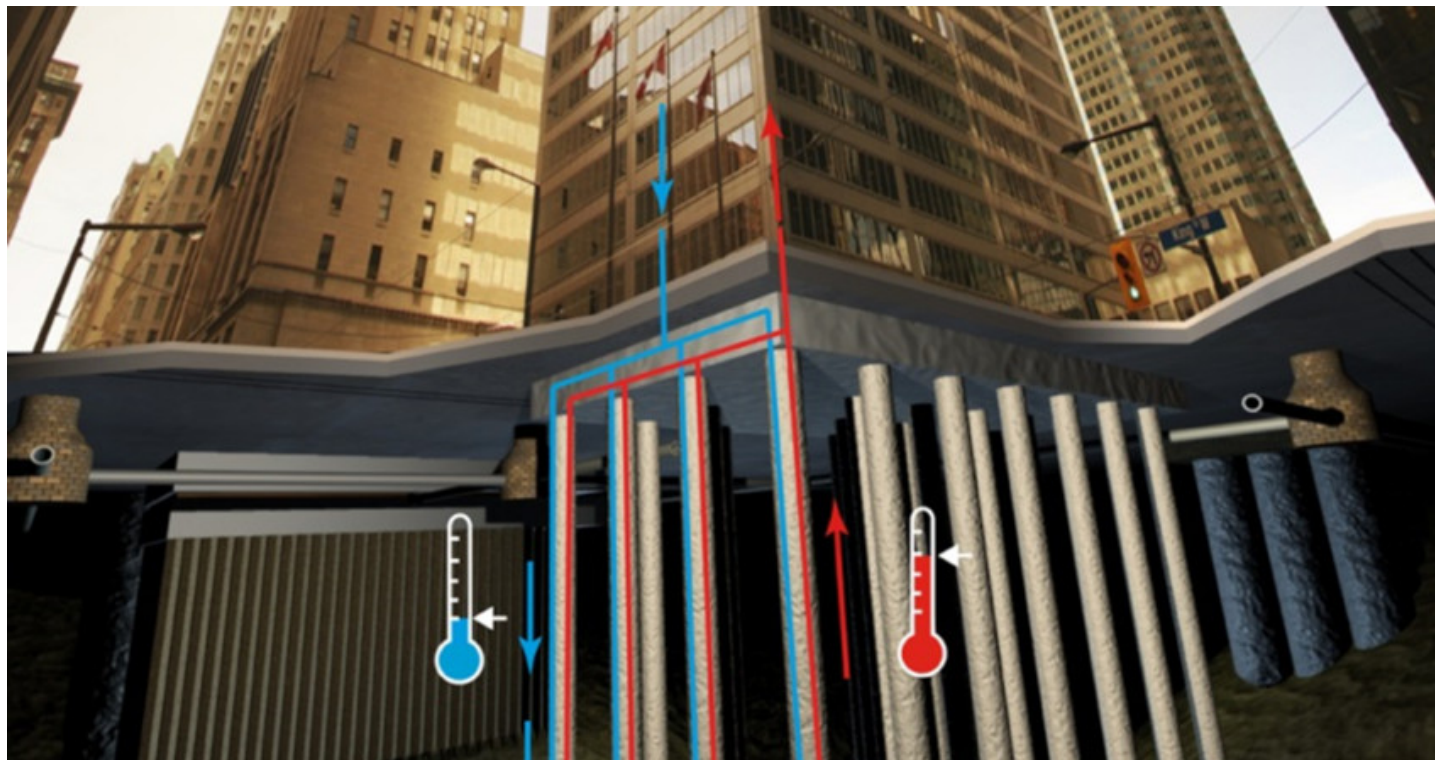


Geothermal energy, a source of green energy under our buildings

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Energy geostructures are a modern application of low enthalpy geothermal systems (i.e. with low temperature differentials), with the major advantage of reducing initial installation costs compared to standard systems. The principle consists in setting up a network of pipes inside the reinforcement cages inside the concrete structures. A heat transfer fluid, which circulates in the pipe network, exchanges heat with the ground through the concrete. A heat pump adapts the temperature from the ground to that required to heat or cool buildings. The efficiency of the system must meet both energy (heat or cold production) and geotechnical-structural (limited additional stresses and displacements) criteria, which are highly dependent on the local conditions of the site hosting the construction.

In a world where energy needs are constantly increasing and where the research for green, local and renewable energy sources is becoming increasingly important, **energy geostructures** are perfectly suited. They represent an innovative and promising alternative for **heating** or **cooling buildings** and infrastructures.

1. What is an energy geostructure?

Geostructures, i.e. structures in contact with the ground can be used to exchange heat with the ground [1]. More precisely, the term geostructures includes **piles** for deep foundations, retaining **walls**, **tunnel** lining segments, etc. The heat exchange between the ground and these concrete structures is ensured by a system of tubes arranged inside the structure and within which a heat transfer fluid circulates.

The principle is that of **shallow geothermal energy**: thanks to the fact that the subsoil temperature remains constant throughout the year (except for the first 5 to 8 m), this temperature will be higher than that of the external air in winter and lower in summer. This temperature difference allows heat to be extracted from the ground to the building during the winter (for heating

purposes) and injected from the building during summer (for cooling purposes). This falls into the category of the so-called “**low enthalpy**” geothermal systems, i.e. systems that involve the first 100 m of ground and work with temperature variations of around 10 to 20 degrees Celsius. To adapt the temperature coming from the heat exchangers to that required to heat or cool buildings, these systems are connected to a **heat pump** (read [Geothermal: a significant source of energy](#)).

1.1. Operating modes

The system can be used for both heating and cooling of buildings (**dual mode**) as well as only for heating or only for cooling (**single mode**). The choice of the operating mode depends, among other things, on the local **groundwater flow** conditions.

In the case where groundwater flow is zero or very low, a thermal recharge of the soil is necessary in order to keep the temperature constant over the long term. In this case, it is strongly recommended to use the system in dual mode to ensure its efficiency.

If, on the other hand, the soil is sufficiently permeable (sand) and subjected to a groundwater flow greater than 0.5 or 1 m per day, the soil temperature is automatically rebalanced and a simple mode is possible [2].

On the other hand, if in the first case (no ground water flow) **seasonal heat storage** is feasible, in the second one (significant ground water flow) this is not possible and extraction is naturally decoupled from injection.

1.2. Technology diffusion

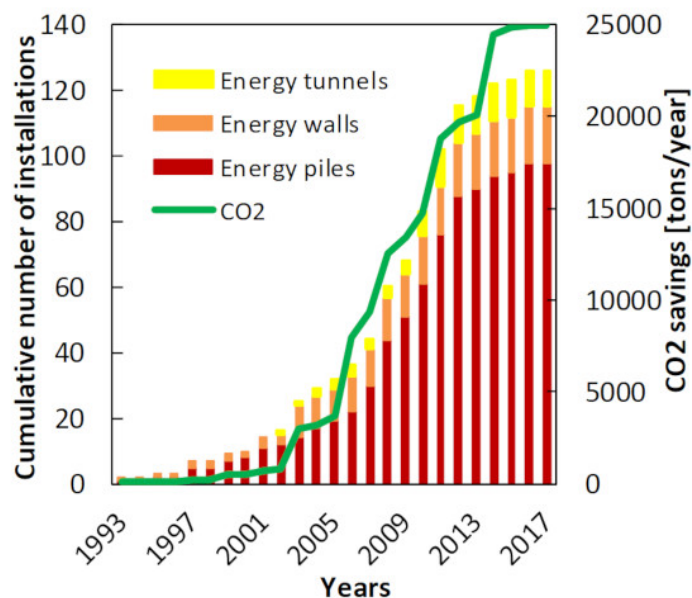


Figure 1. Number of installations and CO2 reduction as a function of time [Source: Di Donna et al. 2017 (Ref.[3])]

Figure 1 shows the evolution of the number of energy geostuctures installations over the last ten years, as well as the corresponding reduction in **CO₂emissions** [3]. The available data are probably not representative of all existing real cases, but the figure gives an overview of the interest in this technology and its benefits. Energy piles remain by far the most common application. This type of deep foundation is widely used to cross a layer of soil with poor mechanical properties and to lean on a rocky bedrock, for example.

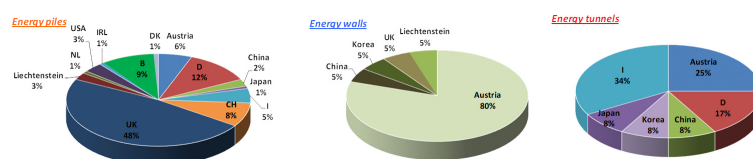


Figure 2. Dissemination of energy geostuctures in different countries [Source: © Di Donna]

Energy geostructures have developed in Europe and in the rest of the world since the **1980s**. The first installations were realised in Austria, but the technology spread quickly to Switzerland, Germany, and England (Figure 2). In other countries, such as France and Italy, their social acceptance is still limited and their development is slower.

Energy geostructures have also been recently introduced in the United States and Asia. An example is the Shanghai Tower in China. It is the tallest tower in China with a height of 630 m, it rests on 2000 piles of 86 m in length and 1 m in diameter, about a hundred of which are equipped as energy piles.

1.3. Some examples of this are

In Europe, many projects have already been carried out in schools, private buildings or public buildings.

1.3.1. Energy piles

One of the most documented examples is probably the **Terminal E at Kloten Airport (Zurich)**, which is operational since 2003. Designed by Amstein and Walthert AG, in partnership with ARGE ZAYETA, it is built on a clay and silty soil and its foundations consist of 350 drilled piles 27 m long and with a diameter between 90 and 150 cm. Of these, **306** are equipped as **energy piles** and provide **70%** of the terminal's **heat requirements** [4]. The cooling of the building is also ensured by energy piles, 53% by free cooling and 15% by using the heat pump. In this specific case, the additional cost due to the instrumentation of the piles represented **0.3% of the building cost**, which was paid back in **8 years**.

1.3.2. Energy walls

Another classic example is the **Lainzer Tunnel in Vienna**, an energy tunnel built by the cut-and-cover method, where the excavation is first dug in the open air and then covered by concrete slabs. In this case, the heat is exchanged with the ground using the side walls, made of piles 20 m long and 120 cm in diameter. One out of three piles is equipped as an energy pile, which represents a total of **59 heat exchanger piles**.

Also in Vienna, 4 sections of the **U2 metro line** are equipped with energy **piles, invert and walls**, for a total production of 449 kW of heating power and 231 kW of cooling capacity.

1.3.3. Energy tunnel

Energy tunnels are today the least developed application of this technology, despite their remarkable **heat exchange potential**. Indeed, the geothermal activation of tunnel linings (carried out either by mechanical excavation using a tunnel boring machine or conventional digging with a mechanical shovel) involves a larger **volume of soil** and therefore a generally larger exchange surface than piles.

The first example of an energy tunnel was built in Austria: the **Janbach Tunnel**. More recently, a full-scale experimental test was realised in the [Turin metro tunnel in Italy](#).

1.4. Advantages

1.4.1. Economic

The main advantage of the installation of energy geostructures over other conventional geothermal systems is that structural elements that are necessary for the structural stability and thus would be constructed in any case are use also for energy purposes. This results in a **reduction** of the initial **installation costs**. Experience shows a payback period included between 4 and 8 years, the initial investment being in the order of 2 to 4% of the cost of the work.

1.4.2. Environmental issues

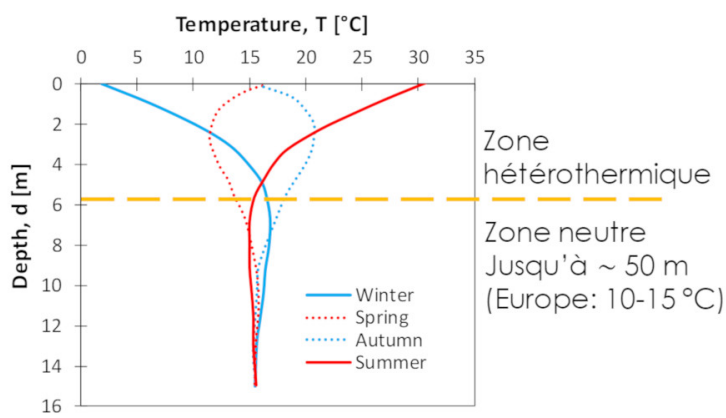


Figure 3. Seasonal evolution of subsoil temperature with depth. [Source: © Di Donna]

Like other conventional low enthalpy geothermal systems (horizontal and vertical probes), it is above all a local and renewable as well as a green energy source. Energy is produced from **heat stored in the soil**, which originates partly from our sun (heating the earth's surface with solar radiation) and partly from the earth itself (heat flux from the earth's core). This energy is transferred by the groundwater flow. The combination of these effects results in a seasonal fluctuation of the temperature of the first few meters of ground, as a function of the temperature of the external air (so-called heterothermic zone). Deeper, the temperature remains constant all over the year up to about 50 m depth (known as the **neutral zone**). From this depth, the temperature begins to rise at a rate of about 3°C every 100 m: this is called the geothermal gradient. Energy geostructures operate in the intermediate zone, the one at constant temperature, which in Europe is in the range between 10 and 15°C all year round (Figure 3). Their use can lead to a reduction in a building's **CO₂ emissions** of about 320 kg per kW produced (see Figure 1).

2. Energy efficiency

Figures 4, 5 and 6 summarize the **heat exchange** potential measured in operational energy geostructures, presented in Watt per metre of pile length and Watt per square metre of wall and tunnel surface, respectively.

2.1. Energy piles

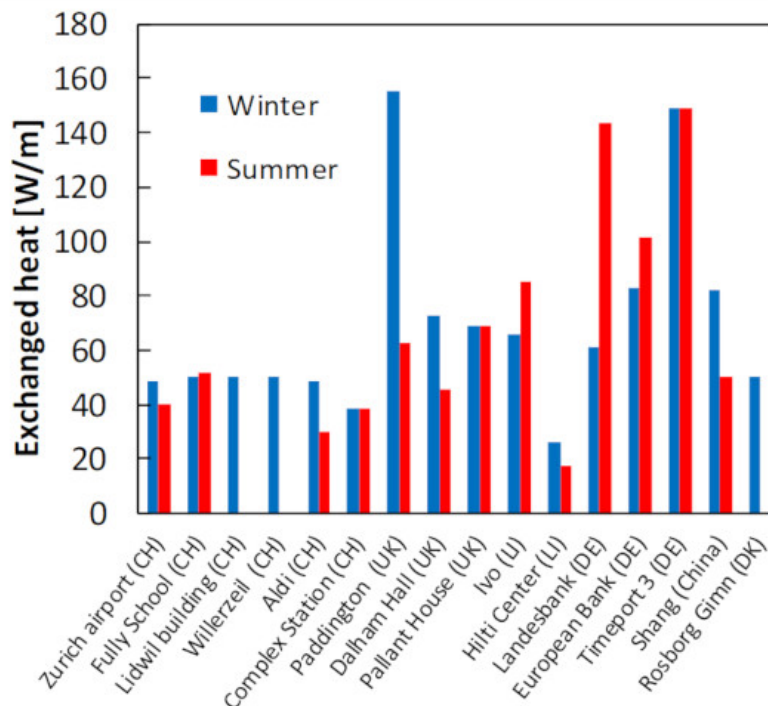


Figure 4. Heat exchanged by energy piles [Source: Di Donna et al. 2017 (Ref.[3])]

According to these data, except in rare cases, it is possible to extract between **20 and 100 Watt per meter of pile length**. The

order of magnitude is the same as that suggested by the English standards (BS 15450), which recommend considering between 30 and 50 W/m in fine soil (clays, silts) and between 55 and 80 W/m in coarse soil (sand, gravel). The numerous active installations and the geometric similarities with conventional geothermal probes have made it possible to acquire a precise knowledge of the behaviour of energy piles and to develop **analysis methods** that are now well established.

2.2. Energy walls and tunnels

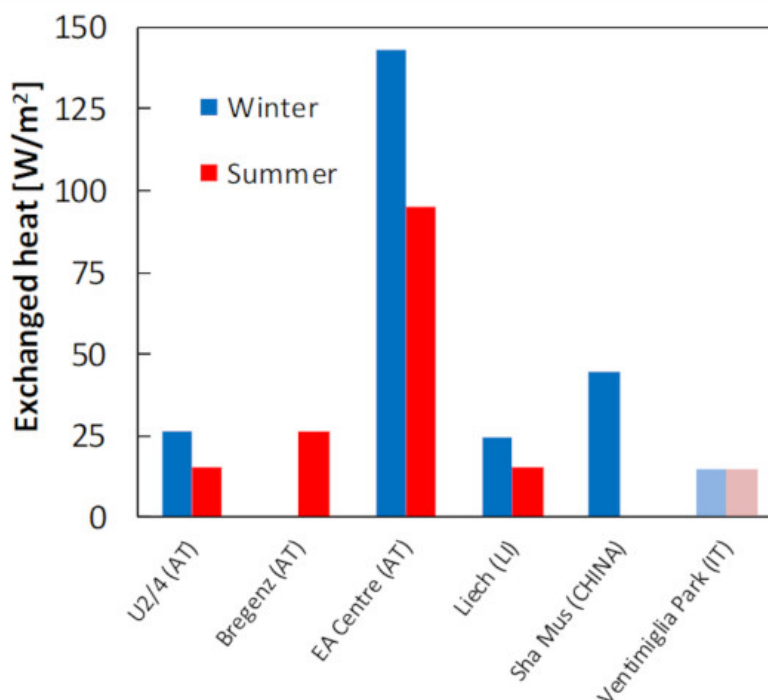


Figure 5. Heat exchanged by energy walls [Source: Di Donna et al. 2017 (Ref.[3])]

A limited number of examples is available for retaining walls and tunnels. According to the available data, it is possible to exchange between **10 and 30 Watt per square metre of wall or tunnel surface area**. These values that might vary significantly depending on the soil properties (especially ground water flow), the geometry of the foundation and the operating conditions of the system.

The numerical and analytical analysis of these structures is less straight forward due to the substantial difference with respect to geothermal probes. The main difference is represented by the boundary conditions on the excavation sides (for example inside a car park or tunnel or station). This obliges to take into consideration the **heat exchange with the internal air** as well. Moreover, the limited number of monitored cases makes things more complicated.

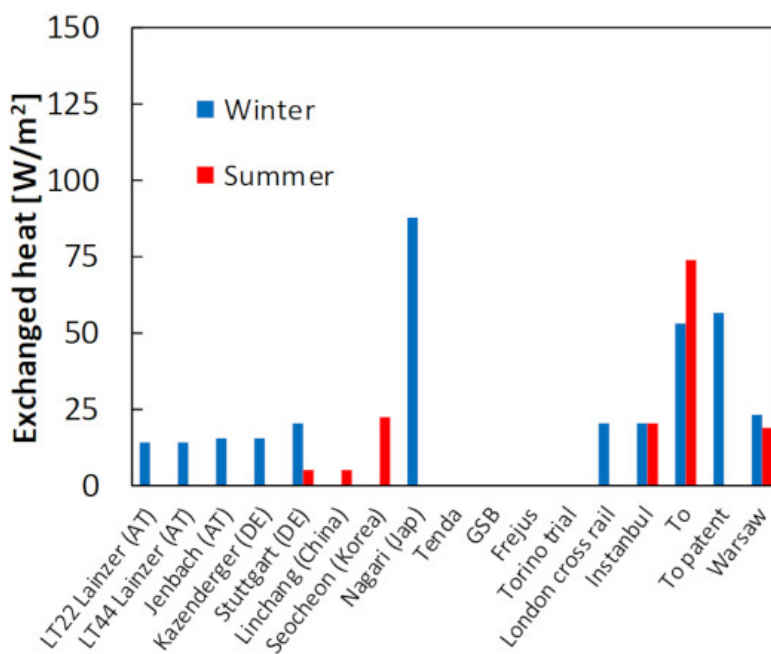


Figure 6. Heat exchanged by energy tunnels [Source: Di Donna et al. 2017 (Ref.[3])]

Recent numerical studies on energy walls shows that the difference in temperature between the ground and the air inside the excavation significantly affects the heat exchange, especially over the long term.

3. Geotechnical aspects

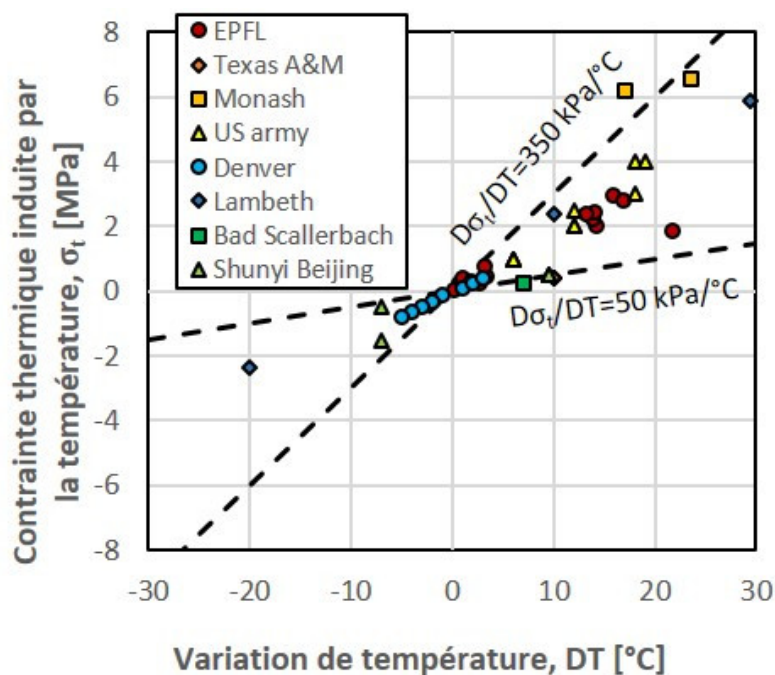


Figure 7. Temperature-induced stress, measured in situ [Source: Di Donna et al. 2017 (Ref.[3])]

The structural and geotechnical performance of energy geostructures remains their primary role and ensure it is of fundamental importance. For this reason, many studies have been carried out to understand whether using these structures as ground heat exchangers, by subjecting them to cycles of temperature variation, could affect their structural and geotechnical behaviour.

In other words, can the use of geostructures as ground heat exchangers induce additional displacements or reduce their load-bearing capacity (i.e. their ability to support applied loads such as the weight of a building)? Once again, the experimental

and numerical results available concern mainly piles.

As a first approximation, a pile can be schematized as a vertical homogeneous bar. If we imagine heating it when it is completely free to deform, it will expand with respect to its center according to its **coefficient of thermal expansion**. To have an order of magnitude, let us consider a 30 m long pile, free to deform, and made of concrete, which has a coefficient of thermal expansion of about $10^{-5} \text{ }^\circ\text{C}^{-1}$. A temperature variation of $30 \text{ }^\circ\text{C}$ would induce a displacement of 4.5 mm (**0.15 mm/°C**) symmetrically at the top and at the bottom of it (and therefore at the head of the pile).

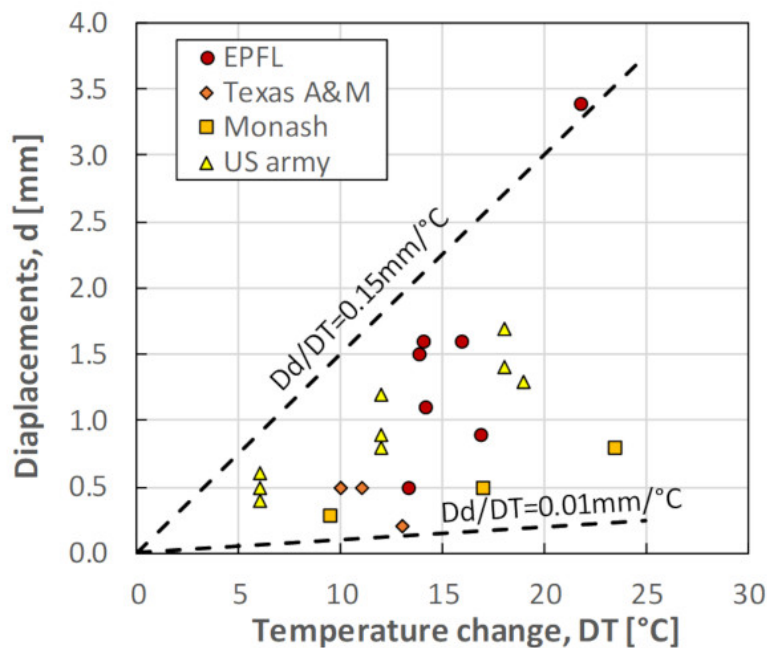


Figure 8. Temperature-induced displacements, measured in situ [Source: Di Donna et al. 2017 (Ref.[3])]

In reality, the pile is not free to expand, but its deformation is at least **partially prevented** by the surrounding soil and the upper structure. This reduces its free deformation and therefore its **displacement at the head**, but induces additional **thermal stresses**

(compressive **stresses** in the case of pile heating). The additional stresses can be calculated as a first approximation as the product of the elastic modulus of concrete (read [How the material deforms: fluids and solids](#)) and the prevented deformation. Considering an elastic modulus for concrete of 30 GPa and assuming that the **pile was completely blocked** (all thermal deformation is prevented), this would correspond to an additional stress in the pile of 9 MPa, i.e. 300 kPa/°C.

Of course, these are two extreme cases. The reality is a **in between them**, but overall one could say that the more the pile will be free to expand, the more there will be a significant displacement at the head and the less thermal stress and vice versa. Similar considerations can be made for cooling.

Figures 7 and 8 show the stress and displacement values induced by temperature variations, measured in **full-scale tests** carried out on energy piles. In practice, they can be used to have an order of magnitude of the effects that temperature changes induce on the geotechnical behaviour of real energy piles. It is important to note that, even if the thermal stresses look high, they remain well below the concrete strength.

4. Messages to remember

Energy geostructures represent a **green, renewable and local** source of **energy** for heating and cooling of buildings.

The main advantage with respect to other conventional closed geothermal systems (probes) is the significant **reduction in initial installation costs**, this reduction being due to the use of geostructures that would be constructed anyway.

This **technology is still under development**, but the number of structures and buildings based on heat exchanger piles is increasing exponentially in Europe without any slowdown being expected at present.

The application to energy **walls and tunnels** is less developed, but many projects are ongoing to better understand their

Notes and references

Cover image. Laloui, L., and Di Donna, A. 2013. Energy geostructures: innovation in underground engineering. ISTE Ltd and John Wiley & sons Inc. [Source: © EPFL-LMS /M. NUTH 2010]

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