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COLLABORATIVE DEVELOPMENT OF SUSTAINABLE & ECONOMICAL SOLUTIONS FOR UNDERGROUND STRUCTURES

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Whilst safety is considered to be of high priority in every aspect of engineering projects, it is equally important for designers and contractors to be continually aware of their obligations to the immediate environment and the society as a whole. These include responsibilities to minimise the amount of non-renewable natural resources and energy used on projects, to reduce carbon foot prints on projects, to minimise the quantity of wastes produced on projects, to minimise the level of pollution on construction sites and to reuse materials and waste products whenever and wherever possible.

In other words, professional engineering practice needs to be accompanied by an underlying fundamental objective to improve, restore and sustain the environment. However, achieving this objective requires continuous collaborative interaction and effective communication between the different specialists involved on every project from the early stages. In addition, developing a well-thought-out economical solution is key to achieving the sustainability aspect of the above objective.

This paper focuses on the design, construction and management of a recently completed large multi-level basement scheme in Central London, with greater emphasis on collaborative approaches taken by the design engineers, commercial managers, construction managers and site operatives to deliver the most reasonably economical and sustainable solutions to the client. Solutions were based on combinations of general and specialist engineering knowledge, with due considerations for health & safety, sustainability, cost, practicality, time and community requirements.

INTRODUCTION

Underground structures have become vital components of urban life worldwide e.g. tunnels serve many water, wastewater, highway and railway schemes, basements have been incorporated into many urban commercial, institutional and residential developments, while many public underground car parks have been built to deal with the incessant problem of insufficient surface parking spaces in busy urban centres.

The safe design, construction and maintenance of underground structures have been well-mastered by the deep foundation industry over the years. However, just like many other areas of engineering, aside the need to satisfy safety requirements, underground construction practice is now faced with a new set of requirements; the demand for more sustainable and cost-effective solutions, with reduced environmental and societal impacts. Designers and managers of underground construction schemes are now compelled to minimise the use of natural resources and energy, to minimise the amount of waste produced, to minimise the level of environmental pollution, noise and disruption to traffic and normal societal life at ground level around underground construction sites. In addition, the recycling of site wastes and reuse of materials have now become important aspects of underground space development. Considerable effort is being put into promoting sustainable development across the industry.

According to Brundtland (1987), sustainable development may be defined as a developmental process that satisfies the requirements of the present, without negatively affecting the potential of future generations to satisfy their own needs. This definition clearly conveys the importance of sustainable practice to not only the present, but also the future. On underground construction projects, the three main pillars of sustainability assessment are; economy, the environment and the society. However, as suggested by Jefferson et al. (2006), the three assessment criteria need to be considered concurrently and not in isolation. This relatively complex process requires the determination and collaboration of all the specialists involved, to adopt an integrated approach to sustainability through planning, target setting, monitoring and reporting from

design stage to construction and post-commissioning stages.

This paper presents a recently completed 3-4 level basement construction scheme in Central London, with particular focus on the sustainability aspect of the project from planning to design and construction stages. Collaboration between the specialists involved and the resultant sustainable solutions delivered are carefully highlighted. The precautionary measures taken to minimise environmental and societal impacts are outlined. The paper also presents a couple of novel numerical methods developed and adopted by the project team to optimise the design for the excavation support system and to achieve significant savings in cost of construction materials and energy.

SITE GEOLOGY

The project site was located in Vauxhall, Central London, United Kingdom. Site stratigraphy comprises of up to 3m thick made ground directly underlain by a layer of very soft to soft 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 it is underlain by a layer of very dense Thanet Sand at 48m depth. As the site was next to the River Thames on the south eastern 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.

PROJECT INFORMATION

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 foot print 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 a necessity, to enable basement construction.

Table 1 – Generalised stratigraphy & geotechnical design parameters

Depth (m) bgl	**Description**	**N_{spt}**	**Angle of Shearing Resistance ϕ' (°)**	**Young's Modulus E_u or [E'] (kPa)**	**Cohesion C_u or [C'] (kPa)**
0.0 – 9.0	Made Ground & Very Soft to Soft Clay & Peat	1 - 8	25.0	[10000]	[0.0]
9.0 – 10.0	Medium Dense to Dense to Very Dense Sandy Gravel	17 - 41	36.0	[50000]	[0.0]
10.0 – 16.0	Firm to Stiff London Clay	13 – 30	25.0	80000 [65000]	100.0 [5.0]
16.0 – 29.0	Very Stiff London Clay	32 – 44	25.0	120000 [95000]	150.0 [5.0]
29.0 – 48.0	Very Stiff to Hard London Clay & Weak Mudstone Bands	43 – R	25.0	175000 [140000]	220.0 [5.0]
Below 48.0	Very Dense Thanet Sand	R	37.0	[150000]	[0.0]

ECONOMY & SUSTAINABILITY

Design, Commercial, Construction & Environmental Considerations

(i) Planning, Design & Pre-Construction Stages

The project developer's original proposal for the sub-structure package was based on the installation of a reinforced concrete (RC) diaphragm wall for earth retention and groundwater cut-off and the construction of a 3m-thick raft foundation to support the structure. However, a careful review of the developer's original proposal by the foundation specialist contractor's design engineers, commercial managers and construction managers from the perspectives of economy and sustainability, resulted in a number of changes to the original scheme.

The commercial managers thought that the installation of a diaphragm wall would have been a relatively slow and expensive process, which would have had a negative effect on overall construction cost. Therefore, the originally proposed diaphragm wall was replaced with a bored pile retaining wall scheme for higher production rate, reduced installation cost, reduced volume of structural concrete, reduced quantity of steel reinforcement and reduced overall construction cost.

The revised scheme was supported by the foundation specialist contractor's construction managers, who were concerned about the non-availability of adequate space on the site to accommodate the large machineries, bentonite mixing and recycling plants and other ancillary equipment that would have been associated with a diaphragm wall scheme. They suggested the installation of a secant pile wall (comprising of interlocking male and female piles), to provide both earth retention and groundwater cut-off.

However, for improved efficiency and economy, the construction managers and commercial managers jointly suggested that the installation of the male and female piles be carried out concurrently with two different rig types. It was proposed to install the male piles with a cased secant piling (CSP) rig for improved verticality tolerance. The CSP rig is a customised 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. The technique improves the achievable verticality tolerance to 1:150, when compared with 1:75 achievable with a traditional uncased CFA bore (after ICE, 2007). In addition, the customised technique results in reduced overbreak and hence reduced volume of concrete per pile when compared with CFA drilling, while the finished wall appearance is aesthetically better.

On the other hand, for economy, it was recommended that the female piles be installed by traditional CFA drilling; the reduced verticality tolerance associated with this technique was off-set by the commercial benefit derived from the lower higher rate of the CFA rig, when compared with the CSP rig. Both techniques chosen for the secant pile wall (CSP & CFA) are faster and more economical than rotary bored piling. The relatively faster wall installation techniques contributed towards the project team's objective of limiting energy consumption and CO_2 emission on the project. Figure 1 shows wall installation on the site.



Figure 1 – Secant wall installation on the site involved concurrent use of CSP and CFA rigs for the male and female piles respectively.

A hard-soft secant pile wall solution was initially preferred by the foundation specialist contractor's construction managers. However, subsequent detailed review by the specialist design engineers revealed that a hard-soft secant pile wall would not have been the most appropriate and

economical solution. This is because the female piles would have been made of 5 N/mm^2 concrete. The hardening of a pile is an exothermic process; associated with the release of heat. Heat release would have resulted in the formation of cracks in the weak 5 N/mm^2 concrete and these would have served as conduits for the seepage of groundwater into the basement in the long term. Therefore, the adoption of a hard-soft secant wall solution would have necessitated the construction of a permanent reinforced concrete (RC) wall (200mm minimum thickness) in front of the secant pile wall for long term water retention.

As a more economical alternative, the design engineers suggested the use of a hard-firm secant pile wall, which was eventually adopted by the construction managers. Firm piles were made of 10 N/mm^2 concrete, which could withstand the exothermic hardening process with no serviceability defects. This solution eliminated the need for the construction of a permanent RC wall in front of the secant wall and consequently, savings were made in structural concrete and steel reinforcement. For reduced embodied carbon in the wall, the design mix for the firm/female piles comprised of > 80% ground granulated blast furnace slag (GGBS), which is a cement replacement with lower environmental burden. The use of GGBS in concrete offers three distinct benefits;

- energy savings;
- reduction in carbon dioxide (CO_2) emissions;
- natural resources conservation.

To optimise the efficiency and economy of the secant pile wall, the foundation specialist contractor's design engineers formulated, validated and adopted a new set of empirical equations for estimating the optimum geometry of secant pile walls (see Adekunte, 2014). The new set of empirical equations expresses the optimum bite thickness β between male and female piles as;

$$\beta = k\,[(\upsilon * L) + h] + \alpha \qquad \text{---------- (1)}$$

while optimum spacing between male piles is expressed as;

$$\therefore S = D_m + D_f - 2[2\,(\upsilon L + h) + \alpha] \qquad \text{------ (2)}$$

In equations (1) and (2);

β = estimated required bite thickness between male and female piles at piling commencement level in mm;

k = a constant, which accounts for the potential horizontal and vertical deviation of immediately adjacent male and female piles in opposite directions. k should be taken to be 2.

υ = average verticality tolerance of both male and female piles in mm/m depth of installation, which is dependent on rig type and piling technique.

L = pile length required for cut-off; this is equivalent to depth of female pile toe.

h = 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, 2007).

α = minimum allowable bite thickness in mm between male and female piles at cut-off depth. This may be taken as 25mm (after ICE, 2007).

S = centre to centre spacing of male piles.

D_m = male pile diameter

D_f = female pile diameter

The application of equations (1) and (2) on the project ensured the construction of a perfectly water tight wall and completely dry excavation as shown in figures 2a and 2b. Therefore, no additional materials, labour or equipment was required for remedial works after completion of excavation; a common problem with secant pile walls.

The design engineers' review of the site's geological data showed that the proposed 4th level of basement at the centre of the site would lie wholly within the stiff to very stiff London clay stratum. Therefore, a secant pile wall was thought to be uneconomical for this section of works, as groundwater control wouldn't have been a major issue. Therefore, a contiguous pile wall was recommended as the most appropriate and economical excavation support system for the 4th basement level. While the construction managers were in support of this recommendation, they suggested the use of a different technique for the installation of the contiguous wall, which was

mainly required for earth retention beneath the excavation level of the perimeter 3 level-secant pile wall. The large diameter auger (LDA) rotary boring technique was recommended and adopted.

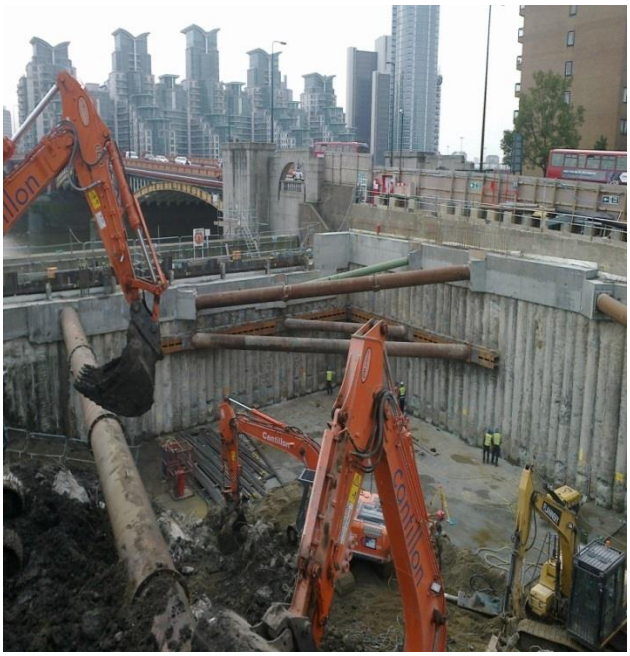


Figure 2a – Excavation for basement in progress.

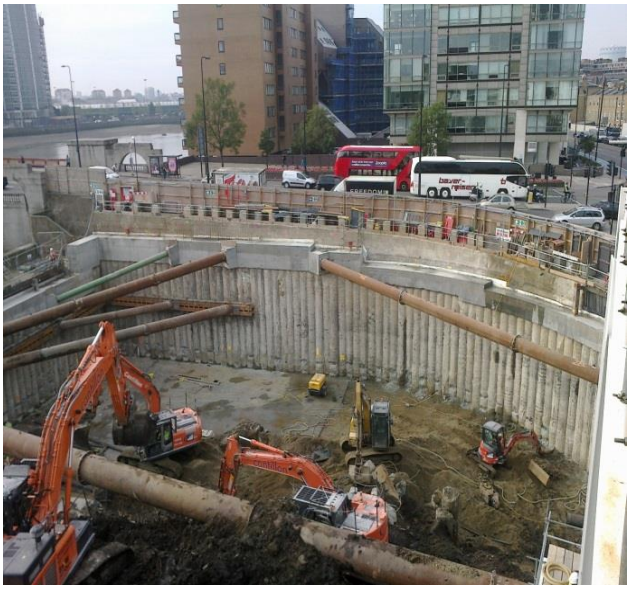


Figure 2b – Perfectly dry excavation was achieved with the secant pile wall on the site.

The LDA technique allowed each drillhole to be partially concreted up to the formation level of the general 3 level-basement (approx. 11m below ground level), while the rest of the hole was back-filled with uniformly graded pea gravels to ground/piling platform level. This approach resulted in significant savings in concrete and steel. It also allowed for the concurrent 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 carried out without having to deal with concrete piles projecting from the 4th level contiguous pile wall in the middle of the site. Overall, the basement works package involved the use of 3 different bored piling techniques for improved efficiency and economy.

In addition, with the aim of reducing the thickness of the originally proposed raft slab, the foundation specialist contractor's design engineers and the project developer's structural engineers agreed on a revised scheme, which allowed for the transfer of a sizeable fraction of the superstructure loads to the perimeter secant wall and the central contiguous pile wall. Therefore, the bored pile retaining walls were designed to serve the multiple function of retaining earth, cutting-off groundwater and providing vertical support to the superstructure. This yielded significant savings in concrete and steel for the raft slab.

While designing the bored pile walls to support vertical compressive and tension loading from the superstructure, the foundation specialist contractor's design engineers developed and adopted a new alternative approach for estimating the vertical capacities of bored pile walls. The approach was shown to be considerably less conservative in comparison with common routine design approaches, while predictions made with the method were shown to be in reasonably good agreement with the results of a recent research-based small scale model tests on perimeter piles (see Adekunte, 2014).

Generally, the geostructural design for all aspects of the basement structure involved the use of moderately conservative parameters, so as to minimise material and equipment usage on the project, whilst also ensuring that safety requirements were not compromised. Priority was given to value engineering through design, such that pile lengths were as short as practicable. Limited pile lengths allowed for reduced energy consumption during piling operations, reduced quantities of spoils produced during drilling and hence reduced haulage

requirement, which was a positive from an ecological perspective.

(ii) Construction Stage

In order to limit the disturbance of construction works to adjacent properties and occupants, as well as traffic on roads adjacent to the site, whilst ensuring minimal visual impact on the public, the site was surrounded by hoarding, which displayed project information. Allowance was also made for observation windows in the hoarding, to allow members of the public to view progress on site.

Piling operations were preceded by the construction of a suitable working platform to support the piling rigs and associated ancillary equipment. The 700mm thick piling platform was made of recycled aggregates derived from demolition wastes on the site. A reinforced concrete frame multi-storey structure had existed on the site before the current development. This had to be demolished, to make way for the new development. The decision to construct the working platform with recycled aggregates was preceded by consultation between the demolition contractor, the main contractor, the developer's engineers, the foundation specialist contractor's design engineers and construction managers. This piling platform solution allowed for savings in aggregate and associated haulage costs, reduced energy consumption, reduced carbon footprint and reduced quantity of natural resources used on the project.

An environmental management system (EMS) equivalent to the ISO 14001:2015 was established and implemented. As the project was next to the River Thames, prevention of surface water pollution was prioritised at all stages of the project; appropriate monitoring systems and emergency procedures were put in place. To minimise waste, the site waste management plan compelled every site operative to pay attention to material quantity requirements, so as to avoid over-ordering and consequent generation of wasted materials. Materials were reused on site wherever feasible, while wastes were segregated at source where possible, to maximise the proportion of site waste recycled. Wherever and whenever material reuse was impracticable on site, reuse or recycling of materials was done off-site. A 'just-in-time' material delivery system was also implemented, such that stock-piling of materials over long periods was avoided; this reduced risk of damage and disposal as waste.

The geo-environmental investigation report for the site had shown no evidence of contamination and therefore, spoils from hole drilling were thought to be reasonably safe for reuse. An agreement was reached between the foundation specialist contractor and the developers of a nearby construction site, such that nearly 100% of the spoils produced during wall installation were reused as fill on the nearby site. Haulage procedure was arranged such that vehicle trips and associated impact on noise levels, traffic and pollution were minimised. Safe movement and pedestrian consideration were also well accounted for.

Water conservation was another important sustainability aspect of the project. To limit water consumption on the site, the following approaches were taken;

- careful selection of plant and equipment, such that quantity of water required was minimised;
- recommendation and enforcement of staff-based initiatives such as closing of taps and water supply plant & equipment when not in use;
- specification of recycling water systems such as wheel washes, site toilet hand wash, etc.;
- strict recommendations on minimised use of portable water for sanitary uses. This allowed for the installation of water efficient sanitary ware for the use of site operatives e.g. low pressure spray taps in bathrooms, low-water dual flush toilet cisterns, etc.

Ground engineering works typically generate dust and other air-borne emissions as a result of the earthworks, plant and equipment involved. Therefore, air quality management during construction was another major issue that had to be catered for by the construction managers and site operatives. To limit the impact of groundworks on local air quality in the form of gaseous or particulate pollutants, a number of mitigation and control measures were implemented. These include;

- use of low emission vehicles;

- site operatives were compelled to ensure that engines of plant and vehicles were never left to run unnecessarily;
- use of ultra-low sulphur fuels in plant and vehicles;
- use of diesel particulate filters where appropriate and practicable;
- various dust mitigation and control measures during piling and associated groundworks; strictly enforced on-site management practices ensured that quantities of dusts generated and associated consequential effects were insignificant.

In respect of noise impacts on the environment, the chosen piling rig types and associated installation techniques (CFA, CSP & LDA) are characterised by low levels of noise and vibration. Therefore, they all had no impact on adjacent properties, neighbouring residents, workers, pedestrians and other nearby sensitive receptors. However, as a precautionary measure, noise and vibration monitors were installed at various points within and outside the site. These were regularly monitored during construction, to ensure that noise and vibration remained within tolerable levels as predicted.

CONCLUSIONS

The planning, design, construction and management of a deep basement scheme has been presented. Emphasis has been placed on economy, sustainability and measures taken to mitigate and control the impact of the ground engineering works on the environment and societal life from planning stage to construction stage.

The paper shows that the delivery of a sustainable underground solution requires an integrated approach, through continuous collaboration and effective communication between the project developer, the developer's engineers, the main contractor, the ground engineering specialist contractor's design engineers, commercial managers, construction managers and site operatives from project conception stage to commissioning. The development and delivery of an economical solution requires the input of all specialists involved at every stage of the project.

The paper also presents a number of customised ground engineering techniques and novel numerical methods that were developed on the project, to optimise the efficiency of the scheme and thus delivering the best value to the project owner. The novel numerical solutions could be useful to many foundation specialists at developing efficient and sustainable excavation support and groundwater cut-off solutions on underground construction projects that involve the use of bored pile retaining walls.

REFERENCES

ADEKUNTE, A., 2014. Dealing with complexities associated with the application of bored pile retaining walls in urban developments. Proceedings of the Deep Foundations Institute's 39th Annual Conference on Deep Foundations, Atlanta Georgia, USA, October 21-24, 2014.

BRUNDTLAND, G.H., 1987. Our common future. Oxford University Press, Oxford, UK.

INSTITUTION OF CIVIL ENGINEERS., 2007. ICE specification for piling and embedded retaining walls, 2nd edition. Institution of Civil Engineers, the Crown and Thomas Telford Publishing Limited, London, 2007.

INTERNATIONAL STANDARDS ORGANISATION., 2015. ISO 14001 – Environmental management. ISO Central Secretariat, Switzerland, 2015.

JEFFERSON, I., ROGERS, C., and HUNT, D., 2006. Achieving sustainable underground construction in Birmingham eastside. Proceedings of the 10th IAEG International Congress, Nottingham, United Kingdom, 6-10 September 2006.

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