_w = nS_r$ and $\chi_a = n(1 - S_r)$ the respective volumetric fractions, n the porosity and S_r the saturation ratio.

As regards the heat capacity of soils, as it is not a directional variable, it can be obtained by adding the heat capacities of the different constituents based on to their volumetric fractions. For example by:

$$c_p = \chi_s c_s + \chi_w c_w + \chi_a c_a \tag{2}$$

where c_s,c_w c_a are, respectively, the heat capacity of solid, water and air phases.

The Thermal Thermal Response Test (TRT) (Gehlin, 2002) is an in-situ test executed in an already built GHE, which yields the thermal conductivity of the surrounding soil, the GHE thermal resistance and the initial undisturbed temperature (Figure 4). In a TRT heat is injected into the ground at a constant rate in a borehole heat exchanger and the temperature change of the circulating fluid is monitored. Due to its simplicity of design, control and implementation, it is the preferred method for estimating thermal properties. The TRT, originally conceived for vertical BHEs (Spitler & Gehlin, 2015), has been extended to energy piles (GSHPA, 2012; Loveridge et al., 2014). For energy piles, the principle of the test remains the same as for BHEs, yet longer times are usually required to overcome the thermal inertia of the concrete pile. According to Alberdi-Pagola et al. (2018) for 30×30 cm^2 square piles, 60 hours test durations are required, while for wider piles, according to GSHPA (2012) and Loveridge et al. (2014), at least 100 hours are required. Further recommendations are given in GSHPA (2012).

The main challenge with energy pile TRT arises when interpreting the observed data. Appropriate models need to be used to yield reliable estimates. The models applied (analytical, empirical or numerical) need to account for the length and cross-section of the piles (Alberdi-Pagola et al., 2018), and, therefore, frequently, tailored models, such as the

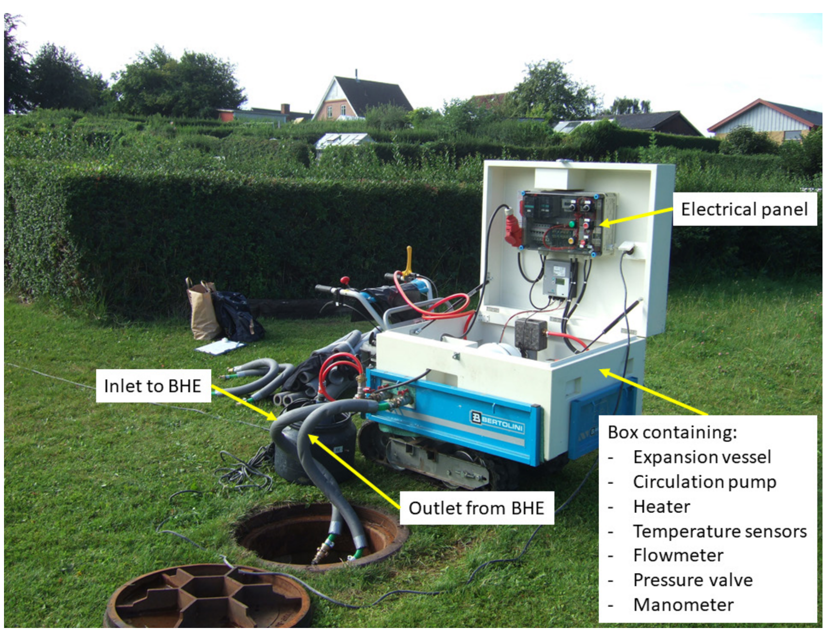

Figure 4. Example of a TRT performed in a 18 m BHE in Denmark, Jutland. From Alberdi-Pagola (2018).

ones proposed in Alberdi-Pagola et al. (2018) and Loveridge & Powrie (2013), are required.

The thermal conductivity of the ground and the thermal resistance of the GHE, which, as said, can be obtained from the TRT data, have counterbalancing effects on the design; using the experimentally determined values of both parameters mitigates some of the error that would occur if only the ground conductivity value estimated from the test was used for the design (Javed et al., 2011). It is still, however, recommended to separately calculate the thermal resistance value of the GHE to control the experimentally determined value. It is recommended that the thermal resistance be determined using the Multipole method (Claesson & Hellström, 2011), which is an analytical method that can be used for any number of arbitrarily placed pipes in a composite region with remarkable accuracy.

TRT measurements can be affected when sufficiently high groundwater flow occurs. The enhanced heat transfer caused by groundwater advection yields a higher effective thermal conductivity of the soil. The advantage of the TRT is that it gives an effective ground conductivity, which already includes the effect of groundwater flow. However, to uncouple the conduction and advection effects, it is recommended to perform a stepwise analysis or to use a moving line source solution when dealing with this type of data (Diao et al., 2004; Sanner et al., 2007). Further hydrogeological effects will be treated later.

Occasionally, TRT has also been used to estimate the volumetric heat capacity of soils. Wagner & Clauser (2005) used synthetic TRT data to perform parameter estimation varying the thermal conductivity and the volumetric heat capacity of the soil in a finite difference model. Moreover, Christodoulides et al. (2016) proposed a methodology for the computation of the ground thermal diffusivity, the volumetric heat capacity and the thermal resistance of a GHE. The methodology was based on the actual parameters used in a TRT experiment and the line source model. However, Austin (2000) suggests that volumetric heat capacity values estimated from standard TRT are not always acceptable. Therefore, it is recommended to assign a volumetric heat capacity value based on the knowledge of the existing soil and treat it as a known value. This assumption will not have a significant impact on the final estimation of the thermal conductivity of the soil. Although less common as they are less easy to perform, in-situ tests can be also used to determine the specific heat capacity of soils by realizing pits of about 1.5 m below the ground surface, in and around the SGE plant (Oladunjoye & Sanuade, 2012).

It is difficult to determine the ground thermal conductivity and the GHE thermal resistance from TRTing of energy geostructures other than energy piles and this is not, therefore, common practice. However, some authors perform thermal performance tests to determine the efficiency of energy geostructures, such as for energy slabs (Lee et al., 2021), energy walls (Di Donna et al., 2017) and tunnel linings (Barla et al., 2019). Note that these tests do not provide information about the ground properties. Furthermore, when dealing with energy tunnels and diaphragm walls, an important role on heat transfer processes that can crucially affect thermal performance is also played by the climate inside the excavation (Bourne-Webb et al., 2016; Dornberger et al., 2020; Ma et al., 2021). Therefore, a good understanding of the expected airflow temperature and velocity is also suggested.

The characterization of the ground thermal parameters can also be carried out by laboratory tests. There is a large number of different types of tests, some of them standardized. The main advantages of laboratory tests is that they are quick, relatively inexpensive and allow a better control of the boundary conditions, however they do not consider the real field conditions and several determinations are required to obtain representative values of the thermal properties, due to the ground heterogeneity and variability. Nevertheless, in contrast or in complement to TRT, the thermal conductivity of the different soils layers involved can be estimated.

Laboratory techniques for the determination of ground thermal properties, can be divided into steady-state and transient techniques. In the first type a permanent heat flux must be established in the soil sample, whilst in the second, the evaluation of thermal conductivity is performed during the modulated heating up process. As a consequence, transient time or frequency domain methods enable quicker measurement of thermal conductivity as they do not need to wait for a steady-state to be reached. The comparison between test results by using these different approaches suggests some influence of the soil granulometry and saturation conditions; that is the effect of longer test duration in steady-state methods might induce water migration within the sample and larger heat losses which will likely to affect the measurements.

The selection of the most suitable method depends on the type of soil or rock. Typical laboratory tests devices include the needle probe, the transient plane heat source and the thermal cell. The guarded hot plate and the thermal needle probe have been standardized to determine the thermal conductivity for rocks and soils, respectively (ASTM, 2014, 2016). The latter could also be taken to the field.

The comparison of results using different testing procedures also gives an important insight with regard to their capabilities and limitations. For instance, Popov et al. (1999) compared the thermal needle probe, the divided bar and the optical scanning techniques to measure rock samples. Also, the transient plane source technique has shown consistent results when used to measure clayey and sandy soils in Alberdi-Pagola et al. (2018).

As discussed several factors and sources of errors affect the measurement of thermal conductivity. Loveridge et al. (2017) have noted that thermal conductivity values measured in-situ by TRT are systematically higher than those obtained by laboratory tests (Figure 5). These differences can be attributed to different factors such as the sampling disturbance, the water migration within the sample, the in-situ stress and

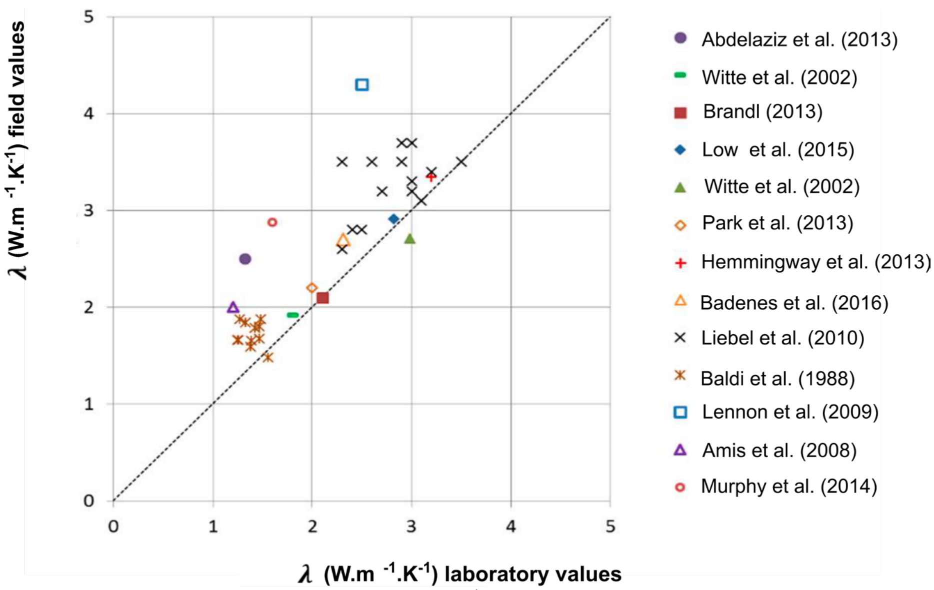

Figure 5. Comparison between conductivity values derived from laboratory and field tests. Adapted from Loveridge et al. (2017) and Vieira et al. (2017).

flow conditions and scale effects, and might influence the SGE design.

3.2 Hydrogeological parameters

Designing SGE systems requires a multidisciplinary approach and a deep understanding of the ground conditions among which the hydrogeological ones play a critical role to ensure the planned thermal efficiency (e.g.: for heat recovery and storage) in a sustainable way.

The most important hydrogeological aspects for the design of thermoactive geostructures are: (i) the geological profile; (ii) the effective porosity of the ground, which will mainly influence the thermal and hydraulic properties of the soil/rock mass; (iii) the horizontal soil/rock hydraulic conductivity; (iv) the vertical to horizontal hydraulic conductivity anisotropy ratio; (v) the groundwater flow characteristics in terms of piezometric levels, seasonal oscillations (especially for very shallow energy geostructures), hydraulic gradient and ground water flow predominant direction with respect to the SGE (particularly those with an important longitudinal extension, as in the case of tunnels or diaphragm walls). The latter will mainly influence seepage velocity, energy yield, heat storage capacity, time to steady state recovery during intermittent operation and features of the possible thermal plume.

The geological profile needs to be defined based on specific geotechnical investigations (continuous boreholes drillings with collection of samples), whose number increases when dealing with linear structures, such as energy tunnels. Effective porosity can be evaluated according to granulometric curves or, if unavailable, from literature data based on the type of soil/rock. The hydraulic conductivity anisotropy ratio depends on the soil layers stratification, which may lead to a higher horizontal conductivity compared to the vertical one. Back-analyses of in-situ pumping tests can be performed to evaluate such parameter. Phreatic surface location and seasonal oscillation, as well as, groundwater direction and hydraulic gradient can be evaluated based on available maps of isopiezometric curves and on specific in-situ measurements of groundwater level on existing or new piezometer wells in different times of the year.

For the assessment of hydraulic conductivity, in-situ tests can be performed to improve the reliability of models, such as slug tests, push/pull (Klepikova et al., 2016), heat storage experiments (Palmer et al., 1992), heat tracer tests (Macfarlane et al., 2002) or other specific tests (e.g.: Kuo & Liao, 2012). However, these conventional approaches often rely on a global measure and generally lack the spatial coverage required to characterize the heterogeneity of the subsurface. The complementary use of spatially distributed information with geophysical methods or distributed temperature sensing (DTS), which provide spatial information on the subsurface with greater coverage than boreholes and a greater vertical resolution, has increased in the past years (Hermans et al., 2014) and allows to better investigate the heterogeneity of the geology and the groundwater flow. Fujii et al. (2009) used optical fiber sensors to record vertical temperature profiles in two bedrock case studies in Japan and related the results with local geological and groundwater information identifying active groundwater flow.

Efficient recovery of thermal energy stored in the aquifer is only possible in specific hydrogeological conditions such as low natural gradients (Hermans et al., 2018). In addition to the cited characteristics, the heterogeneity of aquifers, whether located in bedrock or in alluvial plain, makes the efficiency of SGE difficult to predict, due to its influence on groundwater flow and the spatial distribution of hot and cold groundwater plumes (Sommer et al., 2013, 2014). For this reason, a methodology was proposed with specific reference to energy tunnels, that have the particularity to be long linear structures crossing a city for several kilometers, as in the case of urban tunnels (Baralis et al., 2020; Barla et al., 2021). The idea is to subdivide the tunnel path into a number of sections that are characterized by a specific set of hydrogeological and also thermal parameters, so that the study can be performed with reference to such characteristic sections.

Globally, the presence and magnitude of groundwater flow is crucial for the SGE system sustainable long-term behavior. If the flow is high enough, winter extraction mode will be decoupled from summer injection mode (SIA, 2005). Moreover, in case of winter-only operation, groundwater flow will enhance thermal recharge and make an ad hoc thermal recharge useless. It helps dissipating the induced by geothermal activity thermal changes, which take the form of a thermal plume from upstream to downstream. The shape and the amplitude of the thermal plume depend on the thermal change induced by the SGE which is determined by the building or infrastructure energy demand, on the ground thermal properties and on the water flow velocity. As regards the groundwater flow, high velocity may imply a long and thin thermal plume with a moderate intensity. Inversely, a moderate velocity causes a short and large thermal plume with a decreasing intensity with distance. Figure 6 shows examples of thermal plumes related to the groundwater flow velocity.

The development of models able to simulate heat flow and transport within the subsurface and account for uncertainties related to the subsurface is a challenging and time-consuming task (Baralis, 2020). It often relies on many uncertain parameters involved in heat flow and transport such as hydraulic conductivity, porosity, thermal conductivity or volumetric heat capacity, their associated

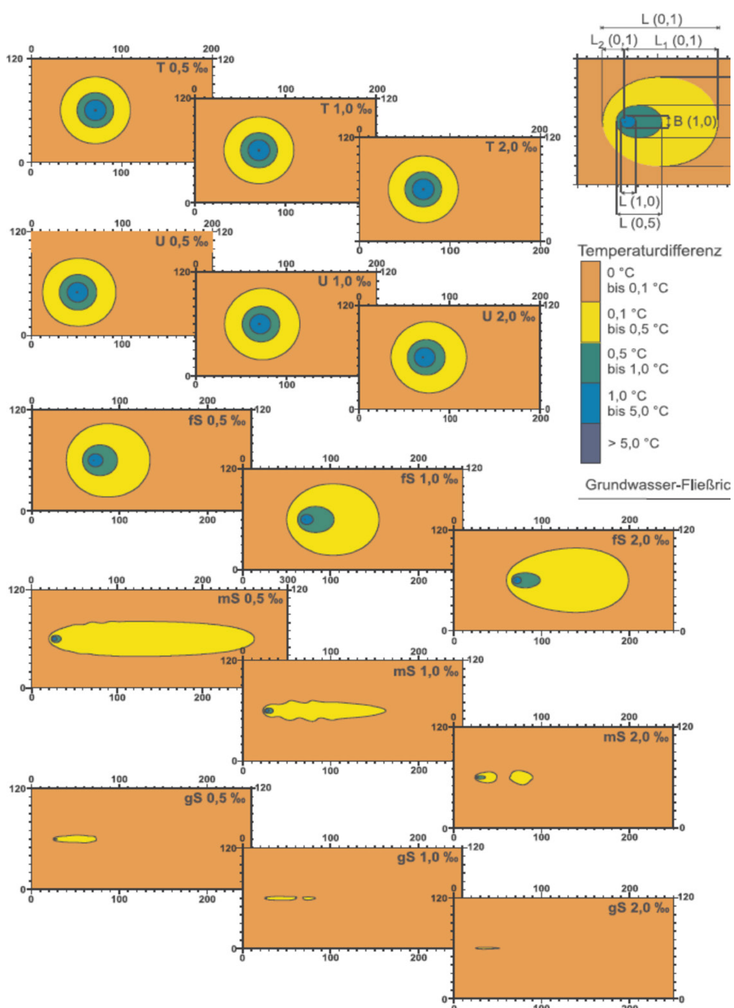

Figure 6. Development of thermal plume according to permeability (5 values, increasing from top to bottom) and hydraulic gradient (0,5%, 1% and 2%) (BRGM, 2012).

spatial heterogeneity and external inputs (e.g.: aquifer recharge or boundary conditions) (Hermans et al., 2018). In many cases, the lack of available data leads the modeler to consider homogeneous layered conceptual models (Lo Russo & Civita, 2009; Nam & Ooka, 2010; Kim et al., 2010; Yapparova et al., 2014) but bears the risk of making poorly-based decisions. As a counter-example, in the case study presented by Radioti et al. (2017), the authors showed that through a long term TRT experiment in heterogeneous geology with very low groundwater flow, the bedrock heterogeneity and the air temperature variations were not critical for a SGE system modeling.

3.3 Thermo-mechanical parameters

The design of thermoactive geostructures (energy piles, diaphragm walls or tunnel linings) must ensure that the geotechnical and structural limit states are not exceeded due to the additional stresses and strains resulting from the temperature changes imposed by their use as heat exchangers. Yet this analysis requires a few additional ground geotechnical parameters, and an understanding of how they are affected by the temperature changes, apart from those for typical ground-structure design.

The principal soil parameters needed for current geotechnical design are related to soil deformability, strength, in-situ stress state, stress history, overconsolidation ratio (OCR) and water regime. Numerous reference texts and standards are available for that issue (e.g. :Look, 2007) with particular reference to Eurocode 7 – Geotechnical Design. The supplementary information required for SGE system design, apart from that of the geostructure itself (concrete or grout thermal expansion coefficient), mainly refers to the ground thermal volumetric behavior, by means of the thermal expansion coefficient of soil, and whether there is a meaningful change of the geotechnical parameters with temperature, i.e., soil non-isothermal behaviour.

Typically, the range of temperature changes imposed in the ground by the operation of a thermoactive geostructure is relatively modest (Knellwolf et al., 2011), mostly ±20 °C (Loveridge et al., 2017). Moreover, the major changes occurring in the soil are rather localized and act seasonally under a large wavelength. For these reasons, a significant change in soil geotechnical parameters under SGE operational temperature is not expected (Brandl, 2006; Loveridge et al., 2017; Insana, 2020). Nonetheless, this aspect should be considered depending on the site-specific conditions, the climatic conditions, the complexity of the project, the expected thermal demand and on the characteristics of the thermoactive geostructure.

The mechanical effect of the seasonal thermal loads in the thermoactive geostructure depends on its interaction with the surrounding ground (e.g.: Cekerevac & Laloui, 2004; Di Donna & Laloui, 2015). A comprehensive review of the main features of soil thermo-mechanical behavior related to the operation of SGE and the main trends observed in the geotechnical parameters' evolution is described in Laloui et al. (2014). Some of this trends are as follows:

- the volumetric change depends on the loading history of soils; normally consolidated clays contract and highly overconsolidated clays dilate when heated under isotropic and drained conditions (Figure 7); normally consolidated clays show an irreversible volume change whereas highly overconsolidated clays show mostly and reversible behavior (Baldi et al., 1988; Hueckel & Baldi, 1990);
- cyclic effects have been observed in drained tests (Burghignoli et al., 1992; Vega & McCartney, 2015), small continued thermally induced changes in volume were registered after the first heating-cooling cycle;
- the effect of temperature changes on the shear strength of the soil still remains to be a subject of controversy, although a significant number of studies has been performed on this issue, some studies report that temperature increase strengthens clay, while there are many experimental results which show that an increase in temperature can slightly reduce the soil shear strength; a variety of factors might be the cause of this discrepancy, such as the soil type, mineralogy, overconsolidation ratio, drainage conditions during heating and shearing;
- oedometer test results (Campanella & Mitchell, 1968) show that the compressibility curves at different temperatures have the same slope, with lower void ratios occurring at higher temperatures; i.e. the preconsolidation pressure decreases with increasing temperature, but the compression index remains unchanged, this behavior has been confirmed by other researchers.

As above-mentioned, the temperature increase of clayey soils in normally consolidated conditions can lead

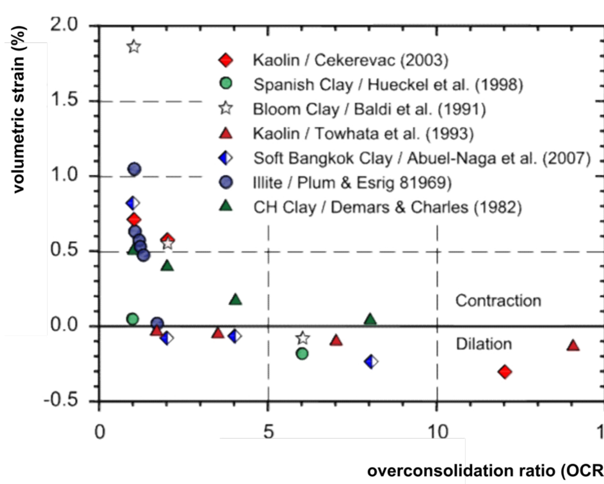

Figure 7. Effect of temperature change and OCR on volume change of saturated clays for ΔT520-40 °C. Adapted from Laloui et al. (2014).

to a decrease in the soil yield surface, which might induce a volumetric decrease and the occurrence of irreversible strains. This effect generally referred to as thermal compaction requires the use of thermoplastic constitutive soil models to be accounted for (e.g.: Laloui et al., 2014). These possible additional strains, namely in thermoactive floating piles, should be evaluated with adequate numerical modelling (Vieira & Maranha, 2016). According to (Loveridge et al., 2017) the construction of geostructures in this soil conditions is more challenging

Laloui et al. (2014) also addressed the issue of the evaluation of the temperature variation at the soil/pile interface, referring the fact that stresses induced by temperature variations can be possibly neglected however, this aspect should be further validated and the maximum allowable temperature swing should be considered in the standards.

The soil volumetric expansion is of particular importance, due to its interaction effect with the concrete structure (Loveridge et al., 2017). The relative expansion between the geostructure concrete and the surrounding soil together with the geostructure constrained conditions are determining factors in the stresses and strains induced both in the concrete and in the soil. They also affect the deformation of groups of energy piles and the thermally induced deformation of the soil (Rotta Loria & Laloui, 2017).

The thermo-mechanical volumetric behavior of soil is complex due to its highly non-linear and irreversible stress-strain behavior and to its multiphase constitution. It is not possible to define a simple thermal volumetric soil thermal expansion coefficient (Mitchell, 1993) as it depends on several aspects related to the soil constitution, to the in-situ conditions (effective stresses, pore water pressure, permeability and drainage conditions) and the imposed thermal loads. However, due to the difficulty in assessing this parameter, and for simplification, a constant value is generally considered. Typical values for solid grains range from 1×10^{-5} to 3.4×10^{-5} [°C^{-1}] (Delage, 2013), whilst the thermal expansion coefficient of water is 27×10^{-5} [°C^{-1}]. Due to the higher value of water thermal volumetric expansion positive pore pressures can be generated during heating in clayey soils, which results in the reduction of soil effective stress. This effect is more pronounced in fully saturated conditions, decreasing significantly for reduced degrees of saturation due to the presence of air in the pores. To account for this effect, numerical modeling of the overall soil/structure system must be carried out.

The evaluation of soil thermal expansion coefficient in drained or undrained conditions depends on the rate of the thermal loading applied to the ground and soil permeability. It is assumed that, in most situations, a drained expansion should be assessed due to the slow rate of thermal loading in SGE. Globally, there is a lack of information in what concerns to the quantification of soil thermal expansion and further research is needed.

3.4 Interferences and environmental constraints

To improve the understanding of a SGE system and guarantee the service life of the geostructure, the site characterization demands further to consider possible environmental influences and influencers. Indeed, potentially, the reservoir can be used by multiple users such as other geothermal or anthropogenic activities and, subsequently, interactions can occur if a thermal plume goes through the geothermal zone of influence of another structure, giving rise to what is commonly called Thermally Affected Zone (TAZ) (Barla et al., 2020). Such condition changes the initial state of another structure with an input of a new source of energy, causing an increase or decrease in the performance of the geothermal system. The lower performance can occur when the new source of heat causes a reduction of the geothermal potential of the structure. Indeed, during summer, the geothermal buildings inject heat in the ground and cause an increase of its temperature. If the ground is already heated by another source, the injected heat decreases. It leads to a decrease of the coefficient of performance (COP) of the heat pump and increases the risk of thermal drift (Figure 8).

Hence, a thorough survey of the installations and of potential interferences must be performed, registering the presence of (Baralis, 2020; Spitler et al., 2021):

- Neighboring installations, as well as their operating features, i.e.,
    - Open-loop systems (Aquifer Thermal Energy Storage, ATES) or
    - Closed-loop systems (BHEs, thermoactive geo-structures, etc.);
- Groundwater wells (and their interference with thermoactive geostructures and vice versa);
- City underground structures and linear infrastructures (buildings' deep basements, which could have an impact on the subsurface due to heat buildup/leakage, cables, roads and rail tunnels, metro lines, district heating networks, sewage network, buried foundations, car parking);
- Community spatial plan (future investments and projects).

However, the relevance of the above information is inversely proportional to the ease of retrieval, such as in the case of neighboring installations, especially when specific national or regional inventories are lacking. Therefore, the collection of the needed information is not an easy task at all.

For a comprehensive assessment of the initial state, besides the thermal and geotechnical design procedures, the following environmental constraints should be considered specifically for thermoactive geostructures:

- Multi-layered groundwater systems;
- Main groundwater bodies and their type (confined and artesian);

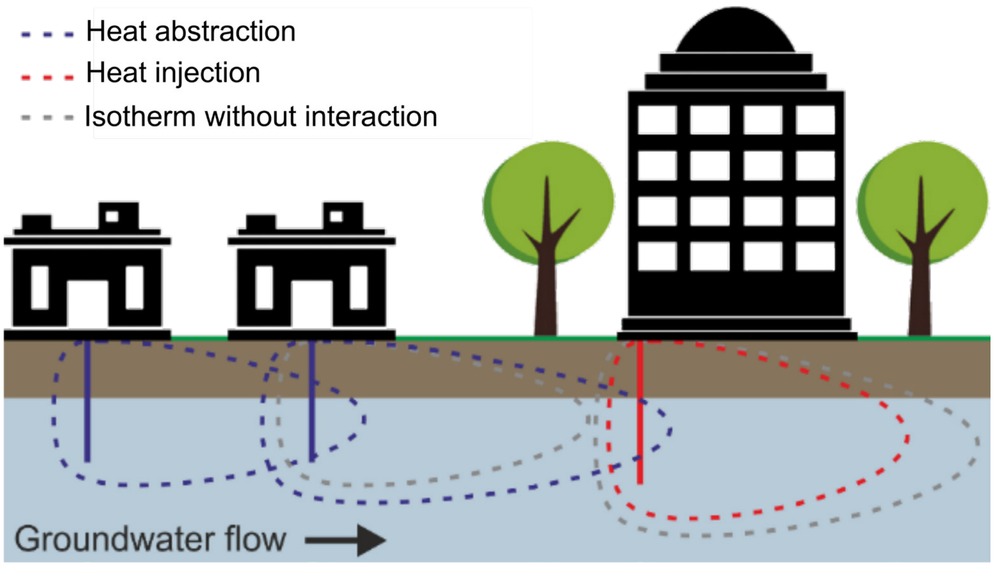

Figure 8. Schematic of interference of geothermal use in urban areas (Rivera et al., 2015).

- Neighboring sensitive buildings (mechanically influenced by thermoactive geostructure) and infrastructure;
- Polluted areas (contaminated soil, legacy pollution);
- Sensitive ecosystems (e.g.: NPWS, 2000): thermoactive geostructures may induce thermal disturbance to ecosystems (Brielmann et al., 2011), as well as impact on groundwater quality caused by induced changes to physicochemical and microbial processes;
- Surface water bodies.

4. Conclusions

For the design of Shallow Geothermal Energy (SGE) systems design service life, namely of thermoactive geostructures, a comprehensive knowledge of the ground conditions at the site is mandatory in order to ensure its energy efficacy and the non-exceedance of its structural and geotechnical limit states. The key aspects involved with site characterization were addressed in this paper, identifying the following main conclusions:

- The site characterization for shallow geothermal systems involves different stages, from desk studies to detailed characterization, including in-situ trials and laboratory testing of undisturbed soil samples;
- A preliminary design assessment represents the first step and requires the estimation of the initial conditions and the thermal properties of the soil on site, including the undisturbed ground temperature, the ground thermal conductivity, the ground volumetric heat capacity, the thermal resistance of the ground heat exchanger and the existence of a groundwater flow;
- The detailed characterization, which is needed at a later stage of the design, includes improved characterisation of the ground mainly based of TRT, identification of the hydrogeological conditions at the site and the thermo-mechanical aspects. In addition to detailed characterization and in-situ testing, correct interpretation of the tests and influencing factors is also an important aspect that needs to be considered. It is at this stage that the evaluation of the energy features, and the extent to which the system can provide the required energy needs during the operational period, is to be conducted as well as the verification of the structural and geotechnical safety and functionality requirements;
- An additional aspect to be addressed is the identification of possible interferences, collecting information related to the environmental constraints and to existing users in the field.

The use of ground as a thermal reservoir has also brought new challenges in what concerns to its thermal characterization and modelling. Although significant knowledge has been gained in recent years further research and experience is needed. Proper input parameters in the design of thermoactive geostructures will impact the further steps in the implementation of these systems and finally their performance during exploitation. Design of these systems needs to be performed in an integrated multidisciplinary manner. Thermoactive geostructures do represent an innovative part of the SGE systems providing a series of advantages that make them a sustainable and feasible solution for both implementation and exploitation perspectives. The variety of geostructures that can be thermally activated makes of these systems very good solutions for ensuring renewable energy sources for heating and cooling especially in urban dense built environments.

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Declaration of interest

The authors declare no conflict of interest.

Authors' contributions

This manuscript was initiated in the aim of Working Group 1 of COST Action TU1405 activities. Ana Vieira coordinated its realization in collaboration with Maria Alberdi-Pagola, Marco Barla, Paul Christodoulides, Alessandra Insana and Iulia Prodan forming an editorial group which has worked closely together in the final production stages and constitute the main authors of the manuscript. All authors provided technical, theoretical and practical support and approved the final version.

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