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A field trial of a sustainable, reusable, hollow cast *in situ* pile

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Abstract

This paper describes the concept and field testing of a 1200mm diameter x 30m deep hollow cast *in situ* rotary bored pile foundation. The aim of the foundation is to allow large diameter piles to be constructed using less concrete than in an equivalent conventional solid pile and with a view to allowing reuse at a later date. Reuse is made possible because the hollow core of the pile allows access for inspection after demolition of an existing structure. The new piles may also allow modification to enhance load capacity by augering through the base and extending their length. In addition, the piles are better suited than conventional piles for use as 'energy piles' to allow environmentally friendly heating and cooling. The geotechnical performance of the hollow test pile was comparable with a conventional solid pile constructed during the same trial. Details of construction are given including lessons learned.

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A list of notations, defining all of the symbols used.
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- E_c Young's modulus for concrete
- E_s Young's modulus for steel
- Su   Undrained shear strength

A field trial of the City University SuRe pile

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Introduction

Since the 1960s most large commercial buildings in central London have been built on piled foundations. Before the 1980s bored piles were mostly installed using a tripod rig and were typically 400 to 600mm diameter and often about 12 to 15m long. Pile capacity was therefore severely limited in comparison with today's options and this resulted in installation of large numbers of piles on a closely spaced grid.

The expected life of a commercial building in London is about 20 to 30 years and consequently many of the 1960's buildings were redeveloped during the 1980s and early 1990s when larger and deeper rotary bored or continuous flight auger piles were installed. Many of the 1980s buildings are in turn now being considered for redevelopment and it is therefore necessary to provide a new set of foundations that are sympathetic with two previous pile layouts. Exacerbated by other common restrictions such as tunnels and buried services, this situation is clearly unsustainable.

In 2006 the Reuse of foundations for urban sites, a best practice (Butcher et al, 2006) was published by the Building Research Establishment. The handbook was the culmination of the RuFUS project, an EU 5th Framework research project involving many of the leading professionals and aimed at 'overcoming the barriers, both technical and non technical, to the reuse of foundations for sustainable development.' The handbook has provided valuable guidance to those seeking sustainable foundation solutions for new developments but apart from advocating good record keeping and monitoring of foundation performance offers little towards a truly sustainable foundation solution.

In principle there are obvious advantages in foundation reuse from the point of view of cost and programme savings. However, the reality of the situation is that, even with access to good existing pile records it is usually impossible to make any accurate assessment of the condition and capacity of existing foundations prior to completion of demolition. At this point, for risk averse developers who require their building on time, it is usually more cost effective to install a new foundation system than to waste time investigating the existing piles to ensure that the as-built records are correct and that the condition of the piles is satisfactory. In any case, it would almost certainly be necessary at this stage to install at least some new piles to take account of a different structural layout. Old foundation layouts are usually incompatible with the current trend of longer floor spans and taller buildings.

A key problem is that, even if the existing pile layout can be made to work with the new frame, existing pile capacity is often woefully inadequate. This problem is itself often compounded by a general reluctance to allow the existing piles to carry their full intended design load. In reality, pile capacity often increases with time (Wardle et al 1992, Powell and Butcher, 2003, Powell and Skinner, 2006 and Begaj and McNamara, 2011) although there may be problems to overcome such as the heave cracking that can occur when unreinforced piles are unloaded during demolition of a building.

A new approach to pile construction

The RuFUS project has been successful in developing a framework within which existing piled foundations can be considered for reuse. It offers a generally pragmatic approach to the engineer faced with an often complex problem but mostly advocates good record keeping by way of guidance for designers seeking to maximise the chances of their foundations being reused for future

developments. The main practical recommendations are to suggest that the foundations should be arranged such that a 'platform' could support a variety of future superstructure layouts and that their design should consider a longer working life than envisaged for the immediate development. These, combined with ongoing monitoring go some way to providing for the future.

In order to provide the engineer with a deep foundation specifically designed to allow reuse a new type of pile has been proposed (McNamara et al, 2012) that offers environmental benefits as it uses less concrete than conventional piles and provides the potential of access to inspect the old foundations before demolition of an existing structure as well as the ability to enhance capacity for a future development by extending its length. The key difference between conventional bored cast *in situ* piles and the new type of foundation is that the new foundation is a large diameter hollow cast *in situ* pile. Hollow piles are used extensively in marine works and hollow precast concrete piles for driving have been available for many years. However, the concept of a hollow cast *in situ* pile may have only ever been explored with the idea of making savings on materials or providing a useful space for dumping excavated inert spoil.

Currently, the disadvantages that exist with using large diameter piles are that they require very large amounts of concrete and spoil removal and are also time consuming to build compared with multiple small diameter piles. For instance, a 20m long 2.4m diameter pile requires $90m^3$ of concrete (15 lorry loads of $6m^3$ each) whereas approximately the same geotechnical capacity can be obtained by using two 20m long, 1.2m diameter piles with half the amount of concrete. This means that large diameter piles are generally very wasteful because only small gains are made in shaft capacity with relatively large increases in material use. Increases in base capacity are more substantial, particularly for relatively large diameter piles. For a 27m long pile in a stiff clay such as London Clay the contribution of the base capacity to the overall ultimate capacity of the pile will increase from around 20% for a 1.2m diameter pile to 40% for a 2.4m diameter pile. This increase in base capacity is maintained with a hollow pile whilst the redundant concrete in the centre of the pile is omitted and the additional cost of wasted concrete is therefore eliminated and the overall time to construct the foundation is greatly reduced. Figure 1 shows the increasing benefit, expressed in terms of reduced material that can accrue from progressively larger hollow piles compared with equivalent solid foundations. The figure shows that a hollow pile of 2.1m diameter can be constructed with approximately the same volume of concrete used in a 1.2m diameter solid pile. The reduced material needed in the hollow pile leads to much greater concrete efficiency which is depicted in Figure 2. In practical terms, for bored piles in stiff clay, it is generally possible to make full use of the concrete strength in piles of 450mm diameter or less. Above 450mm diameter there is usually some redundancy in concrete capacity as the governing factor in the design of the foundation is geotechnical rather than structural. For the practical minimum diameter of a hollow pile a solid pile of the same geotechnical capacity may have a concrete efficiency of around 45% and this would reduce to around 30% for a 2.4m diameter pile. Much greater efficiency is possible with the equivalent hollow piles as the concrete annulus can be designed to match the geotechnical capacity and concrete efficiency actually increases with increasing diameter of pile.

Access to inspect the pile for future reuse can be achieved by providing a duct through the basement slab into the pile void. Physical access over the entire length of a pile may permit sampling of either the pile material or the surrounding soil; the size of the void may even permit manned access if conducted in a safe manner. However, with smaller diameters access for sampling can only be with tools that are lowered into the hollow core and operated remotely but this will still give designers confidence in assessing the load capacity of the pile many years after it was first constructed in the same way that superstructure frames can be assessed for reuse during refurbishment.

Hollow piles may allow modification in the future to enhance load capacity whereas a conventional pile may well be overlooked if found to possess inadequate capacity. With a hollow core, access can be gained to allow the pile to be extended to a greater depth by augering through the base. In addition, the piles are well suited for use as 'energy piles' to allow sustainable heating and cooling. This provides designers with a positive means of ensuring that an existing pile has the capacity required.

Construction concept

The principle of construction of the hollow test pile is shown in Figure 3. The pile structure requires either a temporary or permanent tube to form the hollow core. The tube used for the test described in

this paper was steel but plastic or some other alternative material is possible depending on the design of the pile. The tube may be removed after the initial setting of the concrete in the same way as concrete shutters are routinely used on reinforced concrete frame superstructures but this was not attempted for this field trial. Clearly, such formwork would be costly to design and produce but would be reusable.

It would be possible to fix a reinforcement cage around the annulus of the tube but this was not attempted in the trial reported here. For piles with very high loads a steel tube could be designed to contribute to the structural capacity of the pile by generating composite action between the concrete annulus and the steel tube although this design would make any future removal of the pile difficult and costly. Difficulties in compacting the concrete around a pile annulus, with heavy reinforcement at depth, could be overcome by using formwork vibrators inside the tube although for the test described this was not found to be necessary.

The test site and ground profile

The pile test was undertaken at a site immediately adjacent Wembley Stadium in North London where a significant amount of site investigation had been carried out and London Clay was present over the entire length of the pile up to piling platform level. Two test piles were constructed, each being 1200mm diameter and 27m long, with an ultimate design capacity of 10MN based on the undrained shear strength profile given below and standard undrained pile capacity calculations using α of 0.5. One pile was a conventional rotary bored, cast *in situ* solid pile whilst the other was a rotary bored, cast *in situ*, hollow pile. The location of the piles relative to the site investigation boreholes is shown in Figure 4 whilst the setting out of the test piles relative to the reaction piles is shown in Figure 5. The test piles and reaction piles were incorporated amongst some new permanent piles that had been installed for a future development on the site. Whilst the new permanent piles had not been loaded at the time of the test one pile, P103, was quite close to the solid test pile (1.86m away) and its potential influence should not be ignored. The presence of P103 seems unlikely to have had a detrimental effect on the performance of either of the test piles as it would have provided general stiffening to the ground in the vicinity of the piles and therefore increase their capacity (Begaj and McNamara, 2011). If any affect existed it could be expected to enhance the solid pile capacity more than the hollow pile because of its relative proximity.

The geology encountered in the boreholes and the results of *in situ* testing consisting of SPT tests is shown in Figure 6. From these results an undrained shear strength profile was derived from:

Su = SPT 'N' count x 5. (Stroud, 1974)

This gave a design line for both piles of Su = (50 + 6.1z) kN/m^2 where z is depth in metres below ground level.

Test pile details

The field trial and loading test had three main aims:

i   To confirm that it was possible to build such a pile;

ii To confirm that behaviour of the hollow pile was at least as good as a conventional solid pile of the same size;

iii To inform potential improvements in both the construction and design of the hollow pile to ensure that it can be made an economic alternative to conventional piles.

The structural design of the pile confirmed that a conventional pile is wasteful of concrete and that for a 1200mm diameter pile a concrete annulus of just 200mm was necessary reducing the volume of concrete required by nearly 50%. However, a major concern was that during construction of the pile the fluid pressure of the concrete, the level of which would be expected to rise quickly owing to the relatively small volume required, would cause buckling of the tube used to create the central void. In view of this a very conservative approach was taken and an 800mm tube with a 12.5mm wall thickness was selected. These concerns proved to be unfounded, as described below, but in reality

such a tube would be uneconomical for commercial use. The thick walled steel member undoubtedly affected the test results by creating a stiffer section than would be used in reality even though the combined concrete and steel tube section was much less stiff than the solid pile. A comparison is made below of the relative stiffness of the conventional solid and hollow piles tested:

• Young's modulus for concrete E_c = 25kN/mm^2.
• Young's modulus for steel E_s = 205kN/mm^2

Hence, the axial stiffness of the solid pile = E_cA_c, where A_c is the area of the pile:

$25 \times \pi \times 1200^2/4 = 28.28 \times 10^6$ kN

Whereas the axial stiffness of the hollow pile = $E_cA_c + E_sA_s$

$\{25 \times [(\pi \times 1200^2/4) - (\pi \times 800^2/4)]\} + \{205 \times [(\pi \times 800^2/4) - (\pi \times 775^2/4)]\} = 22.15 \times 10^6$ kN

The conventional solid pile tested was therefore about 30% stiffer than the hollow pile. However, for commercial use, a realistic and cost effective product for use as a liner would be a corrugated steel tube with a wall thickness of about 1.5mm providing a hollow pile stiffness of 16.48 x 10^6 kN. A conventional solid pile would be about 70% stiffer axially than this.

Pile construction

The solid pile was constructed first; the hollow pile second. Pile construction was generally straight forward. A temporary oversize steel casing was used to support the superficial soils overlying the London Clay and the pile was then bored using a Casagrande B125 rotary auger. Both piles were concreted using a discharge pipe which extended near to the base of the pile, and was used to prevent potential damage to the instrumentation. The diameter of the concrete discharge pipe was less for the hollow pile so that it could fit within the 200mm annulus. Both piles had the same overall geometry and concrete mix thus:

- Piling platform level = 40mOD
- Bored length = 27m
- Pile founding level = 13mOD
- Pile concrete was C35 at 14 days with 10mm maximum aggregate size

The exact timing and breakdown of construction for each pile differed and this is summarised in Tables 1 and 2 for the solid and hollow pile respectively. The additional work over and above that normally encountered in pile construction for both piles meant that the delay between excavation and concreting was about 5½ hours for the solid pile and 6½ hours for the hollow pile.

In summary, the overall concreting time for the solid pile was approximately 1 hour 45 minutes compared with 1 hour 40 minutes for the hollow pile which was finally topped up by 2m to ground level following removal of the casing because of a delay in supply of concrete. Owing to the low concrete volume needed to fill the hollow pile the slump resulting from casing removal was very significant and required a gradual removal of the casing whilst topping up.

Hollow pile key construction lessons:

- Hollow pile construction is reasonably straightforward if well planned beforehand.
- Placing the void former should take about the same time as placing a full depth reinforcement cage.
- Concrete slumping during removal of the temporary casing will be more dramatic because in a hollow pile the casing volume is a higher percentage of the concrete volume, so even with short casings it should be expected that it will be necessary to top up the concrete using a concrete skip and that this procedure may need to be repeated several times.

Concrete pressure

It was not known prior to the trial whether the concrete pressure exerted onto the side of the steel void former would be hydrostatic with depth or not. It is well known that concrete does not behave as a pure fluid, being a suspension of fine to coarse particles in water and having gel strength as the structure changes. Previous work on wet concrete pressures in diaphragm walls (for example Konig and Loreck, 2010) indicates that concrete velocity is a key factor in these pressures and hence comparisons with pressures developed in diaphragm walls are not appropriate because of the very different rate of rise of concrete. Ciria Report 108 (Clear and Harrison, 1985) provides guidance on limiting concrete pressures for use in column and formwork design. However, pile concrete is designed to be of high workability with a target slump around 175mm, and consequently may behave differently to the low slump concrete characteristically used in buildings.

Vibrating wire piezometers were used to measure the concrete pressures prior to initial setting of the concrete. It is thought that this may be the first use of piezometers to measure concrete fluid pressure, rather than that of water. The piezometers were used in pairs on opposing sides of the pile and attached to either the reinforcement cage in the case of the solid pile or to the steel tube in the hollow pile prior to them being lifted vertically for placement in the pile bore (Figure 7). For this reason it was necessary to fill them with water once vertical. Pairs of piezometers were adopted because of concerns that concrete would fail to self level when placed and that the steel liner may be subjected to a very high fluid pressure on one side only. The positions of the piezometers along the shafts of each pile are shown in Table 3.

Whilst the piezometers used in the solid pile were fixed to the reinforcement cage and can reasonably be assumed to have been subjected to the full concrete pressure ($23h_c$ kN/m^2, where h_c is the height of concrete and 23kN/m^3 is the unit weight of the concrete) those used in the hollow pile may not have been capable of measuring the true pressure owing to their position against the steel lining tube. With hindsight; it may have been beneficial to position the piezometers nearer to the middle of the concrete annulus. However, such positioning would have led to an increased risk of damage during concreting.

For the solid pile extremely consistent data between the pairs of piezometers were measured. Most pairs of piezometers gave readings within a range of 5kN/m^2 of each other and with a maximum differential of 17.4kN/m^2. The pairs of piezometers in the hollow pile mostly suggested similar consistency although some anomalies between the readings during the later stages of concreting may suggest that the instruments stopped performing properly (Figure 8). Sufficient data confirmed however that the top of the wet concrete in both piles remained generally level during concrete placement and the results from each pair of piezometers have allowed these to be expressed as a single average value without distorting the data. Limiting values of 250kN/m^2 and 505kN/m^2 were measured for the hollow and solid piles respectively suggesting that at the base of the pile the concrete pressure in the hollow pile only marginally exceeded hydrostatic pressure of water. In general measured values lie both above and below the pressure equivalent to the hydrostatic pressure from water as there is some scatter in the piezometer readings, see Figure 8.

When compared to the magnitude of pressure that might be expected based on the Ciria 108 guidance on limiting concrete pressures for use in column and formwork design the piles could be expected to exceed the maximum values owing to rates of concrete rise of nearly 17m per hour. The maximum magnitudes of concrete pressure that would be calculated using the Ciria guide are 135kN/m^2 and 210kN/m^2 for rises of 10m/h and 15m/h for walls and columns respectively assuming a concrete temperature of 10ºC.

When comparing the concrete pressures measured with respect to the applied pressure on formwork in the solid pile and hollow pile it may be reasonable to regard the solid pile as a column and the hollow pile as a wall. This allows comparison with the values given in Table 2 of Ciria 108.

The ratio of vertical to horizontal pressure generated in 10m high formwork for a column and wall with concrete temperature at 10ºC and a rate of rise of 10m/h is 1.26 compared to 1.90 for the solid/hollow pile. This suggests that the reduction in concrete pressure on the liner is more than could be expected by simply extrapolating from the Ciria guidance and this information will provide confidence to investigate more economic design of the void former in the future.

Load testing of piles

Maintained load tests were carried out on both solid and hollow piles approximately one month after construction. The tests were in accordance with the ICE Specification for Piling and Embedded Retaining Walls (ICE, 2007) which uses observed rate of settlement as a means of controlling the application of loading. For this reason, the solid pile test was carried out over an extended period of time in comparison to the hollow pile; it exhibited greater sensitivity to loading increments beyond working load.

Figure 9 shows the variation in load and displacement at the head of each pile with time and it can be seen that, at the end of testing, the total settlement of the solid pile was approximately 1.5 times that of the hollow pile for less total load. However, to enable the behaviour of the two piles to be compared in detail the load/displacement behaviour of the piles have been plotted together in Figure 10 (initial loading only) and Figure 11 (ultimate loading). During the first stage of the tests (Figure 10) each pile was loaded to 1.5 times working load in 25% increments with the load held for a short period at each increment. The load was then reduced to zero. The second stage of the test (Figure 11) was aimed at loading the piles to failure. Failure is normally defined as vertical displacement equal to or greater than 10% of the pile diameter; 120mm in this instance. This resulted in the solid pile being reloaded to 1.75 times working load whilst the hollow pile was reloaded to about twice working load. The load displacement response indicates that the solid pile would definitely have failed at or before the calculated ultimate load of 10MN, whereas the hollow pile reached a load of 9MN with only 61mm displacement and would reasonably be expected to exceed the predicted ultimate capacity. Time constraints precluded an additional increment of load being applied to the hollow pile.

Upon initial loading to working load the piles behaved in a similar manner with settlements of 3.9mm and 4.3mm after the holding phase for the solid and hollow piles respectively. This is well within the limit of 1% of pile diameter that could reasonably be expected. Two identical piles tested in consistent ground conditions such as were encountered at the test site could be expected to yield very similar test results up to working load. The difference in performance between the solid and hollow piles at working load was about 10% which could be regarded as being at the limit of expectations. However, when the load was increased and held at 1.5 times working load the displacement of the solid pile was 50% more than the hollow pile. Figure 11 shows the comparative pile behaviour during the entire load/unload/reload sequence and indicates quite different responses for the two piles.

The initial load increment to 1.5 times working load was released and upon reloading to the same magnitude of load the solid pile underwent significant additional settlement whereas the hollow pile settled only fractionally more. When a further increment of load was applied (up to 1.75 times working load) the magnitude of settlement of the solid pile was approximately twice that of the hollow pile. Two attempts at reducing the load and subsequently reloading the solid pile (in accordance with the requirements of SPERWALL) failed to prevent further settlement and the test was abandoned when settlement of about 90mm was reached. In contrast the hollow pile exhibited a markedly stiffer response which enabled loading up to twice working load with a total settlement of about 60mm when the test was abandoned.

The reason for the difference in performance under similar loading conditions is not yet known and may merely have resulted from variation in soil conditions. However, the test site was chosen because ground conditions had been found to be very uniform in extensive site investigations. The general consensus is that stiffer piles settle less although Randolph and Wroth (1982) suggest that the distribution of load along the shaft of piles of varying stiffness is different. It is clear that such a difference would be governed by both the structural pile stiffness and the soil profile and would lead to mobilisation of peak stresses between the pile shaft and the ground sooner in a lower stiffness hollow pile owing to increased strain, compared with an equivalent solid pile. Investigation of this hypothesis would require a more intimate knowledge of the ground conditions around both piles to enable conclusive statements to be made but it would appear that the lower stiffness section of the hollow pile may be better able to transfer load into the surrounding soil. Rod extensometer data from each of the piles were examined in an attempt to understand the behaviour but proved inconclusive. This is an area of significant interest with implications for pile design generally. Further research into this phenomenon is therefore necessary.

Conclusions and lesson learned

The reuse of pile foundations is a sustainable approach for new construction but is currently difficult to apply in practice. A new approach to pile construction has been investigated with a heavily instrumented field trial. A hollow cast *in situ* bored pile saves concrete and then also provides a void which may have many uses;

- For inert waste spoil
- For geothermal heating and cooling
- To provide access for inspection and testing of the pile and the surrounding ground
- To enable enhanced pile capacity for future use.

The field trial has proved that it is possible to construct hollow cast in place bored piles successfully and that the reduction in stiffness of such a pile compared to a conventional solid piles does not detrimentally affect the geotechnical capacity and may improve it.

Measurements have shown that the limiting pressure from fluid concrete applied to the void former is much less than had been anticipated and proved to be less than the equivalent hydrostatic head of water.

Practical relevance and potential applications

The hollow cast *in situ* pile is suitable for construction of foundations for city centre sites where future reuse is likely to be of issue. Such piles would currently need to be constructed dry without support fluids such as bentonite or polymer. However, hollow piles of any diameter require the use of much less concrete than equivalent solid piles and there is no penalty, in terms of material use, in opting for short large diameter piles over equivalent long small diameter piles This means it is now possible to avoid wet piles, in many instances, whilst providing a truly sustainable foundation.

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Tables

Solid pile construction details	
Note : Pile was reinforced full depth with two 10H25 reinforcement cages lapped together. A standard tremie pipe was used to place concrete.	
Time	**Activity**
08.30 – 09.20	install 5m long temporary casing with 1.1m upstand and boring pile
09.20 – 10.15	hand digging around casing for test cap former
10.15 – 11.50	installing reinforcement and cables for instrumentation
11.50 – 14.30	fixing and placing rod extensometer
14.30 – 14.50	placing 26m discharge pipe
14.50 – 15.01	placing $8m^3$ concrete through 26m discharge pipe, concrete rose to 20.92mOD, i.e. 7.92m above base of pile
15.03 – 15.13	placing $8m^3$ concrete through 18m discharge pipe, concrete rose to 28.42mOD, i.e. 15.62m above base of pile
15.38 – 15.42	placing $8m^3$ concrete through 12m discharge pipe, concrete rose to 35.62mOD, i.e. 22.62m above base of pile
15.56 – 16.36	placing $8m^3$ concrete poured directly
16.50 – 16.53	placing $1m^3$ concrete poured directly.

Table 1   Timescale and construction of solid pile

Hollow pile construction details	
Steel tube for the void former was 800mm outside diameter, 12.5mm wall thickness. Tube was provided in two equal lengths with a 50mm wide bolted flange connection Spacers were fabricated and were 1184mm outside diameter, on 824mm outside diameter rings formed of 12mm steel, and 300mm deep Tremie pipe used was 100mm inside diameter (125mm outside diameter at joints) with a specially fabricated hopper	
Time	**Activity**
08.00 – 09.00	install 4m long temporary casing with 0.5m upstand and boring pile
09.30 – 10.00	hand digging around casing for test cap former
10.30 – 11.15	installing lower steel tube and cables for instrumentation
11.20 – 12.25	installing upper steel tube and cables for instrumentation
12.30 – 14.15	fixing and placing rod extensometer
14.15 – 14.35	raised steel tube 1.5m and placed 1m thick concrete plug
14.35 – 14.45	replaced steel tube which sank 80mm lower than its original position, and placed steel plate on top
14.45 – 15.20	placing 24m long 100mm ID discharge pipe
16.35 – 17.10	placing $8m^3$ concrete through 24m discharge pipe, concrete rose to 27.79mOD, i.e. 14.79m above the base of the pile (the depth to concrete was checked on two sides and was found to be the same)

17.15 – 18.15	placing $8m^3$ concrete initially through 12m discharge pipe;
	    a) at 17.28 concrete had risen to 35.49mOD, i.e. 22.49m above base of pile (depth to concrete checked on 2 sides and 100mm difference was noted),
	    b) at 17.31 discharge pipe removed
	    c) between 17.37 – 17.58 installing 3.2m long nominal reinforcement cage
	    d) from 17.58 concrete poured directly
	    e) at 18.05 concrete level had risen to 40mOD, i.e. 27m above base of pile

18.17 – 18.45	placing $4m^3$ concrete poured directly
20.25 – 20.35	placing $3m^3$ concrete poured directly.

Table 2   Timescale for construction of hollow pile

	Level below pile head					
	-1.5m	-5m	-10m	-15m	-20m	-25m
Vibrating wire piezometers	✓	✓	✓	✓	✓	✓

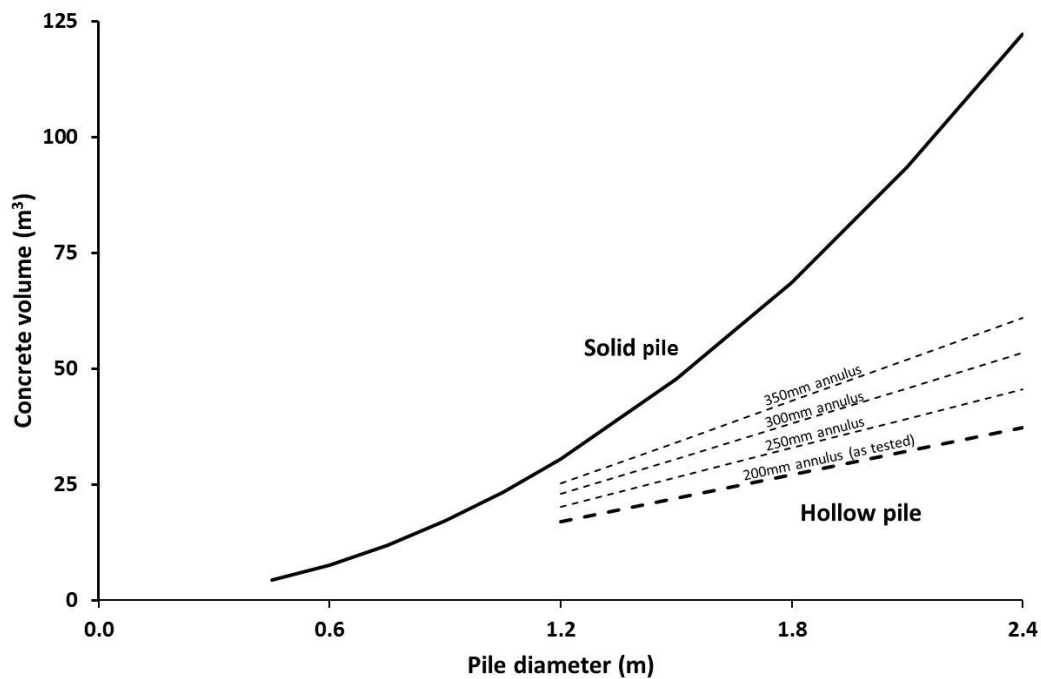Table 3   Summary of piezometer positions

Figures:

Figure 1   Comparison of concrete volume necessary to construct 27m long solid and hollow piles. A range of annulus thicknesses are shown to demonstrate the reducing benefit as the thickness of the annulus is increased.
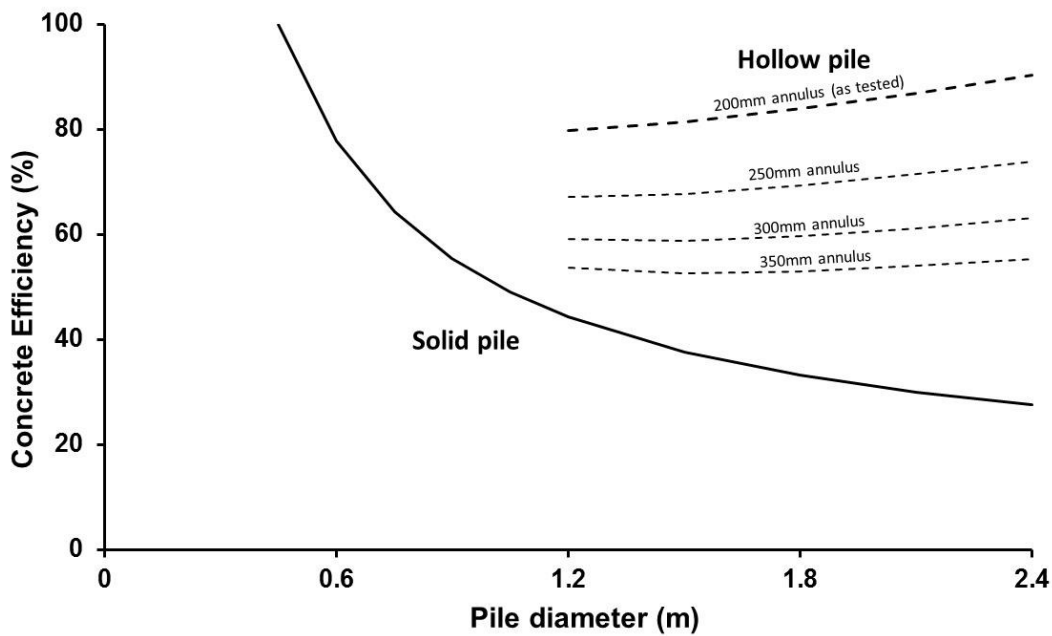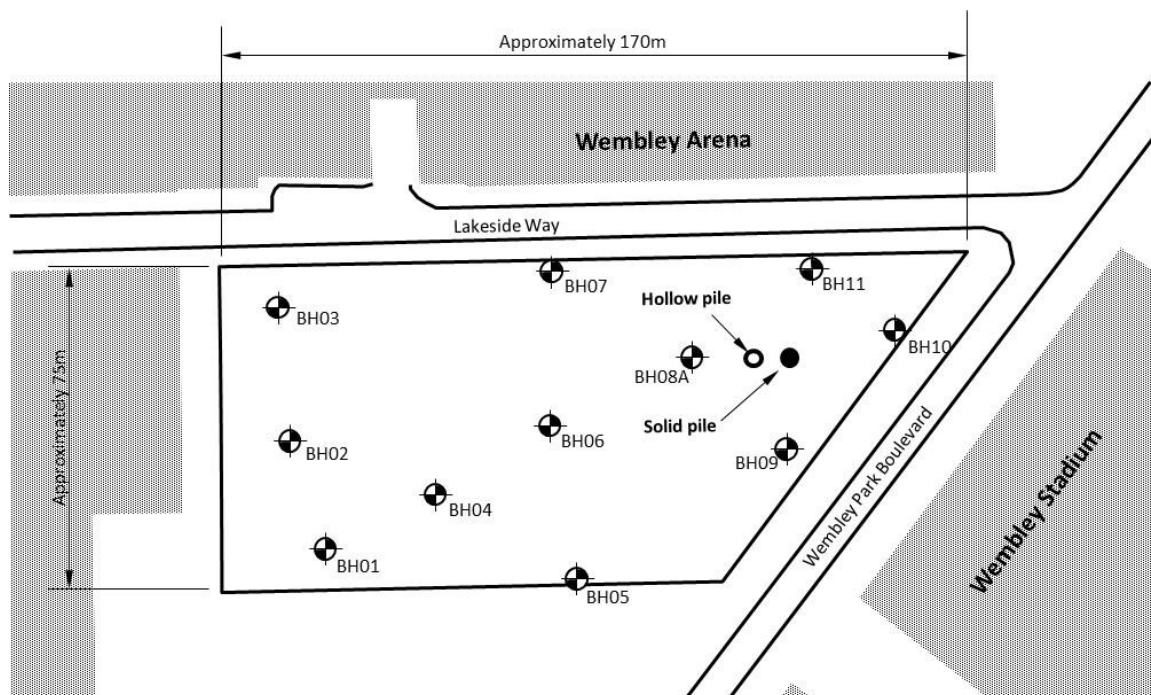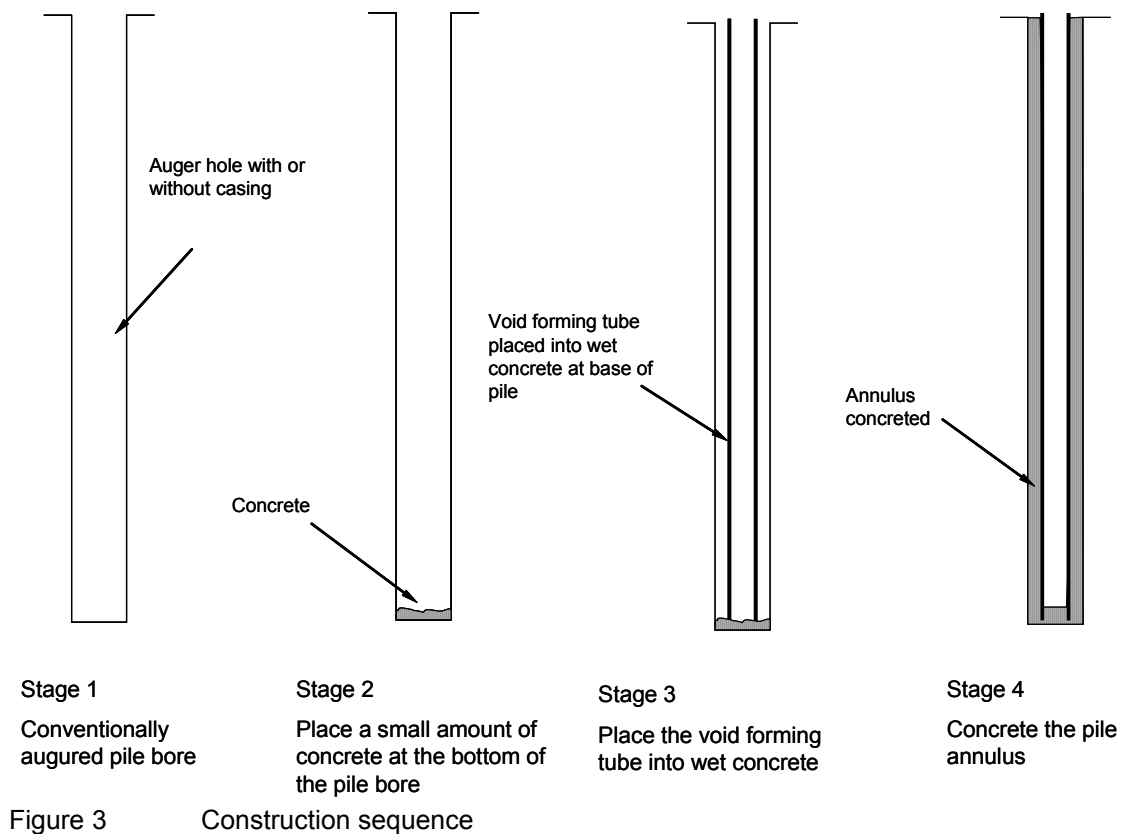

Figure 2   Concrete efficiency achieved in 27m long solid and hollow piles of varying diameter and with varying thickness of concrete annulus.

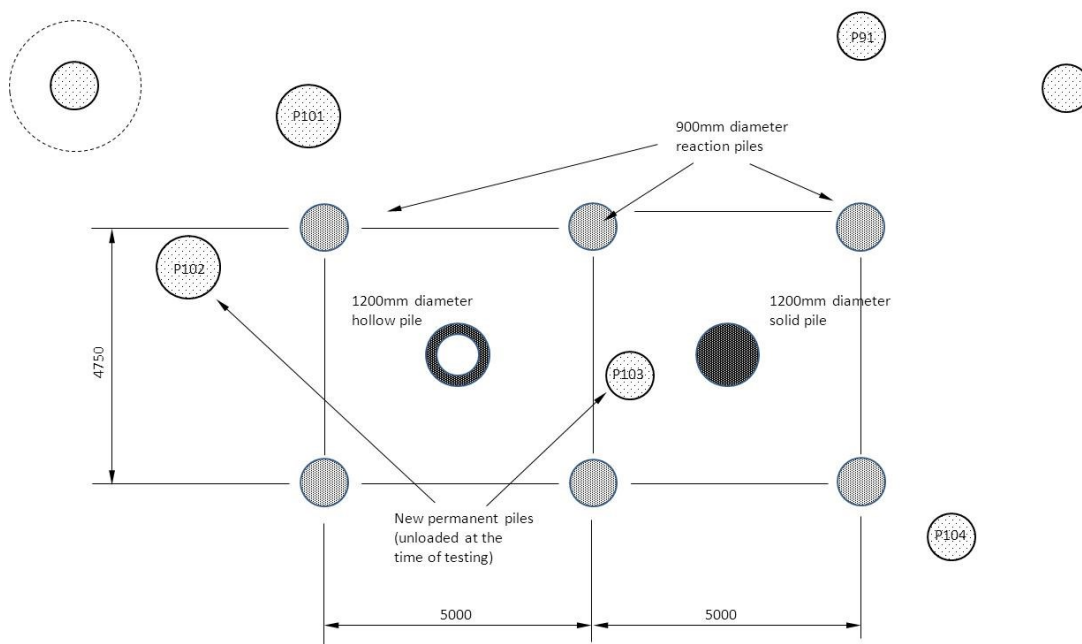Auger hole with or
without casing

Void forming tube
placed into wet
concrete at base of
pile

Annulus
concreted

Concrete

Stage 1

Conventionally
augured pile bore

Stage 2

Place a small amount of
concrete at the bottom of
the pile bore

Stage 3

Place the void forming
tube into wet concrete

Stage 4

Concrete the pile
annulus

Figure 3   Construction sequence

Approximately 170m

Wembley Arena

Lakeside Way

Approximately 75m

BH07

BH11

Hollow pile

BH03

BH10

BH08A

Solid pile

BH02

BH06

BH09

BH04

Wembley Park Boulevard

BH01

Wembley Stadium

BH05

Figure 4   Location and setting out of test piles in relation to site investigation boreholes

Figure 5   Setting out of test piles and reaction piles relative to unloaded permanent piles already installed
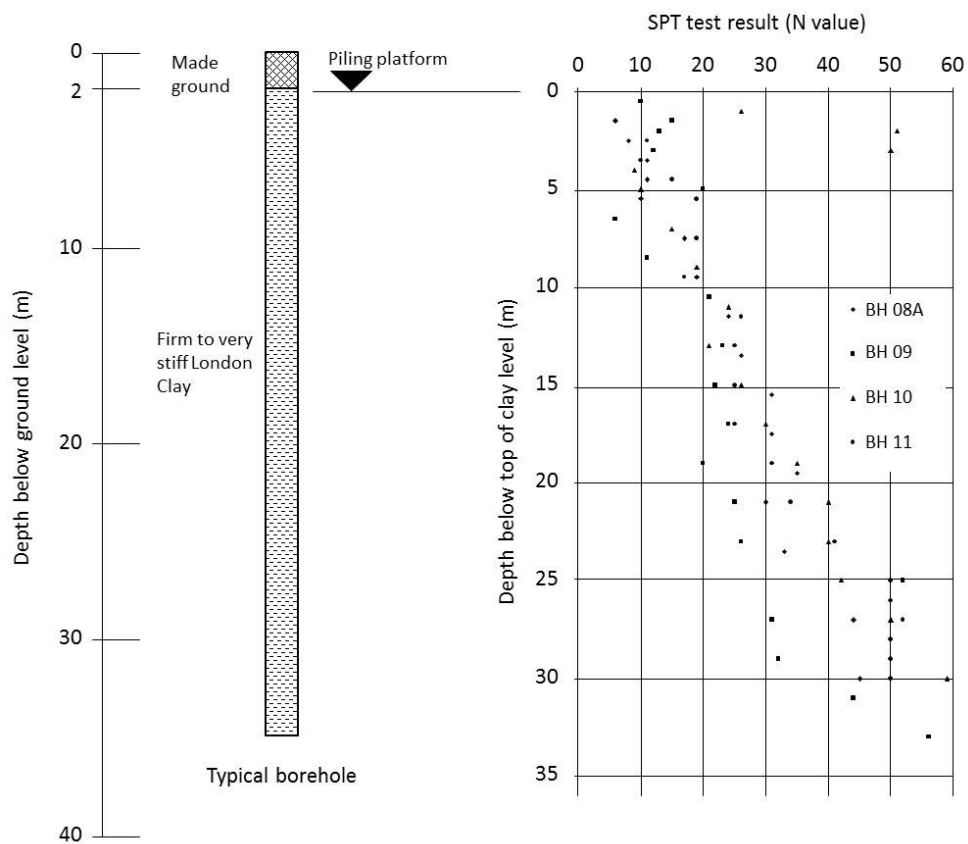
Fgure 6 Typical borehole description from site investigation report and SPT 'N' values from in situ testing
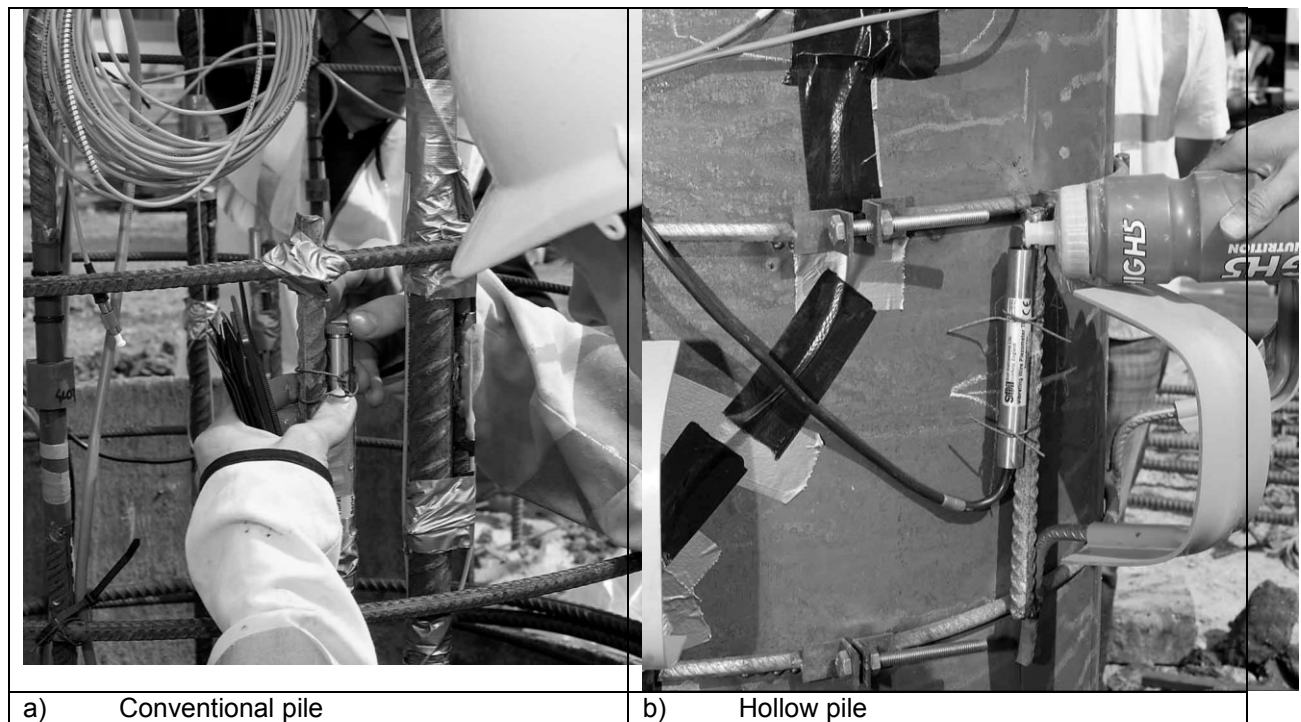
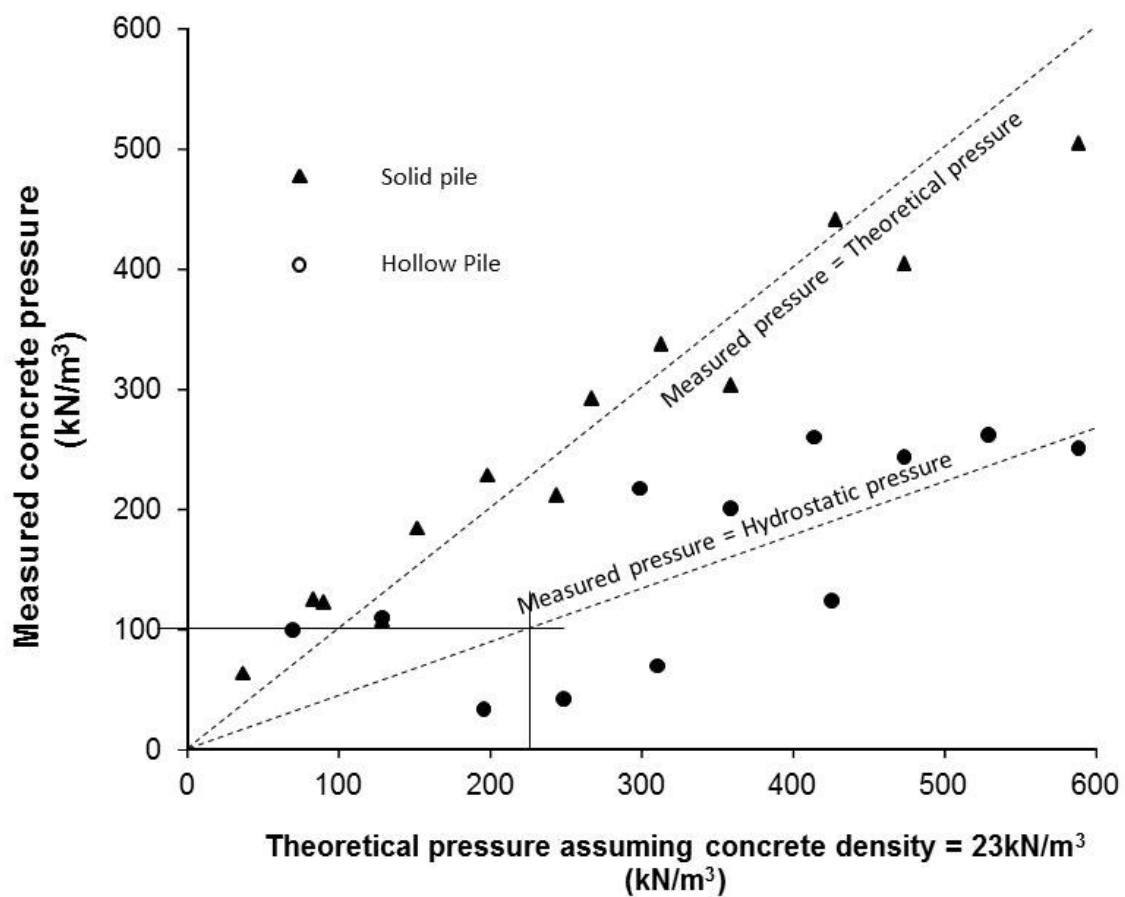| a) | Conventional pile | b) | Hollow pile |

Figure 7   Filing vibrating wire piezometers with water

Figure 8   Comparison of concrete pressures in conventional solid and hollow piles measured with piezometers
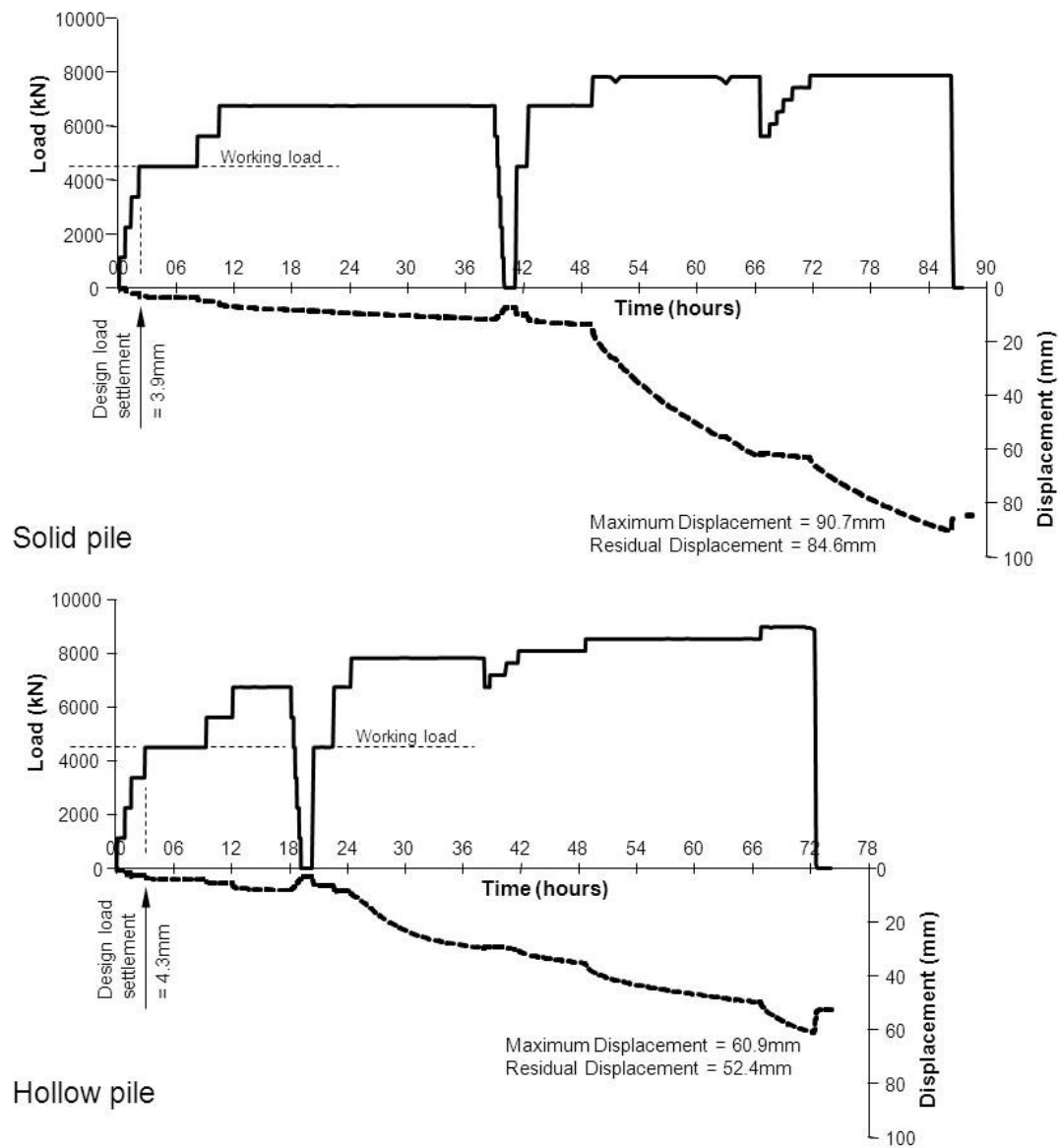
Figure 9   Comparison between maintained load tests on solid pile and hollow pile.
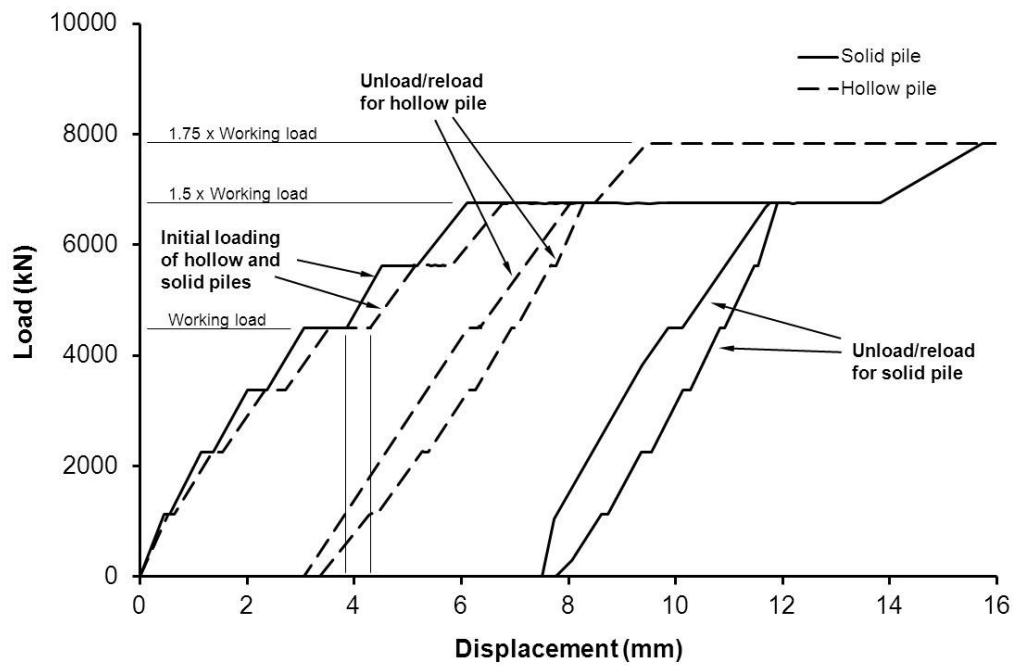
Figure 10   Early stages of pile load plotted against displacement showing stiffer response of hollow pile on reloading
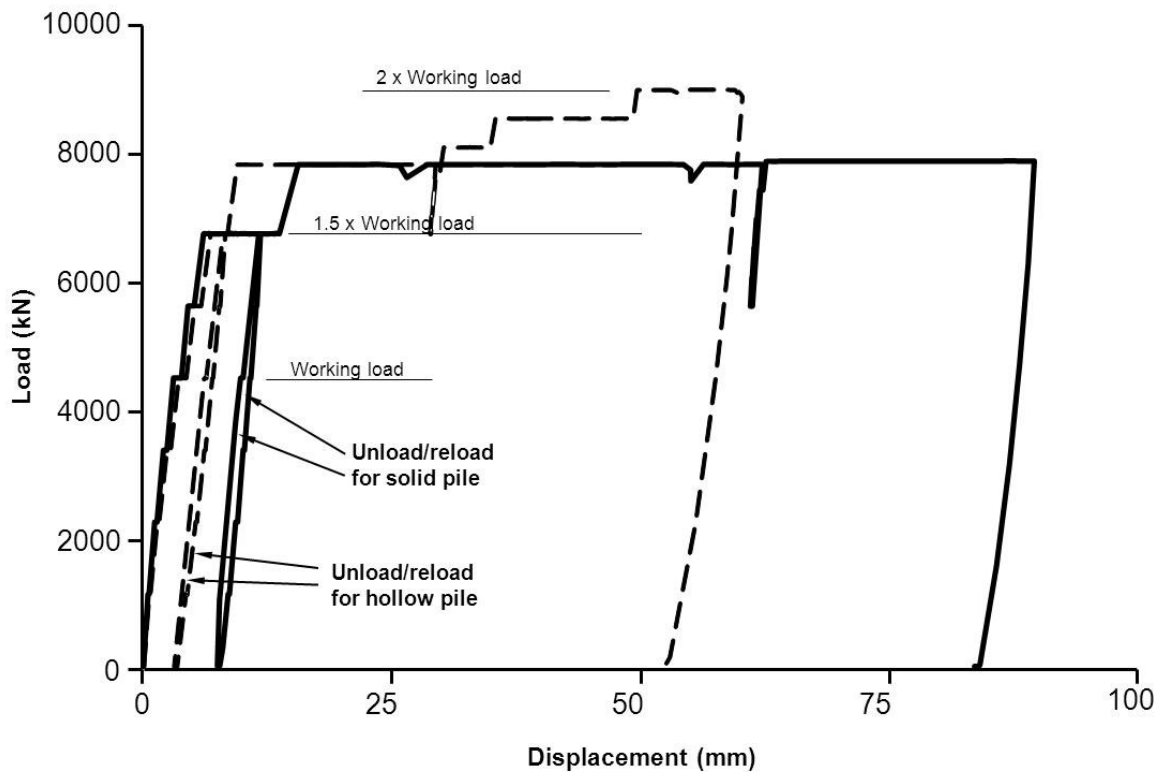

Figure 11   Full pile load test results showing stiffer response of hollow pile under ultimate load.