An investigation into the vertical axial capacities and groundwater cut-off capabilities of secant pile walls

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ABSTRACT: Secant pile walls are increasingly becoming popular groundwater cut-off systems of choice on underground construction sites, as they offer a number of advantages over traditional sheet piling and diaphragm walls. However, some elements of uncertainty surround the design and construction of secant pile walls. Vertical and horizontal installation tolerances are major issues, especially in the case of multi-level basements, as required tolerances are difficult to achieve with deep piles associated with deep basements. In addition, while conventional foundation piles are routinely statically or dynamically load-tested, hard piles in secant pile walls are rarely axially tested and this does not allow for the routine verification of existing design methods and assumptions.

This paper presents the design, construction and testing of the secant pile wall on a 3-4 level basement construction scheme in Central London. Simple empirical correlations for estimating the geometry of secant pile walls for effective groundwater cut-off are derived and validated. An alternative approach for estimating the vertical capacities of secant pile walls is also presented and compared with a common routine method in the industry. The alternative method is shown to be less conservative than the common industry approach, while predictions are also in good agreement with results of a recent series of model tests on perimeter pile groups.

1. INTRODUCTION

The construction of deep basements routinely requires the installation of temporary or permanent excavation support systems, to enable the construction of the sub-structure. Reinforced concrete diaphragm walls and sheet pile walls have been globally adopted for this purpose for many years. However, in recent years, bored pile retaining walls are increasingly becoming more popular, as they offer a number of advantages over diaphragm and sheet pile walls. With bored pile retaining walls, installation process is more straightforward, while production rate is higher and for these reasons, they are often adopted as more economical alternatives to D-walls. Reduced space requirement for machineries is another advantage of bored pile walls over D-walls. When compared with steel sheet piles walls, bored pile walls provide higher stiffness, higher flexural rigidity and higher vertical axial capacity, while durability in the long term is of less concern.

Many publications on case histories of bored pile retaining walls abound in the literature e.g. Adekunte (2013, 2011, 2008 & 2007), Adekun et al. (2010), Finno & Bryson (2002), Long et al. (2012) and Looby & Long (2007). However, many of these publications have concentrated on wall overall stability, lateral deflection and ground movement under service loads. Currently, there is a dearth of publications that focus on the design of optimum geometries for pile walls to provide effective groundwater cut-off.

On basement schemes where groundwater cut-off is required in addition to lateral earth retention, secant pile walls are often considered. In the case of multi-level basements, horizontal and verticality tolerances often become major issues to contend with, as it is difficult to achieve required installation tolerances with deep piles associated with multi-storey basements and ultimately, this complexity has a significant influence on the ability of a secant pile wall to provide effective groundwater cut-off.

And nowadays, in addition to soil and water retention, secant pile walls are being commonly required to support vertical compressive and/or tension loading from the superstructure. As piles in secant walls are rarely load-tested, design methods and assumptions are not routinely verified and as a result, there is a degree of uncertainty surrounding common methods of predicting axial capacities of secant pile walls.

This paper focuses on the prediction of vertical axial capacities of secant pile walls, as well as the fundamental principles of design of secant pile walls to provide effective groundwater cut-off. For both subjects, direct references are made to a recently completed multi-level basement construction project in Central London, United Kingdom.
2. SITE GEOLOGY & GROUND MODEL

The site is located in Vauxhall, Central London. Site stratigraphy comprises of up to 3m thick made ground underlain by a layer of very soft to soft alluvial clay and peat to 9m depth, which in turn overlies a 1m thick layer of medium dense to dense sandy gravel. Firm to stiff to very stiff to hard London clay lies below the sandy gravel stratum at 10m depth and this is underlain by a layer of very dense Thanet Sand at 48m depth. The London clay is an overconsolidated material of high plasticity, with plasticity indices ranging between 35%-45%. As the site was immediately adjacent to the River Thames on the southeastern boundary, groundwater level was subject to tidal fluctuation and standpipe monitoring results show that water level could be as high as 1m below ground level (bgl). Generalised site stratigraphy and associated geotechnical design parameters are presented in table 1.

Coefficient of earth pressure \( K_o \) was generally limited to 1.0 for the overconsolidated materials (after CIRIA Report No. C580, 2003). This was to allow for remoulding and stress relief in the soils; conditions associated with embedded retaining wall installation and excavation. In the temporary condition, effective wall friction angles \( \delta \) on the active and passive sides were taken to be 0.67\( \phi' \) and 0.5\( \phi' \) respectively (where \( \phi' \) is effective angle of shearing resistance). However, in the permanent condition, angle of wall friction was assumed to be zero; this was to allow for the effect of vertical compressive loading on the wall from the superstructure in the long term.

3. PROPOSED DEVELOPMENT & CONSTRUCTION PROCEDURE

The site was adjacent to the River Thames and the Vauxhall Bridge in Central London. The project was a large scale high rise development comprising of two separate structures on the same site; a 28 storey-commercial tower and an 18 storey-residential block of luxury apartments. The development included a 3-4 level basement, a 3 level-basement over the entire footprint of the site and a 4th level of basement in the centre of the site. Due to the proximity of the site to the Thames River, groundwater level was relatively high and subject to tidal fluctuation. Therefore, in addition to soil retention, groundwater cut-off was also a necessity, to enable basement construction and a hard-firm secant pile wall was considered to be a potentially effective and economical solution for the first 3 levels of basement across the site. The secant pile wall system comprises of interlocking male and female piles. The female piles are only required to provide groundwater cut-off and they do not provide any structural support in respect of wall overall stability. An illustration of the wall geometry is shown in figure 1.

Male piles were made of grade 35 structural concrete and reinforced down to depth required for overall wall lateral stability, while the female piles were made of 10 N/mm² concrete and unreinforced. Both male and female piles were provided with a minimum embedment of 1m in London clay below basement formation level, for groundwater cut-off. Male piles were of 880mm diameter, while female piles were of 900mm diameter. A photo of the secant pile wall is shown in figure 2. However, as the 4th level of basement wholly lies within the London clay stratum, groundwater control was not considered to be a major issue and therefore, a contiguous pile wall was considered to be the most economical and effective solution. Contiguous pile wall comprised of 750mm diameter bored piles spaced at 900mm centre to centre (c/c).

Maintaining a perfect interlock between adjacent male and female piles is often difficult to realize when dealing with multi-level basements, as required horizontal and vertical tolerances are difficult to achieve with many conventional piling rigs, for deep bored piles associated with deep basements. To mitigate this risk, prior to commencement of piling, a guide wall was put in place along the wall alignment, for improved horizontal positional tolerance. In addition, for improved verticality tolerance, male piles were installed with a Cased Secant Piling (CSP) rig, which is a customized version of the traditional Continuous Flight Auger (CFA) drilling rig, equipped with a temporary heavy duty steel casing over the full depth of the pile.
Table 1. Generalised stratigraphy & geotechnical design parameters

<table>
<thead>
<tr>
<th>Depth (m) bgl</th>
<th>Description</th>
<th>N_spt</th>
<th>Angle of Shearing Resistance $\phi'$ (°)</th>
<th>Young's Modulus $E_u$ or $[E']$ (kPa)</th>
<th>Cohesion $C_u$ or $[C']$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 – 9.0</td>
<td>Made Ground &amp; Very Soft to Soft Clay &amp; Peat</td>
<td>1 - 8</td>
<td>25.0</td>
<td>[10000]</td>
<td>[0.0]</td>
</tr>
<tr>
<td>9.0 – 10.0</td>
<td>Medium Dense to Dense to Very Dense Sandy Gravel</td>
<td>17 - 41</td>
<td>36.0</td>
<td>[50000]</td>
<td>[0.0]</td>
</tr>
<tr>
<td>10.0 – 16.0</td>
<td>Firm to Stiff London Clay</td>
<td>13 – 30</td>
<td>25.0</td>
<td>80000 [65000]</td>
<td>100.0 [5.0]</td>
</tr>
<tr>
<td>16.0 – 29.0</td>
<td>Very Stiff London Clay</td>
<td>32 – 44</td>
<td>25.0</td>
<td>120000 [95000]</td>
<td>150.0 [5.0]</td>
</tr>
<tr>
<td>29.0 – 48.0</td>
<td>Very Stiff to Hard London Clay &amp; Weak Mudstone Bands</td>
<td>43 – R</td>
<td>25.0</td>
<td>175000 [140000]</td>
<td>220.0 [5.0]</td>
</tr>
<tr>
<td>Below 48.0</td>
<td>Very Dense Thanet Sand</td>
<td>R</td>
<td>37.0</td>
<td>[150000]</td>
<td>[0.0]</td>
</tr>
</tbody>
</table>

The CSP technique improves the achievable vertical tolerance to 1:150, when compared with 1:75 achievable with a conventional uncased CFA bore (after ICE SPERW, 2007). In addition, the customized technique results in better finished wall appearance and reduced overbreak when compared with traditional CFA drilling, while it is also faster and more economical when compared with rotary bored piling.

Economy is another important factor in foundation engineering and construction (especially from a contractor’s perspective) and this has to be accounted for in every aspect of wall design and installation. For economical reason, female piles were designed to be installed by traditional CFA drilling; the reduced verticality tolerance was off-set by the commercial benefit derived from the lower higher rate of the CFA rig, when compared with the CSP rig.

The 4th level of basement at the centre of the site, which had to be constructed beneath the excavation level of the perimeter 3 level-secant pile wall, was supported with a contiguous pile wall. This was installed by a Bachy Soletanche Large Diameter Auger (LDA) rotary boring technique. Above the London clay stratum, the LDA rig advanced the drillhole with the combination of an auger and a thick-walled temporary casing, rotating in opposite directions. The temporary casing was required to provide lateral support to the hole in the unstable made ground and alluvial deposits above the London clay. In the London clay, hole was drilled with the auger.
only. This rotary boring technique allowed each hole to be partially concreted up to the formation level of the general 3-level basement (approximately 11m bgl), while the rest of the hole was backfilled with carefully selected gravel peas up to ground/piling platform level. This approach allowed for the installation of both the secant and contiguous pile walls from ground/piling platform level, such that excavation for the top 3 levels of basement was done without having to deal with concrete piles projecting from the 4th level contiguous pile wall in the middle of the site; this also resulted in savings in concrete.

Overall, the basement works package involved the use of three different bored piling techniques for improved efficiency and economy. Figure 3 shows wall installation with piling rigs on the site.

4. GROUNDWATER CUT-OFF

Many cases of flooded and/or abandoned secant wall-supported basements have been recorded. Such problems arise because many engineers are unaware of the fundamental principles underlying the accurate estimation of optimum interlock thickness between male and female piles (and ultimately pile spacing) required to ensure an effective groundwater cut-off solution. To provide effective groundwater cut-off with a secant pile wall, many factors would need to be accounted for. These include:

- rig type;
- rig capability;
- installation technique;
- pile size;
- verticality tolerance;
- horizontal positional tolerance;
- depth of sealing stratum;
- minimum required pile embedment in sealing layer.

For effective groundwater cut-off to be guaranteed, all of the above factors must be accounted for. Inability to account for only one of the factors could result in significant consequences. While publications with comprehensive specific information on this subject are very rare, field experience has shown that the minimum required interlock thickness between male and female piles may be expressed by the equation;

\[ \beta = \delta + \alpha \]  

where \( \beta \) is estimated required bite thickness between male and female piles at piling commencement level in mm. \( \delta \) is estimated potential gap in mm between male and female piles at pile depth required for cut-off; this is a function of horizontal positional tolerance, verticality tolerance and length of pile L required for cut-off (equivalent to length of female pile). \( \alpha \) is minimum allowable bite thickness in mm between male and female piles at cut-off depth. This may be taken as 25mm (after ICE SPERW, 2007).

\( \delta \) in Equation (1) can be expressed as;

\[ \delta = k \left( \nu \times L + h \right) \]  

where \( \nu \) is average verticality tolerance of both male and female piles in mm/m depth of installation, which is dependent on rig type and piling technique. \( h \) is horizontal positional tolerance in mm at piling commencement level; this is dependent on availability of guide wall prior to the commencement of piling. A conservative value of 25mm may be assumed (after ICE SPERW, 2007). \( L \) is pile length required for cut-off; this is equivalent to depth of female pile toe. \( k \) is a constant, which accounts for the potential horizontal and vertical deviation of immediately adjacent male and female piles in opposite directions. Generally, the value of \( k \) should be taken to be a minimum of 2. Therefore, Equation (1) may be rewritten as;

\[ \beta = k \left( \nu \times L + h \right) + \alpha \]  

The value of \( \beta \) can be used to estimate the required centre to centre spacing of the male piles, provided male and female pile diameters are known. This is illustrated in figure 4. In figure 4, \( D_m \) is male pile diameter, \( D_f \) is female pile diameter and \( \beta \) is thickness of interlock between overlapping male and female piles. From the figure, male pile centre to centre spacing \( S \) can be expressed as;

\[ S = \left[ \frac{D_m}{2} + \left( \frac{D_f}{2} - \beta \right) \right] + \left[ \frac{D_f}{2} + \left( \frac{D_m}{2} - \beta \right) \right] \]  

(4)
If $\beta$ is replaced with Equation (3), Equation (5) becomes;

$$S = D_m + D_f - 2\beta$$  \hspace{1cm} (5)

Adopting a value of 2 for $k$ as suggested above, Equation (6) becomes;

$$S = D_m + D_f - 2k [(\nu \times L) + h] - 2\alpha$$  \hspace{1cm} (6)

By using the current project as a reference, Equation (3) and Equation (8) can be used to estimate the required bite thickness $\beta$ at commencement level and associated male pile centre to centre spacing $S$ respectively. On the project, secant pile wall retained height was 11m. Basement formation level was in London clay and a minimum embedment of 1m in London clay (sealing stratum) below basement formation level was required for groundwater cut-off.

Therefore, length of pile $L$ required for groundwater cut-off $= (11 + 1)m = 12m$.

Male piles were installed by CSP technique; verticality tolerance $= 1:150$ (after ICE SPERW, 2007) and this is equivalent to a deviation of 6.67mm per metre depth of installation.

Female piles were installed by CFA technique with heavy duty augers; verticality tolerance $= 1:100$ (after ICE SPERW, 2007) and this is equivalent to a deviation of 10mm per meter depth of installation.

Therefore, average verticality tolerance $\nu$ of both male and female piles $= [(6.67 + 10)/2] \text{ mm/m} = 8\text{ mm/m}$

While guide wall was installed along wall alignment prior to start of piling works, horizontal positional tolerance $h$ at piling commencement level can be conservatively taken to be 25mm.

Minimum allowable bite thickness $\alpha$ at pile toe can be taken to be 25mm (after ICE SPERW, 2007).
Constant \( k \) accounting for potential deviation of overlapping piles in opposite directions can be taken to be 2 as suggested above. By substituting the above values in Equation (3), minimum required bite thickness \( \beta \) between overlapping male and female piles is estimated to be:

\[
\beta = 2[(8 \text{mm/m} \times 12 \text{m}) + 25 \text{mm}] + 25 \text{mm} \approx 270 \text{mm}
\]

Male pile diameter \( D_m = 880 \text{mm} \), Female pile diameter \( D_f = 900 \text{mm} \)

Substituting the above values in Equation (8), required male pile centre to centre spacing is estimated to be:

\[
S = [1880 + 900 - 2(8 \times 12 + 25)] \text{mm} = 1246 \text{mm} \approx 1.25 \text{m}
\]

Therefore, required centre to centre spacing of male piles is 1.25m c/c, which is approximately equivalent to 1.4D (where D is pile diameter). Installation of the secant pile wall on the site was based on the above figures and the end result was a perfectly dry excavation as can be seen in figure 5 below, despite the wall having to deal with relatively high water level that was subject to tidal fluctuation and more than 10m of cohesionless made ground, very soft to soft alluvial deposits and sandy gravel.

![Figure 5 - Perfectly dry excavation was achieved with secant pile wall on the site](image)

5. PREDICTION OF WALL AXIAL CAPACITY

In addition to earth and water retention, the hard piles in the secant wall were required to support vertical compressive column loads from the superstructure. The RC capping beam on the piles was designed to spread the point loads from the columns over a minimum of 3 No. hard piles, such that the maximum estimated service compressive load on any hard pile was 2450 KN.

As stated in earlier sections, the estimation of axial capacities of pile retaining walls is an area shrouded in uncertainty because unlike traditional bearing piles, hard piles in bored pile walls are rarely tested. It is common practice among designers to routinely approach this problem by estimating the capacity of a singly acting pile in similar ground conditions and thereafter, factoring down the estimated capacity to 50%-60% of estimated figure, to account for pile group efficiency in the wall. This approach is common for walls in clay. However, Rose & Taylor (2010, 2012 & 2013) carried out some experimental work and parallel finite element modelling on the behaviour of pile groups arranged in grids in clay at the City University London. They discovered that piles on the perimeter are subject to higher loads when compared with the internal piles; this they have attributed to increased soil-pile interaction.

Further to this, they carried out a series of tests on piles arranged in single row, to model the behaviour of perimeter pile groups with no internal piles, whilst also considering several variables that influence pile group behaviour; number of piles, pile spacing, length/diameter ratio and soil strength. From their experimental results, Rose & Taylor (2013) discovered that pile group efficiency of perimeter piles could be as high as 100%, while perimeter pile groups with pile centre to centre spacing of less than 2D (where D is pile diameter) tend to exhibit block type failure. Hard piles in secant pile walls are typically spaced at \( \leq 1.5D \) centre to centre.

Based on Rose & Taylor’s (2010, 2012 & 2013) test results, at design stage, the wall on the current site was considered to act as a continuous deep strip footing below basement formation level, surrounded by a block of soil, with the assumption of a block type failure mechanism in the ultimate state. In addition, the bearing capacity factor \( N_c \) in the London clay was reduced by multiplying with a reduction factor \( f \), to account for the existence of non-structural female piles in the wall. The reduction factor \( f \) is expressed as;
\[ f = \frac{\pi D}{4S} \]  

(9)

where D is pile diameter and S is male pile centre to centre spacing. This approach produces an estimate of the axial capacity of the wall per metre run. Multiplying this value by the centre to centre spacing of the hard piles yields the vertical capacity of an individual hard pile.

Prior to the construction of the RC capping beam on the wall, a number of hard piles in the wall were tested to 1.5 times the safe working load (SWL) in compression. As tests were carried out before excavation for the basement, additional capacities derived by test piles through skin friction in soils above proposed basement formation level were discounted while assessing measured capacities of the test piles. The load-settlement curves for the non-failed load tests were extrapolated beyond the maximum test loads, following the analytical approach of Paikowsky & Tolosko (1999), to determine the ultimate vertical capacities of the piles in compression. Load-settlement curve for one of the test piles is shown in figure 6.

Figure 6 shows a reasonable level of agreement between ultimate capacity predicted with the method outlined above and actual measured capacity, while the common industry approach of factoring down the estimated capacity of an equivalent singly acting pile to 50%-60% to account for pile group efficiency is seen to be quite conservative. In addition, the pile group efficiency of the wall was deduced to be approximately 90%, which is in line with Rose & Taylor’s (2010, 2012 & 2013) assertion that pile group efficiency of perimeter piles could be close to unity. The 90% pile group efficiency recorded is also noted to be higher than 50%-60% suggested by some workers (e.g. Broms, 2007 and Sowers et al., 1961) for piles spaced at < 1.5D in clay and which are typically adopted in practice.

6. CONCLUSIONS

The principal factors influencing the groundwater cut-off capabilities of secant pile walls have been identified. These include: rig type, rig capability, installation technique, pile size, verticality tolerance, horizontal positional tolerance, depth of sealing stratum and minimum required pile embedment in sealing layer. The dearth of publications with comprehensive specific information on the estimation of optimum interlock thickness and pile spacing for effective groundwater cut-off to acceptable levels of accuracy has also been highlighted. As helpful guides to secant wall designers in the industry, simple empirical equations for estimating optimum bite thickness and pile spacing for groundwater cut-off have been presented and validated by reference to a recently completed multi-level basement project. These equations account for all the factors enumerated above.

![Figure 6. Extrapolated load-settlement curve for a selected hard pile on the site](image-url)
been shown to be considerably less conservative when compared with a common routine design approach, while predictions of the method are shown to be in reasonably good agreement with the results of a recent research-based small scale model tests on perimeter piles.

7. REFERENCES


8. ACKNOWLEDGEMENTS

I would like to specially dedicate this paper to my newborn baby; Princess Alicia Omojadesola Adehimpe and her mum Adebayo. They both make my world so colourful and exciting. The paper is also dedicated to every child in Yewa-land, Southwest Nigeria and every member of the Young Yewa Professionals Foundation; a non-profit youth-led organization committed to the improvement of the standard of education and the overall standard of living in the community.

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