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OPTIMUM DESIGN OF REINFORCED CONCRETE PILE FOUNDATION USING GENERALIZED REDUCED GRADIENT METHOD

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ABSTRACT

Pile foundations are structural members used for heavy structures when the depth requirement for supporting the load is large. They transmit the loads of the superstructure to the lower resistant layers of the soil. Piles are used in a wide variety of important structures and are not only subjected to vertical loadings coming from the superstructure, but also to lateral loads such as; wind, waves, earthquakes, etc. It has been established that the acceptability of any design should address at least these three basic requirements: ultimate limit state (ULS), serviceability limit state (SLS) and economics. The fulfillment of ULS, SLS and economics separates acceptable designs from unacceptable ones. In the light of the forgo discussions, Optimum design of reinforced concrete structures is considered to be the most economical design. For an optimum design, a suitable method has to be employed for the design to be economical. Such methods could be the Generalized Reduced Gradient (GRG) method which uses the Solver add-In of Microsoft Excel due to its simplicity and efficiency. Thus, this study is to optimize the cost of Reinforced Concrete (RC) pile foundation subjected to axial load using the The Generalised Reduced Gradient (GRG) optimization techniques which was embedded in MS Excel Solver Add-In tool. This optimization technique enables the designer to select the best and most economical design which meets the requirements as specified by the Eurocode 2 (Partial factors for structural (STR) and geotechnical (GEO) limit states verification (A3, EN 1997-1) *and 7 (Geotechnical design - Part 1). A computer model of the problem with the objective function subjected to its constraints was formulated in an MS Excel Spreadsheet. The model which includes automated and conventional design method was used to optimize the pile at several intensities of loading. The results obtained showed that the optimum diameter of the pile (d_{opt}) increased as the live load on the pile increases. More so, it was seen that an increase in the intensity of load, either dead load or live load or both, applied to the pile, causes a decrease in the difference between the ordinary and the optimum cost, as well as the percentage gain. This cost was obtained to be averagely 30% optimum when compared the use of optimization to the conventional design methods. The results demonstrated the simplicity and efficiency of the MS Excel Solver add-In tool with its embedded GRG function. The model developed can allow engineers to design and obtain optimum value of a RC pile within a very short time, thus reduces effort and saves time.*

Keywords: RC pile foundation, Cost Optimization, Solver Add-In tool, GRG Method, Eurocode, Optimization.

1.0 INTRODUCTION

Pile foundations are structural members used for heavy structures when the depth requirement for supporting the load is large (Das, B.M 2016). They transmit the load of the superstructure to the lower resistant layers of the soil. Piles are used in a wide variety of important structures and are not only subjected to vertical loadings coming from the superstructure, but also to lateral loads coming from inclined loads, wind, waves, earthquakes, etc. It has been noticed in the past that piles have faced major damages due to lateral loads Miwa et.al, (2006).

Today, the main types of pile in general use are driven piles, driven and cast-in- place piles, jacked piles, bored and cast-in-place piles and composite piles. The first three of the above types are sometimes called displacement piles since the soil is displaced as the pile is driven or jacked into the ground. In all forms of bored piles, and in some forms of composite piles, the soil is first removed by boring a hole into which concrete is placed or various types of precast concrete or other proprietary units are inserted. Having decided that piling is necessary, the engineer must make a choice from a variety of types and sizes. Usually, there is only one type of pile which is satisfactory for any particular site conditions (Ulitskii, V. M., 1995).

Reinforced concrete piles supporting bridges or mega-structures are part of the emerging structures usually constructed in cities worldwide. One of the major challenges faced by the stakeholders who want to build these type of structures is the cost of construction, which includes the cost of producing the reinforced concrete (structural) elements (beams, columns, girders, deck, piers, piles etc.) for the structure, the cost of producing these elements is relatively high and keeps increasing day by day. In this work, an optimum design of a reinforced concrete pile is treated, with an objective of minimizing the cost of production, taking note of the criteria of design specified by the Eurocode of practice. The foundation cost, of real world structural systems of increased scale, can vary from 2% to 20% of the construction cost of the structure while the number of piles required might exceed several thousand (Ulitskii, V. M., 1995).

According to Wang & Kulhawy, (2008), the designed foundation should address at least three basic requirements: ultimate limit state (ULS), serviceability limit state (SLS) and economics. The fulfillment of both ULS and SLS requirements separates acceptable designs from unacceptable ones and economics assist the choice between possible alternative solutions. (Das, B.M 2016), mentioned that “with the growth of science and technology, the need for better and more economical structural design and construction became critical” and significant cost savings can be achieved by optimization of pile type and section.

Optimization methods, coupled with modern tools of computer-aided design, are also being used to enhance the creative process of conceptual and detailed design of engineering systems Wang, & Kulhawy, (2008). Optimization techniques are not exclusive to the civil engineering area, they are being used in a wide spectrum of industries such as structural mechanics, aerospace Wang et.al, (2002), automotive Mizuno, H. (1987), chemical, Sahinidis, et.al,(1989), Kanagarajan et.al, (2008) etc. From the forgo discussion, the study is thus aimed at addressing the cost of construction materials such as steel used in Reinforced concrete piles supporting bridges or mega-structures foundations using the most economical method of optimization.

2. MATERIALS AND METHODS

2.1 Preambles

In this section, the materials and methods used were outlined. Design model for the optimum design and conventional design of the RC pile was prepared in a Microsoft Excel Spreadsheet and was used for the design.

The pile was loaded with characteristics dead loads starting with 2000kN up to 3000kN with an increment of 100kN while keeping the imposed load at 800kN and 1000kN. The design axial load, cross-sectional area of pile, and area of steel reinforcement required for each load combination was determined.

The optimum design as well as the conventional design for each combination of the above dead and live loads was carried out. The optimum cost and the conventional cost were found on the completion of the design for each load case, and the values of the design variables such as optimum area of steel reinforcement, conventional area of steel reinforcement, optimum diameter, and optimum length were tabulated for each loading. The difference between the optimum cost and the conventional cost was also calculated for each load combination, and the percentage gain obtained for each of the design load was then calculated and tabulated as well. Graphs of optimum diameter against dead load, optimum area of steel reinforcement against dead load and percentage gain against dead load for piles of span 20m and 24m were plotted.

2.1.1 Materials

The software used for the analysis, designed and cost optimization of the reinforced concrete pile considered are;

I. Eurocode 2 (1991) & Eurocode 7(1997)
II. Microsoft Excel Spread-sheet (MS Office, 2016)

2.2 Methods

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The methods employed in this analysis and design involved the following;

2.2.1 Preambles

The pile was loaded with characteristics dead loads starting with 2000kN up to 3000kN with an increment of 100kN while keeping the imposed load at 800kN and 1000kN. The design axial load, cross-sectional area of pile, and area of steel reinforcement required for each load combination was determined.

2.2.2 Equilibrium Equation for ULS Design:

The equilibrium equation to be satisfied in the ultimate limit state design of axially loaded piles in compression is

$$N_{cd} \leq R_{cd} \quad . \; . \; . \quad (1)$$

Where: N_{cd} is the design axial compression load and R_{cd} is the pile compressive design resistance.

2.2.3 The Generalised Reduced Gradient (GRG) Method

Generalized Reduced Gradient (GRG) Algorithm method (built-in in Microsoft Excel Solver) was used for the optimization of the reinforced concrete pile. A sample dialog box is as shown in plate I (a and b).

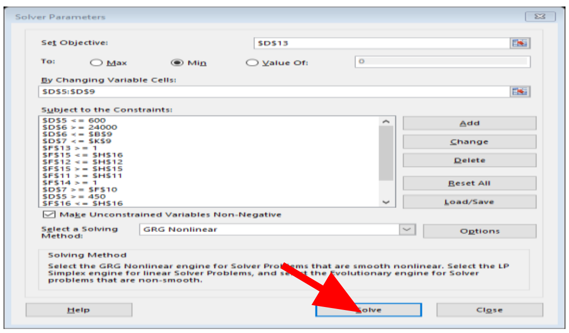

Plate I (a): 'Solve' Button

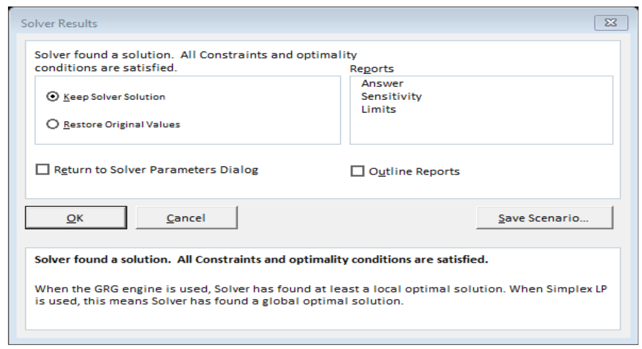

Plate I (b): 'Solver Results' dialog box

2.2.4 Design Axial Load of Pile:

The design axial compression load N_{cd} is obtained by multiplying the respective dead loads (G_k) and imposed loads (Q_k) with their corresponding respective partial factor of safety γ_G and γ_Q to obtain the design axial load. This is as given in equation (2).

Thus;

$$\text{Design axial load, } N_{cd} = (\gamma_G G_k + \gamma_Q Q_k) \quad (2)$$

Table 1 presented the recommended partial factors of safety on actions and the effects of actions.

Table 1 : Recommended partial factors on actions and effects of actions (Eurocode 1 (1991-(2004))

Action		Symbol	Set	
			A1	**A2**
			DA1.C1, DA2,DA3 (structural actions)	**DA1.C2,DA3 (geo-technics actions)**
Permanent	Favourable	γ_G	1.35	1.0
	Unfavourable		1.00	1.0
Variable	Favourable	γ_Q	1.5	1.3
	Unfavourable		0	0

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2.2. 5 Optimization Model

An optimization model of a reinforced concrete pile loaded as shown in **plate II** was considered

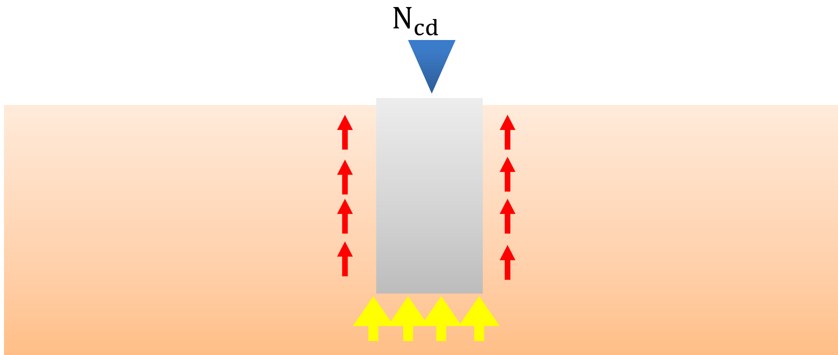

Plate II: A Reinforced Concrete Pile Model

2.2.6 Characteristic pile Resistance from Ground parameters

The characteristic base and shaft resistances may also be determined directly from ground parameters using the following equations given in Eurocode 1 (1991-(2004);

$$R_{b,k} = A_b q_{b,k} = \frac{9C_u \pi D^2}{4} \qquad (3)$$

$$R_{s,k} = \sum_{i=1}^{n} A_{si} q_{si,k} = \alpha C_u \pi D L \qquad (4)$$

Where:

$A_b =$ The nominal plan area of the base of the pile;

$A_{si} =$ The nominal surface area of the pile in soil layer i

$q_{b,k} =$ The unit base resistance

$q_{si,k} =$ The unit shaft resistance in soil layer i

D and L = Diameter and length of pile respectively

2.2.7 Design Compressive Resistance

The design resistance is obtained by dividing the characteristic base, ($R_{b,k}$) and shaft resistances, ($R_{s,k}$) by the relevant partial factors γ_b and γ_s

$$R_{cd} = \left(\frac{R_{b,k}}{\gamma_b} + \frac{R_{s,k}}{\gamma_s}\right) = R_{cd} = f_{cd} A_{cd} + f_{yd} A_{sd} \qquad (5)$$

Thus it can then be stated that

$$R_{cd} = \frac{(\propto_{cc} \times f_{ck})}{(k_f \times \gamma_c)} \times A_{cd} + \frac{f_{yk}}{\gamma_s} \times A_{sd} \qquad (6)$$

While the Allowable design load (Geotechnical carrying capacity) is given as

$$Q_{all} = \left(\frac{9C_u \pi D^2}{4\gamma_b} + \frac{\alpha C_u \pi D L}{\gamma_s}\right) \qquad (7)$$

Equations (5) to (7) are used in the optimization analysis of the pile noting the recommended safety factors.

EN 1997-1 provides different sets of recommended partial resistance factor values for bored piles in Tables A7 of Annex A. This is as shown in **Table 2**

Table 2: Recommended partial resistance factors for bored; Eurocode 7 (1997-1(2004))

Resistance	Symbol	Set			
		R1	R2	R3	R4
Base	γ_b	1.25	1.10	1.00	1.6
Shaft (compression)	γ_s	1.00	1.10	1.00	1.3
Total/combine (compression)	γ_s	1.15	1.10	1.00	1.5
Shaft in tension	γ_{ts}	1.25	1.15	1.10	1.6

An optimization model consists of the design variables, objective function, and the constraints Arora, & Cardoso,(1989)

3.2.7 Fixed parameters

The total cost of the pile in consideration was calculated using the cost function which depends on the fixed parameters and design variables. The fixed parameters used are:

i. Unit weight of steel reinforcement in kg/m³ (γ_S)
ii. The cost/m³ of concrete (C_C)
iii. The cost/ton of steel (C_S)
iv. The yield strength of reinforcement (f_{yk})
v. The value of the distributed dead and live loads (G_k and Q_k)
vi. The design load (N_{cd})

2.2.8 Design variables

The first step in the formulation of an optimization model for the optimization problem is to identify the design variables. The design variables which are considered in this RC pile model are listed as:

i. The diameter of the pile (d), ii) Area of steel required (A_{sd}), ii) Grade of concrete (f_{yk})

2.2.9 Objective Function

Usually, a designer can produce several valid designs, but for an optimum design, which is usually the best out of all other valid designs, we need to have an objective function Arora, & Cardoso,(1989). For this research, the objective function used to obtain the minimum cost of the simple reinforced concrete pile is as given in equation (8) Mizuno, (1987).

$$f(d, f_{ck}, A_{sd}) = C_c(A_{cd})L + \gamma_s C_s(A_{sd})L - C_c(A_{sd})L \quad (8)$$

Where; $C_c =$ the $\frac{cost}{m^3}$ in Naira of concrete, $C_s =$ the $\frac{cost}{ton}$ in Naira of steel reinforcement, $\gamma_S =$ the unit weight of the steel reinforcement bar in kg/m³, $A_{sd} =$ the Area of steel required, $f_{yk} =$ Charateristic Grade of concrete, $A_{cd} =$ Area of concrete, d and L = Diameter and length of pile respectively

2.2.10 Constraints

Constraints have influence on the design variables, and they are referred to as all restrictions placed to obtain the design Arora, & Cardoso, (1989). To complete an optimization model, these constraints must be identified and expressions representing them must also be formulated. For the purpose of this work, all constraints are derived from specifications (from practice), criteria of design from design code of practice Eurocode 1 (EN 1991-(2004); Eurocode 7 (1997-1(2004).) This is to ensure that the RC pile does not fail under service loads (dead and live loads), and satisfy the serviceability limit state. The following constraints were considered for this work:

i. $1.35G_k + 1.5Q_k \leq f_{cd}A_{cd} + f_{yd}A_{sd}$
ii. $A_{cd} = \frac{\pi d^2}{4}$
iii. If $A_{cd} \leq 0.5m^2$
Then $A_{s,bpmin} \geq 0.005A_{cd}$
iv. If $0.5m^2 < A_{cd} \leq 1.0m^2$
Then $A_{s,bpmin} \geq 25cm^2$
v. If $A_{cd} > 1.0m^2$
Then $A_{s,bpmin} \geq 0.0025A_{cd}$
vi. $\emptyset_{max} = 4\% \times A_{cd}$
vii. $A_{sd} \geq 0$
viii. $Q_{all} = 0.25 \times f_{ck} \times A_{cd}$
ix. $1.35G_k + 1.5Q_k \leq \left(\frac{9C_u\pi D^2}{4\gamma_b} + \frac{\alpha C_u \pi DL}{\gamma_s}\right)$

2.2.11 Optimum Design Flow Chart

The general process of the optimum design flow chart is as shown in **Fig 1**

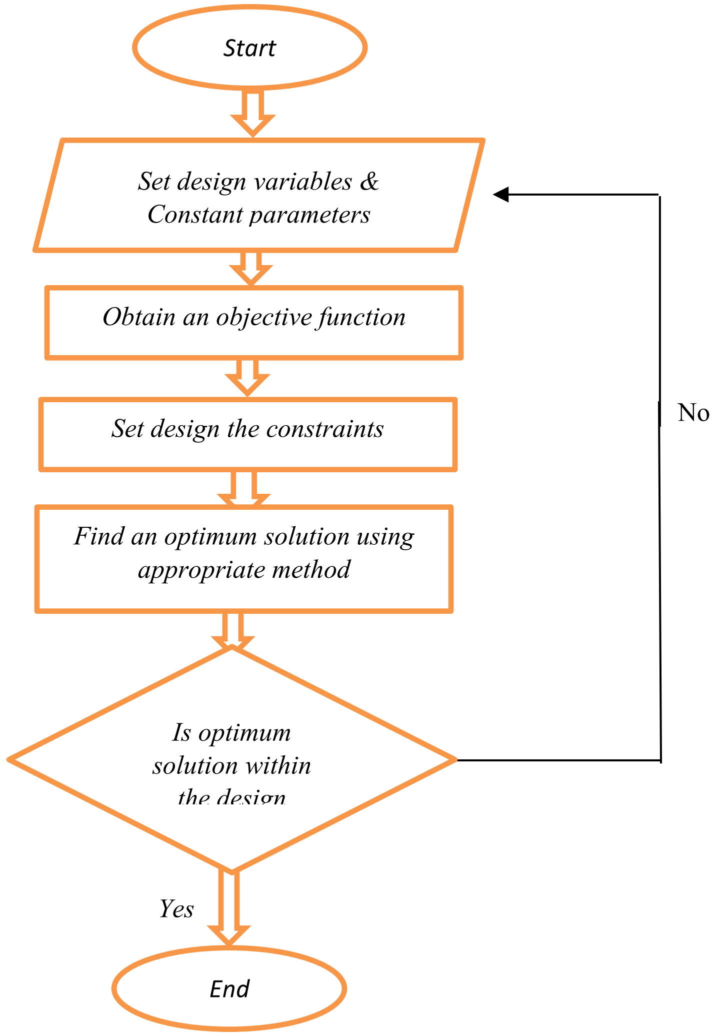

Fig. 1: Optimum Design Flow Chart

2.2.12 Optimization using Microsoft Excel solver add-in

For this project, the optimization problem involves finding the least possible cost of producing a simple RC pile with diameter d, length L, and grade f_{ck}, without violating any design criteria of the code of practice. Using the Microsoft Excel Solver add-in, the values obtained for the pile loading giving the average diameter and pile thickness is as presented in table 3.

2.2.11 The Microsoft Excel solver Add-In

As mentioned earlier, the solver add-In is part of the Microsoft Excel, which can be used to solve optimization problem using the Generalised Reduced Gradient built-in function. A model of the problem is formulated, and then inserted into a Microsoft Excel spread sheet as presented in **Table 3.**

Table 3: OPTIMUM DESIGN OF REINFORCED CONCRETE PILE USING GENERALIZED REDUCED GRADIENT METHOD

INPUT DATA		**OPTIMUM DESIGN**							**CONVENTIONAL DESIGN**		**OUTPUT DATA**	
PARAMETER	VALUE	DESIGN VARIABLES		CONSTRAINTS					parameters	value	parameters	value
G_k (N)	200000	variable	Opt value	variable	value	condition	value	variable	Rcd (N)	5010260.87	Ordinary cost (N)	327,778.64
Q_k (N)	80000	d (mm)	450.00	Ncd	3900000.00	≤	3900000.05	Qall	F_{cd} (N/mm^2)	17.00	Optimum cost (N)	194.128.64
F_{ck} (N/mm2)	30	L (mm)	24000	Ncd	3900000.00	≤	4902950.25	Rcd	F_{yd} (N/mm^2)	356.52	Difference (N)	133,650.00
F_{yk} (N/mm2)	410	As rq (mm^2)	565.71	d	450	>	0		Acd (mm^2)	282857.14	Gain (%)	40.77
D (mm)	600	Cu(N/mm^2)	0.09	L	24000	>	0		Asd (mm^2)	-2548.43		
L (mm)	24000	F_{ck}(N/mm^2)	41.02	Acd	159107.14	>	0		As req (mm^2)	565.71		
d_b (mm)	12	As proved (mm^2)	679	Asd	565.71	≥		As,bp (min)	As $_{Prov}$.(mm^2)	679		
		Provide	6H12	Cu	0.09	≥	0.04		Provide	6H12		
Fixed parameters			Opt cost	Cu	0.09	≤	0.09		Cost (n)	327,778.64		
Parameters	values	Objective FTN	194,128.64	fcd	23.24	>	0					
Cc (cost/m^3)	45,0000			fyd	356.52	>	0					
Cs (cost/tons)	180,000			fck	41.02	≥	30					
Ys (kg/m^3)	7,850			fck	41.02	≤	50					

3.0 RESULTS AND DISCUSSIONS

3.1 Presentations of Results

3.1.1 Loading and Analysis

i) Allowable Design load

The allowable design load (N_{cd}) for each of the characteristic dead load of the pile was obtained using equation (9) $N_{cd} = \gamma_G G_k + \gamma_Q Q_k$ (9)

From equation (10) given the following data, $G_k = 2000kN$, $Q_k = 800kN$, $f_{ck} = 30\,N/mm^2$, $f_{yk} = 410\,N/mm^2$, d = 500mm, L = 20000mm *and* $C_u = 90\,kN/m^2$, the allowable design load N_{cd}) can be determine.

ii) Calculations

A sample of the calculations is carried out explicitly for the first load combination as follows:

$$N_{cd} = \gamma_G G_k + \gamma_Q Q_k \quad (10)$$

N_{cd} = 1.35(2000) + 1.5(800) = 3900kN

$f_{cd} = (k_f \times \gamma_c)/(k_f \times \gamma_c) = (0.85 \times 30)/(1.0 \times 1.5) = 17.00\,N/mm^2$

$f_{yd} = (f_{yk}/\gamma_s) = (410/1.15) = 356.52\,N/mm^2$

$A_{cd} = \pi d^2/4 = (\pi \times 600^2)/4 = 282743.34mm^2$

Where;

Gk is the Characteristics dead load, Qk is the Characteristics imposed load, fck is the Characteristics conctrte strength, fyk is the Characteristics steel strength, d is the diameter of pile, L is the length of pile, Cu is the Undrained shear strength of the soil, Ncd is the allowable design load, γ_G is the safety factor for dead load, γ_Q is the safety factor for live load, Rcd is the design compressive strength, γ_c is the partial safety factor for concrete., A_{cd} is the cross-sectional area of pile, γ_s is the partial safety factor for steel, k_f is $a\ multiplier\ to\ partial\ factor\ of\ concrete\ for\ concrete\ piles\ cast - in - place\ without\ permanent\ casing\ (value\ is\ 1.0)$ and Q_{all} is the *characteristic variable load* for pile.

3.2 Discussion of Results

3.2.1 Conventional Design

Equation (11) gives the equilibrium equation for ultimate limit state (ULS) design. [Eurocode 1 (1991-(2004); The equation enable one to check which of the applied load and the maximum load resistance the pile can carried is greater for an economical design while equations (12) to (13) gives the design compressive resistance and the norminal reinforcements to be provided respectively.

$$N_{cd} \leq R_{cd} \quad (11)$$

For the first load combination, it is assumed that $N_{cd} = R_{cd} = 3900kN$,

Then check if $N_{cd} \leq Q_{all}$ and

$$Q_{all} = \left({}^{9C_u\pi D^2}/_{4} + \alpha C_u \pi DL\right)/1.3 \quad (12)$$

Q_{all} = ((9×90×π×0.5²/4) + 1.0×40×π×0.5×20)/1.3 = 5975.36kN

Since N_{cd} = 3900kN < Q_{all} = 5975.36kN, therefore it's "OK"

However from Design compressive resistance;

$$R_{cd} = f_{cd}A_{cd} + f_{yd}A_{sd} \quad (13)$$

$A_{sd} = (R_{cd} - f_{cd}A_{cd})/f_{yd}$

$= (3900000 - 17.00 \times 282743.34)/356.52$

$= -2543.02mm^2$

But A_{sd} gives a negative value, therefore provide minimum reinforcement.

Since, $A_{cd} = 0.20m^2 < 0.5m^2$;

Then, $A_{s,bpmin} \geq 0.002A_{cd} = 0.002 \times 282743.34 = 565.49mm^2$

Therefore, provide 6H12 ($A_{s,prov} = 679mm^2$)

3.2.2 Optimum Area of Steel Reinforcement ($A_{s,opt}$)

The optimum area of steel reinforcement and its diameter at a load of 800kN and 1000kN respectively derived after the loading, analysis and optimum design of the 20m long RC piles is as presented in **Fig 2**.

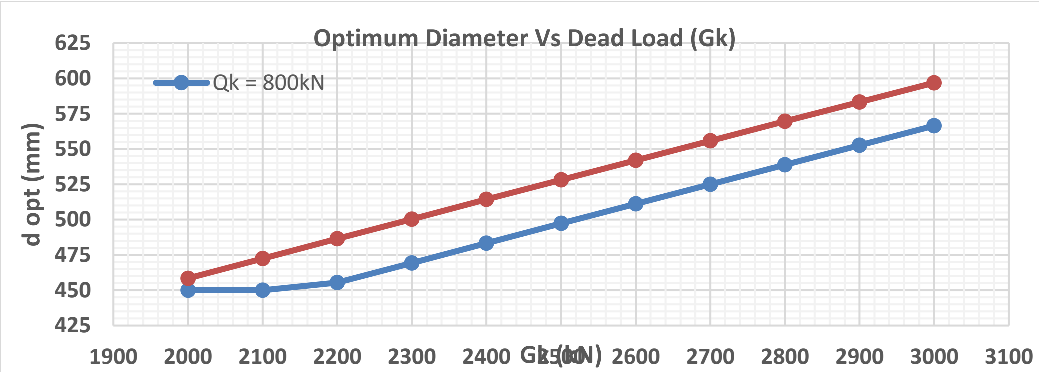

Figure 2: Graph of Optimum Pile Diameter d_{opt} (mm) Against Dead Loads

From Fig 2, it can be observed that the optimum pile diameter d_{opt}(mm) is barely proportional to the dead load, which implies that as the pile diameter increases, the dead load also increases. This was proved to be in agreement with the work of Das (2016) who carried out a study on Numerical Investigations on Load Distribution of Pile Group Foundation subjected to Vertical Load and Large Moment. Furthermore, it was also observed that the optimum diameter of the pile (d_{opt}) increased when the live load on the pile increased. This was true since the optimum diameter of the pile at live load of 1000kN was seen to be greater than that of live load of 800kN. This also justify the findings of Das (2016) who stated that the optimum diameter of reinforcement increases as the load increased.

Generally, the area of pile section increases as the intensity of load (either dead or imposed, or both) applied to the pile increases.

3.2.3 Objective function (Optimum Cost)

A study on the behaviour of the objective function (optimum cost) in relation to the intensity of loading was conducted. After taking the difference between optimum cost and ordinary cost of a pile, it was found that the gain (difference between optimum cost and ordinary cost expressed as a percentage of ordinary cost) keeps reducing as the amount of design load is increased. Thus, gain (%) is expressed as:

$$\text{Gain (\%)} = \frac{(\text{ordinary cost} - \text{optimum cost})}{\text{ordinary cost}} \times 100\% \quad (14)$$

However, the objective function of the pile is given in equation (15) as;

$$f(d, L, f_{ck}, A_{sd}) = C_c(A_{cd})L + \gamma_s C_s(A_{sd})L - C_c(A_{sd})L$$
(15)

With the objective function given in equation (16), for the load combinations, G_k = 2000kN and 800kN respectively with a pile length of L = 20m and 24m, design axial load $N_{cd} = R_{cd}$ = 3900kN, $d = d_{opt}$ = 450mm, while A_{sd} obtained using constrains in(2.2.6(ii)), noting that $A_{cd} = {\pi d^2}/{4}$ and the cost per unit volume of concrete (Cc), cost per unit tonne of steel (Cs) and cost per unit weight of steel (γ_S), obtained using relevant equations, then, a Percentage Gains (%) for the 20m and 24m Long Piles is as presented in graphs of Gain (%) Against Dead Load Gk (kN), for L = 20m and 24m in **Fig. 3 and 4** respectively.

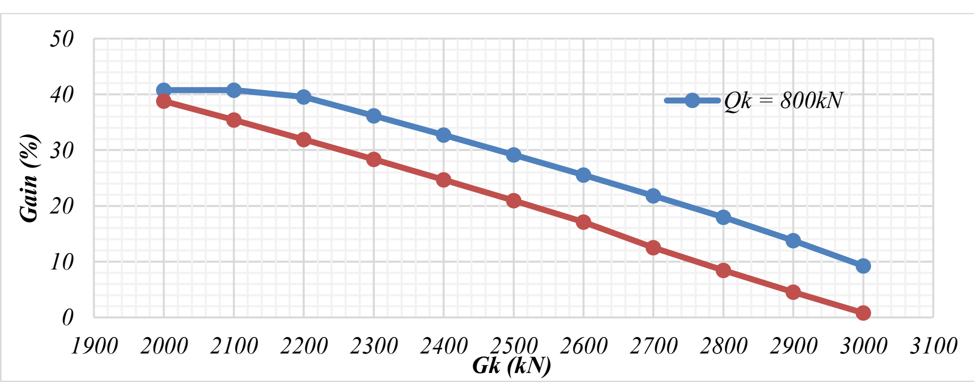

Figure 3: Graph of Gain (%) Against Dead Load Gk (kN), for L = 20m

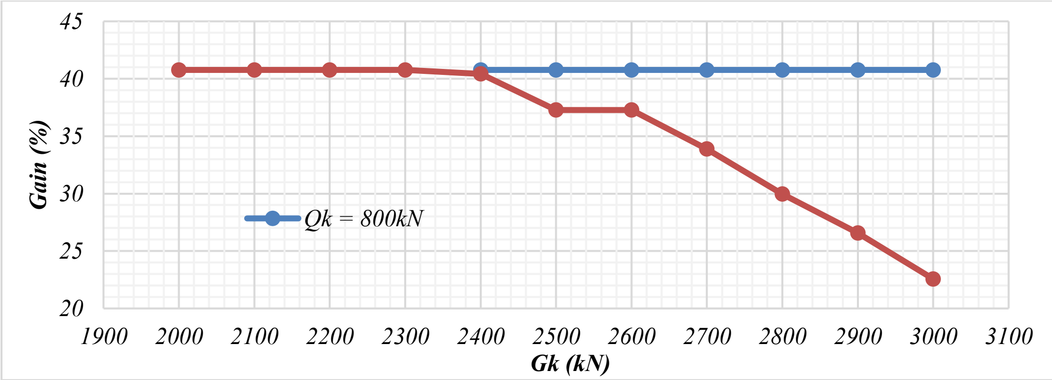

Figure 4: Graph of Gain (%) Against Dead Load Gk (kN), for L = 24m

From figures 3 and 4, the following can be deduced:

i. Percentage gain is barely inversely proportional to the load (G_K). This means that the higher the value of load subjected to the pile during the process of design, the lower the gain that is a positive difference between the ordinary cost and the optimum cost of the beam.

ii. Also, the graph of gain (%) against G_K when Q_K = 1000kN is slightly below when Q_K = 800kN. This implies that the percentage gain reduces as the load is increased. Generally, an increase in the intensity of load, either dead load or live load or both, applied to the pile, causes a decrease in the difference between the ordinary and the optimum cost, as well as the %gain. This was in agrrment with the findings of Miwa *et.al* (2006).

iii. By observing the two distinct graphs, it is clear that change in length (L) of the pile does not appreciably resulted in corresponding change in the respective percentage gain. The optimum costs of an axially loaded RC pile at different intensities of design loads were found. It was also found that the cost of producing a simple RC pile designed using normal design procedures is greater than the optimum cost of the pile. Also, optimum area of steel reinforcement and optimum diameter increase with increased loading, which reduces the percentage gain, that is, reduce the optimum cost of the pile

4. CONCLUSIONS

The following conclusions were drawn at the end of the study;

i. The results obtained from the Microsoft Excel spread-sheet with its embedded Generalised Reduced Gradient optimization technique showed a cost that is averagely 30% less than the cost obtained from an ordinary design method.
ii. The optimum diameter of the pile (d_{opt}) increased as the live load on the pile increases. This is true since the optimum diameter of the pile at live load of 1000kN was seen to be greater than that of live load of 800kN.
iii. It was observed that the percentage gain in pile cost reduces as the load is increased. Generally, an increase in the intensity of load, either dead load or live load or both, applied to the pile, causes a decrease in the difference between the ordinary and the optimum cost, as well as the percentage gain.
iv. The results demonstrated that the Microsoft Excel Solver add-In tool with its embedded GRG function can be efficiently and powerfully used for carrying out the cost optimization of an axially loaded reinforced concrete cast-in-situ bored pile.
v. Optimum design charts for 20m and 24m long axially loaded RC piles were prepared that allow structural engineers to obtain optimum reinforced concrete pile cross-sectional dimensions and the reinforcement area needed, which reduces effort requirements and saves time for calculation.

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