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Residual load development in cast-in-situ piles – a review and new case history

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ABSTRACT: The development of residual (or locked-in) loads in driven pre-formed piles has been investigated extensively over the past 40 years or so. In contrast, cast-in-situ piles are often erroneously assumed to be free of residual loads. This paper aims to review the limited number of published studies into the processes which lead to the development of residual loads in bored, augered and driven cast-in-situ piles during curing. Unlike precast piles, concrete for cast-in-situ piles must be given sufficient time to cure and develop strength in the ground prior to loading. The interaction between the concrete and surrounding soil is complex and there are a number of processes which influence the strains within the pile during this period. By continuously monitoring strain and temperature development between casting and static load testing, these processes can be identified as initial concrete set, hydration/curing and soil disturbance and consolidation effects in the vicinity of the pile. A limited database of reported studies which monitor such processes is presented, together with the proposed methods for deducing the level of residual load from strains present at the time of testing. Finally, a new case study with strain and temperature measurements within a driven cast-in-situ pile is presented.

1 INTRODUCTION

The load developed in a pile between its installation and a subsequent load test is often referred to as ‘residual load’, and there are a number of sources of residual loads depending on the pile type and installation process. For pre-formed piles (i.e. precast concrete piles and steel piles), the dominant cause of residual load is the reversal of shaft resistance along the pile as it attempts to rebound after hammer impact during driving. A large number of studies have examined this particular phenomenon and several methods for estimating the quantity of residual load present have been developed, e.g. Briaud and Tucker (1984), Poulos (1987) and Fellenius (2002). Unfortunately, an exclusive association has developed between residual load and driven piles in industry among those who do not appreciate that there are other sources of residual load; some of these sources are relevant to cast-in-place piles.

Cast-in-situ piles must cure in the ground (unlike pre-formed piles) and therefore will undergo changes in volume as the concrete sets and cures. In addition, the installation of a pile, regardless of type, will result in disturbance to the surrounding soil (from either lateral or vertical soil movements) and the generation of excess pore pressures in cohesive soils which will induce downdrag on the pile as they dissipate (Fellenius 2002). Therefore, the assumption of a load-free pile as the initial condition at the time of a load test is questionable.

A limited number of studies have been conducted in recent years into the processes which occur within the concrete and soil after installation of a cast-in-situ pile to gain a better understanding of the development of residual loads. The level of detail of these studies varies from basic two-point concrete strain measurements (i.e. immediately post-installation and just before the load test) to more detailed monitoring of strain and temperature over part or all of this period. This paper aims to review these studies which pertain to different cast-in-situ pile types in a systematic way, along with current methods of interpreting residual load present in a pile prior to conducting a load test from measured strains. Finally, a new case study is presented of a driven cast-in-situ (DCIS) pile in mixed ground conditions in which strain and temperature behaviour were continuously monitored during curing. These pile types are particularly interesting as contributions to residual load can potentially arise from both driving and casting phases.

2 PROCESSES LEADING TO RESIDUAL LOAD DEVELOPMENT

Despite the assumption that cast-in-situ piles are not prone to residual load effects, a limited number of studies have investigated the strain and temperature behaviour within such piles. A summary of the scope of these tests is provided in Table 1, which includes details of pile type, pile dimensions, and duration of curing, as well as highlighting the various processes for which measurements were made within the concrete and soil. This section aims to describe each process in terms of strain and temperature (where relevant) as these can be measured with relative ease using instrumentation incorporated in the pile prior to casting (reference can be made to Table 1 throughout).

The most popular type of instrumentation for measuring strain within cast-in-situ piles are vibrating wire strain gauges due to their ease of installation and long-term reliability (Hayes and Simmonds 2002), and these were used by the majority of the studies reviewed in this paper. The gauges measure *total* strains which comprise of mechanical strains in the pile and thermal strains due to temperature variations. As the variation in temperature during initial set and hydration can be large, a number of studies have applied a temperature correction to the measured total strains in order to eliminate any thermal-related effects (these studies are highlighted in Table 1 under the 'thermal strains' column). Depending on the choice of coefficient of thermal expansion (CTE), the derived thermal strains can be significantly large. As a consequence of this, the correction for temperature effects can result in a complete reversal in strain behaviour (i.e. changing from total tensile strain to a compressive mechanical strain, and vice versa). This has led to contrasting early-age strain behaviour profiles in the literature, as several studies report total (i.e. uncorrected) strain profiles while others present temperature-corrected mechanical profiles.

2.1 Initial concrete set and hydration

Once a cast-in-situ pile is constructed, the mixture of the cement binder and water results in an exothermic chemical reaction. The level of heat generated during hydration varies with the properties of the binder, the pile width/diameter, the ambient temperature of the mix during casting and the ambient temperature of the soil in which the concrete is cast. As the reaction takes place, the hydration temperatures will continue to rise for several hours after casting, and the concrete will begin to harden or 'set' during this period. Initial set is assumed to be complete at peak temperature (Neville and Brooks 1987).

Peak pile temperatures during initial set and hydration were reported by Pennington (1995), Walter et al. (1997), Fellenius et al. (2009) and Kim et al. (2011). The highest temperatures were observed by Fellenius et al. (2009) in two 600 mm diameter precast post-grouted cylindrical piles with peaks in the region of 85 ^{o}C while Pennington (1995) reported temperatures of up to 75 ^{o}C in 1.5 m diameter bored piles in Bangkok. The magnitude of peak temperature will inevitably depend on the concrete (or grout) mix. The authors have extracted data from the literature to produce Figure 1 which shows that the duration of initial set (i.e. the time required to reach peak temperature) is a near-linear function of pile diameter (over a wide range of pile diameters). As hydration temperatures were not reported in the studies by Farrell and Lawler (2008) and Siegel and McGillivray (2009), the duration between casting and peak temperature has been assumed to correspond to the peak strain during this period in Figure 1. Also included are temperature data from a new case study of a driven cast-in-situ (DCIS) pile at Dagenham, UK (presented later in this paper), as well as unpublished data from another DCIS pile at Shotton, UK. This figure serves as a useful means of estimating the duration of initial set for cast-in-place piles.

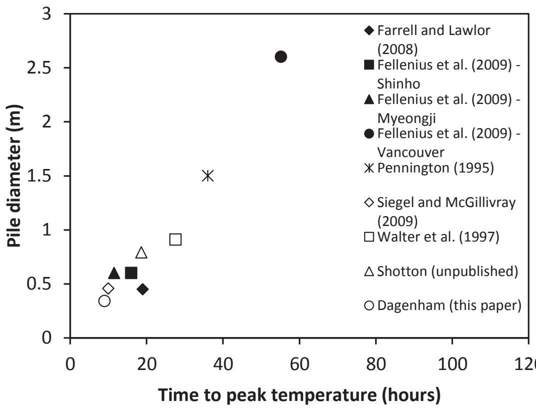

Figure 1. Variation in time to peak temperature with pile diameter.

Studies in which total strains during initial set were reported, and were uncorrected for effects of temperature, include Pennington (1995), Siegel and McGillivray (2009), Fellenius et al. (2009) and Lam and Jefferis (2011). All of these studies measured compressive total strains as the hydration temperatures increased. On closer examination of the strain and temperature profiles in a driven precast post-grouted cylindrical pile by Fellenius et al. (2009), the largest compressive strains (≈ 150 με) developed at sections of the pile where the hydration temperatures were greatest. Fellenius et al. (2009)

concluded that the compressive strains were a result of the steel vibrating wire strain gauges attempting to elongate at a faster rate than the surrounding concrete, due to the difference in coefficient of thermal expansion (CTE) of the two materials (i.e. a net value of ≈ 2.2 με/°C according to Fellenius et al. 2009). Siegel and McGillivray (2009) observed a peak compressive strain of 100 με in a 457 mm diameter auger cast-in-place (ACIP) pile approximately 10 hours after casting. Unfortunately, hydration temperatures were not reported and thus the relationship between compressive strains and temperature was unknown.

The level of thermal strain $\varepsilon_{thermal}$ present in a pile at a particular instance after casting can be determined using Equation 1 (Pennington 1995), where α is the CTE of the material in question, ΔT is the difference in temperature, T_0 is the temperature at time of casting and T_1 is the current temperature.

$$\varepsilon_{thermal} = \alpha \Delta T = \alpha (T_1 - T_0) \quad (1)$$

Despite the simplicity of Equation 1, inconsistency exists in the literature regarding the choice of the CTE value for correction. As vibrating wire strain gauges are traditionally composed of a steel wire enclosed in steel casing, the CTE value of the gauge is assumed to be between 10 με/°C and 12 με/°C (based on steel). Pennington (1995) and Farrell and Lawler (2008) presented strain profiles during initial set and hydration which were corrected for thermal strains. The study by Pennington (1995) calculated thermal strains using Equation 1, based on a CTE value of 10.8 με/°C. To obtain the 'mechanical' strain in the pile during this period, the derived thermal strains from Equation 1 were subtracted from the compressive total strains, resulting in a tensile strain response at peak temperature. A CTE value of 10.8 με/°C was also used by Farrell and Lawler (2008) to correct strains during initial set. However, the peak tensile strains were considerably less in comparison to those observed by Pennington (1995). Fellenius et al. (2009) back-calculated a net CTE value of 1.7 με/°C from strain and temperature data from concrete scale pile specimens, which is broadly in agreement with the theoretical difference in CTE values of concrete and steel of 2.2 με/°C.

The influence of the correction for thermal strains on the strain profile during initial set and hydration is significant. If uncorrected, the strain response is compressive. However, the studies in which the correction was applied show a tensile mechanical response. Unfortunately, the dearth of detailed studies on these factors for cast-in-situ piles prevents any comprehensive conclusions to be made regarding the most appropriate CTE value to use.

2.2 Cooling and strength development (curing)

After hydration temperatures have peaked, the pile will begin to cool and develop further strength. This is characterised by a gradual reduction in temperature with time and a change in volume (and hence strain) within the pile due to either shrinkage or swelling effects. The duration for full decay of hydration temperatures after casting were in the region of 8-10 days for the studies by Fellenius et al. (2009) and Pennington et al. (1995). However, Fellenius et al. (2009) also reported the temperature profile within a 2.6 m diameter bored pile in Vancouver, Canada where a period of 30 days was required for pile temperatures to stabilise. The authors have compiled published data to show that the time taken for pile temperatures to reduce from peak temperature T_{max} to $0.5(T_{max}\text{-}T_0)$ is once again a function of pile diameter as shown in Figure 2. An attempt to correlate the time between T_{max} and $0.1(T_{max}\text{-}T_0)$ was not as fruitful, as measurements were not always carried through to the latter temperature, and small discrepancies between T_0 measured before casting and after curing were influential. Hydration temperatures will have a prolonged effect on the strain profile (in terms of thermal strains) of large diameter piles during curing. Figures 1 and 2 combined serve as a useful means of estimating the time to the end of curing, with a view to isolating the effect of other possible residual load processes, such as dragload.

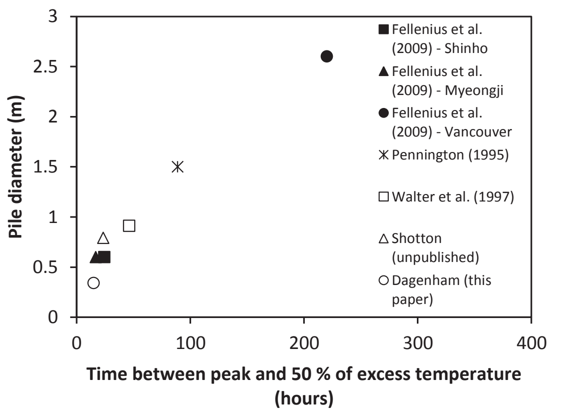

Figure 2. Variation in time between peak and 50 % of excess temperature with pile diameter.

As the pile cools, it will continue to absorb moisture for hydration. The process of promoting concrete hydration is referred to as curing (Neville and Brooks 1987). For conventional concrete structures, curing takes place within steel or plywood formwork under carefully controlled conditions, with moisture provided by spraying or steam. However, for cast-in-situ piles, the surrounding soil must act as formwork and moisture is free to migrate across the soil-pile interface. If the pile is constructed in saturated soil, a continuous supply of moisture will be available for hydration which may cause the pile to elongate or swell. Pennington (1995), Kim et al. (2004), Siegel and McGillivray (2009), Fellenius et al. (2009) and Lam and Jefferis (2011) reported tensile total strains after hydration temperatures had stabilised. The magnitudes of elongation varied from study to study, although Fellenius et al. (2009) observed tensile strains as large as 320 με. In order to confirm whether the swelling was related to moisture absorption, Fellenius et al. (2009) conducted a comprehensive laboratory study on 2.0 m long concrete pile specimens which were initially cast and cured in a dry environment for 154 days. The strain response during this period was generally compressive, although relaxation of the pieces was observed for about 4 days after peak hydration temperature. After 154 days, the pieces were placed in water which resulted in a significant tensile strain response as the concrete began to swell. Thus, a tensile strain response in piles during curing may be a consequence of swelling due to moisture absorption. Another possible source of tensile strains is internal restraint in the concrete due to drying shrinkage (Hayes and Simmonds 2002).

While the uncorrected total strain profiles in the literature show a trend of tensile strain development during curing, the temperature-corrected strain behaviour during this period is less clearcut. The correction for thermal effects results in strain profiles which may be either tensile or compressive, depending on the magnitude of the thermal strain derived using Equation 1. For example, Pennington (1995) presents the corrected strain profile during curing where, despite the elimination of thermal effects, the test pile remained in a tensile state. In contrast, the temperature-corrected strain profile within an continuous flight auger (CFA) pile in glacial till by Farrell and Lawler (2008) revealed a compressive state (≈ 100 με) approximately 3 days after casting, although temperatures were most likely still reducing and further reductions in compressive strain may have occurred had the pile not been tested so soon after installation. Walter et al. (1997) also reported net compressive strains in a drilled shaft after cooling. As hydration temperatures diminish with time during curing however, the temperature differential (ΔT) component in Equation 1 reduces. Therefore, the thermal strain correction during the latter stages of curing will tend to zero.

2.3 Pile installation and soil consolidation effects

The installation of a pile results in disturbance to the surrounding soil, irrespective of pile type (Fellenius 2002), although this category is most relevant to displacement pile types. Preformed piles may develop residual loads due to elastic rebound during driving (as mentioned previously).

In addition, the generation of excess pore pressures during pile construction in cohesive deposits may lead to consolidation of the soil and the resulting settlement will induce compressive loads in the pile over time (due to negative skin friction). Such behaviour will occur independently of and in parallel with the processes within the concrete as described in Section 2. The development of such loads is characterised by an increase in compressive strain with time at various sections of the pile. To highlight the long-term increase in residual loads due to consolidation settlement, Siegel and McGillivray (2009) continued to monitor the total strain behaviour within an ACIP pile in clay after the internal concrete processes has ceased. Approximately 200 hours after casting, the gauges in the lower half of the pile began to show a trend of increasing compressive strains in the pile due to the development of residual load as the clay layer began to settle. Similar findings were reported by Fellenius et al. (2009) in precast post-grouted concrete cylinder piles in soft marine clay after concrete-related effects had diminished. For both studies, the strains near the head of the pile remained relatively constant during this period, indicating the absence of residual load at this location as might be expected.

2.4 Summary

Based on the reported literature, the concrete-related processes appear to have a dominant effect on both strain and temperature profiles in the pile in the early stages after casting, while long-term strain changes are due to swelling as the pile absorbs moisture and compressive loads due to consolidation settlement (which occurs independently of and in parallel with the internal processes in the concrete). The review also highlights inconsistencies in reported strain profiles during initial set and hydration, as well as curing, mainly arising from whether a correction for thermal strains was applied, as well as the choice of CTE value for the correction.

3 RESIDUAL LOAD INTERPRETATION METHODS

The review of the literature in Section 2 highlights the contribution of concrete curing and soil consolidation to the development of residual load in cast-in-situ piles. Given the observed strain profiles, three methods for interpreting the level of residual load present in a cast-in-situ pile have been proposed. This section aims to describe each interpretation method in detail.

3.1 *Simplified method*

A simplified method of interpretation, described by Kim et al. (2004), assumes that the absolute change in total strain during the period between casting and conducting a load test is entirely due to residual loads. This method is convenient as strain readings are only required immediately after casting and prior to conducting a load test. However, the variation in strain and temperature during this period remains unknown. Furthermore, several papers have reported significant tensile strains in existence after the effects of hydration had diminished (as described in Section 2.2) which would result in unrealistically large tensile loads throughout the pile. Thus, this method is deemed to be the least accurate for determining residual loads in cast-in-situ piles.

3.2 *Continuous measurement methods*

The downfall of the simplified method lies in its inability to separate the change in strain between casting and load testing into the various processes described in Section 2. To overcome this, continuous or frequent measurements of strain and temperature can be obtained using a data-logger, enabling an accurate profile of strain and temperature variation in the pile during curing to be known. Two methods of interpretation of residual loads based on frequent measurements of strain and temperature have been proposed, with the main difference between the methods relating to the times at which residual load is assumed to develop.

3.2.1 *Pennington (1995)*

Pennington (1995) proposed calculating the change in strain between peak temperature and load testing to represent the residual load in a cast-in-situ pile, on the basis that the pile is in a stress-free state at peak temperature. The temperature-corrected strain profile was used for the interpretation, resulting in a change in strain which was compressive at each gauge level.

3.2.2 *Siegel and McGillivray (2009)*

The alternative interpretation method for residual loads using continuous strain measurements was recommended by Siegel and McGillivray (2009) and Kim et al. (2011). The correction procedure is based on the assumption that residual loads are negligible at or near the head of the pile. By placing a set of strain gauges at this level, a strain profile which is independent of residual load can be obtained. This profile can then be compared to the profiles at the remaining sections of the pile. The instance at which a strain profile at a particular section begins to deviate from the top gauge level is deemed to be the time at which residual loads begin to develop, and the change in strain at each gauge level after this instance represents the strain due to residual load.

4 CASE STUDY – RESIDUAL LOAD DEVELOPMENT IN A DRIVEN CAST-IN-SITU PILE

In light of the limited database of studies of residual load in cast-in-situ piles, the strain and temperature profiles within an instrumented driven cast-in-situ (DCIS) pile in mixed ground conditions were monitored continuously for a 14 day period after casting in order to assess the level of residual load which developed. The influence of thermal-strain correction was investigated, as well as the residual load interpretation methods described in Section 3.

4.1 *DCIS test pile details*

The test site was located at Dagenham, UK, where the ground conditions consisted of a 3 m layer of compacted fill overlying 4.2 m of alluvial silty clay and peat, which in turn was underlain by dense gravelly sand. The phreatic surface was located approximately 3 m below ground level.

The DCIS pile used in this study is constructed by top-driving a steel hollow steel tube with a sacrificial driving shoe at the base. The shoe has a slightly larger diameter in comparison to the tube in order to create an annular space, thus minimising shaft resistance during driving. When the required depth of penetration is reached, concrete is cast in the tube by either pumping or skipping, followed by tube removal. The reinforcement is normally inserted into the tube prior to concreting. However, in order to protect the strain gauge instrumentation from any damage, the reinforcement for the test pile was inserted into the concrete after the tube was removed.

The test pile was 7.7 m in length, with a nominal diameter of 340 mm. A total of 16 no. vibrating-wire strain gauges with temperature measurement capability were used, with four gauges installed at four separate levels (1.3 m, 3.5 m, 6.5 m and 7.5 m below ground level) for the purposes of accounting for potential bending and for redundancy. A data-logger was connected to the gauges after construction and was programmed to record strain and temperature in the pile at 15 minute intervals for the first 2 days after casting, followed by hourly intervals for the remaining 12 days. The test pile was subjected to a static load test after this period, the details of which will be reported in a future paper.

4.2 *Temperature response*

The variation in temperature in the test pile during the 14 day curing period is shown in Figure 3. The hydration temperatures took approximately 9 hours to peak after casting (consistent with the data in Figure 1 into which it has been incorporated). The largest peak temperature was measured near the pile head (37 ^{o}C). A reduction in peak temperature with depth was also observed, resulting in a temperature difference of approximately 8 °C between the pile head and base, most likely due to variations in ground temperature. The hydration temperatures reduced gradually thereafter and had stabilised approximately 200 hours after casting.

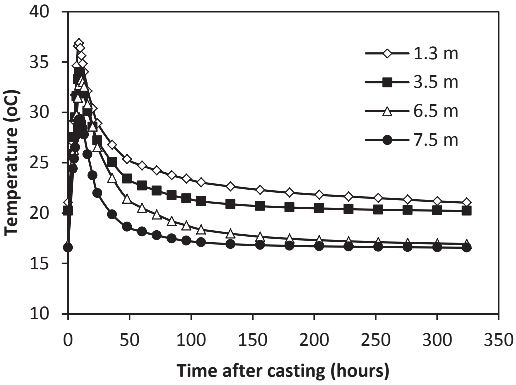

Figure 3. Variation in temperature after casting.

4.3 *Strain response*

The variation in total (i.e. uncorrected) strain after casting is shown in Figure 4 (note that compressive strains have been designated as positive). During initial hydration, the total strain response was compressive throughout the pile, in agreement with the studies by Fellenius et al. (2009) and Siegel and McGillivray (2009). A maximum compressive total strain of 120 με was observed near the base of the pile (6.5 m). In contrast with the findings by Fellenius et al. (2009), the lowest peak compressive strain was measured at the head of the pile, despite having the largest peak hydration temperature.

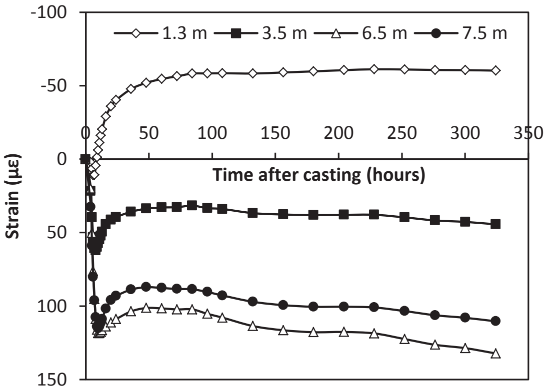

Figure 4. Variation in total (uncorrected) strain after casting.

As the temperatures reduced and began to stabilise during the curing phase, the compressive strains reduced at all gauge levels, in line with the observations in other cast-in-place pile types by Pennington (1995), Siegel and McGillivray (2009) and Fellenius et al. (2009). The largest reduction occurred near the head of the pile, resulting in a tensile strain of 60 με which remained relatively constant for the remainder of the curing period. The reduction in compressive strain at the other gauge locations was considerably less, with strains stabilising in a compressive state of between 30 με and 100 με approximately 60 hours after casting. However, with the exception of the strain near the head (which remained steady as mentioned previously), compressive strains began to develop in the pile once again after 80 hours and continued to increase for the remainder of the measurement period. Such strains are a consequence of residual load due to the internal processes in the concrete and external processes in the soil (as described in Section 2).

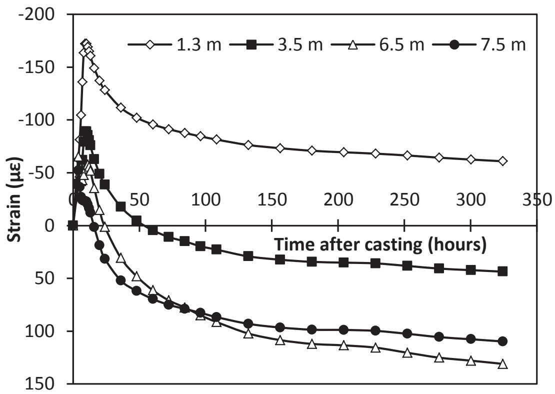

Figure 5. Variation in temperature-corrected strain after casting.

Thermal strains were calculated using Equation 1 with a CTE value of 10.8 με/°C (based on Pennington 1995) and the total strain profile was corrected accordingly. The correction resulted in tensile strains as large as 175 με at peak temperature, followed by the development of compression strains at each level during curing (Figure 5). Similar to the observed total strain behaviour in Figure 4, the compressive strains appeared to stabilise temporarily between 150 to 225 hours after casting, before increasing again at a reduced rate for the remainder of the monitoring period. The effect of thermal strains was negligible after 150 hours, resulting in a corrected strain response which was almost identical to the total strain response in Figure 4.

4.4 *Comparison of residual load interpretation methods*

The three interpretation methods for residual loads (Section 3) were applied to the measured strain data. The uppermost strain gauge level was deliberately placed as close as possible to the head of the pile (1.3 m) to enable an assessment of the method by Siegel and McGillivray (2009). An elastic pile modulus E_p of 31 GPa was derived using the tangent modulus method by Fellenius (2001) based on the strains measured during the subsequent load test.

As the methods by Kim et al. (2004) and Siegel and McGillivray (2009) were based on uncorrected total strain profiles, the distributions of residual load with depth for these methods were calculated using the total strain profile in Figure 4, while the temperature-corrected strain profile in Figure 5 was used for Pennington's (1995) method. A comparison of the derived residual load distributions approximately 14 days after casting is shown in Figure 6.

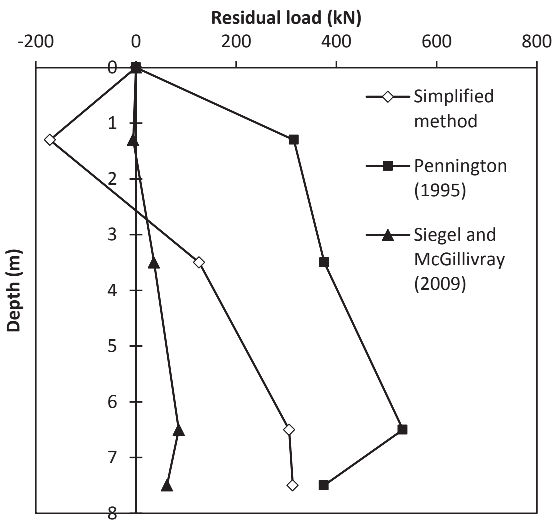

Figure 6. Comparison of derived residual loads using interpretation methods.

From Figure 6, it is clear that the three interpretation methods give contrasting distributions of residual load based on the data measured from the DCIS test pile. The simplified method by Kim et al. (2004) was deemed to be the least accurate as the tensile load of 171 kN at 1.3 m could have resulted in cracking of the concrete, while the compressive loads calculated using Pennington's (1995) method appear excessive (> 400 kN). For both methods, the addition of the residual loads to the load measurements during the subsequent static load test yielded distributions of increasing load with depth at failure which seem highly unrealistic. The method by Siegel and McGillivray (2009) appears to give the most realistic results, as the derived residual load distribution is similar to the dragload which was anticipated to develop due to the influence of external processes in the silty clay and peat (i.e. negative skin friction due to consolidation). Furthermore, this method resulted in a 'true' load distribution at failure which reduced with depth, as expected.

5 CONCLUSIONS

A review of literature on the contribution of internal processes within the concrete and external processes such as soil consolidation to the development of residual load in cast-in-situ piles was presented and the following conclusions were made:

a) The processes which occur within the concrete and soil after casting can be identified as initial set and hydration, curing, and installation/consolidation effects.
b) The time required to reach peak hydration temperature is a near-linear function of pile diameter.
c) The strain profiles in the literature during initial set and hydration are conflicting due to the application of thermal strain corrections to the raw data. The choice of coefficient of thermal expansion is also lacking consensus.
d) Several studies showed a tensile strain response during curing which may be attributed to swelling of the concrete as additional moisture is absorbed from the surrounding saturated soil.
e) There are three methods for interpreting the quantity of residual load present in a cast-in-situ pile based on measurement of strain and temperature during curing. Two of these methods require use of a data-logger in order to obtain continuous or frequent measurements.
f) A new case study of strain and temperature behaviour within a driven cast-in-situ pile in mixed ground conditions showed contrasting residual load distributions derived from the three interpretation methods. However, the method by Siegel and McGillivray (2009) appears to give the most realistic residual loads.

The database of studies of residual loads in cast-in-situ piles remains rather limited. However, it is envisaged that the conclusions of this review will highlight the need to consider residual loads in cast-in-situ piles in future studies.

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REFERENCES

Briaud JL, Tucker L (1984) Piles in sand: a method including residual stresses. Journal of Geotechnical and Geoenvironmental Engineering 110 (11):1666-1680

Farrell E, Lawler M (2008) CFA pile behaviour in very stiff lodgement till. Proceedings of the Institution of Civil Engineers Geotechnical Engineering 161 (1):49-57

Fellenius B (2001) From strain measurements to load in an instrumented pile. Geotechnical News Magazine 19 (1):35-38

Fellenius B (2002) Determining the resistance distribution in piles - part 2: method for determining the residual load. Geotechnical News Magazine 20 (3):25-29

Fellenius B, Kim S, Chung S (2009) Long-term monitoring of strain in instrumented piles. Journal of Geotechnical and Geoenvironmental Engineering 135 (11):1583-1595

Hayes J, Simmonds, T (2002) Interpreting strain measurements from load tests in bored piles. *In:* Proceedings of the 9th international conference on piling and deep foundations, Nice, France.

Kim M, Cavusoglu E, O'Neill M, Roberts T, Yin S (2004) Residual load development in ACIP piles in a bridge foundation. *In:* GeoSupport 2004 - GSP No. 124.

Kim S, Chung S, Fellenius B (2011) Distribution of residual load and true shaft resistance for a driven instrumented test pile. Canadian Geotechnical Journal 48 (4):583-598

Lam C, Jefferis S (2011) Critical assessment of pile modulus determination methods. Canadian Geotechnical Journal 48 (10):1433-1448

Neville A, Brooks J (1987) Concrete technology. Longman Group, Harlow, UK

Pennington D (1995) Cracked? Exploring post-construction evidence in the interpretation of trial pile data. Proceedings of the Institution of Civil Engineers Geotechnical Engineering 113 (3):132-143

Poulos HG (1987) Analysis of residual stress effects in piles. Journal of Geotechnical Engineering 113 (3):216-229

Siegel T, McGillivray A (2009) Interpreted residual load in an augered cast-in-place pile. *In:* Proceedings of the Deep Foundations Institute 34th annual conference on deep foundations, Kansas City, MO.

Vipulanandan C, Guvener O, McClelland M (2007) Monitoring the installation and curing of a large diameter ACIP pile in very dense sand. *In*: Contemporary Issues in Deep Foundations (GSP 158) ASCE, pp 1-10

Walter, D, Burwash, W, Montgomery, R (1997) Design of large-diameter drilled shafts for the Northumberland Strait bridge project. Canadian Geotechnical Journal 34: 580-587

Table 1. Summary of published data on strain behaviour in cast-in-situ piles during curing.

Reference	Location	Pile type	Length (m)	Diameter (m)	Initial set	Curing strains	Thermal strains	Curing period (days)
Pennington (1995)	Bangkok, Thailand	Bored cast-in-situ	36, 51	1.5	✓	✓	✓	> 28
Walter et al. (1997)	Bayfield, Canada	Drilled shaft	22	0.91	✓	✓	✓	10
Kim et al. (2004)	Texas, USA	Auger cast-in-place	19	0.46		✓		18
Vipulanandan et al. (2007)	Texas, USA	Auger cast-in-place	10	0.76	✓	✓	✓	7
Farrell and Lawler (2008)	Dublin, Ireland	Continuous flight auger	12.3	0.45	✓	✓	✓	3
Fellenius et al. (2009) / Kim et al. (2011)	Shinho, South Korea	Post-grouted concrete cylinder pile	56	0.6	✓	✓	✓	> 40
	Myeongji, South Korea	Post-grouted concrete cylinder pile	31	0.6	✓	✓	✓	> 40
	Vancouver, Canada	Bored cast-in-situ	74.5	2.6	✓	✓	✓	> 35
Siegel and McGillivray (2009)	Rincon, USA	Auger cast-in-place	9.15	0.457	✓	✓		103
Lam and Jefferies (2011)	Stratford, UK	Bored cast-in-situ	27	1.2	✓	✓		28
This study	Dagenham, UK	Driven cast-in-situ	7.7	0.34	✓	✓	✓	14