EXPERIENCE-BASED VALUE ENGINEERING OF FOUNDATIONS & DEEP EXCAVATION SUPPORT SYSTEMS

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ABSTRACT

Good engineering practice is a function of sound theoretical knowledge, first-hand experience on previous projects of similar scope and scale, good acquaintance with case histories of similar projects completed by others in similar environmental conditions, as well as satisfactory degree of exposure to state-of-the-art methodologies.

The four factors itemised above are typically interdependent. They amalgamatively influence the judgement of the Engineer and they ultimately result in the delivery of safe and cost-effective solutions by Professional Engineers.

This technical paper presents detailed information on the ground engineering aspects of a large-scale housing development project located on a sloping site that had been presumed to be unstable in West Sussex, England. The ground engineering design package for the scheme comprised of temporary working platform designs & stability assessment for piling rigs and other construction machinery, geostructural designs for approximately 1km total run of permanent bored pile retaining walls to support the split-level construction on the sloping site and geostructural designs for the permanent foundation piles to support the housing units.

The paper details how the four factors outlined above were amalgamated by the project's foundation specialist consultants & piling contractors to deliver safe and practical solutions for the development, with significant savings in materials, cost and project completion time.

Keywords: sustainability, carbon footprint, safety, economy, piling, bored piles, foundations, working platforms, slope stability, excavation support, pile retaining walls, twin-buttress piles (TBP), push-pull mechanism, finite element (FE) modelling, geostructural design.

INTRODUCTION

Sustainability is increasingly becoming one of the most important aspects of civil & structural engineering practice. The significance of sustainable practice in the delivery of underground structures had already been highlighted by a number of authors e.g. Adekunte (2015), Jefferson et al. (2006 & 2007) and Brundtland (1987). Brundtland (1987) categorically defines sustainable development as an approach that fulfils the requirements of the present day, with no negative impact on the potential of future generations to satisfy their own requirements. In essence, Brundtland's (1987) definition clearly conveys the significance of sustainable practice to both the present society and the future.

Therefore, in the area of ground engineering practice, in addition to standard safety requirements, there are a few other vital requirements that must be satisfied by the present-day geotechnical engineer/geostructural engineer. These include the delivery of sustainable and cost-effective solutions, with reduced environmental and societal impacts. Essentially, many ethical codes now compel ground engineering specialists to limit

the consumption of natural resources and energy on development schemes. They are also required to minimise the quantities of wastes produced, as well as the levels of environmental pollution, noise and disruption to traffic and normal societal life around every construction site.

In line with the requirements outlined above, the ground engineering package of a large-scale residential development named 'Greenhill Gardens' was recently completed in West Sussex, England, with strict considerations for economy, the environment and society. Greenhill Gardens is one of the largest on-going residential developments in Southeast England. The overall scheme comprises of 175 low to medium rise houses and apartment blocks, with 299 parking spaces, over a total land area of 6 hectares in a greenfield setting.

The topography of the sloping site falls steeply in multiple directions, with a worst-case gradient of 1:8. Site topographical levels vary from +48.000m above ordnance datum (AOD) in the south eastern area of the site to +70.000m AOD in the northwest corner of the site. The site-specific ground investigation report points to on-going slope stability issues in the superficial soil layers overlying the mudstone/sandstone bedrock on the site. The complex relief of the site, as well as the presumed slope stability issues formed the basis of the geotechnical challenges associated with construction works on the site.

The ground engineering package for the scheme included; the design, stability assessment, construction and quality control testing of temporary working platforms to support piling rigs and other construction machinery, detailed designs and construction of approximately 1km total run of permanent bored pile retaining walls to laterally support the split-level construction on the sloping site and detailed design & construction of bored foundation piles to support the buildings. The piling works involved the installation of more than 2,700 piles of variable sizes and embedment depths across the site.

This paper chiefly presents how the ground engineering specialists' experience on previous similar projects, theoretical knowledge, exposure to recent research information and state-of-the-art practice have contributed to the development and delivery of safe, sustainable and cost-effective solutions across the site at Greenhill Gardens. The paper also encompasses the numerical modelling, design and construction of a rare wall restraining system by the project team to optimise the excavation support systems on the site and thus achieving significant savings in material usage, cost and completion time.

SITE GEOLOGY & GROUND MODELLING

Pre-existing site topography sloped in multiple directions across the site. Site stratigraphy chiefly comprises of a relatively thin layer of topsoil of less than 500mm thickness, underlain by firm to stiff to very stiff sandy silty clay layers of up to 8m thickness. These superficial soil layers overlie interbedded layers of extremely weak to weak to medium strong mudstone/sandstone/siltstone bedrock.

Measured plasticity indices in the superficial clay layers vary between 9%-50%, while moisture content varies between 15%-30%. Measured standard penetration test (SPT) N values range between 7-50. An approximately representative equation for the variation of undrained shear strength C_u (in kPa) with depth (in metres) within the superficial clay layers on the site is given by:

$$C_u = 40 + 20z \quad [1]$$

Where z is depth below the top of the clay stratum.

Unconfined compressive strength (UCS) measurements on samples of the mudstone/sandstone/siltstone range between 0.11 MPa – 15.5 MPa.

Prior to detailed design stage, the authors of the site-specific ground investigation report had suggested that the existing slopes on the site were presumably unstable. This particular assertion had influenced the decision of many piling contractors to decline the opportunity to tender or get involved on the scheme, as most piling contractors were concerned about the stability of large piling rigs on working platforms that could potentially be placed on actively unstable slopes.

The site-specific soil report's assertion of potential slope instability was based upon observations of relatively thin pockets of isolated, slope-parallel, smooth, undulating surfaces of distinctive colours from the surrounding soil matrices, within a number of trial pits dug on the site. These anomalous features were non-existent in several other trial pits. Also, they were mainly found around superficial soil-bedrock interfaces on the site. Based on the observations of the ground investigation specialists as described above, the site-specific soil report had recommended the use of very low residual shear strength parameters for the modelling of the superficial soil layers in retaining wall & earthworks designs for the site.

However, at detailed design stage, the appointed foundation specialist design engineers primarily carried out a detailed review of the geotechnical data presented in the site-specific soil report, whilst making parallel comparisons with historical information and research data on the shear strength of soils susceptible to slope failure, which are available in the literature. This analytical and comparative exercise confirmed that the recommendations presented in the site-specific soil report for Greenfield Gardens in respect of slope stability was misleading. In essence, the original presumption of the observed anomalous features as being slip surfaces was deemed to be incorrect, as the measured in-situ undrained shear strength of the presumed slip surfaces were inconsistent with typical shear strength of slip planes within unstable slopes, as shown in multiple research publications available in the literature (e.g. Hu et. al., 2017).

A simple illustrative example is the case of a presumed slip surface identified at 2m depth in one of the trial pits dug on the site. The in-situ undrained strength within the anomalous feature was measured to be 100 kPa. This measured shear strength is not consistent with typical in-situ strength of shear surfaces within unstable/failing slopes; in-situ undrained strengths of shear lanes within failing slopes typically range between 0.0-3.0 kPa, while residual undrained strength-peak undrained strength ratios typically range between 0.1-0.15 (after Hu et al., 2017). Generally, on the Greenfield Gardens site, in-situ measurements of undrained strength in the superficial soil layers that had been suggested to be unstable in the site-specific soil report range between 75 kPa-225 kPa; these measured values are generally inconsistent with existing published data.

Based on the above, the foundation specialist design engineers established the fact that the isolated anomalies observed in the trial pits could not have been slip planes. They were attributed to weathering effects around soil-rock interfaces on the site, which could be associated with the chemical or physical processes involved. In essence, the foundation specialist consulting engineers had no concerns over slope stability, working platform stability or piling rig stability on the site in both temporary and permanent conditions. Therefore, an alternative set of geotechnical design parameters were established for the detailed designs for the earthworks, working platforms, retaining walls and foundations across the site. These were generally less conservative than those that were originally recommended in the site-specific ground investigation report and they have ultimately resulted in the adoption of safe, cost-effective, sustainable and competitive ground engineering solutions across the site. The completion of works on the site, with no overall stability or serviceability issues during and after construction of the permanent structures and services on the site essentially justifies the alternative ground model adopted by the foundation specialist consulting engineers for the scheme.

Geotechnical design parameters originally proposed by the authors of the site-specific ground investigation report are presented in table 1. Alternative geotechnical design parameters established and adopted by the

appointed foundation specialist design engineers for the development are presented in table 2. Groundwater levels on the site generally lie below excavation levels.

In order to allow for the influence of stress relief and remoulding during excavation in front of the bored pile retaining walls on the site, coefficients of earth pressure K_o for the overconsolidated clay layers were limited to 1.0, in accordance with the recommendations of the CIRIA reports No's C580 (2003) and C760 (2017). The clay layers were modelled with total stress parameters in the temporary condition. In the permanent condition, the clay layers were assumed to exhibit drained behaviour and thus modelled with effective stress parameters. All other soil layers were conservatively assumed to exhibit drained behaviour in both temporary and permanent conditions and thus modelled with effective stress parameters only.

Coefficients of active and passive pressure K_a and K_p were deduced from Caquot & Kensel's (1984) chart. Effective wall friction angles δ on the passive and active sides were generally taken to be $0.5\phi'$ and $0.67\phi'$ respectively (where ϕ' is the effective angle of shearing resistance).

Table 1 – Geotechnical Design Parameters as Originally Recommended in the Site-Specific Ground Investigation Report.

Depth (m) bgl	Description	Measured N_{spt}	Recommended Angle of Shearing Resistance ϕ' (°)	Recommended Cohesion C_u or *[C']* (kPa)
0.0 – 0.5	Topsoil	-	11.0	*[0.0]*
0.5 – 8.0	Firm to Stiff to Very Stiff Sandy Silty Clay	7 - R	15.0	*[0.0[*
Below 8.0m bgl	Extremely Weak to Weak to Medium Strong Mudstone/Sandstone/Siltstone	R	50.0	*[10.0[*

Table 2 – Alternative Geotechnical Design Parameters as Adopted by Project Foundation Specialist Design Engineers at Detailed Design Stage

Depth (m) bgl	Description	Measured N_{spt}	Recommended Angle of Shearing Resistance ϕ' (°)	Recommended Cohesion C_u or [C'] (kPa)
0.0 – 0.5	Topsoil	-	25.0	*[0.0]*
0.5 – 8.0	Firm to Stiff to Very Stiff Sandy Silty Clay	7 - R	28.0	40 + 20z *[5.0[*
Below 8.0m bgl	Extremely Weak to Weak to Medium Strong Mudstone/Sandstone/Siltstone	R	39.0	*[10.0[*

PROJECT INFORMATION & CONSTRUCTION METHODOLOGIES

Pre-existing site topography sloped in multiple directions across the site. Site stratigraphy chiefly comprises of a relatively thin layer of topsoil of less than 500mm thickness, underlain by firm to stiff to very stiff sandy silty clay layers of up to 8m thickness. These superficial soil layers overlie interbedded layers of extremely weak to weak to medium strong mudstone/sandstone/siltstone bedrock. The highly variable

topographical levels across the site necessitated the division of the site into 12 No. separate piling zones, with distinct working platform levels, separate earthworks (cut & fill) designs, separate working platform designs & finite element stability assessments under rig loading, as well as separate contiguous bored pile retaining wall designs for each zone. A drone view of a section of the site is shown in figure 1. Figure 2 shows a typical finite element model for the working platform stability assessment for one of the piling zones, while figure 3 shows a 65 tonne-Casagrande B200 XP-2 piling rig installing a section of the bored pile retaining walls from an engineered working platform. Layouts of some of the piling zones are shown in figures 4a-4c, while typical cross-sections through the engineered working platforms in zones 1 and 8 are shown in figures 5a & 5b respectively.



Figure 1 – A drone view of a section of the site.

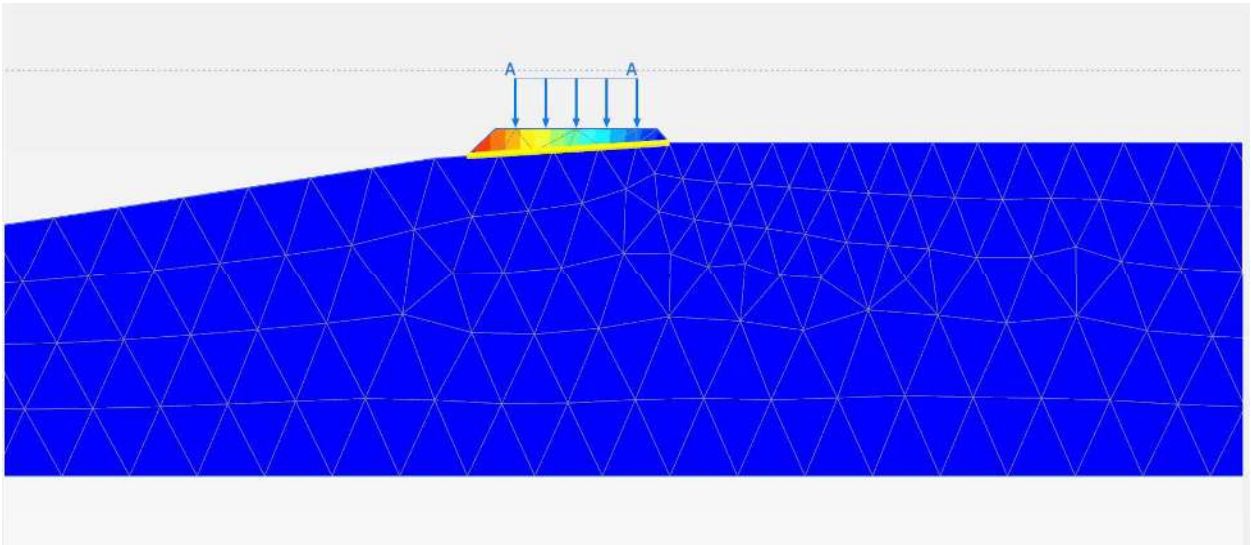


Figure 2 – Sample finite element (FE) model for zone 2 working platform stability assessment.



Figure 3 – Pile installation from an engineered working platform in zone 12 of the site.

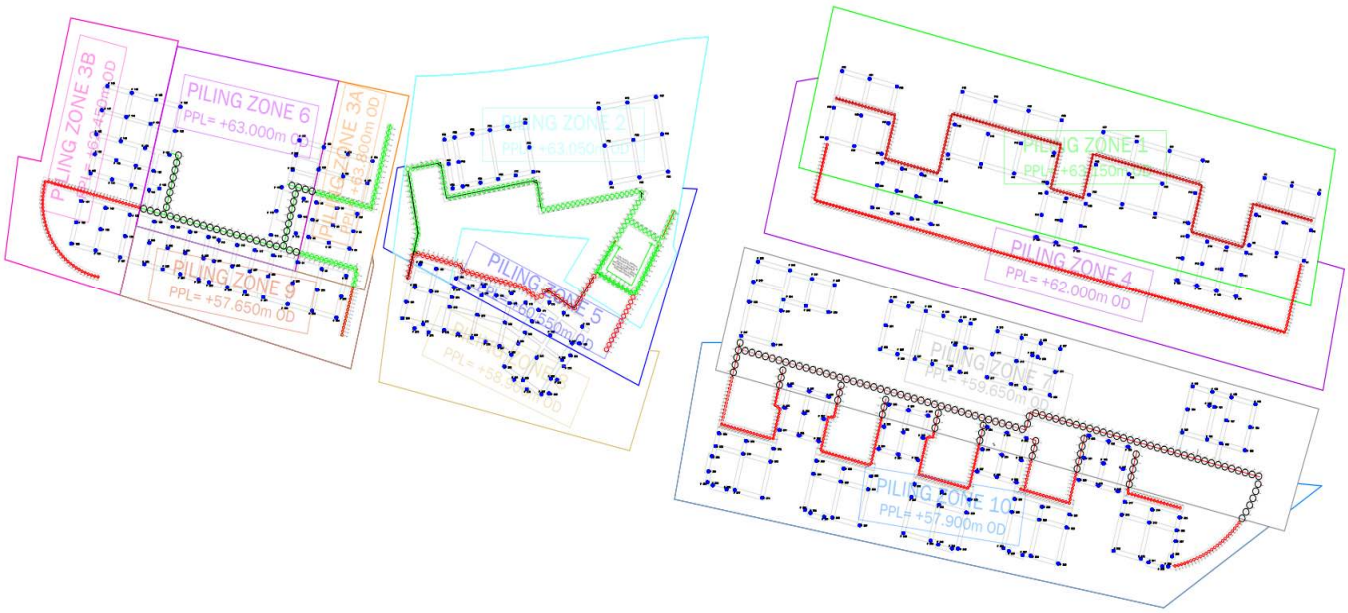


Figure 4a – Layout of some piling zones on the site.

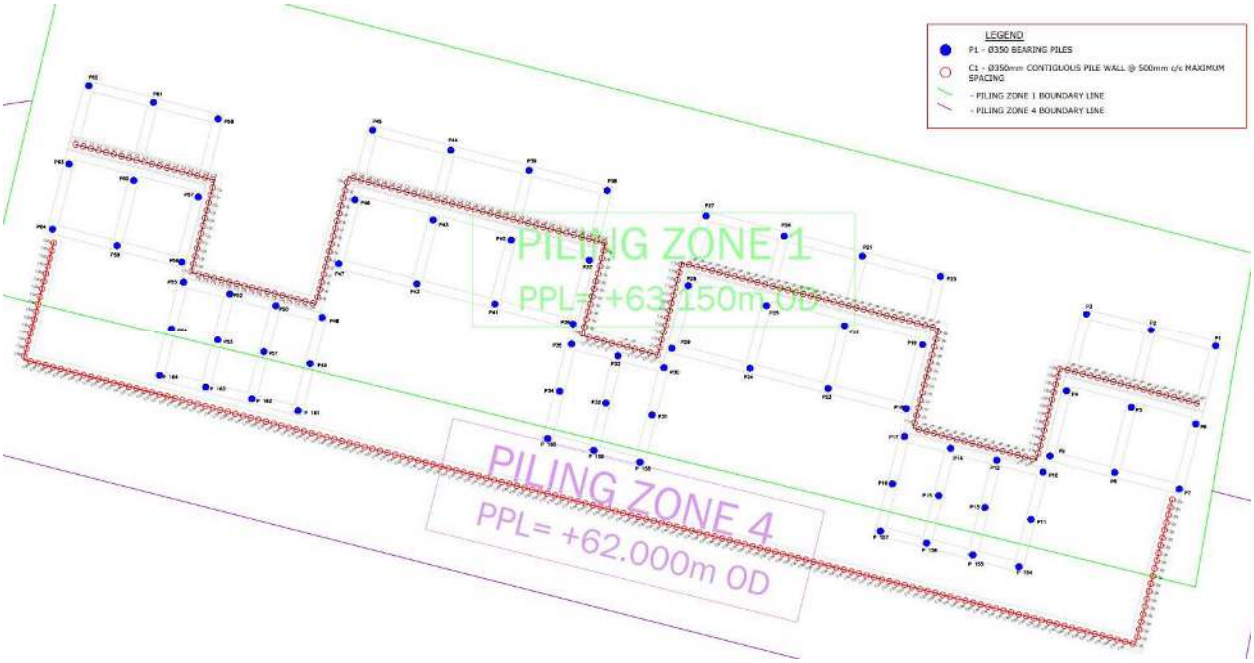


Figure 4b – Layout of some piling zones on the site.

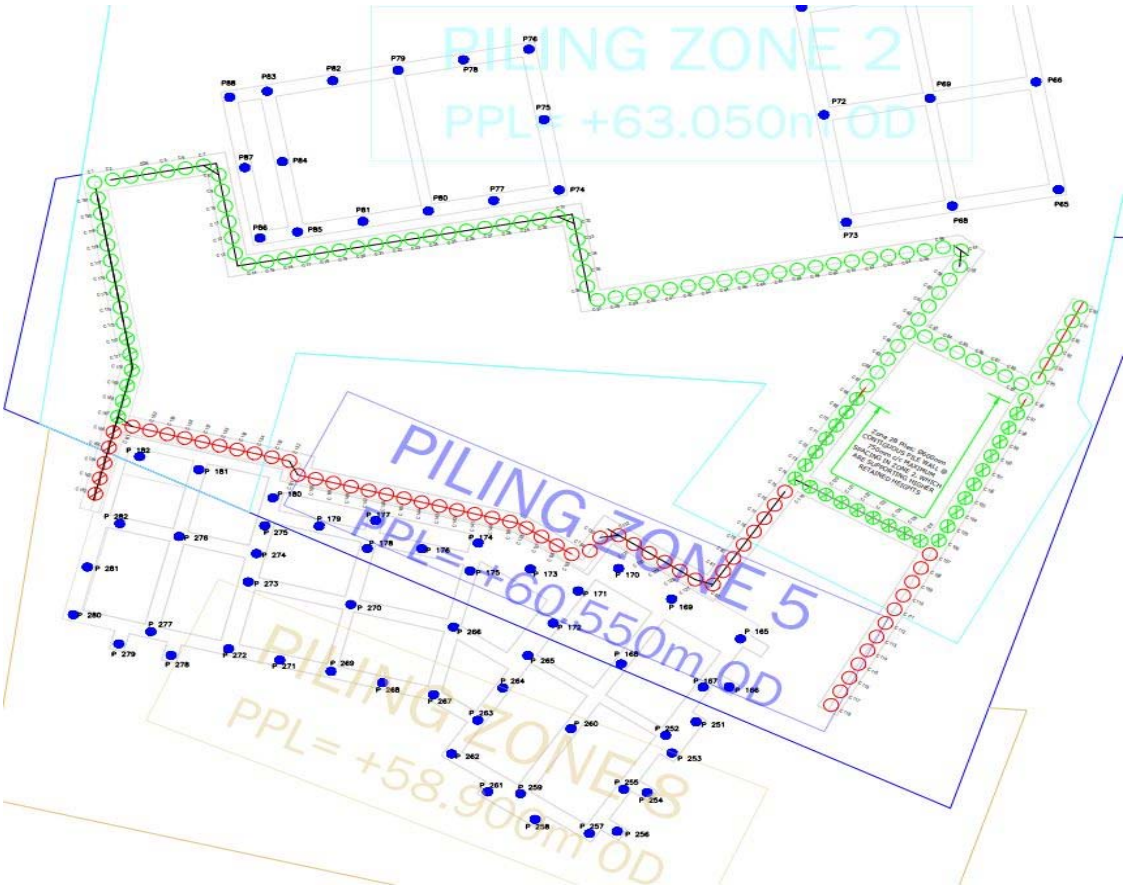


Figure 4c – Layout of some piling zones on the site.

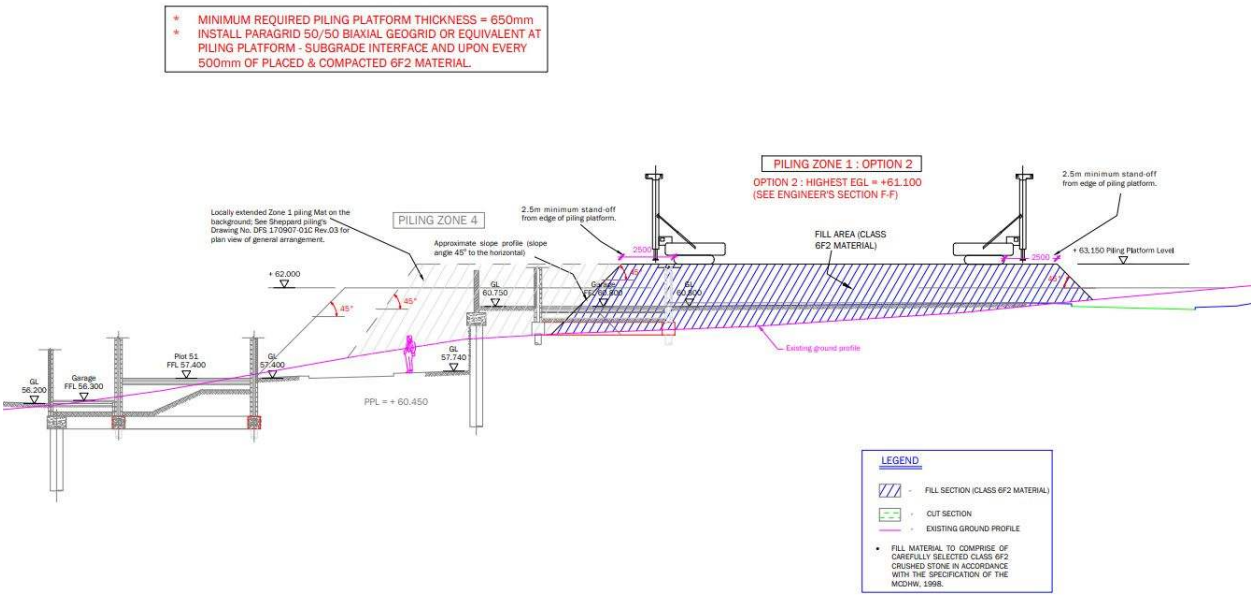


Figure 5a – Typical cross-section through engineered working platforms in zones 1 and 4.

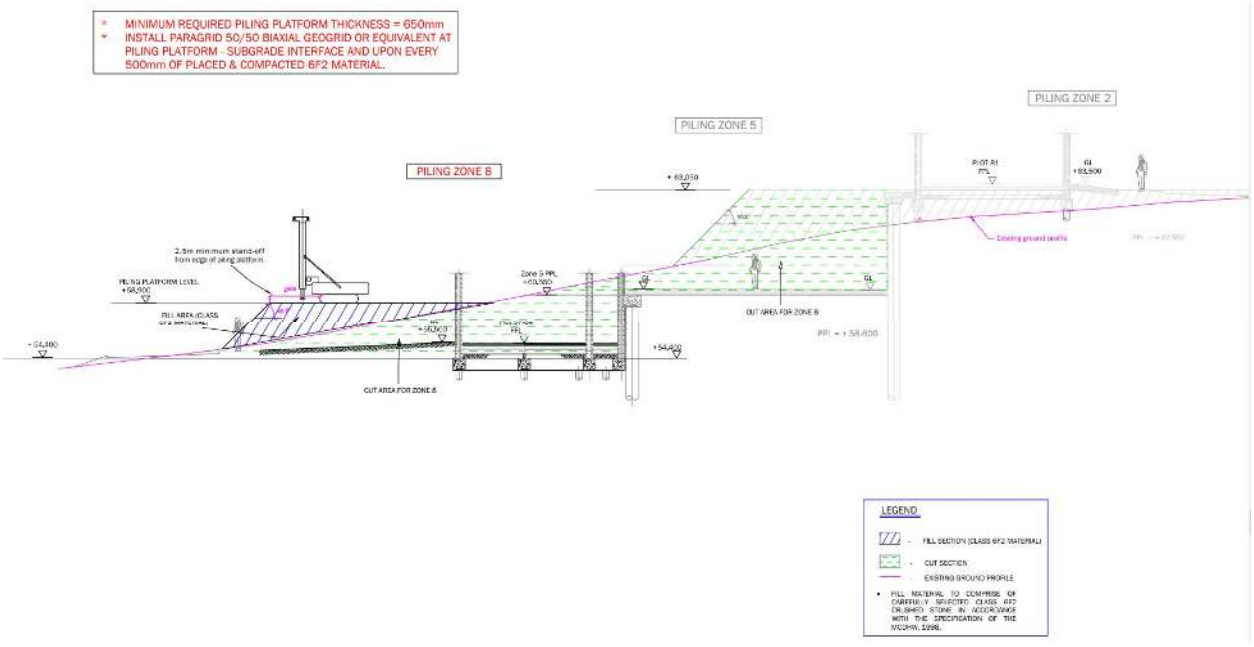


Figure 5b – Typical cross-section through engineered working platforms in zones 8, 5 and 2.

The sequencing of the working platform construction and piling works within each zone was carefully planned to optimise the construction programme, whilst also efficiently minimising material usage for working platforms, with minimal or non-existent disruption to other construction works happening on the site concurrently.

As rock head levels were highly variable across the site, the zoning of the site into 12 separate work areas allowed for the development of the most economical retaining wall & foundation designs for each zone,

based on the most representative bedrock level for the zone. This essentially resulted in the optimisation of production time and material usage for the piling works in each zone. In addition, rock strength and consistency were highly variable across the site, as the bedrock comprises of very weak to weak to medium strong to strong mudstone/sandstone/siltstone layers interceded in no definitive pattern. The zoning of the site also allowed for the efficient management of this particular risk. Designs for the retaining walls and bearing piles in each zone were based on the most representative and moderately conservative rock parameters for the zone and thus allowing for the optimisation of resources usage in each zone.

All contiguous bored pile retaining walls on the site were originally required to act as free-standing cantilevered walls in both temporary and permanent conditions, as free spaces were permanently required in front of the walls. Therefore, the use of temporary struts was impractical as a wall restraining system. In addition, as new buildings were to be built behind the retaining walls, use of tie-back anchors was also impractical. However, at construction stage, for budgetary reasons, the project developers requested for the value-engineering of the bored pile walls in zones 5, 6, 7 & 8. Retained heights in zones 5,6,7 & 8 were as high as 7.2m, while the retaining walls in the zones had originally been designed as 900mm diameter free-standing cantilevered sections.

In order to satisfy the revised project budgetary requirements, the pile retaining walls in zones 5, 6, 7 & 8 were redesigned to be restrained with a twin-buttress pile (TBP) system at regular intervals behind the wall runs. The TBP system comprises of 2 piles aligned perpendicularly against the direction of wall run. They are connected to the pile wall run by reinforced concrete capping beams. The wall piles are also connected by a reinforced concrete capping beam. The pile wall essentially relies on the push-pull mechanism that develops between the 2 twin-buttress piles to maintain overall stability and serviceability. Typical layout of a buttressed pile wall in zone 7 of the site is shown in figure 6. A typical section of the buttressed wall in zone 8 is shown in figure 7, while a typical FE model of the section is illustrated in figure 8. Please see Adekunte et al. (2010), Adekunte (2014) and Adekunte et al. (2018) for more detailed information on the engineering mechanics that enable TBP systems to function effectively in retaining wall applications.

The adoption of the TBPs in piling zones 5, 6, 7 & 8 essentially resulted in the reduction of the originally required pile size from 900mm to 600mm, considerably reduced pile lengths and significantly reduced steel reinforcement quantities in piles, without compromising the project requirement for permanent free space in front of the retaining walls. In monetary terms, a total saving of circa. £300,000 was achieved with this alternative solution. The TBP system had been successfully adopted by the project's geostructural design consultants on a number of projects in the UK & Ireland, while several technical papers on the development and application of the system had been published in a number of ground engineering-specialist conferences; see Adekunte et al. (2018), Adekunte (2014 & 2015). These preceding project experiences facilitated the smooth pathway to the application of the novel system on the subject scheme at Greenhill Gardens, West Sussex, England.

SUMMARY OF KEY PROJECT ACHIEVEMENTS

From the perspective of ground engineering, the main achievements of the project team are outlined below;

1. By critically reviewing the site-specific ground investigation report, whilst also making reference to published historical data in the literature, the team successfully established and adopted considerably less conservative design parameters, when compared with the ones originally recommended in the site-specific soil report. This allowed for the development and adoption of much more economical ground engineering solutions, with optimised construction programme across the site.

2. The division of the steeply sloping site into 12 No. separate zones and associated sequencing of works between the zones allowed for variations in topographical levels, rock head levels, rock strength, as

well as stratigraphic inconsistencies across the site to be efficiently dealt with. The zoning system allowed for the establishment and adoption of the most reasonably representative design geometries and parameters for each area. These ultimately culminated in reduced material usage, increased productivity and minimal or non-existent disruption to other construction activities that were being executed on the site concurrently.

3. The adoption of the TBP system, which is a novel restraining system for bored pile retaining walls, resulted in considerable reduction in material usage and significant monetary savings of up to £300,000, which ultimately helped at keeping the project cost within the downwardly revised budget, whilst also ensuring the commercial viability of the project.

4. Lateral deflection readings obtained from inclinometers installed in a number of piles within the retaining walls show wall lateral movements to be generally less than 8mm over an 8 month-period after completion of bulk excavation. Worst-case change in lateral displacement was < 0.5mm over the last 2 months of monitoring. These essentially confirm the effectiveness of the bored pile retaining walls and the TBP restraining systems at maintaining ground stability on the site, whilst limiting ground and structural movements to tolerable magnitudes.

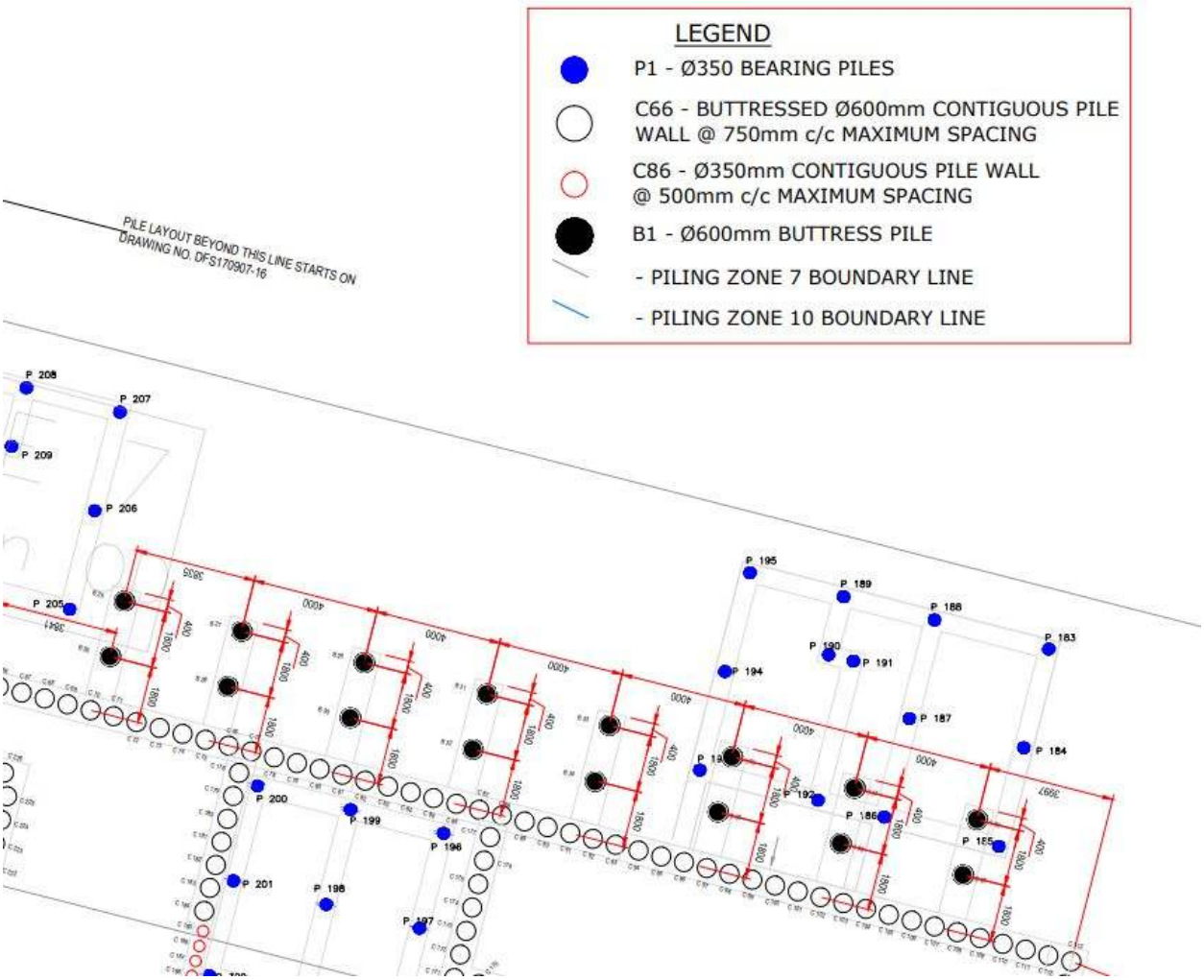


Figure 6 – Typical layout of buttressed pile wall in zone 7.

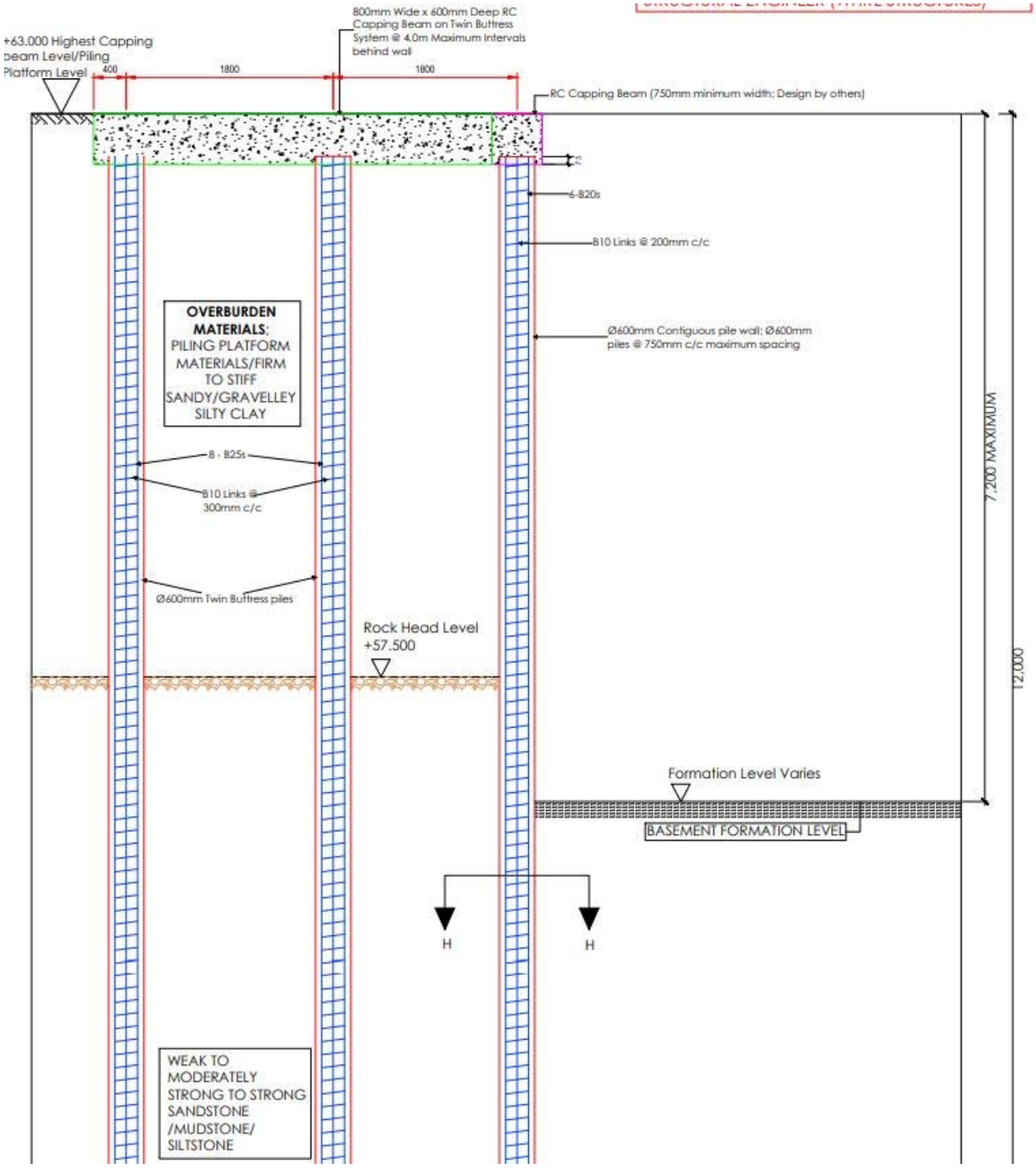


Figure 7 – Typical section of buttressed pile wall in zone 8.

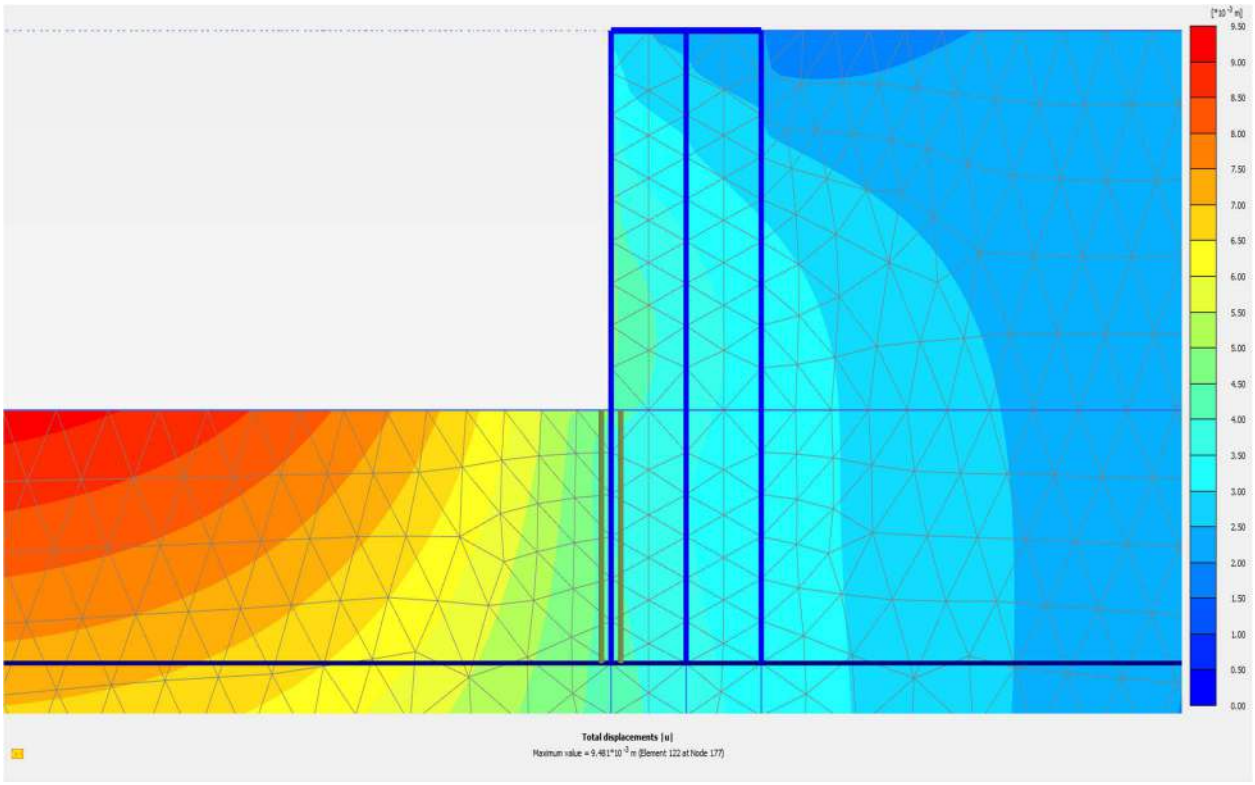


Figure 8 – Typical FE model for buttressed pile wall in zone 8.

CONCLUSIONS & RECOMMENDATIONS

This paper details the ground engineering aspects of a large-scale housing development scheme located on a sloping site that had been presumed to be unstable in West Sussex, England. The paper highlights how exactly the project team dealt with the numerous risks associated with the site, whilst delivering the most economical, safe, practical and competitive ground engineering solutions across the site, with significant savings in materials, cost and project completion time, by adopting a combination of sound theoretical knowledge, first-hand experience on previous projects of similar scope and scale, good acquaintance with case histories of similar projects completed by others in similar environmental conditions, as well as the team's exposure to state-of-the-art ground engineering methodologies. Every practising ground engineering professional must be encouraged to amalgamate these four supporting values to deliver safe and cost-effective solutions on every project.

The paper confirms that there are alternatives to traditional use of props and tie-backs as restraining systems for bored pile retaining walls and one of such alternative solutions is the novel TBP system adopted by the team on the site. While the application of the TBP system resulted in substantial savings on the scheme, the system also offers a number of advantages over conventional props and anchors. When compared with props, they are more suitable for the maximisation of space in front of retaining walls. Also, when compared with tie-back anchors, they significantly reduce the potential for intrusion into neighbouring properties. In addition, as the TBPs are installed concurrently with the pile retaining wall and with the same equipment, they offer significant benefits in respect of construction programme/project completion time. Therefore, the application of the TBP restraining system should be encouraged on future deep excavation/basement projects.

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