Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0238

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Precast pile heat exchangers in Denmark: case study and on-going projects

Pieux géothermiques préfabriqués au Danemark: cas d'étude et projets en cours

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ABSTRACT: Pile heat exchangers, also known as energy piles, are standard precast piles with built in geothermal pipes. They appeared as an alternative to traditional borehole heat exchangers and they are used to supply space heating and cooling to buildings. The design of energy piles involves several challenges and this paper presents the work carried out in Denmark to overcome some of these. First, two case studies are presented, a high school and a sport hall. Next, a design method is presented, which yields the energy pile arrangement required to supply the heating and/or cooling needs of a building. Based on this research, a new development project is currently investigating the potential of energy piles to supply the heating and cooling needs of a district (Ny Rosborg in Vejle, DK). Preliminary investigation of the geology and the thermal properties of the area suggests energy piles are a suitable and sustainable thermal energy supply alternative in this area.

RÉSUMÉ: Les échangeurs thermiques intégrés dans des pieux de fondation (plus communément appelés *pieux géothermiques*) sont des éléments standards de fondations préfabriquées incluant un circuit hydraulique pour de la géothermie. Cette technologie a été développée comme une alternative aux traditionnels puits géothermiques, et est utilisé comme source chaude ou source froide pour subvenir aux besoins de chauffage ou de refroidissement d'un bâtiment. Le dimensionnement et le design de fondations avec pieux géothermiques présentent plusieurs défis. Cet article présente des travaux de recherche et développement menés au Danemark qui permettent de relever certains de ces défis. Premièrement, deux études de cas sont présentées: le complexe scolaire d'un lycée et une salle de sport. Une méthode de dimensionnement est ensuite expliquée et détaillée. Cette méthode permet ainsi de déterminer la disposition des pieux géothermiques afin de subvenir aux besoins énergétiques de chauffage et refroidissement du bâtiment. À la suite de ces recherches, un nouveau projet est actuellement en cours pour étudier le potentiel des pieux géothermiques pour une utilisation à l'échelle d'un quartier résidentiel (quartier de *Ny Rosborg* dans la commune de *Vejle* au Danemark). Les premières études thermo-géologiques du site suggèrent que des fondations avec pieux énergétiques sont une alternative viable et durable de source de chaleur pour les bâtiments de ce quartier.

Keywords: Energy pile; precast pile heat exchanger; ground source heating; ground source cooling; thermal response.

1 INTRODUCTION

Energy piles are thermo-active ground structures that utilise reinforced concrete foundation piles as closed-loop ground heat exchangers (Brandl, 2006). Using energy piles, the foundation of the building serves both as a structural component as well as a heating and cooling supply element (Figure 1).

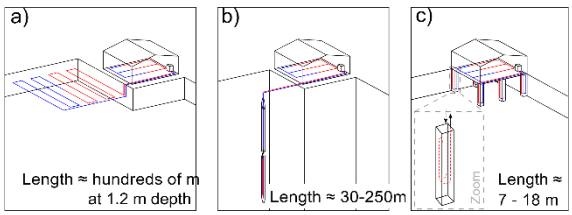


Figure 1: Closed loop shallow geothermal systems: a) horizontal, b) vertical and c) pile heat exchangers. After (Alberdi -Pagola et al., 2018).

Energy piles can be cast in place or precast driven piles. The latter can be either concrete or steel piles, varying in length from 7 to 50 m with a diameter of 0.3 to 1.5 m. Around 115 energy pile installations were registered worldwide in 2017, from which 60% were built in the UK (Di Donna *et al*., 2017).

Compared to borehole heat exchangers, energy piles have lower initial costs (Laloui and Di Donna, 2013) and their potential to minimise the overall environmental impact of a structure has been demonstrated, based on the dual role of the piles (Nicholson *et al*., 2014).

However, unlike borehole heat exchangers, energy piles are structural elements and their position is determined by mechanical loads from the building. To ensure that the geotechnical integrity of the pile-soil system is not threatened by the heating and cooling resulted from the geothermal use, the ground loop fluid temperatures should always be kept above 2 °C (GSHP Association, 2012). Thus, the operational temperature span of energy piles ranges between 2 and 30 °C (Knellwolf *et al*., 2011).

This restricted temperature span demands reliable methods to predict the long-term ground loop temperature in the energy pile foundation. The methods developed for borehole heat exchanger field thermal design are not always applicable to energy pile foundations because they do not allow: irregular pile spacing, low length to diameter ratios, different pipe configurations, pile geometries, etc.

In the following, the work on thermal design challenges related to precast energy pile foundations carried out in Denmark in the last years is presented. First, a pilot project is presented, which served as a basis to develop a design method for precast energy pile thermal dimensioning, also shortly described. Then, preliminary results of an ongoing large-scale project are presented.

2 PRECAST ENERGY PILES

The Danish company Centrum Pæle A/S produces precast quadratic energy piles. They have a square cross section (from 25 cm to 45 cm side size) and a length limited to 18 m due to transportation constraints. The geothermal pipes are fixed to the reinforcement cage in different arrangements as shown in Figure 2.

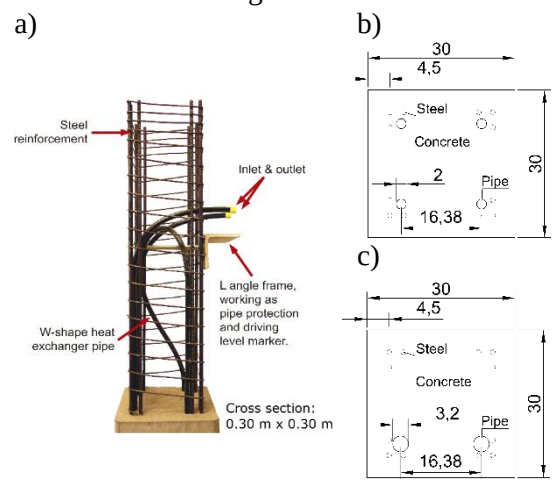


Figure 2. a) Demonstration model of energy pile; b and c) horizontal cross sections of W- and single

U-shape pipes, respectively (cotes in cm). After (Alberdi-Pagola *et al*., 2018).

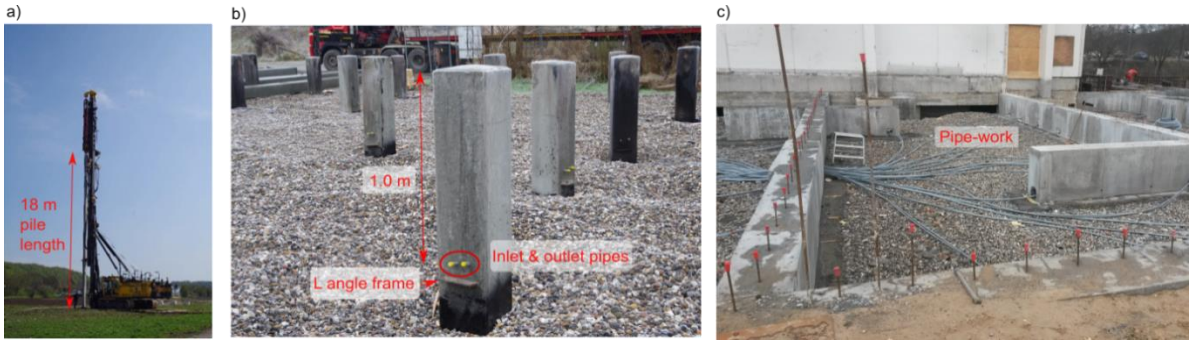


Figure 3: a) 18 m long energy pile driving; b) energy pile field; c) pipework. After (Alberdi-Pagola *et al*., 2018).

Energy piles are installed using the same hammering procedure as for standard precast piles (Figure 3). The inlet and outlet pipes are left accessible immediately above ground level (10 to 20 cm), for the pipe-work.

2.1 Case studies

Herein two case studies in Vejle, Denmark, are presented where the described energy piles have been utilised: Rosborg High School and Rosborg Sports Hall. These energy foundations have been designed under conservative assumptions due to the lack of applicable models.

The two buildings have different uses but are built in on comparable soil conditions because of their proximity (see section 4.1.1).

The Rosborg High School building is founded on 280 piles, 220 of which are energy piles (15 m long). 60 piles had to be cut since could not reach the desired driving level. The piles and energy piles are distributed in the building footprint as shown in Figure 4. Notice the pile spacing is as low as 0.5 m in high pile-density areas.

The ground source heat pump (GSHP) installation has covered the space heating need of the 3950 m^2 living area since autumn 2012. The monitoring system of the building collects operational data, e.g., ground loop fluid temperatures, flows and energy extraction from the ground. Measurements from the last three years of monitoring, i.e., since 2015, are shown in Figure 5.

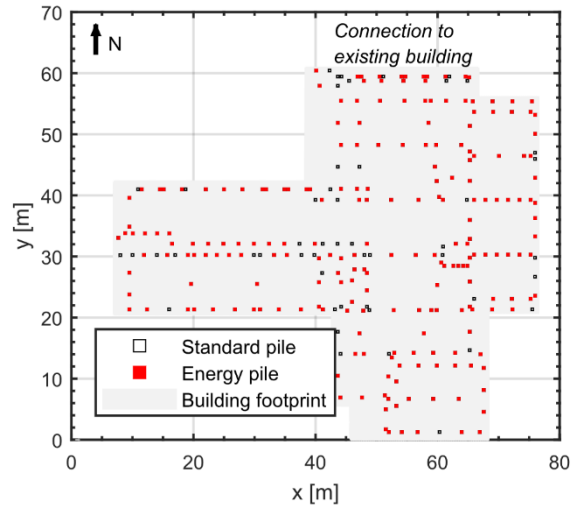


Figure 4: Top view of foundation of Rosborg High School (Alberdi-Pagola et al., 2018b).

Figure 5a shows the daily average outdoor ambient air temperatures and the daily thermal energy extracted from and injected to the ground. Note, the heating need of the building in spring is insignificant. Also, the cooling capability during summer is hardly ever used. The average heating lead per year is 135 MWh, while for free cooling supplied in 2015 has just 4 MWh and even less the following years.

The uneven utilisation of the soil where the net heat flow into the ground between discharge and

charge fluxes is not balanced, should, in principle, imply a decrease in the long-term ground temperature. However, in this case, ground loop temperatures are quite high over the analysed period (Figure 5b). The average daily return fluid temperature rarely goes below 5 °C, while the maximum temperature in the ground loop remains below 15 °C. The observed behaviour indicates that either the GSHP system is over-sized in terms of thermal performance and capacity or existing groundwater flow enhances the heat recharge of the ground (Alberdi-Pagola, 2018a).

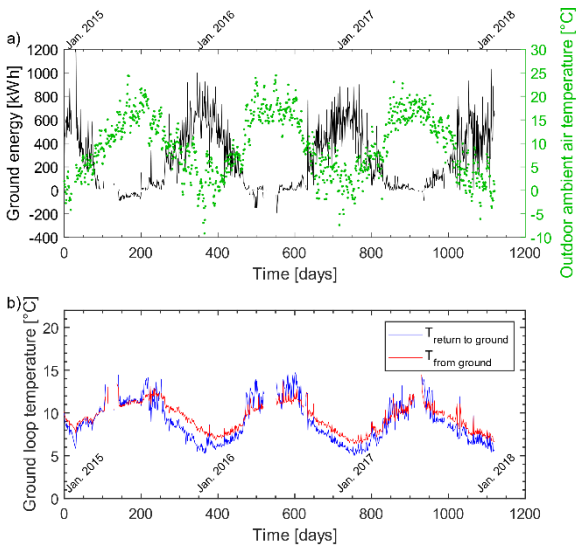


Figure 5: a) Daily average outdoor air temperatures and thermal energy applied to the ground; b) Ground-loop fluid temperatures. After (Alberdi-Pagola, 2018a).

The Rosborg Sports Hall building is founded on 220 energy piles (16 to 17 m long) which have supplied the space heating needs of 3400 m^2 since December 2017 (Figure 6). The GSHP system is very similar to the one in Rosborg High School. Operational data is not available yet and it will be presented in coming publications.

3 DIMENSIONING TOOL

Construction requirements for the building may necessitate pile spacings less than 1 m. This increases the thermal interaction between energy piles, unintentionally hampering the performance of the installation.

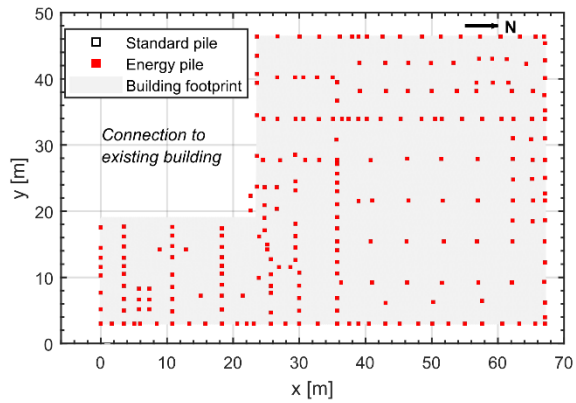


Figure 6: Top view of foundation of Rosborg Sports Hall (Alberdi-Pagola et al., 2018b).

To assist the thermal dimensioning of energy piles, a model has been developed, which includes the thermal influence between adjacent piles (Alberdi-Pagola, 2018b). It generates multiple energy pile g-functions relying on spatial and time superposition of semi-empirical single pile g-functions, following the method proposed by Loveridge and Powrie (2014). The model yields predicted temperatures close to the measured ones (Alberdi-Pagola *et al*., 2018).

Using the observed ground thermal load (Figure 5a) and assuming a similar behaviour in the coming years, the model has been applied to predict long-term average ground loop fluid temperatures (Figure 7). The predicted temperatures remain above 4 °C over the full simulation period.

The model has also been integrated in an optimisation strategy to minimise the amount of energy piles required to cover the building heating and cooling needs, as well as determining their position within the foundation (Alberdi-Pagola *et al*., 2018).

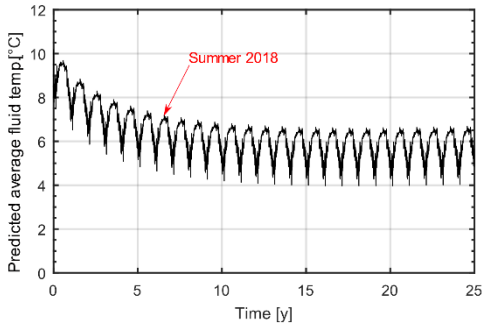


Figure 7: Predicted long-term temperatures at the case study, after (Alberdi-Pagola et al., 2018b).

4 LARGE SCALE APPLICATION

To put the knowledge acquired during the previous research stage into practice, an EUDP project (Danish program for technology development and demonstration) involving academic and industrial partners is in progress, ending in late 2019.

The project investigates the cooling potential of the energy piles for single buildings, and it departs from the anticipated role of heat pumps in the district heating networks, not just in the traditional district heating grid but also in the coming 4th generation district heating networks (Danish Energy Agency, 2017; Lund *et al*., 2014).

The project is being implemented in the Ny Rosborg area (Figure 8) in Vejle (Denmark) close to the Rosborg High School and Rosborg Sports Hall described in Section 3.

The tasks of the project are divided in three main work packages: i) mapping of the geothermal potential of the area, ii) testing of energy piles and iii) analysis of energy pile installations for district heating and cooling supply. In the following, the work done in the first work package is described.

4.1 Geothermal mapping

Geological and hydrogeological conditions affect the capacity and efficiency of the energy pile foundations. Several exploratory drillings serve to develop a geological description of the area and to collect soil samples to measure thermal properties. These thermal properties form the basis of a complete geothermal map of the area.

4.1.1 Geological setting

Twelve drillings were carried out in the Ny Rosborg area in December 2017. The position of the drillings is shown in Figure 8. Each drilling was 10 m deep, except for B16 which was carried out for a previous project and is 16 m deep. Soil

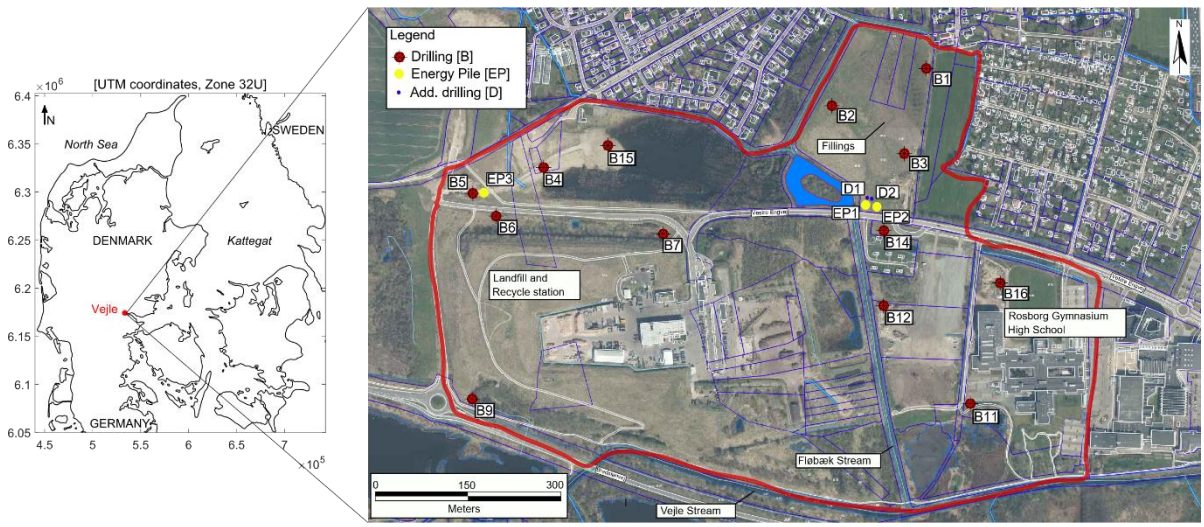


Figure 8: Overview map of the Ny Rosborg study area and exploratory drilling location.

samples were collected every 0.5 m, when possible, and they were kept in sealed plastic bags.

The geological sequence interpreted in the area is consistent with glacial meltwater 5 to 8 m.b.t. (meters below terrain) followed by postglacial sequence comprising of alternating marine sand, organic clay and peat deposits. On top up to 10 m of fillings are observed. The clayey sediments (gyttja and peat) show a higher water content than the surrounding deposits, in some cases more than 100%.

4.1.2 Thermal properties

The laboratory work took place immediately after the drilling works. The thermal properties have been measured by means of a Hot Disk apparatus (Hot Disk AB, 2014), which yields estimates of the thermal conductivity λ [W/m/K], volumetric heat capacity ρc_p [MJ/m^3/K].

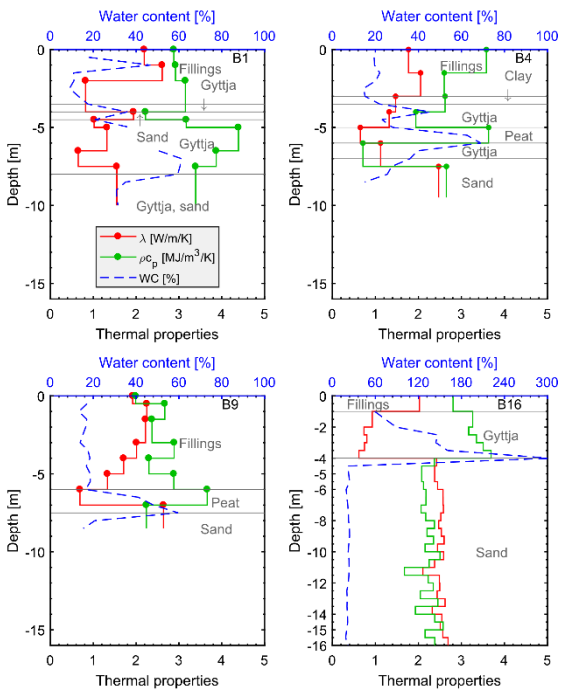


Figure 9: Thermal property profiles for drillings B1, B4, B9 and B16.

Five repeated measurements have been taken for each sample at a room temperature between 19 to 21 °C. The measurement procedure follows the steps defined by Alberdi-Pagola *et al.* (2017). Thermal properties have been measured in drillings B1, B4, B9 and B16, in selected samples.

Figure 9 shows the measured thermal property profiles. The thermal properties vary depending on the type of soil. Sand is expected below the shown sediments in B1, B4 and B9, and, therefore, the thermal conductivity is expected to rise as observed in B16. Table 1 provides the weighted average values of the thermal properties.

Table 1: Weighed average values for thermal conductivity and volumetric heat capacities.

Drilling	Thermal conductivity [W/m/K]	Volumetric heat capacity [MJ/m^3/K]
B1 (10 m)	1.44 ± 0.08	3.37 ± 0.37
B4 (10 m)	1.66 ± 0.09	2.51 ± 0.29
B9 (10 m)	1.91 ± 0.10	2.62 ± 0.31
B16* (16 m)	2.14 ± 0.11	2.47 ± 0.29

*from (Alberdi-Pagola *et al.*, 2018).

A preliminary simplification of the geology in main units is done. Then, a relation is established between measured samples and corresponding units. The values of the thermal properties are averages of all the measurements of the samples corresponding to each unit (Table 2).

Table 2: Assignment of thermal properties to units.

Unit name	Thermal conductivity λ [W/m/K]	Volumetric heat capacity ρc_p [MJ/m^3/K]
Fillings	2.05	2.93
Gyttja*	0.91	3.11
Peat*	1.08	3.14
Clay	1.08	3.14
Sand	2.47	2.24
Gyttja-sand	1.55	3.39

*Organic sediments.

4.1.3 Mapping

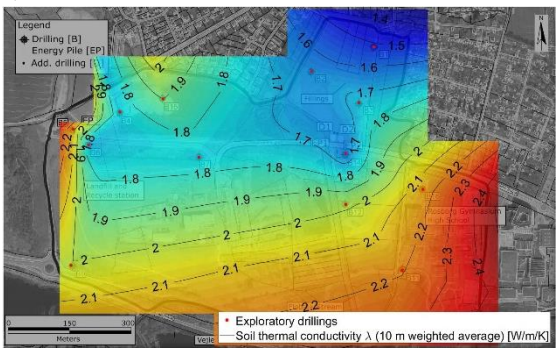
The drilling locations (Figure 8) and the geological sequences observed in them are combined with the thermal properties measured for the geological units. Weighted averages are calculated

and interpolated over the study area. Contour plots are shown in Figure 10, providing an overall visualisation of the expected thermal properties in the area.

4.1.4 Discussion

Figure 10a shows an increase in the thermal conductivity towards the south east part of the area, i. e., near Rosborg High School. Here, sandy sediments emerge at 4 to 5 m below the surface (profile B16 in Figure 9). In the northern part the thickness of the filling and organic deposits increases, yielding a lower thermal conductivity. In terms of volumetric heat capacity, fine-grained sediments show higher values, as observed in the north and north-west parts of the area (Figure 10b).

a)



b)

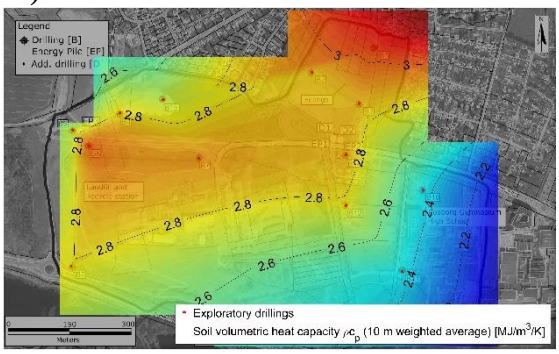


Figure 10: Contour plots of thermal conductivity and volumetric heat capacity, a) and b) respectively, in Ny Rosborg area.

Thermal properties affect the efficiency of the GSHP systems. High thermal conductivities are preferable, since the soil recovers faster. However, high volumetric heat capacities are advantageous for underground thermal energy storage to keep the heat for longer periods.

In general, fine grained deposits, such as fillings, gyttja and clays, display poor strength parameters. These have been observed in all parts of the study area, with thicknesses ranging up to 10 m, suggesting pile foundations will be required and energy piles may be employed.

4.2 Next steps

The on-going work is focused on completing the geological profiles to improve the maps. Thermal response tests will be performed in single energy piles and energy piles connected in series, to provide information of deeper soil layers and of the performance of energy piles. Besides, cooling tests in the case study and a small setup with a heat pump, where operational patterns will be analysed, will assist the investigation of the cooling and district supply potentials.

5 CONCLUSIONS

This paper presents the Danish efforts to solve design challenges related to energy pile foundations.

Two case studies demonstrate that energy piles can be used in heating dominant scenarios.

Based on the case studies, a design methodology for precast energy piles has been developed and will be applied for future buildings. This method eases the thermal dimensioning of energy pile foundations (for heating and cooling) in terms of the number of energy piles and their position, required to supply a given building need.

Large-scale application of energy pile technology investigates their suitability to supply districts. Preliminary investigation of the geology and the thermal properties of the area suggests energy piles are a suitable alternative.

6 ACKNOWLEDGEMENTS

The authors would like to thank Rosborg Gymnasium and all the partners supporting this research: VIA University College, Aalborg University, Centrum Pæle A/S, Vølund Varmeteknik A/S, Vejle Kommune, Vejle Fjernvarme a.m.b.a., Innovationsfonden Denmark (project number 4135-00105A), EUDP Denmark (64017-05182) and INSERO Horsens. We also thank Karl Woldum Tordrup for his comments.

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