OPTIMIZING THE EMBODIED CARBON OF CONCRETE PILES - CASE STUDY

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Abstract

A recent UN report has shown that the construction industry is one of the seven major sectors that contribute significantly to environmental pollution and was responsible for around 20% of energy-related CO_2 emissions in 2020, and this is expected to increase during the upcoming years unless preventive actions are taken**.** Many studies have addressed the carbon footprint of superstructures and proposed innovative conceptual designs with a lower carbon footprint. However, the carbon footprint of substructures has only been investigated to a limited extent, this is believed to be due to a lack of certainty in the mechanical behaviour of soil and its interaction with structures as well as the construction complexity for deep foundations. This project aims to establish a robust algorithm for optimising the environmental impact of concrete piles bored or driven in different soil types. This will be achieved through varying different design parameters (concrete grade, steel-to-concrete ratio and pile slenderness ratio) across a multi-level optimisation algorithm tested for different pile-design cases. The change of these parameters will in turn lead to innovative conceptual designs for deep foundations corresponding to a better environmental impact while achieving the required load-bearing capacity. The analysis results show that piles with low capacities favour concrete with low compressive strength and high slenderness ratios. However, for piles with larger capacities, there exist critical threshold values for concrete compressive strength, steel reinforcement ratio and slenderness ratio corresponding to designs with the lowest environmental impact, these values are case-dependent and vary with the properties of soil and concrete used. The algorithm is tested on an existing case study of deep foundations for a mono-rail train bridge and a potential carbon saving of 72.4% is achieved. The findings also highlight the potential for future carbon reduction through a novel conceptual pile design utilising the lowest possible amount of concrete while achieving higher load-bearing capacity.

Keywords: deep foundations – carbon footprint – optimisation algorithm

INTRODUCTION

The amount of greenhouse gases produced by human activity and released into the environment has increased alarmingly during the last several decades. According to a recent UN report, the construction sector is one of the seven major industries that significantly contribute to environmental pollution. In 2020, it was responsible for 20% of the total energy-related CO_2 emissions, and unless preventive measures are taken, this percentage is expected to rise during the coming years [1]. As a result, the leading world institutions are pursuing urgent actions to reduce emissions by 78% by 2035, a crucial step to the planned global transition to net zero by 2050. There exists a wide body of research addressing the environmental impact of superstructures including life cycle analyses, attempts to limit the amount of material used in construction, and the discovery of new production methods with lower environmental emissions [2-3]. Unfortunately, there hasn't been much research on the carbon footprint of sub-structures [4-5], this is believed to be due to a lack of certainty in the mechanical behaviour of soil and its interaction with structures as well as the construction complexity for deep foundations. Accordingly, there is an obvious rationale for decreasing the embodied carbon of foundations via both innovation and scrutiny of codes and standards as foundations have shown to be responsible for a significant share of the total embodied carbon within any construction process [6]. Although many researchers have agreed that deep foundations are usually over-designed and designers are typically using high factors of safety, the majority of the literature on optimising the design of foundations has focused on cost efficiency rather than environmental impact, using this as a reference for judging the efficiency of structures while overlooking the link between cost-efficiency and sustainability [5,7,8]. Nevertheless, there have been some individual efforts to optimise the environmental impact of foundations through comparing the environmental impacts of precast and on-site cast concrete foundations, as well as some trials to use genetic algorithms to optimise the design of piled foundations and adjust design parameters like pile length, diameter, spacing, and pile cap thickness [4,9]. This research is a continuation of the work published in the *fib* PhD symposium 2022, Rome [10], and introduces an innovative pile optimisation algorithm tested to reduce the environmental impact of deep foundations through changing various design parameters (currently; concrete grade (f_{ck}), steel-to-concrete ratio (A_s/A_c) and slenderness ratio (L/D) and quantify the effect of each of these factors on the environmental impact of piles bored or driven in clayey soil. The algorithm will be applied to an existing case study of a deep-foundation project of a monorail train bridge constructed in the New Capital – Egypt to test the potential of carbon reduction in a real project.

METHODOLOGY

Ultimate limit state and structural capacity

A safe pile design must have a sufficient mix of base and friction resistances (geotechnical capacity), an acceptable settlement (serviceability limit), and the ability to resist the applied straining actions as a concrete element (structural capacity). For this part of the research, the geotechnical and structural capacities of piles are calculated using the globally recognised and utilised Eurocode formulae. While equation (1) determines the structural capacity of piles as short concrete columns in accordance with EC2 [11], equations (2-4) determine the geotechnical capacity of piles subjected to compressive loads.

$$N = 0.4 f_{ck} A_c + 0.75 f_y A_s \tag{1}$$

$$Q_t = Q_b + Q_s \tag{2}$$

$$Q_b = A_c . N_q . L_p . \frac{\gamma}{\gamma_\gamma} . \frac{1}{\gamma_{Rb}} \tag{3}$$

$$Q_s = \pi . D \int_0^{L_p} K . L_p . tan\,(\frac{\delta'}{\gamma_{tan\delta'}}) . dz . \frac{\gamma}{\gamma_\gamma} . \frac{1}{\gamma_{Rs}} \tag{4}$$

Where:

- A_c = concrete cross-sectional area.
- A_s = reinforcement steel cross-sectional area.
- f_{ck} = compressive strength of concrete.
- f_y = yield strength of steel.
- Q_t = geotechnical total capacity of the pile.
- Q_b = base bearing capacity of the pile.
- Q_s = shaft friction resistance of the pile.
- L_p = length of the pile.
- γ_γ , γ_{Rb} , $\gamma_{tan\delta'}$ = factors of safety as recommended by Eurocode.

A theoretical model is developed to compare the structural and geotechnical capacities of piles at different diameters. The material properties used for comparison are tested by Craig (2012) [12]. Comparison results are shown in Figure 1 and show that there is a growing difference between the two capacities as the pile diameter increases, at a pile diameter of 2400 mm and steel-to-concrete ratio = 0.01, the pile's structural capacity is about four times its geotechnical capacity. This finding agrees with the construction report published by Keltbray in 2021 [13] and indicates that piles designed to current codes are not making the best use of all the deployed material and that there is a wide margin to optimise the design through either adjusting the geometry of the pile or cutting out some of the ineffective concrete from the pile's body.

Serviceability limit state

Any pile's settlement can be calculated through various methods and according to different codes, also the allowable settlement limit can be assessed through different approaches and mainly depends on the sensitivity of the structure and the allowable differential settlement. Following is a summary of the two methods utilised in this research for calculating the pile's settlement and settlement limit.

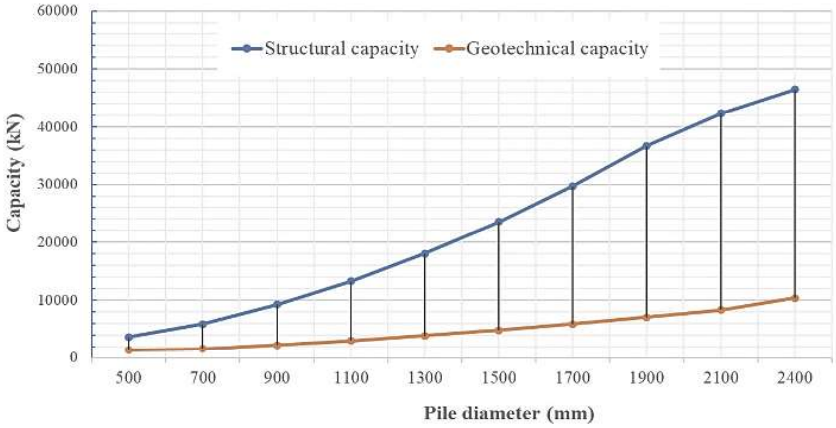


Figure 1: *Geotechnical capacity vs. structural capacity at different pile diameters calculated through equations (1-4).*

Calculating the predicted pile settlement

The force-displacement method (*t-z* method), also termed the load-transfer method, is used for theoretically calculating the pile's settlement, the pile's body is divided into a number of discrete sections (finite elements) with assigned properties, the pile-soil interaction is modelled using nodal springs with predefined nonlinear stiffness [12]. Each element has contributions from its two neighbouring nodes. The finite element method is then used to formulate the global equilibrium problem and therefore obtain the displacements and corresponding reactions at the nodes of each element under the applied load using the following equations:

$$\{F\} = \left[K_p + K_s\right] \cdot \{u\} \tag{5}$$

$$\{u\} = \left[K_p + K_s\right]^{-1} \cdot \{F\} \tag{6}$$

Where, $\{F\}$ and $\{u\}$ are the vectors of known actions (axial force) and unknown degrees of freedom (vertical displacements), whereas $\left[K_p\right]$ and $[K_s]$ are the stiffness matrices of pile and soil. The latter matrix includes the stiffnesses of the soil springs which are defined using the Randolph & Wroth (1978) relations and are as follows:

$$k_s = \frac{G}{r \cdot \ln\left(2.5\, L_p \dfrac{1-\nu}{r}\right)} \tag{7}$$

Where, G and ν are the shear modulus and Poisson's ratio of the soil, whereas L and r are the length and radius of the pile.

Allowable settlement limit

The allowable limit of settlement for each pile design is checked using the empirical equation presented in Eurocode 7 (EN 1997). The allowable limit of pile settlement according to Eurocode 7 (S_{tl7}) is calculated in terms of the pile's diameter d as follows:

$$S_{tl7} = 0.1\,(D) \tag{8}$$

Total embodied carbon

The work by Orr et al. (2020), in compliance with the Institution of Structural Engineers (IStructE), entitled "Short guide to computing embodied carbon" and based on BS EN 15978, is one of the most commonly acknowledged techniques for evaluating the environmental impact of structures [14]. The guide was published to aid structural engineers to evaluate the environmental impact of their designs by applying a few simple equations and using embodied carbon factors (ECF) for each material, some of which are given within the guide. The process divides any structure's life cycle into several stages, starting with the supply of raw materials (A1) and ending with recycling (D). The method is used for this research as it is considered to be one of the most comprehensive and straightforward methods. The total embodied carbon is then calculated using equation (9) [14].

$$\sum EC = (m_s)(ECF_s) + (m_c)(ECF_c) \tag{9}$$

Where:

- $\sum EC$ = total embodied carbon (kg)
- m_s = reinforcement steel mass (kg)
- m_c = concrete mass (kg)
- ECF_s = embodied carbon factor for steel ($kgCO_2e/kg$)
- ECF_c = embodied carbon factor for concrete ($kgCO_2e/kg$)

Optimisation algorithm

The optimisation algorithm is programmed using MATLAB and utilises the multi-level optimisation technique discussed by [15] and [16]. The optimisation process is composed of three different levels as follows:

Level 1: the input phase:
During this level all data is being input, data types are further classified as follows:

- Concrete properties: these are the properties of the used concrete including concrete grade (f_{ck}), steel-to-concrete ratio (A_s/A_c), steel grade as well as sustainability indices for the constitutes.
- Soil properties: these are the properties of soil including soil type, drainage conditions, angle of internal friction (φ') and soil cohesion (c').
- Design codes and factors of safety: the design equations, settlement calculation method, settlement limit calculation method, geotechnical capacity formulae as well as the different factors of safety.
- Embodied carbon calculator: this includes the used life cycle assessment LCA method depending on the available data, embodied carbon factors (ECF) as well as different formulae calculating the change in embodied carbon factors with material properties i.e. change of the embodied carbon factor of concrete $(ECO)_{conc}$ with the concrete grade and compressive strength.

Level 2: the processing phase
During this level the minimum quantities of material (both concrete and steel) needed to satisfy each of the three design limits (structural capacity, geotechnical capacity and serviceability state) are calculated through three different steps as follows:

- Step 1: the minimum pile dimensions to satisfy the structural capacity of the pile are calculated (L_{str} & D_{str}) these dimensions are then considered as the minimum feasible dimensions for the two following optimisation steps.
- Step 2: the minimum pile dimensions to satisfy the geotechnical capacity of the pile (L_{geo} & D_{geo}) are calculated considering the dimension calculated from step 1 as the calculation baseline.
- Step 3: the minimum pile dimensions to satisfy the serviceability limit state of the pile (L_{sett} & D_{sett}) are calculated considering the dimension calculated from step 1 as the calculation baseline.

Level 3: the carbon calculation phase

During this level, the final pile design dimensions (L_d & D_d) are chosen given all the previously calculated dimensions in level 2. These dimensions are then used to evaluate the total embodied carbon for each given design. Finally, the whole optimisation process is repeated as many times as needed varying one or more of the inputs in Phase 1. The whole optimisation process is simplified and shown in Figure 2.

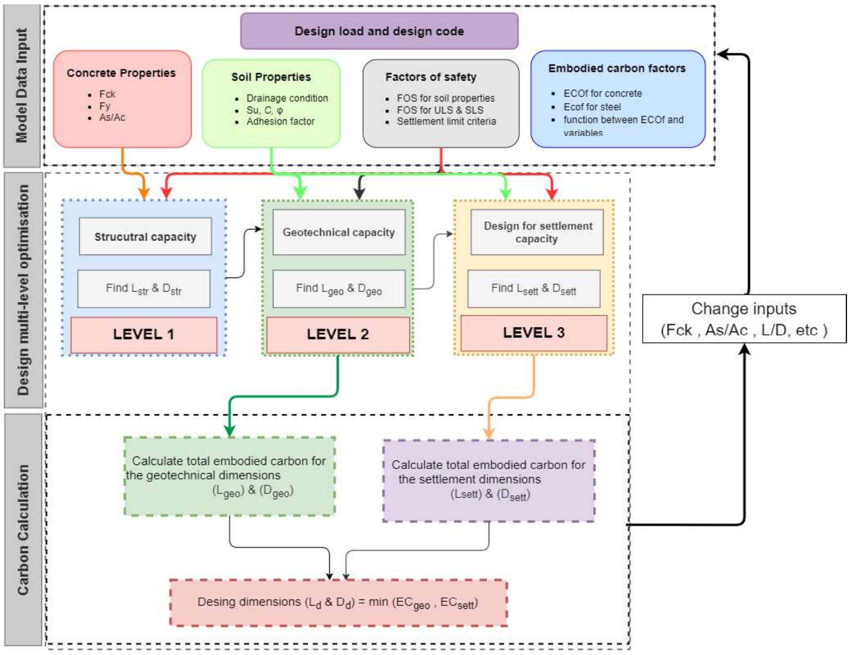


Figure 2: *schematic of the used optimisation algorithm*

RESULTS AND DISCUSSION

Effect of concrete grade (f_{ck}) on the environmental impact of piles

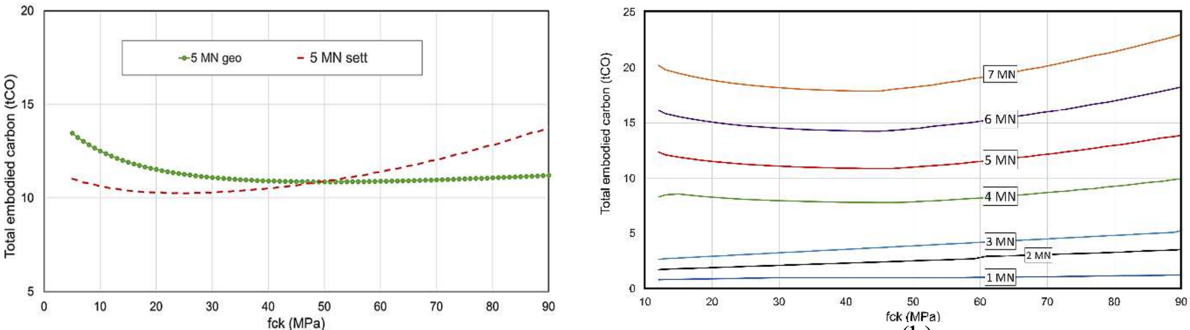
The model presented in section 2.4 was run to test the effect of concrete grade (f_{ck}) on the environmental impact of piles. The concrete grade limit matches Table 3.1 in EC2 starting at f_{ck} = 12 MPa to f_{ck} = 90 MPa. The change of embodied carbon factor ECF with concrete grade is evaluated as published by ICE freely-available calculator, results of the analysis are shown in Figure 3. Figure 3a shows the change of the embodied carbon for a pile with a capacity of 5 MN bored in clayey soil with properties tested by Craig (2012) [12]. It is clear that the embodied carbon from the geotechnical capacity decreases with increasing the concrete grade, however, the embodied carbon from the EC7 (10% d) settlement criteria increases with increasing the concrete grade. The two curves then come to meet at one point which is the critical concrete grade $(f_{ck})_c$; the concrete grade corresponding to a pile design with the lowest embodied carbon, this value is shown to be (f_{ck} = 47.7 MPa). Figure 3b shows the envelope line of the calculated values of total embodied carbon for piles with different capacities. It is clear that piles with lower load capacities favour low-grade concrete, while piles with higher capacities favour higher grades of concrete. Table 1 summarises the critical values of concrete $(f_{ck})_c$ for piles of different load capacities.

Effect of slenderness ratio (L/D) on the environmental impact of piles

The previously discussed model is used to investigate the effect of the design slenderness ratio on the environmental impact of piles. Analysis results for a pile of capacity 5 MN bored in clayey soil with properties tested by Craig (2012) [12] are shown in Figure 4. It is shown that piles designed at higher slenderness ratios will have a lower environmental impact than stocky ones if the proper concrete grade (f_{ck}) is used. Accordingly, a considerable reduction in the total embodied carbon can be achieved if the best combination of slenderness ratio (*L/D*) and concrete grade (f_{ck}) is used. A detailed discussion on the effect of the slenderness ratio on the environmental impact of piles was previously published [10].

Effect of steel-to-concrete ratio (A_s/A_c) on the environmental impact of piles

The previously discussed model is used to investigate the effect of the steel-to-concrete ratio (A_s/A_c) on the environmental impact of piles. The analysis is carried out for two different steel types; UK CARES steel of high recycled content with an embodied carbon factor ECF = 0.76 kgCO_2e/kg, and the global average unrecycled steel with an embodied carbon factor ECF = 1.96 kgCO_2e/kg [14]. Figure 5a shows the analysis results for the global average steel, and it's shown that a lower steel-to-concrete ratio is always corresponding to a design with lower environmental impact. However, for more sustainable steel, there exists a critical steel-to-concrete ratio that is corresponding to 8% lower emissions than steel the global average steel $(A_s/A_c)_c = 0.0078$ for this case.



(a) (b)

Figure 3: *Total embodied carbon at different concrete grades*
a) for a pile of load capacity 5 MN – b) for piles of different load capacities

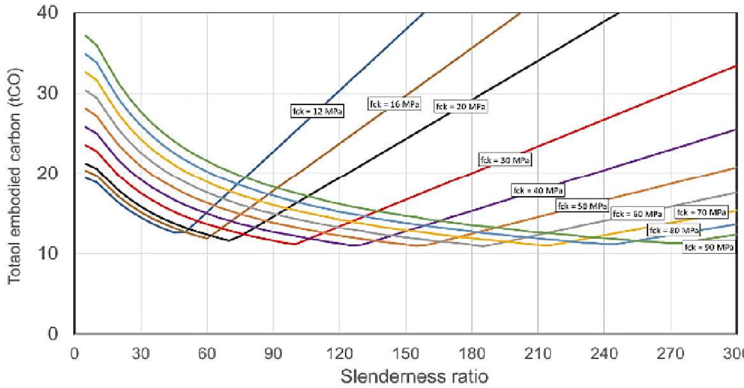
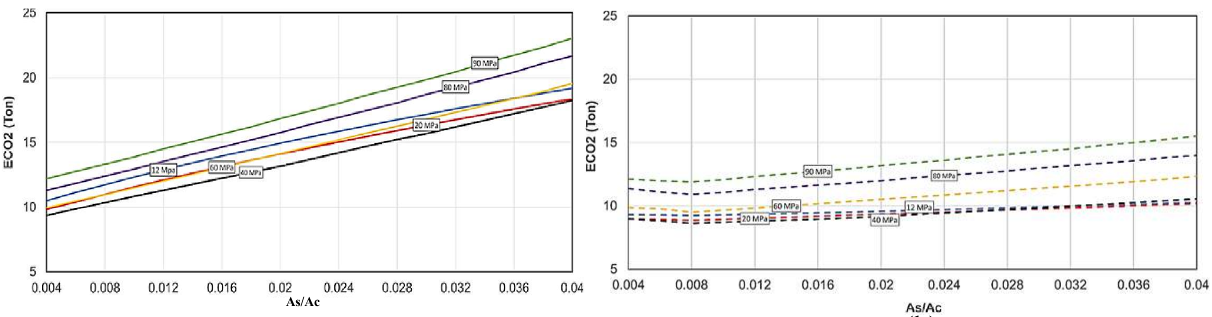


Figure 4: *Total embodied carbon at different slenderness ratios and concrete grades for a pile of load capacity 5 MN.*



(a) (b)

Figure 5: *Total embodied carbon at different (A_s/A_c) and concrete grades for a pile of capacity 5 MN*
a) global average steel – b) UK CARES average steel

Table 1 *Values of critical concrete grade*

Pile load capacity (MN)	Critical concrete grade $(f_{ck})_C$ (MPa)
1 - 3	Minimum = 12
4	48
5	47.7
6	45.4
7	45

CASE STUDY

In this section, the developed algorithm is used to optimise the design of a case study of deep foundations for a monorail train bridge in Egypt.

Project definition

The case study is for a monorail train bridge in New Capital – Egypt and is considered to be one of many steps Egypt has recently taken to reduce carbon emissions from the transportation sector through developing public-transport facilities and infrastructure. The addressed bridge is supported via large piers evenly distributed over the entire length of the bridge as shown in Figure 6, these piers are then supported over monopiles bored in clayey soil. The presented case study is for one of the pilot piles cast to test the actual soil resistance and compare it to theoretical calculations.

Figure 6: *Mono-rail train project, new capital – Egypt: a) supporting piers b) first trial to operate the train.* [17]

Soil Properties

The soil encountered was composed of two main layers; Layer 01 is sand to a depth of -2 m and Layer 02 is silty clay extending to a depth of -30 m. Groundwater was not recorded in any of the test boreholes at the time of boring. The soil properties are summarised in Table 2, and a Mohr-Coulomb (c'-φ') soil model was used based on the available data.

Tested pile

The pilot pile is a bored 12 m long and 0.8 m in diameter pile, and the applied test load was 1080 kN. The pile gained its resistance from friction within layer 02 while layer 01 was neglected, in addition to the base bearing capacity. The structural and geotechnical capacities of the pile are calculated by applying equations 1 and 2 as previously shown in section 2.1. The results of theoretical calculations are summarised in Table 3 and show that the actual structural capacity is almost 6 times higher than its geotechnical capacity, which proves that there is a wide scope for optimising the pile design through cutting some of the ineffectively used material. A static loading test was carried out to measure the accurate pile settlement and test results showed that the pile's settlement was 0.48 mm at 100% load, this value is way lower than the allowable limits in both Eurocode 7 and the Egyptian code of deep foundations ECP 202; 80.0 mm and 16.5 mm respectively [18,19].

Pile optimisation

Optimising design parameters

The optimisation algorithm was run given the applied load and soil properties. Firstly, the $f_{ck} - L/D$ model was run and a construction slenderness ratio of 48.5 is recommended at a concrete grade of 32 MPa. Afterwards, the $f_{ck} - A_s/A_c$ model is run and a recommended steel ratio of 0.004 is recommended, this led to a significant 51.4% cut in the total embodied carbon compared to the as-built pile design.

Optimising material type

This phase is run to test the effect of replacing the used material with materials from sustainable sources. The used steel was a global average steel with embodied carbon factor (ECF = 1.96 $kgCO_2e/kg$), this steel was theoretically replaced with steel from a sustainable source and embodied carbon factor (ECF = 0.76 $kgCO_2e/kg$) [14]. The concrete used to cast this pile was high carbon concrete, this is replaced by a sustainable concrete of GGBS = 70%. Switching to more sustainable materials led to an extra 21% cut in the total embodied carbon and reduced the overall embodied carbon by 72.4% compared to as-built. Table 3 summarises the as-built pile and the optimisation results.

Table 2 *Soil layers and measured soil properties.*

Property	Symbol	Layer 01	Layer 02
Depth	-	0 to -2	-2 to -30
Soil type	-	Sandy soil	Silty-clay soil
Unit weight (kN/m^3)	γ	19.0	20.0
Young's modulus (MPa)	E	25-50.0	25.0-30.0
Effective cohesion (kPa)	c'	-	20.0-30.0
Effective friction angle (degree)	φ'	32-36	20.0

Table 3 *Pile optimisation results*

Property	As-built pile design	Redesign 1 (Design parameters)	Redesign 2 (Sustainable material)
Length	12 m	19.4 m	19.4 m
Diameter	0.8 m	0.4 m	0.4 m
Conc. volume	6.031 m^3	2.438 m^3	2.438 m^3
L/D	15	48.5	48.5
Applied load	1080 kN	1080 kN	1080 kN
Str. Capacity	7350 kN	1595 kN (Safe)	1595 kN (Safe)
Geo. Capacity	1350 kN	1098 kN (Safe)	1098 KN (Safe)
f_{ck}	25 MPa	32 MPa	32 MPa
A_s/A_c	0.01	0.004	0.008
Steel type	Global average ECF = 1.96 $kgCO_2e/kg$	Global average ECF = 1.96 $kgCO_2e/kg$	UK CARES average ECF = 0.76 $kgCO_2e/kg$
Conc. type	Normal high carbon ECF = 0.175 $kgCO_2e/kg$	Normal high carbon ECF = 0.175 $kgCO_2e/kg$	Low carbon ECF = 0.063 $kgCO_2e/kg$
TEC	2.67 tCO2/pile	1.03 tCO2/pile (-51.4%)	0.737 tCO2/pile (-72.4%)

FUTURE ENDEAVOURS AND PROPOSED CONCEPTUAL DESIGN

Future endeavours

The results of this research show that optimising the different design parameters can lead to a considerable cut in the total embodied carbon of deep foundations. For future endeavours, it is planned to further develop the proposed algorithm to investigate the effect of more design parameters such as pile inclination angle and pile location. Also, the algorithm will be further developed to be used for assessing the available construction options and decision making during early the design stages with high potential to be BIM integrated. This is believed to revolutionise the pile construction industry and lead to novel conceptual designs with lower environmental impact and lower construction costs.

Proposed conceptual design

Results in section 2.1 show that piles designed to our current codes and design practice usually have higher structural capacity than their geotechnical and settlement capacities although load capacity will always be dictated by the lowest of these three design limits. Following is a novel pile conceptual design suggested to reduce emissions from the piles industry. The proposed pile is designed to maximise the outer friction through utilising external friction ribs constructed through a special impression tool as tested by Keltbray in 2021 [13]. A big portion of the inner concrete core is cut to reduce the overdesigned structural capacity of piles, the inner voids geometry will be optimised to reduce the environmental footprint while achieving the highest possible load capacity. The optimised voids geometry will be formed using either inflatable membranes or recycled polymer void creator as shown in Figure 7. This design is believed to achieve a very high geotechnical capacity at a lower carbon footprint as well as overcoming the practical execution difficulties accompanied by casting hollow cylindrical piles as discussed by McNamara [20]. A prototype of the suggested pile will be experimentally tested, and results are to be published soon.

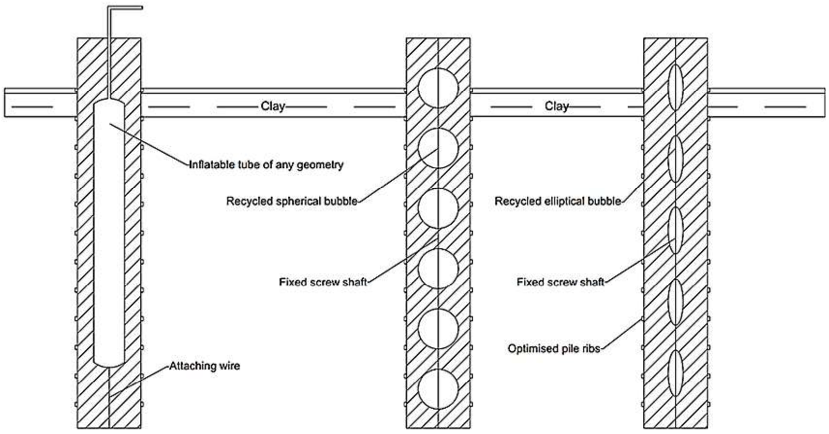


Figure 7: *Sketch of the proposed pile design with different void geometries.*

CONCLUSION

To conclude, this research optimised the design of deep foundations through a developed tool which investigates the effect of different design parameters on the environmental impact of piles. The following are the main concluded points:

- Using lower-grade concrete results in lower environmental impact for piles of low load capacities, however, for piles of higher load capacities there exist critical values of concrete grade $(f_{ck})_c$ corresponding to the lowest possible environmental impact and these values should be well considered during the design stage.
- Generally, slenderer piles result in lower environmental impact than stocky ones, however, the proper concrete grade should be considered through the two-objective optimisation model presented in section 3.2.
- For global average steel (ECF = 1.96 $kgCO_2e/kg$), designers are recommended to use the lowest possible steel-to-concrete ratio. However, for steel produced from a fully sustainable process (ECF = 0.728 $kgCO_2e/kg$) a critical value for steel-to-concrete ratio $(A_s/A_c)_c$ exists and is corresponding to a lower overall carbon footprint, this ratio should be well evaluated and used during the design stage utilising the optimisation model previously discussed in section 3.3.

- Where possible low carbon materials (steel and concrete) should be used as this results in a significant reduction in the structure's total embodied carbon.
- The previously discussed method was applied to an existing case study of deep foundations and an overall reduction of 51.4% was achieved through optimising the design parameters, while a 72.4% cut of the total embodied carbon was achieved when this was accompanied by switching to more sustainable materials.

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