Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

1 Leadenhall advanced pile-enhanced raft sustainable design

Conception durable avancée de radier amélioré sur pieux du 1 Leadenhall

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ABSTRACT: The 1 Leadenhall building will be a premium office development located within London's financial district. The tower is 34-storeys with a two-level basement, located within a highly constrained site. Robert Bird Group (RBG) undertook foundation feasibility studies in parallel to the development of a more traditional foundation solution. The preliminary solution included 74No. 45m long 'wet' bored piles, 1500mm to 2400mm in diameter, requiring fluid to support the pile bore. RBG's subsequent detailed design included 100No. 1200mm diameter, 33m long dry piles into the London Clay, by delivering a pile-enhanced raft solution that minimised the number of new piles and omitted the need of support fluid. This design required departure from generally accepted practice including Eurocode factors on the pile capacities, which was achieved by going back to first design principles and adopting finite element modelling. The combination of further in-situ testing and foundation optimisation enabled the design team to offer significant value engineering and sustainability initiatives throughout the project. The optimised foundation scheme unlocked the site and largely improved the overall system efficiency and safety on site, whilst providing over 30% of cost and programme savings.

RÉSUMÉ : Le 1 Leadenhall sera un immeuble de bureaux dans le quartier financier de Londres. La tour est composée de 34 étages avec deux sous-sols. Robert Bird Group (RBG) a conduit des études de faisabilité pour les fondations en parallèle du développement d'une solution plus traditionnelle. La solution préliminaire inclut 74 pieux forés à la boue de 45m de long, d'un diamètre de 1500mm à 2400mm. Le concept détaillé de RBG suivant inclut 100 pieux forés simples dans l'argile de Londres, un diamètre de 1200mm et une longueur de 33m, grâce à un système de radier amélioré sur pieux minimisant le nombre de nouveaux pieux et ne nécessitant pas de pieu foré à la boue. Des pratiques généralement acceptées tels que des facteurs d'Eurocode appliqués à la capacité des pieux ont été utilisées au départ, ce qui a pu être réalisé en partant des principes fondamentaux de conception et de modélisation par éléments finis. Des tests in situ supplémentaires, combinés à l'optimisation de la fondation, ont permis à l'équipe de proposer une valeur ajoutée importante par l'ingénierie et des initiatives durables durant le projet. Ce procédé de fondation optimisée a débloqué le site et a largement amélioré l'efficacité globale du système ainsi que la sécurité sur place, tout en permettant des réductions de 30 à 40% du coût et du programme.

KEYWORDS: Numerical modelling, piled raft, sustainability.

1 INTRODUCTION

The 1 Leadenhall building will be a premium office development located within the financial district of London, UK. The tower is 34 storeys with two basement levels, located within a site, highly constrained by the historic listed Leadenhall Market, existing services, roads and buildings.

Robert Bird Group's (RBG) understanding of the Client's design programme and logistics drivers enabled the design team to unlock the site and add significant value to the proposed foundation scheme, whilst working within the constraints imposed by the existing basement footprint and piled foundations, as well as by the highly sensitive surrounding utilities and buildings. RBG worked closely with the Client's team to undertake feasibility studies in parallel to the development of a more traditional foundation solution. At the end of this process, RBG's geotechnical and structural team delivered a pile-enhanced raft foundation solution that reduced the sub-structure build complexity and significantly improved constructability and logistics. RBG delivered a solution that can effectively be built around the physical site constraints and the imposed tight construction programme and site logistics, without incurring additional cost.

The pile-enhance raft solution improved the construction programme and site logistics, generated cost savings, removed the need for support fluid during piling, removed the need for pile load testing, reduced construction noise, vibrations and workers shifts, reduced CO_2 equivalent emissions, and made the streets safer for pedestrians, cyclists and traffic.

This paper provides an analysis of the pile enhanced foundation design with the use of finite element analysis software with some focus on its sustainability contribution.

2 PROJECT DESCRIPTION

2.1 *Existing site*

The site is located in the eastern cluster of the City of London in the United Kingdom, and is bordered by Gracechurch Street to the west, Whittington Avenue to the east, Leadenhall Street to the north, and Leadenhall Market to the south. Several sensitive underground services run under the roads bounding the site. The site area is approximately 0.25 hectares.

The Leadenhall Market dates back to 1881 and abuts the entire southern boundary of the site. The structure is a National Heritage Grade II* listed building, to be protected due to its special national architectural and historic interest. The market consists of three roofed footways with three detached portions to the south lined with open fronted shops. It was built in red brick and Portland Stone externally with internal cast iron columns supporting an arched roof of timber and glass.

The site is currently occupied by a building named Leadenhall Court that has eight storeys above ground level and a two-level basement. The existing basement perimeter is supported by a contiguous piled wall, from 600mm to 1200mm in diameter, up to 5.7m c-c pile spacing, from 13.5m to 20.5m in length. The existing structure is supported by shallow piles founded in the London Clay, from 800mm to 1200mm in diameter and from 6.9m to 20.9m in length; several piles have an underream (1500 to 3600mm diameter). The existing building is to be fully demolished to basement level B2. The two-level basement space will be retained and enhanced to address the requirements of the new development. The existing shallow bearing piles will be disconnected from the new basement raft and not reused, whilst the contiguous piled walls will be reused to provide temporary support during the construction of the new substructure elements.

2.2 *Ground conditions*

The Ground Investigation works were carried out in two stages, with the first phase completed in 2017, in advanced of Stage 3 design completion (RIBA 2020), whilst the second phase was carried out in 2019 to deliver advanced testing in order to validate the piled raft feasibility study undertaken during Stage 4.

The original ground investigation consisted of:

- 2 No. cable percussion boreholes with rotary follow- on from the top of the London Clay to a maximum depth of 85.5m, executed outside the footprint of the existing building, with Standard Penetration Tests (SPTs) and groundwater and gas monitoring.
- 4 No. cable percussion boreholes to a maximum depth of 40.0m, executed inside the existing building sub- basement level, with Standard Penetration Tests (SPTs) and groundwater and gas monitoring.
- Geotechnical classification, shear box, triaxial and oedometer laboratory testing.
- Geo-environmental laboratory testing.
- Several intrusive investigations including 3No. parallel seismic tests to determine the toe levels of the existing bearing and contiguous piles, coring of the existing contiguous wall and concrete testing, and ferroscans to determine the properties of the reinforcement steel along the existing contiguous wall.

The subsequent advanced ground investigation was carried out to collect supplementary data to enable a more accurate ground interpretation, to further refine the ground profile and to obtain additional strength and stiffness parameters at different strain levels. The works included:

- 1 No. rotary borehole to a depth of 64.5m below ground level.
- 2 No. self-boring pressuremeter exploratory holes with 42 No. tests undertaken at around 2.0m intervals, from the top of the London Clay stratum to the bottom of the Lambeth Group stratum, executed from the ground floor slab of the existing basement.
- Geotechnical classification, triaxial and oedometer laboratory testing.

Table 1 outlines the derived ground model. A moderately conservative characteristic groundwater level of +8.5mOD was adopted for design purposes, just below the proposed basement B2 structural slab level (SSL) of +9mOD.

Table 1. Idealised ground model (existing ground level at +17.6mOD).

Stratum	*Level at top*	*General description*
Made Ground	+17.6	Gravel & Clay
Alluvium*	+10.9	Soft silty Clay
River Terrace Deposits	+10.3	Medium dense to very dense silty
London Clay	+6.0	Weathered to unweathered stiff Clay
Harwich Formation	-28.5	Stiff to very stiff sandy silty Clay
Lambeth Group	-29.0	Very stiff Clay with very dense
Thanet Sands	-47.2	Very dense Sand
Bullhead Beds	-57.5	Very dense sandy clayey Gravel
Chalk	-57.7	Moderately weak to extremely

3 FOUNDATION DESIGN

2.3 *Foundation Strategy*

During the initial foundation studies, the possibility of reusing the existing piles from the current building was assessed to create a more sustainable foundation scheme. However, upon review, this was concluded as being unviable due to the as-built information for the existing pile locations not being available. Additionally, their relatively short lengths resulted in insufficient capacities. Therefore, a hybrid solution to re-use the existing bearing piles was not taken forward and the tops of the existing piles would be trimmed to avoid direct contact with the new basement raft. However, the existing piles may provide some stiffening effect within the ground leading to reduced settlements, albeit a limited contribution due to their relatively short length compared to the overall deep 'pile group' behaviour, which the piled raft is likely to experience.

An exclusion envelope for each existing pile was formulated based on expected pile tolerances. Allowances were made for plan and verticality tolerances of both the new and the existing piles, it was assumed that the new piles would require steel casings extending through the granular material up to the top of the London Clay. The exclusion envelopes reflected the likelihood of clashes between existing and new piles at the bottom of the steel casing (taken as +3.5m OD); only clashes and coring through the existing pile under-reams were deemed acceptable as the under-reams are not reinforced.

The original RIBA Stage 3 design delivered a traditional piled foundation option comprising of 74 No. bored piles, 1500mm to 2400mm in diameter, approximately 45m long, requiring support fluid throughout the Lambeth Group soil stratum. A feasibility study was carried out at the beginning of the RIBA Stage 4 design to confirm the viability of eliminating support fluid by reducing the length of the piles to terminate within the London Clay stratum. The positive outcome of this feasibility study prompted the procurement of the additional advanced ground investigation works, which enabled the development of the final RIBA Stage 4 pile-enhanced raft foundation solution, comprising of 100 no. dry piles, 1200mm in diameter and 33m long. Figure 1 shows a comparison between the modelling of the preliminary and final schemes.

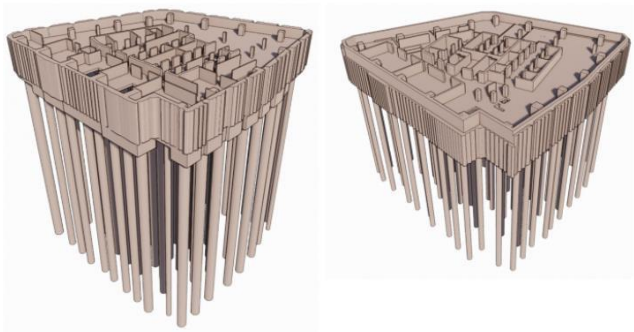

Figure 1. Substructure Modelling of RIBA Stage 3 vs RIBA Stage 4 Designs.

2.4 *Preliminary piled foundation design*

During the RIBA Stage 3 design stage it was determined that the most suitable foundation solution was a pile group under a large pile cap to support the proposed building core, and perimeter piles to support the outer columns. This solution was deemed to provide the best spatial distribution to support the imposed loading and the greatest economy while complying with the assumed ground model, the physical constraints imposed by the existing bearing piles and contiguous walls, the relatively tight site footprint, the adjacent historical buildings and utilities, and the proposed construction sequence.

The 3000mm thick core pile cap was proposed to overlie 38 No. 1800mm diameter piles, 44.0m long, to distribute the core loads into the pile group. The perimeter piles with diameters of 1500mm (13 No.), 1800mm (8 No.), 2100mm (11 No.) and 2400mm (4 No.), pile length between 39.2m and 46.0m, would support the outer building tower columns, with a system of large diameter monopiles connected by the general 1000mm thick basement slab, and capped groups with 2500mm thick pile caps.

Figure 2 and Figure 3 show the original adopted pile layout and the constraint imposed by the existing piles.

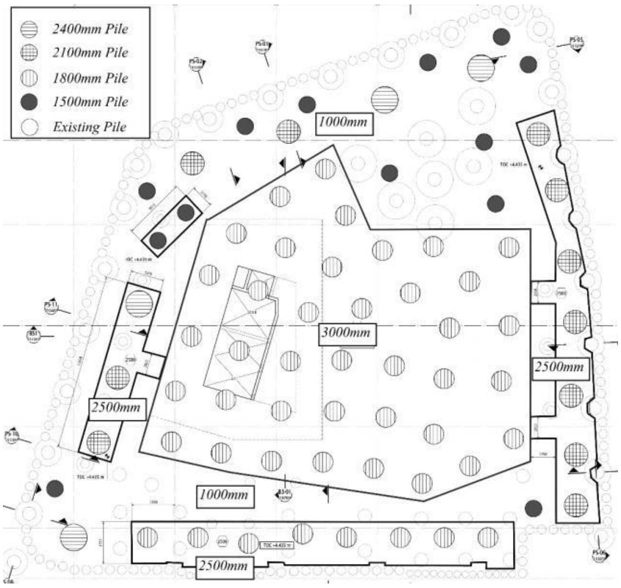

Figure 2. RIBA Stage 3 adopted pile layout and pile cap size.

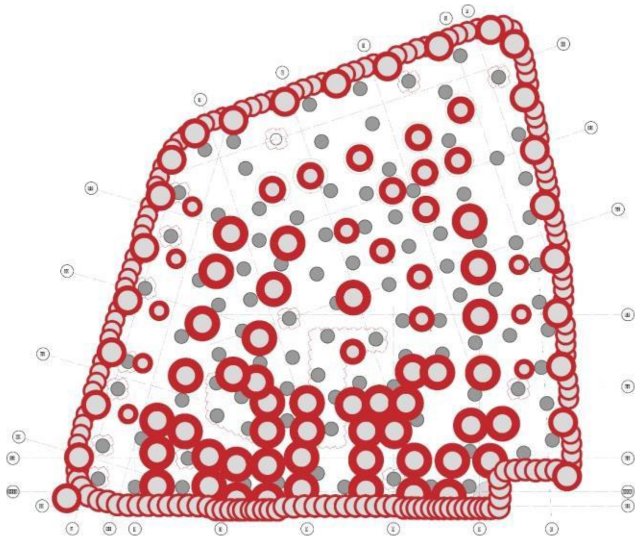

Figure 3. Illustration of the exclusion envelopes (in red-gray) applied to each existing pile and contiguous wall. Piles in gray denote proposed new foundation.

All piles were designed in accordance with the Eurocodes & UK Nation Annex (BS EN 1997, 2013) to guarantee the performance during the design life of the building and to verify the safety against failure. The piled foundation satisfied both the serviceability limit state (SLS) requirements in terms of absolute and relative settlement, as well as the required geotechnical and structural ultimate limit states (ULSs). In order to maximise the geotechnical compression and tension pile capacities, working and preliminary pile testing was required to enable the adoption of the smaller model and partial factors (BS EN 1997, 2013).

2.5 *Pile-enhanced raft solution*

To deliver the optimised pile-enhanced raft solution, the design required departure from 'standard' practice (i.e. Eurocodes). RBG merged the project's geotechnical and structural teams to create a focused 'substructure' team that went back to the first principles of piled raft design and outlined a robust methodology that could depart from the prescriptive Eurocode rules for traditional pile design. RBG's design comprised settlement reducing piles that operate under serviceability limit state (SLS) to ensure that the performance of the building is always guaranteed during its design life, without the need to justify ultimate limit state (ULS) pile capacities. The ultimate limit states are fully verified by the raft with the presence of piles to control absolute and differential building displacements and to provide additional redundancy against the geotechnical failure.

The first stage of the assessment of this scheme was to confirm whether a raft foundation satisfied serviceability (SLS) and ultimate (ULS) design checks. The geotechnical ULS design check was confirmed, however the raft settled approximately 240mm. This was deemed satisfactory from a ULS perspective but not for the SLS case. The structural ULS load cases were also checked using the structural CSI software SAFE. Under quasi- permanent SLS conditions, the raft was predicted to settle by approximately 165mm thus exceeding the limit of 75mm set by RBG's structures team. As noted, predicted serviceability settlements were in excess of tolerable limits for the superstructure, both in terms of total and differential settlement, as well as for existing adjacent historical buildings, buried utilities and highways criteria. Therefore, settlement reducing piles were introduced to reduce the deflection of the raft to within acceptable limits.

The subsequent step was to design the pile-enhanced raft in accordance with the guidelines outlined in the ICE Manual of Geotechnical Engineering (O'Brien at al. 2012). Given that the raft alone was confirmed to satisfy the ULS design cases, the piles could be designed to satisfy quasi-permanent SLS settlement criteria only, without the need to verify ULS pile capacities (refer to Figure 4). This approach also provided the opportunity to eliminate the need for pile testing.

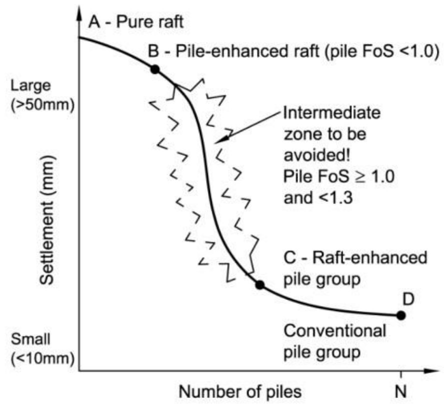

Figure 4. Pile-enhanced rafts versus raft-enhanced pile groups (O'Brien et al. 2012).

Straight-shafted piles are used to deliver pile-enhanced rafts, with an essential requirement to have a load-settlement ductile behaviour, which is typical of piles in clayey soils. The shaft resistance is essentially a frictional phenomenon and once it is fully mobilized, it usually does not change significantly with further displacement.

The final pile-enhanced raft layout (Figure 5) has been confirmed to minimise the number of piles whilst meeting the performance acceptable criteria, and consisted of the following:

- Central core supported on the 3500mm slab.

- Perimeter superstructure columns supported on the 2750mm slab.
- 100 No. 1200mm diameter bored piles, 33m long fully constructed within the London Clay layer, omitting altogether the need for bentonite or support fluids.

A further level of design checking was also applied where the ‘pile block’ was also checked against Eurocode 7 ULS geotechnical and structural combinations.

Figure 5. RIBA Stage 4 pile-enhanced raft layout of new piles on existing piles with exclusion zone.

3 SOIL STRUCTURE INTERACTION (SSI) ANALYSIS

An iterative process (Figure 6) was set up using both geotechnical and structural 3D numerical modelling software with the designers from each discipline working very closely together to ensure full design integration and coordination. This collaboration between geotechnical and structural engineers was essential to overcome modelling limitations and to deliver the innovative design by undertaking more advanced integrated soil-structure interaction 3D Finite Element (FE) analyses, interfacing Plaxis 3D, SAFE and Etabs.

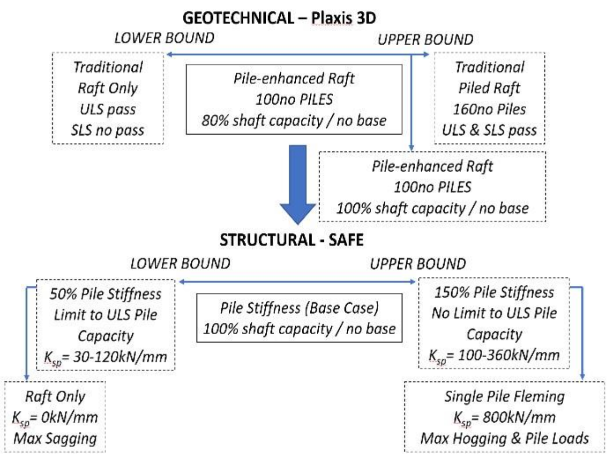

Figure 6. Soil-Structure Interaction process and bounding cases.

Figure 7 shows the combined geotechnical Plaxis 3D and structural Etabs 3D models.

Figure 7. Soil-Structure Interaction combined 3D geotechnical and structural models.

3.1 *Plaxis 3D finite element modelling*

The Plaxis 3D model was based on historical information available from the existing building (retaining walls and piles details) and the proposed 34-storey building (new foundation). The existing under-reamed piles were not modelled for simplicity. This was also to provide a more robust and conservative analysis by ignoring the positive strengthening effect that the existing piles may provide in the ground.

The pile locations and quantity were refined as the soil-structure interaction (SSI) process developed. Initially the pile layout consisted of 160No. piles and it evolved to the final layout of 100No. piles.

Two models were run in parallel:

- a model with a foundation system that consists of a raft only.
- a model with the pile-enhanced raft foundation system.

In both models, the soil block around the site was extended 70m in the x and y-axis (~2 times the excavation width), to ensure boundary conditions were set at a sufficient distance so as to not influence the modelling outcome. The depth of the z-axis boundary was set to extend to the bottom of Thanet Sands at -58mOD (approx. 64.25m below the pile cut-off level).

The analyses considered different load stages for the proposed structure:

1. Construct the 3.5m thick core raft.

2. Construct the core walls and core to the 14th floor.
3. Construct the 2.75m thick raft around the core.
4. Long-term building loads and consolidation.

In addition to the above load stages, the historical excavation of the existing basement has been modelled together with the surcharge load of the existing Leadenhall Court. A consolidation stage has also been modelled prior to the demolition of the existing building and proposed pile construction.

The existing and proposed basement was modelled using plates elements. The proposed basement raft for the 1 Leadenhall building was modelled using a 3.5m thick plate at the core with a fixed connection to the surrounding 2.75m thick plate. The 2.75m thick plate has a free connection with the retaining wall plate modelling the existing contiguous and proposed liner walls. The proposed 100No, 1200mm diameter piles were modelled using embedded beams with multi-linear shaft capacity from cut-off level +6.25mOD. In the embedded beam input, Plaxis only allows to input a base capacity in kN and a shaft capacity (multi linear) in kN/m. In accordance with the UK pile design best practice of piles constructed within the London Clay, the unfactored shaft pile capacity of the embedded beam was capped at 20m below the pile head as the undrained shear strength reaches 220kPa, hence, 110kPa shaft limitation (LSDA 2017).

Plaxis has a limitation when using embedded beams to model piles. As anticipated, the perimeter piles would be stiffer and attract more load. When these piles achieved their maximum specified capacities, Plaxis was able to redistribute their loads to the adjacent piles and the to the raft. However, when this redistribution leads to most of the piles achieving their maximum capacity, rather than allowing the foundation to move further, as would happen in reality, the analysis could not numerically converge, and the model did not consolidate. To overcome this modelling limitation, Plaxis 3D was used primarily to model the SLS case to guarantee the pile-enhanced raft was consistent with serviceability (SLS) requirements. The Eurocode geotechnical and structural ULS load cases, have been checked using the structural software SAFE. The geotechnical SLS based model conservatively considered 80% unfactored shaft capacity and no base capacity. The reduction of 20% of the shaft and zero base was implemented to provide additional redundancy to the design considering that preliminary and working pile tests will not be undertaken and to provide a more robust assessment of predicted absolute and relative settlement of the raft during the design life of the new building.

The piles could have been modelled using volume elements in Plaxis 3D to avoid having to limit the ULS pile capacity; however, the mesh would become cumbersome, and the model would not be able to run due to the number of volumes modelled. The superstructure loads were applied to structural shear walls or directly to the raft slab to model the core superstructure and columns, respectively. The settlement profile of the raft from this model accounted for the combination of the bearing potential of both the raft and the piles and allowed for the interaction between these elements and between the group of piles.

197No. point loads have been modelled acting on the core area in the temporary case. These point loads become permanent loads and a total of 388No. point loads were applied on the entire raft in addition to line loads along the perimeter of the building. A surcharge load of 10kPa was also applied on the 2.75m and 3.5m thick plates to replicate additional loads on top of the raft.

Both Mohr Coulomb and Hardening Soil with Small Strain Stiffness (HSS) soil models were adopted. The HSS parameters were derived using the pressuremeter tests, in order to account for the strain hardening and small-strain stiffness behaviours of the soils. The HSS soil model was used in parallel to the Mohr Coulomb soil model to study lower and upper bound behaviours of the piled-enhanced raft foundation, whilst it was decided that the Mohr Coulomb results were more suitable to undertake the final foundation assessment as more conservative.

4.2 *3D structural model bounding cases*

CSI software Etabs was adopted to model the entire structure allowing for staged construction. CSI software SAFE was adopted to design the raft. Linear springs, calculated based on the PLAXIS 3D results, were introduced below the raft to model the soil and the piles. The soil springs were spaced over a grid of 1.5m x 1.5m and the pile springs located according to the designated pile coordinates. To validate the ultimate limit state (ULS) checks as well as the load distribution between the soils and the piles provided by Plaxis 3D, the global Etabs model accounted for the staged construction of the building and used non-linear springs. The springs were allocated to the piles and based on load settlement curves (Fleming 1992). These were then modified using the results from Plaxis 3D to account for the additional settlements induced by the pile group effect and by the interaction between the piles and the raft.

To account for the potential variability in soil and pile stiffnesses, the Plaxis 3D springs adopted for the structural design of the raft in CSI SAFE were bounded as per the following:

- Base Case – 100% Pile Stiffness.
- Lower Bound Case – 50% Pile Stiffness.
- Upper Bound Case – 150% Pile Stiffness.

Although the geotechnical SLS Plaxis 3D base model considered 80% of the unfactored shaft capacity and no base capacity for the piles, all structural models (pile springs) have realistically been based considering 100% unfactored shaft capacity and no base.

SLS settlement limits for the raft, based on the requirements of the superstructure, have been set as follows:

- Total settlement = 75mm.
- Settlement along the perimeter = 60mm.
- Differential settlement (Column to Column) = 1:1000.
- Differential settlement (Column to Core) = 1:750.
- Incremental raft to perimeter = 25mm.
- Incremental core short term to long term = 25mm.

4.3 *Modelling Outcome*

From the Plaxis 3D modelling, the maximum quasi-permanent SLS settlement was estimated to be 56mm in the short term condition and 74mm in the long term & post consolidation condition (Figure 8). The maximum differential settlement between the centre of the core and the perimeter of the basement raft was less than 25mm in the long term & post consolidation condition (Figure 8).

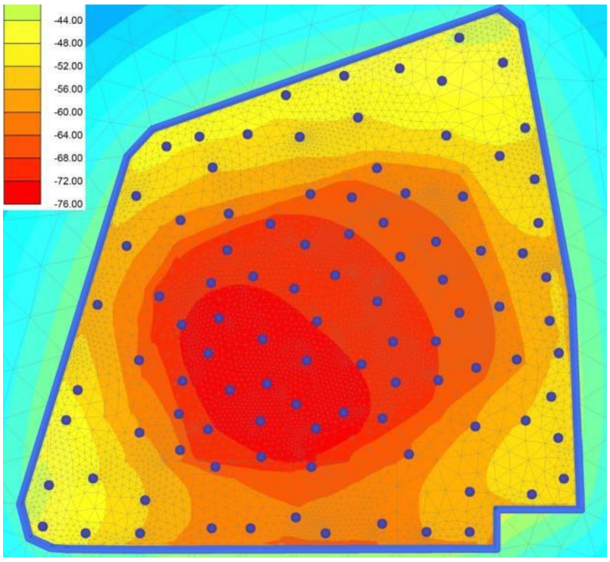

Figure 8. Plaxis 3D SLS settlement long term results (mm).

5 SUSTAINABILITY

The shift from a traditional piled foundation design to the final pile-enhanced raft solution, introduced important sustainability opportunities. The adoption of shorter and smaller dry piles has resulted in the following benefits:

- No need for support fluid with potential of soil and groundwater contamination.
- No need for bentonite plant.
- No need for piling rigs to carry out testing.
- Reduced material use (spoil, concrete and steel).
- Reduced material movements and therefore less vehicle movements to and from the site (noise, dust, air pollution).
- Smaller piling rigs and reduced working hours on site (less duration and reduced noise and vibration for the community).
- Simplified site logistics around the very trafficked London Streets.
- Overall, less uncomfortable conditions for traffic, neighbours, pedestrians, and Leadenhall Market users.

The total equivalent CO_2 saved was calculated to compare the original RIBA Stage 3 piled foundation design with the final RIBA Stage 4 pile-enhanced raft scheme. A Life Cycle Analysis calculation was made in accordance with BSI Standards Publications modules A1 to A5 (BS EN 15978 2011, BS EN 15804 2019), which are defined as outlined in Figure 9.

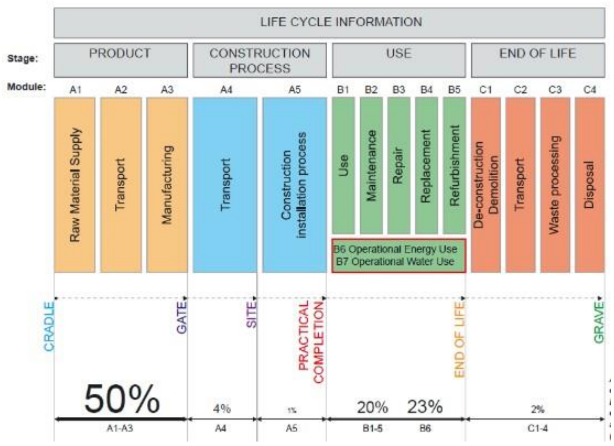

Figure 9. Lifecycle stages and modulus (Orr & Gibbons 2020), where the given percentages represent the approximate distribution of A1-C4 emissions.

The product cradle to gate modulus A1 to A3 assessment adopted concrete and reinforcement embodied carbon rates $kgeCO_2$ per kg from the Inventory of Carbon & Energy (ICE) Database V3.0 dated November 2019. The pile-enhanced raft scheme provided a reduction in total embodied carbon $kgeCO_2$ of approximately 2,000,000, which represents over 20% savings from the original piled foundation solution. The total concrete volume, including volumes from piles, basement raft and pile caps, was reduced by 25% from approximately 12,600m^3 to approximately 9,500m^3.

The construction process modulus A4 & A5w assessment, was also carried out to calculate embodied carbon $kgeCO_2$ saved by the reduction in material spoil removed from site and in materials transport to and from site. It should be noted that waste rates of structural materials (i.e. unused materials, damaged materials etc.) were not accounted for in the module A5w calculation. The assessment estimated the distance travelled between the construction site and the proposed landfill site and concrete batching plants, with embodied carbon rates taken from the iStructE Guide (Gibbons & Orr 2020). The pile-enhanced raft scheme provided a further reduction in embodied carbon $kgeCO_2$ related to the construction process of more than 20% from the original piled foundation solution.

6 CONCLUSIONS

This project demonstrates the real opportunity that advanced 3D finite element soil-structure interaction analyses can provide to deliver innovative designs, and demonstrated the significant potential to benefit future projects, particularly those under similar logistics and programme constraints. Going back to first geotechnical and structural principles of delivering a fully integrated pile-enhanced raft solution, Robert Bird Group (RBG) has defined a robust methodology beyond standard practice that could allow the design to depart from traditional accepted practice and the prescriptive code rules by undertaking more advanced ground investigations and non-linear analyses.

The more sustainable final solution has demonstrated the benefits of the initial financial and time investment for a targeted geotechnical investigation with additional advanced in-situ tests, coupled with the close collaboration between geotechnical and structural engineers throughout all stages of the project. This collaboration between geotechnical and structural engineers was essential to deliver the innovative design.

The optimised pile-enhanced raft foundation scheme has generated a reduction in construction programme of 6 weeks (30%-time reduction), as well as a reduction in cost for piling works of £2,000,000 (40% cost savings) from the original traditional piled foundation scheme. The need for pile testing was also eliminated. The pile-enhanced raft design has delivered a more sustainable solution that reduced material volumes and transportation movements and eliminated the risk of deep aquifer contamination associated to the use of bentonite or support fluid during pile drilling. 25% saving in terms of substructure concrete volume (5,000m^3), over 20% A1 to A3 product embodied carbon savings (2,000,000 $kgeCO_2$), and over 20% A4 & A5w construction embodied carbon savings have been calculated.

7 ACKNOWLEDGEMENTS

The developer Brookfield Properties, the project manager Avison Young and the cost consultant Alinea Consulting.

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