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Italian Geotechnical Association’s recommendations for the design and construction of energy geostructures

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ABSTRACT

Low-temperature geothermal resources are gaining prominence in sustainable energy transition. Among shallow geothermal systems, Energy Geostructures (EGs) emerge as innovative solutions, integrating heat exchangers into structural elements, offering dual functionality and cost advantages. In recent years, EGs have been increasingly implemented in different contexts and applications also in Italy.

In this framework, the Council of the Italian Geotechnical Association has recognized the need for specific recommendations dedicated to the design and implementation of EGs. The guidelines present an overview of shallow geothermal system principles and the foundational elements of EGs’ conceptual design methodology. The recommendations further delineate implementation stages, optimal practices, and protocols for in-situ monitoring. Additionally, they provide directives for conducting comprehensive environmental impact evaluations. The final aim is to offer a practical and accessible resource for public and private stakeholders, professionals in the construction and geotechnical sectors interested in exploring EGs.

1. INTRODUCTION

Driven by global decarbonization efforts, supported by international climate agreements and the EU's 2030 Agenda for Sustainable Development, the utilization and promotion of low-temperature geothermal resources are becoming increasingly important.

These resources are gaining significant attention worldwide for their potential to support sustainable energy transition. Among the diverse existing configurations of shallow geothermal systems for space heating and cooling, in addition to traditional closed-loop and open-loop systems, the innovative concept of EG has recently emerged. EGs are typically constructed by integrating the thermal exchange circuit into structural elements, such as foundation piles, diaphragm walls, or tunnel linings, which are in direct contact with the ground (Figure 1). Heat exchanger pipes are incorporated along the reinforcing cage in various configurations. Although the primary function is the structural one, their dual use as heat exchangers offers significant cost advantages.

Recently, the Council of the Italian Geotechnical Association has promoted the formulation of specific guidelines to support the design and implementation of EGs in Italy.

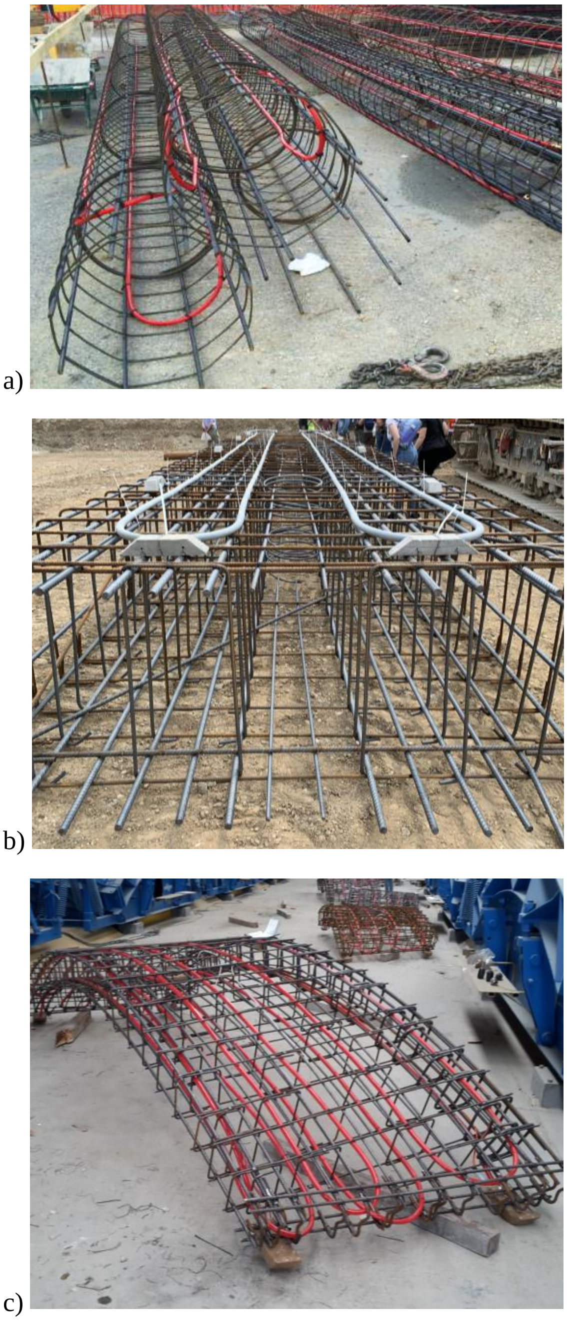

Figure 1: Photos showing the heat exchanger circuits incorporated along reinforcing cages of real installations of EGs: a) energy piles (Pronto Soccorso di Chioggia, Venice), b) energy diaphragm wall (underground car park Politecnico di Torino) and c) energy tunnels (Turin Metro Line 1).

This paper describes the guidelines' structure and contents: the recommendations propose an introduction to the concepts of shallow geothermal systems, and then the specific investigations methods. The following Sections describe the fundamentals of the EG conceptual design process, both short- and long-term structural and thermal modelling, specifically for each EG typology. Finally, it offers an overview of the realization phases, best practices and indications for on-site monitoring as well as for the environmental impact assessment.

2. DEVELOPMENT OF THE TECHNOLOGY

The first EGs were conceptualized and implemented in Austria in the early 1980s, initially as thermo-active foundation slabs. In 1984, EGs evolved into the now more prevalent form of energy piles—foundation piles equipped with a circuit of heat exchanger pipes embedded in concrete, typically anchored to the reinforcement cage prior to casting (Brandl 2006). After a brief period, necessary to establish adequate confidence in these technologies, the first significant impetus for energy pile utilization occurred in 1988. This was followed by a decade of gradual growth, with an average of over 800 new installations annually, reaching nearly 23,000 installations in Austria by 2004. (Brandl 2006). The United Kingdom experienced a similar growth rate between 2005 and 2015, progressing from a few hundred energy piles to several thousand within a single decade (Sani et al 2019). During the same period, other Central European countries, including Germany, France, Switzerland, and Belgium, also engaged in the proliferation of these technologies (Di Donna et al 2017a).

More recently, other EGs have gained prominence, alongside slabs and various pile types—ranging from small-diameter driven piles to large-diameter bored piles—. These include retaining structures (diaphragm walls, sheet piles) and, albeit with a slight delay and less rapidity, tunnel linings (Barla and Insana 2023). The utilization of micropiles is a more recent development, through which energy geostructures are also being incorporated into the process of energy retrofitting of existing buildings (Ronchi et al 2018). It is also feasible to adopt design strategies that incorporate a combination of diverse energetically active elements. For instance, one might integrate energy retaining walls with excavation base slabs and/or foundation piles. Furthermore, hybrid solutions that amalgamate energy geostructures with closed-loop or open-loop systems are equally viable options. With respect to energy utilization, the primary applications are oriented towards seasonal thermal regulation—encompassing both winter heating and summer cooling—as well as the production of domestic hot water. In addition, EGs can provide thermal conditioning of spaces within service infrastructure, such as underground metro stations and parking facilities, as well as applications at urban scale, inserted in low temperatures District Heating and Cooling Networks called 5th generation DHCN (Meibodi and Loveridge 2022).

Up to now, in Italy the proliferation of EGs remains relatively constrained. Nevertheless, numerous applications and pilot cases have been implemented, as represented in Figure 2.

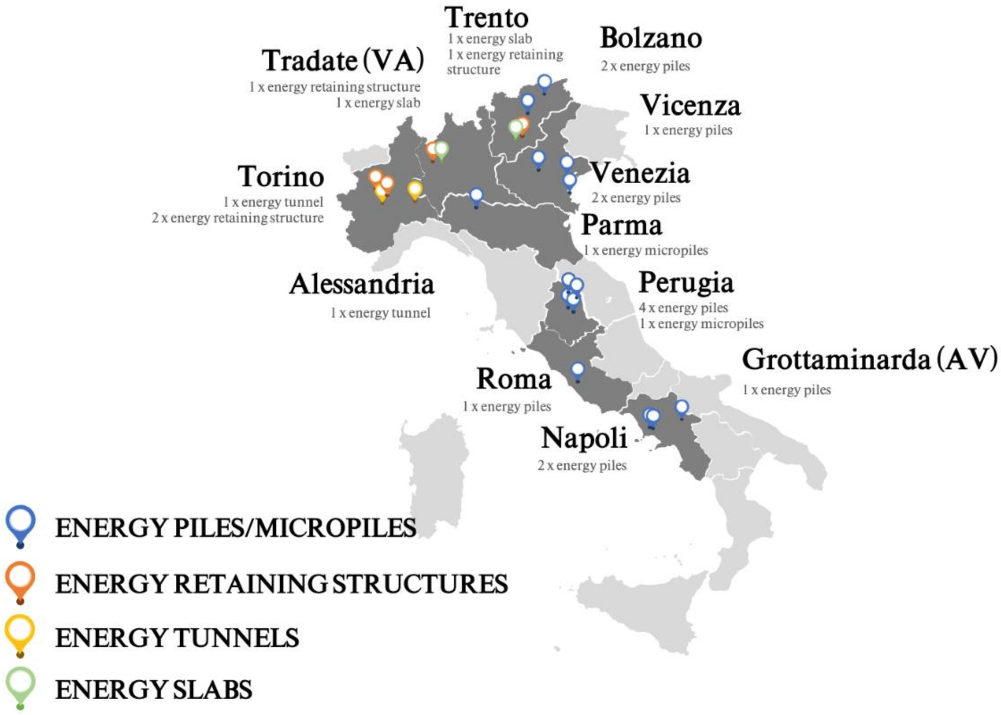

Figure 2: Geographic distribution of some of the EG functioning in Italy.

3. THERMAL AND MECHANICAL SITE CHARACTERIZATION

The characterization of soils in which EGs are installed is of particular significance, as the efficiency of thermal exchange is contingent upon (I) initial/undisturbed temperature, (II) hydrogeological conditions and (III) thermal properties of the ground layers and of the construction materials. The cyclic thermal load to which these structures are subjected induces a state of stress and strain that interacts with that derived solely from mechanical loads, thereby generating additional reciprocal interactions between the structure and the surrounding soil. Therefore, in addition to the geotechnical characterization of the soil and the definition of the geological-geotechnical model traditionally required for all civil engineering works, it is fundamental to also focus attention on the energy-related assessments and on the evaluations of the stress and strain effects induced in the EG by thermal variations.

3.1 Energy-related assessments

For energy-related assessments, pertaining to thermal exchange efficiency, the initial temperature and thermal properties (thermal conductivity and diffusivity) of the soil involved in the heat exchange must be determined. Moreover, particular attention should be directed towards identifying the water table level and seepage regime (direction and velocity), as these factors significantly influence the EG's thermal exchange and thermal alteration induced in the subsoil.

A first level of information about the local heat exchange potential can be provided by proper maps representing the geo-exchange potential or the mean thermal conductivity of the ground layers weighted on the layers' thicknesses (Ramstad et al 2015). Evidently, these maps do not explicitly account for localized effects, as they are constructed by assigning available thermal property data to analogous lithological units, thus extrapolating site-specific information to a regional scale. Consequently, to obtain detailed information pertinent to the site of interest, it is advisable to conduct specific laboratory tests to directly measure the thermal properties of the coring, and in-situ Thermal Response Tests (TRT). The TRT has been developed in the 90s for the traditional vertical Borehole Heat Exchangers (BHE), now standardized by ASHRAE guidelines. The data elaboration is based on the Infinite Line Source method, assuming the heat exchange purely in the radial direction, and only for conduction. Whenever these assumptions are not satisfied by the EG under examination, it is possible to interpret the TRTs through numerical methods, able to represent accurately the geometry of the EG or the soil conditions. The model simulates, in transient regime, the thermal exchange between the heat transfer fluid, the pipe walls, and the surrounding concrete/soil, for the duration of the TRT. The model parameters are the thermo-physical properties of the soil to be estimated, initially assigned equal to typical values from literature and then evaluated by means of model calibration.

3.2 Non isothermal mechanical effects

For evaluations of the stress and strain effects induced in the EG by thermal variations, the alteration of the materials' mechanical properties due to the thermal exchange should be estimated. However, significant variations in the mechanical strength properties and volumetric behaviour of the soil occur under conditions of high-temperature heating and/or cyclic freezing of the soil, that are usually outside the operating range of heat pump systems. The condition requiring the most attention is the presence of normally consolidated clay layers, which may undergo irreversible volume reductions due to thermal cycles.

Within the typically utilized temperature range, where optimal heat pump operation is also achieved, thermal variations induce generally limited deformations and alterations of the stress state within the structural element, which can be evaluated as described in Section 5.

4. THERMAL DESIGN

To ensure efficiency and long-term sustainability of the EG, a preliminary assessment of the geothermal potential is essential. Early-stage estimates offer a quick and low-cost method to understand the energy potentialities, before committing to more complex investigations.

For energy piles, simplified tools such as flow charts or abaci in national recommendations provide reference values of heat exchange potential, starting from knowledge of the hydro-geological conditions (e.g. CFMS 2017, SIA-D-0190 2005). For retaining walls and tunnels, given their more complex geometry and relative scarcity of documented applications, improved alternatives are based on the synthesis of parametric numerical analyses, thus also allowing to consider additional influencing factors, such as material properties, thermal boundary conditions and seepage regime (Di Donna et al 2021, Insana and Barla 2020, Zannin et al 2022). For all the EGs, case studies in literature always represent a useful source of preliminary information although, since they refer to specific cases, their use must be evaluated in relation to the case of interest (Loveridge et al 2020).

Following this initial screening, a detailed thermal design and optimization process is then necessary to tailor the EG to the specific project conditions and the building's thermal demand. Optimization allows to enhance thermal exchange efficiency, in terms of heat transfer between the ground and the circulating fluid, and to ensure adequate energy performance throughout the year and in the long term. It can be performed on geometrical parameters, such as pipe length, spacing, and layout, fluid thermal properties, operation modes, etc.

Analytical solutions based on well-established theories of heat transfer from infinite or finite linear and cylindrical sources are often sufficient for the design of energy piles with high or low length to diameter ratio. In addition, specific functions for energy piles have been proposed in literature, able to provide the transient response as well as the pile thermal resistance (Loveridge and Powrie 2013). For the design of pile groups, the use of spatial superposition principle combined with specific energy pile's functions has been recently investigated (Alberdi-Pagola et al 2019).

More complex EGs, such as energy walls and tunnels, present additional challenges due to their geometries and boundary conditions, particularly on the side of the EG that is exposed to the excavated space, subject to different possible thermal conditions. In these cases, analytical solutions are rare (Kürten et al 2015) and numerical modelling becomes the preferred method for a more robust and realistic design, since it allows for geometry refinement, up to the scale of the exchanger circuit, variable thermal loads and boundary conditions, non-uniform initial temperature, seepage regime, and transient analysis.

If the circuit is explicitly modelled, for a given fluid temperature at the inlet, the analysis provides direct assessment of the outlet temperature and, therefore, the exchanged heat power between inlet and outlet, as well as the temperature variations over the domain and in time. The influence of a range of factors can be easily investigated by changing their values in parametric numerical analyses (Di Donna et al 2017b, Salciarini et al 2017; Sterpi et al 2020).

The Italian Recommendations include details about numerical modelling, e.g., meshing techniques, assumptions for thermal load history and time discretization, solutions for convective conditions on exposed surfaces and ground surface, computational steps, etc. In general, it is summarized that optimal performance is reached with highly conductive soils, circuit layouts suited to enhance heat exchange and avoid thermal interference, well balanced heat extraction/injection periods, high seepage velocities (especially parallel to the EG's surface when planar), which can regenerate the heat reservoir and limit thermal drifts (Cecinato and Loveridge 2015).

Beyond individual EG's analysis, numerical methods offer the significant advantage of evaluating thermal interference effects at larger scales. For instance, in dense urban environments where multiple EGs operate simultaneously, thermal plumes from one system may impact the performance of another. Through numerical simulations, it is possible to consider the built underground, the hydrological conditions and all the heat sources to assess the mutual interactions both at the building scale and across entire urban districts, thus enabling more strategic energy planning (Baralis 2020, Perego et al 2022).

5. GEOTECHNICAL DESIGN

EGs have a primary structural role and a secondary energy role. Due to the latter, internal thermal variations could modify the stress-strain state of the geostructure itself. Thermo-mechanical analyses aim to verify the occurrence of such side effects and their compatibility with the main structural role. In general, thermal variations do not jeopardize the geostructure safety at the ultimate limit state but can affect the serviceability limit state (Bourne-Webb et al 2016a).

Thermo-mechanical effects originate from the connection between the EG, subjected to a temperature variation, and all restraints, i.e. other structural elements and the surrounding soil mass, that undergo different temperature variations and are characterized by different thermal expansion coefficients. The final stress-strain state depends on the thermo-mechanical properties of all involved materials, on kinematic restraints, on pre-existing static loads and, finally, on the thermal loads. The latter are variable actions imposed by the EG heat transfer operations in response to the required thermal needs. Usually, in the design phase, simplified thermal loads in terms of type and of distribution within the geostructures are adopted.

The Italian Recommendations then analyse the calculation methodologies that can be used for the thermo-mechanical analysis of energy piles, energy retaining structures and energy tunnels.

For piles it is required to verify axial deformations and superstructure displacements, changes in the stress state in the pile cross section due to the interaction with the ground and with the foundation structure or the superstructure, strain accumulation due to cyclic thermal actions. Regarding the latter point, floating piles in normally-consolidated clay could exhibit an accumulation of irreversible settlements at the ground surface, with particular reference to the first annual thermal stress cycle. Simplified and available numerical approaches are described. In case of a group of piles, thermo-mechanical interaction effects have to be accounted for (Salciarini et al 2017). Typically, no changes in the pile's bearing capacity due to the combined effects of the thermo-mechanical loads (axial loads and common thermal variations) are to be expected.

In energy retaining structures thermo-mechanical effects are represented by ground horizontal and vertical displacements and by actions within the ground and the structure. These effects are highly affected by the initial ground temperature, the temperature changes due to the EG operation, the boundary condition especially on the excavation side, mechanical loads, thermal and mechanical properties and restraints. Typically, thermo-mechanical effects are studied with the aid of 2D or 3D finite element or finite difference numerical models with a coupled thermo-mechanical or thermo-hydro-mechanical approach. No simplified analytical or empirical methods are currently available. The thermo-mechanical effects, observed partly as additional displacements and partly as changes in internal actions, do not seem to compromise the structural safety of the retaining structures since the resulting overall actions are most likely to remain below the strength limits. However, additional stresses may arise requiring careful evaluation during the design phase, in order to foresee possible unexpected overload situations (Bourne-Webb et al 2016b, Sterpi et al 2017). Of particular importance are the structural conditions and constraints; therefore, in the modelling it is essential to correctly simulate the construction sequence and connection structures in order to obtain reliable results.

Lastly, also for energy tunnels, thermal activation of the lining can lead to side structural effects that are to be properly assessed, in terms of both strains and stresses due to prevented strains. In particular, temperature changes can cause thermal expansion and contraction cycles of the geological formation hosting the tunnel, with consequent variations (I) in the loads acting on the lining, (II)in thermal expansion and contraction cycles of the lining, with consequent variations in its axial force and bending moment, (III) in the effective stresses in the ground, also due to the redistribution of stresses induced by the load and to the stress variations mentioned above. Therefore, the temperature distribution within an energy tunnel needs to be accurately estimated in order to determine the induced strain changes and additional thermal stresses, and to verify the internal actions against the lining capacity. For this purpose, there are currently no simplified analysis methods, but it is possible to refer to previous experiences (such as Barla et al 2019, Insana et al 2020, Insana 2020) or to perform a thermo-mechanical analysis to quantify the stress-strain conditions of the lining. The results described in the literature show that, although effects induced by thermal loads occur, the changes in stresses and strains are, in general, quite limited and do not compromise either the structural integrity or the lining functionality.

6. CONSTRUCTION ASPECTS

The Italian Recommendation has been completed also with a section devoted to construction and installation aspects.

The heat exchange systems for EGs play a crucial role in ensuring the effective functioning of the heat exchange systems. The hydraulic system involves a closed-loop circuit in which the heat carrier fluid circulates through pipes embedded in various structural components as described above. Proper installation, testing, and integration of these systems are essential to maintain thermal efficiency and structural integrity in the long term.

In the case of energy piles, the heat exchange pipes are generally attached to the pile steel reinforcement, with either longitudinal or helical distribution. The pipes are secured in place before the concrete is poured, ensuring the correct distance among them to avoid thermal interferences and optimize the heat exchange. These pipes may also be protected from potential damage during installation. At the end of this first installation phase, hydraulic testing is conducted to check the integrity of the pipes before and after the concrete is placed. The testing process ensures that the pipes are not damaged and that there is no leakage in the system.

For diaphragm walls, the heat exchange pipes are typically arranged in a double "U" or meander configuration and fixed directly to the reinforcement cages. During the installation, the pipes are either placed inside or outside the cage, with appropriate protection to prevent damage. The configuration of the pipes, as well as their connection to other sections of the hydraulic system, is crucial to optimize the thermal exchange with both the surrounding soil and the internal exposed surface of the structure. Each section of the heat exchange system is hydraulically tested before concrete pouring to ensure no leakage occurs during operation.

In tunnel construction, whether using mechanical excavation with a TBM (Tunnel Boring Machine) or traditional methods, heat exchange systems are integrated into the precast concrete segments that form the tunnel lining. The heat exchange pipes are attached to the reinforcement cages before the concrete is poured. After each segment is cast, hydraulic tests are conducted to ensure the pipes' integrity and that no leaks exist. In some cases, it may be necessary to use specially designed couplings or pockets within the tunnel segments to ensure the continuous connection of the pipes between adjacent segments. Once the segments are installed, the hydraulic system is connected, and tests are performed to check for proper fluid circulation.

After the installation of each EG, the heat exchange systems are tested to ensure that they are properly pressurized and free of leaks. Finally, the system is completed with the hydraulic circulation system, including the circulating pumps and necessary valves, and with the connections to the heat pump itself, to guarantee an efficient operation. The system is designed to provide balanced flow to all circuits, ensuring uniform heat transfer. Proper installation, testing, and maintenance of the hydraulic systems are critical for the long-term durability and effectiveness of EGs.

7. IN SITU MONITORING

EGs monitoring includes the assessment of thermal, hydraulic and mechanically induced aspects. The design of the monitoring system shall include the definition of the significant quantities to be measured as well as the choice and location of the monitoring equipment. Among the most relevant quantities there are:

- the electric consumption of the heat pump and circulation pumps,
- flow rate and temperatures at the heat pump inlet/outlet,
- temperatures, flow rate, pressures and heat exchanged by the heat carrier fluid at the inlet/outlet close to the EG,
- temperatures, stresses and strains in some specific points within the EG,
- displacements over time of building target points,
- vertical temperature profiles and porewater pressure at different distances from the structure itself.

For energy piles, temperatures, stresses and strains can be referred to three points in the cross section, for instance connecting the sensors to the steel cage and embedding them in the concrete casting. For energy retaining structures and energy tunnels, sensors can be located both at the intrados and at the extrados. In the case of such EG, it is of interest to measure the temperature and velocity of the adjacent environment, that can be air or water, given that one side is not fully or partially in contact with the ground.

8. CONCLUSIONS

It is of relevance that the Council of the Italian Geotechnical Association has recently recognized the need for specific recommendations dedicated to the design and implementation of EGs, inserting Italy among the countries (currently only UK, France and Switzerland) providing a source of specific information to practitioners.

As described in this paper, the guidelines present an overview of shallow geothermal system principles and the foundational elements of EGs’ conceptual design methodology. The recommendations further delineate implementation stages, optimal practices, and protocols for in-situ monitoring. Additionally, they provide directives for conducting comprehensive environmental impact evaluations.

With this document a practical and accessible resource is provided to public and private stakeholders, geologists, engineers and architects interested in exploring EGs. It is expected that the publication and spreading of the document will help boosting the application of EGs in the building and construction sector.

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