The role of concrete creep under sustained loading, during thermo-
mechanical testing of energy piles

Bourne-Webb, P.J. †
peter.bourne-webb.co.uk@tecnico.ulisboa.pt
† CEris, ICIST, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal formerly
Cementation Skaska, Rickmansworth, United Kingdom

ABSTRACT

The energy pile test at Lambeth College London was first reported some 10 years ago, however this initial appraisal of the test only looked at the thermal response at the end of the first, cooling and heating stages. Since the results were published, some anomalies in the results have been identified. This article revisits the results of this test using a strain dependent pile modulus and allowing for concrete creep under sustained load. The result of this re-evaluation has been to substantially modify the interpreted pile response, especially near the pile head, which leads to a mitigation of the maximum pile head displacements in the cooling phase, and the maximum thermal stresses in the heating phase. Two other case studies have been examined to illustrate that creep is also likely to be a significant factor in the interpreted responses of each. It is highlighted however that while the quantitative interpretation of the tests may change, the underlying mechanisms of behaviour remain consistent with those described in the literature.

KEY WORDS

Energy geostructures, thermally-activated pile, load test, concrete creep
1. INTRODUCTION

In the past decade a number of studies examining the thermo-mechanical behaviour of energy piles have been published. These are a mix of field testing, model testing and numerical modelling. Bourne-Webb et al. (2019) and Bourne-Webb and Bodas Freitas (2018) provide a substantive review of the outcomes of these studies and synthesise the results to demonstrate the trends in responses in terms of maximum pile thermal stresses, $\sigma_{th,max}$ and pile head thermal movements, $\gamma_{th,0}$ which are considered to be parameters of most importance to designers. Broadly, speaking the thermally-induced interaction between piles and the soil is characterized by a balancing between movement and the alteration of internal stresses within the pile, i.e. if movement is restrained, internal stresses will increase, and vice versa.

Amis et al. (2008) and Bourne-Webb et al. (2009) presented results from a field test on an energy pile, carried out during the construction of the Clapham Centre of Lambeth College in South London. These provide a detailed overview of the test conditions and the thermo-mechanical response of the thermally-activated test pile carried out under maintained load. Amatya et al. (2012) extended this assessment further, incorporating the response of the heat sink pile and compared the responses to the case studies of Laloui et al (2006) and Brandl (2006). All of these assessments, except the heat sink pile, were made at the end of extended heating/cooling phases, while a load was maintained at the pile head.

Operational thermally-activated pile foundations such as that reported by Murphy & McCartney (2014) and McCartney & Murphy (2017) have a time-varying thermal loading throughout the year, while the building load remains essentially constant. McCartney & Murphy (2017) discuss what they describe as thermal “downdrag/uplift” which suggests some alteration of the pile deformation response when comparing the pile at the same temperature but differing times, Figure 1.

![Figure 1](image.png)

**Figure 1** – Alterations in interpreted “Pile A” axial response while pile is at about the same average temperature, McCartney & Murphy (2017)
Numerical back-analyses of the Lambeth College test such as that performed by Gawecka et al (2017), consistently reveal discrepancies between the observed behaviour and that predicted (Figure 2) which are especially noticeable at the end of the heating phase of the test where the numerical analysis predicts a substantially lower axial strain than that suggested by Bourne-Webb et al (2009). Elsewhere, the author is aware that others have had to use either unrealistic soil parameters in the superficial soils or introduce an unrealistic restraint, e.g. as evident in Ma et al (2014), to match the axial response. This discrepancy suggests that there is some aspect of the test interpretation or analysis, or both that is preventing good agreement.

![Figure 2 – Back-analysed pile axial thermal response at end of cooling and heating stages, Gawecka et al (2017)](image)

This article was prompted when further discrepancies were revealed when examining the transient data within each cooling and heating stage of the test. The resulting reinterpretation while addressing these, also helps to explain some of the reported discrepancies between the observed results and numerical back-analysis.

2. LAMBETH COLLEGE TEST PILE

2.1. Overview

The Lambeth College energy pile test was undertaken over a period of 2 months between 14 June and 14 August 2007 and involved a preliminary pile test to 1.5x the design working load of 1200 kN, thermal testing involving a period of cooling (Stage 1: 740 hours), heating (Stage 2: 290 hours) and cyclic heating and cooling (Stage 3), and a final load test to 3x the design working load. Full details of the test set-up and results focusing on the response at the end of the various heating/cooling stages can be found in Amis et al. (2008) and Bourne-Webb et al. (2009) but a brief summary follows.
The site for the test pile was located within the grounds of the Clapham Centre of Lambeth College on the south-east edge of Clapham Common in South London. The maintained load-cyclic thermal test was undertaken as part of the development of a new 5-storey sixth form studies building where a shallow geothermal energy system utilizing the 147 foundation piles as ground heat exchangers was employed to provide 302 kW heating and 460 kW cooling.

The test pile was representative of the working piles constructed to support the structure; it is 23 m long and has a nominal diameter of 600 mm and was designed for a working load of 1200 kN. Two heat exchange pipe loops were embedded in the pile. In addition, four anchor piles (same dimensions) for supporting the loading frame, and a 30 m long heat sink pile were installed.

The ground conditions are typical for London with superficial deposits comprising 1 to 1.5 m of Made Ground, and 3 to 4 m of River Terrace Deposits which overlie the London Clay Formation, which extends well below the toe level of the piles. Groundwater stands within the River Terrace Deposits about 1 m above the top of the London Clay, Figure 3.

The MTP and HSP were instrumented with a mix of either, conventional embedded vibrating wire strain gauges and thermistors, and/or optical fibre sensing cable. Six levels of the former were distributed along the length of the test pile, along with continuous OFS for strain and temperature sensing, Figure 3.

Throughout the thermal test, the pile mechanical loading was maintained at 1200 kN using an automated hydraulic loading system, Figure 3 and 4. The pile head was free to move and pile head movements were monitored throughout. During Stage 1, Figure 4, the pile was cooled with an inlet fluid temperature of about -6 °C and the average pile temperature fell by almost 20°C, to close to zero.

In Stage 2, the pile was heated with an inlet fluid temperature of +30°C to +40°C but the process was interrupted by a weekend power cut which is clearly visible in the data set. Daily cycles of cooling and heating followed in Stage 3, and Stage 4 represents the period after the heat pump was removed and temperatures in the pile recovered. In this reinterpretation of the Lambeth College test, only Stages 1 and 2 have been considered.
Figure 3 – Main test pile geometry, ground profile and instrumentation details, and schematic layout of test elements, Bourne-Webb et al. (2009)

Figure 4 – Main test pile load displacement response and average temperature change, at different levels within the pile
2.2. Data interpretation

2.2.1. Effective pile modulus

In order to develop a picture of the response of the pile to thermo-mechanical loading, it is necessary to convert the observed strain to axial stress/load in order to evaluate the load-transfer behaviour of the pile, and the effect the thermal loading has on this. Following Fellenius et al. (2000), the strain gauges in the upper section of the pile (1.5 m and 4.0 m depth) have been examined in order to derive an equivalent Young’s modulus for the pile. The concept behind this method is that the gauges closest to the pile head should be least affected by pile-soil resistance which will be quickly overcome as the pile is loaded.

Figure 5 illustrates the outcome of this interpretation; Figure 5(a) shows the interpreted data from mechanical loading at each stage of the test but based on the total measured strain. Figure 5(b) however shows the same information but after the residual strain at the start of each test has been zeroed out.

Figure 5 – Interpretation of pile effective tangent stiffness
In this assessment, it was apparent that one gauge at each level (SG2 and SG5) was reporting strains that were consistently higher than those in the accompanying gauges at each level. The cause for this is not known but the results were disregarded in the evaluation of the effective modulus and in subsequent averaging for the interpretation of the testing which is presented later.

Typically, as is seen in Figure 5, the effective stiffness tends to a consistent value as the load increases and overwhelms any local shaft resistance; in this case the effective tangent modulus seems to be reasonably represented by [2]:

\[ E_t = 46.5 + 0.14\varepsilon_a \text{ (GPa)} \]  

where \( \varepsilon_a \) is the measured axial strain in micro-strain (compression negative).

Following Fellenius et al. (2000), this leads to an expression for the effective secant modulus [3] which has been used to derive the pile axial load response presented subsequently.

\[ E_s = 46.5 + 0.07\varepsilon_a \text{ (GPa)} \]  

It should be noted that Bourne-Webb et al. (2009) used a constant value of 40 GPa for the effective modulus of the pile. However, the work of e.g. Fellenius, Lam & Jefferis (2011, 2012), Fellenius (2012) and Sahajda (2013) show that it is essential that the strain-dependent nonlinear behaviour of the pile be taken into account when interpreting load tests.

### 2.2.2. Pile residual load

The potential influence of residual load in the observed pile response was also re-assessed:

Figure 6(a) shows the strains recorded in the period between the pile’s construction and the preliminary pile test; in this period there are significant temperature changes as the concrete hydrates and the stiffness of the concrete is changing rapidly, so load interpretation is not possible. It can be seen however that the strains that developed were not large – for comparison, the weight of the pile, at the base of the pile along would be expected to generate strain of about \(-12\ \mu\varepsilon\) (compression). It was felt that the final distribution of strain apparent in the pile shaft was not likely to significantly influence the interpretation of the subsequent loading, and was zeroed out of the data analysis. The greatest effect is likely to be in the interpretation of the base response where the apparent residual load is tensile and of about the same magnitude as the compression mobilised at the pile base during the PTP.

Figure 6(b) compares the load profile determined from the strain profile obtained just before the PTP with the load profiles obtained at differing load levels during the PTP, and also the load profile
obtained after reloading to 1200 kN, just before the thermal test started. Also, shown are the profiles at the start and end of the main load stages in the PTP, this illustrates that the effect of creep was small during these 6 hour hold intervals which is to be expected, as the pile was far from geotechnical failure (factor of safety >2 at 1800 kN) and the concrete compression stresses were less than 20% of the 28 day compressive strength ($f_{ck} = 35$ MPa).

Referring back to the load profiles obtained during the PTP, it seems that significant residual loads are generated when the pile is unloaded. However, given that the load profile for the first loading to 1200 kN and the reload to 1200 kN just before the thermal test started, are essentially the same, it was felt that there was no need to include these apparent residual loads in the subsequent interpretation of the thermal test.

2.2.3. Concrete creep

When considering the ongoing response of the pile during the test, some of the strain gauge behaviour seemed inexplicable and appeared as a drift of the pile axial forces that was not associated with the temperature changes. One aspect not considered by Bourne-Webb et al (2009) and which
does not appear to have been considered by other authors examining pile thermal tests, is that due to the extended duration of the maintained load test, creep of the concrete pile can be expected, Lam & Jefferis (2011).

An assessment of creep under maintained load has been made using the methodology outlined in BS EN 1992-1-1:2004, Appendix A. This evaluation suggests that the recorded strains may contain a significant additional (compression) element of strain which is around 50 to 60 με near the head of the pile, at the end of the test. Figure 7 illustrates the creep correction applied to one of the gauges at 15.5 m depth and how this will lead to a significantly different interpretation of the pile response.

Figure 7 – Allowance for concrete creep under sustained load

Figure 8 illustrates how the use of the strain dependent pile modulus and the inclusion of concrete creep under sustained load, alter the interpretation of the thermally induced axial load in the test pile. This is most apparent for the measurements taken 1.5 m below the pile head where in the uncorrected state, the measurements suggest that a compression load is developing throughout Stage 1, Figure 8(a), while when creep is included the thermal load develops as a tensile load, consistent with the other measurement levels, throughout Stage 1, Figure 8(b). A similar effect is also apparent in the results from 4.0 m, 6.5 m and 9.5 m depth, rather than an apparent relaxation of the thermally-induced tension loads, with creep included, the thermal axial tension loads increase throughout Stage 1.
The estimated creep strain has also been integrated over the pile length to provide an approximate estimate of the additional pile head settlement that would have arisen from this source. Figure 9 illustrates this assessment and interestingly the assessed rate of concrete creep coincides with the pile head settlement rate towards the end of Stage 1 which is illustrated by the superposition of the “creep offset” curve onto the time-settlement curve from the test. This suggests that the ongoing settlements that were measured were not thermally induced. In fact, when the measured settlements are corrected for the creep settlement then towards the end of Stage 1, pile head movement had largely ceased, and show a similar rate of progression as the changes in temperature, Figure 9. In the subsequent stages of the test, the pile thermal loading was not stable long enough to see the same effect.

It is clear therefore that when evaluating the response of such tests, concrete creep under sustained load has a profound impact on the results and cannot be ignored.
2.2.4. Temperature effects

While the PTP may be considered to have been undertaken under essentially isothermal conditions, the remainder of the test programme was not. Neville (1995) discusses how the compressive strength and hence, the Young’s modulus for concrete, reduces with increasing temperature, even in the range of 0°C to 60°C which can be considered applicable to this application. Concrete creep is also affected by both temperature changes, increasing as temperature increases, and also in response to changes in rate of temperature change (a faster increase in temperature will provoke greater strain than a slower change). In addition, temperature gradients will cause water movement inside the concrete mass and could also lead to changes in water content both of which may lead to additional creep/shrinkage strains. These are complex processes however and there does not appear to be a straightforward way of including them in the present analysis.

Temperature has had to be taken account of in terms of the effect that it has on the observed strains however. In effect, as the temperature changes, due to the differing coefficient of thermal expansion (CTE) between the gauge and the surrounding concrete, differential thermal deformations will occur and will impact on the measured strains. This needs to be corrected using [4].

\[ \varepsilon_{corr} = \varepsilon_{meas} + \left( CTE_{gauge} - CTE_{pile} \right) \Delta T \]  

Bourne-Webb et al (2009) evaluated an effective CTE for the pile of 8.5 με/°C which was considered reasonable given that the concrete aggregates were limestone. The embedment gauges were supplied
by Gage Technique International Ltd, and the gauge CTE was indicated to be 11 με/°C. Thus, for
example, for every degree of temperature change the gauge would include in its output a differential
thermal strain of +2.5 με, as the gauge would contract/expand more than the surrounding concrete.
The measured strain has to be corrected using this differential strain to obtain the correct strain using
[5].

\[ \varepsilon_{corr} = \varepsilon_{meas} + 2.5\Delta T \] [5]

where the change in temperature \( \Delta T \) is negative for cooling and positive for heating, leading to
corrective strains which are compressive and tensile respectively. The effect of this temperature
correction is illustrated in Figure 7.

Finally, despite shading being employed to mitigate its effect, climatic temperature changes will
impact on the measurement of pile head displacement both in terms of thermal movement of the
loading frame and in the functioning of the displacement transducers. These effects have not been
de-coupled in this assessment, as this would have required on-site calibration that was not done at
the time, and are apparent as small spikes, at approximately daily intervals, in the displacement data
presented in Figure 9.

3. Discussion

3.1.1. Revised interpretation

This revised examination of the Lambeth college energy pile test led to the introduction of an
allowance for concrete creep under sustained load and a strain dependent modulus. Figure 10
illustrates the impact of the creep correction on the axial strains in comparison with the interpretation
presented by Bourne-Webb et al. (2009). The effect of the creep correction is most obvious in the
upper part of the pile where the maintained stresses are largest and shows that the thermal effect is
larger over a greater proportion of the pile body than previously suggested.

In Figure 11, the axial loads obtained with a strain-dependent modulus are compared to those
presented in Bourne-Webb et al. (2009), who used a constant modulus. It is immediately apparent
that the thermal load is more consistent. The greatest effect is seen in Stage 2 where the large peak
in axial compression at the end of heating, has been migrated in response to a lower pile modulus
(36 GPa compared with 40 GPa) and the inclusion of the creep correction which reduced the observed
axial strain by about 10%.
The benefit of this reinterpretation is further illustrated in Figure 1 where the axial thermal load changes within the first extended cooling and heating cycles are presented. Notwithstanding the problems that continue in the observations at 4 m depth, it is clear that the reinterpreted thermal axial forces are more consistent, tend to zero at the pile head, and show some alterations in the mobilisation of the pile base reaction. This was one of the main discrepancies in the results presented in Bourne-Webb et al (2009) and underlines the importance of this reinterpretation.
The peak visible in the results, at 4 m depth is considered likely to be due to either the use of too high a modulus value in the interpretation of the axial load response, or maybe the pile cross-section differs from that assumed in the assessment, or both. Examining the thermal strains presented in Figure 12, the profiles appear rather more consistent and the spike only occurs once the load has been evaluated. Due to this apparent over-estimation of the thermal stresses at 4 m depth, it is likely that maximum thermal load response during heating should have instead occurred between 6.5 m and 9.5 m depth.

![Figure 12 – Original and re-interpreted axial thermal strain and load profiles](image)

Figure 13 illustrates how the reinterpreted Lambeth College test results compare with the collated results presented in Bourne-Webb et al (2019). Here, the maximum thermal stress $\sigma_{th,max}$ and pile head movement, $y_{th,0}$ have been normalised by [6] and [7] respectively.

$$\sigma_{th, fixed} = \alpha_c \Delta T \cdot E_c \tag{[6]}$$

$$y_{th, free} = \alpha_c \Delta T \cdot L \tag{[7]}$$

where $\alpha_c$ is the effective linear coefficient of thermal expansion of the pile, $\Delta T$ the average change in temperature, $E_c$ the pile modulus and $L$ the initial pile length.

In Figure 13, C1 represents the reinterpreted normalised stress-displacement response at the end of the first extended cooling stage, H1 the end of the first extended heating stage. The arrows indicate how the original interpretation has been modified with a reduction of the pile head movement (after...
correction for creep strain) at the end of cooling and a slight reduction of the maximum thermal stress at the end of heating (due to the strain-dependent pile modulus). In the latter case, the creep correction is not as apparent as it was for the end of cooling, as the results are from incremental changes within the thermal loading stage, which during heating was 288 hours long compared to 740 hours during the cooling stage, and when the rate of accumulation of creep strain would have been less.

Figure 13 – Incremental axial thermal load profiles

3.1.2. Implications for other tests

A number of other maintained load, pile thermal tests have been reported in the literature including Laloui et al (2003), Murphy & McCartney (2014) and McCartney & Murphy (2017), amongst others. Depending on the mechanical loading intensity and chronology, it is clear that each of these tests will have been affected by concrete creep, and they should be revisited. To illustrate, the above cases have been examined. It should be noted however that the creep evaluation is only approximate as the details needed to make a more precise estimate are not present in the respective articles:

Laloui et al (2003) present the results of a field trial for a thermally-activated pile which was heated at differing stages of the construction of a new building on the campus at EPFL, Lausanne. From the information gleaned from Laloui et al (2003), it is possible to make an estimate of the concrete creep under sustained load due to the incremental loading at each stage of construction, and the chronology of the tests that were carried out, Figure 14.
The creep strains clearly have the most effect near the head of the pile where the load intensity is highest. In Figure 15, the results for the strains at 2.5 m depth reported by Laloui et al (2003) are compared to the estimate of concrete creep strains at this level. It is apparent that the potential creep strains are similar to those reported, and if the observations were corrected for concrete creep, the trend of increasingly compressive strain with time, between tests would more-or-less be eliminated, in a similar way to that seen in the uppermost strain gauge set in the Lambeth College test, Figure 8.
Murphy & McCartney (2014) and McCartney & Murphy (2017) present the results of an operational thermally-activated pile system in Denver, Colorado whose response was observed over a period of about five years. Once again, it was possible to make an estimate of the concrete creep under sustained load and Figure 16 illustrates this assessment – note that the creep lines are offset to allow ready comparison of the trends through the data from McCartney & Murphy (2017).

The estimated concrete creep strains in the upper part of the pile (1.1 and 5.3 m depth) show a similar trend to those observed which suggests the apparent drift in strain measurement over time is not solely a thermal effect. At deeper levels, while concrete creep may explain some of the drift, there is a clearer effect of increasing compression with time which may be a thermal effect, and perhaps explained by a differential thermal response between the ground and the pile, as discussed by McCartney & Murphy (2017).

These two cases, in addition to the reinterpreted Lambeth College case, illustrate that over long periods of sustained loading, concrete creep is significant and will alter the interpreted axial strain profiles significantly in zones where the maintained load is high. For the two cases above, it is not possible to reinterpret the axial load response as there is not sufficient information to derive a strain-dependent modulus relationship.
CONCLUSIONS

This article has revisited the Lambeth College, London thermal pile test undertaken during the Summer of 2007 and has presented a revised interpretation of the pile response to cooling and then heating. In this re-evaluation, the importance of allowing for concrete creep under sustained load and using a strain-dependent pile modulus has been highlighted.

This was further underlined by making an estimate of potential concrete creep and applying this to two other case studies involving the thermo-mechanical loading of a pile foundation. Existing studies should be re-evaluated to consider these effects and in future field testing of thermally-activated reinforced concrete foundations, interpretation should allow for both concrete creep and a strain-dependent pile modulus.

It is also recommended that during field tests that measures are taken to allow the decoupling of temperature effects in external displacement measurements by monitoring the reaction frame and e.g. by having a dummy displacement transducer to measure temperature induced dimension changes in the sensor.
Returning to the impact of this re-interpretation on the outcome of the Lambeth College test and subsequent discussions of the interaction between thermally-activated piles and the ground in e.g. Bourne-Webb et al (2009), Bourne-Webb et al (2013) and Bourne-Webb et al (2019); while the magnitude and distribution of thermal effects within the pile have clearly altered:

- The underlying interactions remain unchanged: during cooling the pile contracts, pile head settlement increases (though not as much as previously suggested) and the maximum thermal load (neutral point) is located in the lower half of the pile, and during heating the pile expands, pile head settlement reduces and the location of the maximum thermal load rises into the upper half of the pile shaft (though not as far as suggested previously).
- Further, Figure 14 highlights that the key measures of maximum thermal stress and pile head thermal movement have undergone only modest changes with this re-interpretation of the test.

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Appendix 1. Concrete Creep

Based on BS EN 1992-1-1:2004, concrete creep strain, $\varepsilon_{cc}$, may be evaluated based on the following empirical formulation:

$$\varepsilon_{cc}(t, t_0) = \varphi(t, t_0) \left( \frac{\sigma_c}{E_c} \right)$$

$$\varphi(t, t_0) = \varphi_0 \cdot \beta_c(t, t_0)$$

$$\varphi_0 = \varphi_{RH} \cdot \beta(f_{cm}) \cdot \beta(t_0)$$

$$\varphi_{RH} = 1 + \frac{(1 - RH/100)}{0.137^{h_0}} \quad \text{for } f_{cm} \leq 35 \text{MPa}$$

$$\beta(f_{cm}) = \frac{16.8}{\sqrt{f_{cm}}}$$

$$\beta(t_0) = \frac{1}{0.1 + t_0^{0.2}}$$

$$\beta_c(t, t_0) = \left[ \frac{(t - t_0)}{(\beta_H + t - t_0)} \right]^{0.3}$$

$$\beta_H = 1.5[1 + (0.012RH)^{18}]h_0 + 250 \leq 1500$$

where,

- $f_{cm} =$ Mean value of concrete cylinder compressive strength (about 35 MPa);
- $t_0 =$ the age of the concrete at the time of loading (24 days);
- $t =$ time being considered (days);
- $\sigma_c =$ compressive stress in the concrete which was estimated at each level within the pile based on the interpreted load transfer response;
- $E_c =$ tangent modulus of elasticity of normal weight concrete (35.7 GPa);
- $RH =$ relative humidity (buried concrete, assumed 100%);
- $h_0 =$ notional size of member
- $= 2A_c/u = D/2$ (c. 300 mm);
- $A_c =$ cross-sectional area of member;
Applying the above formulation the creep strain development across the thermal test period was estimated, Figure A.1. This suggests that in the upper part of the pile in particular, the additional strain due to creep under sustained loading of the pile is significant and would lead to the compression in the pile being over-estimated by a few hundred kilo-Newton.

Figure A.1 – Development of creep strain at strain gauge locations along pile shaft, during Lambeth College test