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Driven precast concrete geothermal energy piles: Current state of knowledge

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A R T I C L E I N F O

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A B S T R A C T

Geothermal energy piles are increasingly luring attention in the construction industry as a cost-effective and environmental friendly solution for heating and cooling buildings. Energy piles are used as the primary unit in the ground source heat pump systems, which exchange heat with the ground. Energy piles are generally categorized into driven (displacement) and cast-in-place (non-displacement) piles. The present paper aims to review the available methods of design and construction of driven precast concrete energy pile foundations and provides a clear understanding of its construction challenges. Additionally, precast and cast-in-place energy pile foundations are compared. This paper found that precast concrete-driven energy pile foundations are a competitive alternative to cast-in-place energy piles. Driven concrete energy piles have higher quality control and quality assurance in the construction process; they have an easier, faster, and more reliable installation. Several other advantages and limitations related to the technical, economical, and environmental aspects of such piles are discussed in detail. The driven precast concrete foundations have a large worldwide market; however, there is a lack of guidelines, design standards, and experience for using such foundations as energy piles.

1. Introduction

The increase in the world population and the growing demand for clean and renewable energy resources have made shallow geothermal energy an attractive energy source that can be used for the heating and cooling of buildings and warehouses, as well as for deicing of sidewalks, roads, and bridge decks. Energy geostructures or thermo-active geostructures are defined as a technology that can be utilized as a source of energy for building heating and cooling as well as playing a structural role in any construction project [1]. Energy geostructures can be categorized into several types, such as energy piles, walls, tunnels, slabs, and anchors [2,3]. In addition to the geostructures, many other nonstructural elements such as sewers [2], horizontal and vertical borehole heat exchangers (BHEs), open- and closed-loop systems installed in lakes, rivers, fjords, and old mines can be utilized coupled with the ground source heat pump systems [4].

Energy piles are deep foundations mainly made of concrete reinforced with a steel rebar cage. High-density polyethylene pipes are embedded inside concrete, acting as heat transfer pipes, carrying heat transfer liquid, which is water mixed with antifreeze liquid such as ethylene glycol or propylene glycol. The heat transfer liquid exchanges heat with the pipes, concrete, and then the soil media, and the energy is transferred to a heat pump at the ground surface to be used for heating and cooling buildings at the ground surface [5]. The energy piles can, in general, provide the base heating and cooling loads for a building. However, in some cases, as in the new Google office building in California, which uses 2500 energy piles, such a system can provide 95% of the required cooling in the summer and all the heating required in winter [6]. Fig. 1 shows a cast-in-place energy pile foundation.

The potential use of energy piles is significantly increasing all around the world. For instance, the total number of energy piles installed in the UK from 2005 until 2020 shows an increase of 4174%, as illustrated in Fig. 2 [5]. Using energy piles reduces a significant amount of CO_2 emissions per year, which is crucial for the environment and for stopping global warming. In addition to the well-developed countries, including but not limited to the UK, USA, Switzerland, Germany, and Australia [4], several developing countries, including Iran, are showing interest in using energy pile foundations for heating and cooling residential buildings [7].

Pile foundations can be categorized based on their materials, construction, and installation methods. All categories of pile foundations, according to the literature, are summarized in Fig. 3. Although these

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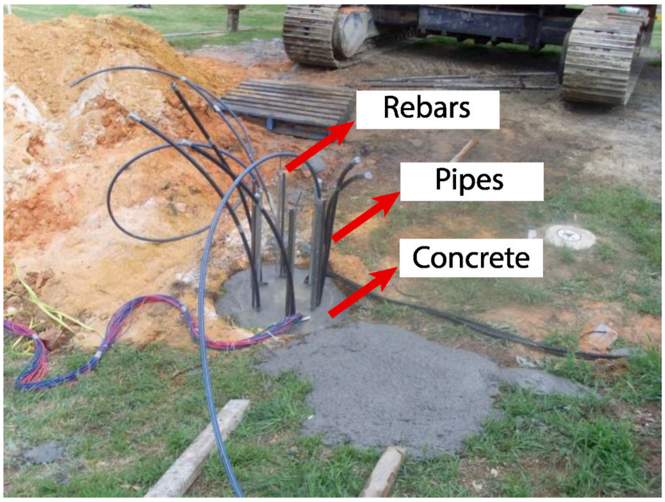


Fig. 1. A cast-in-place energy pile.

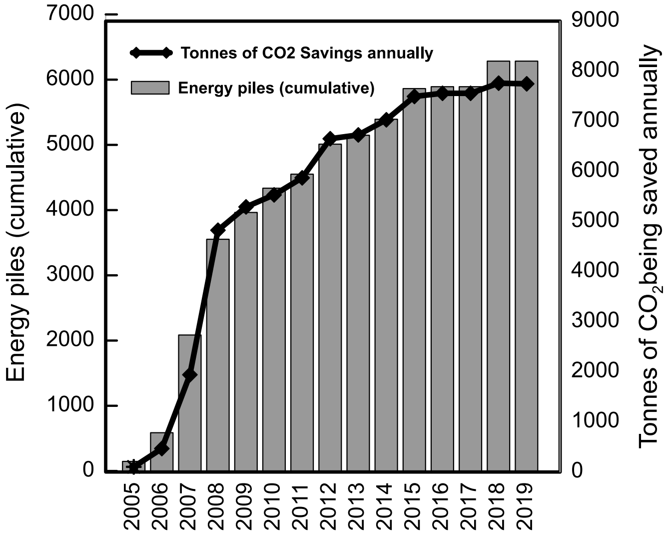


Fig. 2. Energy piles installed in the UK and the annual CO$_2$ savings.

categories are for regular pile foundations, therefore, same categories have been adopted for energy piles in this paper.

According to their construction method, energy pile foundations can be categorized into non-displacement (cast-in-place or replacement) and displacement (precast) piles. Cast-in-place concrete piles, also known as bored piles, are constructed by making boreholes in the ground and then putting the rebars together with heat transfer pipes and pouring concrete into the borehole. Bored piles can be categorized into drilled piles and continuous flight auger (CFA) piles. In CFA piles, a continuous auger drills, and after the drilling is finished, the auger is taken out of the ground while fresh concrete is poured into the ground. After that, the rebars are installed in fresh concrete, with the heat transfer pipes attached to them. Another method of installing heat transfer pipes in such piles is connecting them to single steel rebars and then pushing the rebars into the center of fresh concrete [5].

Precast energy piles can be categorized into steel and concrete energy piles based on their material. The heat transfer pipes are installed inside the steel pile foundation [8]. It is well known that the price of steel pile foundations is generally higher than that of concrete pile foundations. The steel piles can be used hollow, but sometimes they are filled with concrete to provide higher bearing capacity for high-rise buildings. However, driven concrete energy piles can be used to provide similar bearing capacity for high-rise buildings. Hence, they can be a competitive alternative to steel driven piles.

Various statistics show that precast concrete energy pile foundations have a large market size due to the already available market for the normal precast driven piles and the current increasing trend to employ renewable heating energy resources in many countries. Looking at the market for energy-efficient buildings, Businesswire estimates that this will grow by \$103.9 billion globally over 2020–2025 [9]. Considering the recent rules and regulations set by governments, which encourage new buildings to use renewable heating energy sources instead of fossil fuels [10], precast concrete energy piles can facilitate this renewable heating energy revolution.

The thermomechanical behavior of cast-in-place energy piles specially the strains and stress distribution along the pile have been investigated by many researchers [11–13]. However, when it comes to driven precast energy piles, few people investigated the behavior thermomechanical performance of precast piles [14], while the installation effects, and the changes in the soil properties such as density and the soil-pile interface properties, might change the behavior of the pile. Usually the thermal strains and stresses in a pile are measured using a parameter called Degree of Freedom (DOF) [15], which is defined in Equation 1, and is theoretically $0 \leq \text{DOF} \leq 1$.

$$\text{DOF} = \frac{\varepsilon_o^{th}}{\varepsilon_f^{th}} \tag{1}$$

Where ε_f^{th} is the thermal strain in energy pile when it can perform freely (Equation (2)) and ε_o^{th} is the observed thermal strain in the case of partially restrained mechanical boundary conditions. The blocked thermal strains in an energy pile (Equation (3)), cause axial thermal stress (Equation (4)).

$$\varepsilon_f^{th} = -\alpha_{EP}\Delta T \tag{2}$$

$$\varepsilon_b^{th} = \varepsilon_o^{th} - \varepsilon_f^{th} \tag{3}$$

$$\sigma_o^{th} = E_{EP}\varepsilon_b^{th} = E_{EP}\left(\varepsilon_o^{th} - \varepsilon_f^{th}\right) = E_{EP}\left(\varepsilon_o^{th} + \alpha_{EP}\Delta T\right) = E_{EP}\alpha_{EP}\Delta T(1 - DOF) \tag{4}$$

The DOF is an important parameter for the calculation of thermomechanical stresses in a pile, and when it comes to driven precast energy piles, there is lack of understanding of this parameter. Piles with different mechanical boundary conditions are presented in Fig. 4.

Cast-in-place concrete energy piles have been studied extensively over the past two decades. The research about cast-in-place energy piles has been summarized in several review papers such as [5,16] and other similar research such as [17–19], and [20]. Several books have been published on energy piles and energy geostructures [1,21], mainly focusing on cast-in-place energy piles. Although many research papers focused on cast-in-place concrete energy pile foundations, limited research has been done on precast concrete driven energy piles. The reason can be the lack of understanding about precast concrete driven energy piles.

The main incentive for the present paper is to provide a more in-depth understanding of precast concrete energy pile foundations and the challenges associated with their design and construction. Initially, the previous research on concrete driven energy pile foundations is summarized, and a brief overview of the technology is presented. In the technical background, ground temperature profiles of four locations with different climatic conditions are presented, and then the heating/cooling demand diagram for a single residential house in Oslo, Norway, is presented to show the heating and cooling demand for a city in cold climate regions. Then the challenges associated with the design, construction, and installation of this type of energy pile are discussed. Furthermore, the environmental, social, and economic impacts of using precast concrete energy pile foundations are discussed. The ultimate aim of this paper is to highlight the applicability and feasibility of driven precast concrete energy pile technology in many countries worldwide.

2. Driven precast concrete energy pile foundations

Driven precast concrete energy pile foundations can be categorized into two groups of hollow cylindrical (concrete pipe pile) [22] and quadratic energy piles (square-shaped) [23]. Precast concrete energy pile foundation segments are constructed at a concrete factory. The construction process includes installing a cage in a formwork, embedding the high-density polyethylene heat transfer pipe inside the cage, and then pouring concrete into the formwork. When the concrete curing process is finished, they are transported to a construction site. The precast concrete pile segments are installed into the ground using pile-driving machines, which either use impact hammers or vibratory machines to push the pile into the ground. The main advantage of precast concrete energy piles over the cast-in-place piles is that the segments are installed very quickly, and there is a higher quality control and quality assurance through the production of the segments in the factory. Additionally, precast concrete piles can be installed in soil deposits, where installing the cast-in-place energy pile foundations is either expensive or not possible, i.e., polluted grounds and ground with a high level of groundwater table.

Park et al. (2013) performed field experiments and numerical simulations to investigate different loop configurations in precast-high strength concrete (PHC) hollow cylindrical energy piles [24]. Yoon et al. (2013) investigated the heat transfer behavior of W-shaped heat exchangers in hollow cylindrical energy piles installed in multilayer soils [25].

NG et al. (2016) [26] performed a lab-scale experimental study using a centrifuge facility to compare the behavior of bored energy piles (replacement) with that of driven (displacement) energy piles foundations in saturated sand. They observed that for a constant mechanical load and five cycles of thermal load, bored piles settled while the driven pile underwent a slight heave, which was reported to be due to the densification and crushing of soil particles in the vicinity of the driven pile [26].

Santayana et al. (2018) investigated the thermo-mechanical behavior of a precast concrete driven thermopile in Valencia [27]. They studied the effect of building cooling mode on the mechanical behavior of the energy pile. Later, Alberdi-Pagola et al. (2018) compared the heat flow models to interpret the precast quadratic energy piles [28]. Alberdi-Pagola (2019) developed G-functions to predict the thermal performance of the single and group of precast energy piles over the performance time [29]. Alberdi-Pagola et al. (2020) conducted a case study on an energy pile project in Rosborg, Denmark, which used single segment quadratic precast concrete energy pile foundations [30].

Jiang et al. (2021) performed full-scale tests on driven hollow prestressed concrete energy piles to investigate the thermal performance under multiple mechanical loads [31]. Their study shows that the driven energy piles behave differently from the cast-in-place bored piles during the thermal cycles. An essential difference between the driven and bored piles is how they affect the soil density in the vicinity of the pile. The soil around the driven piles is densified, while it may be loosened in most cases for the bored piles [31].

A novel type of driven precast concrete energy pile was proposed by the Balfour Beatty Ground Engineering company, as presented in Fig. 5, which installs HTPs at the sidewall of the piles and then drives them together into the ground [32]. Installing the HTPs at the sidewall of the piles might be challenging since the extreme stresses during the driving process might damage the plastic pipes and, as a result, cause leakage; hence, an extra steel cover is used to protect the pipes over the side walls [33]. These piles are similar to the quadratic energy piles investigated by Alberdi-Pagola (2018) [28], except that the pipes are located at the outside surface of the piles.

A driven energy piling project done by Centrum Pæle A/S in Denmark is shown in Fig. 6, which has pipes inside the concrete precast segments. Putting the inlet and outlet pipes near each other might affect the thermal performance of piles due to short-circuiting [34]. Hence, a proper distance between the pipes must be maintained to avoid

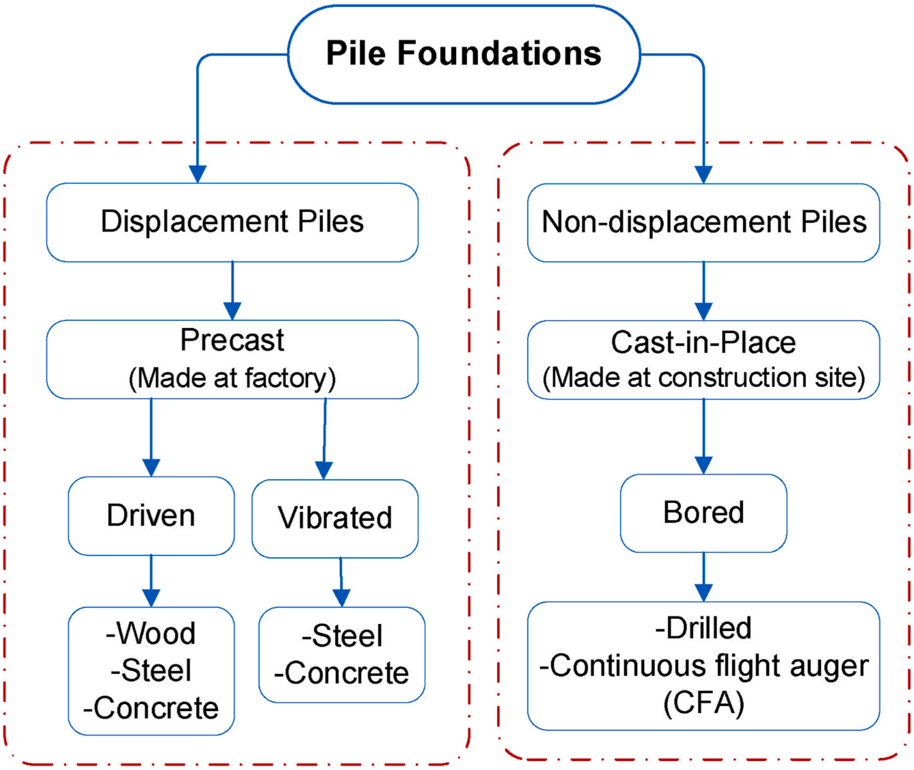


Fig. 3. Different categories of pile foundations.

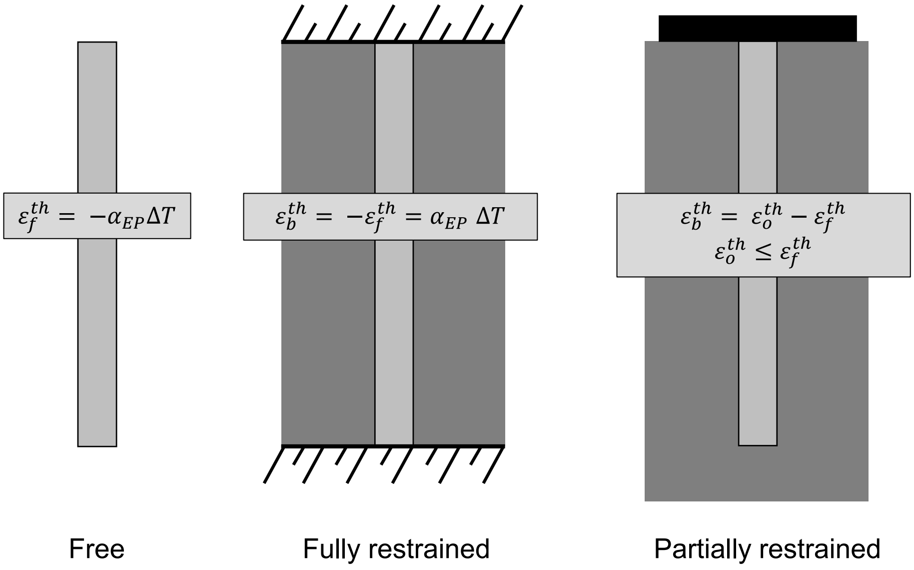


Fig. 4. Assumptive boundary conditions for Energy pile (modified from Ref. [15]).

Fig. 5. A type of driven precast concrete energy pile with pipes at the sidewalls [32].

Fig. 6. Driven precast concrete quadratic energy piles with inner pipes; image courtesy: Centrum Pæle A/S [89].

short-circuiting and a drop in the efficiency of the system.

An innovative type of bored hollow precast energy pile has been recently patented by the City University of London and was commercialized and licensed by the Keltbray company [35]. This type of pile is trademarked under HIPER® pile, which stands for "hollow, impression, precast, energy generating, and reusable pile." However, the HIPER piles are not categorized as driven energy piles, but they are very similar in shape and material to the hollow cylindrical energy piles (concrete pipe piles). In HIPER piles, the precast segments are placed into a borehole that is already bored in the ground, and then the space between the precast segments and the ground is filled with grout [35].

According to the previous works, it is clear that the thermo-mechanical behavior of precast concrete energy piles has not been investigated in detail. Hence, when designing driven energy piles, it is essential to bear in mind that they might behave slightly differently from cast-in-place piles because of the densification and shearing of soil in the vicinity of driven piles. However, according to the case study projects presented in this paper, this difference is insignificant and does not inversely affect the pile bearing capacity.

2.1. *Advantages and limitations of driven energy pile foundations*

Like many other civil engineering structures, driven energy pile foundations have advantages and limitations. In this section, the advantages and limitations of driven precast concrete energy piles in comparison to cast-in-place energy piles are discussed in detail. A summary of the advantages and limitations of driven energy piles is presented in Table 1.

Table 1
A summary of the advantages and limitations of driven energy piles.

Advantages	Limitations
• Higher QA/QC	• Limited cross-sectional length
• Faster, easier and more reliable construction	• Limited segmental length due to transportation
• Large numbers can be manufactured in concrete factories	• Limited number of circulation loops (two or four loops)
• No curing time at the construction site	• Distance between the concrete factory and construction site
• No drilling is required	• Transportation expenses
• No soil waste is produced	• Chiseling is required for protruding length
• Suitable for any ground condition	• No practical joints available currently
• Suitable for a site with a high ground water table	
• No casing and drilling grout required	
• No Leakage of contaminated material into the ground	
• Labor-efficient and cheaper solution	

2.1.1. *Advantages*

One of the main differences between precast and cast-in-place piles is that as precast piles are manufactured in a concrete factory under controlled conditions and with a suitable curing process, they undergo higher quality control and quality assurance (QC/QA) [36]. Using precast piles makes the construction process easier, faster, and more reliable compared to cast-in-place piles since precast piles are manufactured in large numbers, and there is no extra curing time at a construction site. Another advantage is that precast piles require no drilling, as it is time-consuming, expensive, and create large volumes of soil waste. Drilling can be challenging based on the soil conditions at a construction site, especially when the groundwater table is high and sites with loose soil deposits. In such conditions, casing or bentonite grout is needed to stabilize a drilled hole wall to prevent it from caving in. Drilling cast-in-place piles generates a lot of soil waste, which can be problematic if a site is contaminated, such as brownfields. Cast-in-place piles might cause leakage of chemicals from cement and drilling fluids into the ground, while this is not the case in precast concrete driven energy piles. Precast driven piles offer a labor-efficient and cheaper solution because the casting process is done in a factory in a controlled environment, and there is no need for several highly skilled workers at a construction site.

2.1.2. *Limitations*

One of the main limitations of precast concrete driven energy pile foundations is that they have limited segmental length and small cross-sectional sizes due to transportation and construction limitations for larger sections. The small cross-section limits the number of fluid loops to one or two. However, in small cast-in-place piles, the number of loops is also limited to one or two loops, but for cast-in-place piles with larger diameters, it is possible to put more than two loops. The heat exchange rate comparison between the precast and cast-in-place piles is a factor of many items, including the number of loops inside the piles, loop configurations (U-loop, W-loop, spiral loop, etc.), ground thermal conductivity and heat capacity, ground temperature, soil type, and groundwater table. However, in general, precast and cast-in-place piles can provide 70–80 kWh/m^2 over a period of 180 days [37].

Another limitation of precast energy piles is the distance between a construction site and a manufacturing factory, which may incur higher transportation expenses for projects, especially sites located at far distances. As most driven piles aim to reach bedrock, and the bedrock depth is uneven, therefore the top part of driven energy piles often protrude from the ground surface. The protruding length needs to be chiseled to connect the rebars of the pile with the pile cap, while cast-in-place energy piles do not need chiseling. Connecting the pile segments in longer driven energy piles is more challenging since the pipes should be connected using watertight couplers through a joint connecting the pile segments. Placing the pipes at the outside surface of precast pile segments might pose a risk to the pipes since the driving process of the piles imposes high frictional stresses on the pile surface; hence the pipes must be protected inside the pile structure or be shielded.

3. Technical background

This section discusses the technical background of the energy pile foundations, which includes the ground temperature profiles and the ground thermal potential in different locations, the ground source heat pump (GSHP) technology, and the building heating and cooling demand, which acts as the thermal load on the driven energy pile foundations.

3.1. *Ground temperature*

Energy piles utilize the stable temperature of the ground at shallow depths. Although the stable ground temperature varies in different locations, it provides the potential for the use of energy piles in almost all the countries around the world. The shallow ground temperature profile is mainly a function of ambient air temperature, wind velocity, solar radiation, and ground surface temperature; hence it may experience seasonal and monthly changes over a year [38]. However, these fluctuations are observed mainly in the top soil layers at a depth of 6–8 from the ground surface (see Figs. 7 and 8). At more considerable depths, the ground temperature reaches a stable value that does not change significantly over the desired design length of a geothermal energy pile foundation. For most countries, the ground temperature typically falls in the range of 10 °C to 25 °C [1], as it is in the UK (temperate region) and Australia (warm region), according to Fig. 7. For some countries in the cold climate regions, such as Norway, this temperature is between 6 to 8 °C, as illustrated in Fig. 8 [39]. For places far north of Norway, such as Svalbard, which is close to the north pole, the stable ground temperature is below zero all year round, i.e., −5 °C [40].

The low ground temperature profile in cold regions provides a limited potential for energy piles due to the risk of freezing ground over the long-term performance of GSHPs. However, when the low temperature is considered together with the high level of the groundwater table and the groundwater flow, it may provide a significant potential for energy piles. The presence of permeable saturated soil and groundwater seepage will provide the heat transfer due to convection and advection by the water seepage and water flow inside the soil continua. Considering the convective phenomena in the design of the energy piles in saturated permeable soil deposits can increase the thermal potential significantly, and ignoring such phenomena can cause the overdesign of the geostructures [41].

In extremely cold-climate regions like Svalbard, where the ground is frozen all year round, it is theoretically and practically possible to use energy piles and exchange heat with the frozen soil. It is well known that GSHPs are built to pump the heat from low energy levels to high energy levels. Considering frozen soil sites, such as Svalbard Island in the north pole, where the stable ground temperature is −5 °C and the air temperature reaches −30 °C in winter, and utilizing a suitable GSHP and a suitable heat carrier fluid that can perform under extreme conditions down to a temperature of −10 °C without freezing (using antifreeze liquids), we can pump heat even from the frozen ground into buildings. The most important point is that, in such places, the coefficient of performance of the GSHP decreases due to the larger gap between the temperature of the source and destination [42]. It is vital to keep permafrost frozen and avoid melting it, i.e., due to the large deformations caused by permafrost melting [43]. Extracting heat in such conditions is favorable, and considering the high thermal conductivity coefficient of ice (2.18 Wm^{-1}K^{-1}) in comparison to water (0.6 Wm^{-1}K^{-1}), the heat can be extracted at higher rates [5,44]. The

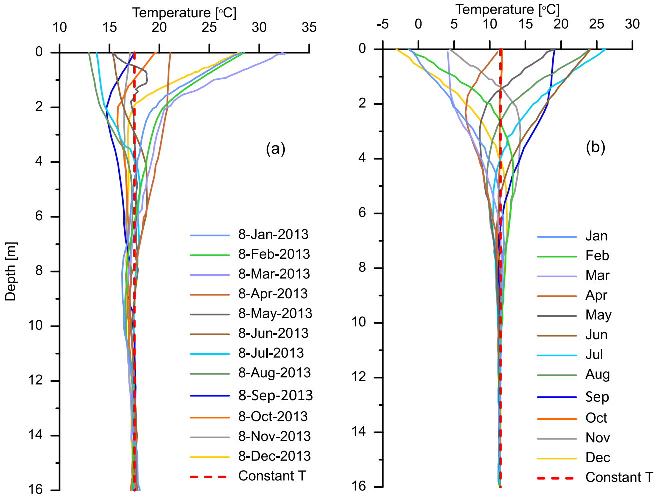


Fig. 7. The ground temperature profile in (a) Melbourne, Australia [90]; (b) London, UK [5].

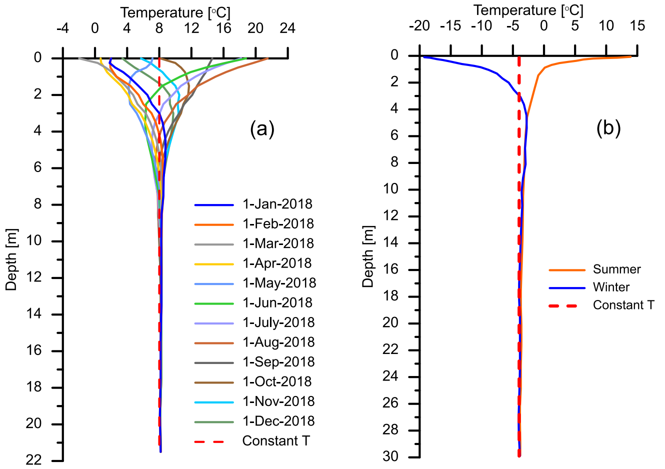


Fig. 8. The ground temperature profile in (a) Halden, Oslo; (b) Longyearbyen, Svalbard [39,40].

thermomechanical behavior of energy piles in frozen ground conditions can be investigated using the already available constitutive models for saturated frozen soils, such as Amiri et al. (2016) [45].

3.2. *The ground source heat pump (GSHP)*

The ground source heat pump is a technology consisting of three main units: the primary unit, the heat pump unit, and the secondary unit. The primary unit can be any energy geostructure such as energy piles, walls, tunnels, etc. The primary unit for the present study is the precast concrete energy pile foundation. A heat pump unit is a mechanical unit that can exchange heat with the primary unit, increase the temperature of the fluid, and eventually transfer this heat to the secondary unit, which can be buildings, road pavements, bridges, etc. A schematic illustration of a GSHP system is presented in Fig. 9.

3.3. *Building heating and cooling demands*

The secondary unit in a GSHP system can be a building with heating and cooling demands based on factors including but not limited to the usage type of the building and the seasonal outdoor air temperature. The cooling and heating performance of GSHP systems with precast concrete pile foundations for the summer and winter seasons is shown in Fig. 10. For some countries that have summer and winter seasons with relatively similar durations, a balance between the heating and cooling of the building is made so that the ground temperature is not affected by the long-term performance of the GSHP system. However, for countries in cold climate regions, such as Norway, Canada, and Russia, where the building heating demand is dominant over its cooling demand, i.e., an imbalanced heat demand, the ground temperature will decrease over the years when the GSHP system is operational. The heating and cooling demand of a 55 m^2 building located in Oslo, Norway, is calculated for 2019 air temperature using Energy plus software [46] and is presented in Fig. 11. Using the daily building heating and cooling demand in numerical simulations increases the computations costs hence a new equivalent energy wave method was developed by Abdelaziz et al. (2015), which replaces the amount of energy calculated from energy plus software with an equivalent smooth sine function which increases the efficiency of the numerical simulations [47].

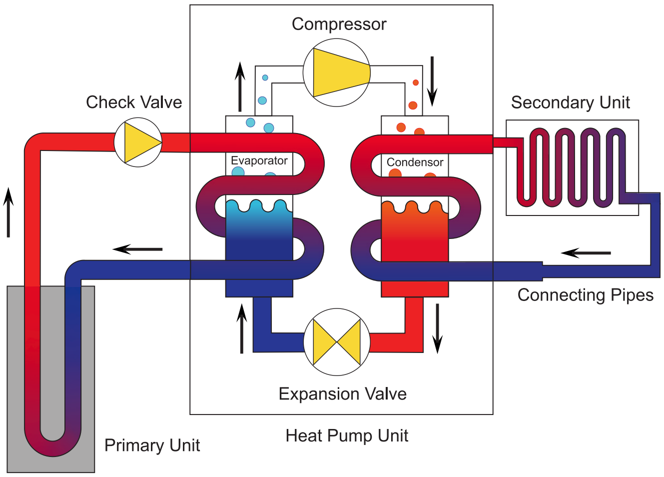


Fig. 9. Schematic illustration of a GSHP system.

If the harvested heat from the ground is not compensated by enough heat injection into the ground during the hot season, the ground temperature will gradually decrease and, in the most extreme case, will eventually fall below zero, and the soil freezes. There are several problems associated with the frozen ground, such as forming ice lenses and frost heave over the ground surface, consequently damaging structures over the ground surface [48].

4. Applications of precast concrete driven energy piles

Precast concrete energy pile foundations can be used in many different places, including but not limited to office and residential buildings, bridges, roads, shopping centers and malls, train and bus stations, and airports. Some of the application precast concrete energy piles are illustrated in Fig. 12. Driven piles can be used under the roads to limit the deformations, such as the several hundred driven concrete piles used in the E18 Bjørvikaprosjektet project [49]. However, the piles in the E18 Bjørvikaprosjektet project were not energy piles, but energy piles can be used in such projects, and the harvested heat can be used for deicing roads and sidewalks. Presently there is a relatively large market for precast concrete pile foundations worldwide. The Norwegian piling standard estimates the total annual length of precast concrete pile foundations built in Norway to be more than 250000 m [50]. If the precast concrete-driven pile foundations are used as energy piles, this will increase their attractiveness in the projects as an energy source and save a significant portion of the money spent on electricity bills, which is used as the primary source for heating buildings in many countries.

4.1. *Case studies*

In this section, we will briefly present two successful, driven energy pile projects. The first project is the residential area in Rosborg in Vejle, Denmark, which uses quadratic precast concrete energy piles. The second project is the library building in Büron in Luzern, Switzerland, which used concrete driven energy pipe piles.

4.1.1. *The residential area in Rosborg in Vejle, Denmark*

In a project in the new urban area in Vejle, Denmark, the feasibility of utilizing precast quadratic energy pile foundations for building heating and cooling was investigated [51]. Initially, a thermogeological map for the region was prepared, and then, based on the heating/cooling demand of the buildings in the area, it was estimated that the energy piles could perfectly cover the heating demand of the three-to four-floor buildings [51]. In another study in the same region, the performance of the precast quadratic energy piles, which were used under the Rosborg Gymnasium (Denmark), was studied [52]. The Gymnasium was built over 200 thermoactive pile foundations, which supplied the heating and cooling of the building with an area of 4000 square meters. In this project, the heating and cooling demands were not symmetric and balanced; hence a decrease in the ground temperature through the winter season was expected; however, the observation data showed that the ground temperature could recover to its initial undisturbed

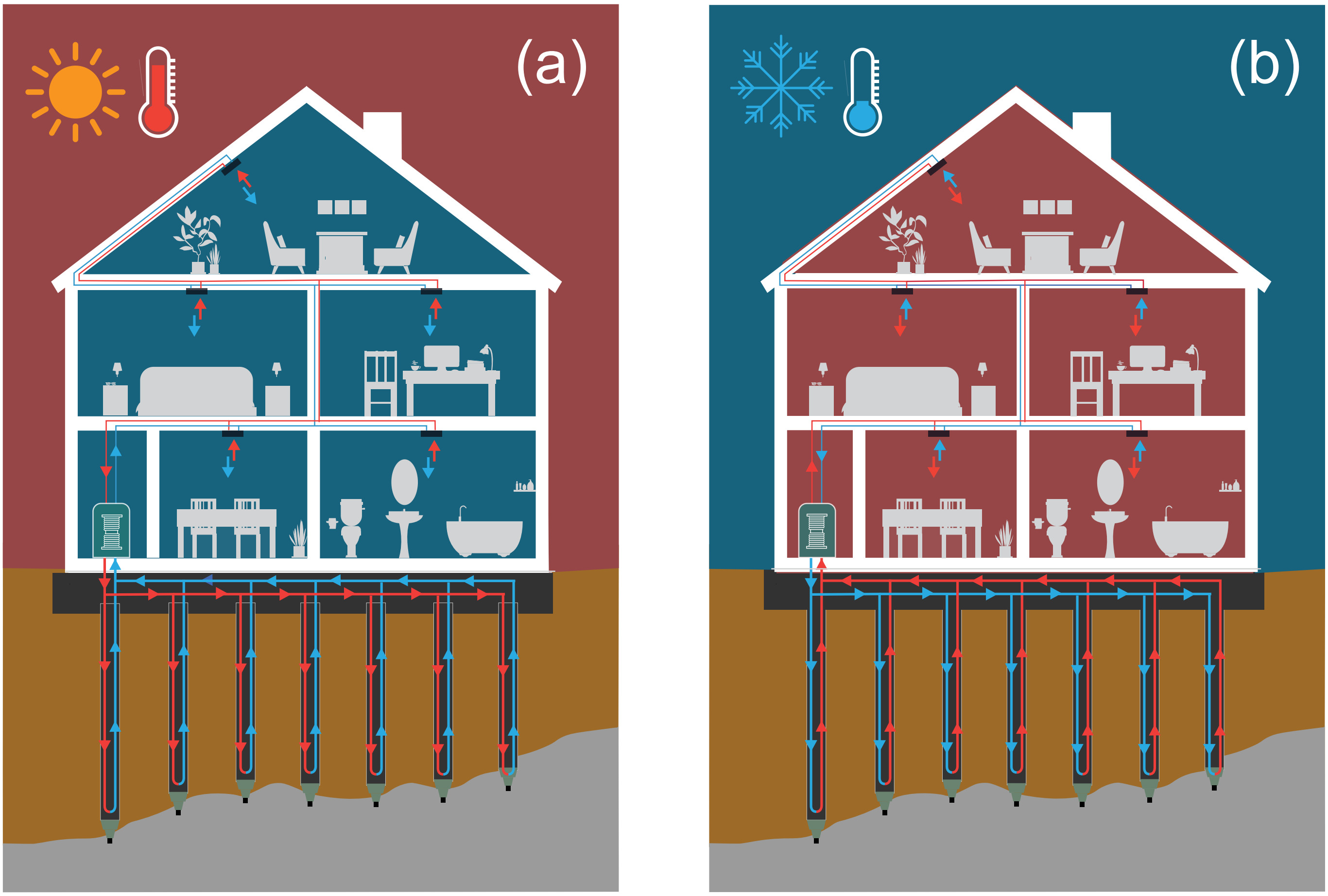


Fig. 10. Cooling and heating performance of GSHP systems with precast concrete energy pile foundations in (a) summer, and (b) winter.

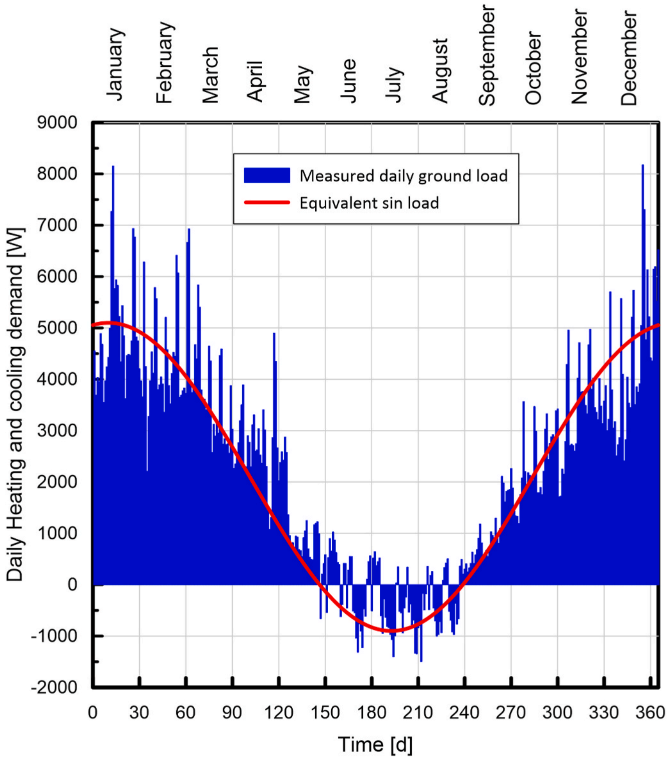


Fig. 11. The heating and cooling demand of a building in Oslo.

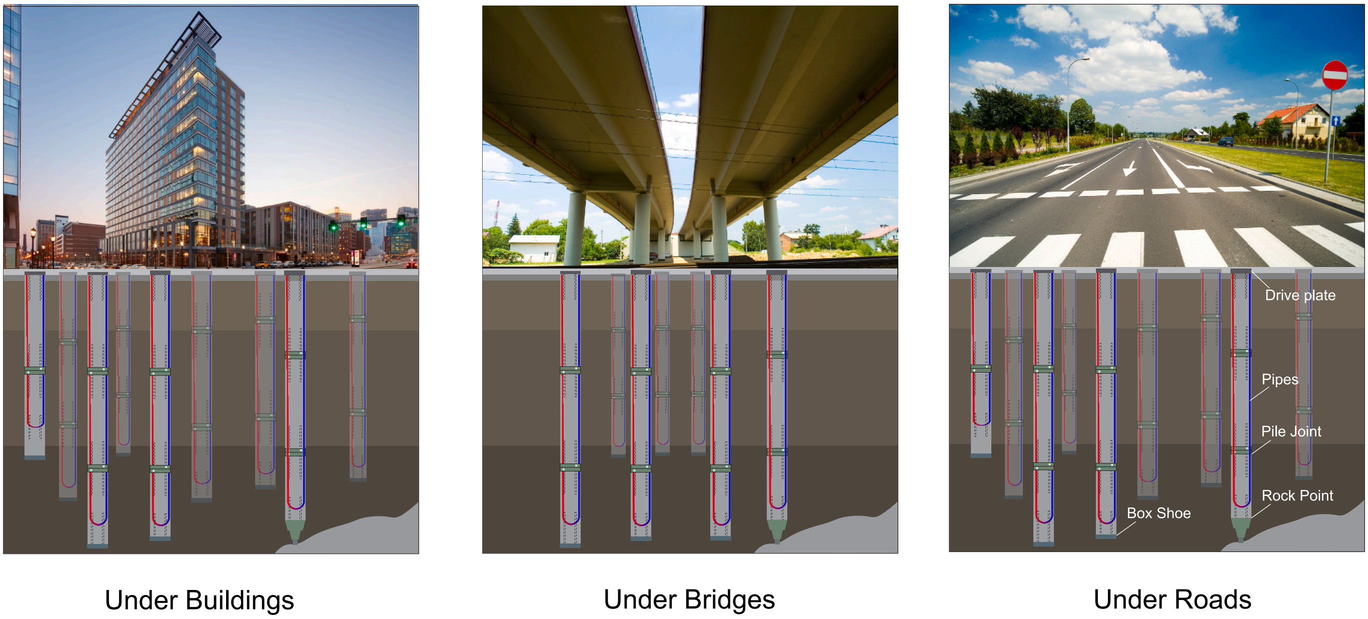
condition during the summer season [30,52]. Another study by Poulsen et al. (2019) developed a simplified method that related the ground thermal power to the room and ground temperature [53]. Their model showed that the ground could cover the cooling demand of the building for the whole year round except for 7–17 h [53]. In another project in the same area in Denmark, the potential use of a network of cooling and heating systems between buildings that utilized driven energy pile foundations was studied [54].

4.1.2. The library building in Büron in Luzern, Switzerland

This project is a library building constructed over an area of 18,000 square meters standing on 216 hollow cylindrical piles (25 m × 450 mm), sixty of which were thermoactive piles. The hollow piles were prepared by the SACAC company equipped with the Pilotherm® system developed by SACAC. The filling material was used to ensure the heat transfer between the pipes and the ground during operation. These piles can be used for cooling purposes as well. The specific heat extraction rate for the installed piles is 40 W/m [55]. A visualization of the library building is presented in Fig. 13.

5. Types of driven precast energy pile foundations

The precast concrete energy piles foundations can be categorized into two types according to their shapes: hollow cylindrical (concrete pipe pile) and quadratic energy piles (square-shaped). In the following paragraphs, the characteristics of each of these types are discussed in detail, and they are compared.



Under Buildings

Under Bridges

Under Roads

Fig. 12. Different applications of precast concrete energy pile foundations.

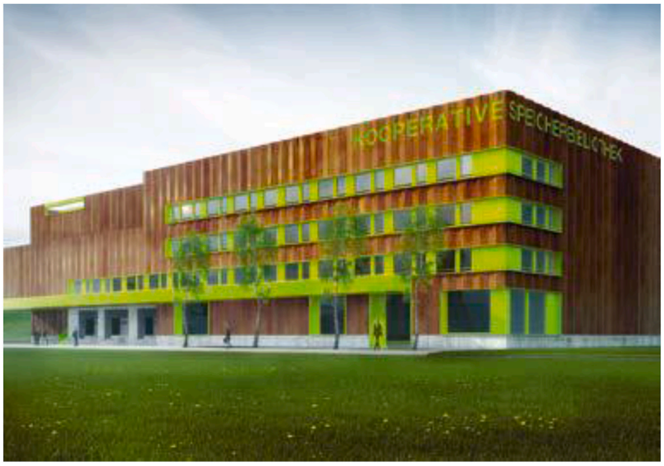


Fig. 13. Library building visualization [55].

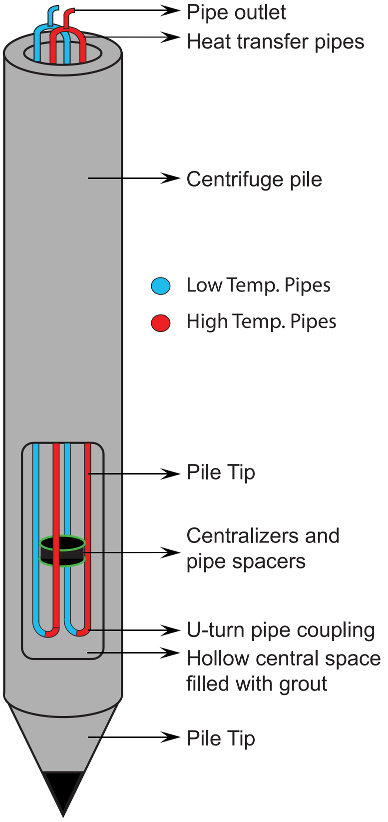


Fig. 14. Schematic illustration of the hollow cylindrical energy piles (concrete pipe pile) [reproduced from Ref. [91]].

5.1. *Hollow cylindrical piles (concrete pipe piles)*

The hollow circular energy pile foundations comprise several segments of cylindrical hollow pile segments known as concrete pipe piles. For production, the concrete is centrifuged in steel molds with up to fifty times the acceleration due to gravity [55]. The advantages of this method include high compressive strength, low air void content, and a dense structure with excellent resistance to environmental influences [55]. These segments are usually connected using the welding technique and steel joints in the field. The central space in the pile segments allows the passage of fluid loops, which can be in single or multiple U-loop formations. Then the space between the polyethylene pipes and the concrete wall of the pile segments is filled with different materials, including but not limited to grout, bentonite, sand, and also water [35], which increases the heat transfer capacity of the piles depending upon the thermal conductivity of the filling material. However, this increases the cost of the pile slightly depending upon the type of the filling material and its cost. A schematic illustration and a real project photo of the hollow cylindrical energy piles are presented in Figs. 14 and 15, respectively. The higher structural strength of this type of pile is due to the lower water-to-cement ratio in the casting process, resulting from the unique centrifuge technique used in the concrete factories. Due to the lower structural cross-sectional area of this type of pile, lower structural resistance causes cracks in the precast segments due to the harsh hammer blows used to install the pile in the field. A similar type of precast-driven energy pile with a cavity was patented by Poot (2002) [56]. These piles are constructed with diameters of 250, 350, 450, and

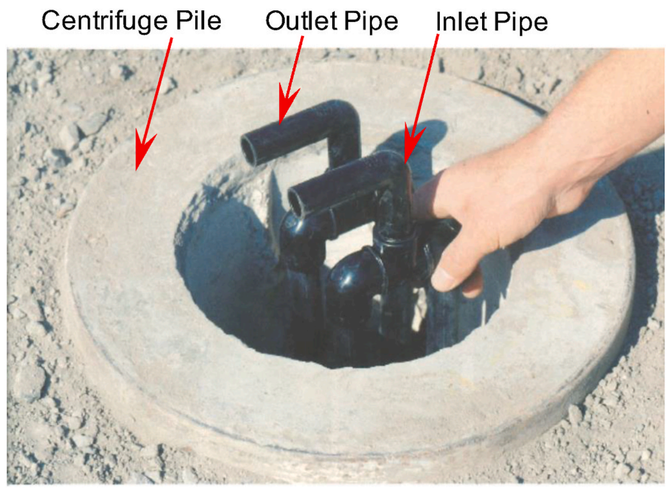


Fig. 15. A hollow cylindrical energy pile (concrete pipe pile) project [modified from Ref. [91]].

550 mm, as illustrated in Fig. 16; however, the smallest size (250 mm) is not commonly used due to its low capacity and the limited size for the installation of the pipe.

According to the IEA 2019 Global report for buildings and construction, 36% of final energy use and 39% of the CO_2 emissions come from building materials such as steel, cement, and glass [57]. The CO_2 emissions related to the construction of one cubic meter of concrete are 100–300 kg [58]. The inner space of the hollow cylindrical piles can be simply filled with bentonite slurry, or a slurring made from the soil in the same construction site, which has much less CO_2 emissions than a rigid non-hollow concrete pile. There are possibilities to use different types of phase change materials in the central hollow space of energy piles as a back filling material [59]. Ziming et al. (2022) [60] also reported that the thermal performance of precast energy piles filled with phase change materials is significantly better than that of normal grout.

The driving process of segmental concrete pipe energy piles is similar to any other precast concrete pile. Each segment is hammered into the ground until less than a meter of the pile head stands out the ground, then the next segment is welded to the already installed segment, and the driving process continues until the pile tip reaches the desired depth or the bedrock. After the installation of the structure is completed, the pipes are installed in the cavity, and then the infilling material fills the gap between the pipes and the concrete pile body.

5.2. *Quadratic energy piles (square-shaped)*

The quadratic precast concrete piles are popular in many countries worldwide, including but not limited to Norway, Denmark, Sweden, Australia, the UK, and the USA. Based on the most updated information in the Norwegian piling standard, 200000–250000 m of square-shaped precast concrete driven pile foundations are used per year just in Norway [50]. With the recent developments in the energy pile industry, the new precast concrete energy piles are taking the market of the conventional non-thermal precast piles in the building industry. In the precast concrete driven energy piles, the polyethylene plastic pipes are installed in the pile segments during the casting process in the concrete factories (see Fig. 17).

The quadratic pile foundations have a more accessible and cheaper casting method in the factories than the hollow cylindrical energy piles. Another strength of quadratic energy piles compared to hollow cylindrical energy piles is their larger cross-sectional area, which increases their structural capacity. The increased structural capacity is crucial for resisting the building loads and vital during the installation process when significant impacts are applied to the pile to drive it into the ground (see Fig. 18).

The quadratic energy piles have three different commercially available dimensions, which include 270 mm, 345 mm, and 450 mm [61]. The most widely used type of these piles in Norway is 270 mm, while the

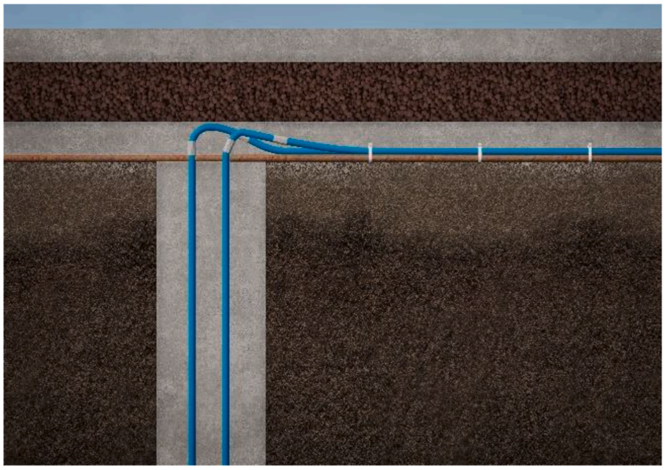


Fig. 17. Schematic illustration of the Quadratic energy piles installed in the ground, Image courtesy: Centrum Pæle A/S.

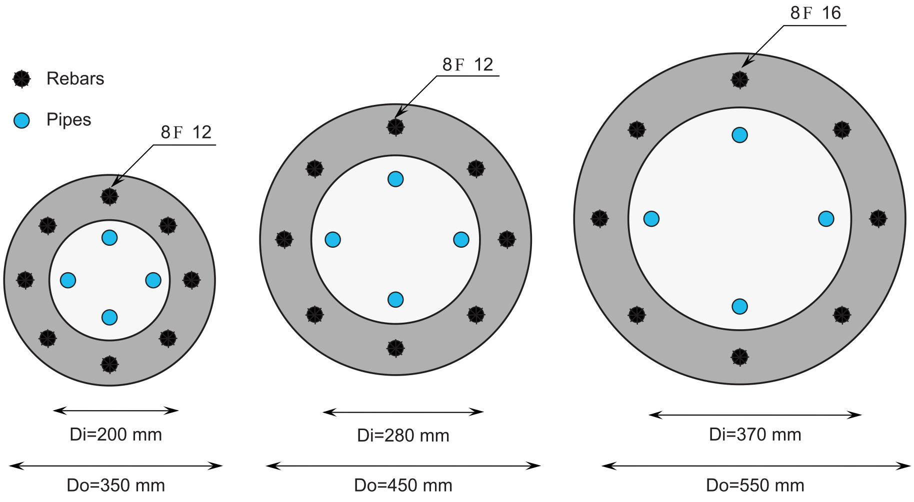


Fig. 16. Different available sizes of circular hollow cylindrical energy piles.

450 mm piles are used mainly for road and bridge piers [50]. The 270 mm has enough space for a single U-loop, but the 345 mm and 450 mm can be equipped with two or more U-loops for the circulation of the heat carrier fluid. The plastic pipes can be placed in the center of the pile or near the sidewalls of the pile. When the pipes are closer to the sidewalls, the concrete thermal resistance will be smaller; hence, the heat flows easier than when the pipes are installed in the center of the piles. Different available sizes of square-shaped energy piles are presented in Fig. 19.

The precast quadratic concrete energy pile can be constructed using a single precast segment when the total length of the pile is shorter than 15 m; otherwise, it is required to build them in several precast segments due to the length limits during the transportation. Longer energy piles have a higher thermal potential than shorter piles made of one segment. When the energy pile is built in several segments, mechanical joints must connect the segments. These joints need to be watertight and maintain the overall structural integrity of the pile.

The driving process of segmental quadratic energy piles is also similar to normal precast concrete piles. Each segment is hammered or vibrated into the ground until less than a meter of the pile head stands out the ground, then the next segment is connected to the already installed segment, using joints that are connected by pins or bolts or by welding. The only additional step at the connection phase of quadratic piles in comparison to concrete pipe piles is that as the pipes rest inside the precast segments, they should be connected at the joint interface, using pipe couplers that can maintain a watertight coupling between the pipes of the two segments. Then as soon as the two segments are connected both structurally and hydraulically, the driving process continues until the pile tip reaches the desired depth or the bedrock.

6. Challenges of installation and design of segmental precast energy piles

6.1. Transportation

The precast concrete pile segment is generally cast in a concrete factory far from the construction site. Then, the precast concrete segments are transported to the construction site using trailer trucks. The maximum length that a truck can carry is between 12 and 15 m. For larger segments, unique means of transportation must be used, which costs expensive and additional limitations exist on many roads and urban streets in larger cities. Hence the energy piles should be constructed in segments no longer than 12 and 15 m.

Fig. 18. A quadratic energy pile project in Rosborg, Denmark [30].

6.2. Joints between the segments

As mentioned earlier, most energy piles constructed in the world are cast-in-place non-displacement energy piles, which is mainly because of the challenges in precast energy piles, such as the absence of proper joints that can connect precast concrete segments of driven pile foundations. This is still a challenge since the connection must guarantee the mechanical integrity between the pile segments, i.e., transfer the compressional, tensile, and bending forces. Additionally, the pipes should pass safely in the pile joints so that no leakage exists. Poor connection of the pile segments might cause structural risks as well as the risk of putting the energy pile off the energy system due to the leakage and reduction in the circulation pressure of the water in the heat transfer pipes. The precast concrete piles and the joints that connect the segment should meet the EN 12794:2005 standard no matter whether the pile is thermoactive or normal [62].

For hollow circular piles (concrete pipe piles), the segments are welded together using a steel joint. The welding connection increases the construction time and requires skilled workers on the construction site to weld the joints properly. The heat transfer pipes are installed within the hollow space inside the pile segments after installing the pile segments. As the pipes pass over the central hollow space of the pile segment, they stay safe from the damages that can cause leakage.

For the quadratic precast concrete pile foundations, the pipes are embedded in the concrete when the casting process is done in a concrete factory. Hence, when we connect the pile segments structurally, we also need to connect the pipes. However, this issue does not exist for the single segment quadratic piles, which have a length of less than 15 m, such as the ones studied by Alberdi-Pagola et al. [30]. For longer quadratic energy pile foundations, several attempts were made to solve the issues regarding the joint to connect the pile segments [63–68]; however, they either put the pipes on the outer surface of the pile which poses damage risks to the pipes, or they put the pipes in the center of the pile which makes it impossible to visually inspect the pipe connection and assure that they are properly connected and sealed. Sadeghi and Singh (2021) [69] proposed an innovative steel joint (patent pending), which can provide both the structural integrity and connect the pipes in side wall slots of the steel joint as illustrated in Fig. 20. After the pipes are connected, the side wall slots are covered using steel plates which shield the pipes and keep them safe from any damage during pile installation and operation. This joint is structurally connected using male and female dowels which are locked by using high strength steel pins, hence no welding is required, and the installation is quick and does not require skilled workers during the installation.

Generally, the precast concrete pile foundations reach the bedrock to utilize the end bearing capacity and reduce the settlements. One crucial problem with single segment piles, which have a length of 15 m, is that the top 6–8 m of the pile falls in the zone of seasonal temperature fluctuations in the soil, and during the winter, this might influence the performance of the energy pile. In many cities, such as Trondheim and Oslo, the bedrock is located at a depth of 20–60 m. This means that if we want to use precast concrete energy piles in such places, we need to use several segments to make a single energy pile up to the bedrock.

6.3. Bedrock depth

Precast concrete driven piles are usually driven up the bedrock so that the tip bearing capacity of the pile can be fully mobilized in addition to the side frictional capacity of the pile. Usually, the tip of the square-shaped concrete piles is equipped with a rock shoe facilitating the penetration of the pile into the hard bedrock, as illustrated in Fig. 21 [70]. A similar conical point is used for hollow cylindrical energy pile foundations, as illustrated in Fig. 14.

As presented in Fig. 22, the uneven bedrock depth in a project site can cause an uneven protruding set of precast concrete driven energy piles from the ground surface. The extra length of the piles must be cut

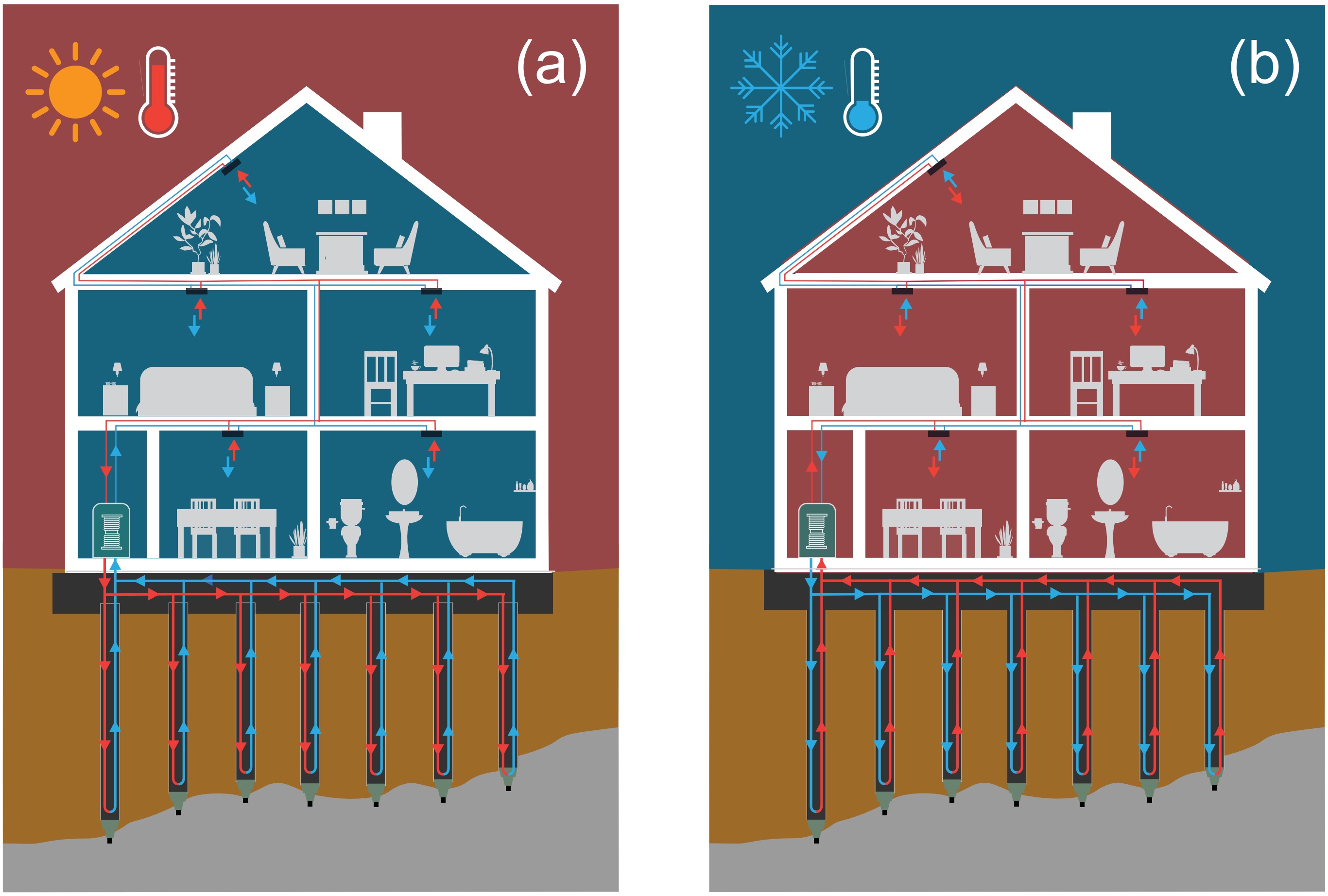


Fig. 19. Different available sizes of square-shaped energy piles.

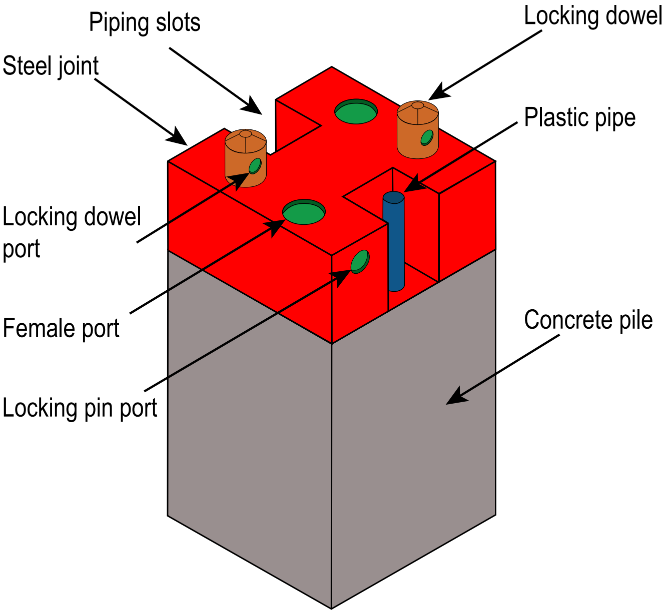


Fig. 20. A schematic illustration of the proposed joint (patent pending) [69].

Fig. 21. Rock shoe of a precast concrete driven energy piles [70].

after the installation (see Fig. 23). The cutting process is done using a saw and chisel machine, which must be done entirely carefully because the pipes and the rebars inside the concrete pile must be exposed safely. The exposed rebars are used to connect the piles to the pile cap, while the exposed pipes will be connected to the network of the pipes at the ground surface, which will be connected to the heat pump located in the basement of the building. Since the pipes are embedded inside the concrete, and there is adhesion between the pipes and concrete, exposing the pipes can be challenging. Special preparations must be done prior to the casting process in the concrete factory so that the pipes

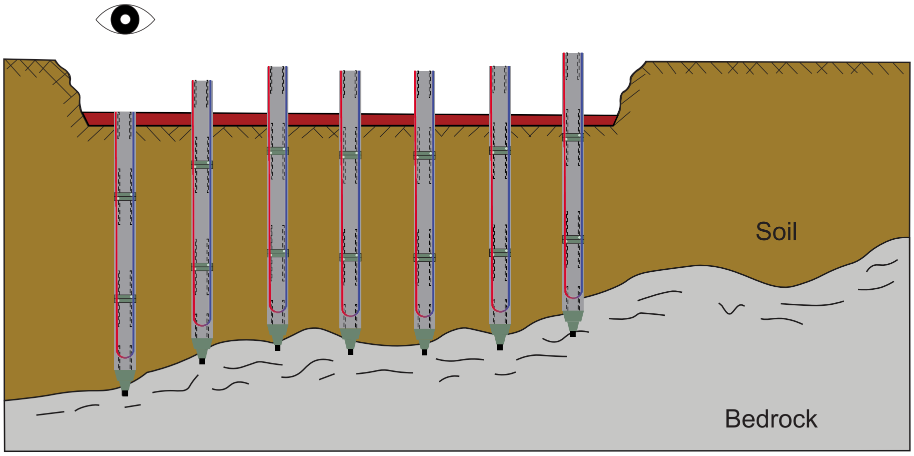


Fig. 22. Uneven protrusion of precast concrete energy piles from the ground surface [reproduced and modified from Ref. [91]].

Fig. 23. A precast driven concrete pile project in Norway [Personal communication with Sandnes & Jærbetong company].

can be easily exposed on the construction site. This is done by using a skinny layer of foam or a secondary duct covering the pipes, which surrounds the plastic pipes over the expected length of the top pile segment protruding from the ground surface.

6.4. *Temperature effects on shear strength of the soil–pile interface*

Many researchers investigated the effect of temperature changes and cycles on the concrete-soil interface with more or less similar results [71–73]. Di Donna et al. [71] found that the sand-concrete interface is affected by cyclic degradation but not by temperature. On the other hand, they found that the concrete-clay interface changed for different temperatures, and an increase in the temperature increased the shear strength at the interface [71]. Although many researchers investigated the pile-soil interface for cast-in-place piles, there is a knowledge gap for the aforementioned interface in the driven precast concrete piles.

6.5. *Lack of design standards and guidelines*

One of the main challenges in the design phase of driven energy piles is the lack of suitable design standards, which give recommendations and guidelines specifically for precast driven energy piles. Empirical correlations are still employed in many countries for the design of energy piles, albeit few countries have design guidelines and standards [17]. Due to the increasing interest in energy geostructures, many countries started to propose standard frameworks for the design and construction of energy geostructures. The most comprehensive standard covering many aspects of energy geostructures is the French standard [74]; however, neither of the standards has any recommendation for precast concrete driven energy pile foundations. Hence, further investigations and recommendations on this type of energy pile are required in future versions of energy geostructure standards. A list of available standards and their countries is summarized in Table 2.

7. Economic and environmental aspects

According to the European Geothermal Energy Council (EGEC), the current decade is the “Geothermal Decade,” and they estimate that the geothermal sector will be thirteen times larger than it is now by 2030 [75]. Looking at the market for energy-efficient buildings only, Businesswire estimates that this will grow by $103.9 billion globally over 2020–2025 [9].

A global commitment drives the demand for energy-efficient buildings to reduce carbon emissions per the Paris Agreement and public awareness of the climate crisis [76]. Norway [77] and the European Union are setting ambitious goals, and the UK is even introducing legislation prohibiting the use of fossil fuels for heating new buildings and replacing them with clean sources of energy such as geothermal energy wherever possible [10]. Precast concrete energy piles can boost utilizing GSHPs and geothermal energy, which will speed up approaching the target EU goal for the transition toward net zero emission buildings.

The market for normal driven piles is very mature and covers many countries worldwide that have their specific related standards. Some of the countries that use driven concrete piles, according to the literature, are presented in Fig. 24. As such, the infrastructure is already in place for the driven precast energy piles, and the use of driven energy pile

Table 2
List of current design standards for energy piles.

#	Title	Year	Country	Language
1	Thermal pile design, installation, and materials standards [85]	2012 2017	UK	English
2	Thermal use of the underground Fundamentals, VDI 4640, Parts 1 and 2 [86,87]	2011 2020	Germany	German, English
3	Recommendations for the design, sizing, and implementation of thermal geostructures [74]	2017	France	French
4	Use of geothermal energy with pile foundation and other concrete components in contact with the ground [88]	2005	Switzerland	German

Fig. 24. Some of the countries that use driven concrete piles.

foundations can be a catalyst for the global adoption of renewable energy.

Solid regulatory frameworks are being implemented to support the transition to a more sustainable construction industry, like the updated BREEAM-NOR 2022 building standard [61], lined up against the EU BREEAM Taxonomy. BREEAM is the oldest established method of assessing, rating, and certifying the sustainability of buildings in the world. This is already pushing the market for sustainable buildings considerably. For instance, the number of BREEAM-NOR certified buildings was remarkably stable over 2015–2019, with 17 each year (except 2017, with 26), while the first six months of 2021 alone had 39 buildings certified [78]. Utilizing precast concrete energy piles will improve the possibility of getting the BREEAM-NOR certification for new buildings.

Furthermore, with the threefold increase in electricity price for households in 2021 compared to 2020 [79], many public and private sectors are awakened to use renewable energy resources, among which shallow geothermal energy is one of the most abundant and easily accessible resources. The coefficient of performance (COP) in a GSHP system is defined as the ratio between the produced energy (energy output) to the energy input (consumed electricity) [5] as defined in equation (5).

$$\mathrm{COP} = \frac{\text{Energy output obtained after HCF circulation}[\mathrm{kW}]}{\text{The energy input to drive the system}[\mathrm{kW}]} \tag{5}$$

A reduction in electricity consumption reduces the electricity bill costs as well as the CO_2 emissions associated with the production of electricity. The US information administration has reported that one kWh of electricity production produces about 0.85 pounds (386 g) of CO_2 emissions [80]. The average Norwegian household electricity consumption is about 16000 kWh per year [81], and the average electricity price in the 4th quarter of 2021 was 1.65 NOK [82]. Moreover, it is known that about 79% of this consumption is used on building heating/cooling and warm water [5]. Hence, one can conclude that by utilizing GSHPs with an average COP of 5 for heating and cooling, the electricity consumption for heating/cooling and warm water reduces by 80%, which will, as a result, save around 16700 NOK money and 3900 kg of CO_2 emission per households in Norway. A reduction in the electricity bill prices will, as a result, have positive social effects on the households and will also lift pressure from the government to propose a subsidy to alleviate the pain of high electricity prices [83].

As the calculations in the previous paragraph show, when the GSHP system with driven energy piles is used, the amount of money saved and the CO_2 reduction per household is considerable. This is achieved by investing a limited amount of capital money in adding the pipes inside the precast pile segments and utilizing steel joints to connect the precast pile segments, which are approximately 20% more expensive than the non-thermal pile joints. Considering the cost of the heat pump and operation and maintenance, utilizing the GSHP system and the energy piles will cost less than 200,000 NOK (25,000 Euros) per household, which might return within a period of shorter than 5–10 years considering the current electricity prices. Sadeghi et al. (2022) [84] performed a cost analysis on energy piles, considering the electricity prices in 2022, and reported that the payback time for the GSHP system utilizing energy piles in Norway is almost 8 years compared to GSHPs which are couple with BHEs which have a payback period of almost 10 years. To put it in a nutshell, utilizing the GSHP system together with driven energy piles will, in the long term, save the energy expenses of households and also reduce the CO_2 emission significantly.

Another financial benefit of using precast driven energy pile foundations is that it does not require drilling and construction of large boreholes, and the installation of the piles is more straightforward, requiring a lower number of skilled laborers. This will reduce the construction expenses associated with using driven energy piles compared to cast-in-place energy piles and borehole heat exchangers.

8. Conclusions

The majority of energy piles are cast-in-place concrete piles. Recently, precast concrete driven energy piles have been developed, and they have been successfully used in recent projects. However, the technology is still new and requires improvements in design and construction techniques. This paper provides the current state of the art of different types of driven precast concrete energy piles. The major findings of the present paper, which must be considered in the design and construction, are:

- Driven precast concrete energy piles are categorized into two groups of (a) hollow cylindrical (concrete pipe pile) and (b) quadratic piles (square-shaped). The quadratic piles employ two pipe configurations, either in the center or close to the sidewalls.
- The major advantages of precast concrete driven energy pile foundations in comparison to cast-in-place energy piles are (a) higher quality control and quality assurance, (b) easier, faster, and more reliable installation and construction, (c) no drilling is required, (d) suitable for almost any ground condition, (e) no soil waste produced during construction, (f) it offers a labor-efficient and cheaper solution, (g) it has no leakage of cement and drilling fluid into the ground.
- The major limitations of precast concrete driven energy pile foundations in comparison to cast-in-place energy piles are (a) it has limited lengths and cross-sections due to constraints in transportation, (b) it has space for a limited number of heat transfer pipes due to the smaller cross-section, (c) challenging connection of

precast segment using joints which must be sealed and provide structural integrity between the segments, (d) placing pipes at the outer surface in one of the pile types might put them at risk, (e) lack of suitable joints to connect the precast concrete quadratic pile segments, (f) lack of proper guidelines and design standards for driven precast concrete energy pile foundations, (g) uneven bedrock depth and the need to cut the extra protrusion of the piles from the ground surface.

- The precast driven energy piles are very similar to cast-in-place piles in terms of the technical background. They use the same type of heat pumps, benefiting from the stable ground temperature, and their thermal performance is a function of building heating and cooling loads. In some heating dominant countries, such as Norway, this load is unbalanced, which must be considered in the design of the piles.
- The driven precast concrete energy pile foundations can be used in many different places, including but not limited to office and residential buildings, bridges, roads, shopping centers and malls, train and bus stations, and airports.
- There are several design standards in many countries, such as in the UK, Germany, France, and Switzerland. The French standard is the most comprehensive standard covering many aspects of energy geostructures. However, none of these standards covers driven energy pile foundations.
- The driven precast concrete energy pile foundations have a large worldwide market. Utilizing driven energy piles in the construction industry can save a considerable portion of money on electricity bills and reduce the CO_2 emissions associated with the heating and cooling of buildings.

CRediT authorship contribution statement

Habibollah Sadeghi: Writing – original draft, Visualization, Investigation. **Rao Martand Singh:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

[1] L. Laloui, A.F.R. Loria, Analysis and Design of Energy Geostructures-Theoretical Essentials and Practical Application, Academic Press, 2019.

[2] D. Adam, R. Markiewicz, Energy from earth-coupled structures, foundations, tunnels and sewers, Geotechnique 59 (2009) 229–236, https://doi.org/10.1680/geot.2009.59.3.229.

[3] H. Sadeghi, R.M. Singh, Energy Geostructures application for heating and cooling in Europe, in: World Sustain. Energy Days 2021, Wels, 2021, https://doi.org/10.13140/RG.2.2.14261.14566.

[4] L. Aresti, P. Christodoulides, G. Florides, A review of the design aspects of ground heat exchangers, Renew. Sustain. Energy Rev. 92 (2018) 757–773, https://doi.org/10.1016/j.rser.2018.04.053.

[5] A.K. Sani, R.M. Singh, T. Amis, I. Cavarretta, A review on the performance of geothermal energy pile foundation, its design process and applications, Renew. Sustain. Energy Rev. 106 (2019) 54–78, https://doi.org/10.1016/j.rser.2019.02.008.

[6] A. Peters, Google's New Office Will Be Heated and Cooled by the Ground underneath, Fast Co, 2017. https://www.fastcompany.com/40484709/googles-new-office-will-be-heated-and-cooled-by-the-ground-underneath#:~:text=In 2%2C500 of the buildings,making the system less efficient.

[7] D.Y. Cherati, O. Ghasemi-Fare, Practical approaches for implementation of energy piles in Iran based on the lessons learned from the developed countries experiences, Renew. Sustain. Energy Rev. 140 (2021), 110748, https://doi.org/10.1016/j.rser.2021.110748.

[8] Jalaluddin, A. Miyara, K. Tsubaki, S. Inoue, K. Yoshida, Experimental study of several types of ground heat exchanger using a steel pile foundation, Renew. Energy 36 (2011) 764–771, https://doi.org/10.1016/j.renene.2010.08.011.

[9] Global Businesswire, Energy-Efficient Building Market Analysis, Trends, and Forecasts 2020-2025, 2022. https://www.businesswire.com/news/home/20200221005162/en/Global-Energy-Efficient-Building-Market-Analysis-Trends-and-Forecasts-2020-2025—ResearchAndMarkets.com. (Accessed 10 February 2022).

[10] UK Department for Business Energy & Industrial Strategy, HM Government, Heat and Buildings Strategy, 2021.

[11] P.J. Bourne-Webb, B. Amatya, K. Soga, T. Amis, C. Davidson, P. Payne, Energy pile test at lambeth college, London: geotechnical and thermodynamic aspects of pile response to heat cycles, Geotechnique 59 (2009) 237–248, https://doi.org/10.1680/geot.2009.59.3.237.

[12] B.L. Amatya, K. Soga, P.J. Bourne-Webb, T. Amis, L. Laloui, Thermo-mechanical behaviour of energy piles, Geotechnique 62 (2012) 503–519, https://doi.org/10.1680/geot.10.P.116.

[13] K.D. Murphy, J.S. McCartney, K.S. Henry, Evaluation of thermo-mechanical and thermal behavior of full-scale energy foundations, Acta Geotech. 10 (2015) 179–195, https://doi.org/10.1007/s11440-013-0298-4.

[14] C. De Santiago, F.P. De Santayana, M. De Groot, J. Urchueguía, B. Badenes, T. Magraner, J.L. Arcos, F. Martín, Thermo-mechanical behavior of a thermo-active precast pile, Bulg. Chem. Commun. 48 (2016) 41–54. http://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=ORCID&SrcApp=OrcidOrg&DestLinkType=FullRecord&DestApp=WOS_CPL&KeyUT=WOS:000392370100006&KeyUID=WOS:000392370100006.

[15] A.F. Rotta Loria, L. Laloui, Thermo-mechanical Schemes for Energy Piles, Springer International Publishing, 2019, https://doi.org/10.1007/978-3-319-99670-7_28.

[16] R.M. Singh, A.K. Sani, T. Amis, An overview of ground-source heat pump technology, in: Manag. Glob. Warm. An Interface Technol. Hum. Issues, 2019, pp. 455–485, https://doi.org/10.1016/B978-0-12-814104-5.00015-6.

[17] R.P. Cunha, P.J. Bourne-Webb, A critical review on the current knowledge of geothermal energy piles to sustainably climatize buildings, Renew. Sustain. Energy Rev. 158 (2022), 112072, https://doi.org/10.1016/j.rser.2022.112072.

[18] Z. Mohamad, F. Fardoun, F. Meftah, A review on energy piles design, evaluation, and optimization, J. Clean. Prod. 292 (2021), 125802, https://doi.org/10.1016/j.jclepro.2021.125802.

[19] J. Fadejev, R. Simson, J. Kurnitski, F. Haghighat, A review on energy piles design, sizing and modelling, Energy 122 (2017) 390–407, https://doi.org/10.1016/j.energy.2017.01.097.

[20] P. Hemmingway, M. Long, Energy piles: site investigation and analysis, Proc. Inst. Civ. Eng. Geotech. Eng. 166 (2013) 561–575, https://doi.org/10.1680/geng.12.00075.

[21] A. Ferrari, L. Laloui, Energy Geotechnics, SEG-2018, Springer, 2018, https://doi.org/10.1201/b21938.

[22] PIEUX EVIDES – car la qualité est plus qu'une simple affaire de confiance, n.d, https://www.sacac.ch/.

[23] Maria Alberdi-Pagola, Design and Performance of Energy Pile Foundations Precast Quadratic Pile Heat Exchangers for Shallow Geothermal Energy Systems, Aalborg University, 2018.

[24] H. Park, S.R. Lee, S. Yoon, J.C. Choi, Evaluation of thermal response and performance of PHC energy pile: field experiments and numerical simulation, Appl. Energy 103 (2013) 12–24, https://doi.org/10.1016/j.apenergy.2012.10.012.

[25] S. Yoon, S.R. Lee, G.H. Go, J. Xue, H. Park, D. Park, Thermal transfer behavior in two types of w-shape ground heat exchangers installed in multilayer soils, Geomech. Eng. 6 (2014) 79–98, https://doi.org/10.12989/gae.2014.6.1.079.

[26] C.W.W. Ng, A. Gunawan, C. Shi, Q.J. Ma, H.L. Liu, Centrifuge modelling of displacement and replacement energy piles constructed in saturated sand: a comparative study, Géotech. Lett. 6 (2016) 34–38, https://doi.org/10.1680/jgele.15.00119.

[27] F.P. De Santayana, C. De Santiago, M. De Groot, J. Uchueguía, J.L. Arcos, B. Badenes, Effect of thermal loads on pre-cast concrete thermopile in Valencia, Spain, Environ. Geotech. 7 (2016) 208–222, https://doi.org/10.1680/jenge.17.00103.

[28] M. Alberdi-Pagola, S.E. Poulsen, F. Loveridge, S. Madsen, R.L. Jensen, Comparing heat flow models for interpretation of precast quadratic pile heat exchanger thermal response tests, Energy 145 (2018) 721–733, https://doi.org/10.1016/j.energy.2017.12.104.

[29] M. Alberdi-Pagola, S.E. Poulsen, R.L. Jensen, S. Madsen, Thermal design method for multiple precast energy piles, Geothermics 78 (2019) 201–210, https://doi.org/10.1016/j.geothermics.2018.12.007.

[30] M. Alberdi-Pagola, S.E. Poulsen, R.L. Jensen, S. Madsen, A case study of the sizing and optimisation of an energy pile foundation (Rosborg, Denmark), Renew. Energy 147 (2020) 2724–2735, https://doi.org/10.1016/j.renene.2018.07.100.

[31] G. Jiang, C. Lin, D. Shao, M. Huang, H. Lu, G. Chen, C. Zong, Thermo-mechanical behavior of driven energy piles from full-scale load tests, Energy Build. 233 (2021), 110668, https://doi.org/10.1016/j.enbuild.2020.110668.

[32] Balfour Beatty, Geothermal Driven Energy Piles, Technique Sheet, 2014. https://www.balfourbeatty.com/media/149339/geothermal-driven-piles.pdf.

[33] CLaire Smith, Proving the Concept of Geothermal Piles, New Civ. Eng., 2013. https://www.newcivilengineer.com/latest/proving-the-concept-of-geothermal-piles-01-10-2013/. (Accessed 21 February 2022).

[34] J.D. Spitler, M. Bernier, Vertical borehole ground heat exchanger design methods, in: Adv. Ground-Source Heat Pump Syst., Woodhead Publishing, 2016, pp. 29–61, https://doi.org/10.1016/B978-0-08-100311-4.00002-9.

[35] Hiper pile Keltarby, Redefining Sustainable Construction, 2022. https://issuu.com/keltbraygroup/docs/keltbray_-_hiper__pile?fr=sNTQ0ZTIxNjEzMzU.

[36] P.J. Hannigan, F. Rausche, G.E. Likins, B.R. Robinson, M.L. Becker, Design and construction of driven pile foundations - volume I, FHWA-NHI-16-009, U.S. Dep. Transp. Fed. Highw. Adm. I (2016) 563.

[37] H. Brandl, Energy foundations and other thermo-active ground structures, Geotechnique 56 (2006) 81–122, https://doi.org/10.1680/geot.2006.56.2.81.

[38] M. Ouzzane, P. Eslami-Nejad, M. Badache, Z. Aidoun, New correlations for the prediction of the undisturbed ground temperature, Geothermics 53 (2015) 379–384, https://doi.org/10.1016/j.geothermics.2014.08.001.

[39] NGI, NGTS Vista Data Vision. http://vistadv01.ngi.no/, 2020. (Accessed 11 February 2021).

[40] G.L. Gilbert, A. Instanes, A.O. Sinitsyn, A. Aalberg, Characterization of two sites for geotechnical testing in permafrost: Longyearbyen, Svalbard, AIMS Geosci 5 (2019) 868–885, https://doi.org/10.3934/geosci.2019.4.868.

[41] A. Bidarmaghz, G.A. Narsilio, Shallow geothermal energy: emerging convective phenomena in permeable saturated soils, Géotech. Lett. 6 (2016) 119–123, https://doi.org/10.1680/jgele.15.00167.

[42] A. Nikitin, M. Deymi-Dashtebayaz, S. Muraveinikov, V. Nikitina, R. Nazeri, M. Farahnak, Comparative study of air source and ground source heat pumps in 10 coldest Russian cities based on energy-exergy-economic-environmental analysis, J. Clean. Prod. 321 (2021), 128979, https://doi.org/10.1016/j.jclepro.2021.128979.

[43] J. Hjort, O. Karjalainen, J. Aalto, S. Westermann, V.E. Romanovsky, F.E. Nelson, B. Etzelmüller, M. Luoto, Degrading permafrost puts Arctic infrastructure at risk by mid-century, Nat. Commun. 9 (2018), https://doi.org/10.1038/s41467-018-07557-4.

[44] A. Gemant, The thermal conductivity of soils, J. Appl. Phys. 21 (1950) 750–752, https://doi.org/10.1063/1.1699752.

[45] S.A. Ghoreishian Amiri, G. Grimstad, Constitutive model for long-term behavior of saturated frozen soil, Can. Geotech. J. 1657 (2017), https://doi.org/10.1139/cgj-2015-0467.

[46] EnergyPlus^{TM} Version 9.4.0 Documentation, U.S. Dep. Energy, 2020, pp. 4–6. https://energyplus.net/documentation.

[47] S.L. Abdelaziz, C.G. Olgun, J.R. Martin, Equivalent energy wave for long-term analysis of ground coupled heat exchangers, Geothermics 53 (2015) 67–84, https://doi.org/10.1016/j.geothermics.2014.04.006.

[48] O. Farouki, Cold Regions Research And Engineering Lab Hanover NH, 1992. European foundation designs for seasonally frozen ground.

[49] Geovita, E18 Bjørvikaprosjektet Project, 2015. https://geovita.no/prosjekt/e18-bjorvikaprosjektet/. (Accessed 1 August 2022).

[50] Den norske Pelekomite, Norwegian Piling Standard (Pele Veiledningen), Norsk Geoteknisk Forening, Oslo, 2019.

[51] D. Cerra, M. Alberdi-Pagola, T.R. Andersen, K.W. Tordrup, S.E. Poulsen, Feasibility study of collective heating and cooling based on foundation pile heat exchangers in Vejle (Denmark), Q. J. Eng. Geol. Hydrogeol. (2020), https://doi.org/10.1144/qjegh2020-114 qjegh2020-q2114.

[52] M. Alberdi-Pagola, R.L. Jensen, S.E. Poulsen, A performance case study of energy pile foundation at Rosborg Gymnasium (Denmark), in: CLIMA 2016 - Proc. 12th REHVA World Congr, 2016, p. 10. http://vbn.aau.dk/files/233716932/paper_472.pdf.

[53] S.E. Poulsen, M. Alberdi-Pagola, D. Cerra, A. Magrini, An experimental and numerical case study of passive building cooling with foundation pile heat exchangers in Denmark, Energies 12 (2019), https://doi.org/10.3390/en12142697.

[54] EUDP-Project 64017-05182, Bygningsintegreret Varme- Og Køleforsyning Til Fremtidens Resiliente Byer, DK - 8700 Horsens, 2019. https://www.ucviden.dk/da/projects/vedvarende-bygningsintegreret-varme-og-køleforsyning-til-fremtide.

[55] SACAC, Bibliothek auf Energiepfählen, Büron, 2015. https://www.sacac.ch/sites/default/files/SACAC_Speicherbibliothek_Bueron_0.pdf.

[56] S.J. Poot, Geothermal Pile Having a Cavity through Which a Fluid Can Flow, 2002. EP1243875A1, http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Designated+Extension+States+:#0.

[57] United Nations Environment Programme, Towards a Zero-Emissions, Efficient and Resilient Buildings and Construction Sector. 2019 Global Status Report 1, IEA, 2019, pp. 9–10.

[58] N.R.M.C.A. Publication, Concrete CO_2 fact sheet, Natl. Ready Mix. Concr. Assoc. June (2008) 7–8.

[59] Z. Cao, G. Zhang, Y. Liu, X. Zhao, C. Li, Influence of backfilling phase change material on thermal performance of precast high-strength concrete energy pile, Renew. Energy 184 (2022) 374–390, https://doi.org/10.1016/j.renene.2021.11.100.

[60] Z. Cao, G. Zhang, Y. Liu, X. Zhao, Thermal performance analysis and assessment of PCM backfilled precast high-strength concrete energy pile under heating and cooling modes of building, Appl. Therm. Eng. 216 (2022) 119144, https://doi.org/10.1016/j.applthermaleng.2022.119144.

[61] Leimet, Leimet Technical Manual, ABB PLUS Pile Joint, 2020.

[62] Precast Concrete Products - Foundation Piles EN 12794:2005, BSI British Standard, 2005.

[63] O. Platell, Concrete Pile for Pile-Driving to Form a Thermal Soil Storage, 2002. WO03/023150A1.

[64] Y. Junneng, L. Ganbin, L. Dai, Y. Tiefeng, Static Drill Rooting Energy Pile and Construction Method Thereof, 2018, CN108570982.

[65] J. Leino, Concrete Pile and Method of Manufacturing Concrete Pile, 2018. EP3358085A1.

[66] J. Gang, Z. Chenfeng, W. Qian, S. Dong, Connecting Joint of Prefabricated Energy Tubular Pile and Connecting Method of Connecting Joint, 2019. CN110158587.

[67] Z. Qiang, L. Xunmeng, Z. Yan, H. Jingxun, Prefabricated Energy Pile Heat Exchange Pipe Joint, 2020. CN210341889U.

[68] W. Zhongjin, L. Fuyuan, X. Xinyu, Z. Rihong, F. Pengfei, Static Drill Rooted Energy Pile and Production Method and Construction Method Thereof, 2020, CN109458757.

[69] H. Sadeghi, R.M. Singh, Joints for Pre-cast Driven Piles, 2021. Pending Patent.

[70] Leimet, Leimet Technical Information for Rock Point, 2020.

[71] A. Di Donna, A. Ferrari, L. Laloui, Experimental investigations of the soil-concrete interface: physical mechanisms, cyclic mobilization, and behaviour at different temperatures, Can. Geotech. J. 53 (2016) 659–672, https://doi.org/10.1139/cgj-2015-0294.

[72] S. Yazdani, S. Helwany, G. Olgun, Influence of temperature on soil-pile interface shear strength, Geomech. Energy Environ. 18 (2019) 69–78, https://doi.org/10.1016/j.gete.2018.08.001.

[73] R. Saggu, Temperature effects on pile-soil interface behaviour in the case of piles in sand, Proc. Inst. Civ. Eng. Geotech. Eng. (2021) 1–13, https://doi.org/10.1680/jgeen.20.00197, 00197.

[74] C.S.I. Soffons-fntp, Recommandations pour la conception, le dimensionnement et la mise en oeuvre des géostructures thermiques, 2017, https://doi.org/10.1051/geotech/2017012.

[75] EGEC, Geothermal Decade, 2022. https://www.egec.org/geothermal-decade-2/. (Accessed 10 February 2022).

[76] IEA, Net Zero by 2050 A Roadmap for the Global Energy Sector, 2021. https://www.iea.org/reports/net-zero-by-2050. (Accessed 31 May 2021).

[77] J. Muller, Norway Country Report, IEA Geothermal, 2020, 2020.

[78] Breeam-nor, Inputs to BREEAM-NOR 2021, 2021.

[79] T. Aanensen, Threefold Increase in Electricity Price for Households, 2021 (accessed February 22, 2022), https://www.ssb.no/en/energi-og-industri/energi/statistikk/elektrisitetspriser/article-for-electricity-prices/threefold-increase-in-electricity-price-for-households.

[80] How much carbon dioxide is produced per kilowatthour of U.S. electricity generation? EIA, 2021. https://www.eia.gov/tools/faqs/faq.php?id=74&t=11#:~:text=In 2020%2C total U.S. electricity,CO2 emissions per kWh. (Accessed 22 February 2022).

[81] Final Energy Consumption in Norway, excluding non-energy use, 2020, 2020, https://energifaktanorge.no/en/norsk-energibruk/energibruken-i-ulike-sektorer/#:~:text=In Norway%2C average household electricity,1.1 per kWh in 2013. (Accessed 22 February 2022).

[82] T. Aanensen, R. Skotvold, M. Holstad, Electricity prices, https://www.ssb.no/en/energi-og-industri/energi/statistikk/elektrisitetspriser, 2022. (Accessed 22 February 2022).

[83] T. Solsvik, Norway Government Proposes Subsidy to Ease Pain of High Power Prices, 2021. https://www.weforum.org/agenda/2021/12/norway-government-subsidy-high-power-prices-electricity/. (Accessed 22 February 2022).

[84] H. Sadeghi, A. Ijaz, R.M. Singh, Current status of heat pumps in Norway and analysis of their performance and payback time, Sustain. Energy Technol. Assessments (2022), https://doi.org/10.1016/j.seta.2022.102829.

[85] GSHP Association, Thermal Pile Design, Installation and Materials Standards, Ground Source Heat Pump Association, 2012.

[86] Nutzung Thermische, VDI 4640 Part 1, Thermal Use of the Underground Fundamentals, Approvals, Environmental Aspects, Vdi-Handb. Energietechnik., 2010.

[87] Nutzung Thermische, VDI 4640 Part 2, Thermal use of the underground Ground source heat pump systems, Vdi-Handb. Energietechnik. (2019).

[88] L. Planung, B. Betrieb, D 0190 Nutzung der Erdwärme mit Fundationspfählen und anderen erdberührten Betonbauteilen Nutzung der Erdwärme mit Fundationspfählen und anderen erdberührten Betonbauteilen, 2005.

[89] A./S. Centrum Pæle, Denmark. https://www.energipaele.dk/, 2022. (Accessed 18 February 2022).

[90] M. Faizal, A. Bouazza, R.M. Singh, Heat transfer enhancement of geothermal energy piles, Renew. Sustain. Energy Rev. 57 (2016) 16–33, https://doi.org/10.1016/j.rser.2015.12.065.

[91] SACAC, Energiepfahlsystem PILOTHERM- Die Energiegewinnung aus Erdwarme, Munich, 2020. https://www.sacac.ch/.