

# Thermo-mechanical performance of driven energy piles in Norwegian quick clay

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**ABSTRACT:** Energy piles are thermoactive foundation elements that combine structural support with geothermal energy exchange for heating and cooling buildings. Among the several heat exchangers for ground source heat pump technologies, energy piles provide the benefits of requiring less area and reduced initial investment cost. While energy piles have been studied in various soil types, their application in sensitive soils such as Norwegian quick clay remains unexplored. This study addresses an existing knowledge gap by conducting the first field-scale thermo-mechanical experiment on energy piles in Norwegian quick clay deposits. Two square shape precast driven concrete energy piles of ~15 m length and 350 mm x 350 mm cross-sectional area, equipped with an innovative steel joint, patented at NTNU, were installed in quick clay and their tips rested on bedrock. One pile was mechanically loaded to 112 tons to simulate operational conditions, while the other remained unloaded to simulate free boundary condition. Both piles were connected to a heat pump system to facilitate controlled heating and cooling cycles, simulating real-world energy exchange scenarios. Advanced instrumentation, including distributed optical fiber sensors, vibrating wire strain gauges, thermistors, and piezometers, were installed in concrete pile as well as in the ground that enabled comprehensive monitoring of thermal responses, mechanical strain, and porewater pressure. The results showed that the thermal cycles induced only minimal excess porewater ( $\approx 3$  kPa) pressures, which remained within safe limits of stability. Furthermore, the piles exhibited negligible displacement and no adverse impacts on structural or geotechnical performance under thermal loading. This study demonstrates the technical feasibility of energy piles in quick clay, addressing critical concerns about soil stability and structural integrity. The findings provide valuable insights into the behavior of segmental precast energy piles under combined thermal and mechanical loads, paving the way for their adoption in sensitive clay.

**KEYWORDS:** Full-scale tests, Geothermal energy piles, Pile heat exchangers, Quick clay, Precast concrete piles, DEP joint, GSHP.

## 1 INTRODUCTION

Energy piles are dual-purpose foundation elements that carry structural loads while exchanging heat with the ground to support building heating and cooling. As cities seek compact, low-carbon HVAC solutions, integrating ground-source heat pump (GSHP) loops into foundation piles avoids dedicated borehole fields, minimizes the construction footprint, and leverages materials already required for support. In practice, circulating fluid within embedded pipe loops enables seasonal heat extraction and storage, where the resulting performance reflects site geology, climate, and service loading as well as pile geometry and construction methods. Over the last two decades, full-scale thermal response tests and thermo-mechanical experiments have established the feasibility of such systems across diverse geomaterials and climates. Seminal works in Europe, notably in Austria and Switzerland, examined bored cast-in-place piles and clarified thermomechanical interactions under different environmental conditions (Brandl, 2006, Laloui et al., 2006). In the UK, Bourne-Webb et al. (2009) delivered one of the most comprehensive instrumented field studies, illustrating load transfer during applied thermal cycles. Subsequent investigations in North America and East Asia broadened the evidence base (McCartney and Murphy, 2012, Park et al., 2013, You et al., 2016, Sutman et al., 2019). More recent contributions have leveraged distributed fiber-optic sensing and advanced 3D numerical modeling to improve prediction of both thermal performance and soil–structure interaction. Despite this progress, literature remains dominated by bored pile systems, with comparatively few studies on driven precast energy piles (DEP) systems that are prevalent in Scandinavia and other regions where driven foundations are standard practice.

In Norway, driven precast concrete piles are the most widely used foundation type. They are commonly produced in 12 to 14 m standard lengths with square sections of 270 mm or 350 mm (Sadeghi and Singh, 2023a). A longstanding barrier to adapting these piles for geothermal use has been the need for

reliable, leak-tight, and structurally robust joints to connect heat-exchange loops across segments. This challenge has been addressed through a patented driven energy pile (DEP) joint developed at NTNU, enabling continuous thermal loops without compromising structural integrity (Sadeghi and Singh, 2023c) (Sadeghi and Singh, 2024b, Sadeghi and Singh, 2024a). The availability of a CE-certified DEP joint now permits rigorous field-scale assessment of driven precast systems in the soils and climates where they are most likely to be deployed.

Only a limited number of field investigations have examined driven energy piles (de Santayana et al., 2016, Badenes et al., 2017, Alberdi-Pagola, 2018, Cao et al., 2022). The Norwegian piling context presents specific characteristics, as the driven piles are typically end-bearing with their tip resting on the bedrock because the surrounding quick clays exhibit low skin-friction capacity. Moreover, consolidation of soft sensitive clays can induce negative skin friction and additional axial loads on the pile, raising legitimate concerns about interaction between thermal cycling and geotechnical performance. However, no large-scale thermo-mechanical field study of precast DEPs in Norwegian quick clay has been reported. This gap limits our understanding of how driven, end-bearing energy piles behave in cold climates and in sensitive soils where stability and serviceability criteria are strict.

This paper presents a fragment of results from the field-scale thermo-mechanical experiment on precast concrete driven energy piles installed in Norwegian quick clay. Two quadratic piles with a cross-section of 350 mm  $\times$  350 mm and a length of ~15 m, were constructed from two segments connected using CE-certified NTNU DEP joints (Sadeghi and Singh, 2023b), and driven to bedrock. To represent practical boundary conditions, one pile was mechanically loaded to 112 tons to simulate operational axial responses, while the other pile remained free to focus mainly on the thermal effects. Both piles were integrated with a heat-pump system to apply controlled heating and cooling cycles representative of real building thermal demand. Monitoring instrumentation included distributed optical-fiber sensing, vibrating-wire strain gauges,

thermistors, and piezometers embedded in the piles and surrounding ground. This configuration enabled continuous measurement of thermal and mechanical strains along the shafts, head displacements, ground temperature, and pore-water pressure (PWP), thereby capturing the coupled thermo-hydro-mechanical response.

## 2 TEST SETUP AND PLAN

The field setup comprised two segmental driven energy piles (EP1 and EP2) assembled with a novel patented inter-segment joint. This joint was previously validated through the full suite of standard structural integrity and hydraulic pressure tests, confirming leak-tightness and load-bearing reliability (Sadeghi et al., 2025). EP1 served as the primary test pile and was subjected to a constant axial load of 112 tons to represent real life building load. The load was applied and maintained using a high-tonnage (350-ton capacity) hydraulic jack powered by an electric hydraulic pump. Concurrently, for this test, EP1 functioned as the heat sink within the thermal loop. In contrast, EP2 was left mechanically free to focus on the thermal effects and was operated as the heat source; its circulating fluid was chilled to approximately 1°C to impose a well-defined temperature gradient. Figure 1 shows the photograph of both piles (EP1 and EP2) along with loading frame.



Figure 1. Test Setup: Energy piles with reaction beam on the main pile

Both piles were hydraulically connected to a 7-kW water-to-water ground-source heat pump. The heat transfer tubes, and the heat pump were instrumented to continuously monitor inlet and outlet fluid temperatures, volumetric flow rates, and electricity consumption, enabling calculation of system heat fluxes and coefficients of performance. This arrangement, loaded sink pile (EP1) paired with a free source pile (EP2), coupled through a temperature controlled 7-kW heat pump loop, provided a clear framework to distinguish purely thermal responses from the coupled thermo-mechanical behavior while also verifying the operational robustness of the patented joint under both heating and cooling field conditions.

### 2.1 Pile instrumentation and data monitoring

Both driven energy piles were instrumented with distributed fiber optic sensors (DFOS) to obtain continuous profiles of strain and temperature along the segments using a Brillouin optical time-domain reflectometer interrogator. Two parallel optical lines were embedded within each pile: tight-buffer fibers, bonded to the concrete, captured the total (thermo-mechanical) strain, while companion loose-tube fibers, mechanically decoupled from the concrete, recorded just the temperature. Mechanical strain was then derived by correcting the tight-buffer strain measurements for the thermal effects

using the colocated loose-tube temperature measurements, yielding a net strain profile suitable for interpreting load transfer and shaft end bearing interaction.

To provide independent point measurements and redundancy, conventional vibrating-wire sister-bar strain gauges were installed at selected elevations, and PT100 RTD thermistors were positioned near the fiber paths as reference temperature sensors. The combined DFOS-VW-RTD approach enables cross-validation of measurements, improves confidence in the derived axial load distribution and thermal gradients, and provides resilience against potential signal loss in any single sensor type. All instruments were securely fixed to the reinforcement cage prior to casting, with leads routed to the pile head through protective conduits to protect terminations and facilitate connection to the data acquisition system. Representative photographs of the in-cage layout and sensor placement during casting are shown in Figure 2.

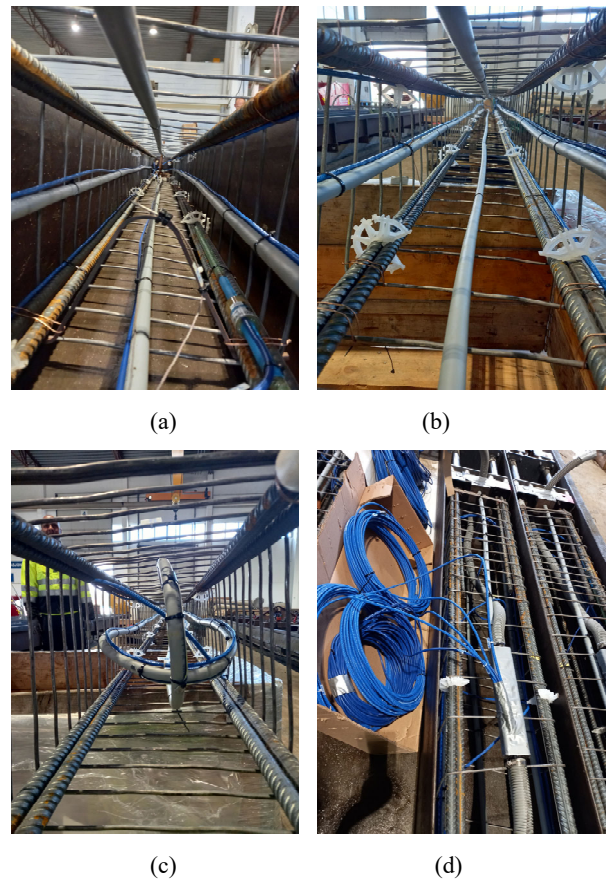


Figure 2. Instrumentations installed in the energy piles during casting, (a) strain gauge and RTD thermistor, (b) DFOS cables, (c) DFOS cables at the pile tip, (d) instrumentation and OFS cables

### 2.2 Reaction beam and loading arrangement

Axial loading of the primary energy pile (EP1) was applied with a hydraulic jack positioned between the pile head and a steel reaction beam rigidly anchored to the bedrock. To track and control the applied load, pressure was monitored at two locations: at the hydraulic pump Figure 3 (a) and immediately upstream of the jack via an in-line gauge Figure 3 (b), providing redundancy and enabling verification of pressure losses within the line. Once the target load was reached, the pressure valve at the pump was closed to lock in the load for sustained testing at the target load. Pile-head displacements were measured on two orthogonal faces using vibrating-wire (VW) extensometers, each fixed at one end to the pile wall and at the other to a stable reference beam, allowing both average vertical movements and

any load-induced eccentricity or bending to be resolved. All sensors were zeroed prior to loading and readings were logged throughout the hold period. A schematic of the reaction beam, anchorage, jack placement, and instrumentation layout are presented in Figure 3. The vertical mechanical load time history at the EP1 pile head is presented in Figure 4.

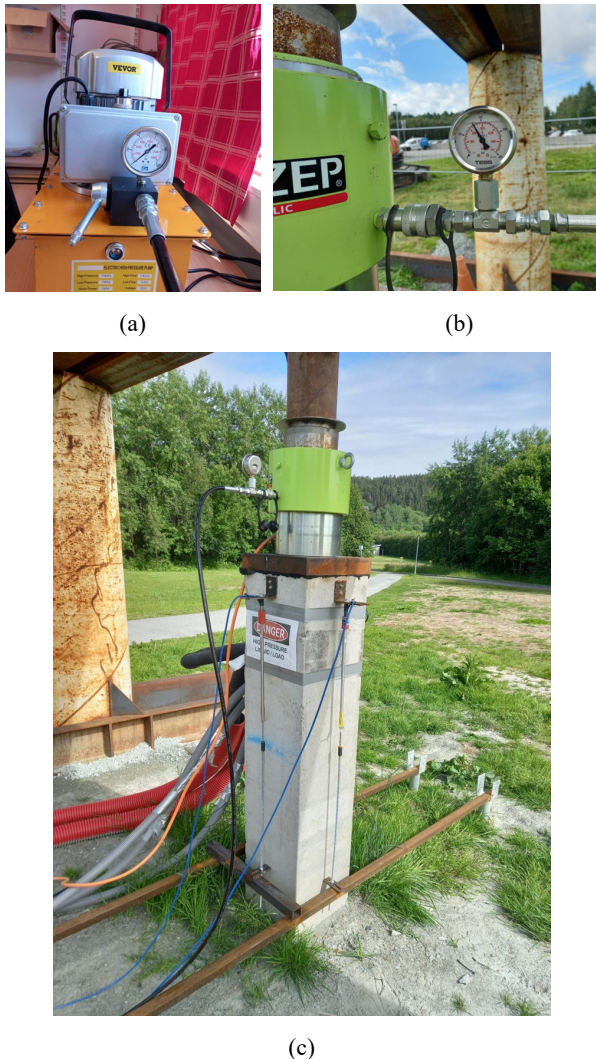


Figure 3. Loading arrangement for mechanical loading on EP1 (a) hydraulic pump, (b) hydraulic jack and gauge, (c) Reference beam and extensometers

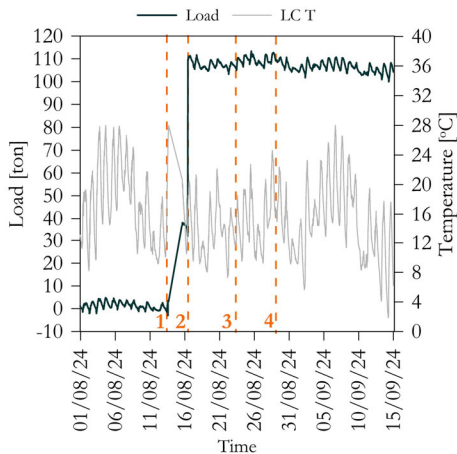


Figure 4. The vertical mechanical load time history at the EP1 pile head

### 3 RESULTS AND DISCUSSIONS

With the aid of the heat pump, temperature in the free pile EP 2 was controlled to 1°C to simulate the heating of building, thus cooling of the surrounding ground. Extracted heat from EP2 was stored in EP1, thus increasing the temperature of EP1 up to 20°C. It is worth to note that the temperature of EP1 was not controlled and the increase in temperature depended on the on-off frequency of heat pump and the amount of heat extracted from the source energy pile EP2.

Figure 5 shows temperature along the depth for both energy piles after 48 hours of controlled thermal operation. The green and blue points are temperature readings at the PT100 RTD and vibrating wire sisterbar embedded temperature sensors, respectively. The in-situ ground and pile temperature prior to testing was approximately  $\sim 7^\circ\text{C}$ . During the test, EP1 (sink pile) was heated to about  $20^\circ\text{C}$  ( $\Delta T \approx +13^\circ\text{C}$ ), while EP2 (source pile) was cooled to roughly  $1^\circ\text{C}$  ( $\Delta T \approx -6^\circ\text{C}$ ). The resulting strain profiles, shown in Figure 6, reflect the expected thermoelastic behavior of reinforced concrete pile: EP1 exhibits positive axial strain (thermal expansion) and EP2 exhibits negative axial strain (thermal contraction). Mechanical strain was obtained by correcting the tight-buffer DFOS signal with colocated temperature measurements from the loose-tube fiber within the same cable, thereby considering the thermal correction, and calculating the deformation associated with the thermo-mechanical soil-pile interactions.

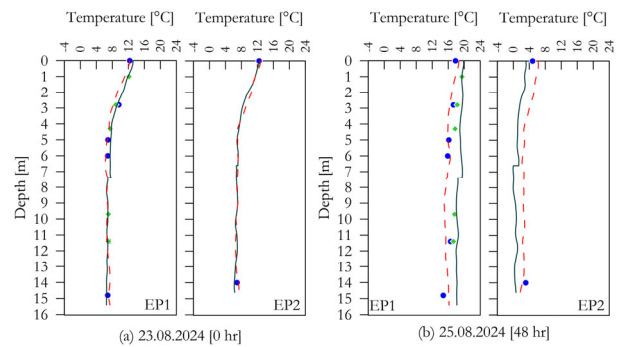


Figure 5. Temperature distribution along the depth of EP1 and EP2 at the start of the test and after 48 hours of heating and cooling

Distributed DFOS measurements align closely with point readings from vibrating-wire sister bars (blue points) over most elevations; the principal deviation occurs at the pile head, where boundary effects and hardware interfaces (e.g., head plates, grout, jack seating) perturb the local strain field and complicate direct comparison. DFOS-derived temperature profiles also agree with independent PT100 RTD readings, supporting both the thermal calibration and the subsequent thermo-mechanical correction.

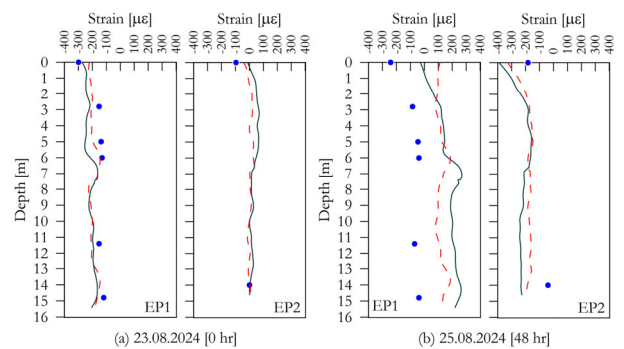


Figure 6. Strain distribution along the depth of EP1 and EP2 at the start of the test and after 48 hours of heating/cooling

From the temperature corrected strain distributions, section stresses and axial loads can be calculated using elastic constitutive relationships and pile section properties. These derived quantities inform assessment of shaft load transfer, end bearing, and serviceability (e.g., pile head settlement). Within the 48-hours observation window, no adverse effects were detected: the magnitudes and shapes of the profiles are consistent with classical thermal-strain predictions and with previously reported responses of energy piles in sands and clays. Notably, the behavior of driven, end-bearing piles in soft Norwegian quick clay does not differ from published results in other soil types, indicating that, when the piles are properly designed, the coupled thermal and mechanical actions remain within predictable, acceptable bounds for this sensitive ground condition.

#### 4 CONCLUSIONS

This study assessed the thermo-mechanical behavior of two segmental precast concrete driven energy piles installed in Norwegian quick clay under controlled heating/cooling, with a realistic 112-ton axial load applied to one of the piles. Strain and temperature were continuously monitored using distributed fiber optic sensors, supplemented by vibrating-wire gauges and PT100 RTDs, enabling cross-validation and separation of thermal and mechanical components. The piles exhibited negligible head displacement and no adverse structural or geotechnical effects; responses were consistent with thermoelastic expectations, supporting the safe use of driven precast energy piles as ground heat exchangers in sensitive and quick clay deposits. While results are promising, they reflect a single site and short observation window; hence, long-term seasonal cycling, group effects, varied load/thermal duties, and pore-pressure-consolidation evolution require future studies to inform design guidance.

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