GEOTECHNICAL ASPECTS OF USE OF ENERGY PILES

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Abstract: *Energy piles represent modern technologies of geothermal energy use, through systems that are integrated in underground structures of multifunctional buildings founded on piles. It is a type of so-called energy geo-structures, which enable significant energy savings for heating and cooling of buildings in comparison to conventional systems. In paper will be presented, besides examples of carried out energy piles in the world, and geotechnical aspects of their application. It is primarily meant on the knowledge of thermal characteristics of soil and rocks, but also on possible stress-strain changes around the pile which besides structural loads are also caused by thermal processes in terrain.*

Keywords: *geotechnical, geothermal energy, energy geo-structures, energy piles*

GEOTEHNIČKI ASPEKTI KORIŠĆENJA ENERGETSKIH ŠIPOVA

Rezime: Energetski šipovi predstavljaju savremene tehnologije korišćenja geotermalne energije putem sistema koji su integrisani u podzemne konstrukcije višenamenskih objekata koji su fundirani na šipovima. Radi se o jednom vidu tzv. energetskih geo-struktura, koje omogućuju znatne uštede energije za grejanje i hlađenje objekata u odnosu na konvencionalne sisteme. U radu će se pored primera izvedenih energetskih šipova u svetu, prikazati i geotehnički aspekti njihove primene. Tu se pre svega misli na značaj poznavanja termalnih karakteristika tla i stena ali i moguće naponsko-deformacijske promene oko šipa koje pored strukturnog opterećenja izazivaju i termalni procesi u terenu.

Ključne reči: *geotehnika, geotermalna energija, energetske geo-structure, energetski šipovi*

INTRODUCTION

The role of geotechnical engineering in solving of the basic social needs related to the sustainable development (economic growth, environmental protection) is very important when it comes to: development of infrastructure and rehabilitation of existing, efficient construction which includes certain innovative and energy efficient techniques for terrain improving, finding new energy sources and recovery of the existing, use of underground space not only for construction but also for energy storage, use of alternative and eco-friendly materials in geotechnical structures, management and reuse of different waste types (municipal, industrial), prediction and mitigation of natural disasters, conservation of geodiversity as well as reducing of CO_2 emissions from fossil fuels and general improvement of environmental conditions (Rakić et al., 2011). Thus, for example, installation of geothermal heat pumps requires drilling of the terrain, obtaining of detail information on groundwater, knowledge of the thermal characteristics of soil in order to prevent long term temperature changes in densely populated areas due to the use of deep energy geo-structures such as energy piles, energy tunnel linings etc.

Therefore, besides the traditional geotechnical engineering phases, starting from the planning phase to the construction and exploitation of the structure, a new phase which includes ''sustainable development'' is being analysed. Its role is multiple, beginning from the fact that you need to ensure the sustainability of society by promoting the importance of the environmental protection of the certain project realisation, to ensure financial guarantees for the project participants and to take care of the project implementation (Basu et al., 2013). This practically means that a system of sustainable development is a balance between ''3E'': Engineering, Environmental and Economy.

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In relation to “3E“ approach of sustainable engineering, the objectives that can be attributed to the geotechnical engineering are: inclusion of all stakeholders in the project planning phase to achieve consensus on the project sustainability (for example reduce of pollution, use of alternative environmental friendly materials etc.), reliable and safe design and construction which include minimal financial burden of all project participants, minimal use of resources and energy during the design, construction and maintenance of geotechnical structures, use of materials and methods that cause minimal negative effects on the environment and finding opportunities for the reuse of the used materials in order to reduce waste quantity. It is important to mention that sustainability in geotechnical engineering should not focus only on reducing the environmental traces, but it must take into account that designed geo-structures should be reliable and durable in order to minimize hazard effects, both natural and artificial. Aspects of reliability and durability are especially important for critical infrastructure facilities such as: dams, thermal power plants, embankments, bridges and similar structures without which other systems could not function.

GEOTECHNICAL CHARACTERISTICS OF SOIL AND GEOTHERMAL ENERGY

The conception that energy is obtained only from fossil fuels (coal, oil and natural gas) and that is produced only in thermal power plants and hydro power plants is the dominant reason why the most present and the most accessible geothermal energy remains hidden and unexploited. One more reason is the comprehension that the geothermal energy can only be obtained from sources where the water temperature is higher than 45°C (Janković, 2009). However, the geothermal energy can be obtained from water, soils and rocks where the temperature is only 10-12°C (Figure 1). Therefore in recent years there is more and more talking about the use of shallow and deep geothermal energy.

However, the majority of the world’s available geothermal energy is in the surface area of rocks and groundwater whose temperature is higher than 10°C (Roland, 2010). In 1980’s technological development enabled the efficient use of this low-temperature geothermal energy through the so-called heat exchangers – heat pump systems (Ground Source Heat Pump Systems – GSHPs). These pump systems transfer thermal energy from one area to another by cooling one area and heating the other one. Using the heat pumps, it is possible to exploit available geothermal energy to the temperature level of approximately 10^0C. This means that in some places it can be used up to three time higher geothermal capacity than currently used.

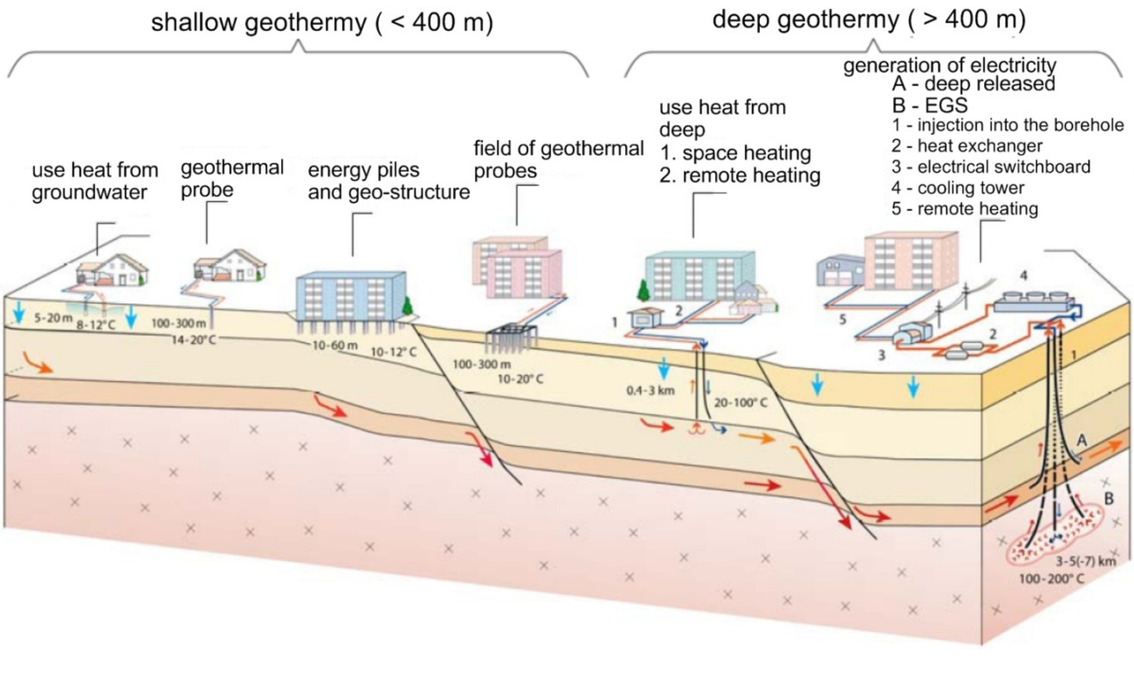

Fig. 1. Possibilities of using geothermal energy at different depths (Roland, 2010)

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Systems for the shallow geothermal resources use are based on the principle that temperature of soil and rock as well as groundwater is constant at the certain depth during the whole year (Brandl, 2006). The surface part is under direct influence of atmospheric conditions and this effect decreases with depth increase down to a depth where the temperature is constant in both summer and winter (Figure 2).

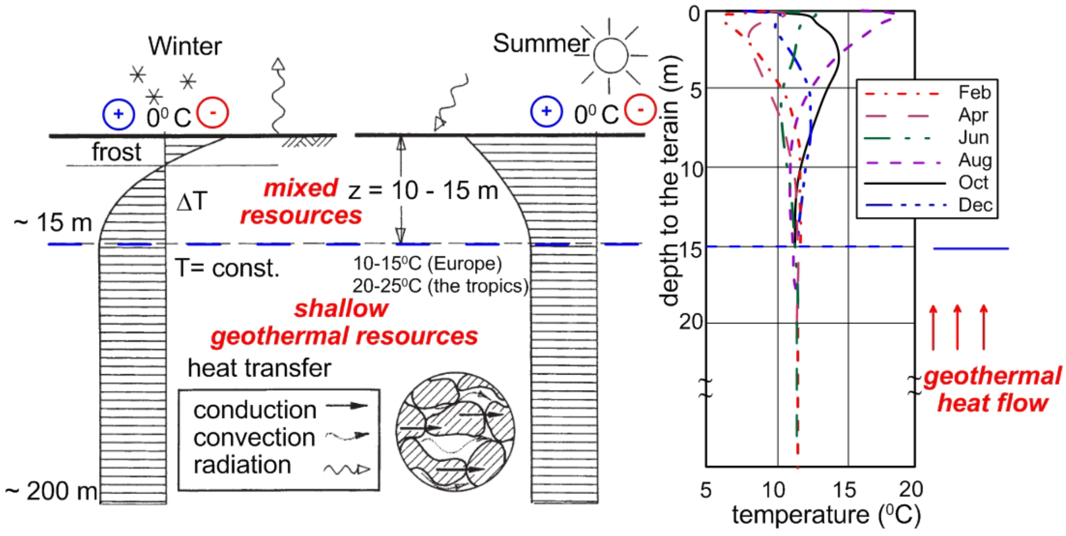

Fig. 2. Geothermal heat scheme and typical temperature variations (Brandl, 2006; Ribach & Sanner, 2000)

In most parts of Europe, season soil temperatures remain relatively constant below a depth of 10-15 m, and predominant values are between 10°C and 15°C to a depth of approximately 50 m (Brandl, 2010). Such temperatures provide cost-effective heating and cooling by energy geo-structures and present ideal conditions for heat pumps.

Geothermal heat transfer through the soil is very complex process and includes a number of mechanisms (conductivity, radiation, convection, condensation, freezing and defrosting etc.) that have an influence on a design of energy pile (GSHP, 2012). The role of geotechnical engineering in the development of energy pile is significant (Figure 3).

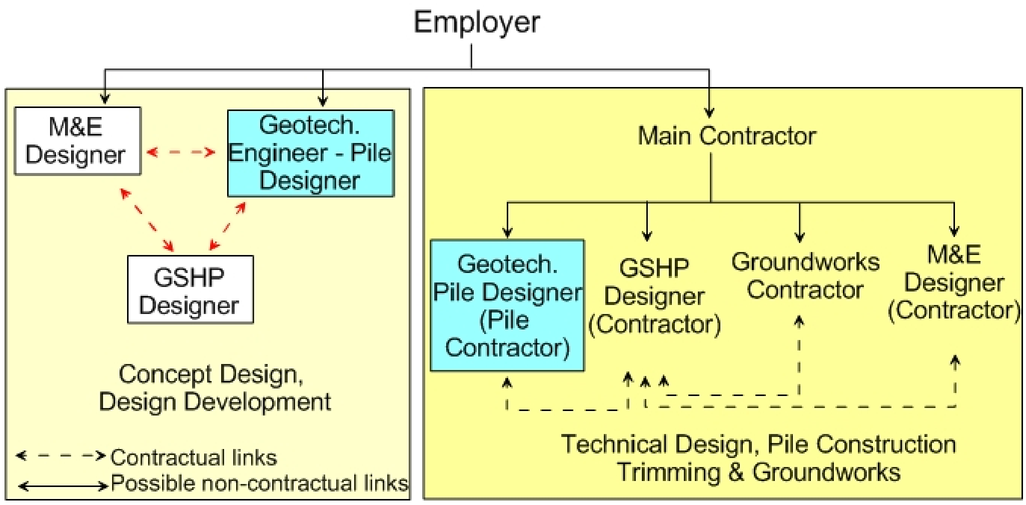

Fig. 3. Contractor design (GSHP, 2012)

The evidence for this is a great number of codes and standards in the area of geotechnical engineering, but also in other areas, which are applied in design and construction of energy piles. This is primarily related to the following:

- BS EN 1997-1:2004 Eurocode 7: Geotechnical design - Part 1: General rules,
- BS EN 1997-2:2007 Eurocode 7: Geotechnical design - Part 2: Ground investigation and testing,

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- BS EN 1536:2010 Execution of special geotechnical works — Bored piles,
- BS EN ISO 22477-1 (draft) Geotechnical Investigation and Testing, Part 1 - Pile load testing by static axially loaded compression,
- BS5930: 1999 + A2:2010 Code of practice for site investigations,
- BS EN 15450:2007 Heating systems in buildings - Design of heat pump heating systems,
- BS EN 12664:2001/BS EN 12667:2001 Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods,
- BS EN 206:2000/BS 8500:2006 Concrete - Specification, performance, production and conformity.

The most important geotechnical characteristics of soil are to know saturation degree, water permeability, unit weight and porosity ratio (Brandl, 2006). Besides, the efficient design requires knowledge of the thermal characteristic of the soil and of other geomaterials, detail information on groundwater and estimation of flow conditions, development of drilling technology especially in deep reservoirs of geothermal energy, analysis of hydro-thermal-chemical-mechanical processes etc. Without progress in these areas, geothermal energy production will be significantly limited.

The most important thermal characteristics of soils are: thermal conductivity λ (W/m^0K) and specific heat capacity c (J/kg^0K).

$$\Gamma = \lambda_s \cdot (1-n) + \lambda_w \cdot n \cdot S_r + \lambda_g \cdot n \cdot (1-S_r) \qquad (1)$$

where:

λ – thermal conductivity (solid, water, gas);

n – porosity;

S_r – saturation degree

The first member in equation refers to the soil characteristics, the second one to the water characteristics and the third to the gas characteristics. Thermal conductivity λ is an indicator of heat transfer from higher to lower sources taking into consideration the temperature balance. It depends on the moisture and saturation degree, soil density and also the mineralogical composition and chemical properties of the pore water have a certain influence. It should be kept in mind that excessive heat extraction through energy pile can cause freezing of the soil which greatly increases the thermal conductivity, because λ_{water} = 0.57 W/m^0K changes into λ_{ice} = 2.18 W/m^0K. For the conceptual design of standard energy pile the value of coefficient λ can be taken from a graph of from a table (Table 1) with adequate precision taking into account water content, saturation and soil texture (Brandl, 2006). For complex and major projects, a coefficient λ is determined by laboratory or field tests by exposure of soil to temperature gradients change. Thermal capacity c (J/kg^0K) defines the energy amount which is in material and it is needed to increase a temperature for 1^0K to a mass of 1 kg at constant pressure.

Table 1. Characteristic values of thermal conductivity and specific heat capacity

Soil, Rock	Thermal conductivity λ (W/m^0K)		Specific heat capacity c ($MJ/m^3\,{}^0K$)		Permeability K_f (m/s)
	dry	saturated	dry	saturated	
Clay	0.2-0.3	1.1-1.6	0.3-0.6	2.1-3.2	10^{-10}-10^{-8}
Silt	0.2-0.3	1.2-2.5	0.6-1.0	2.1-2.4	10^{-8}-10^{-5}
Sand	0.3-0.4	1.7-3.2	1.0-1.3	2.2-2.4	10^{-4}-10^{-3}
Gravel	0.3-0.4	1.8-3.3	1.2-1.6	2.2-2.4	10^{-3}-10^{-1}

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Calcite	3.6		
Quartz	7.7		
Air	0.024		
Water	0.57		

GEOTECHNICAL ASPECTS OF USE OF ENERGY PILES

Generally it can be said that the energy piles represent structural elements of double use. Their main use is structural, because they represent special form of deep foundations over which the load of structure is transmitted through surface soil layers to the deeper layers which have better strength. However, if the systems for use of shallow geothermal energy are been installed in them, they get a role of the energy pile (Figure 4).

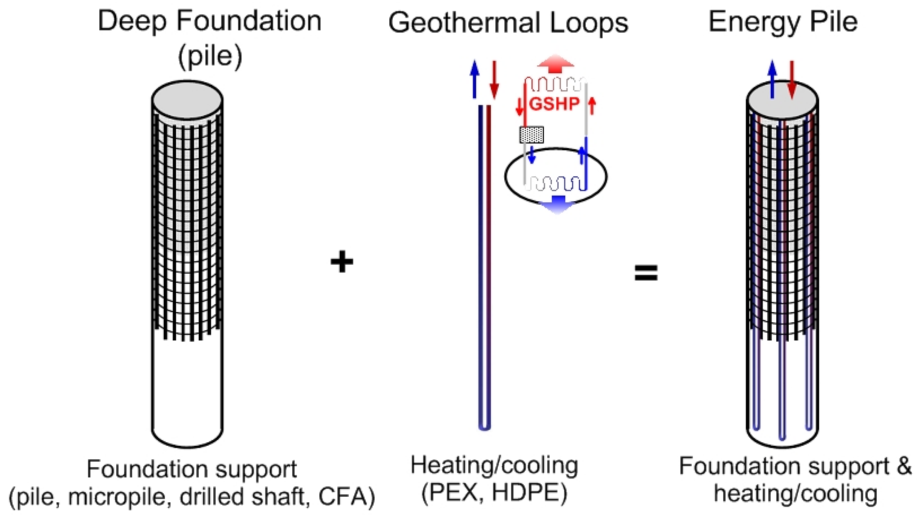

Fig. 4. Energy pile (Guney, 2013)

General principles of their performance come down to the tube installation for the geothermal energy absorption from soil through which the heat is transferred by a fluid which circulates in tubes and later a certain temperature is regulated by using heat pumps.

Tubes for geothermal energy absorption are typically attached to the reinforcement cage and properly are arranged to take heat from soil on the most optimal way (Figure 5).

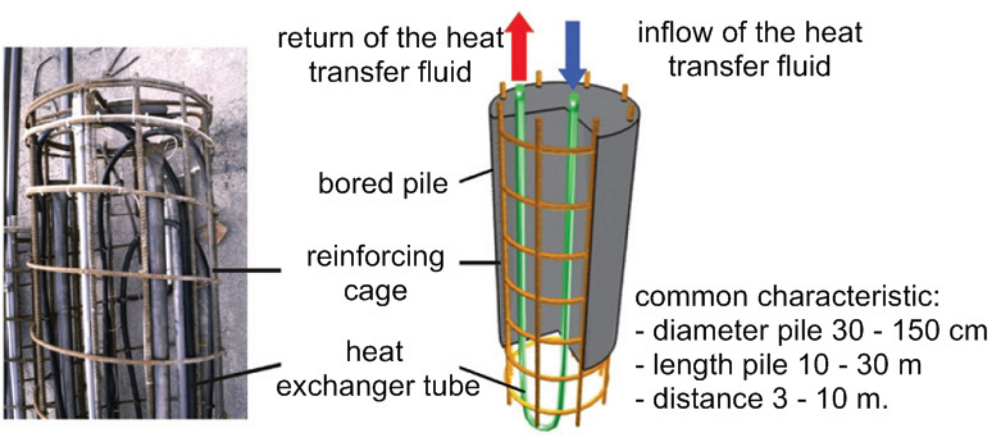

Fig. 5. Typical energy pile arrangement (Laloui et al,. 2013)

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The design of energy piles requires consideration above and beyond the usual pile design process. The aim of the pile design should be to quantify the thermal loads and then apply factors of safety currently used in the normal pile designs (Figure 6).

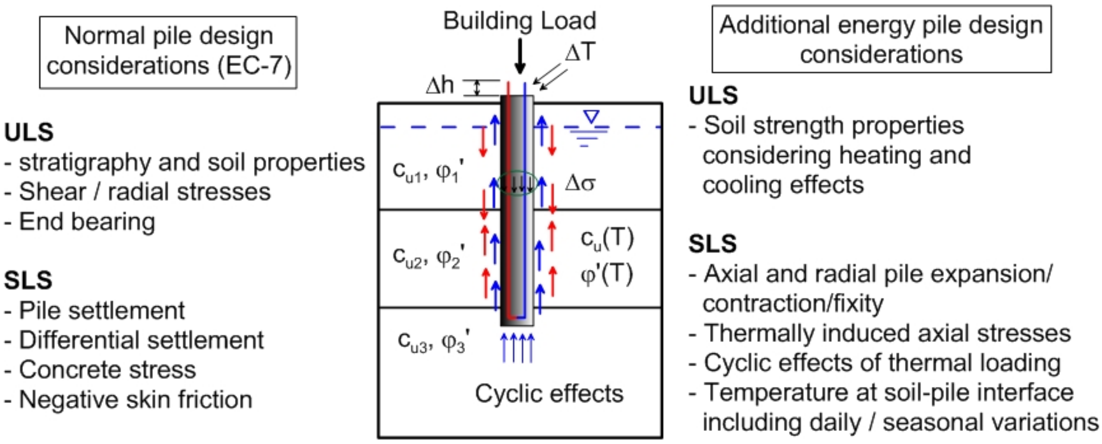

Fig. 6. Additional considerations that should be taken into account in energy pile design (GSHP, 2012).

Previous experiences show that properly designed energy systems do not affect to the bearing capacity of characteristic geo-structures (energy piles etc.) in these types of soil layers. However, it should be very careful in cases where the aboveground structure parts are extremely sensitive to differential settlements (Brandl, 2006). Because, besides the knowing of the soil thermal characteristics, from the point of geotechnics, it is particularly important to know change of stress-strain characteristics due to thermal processes in soil. Assuming that the temperature change is uniform along the pile, the possible mechanism of load transfer in energy piles, especially when it comes to cooling effect and especially when it comes to heating effect of soil, is presented in Figures 7 and 8.

Ground cooling reduces stresses along energy pile cross-section. If the ends of the piles are free to move, cooling results in contraction of the pile about the mid-point. Restraint to the pile shaft causes tensile stresses to develop within the pile. This may lead to cracking of the pile. The resulting shear stress on the soil-pile interface is in the same direction as that mobilized by compression loading in the upper part of the pile, and in the opposite direction in the lower part of the pile. The combined effect of load and cooling causes axial loads to become less compressive at the mid-point and may become tensile at the lower part of the pile (GSHP, 202). The mobilized shaft resistance increases in the upper part of the pile and decreases in the lower part of the pile (Figure 7).

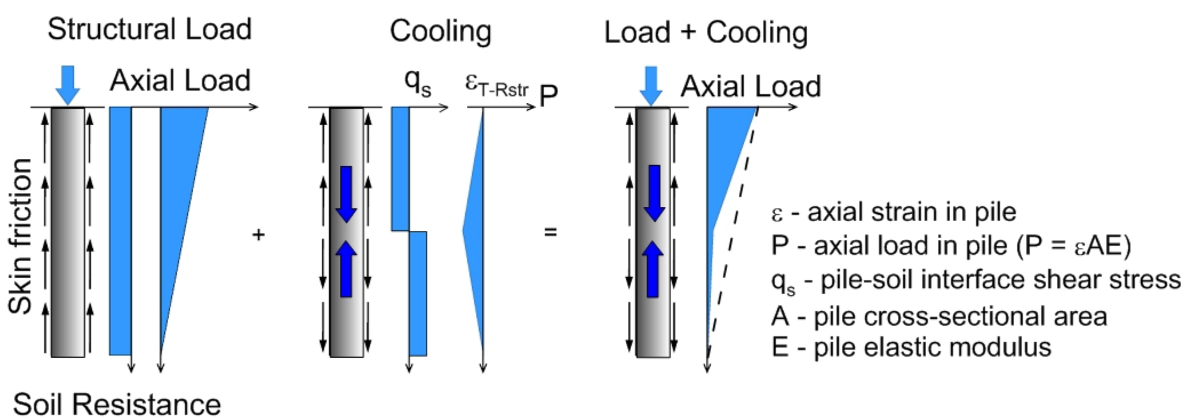

Fig. 7. Mechanisms for the response of energy pile to cooling effect of soil (Guney, 2013)

Heating causes the pile to expand about the mid-point, with shaft resistance causing additional compressive stresses to develop in the pile. The resulting shear stress on the soil-pile interface is in the opposite direction as that mobilized by compression loading in the upper part of the pile, and in the same direction in the lower part of the pile. A combined load and heating cycle results that

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axial loads becoming more compressive. Restraint to the pile shaft causes compressive stresses to develop within the pile shaft. This may lead to compressive failure of the pile. The mobilized shaft resistance is decreased in the upper part of the pile but increased in the lower part of the pile. The mobilization of shaft resistance will produce pile heave during heating and pile settlement during cooling (Figure 8). The magnitude of the movement at the pile head depends on how the shaft resistance mobilize with relative displacement between pile and soil (GSHP, 2012).

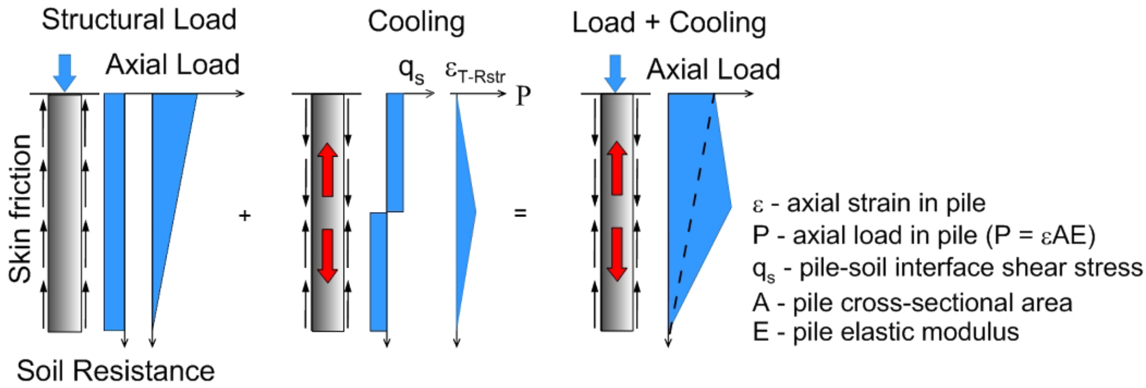

Fig. 8. Mechanisms for the response of energy pile to heating effect of soil (Guney, 2013)

Long term temperature changes along energy pile (cooling and heating effects) may significantly affect the change of stress state around the pile, and thus its bearing capacity and settlement. The cycles of cooling and heating partially affect the volume change of pile but also of soil that surrounds it. The pile expands during heating and contracts during cooling causing axial tensile stresses and also affecting pile-soil interaction (Figure 9).

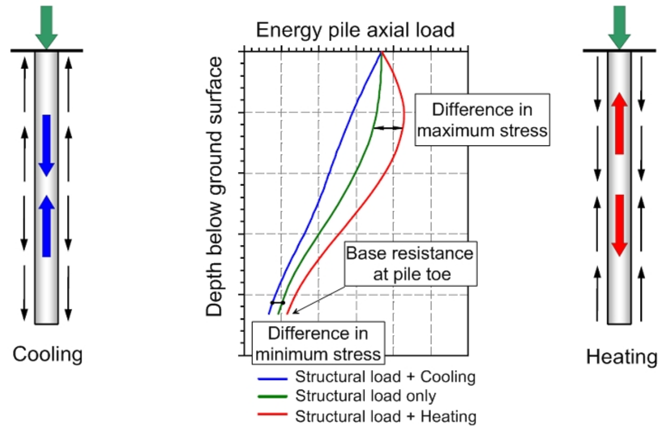

Fig. 9. Energy pile stresses due to thermal loading (Guney, 2013)

In order to avoid problems related with thermal effects in energy foundations it is important to understand the mechanisms of response better and provide indicative values of thermal effects (Figure 10).

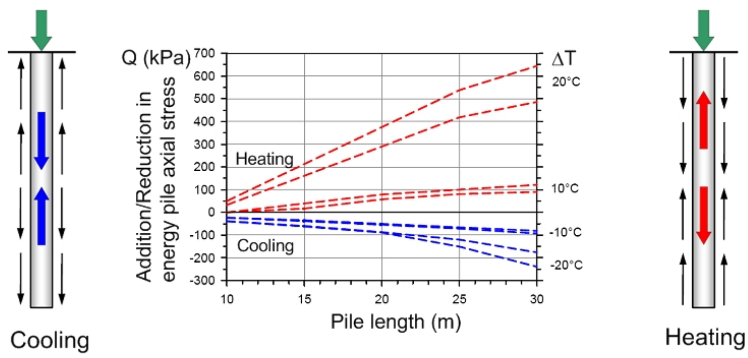

Fig. 10. Energy pile stresses induced by cooling and heating (Guney, 2013)

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The volume change process in the soil and in the pile due to the temperature changes produces deformations (ε_{th}) in the materials (Cervera, 2013). The deformations depend on the thermal expansion coefficient (α) of each material and the temperature variation as mentioned in the equation 2.

$$\varepsilon_{th} = \alpha \cdot \Delta T \qquad (2)$$

If the mechanical load is less than 40% of the ultimate load, a perfect thermo elastic condition can be assumed (Kalantidou et al., 2012), and the total deformation (ε_{tot}) of the material is the sum of the elastic deformation (ε_{el}) and the thermal dilatation (ε_{th}).

$$\varepsilon_{tot} = \varepsilon_{el} + \varepsilon_{th} \qquad (3)$$

New deformations due to the expansion process induce compressive stresses to the pile. They can generate shear stresses between pile-soil and they should be considered in the structural design. Considering a perfect elastic condition, normal stress depends on the modulus of elasticity (E) and elastic deformation (ε_{el}).

$$\sigma = E \cdot \varepsilon_{el} = E \cdot (\varepsilon_{tot} - \varepsilon_{th}) \qquad (4)$$

Besides the impact on the bearing capacity of energy pile, temperature changes have also influence on its settlement (GSHPA, 2012). After the initial settlement due to the structural load, the piles experiment deformations due to the cyclic thermal loading during heating and cooling. Repeated cyclic thermal loading reduces the shaft friction along the pile accumulating head settlement deformations, especially during cooling (Figure 11).

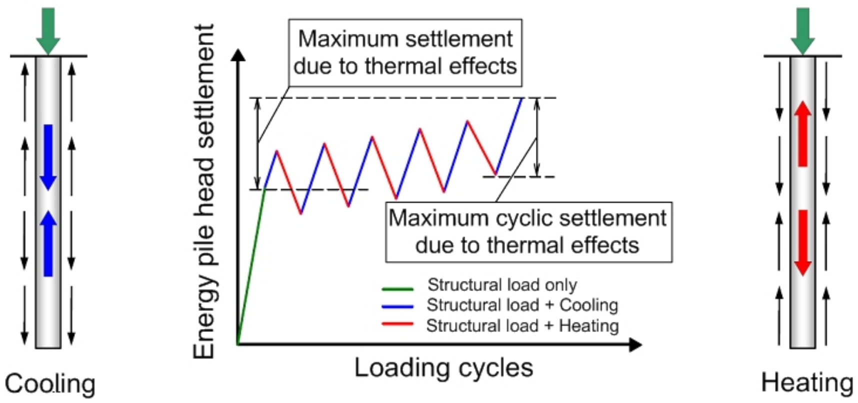

Fig. 11. Pile settlement due to thermal loading (Guney, 2013)

Energy pile settlement induced by temperature changes is presented in Figure 12.

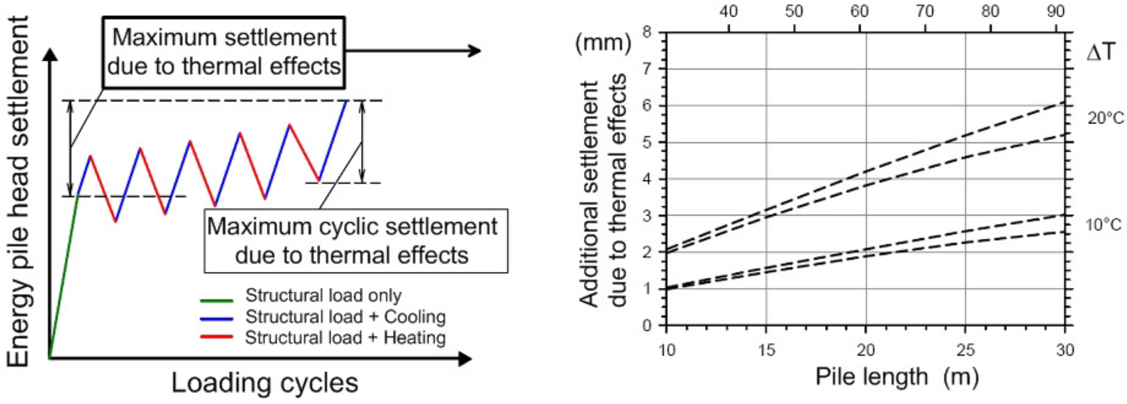

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Fig. 12. Energy pile settlement induced by cooling and heating (Guney, 2013)

Besides that the biggest influence to the functionality of energy geo-structures have the characteristics of soils, rock and groundwater, particular significance have the characteristics of materials used for their construction, dimensions of elements, distance between them, installation method etc.

EXAMPLES OF STRUCTURES FOUNDED ON ENERGY PILES

Worldwide it can be found numerous examples of performed energy geo-structures for the exploitation of geothermal energy. The most characteristic examples are: construction of foundation structures of energy piles for heating and cooling of multifunctional buildings, heating of road structures, parking lots and airport runways, construction of energy tunnels using energy tunnel linings, construction of retaining structures using walls and anchors as part of energy geo-structures etc.

This technology is widely used in Europe, in Austria, Germany, Switzerland, United Kingdom, which are considered its pioneers. Thirty years ago the first activities related to investigation of energy geo-structures started in these countries (Figure 13).

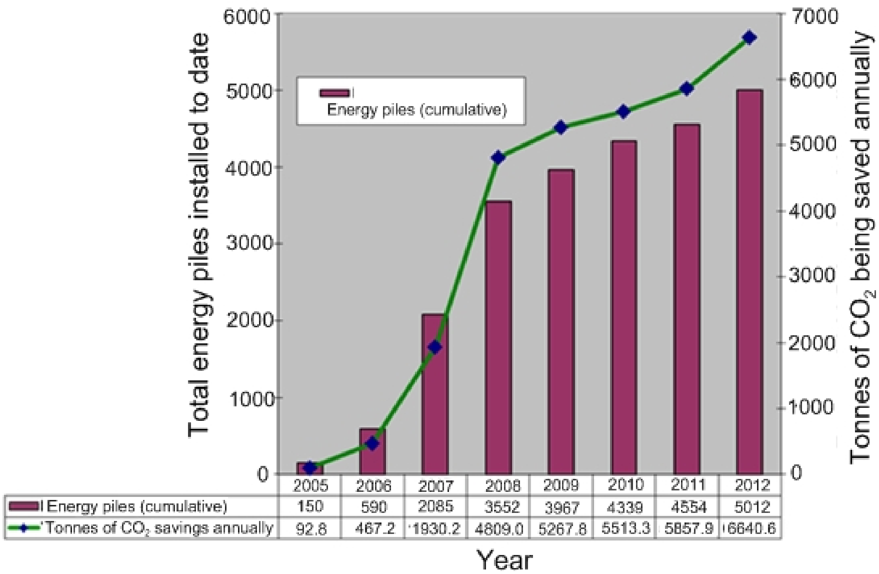

Fig. 13. Energy pile installations and estimated CO_2 savings in the UK (Laloui et al., 2013)

One of the most characteristic examples of energy piles use is Main Tower – Frankfurt, height of 200 m. The foundation structure of the tower is built of 112 energy piles diameter of 1.5 m, variable length of 20 – 30 m, and of 10 energy piles diameter of 0.9 m which in fact represent a protective diaphragm along the edge of foundation structure. The terrain is, in surface layers up to a depth of 10 m, made of quaternary sands in which base are Frankfurt clays with lenses of sand, and terrain base is made of tertiary limestone sediments. This energy geo-structure actively use a volume of approximately 150 000 m^3 of soil, and for obtaining of geothermal energy heat pump with power of 500 kW is installed.

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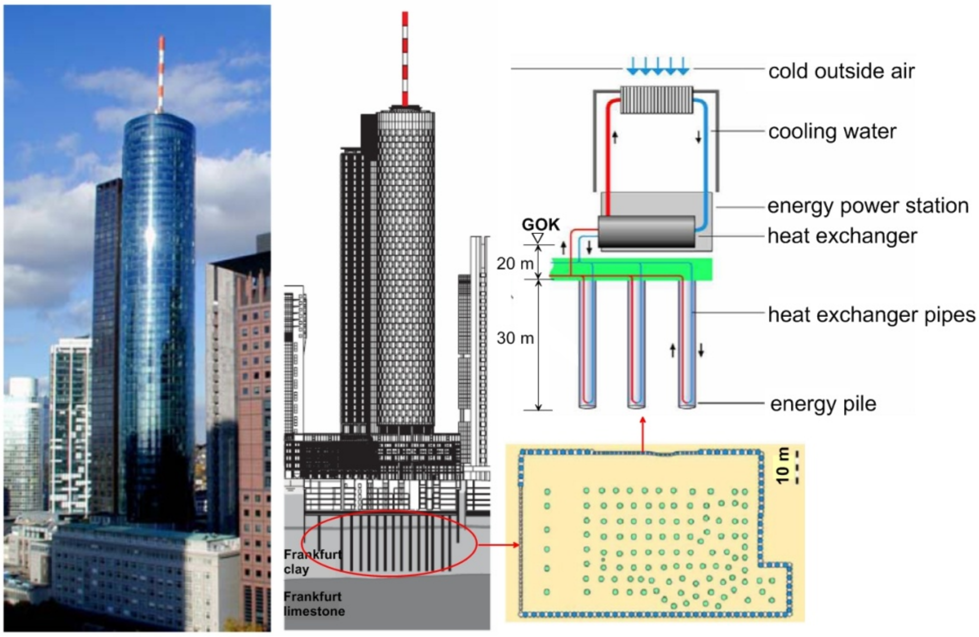

Fig. 14. Main Tower: Ground model /combined energy pile-raft foundation (Brandl, 2006)

A second characteristic example is Dock Midfield, the new terminal E of the Zürich airport, length of 500 m and width of 30 m. The structure is founded on 440 piles of which 306 are energy piles with diameter of 0.9 m to 1.5 m and average length of 26.8 m. For this structure, area of 85200 m^2, 65 – 70 % of energy for heating and cooling is provided through energy piles, i.e. about 2700 MWh (2210 MWh for heating through heating power 630 kW and 4900 MWh for cooling through cooling power 400 kW, Figure 15).

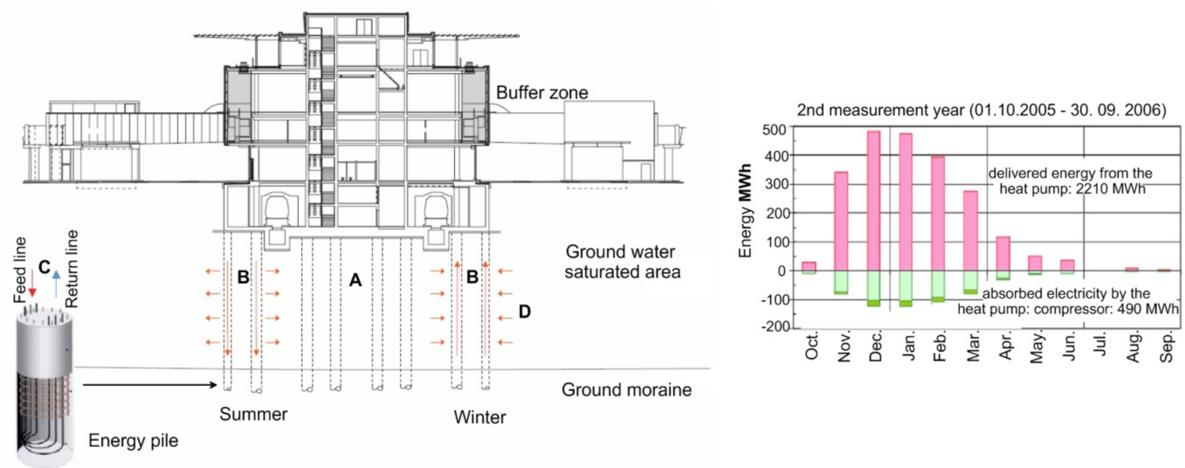

Fig. 15. New terminal E of the Zürich airport – thermal performances of the heat pump (Daniel & Markus, 2007)

CONCLUSION

In recent years in the world, as one way of renewable energy sources use, the objects which through so-called energy geo-structures use shallow and rarely deep geothermal energy are built. Use of geothermal energy is provided by heat exchanges – heat pump systems which are installed in necessary structure elements such as: foundations, retaining walls, tunnel linings etc. Therefore, besides the usual investigations, specific investigations are necessary based on which thermal, mineralogical, geochemical, hydrological characteristics of soil are determined in order to establish the limits of geothermal energy use, either through horizontal or vertical systems, which requires additional geotechnical expertise. This is particularly important when it comes to the temperature changes along the energy pile, because they can significantly influence on the change of stress state around the pile, i.e. on its bearing capacity and settlement. Due to the complexity of this

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foundation system no valid calculation method has yet been implemented in national or international technical codes and standards.

In developed countries, the use of geothermal energy through energy geo-structures is supported by government organizations and has a positive public image. In our country we can say that there is a solid basis for the use of geothermal energy, but both in science and in practice there is no great interest in these aspects of its use so far (Rakić et al., 2013).

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