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A Cost Optimization Model for the Construction of Bored Piles

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***Abstract*—**Adequate management, control, and optimization of cost is an essential element for a successful construction project. A multiple linear regression optimization model was formulated to address the problem of costs associated with pile construction operations. A total of 32 PVC-reinforced concrete piles with diameter of 300 mm, 5.4 m long, were studied during the construction. The soil upon which the piles were installed was mostly silty sand, and completely submerged in water at Bonny, Nigeria. The piles are friction piles installed by boring method, using a piling auger. The volumes of soil removed, the weight of reinforcement cage installed, and volumes of fresh concrete poured into the PVC void were determined. The cost of constructing each pile based on the calculated quantities was determined. A model was derived and subjected to statistical tests using Statistical Package for the Social Sciences (SPSS) software. The model turned out to be adequate, fit, and have a high predictive accuracy with an R^2 value of 0.833.

***Keywords*—**Cost optimization modelling, multiple linear models, pile construction, regression models.

I. Introduction

SEVERAL foundation types are in use today to support buildings and other man-made structures/infrastructures. Pile, strip, raft, pad, grillage, and continuous foundations are among the most common types. A foundation is categorized under deep or shallow types. It is deep when its depth is 3 to 4 times greater than its width, but shallow otherwise [1]. A deep foundation is recommended when the conditions given in [1] are met. Additionally, a low bearing capacity soil or a large magnitude of load transferred from the columns to the soil can also result in the use of a deep foundation. The most common form of a deep foundation is a pile foundation. It is a column that is long and slender. It is buried underground so as to support the superstructure. This can be achieved by boring, driving, or cast-in-situ [2]. According to [1], a pile may be constructed to rest on a rocky support underground, otherwise, it could be supported by weak soils around its perimeter and surface (skin). The former is a point bearing pile, while the latter is a friction pile. A pile foundation costs more to construct than any of the shallow ones. However, they are of a more guaranteed safety [1]. Pile foundations are constructed with materials ranging from timber, concrete, steel, plastic, or composites [1]-[4]. Pile foundations made with timber were the first types to be constructed as far back as biblical times [3]. However, steel piles have been in use since 1800, while concrete piles have been in use since 1900 [3]. Concrete piles according to [4] could be precast, cast-in-situ, barrette, or drilled shaft. When a drilled shaft pile is used, the drilled hole or void is filled with reinforced or plain concrete. On the other hand, a plastic pile can be of varieties such as Polyvinyl Chloride (PVC), recycled materials, or polymer composites [4]. Piles constructed with composites are also commonly used, especially in marine environments where the piles are permanently exposed to moisture. According to [3], plastic and steel composite piles have been in use as far back as the 1980s. They are immune to risks due to corrosion and marine deterioration.

As highlighted earlier, pile construction is costly. This means that the way and manner of constructing piles has to be properly and optimally managed, so as to achieve excellent and efficient delivery in terms of cost and durability. This is a major problem to be addressed by this study. For this same problem, studies [5]-[8] have been previously carried out to improve pile construction cost optimization, construction techniques, productivity, technology, and construction time optimization. Other studies [9], [10] have also been carried out on the cost of pile construction. This study focuses on the cost of construction of reinforced concrete piles made by drilled shafts (or bored) with PVC casings, in order to reduce the foundation settlement.

The Iron Project Triangle (IPT) has been a significant Key Performance Indicator (KPI) in most construction projects. While addressing the construction of the Rivers Monorail, [11] rigorously evaluated the IPT as Continuous Flight Auger (CFA) pile construction (a type of bored pile) was amongst the prominent activities of the project. This goes to show how significant the cost is in pile construction and piling operations. Reference [8] also postulates that the piling cost and productivity are usually very difficult to estimate.

II. Materials and Methods

The study was done on a building designed to be carried by 32 friction piles as explained in [4] and raft beams/slab on silty soil located in Bonny, Nigeria. The total area of the building is 406.1625 m^2 and would have a ground floor and two reinforced concrete suspended floors. Fig. 1 shows the layout of the piles and pile caps, while Fig. 2 shows the soil profile to a depth of 15 m. PVC pile casings were inserted after drilling was done to an average depth of 6 m. The diameter of the drill bit with which the boring was done is 300 mm. The PVC void, after boring, was filled with a reinforcement cage, immediately after which the fresh concrete was poured into it to the brim.

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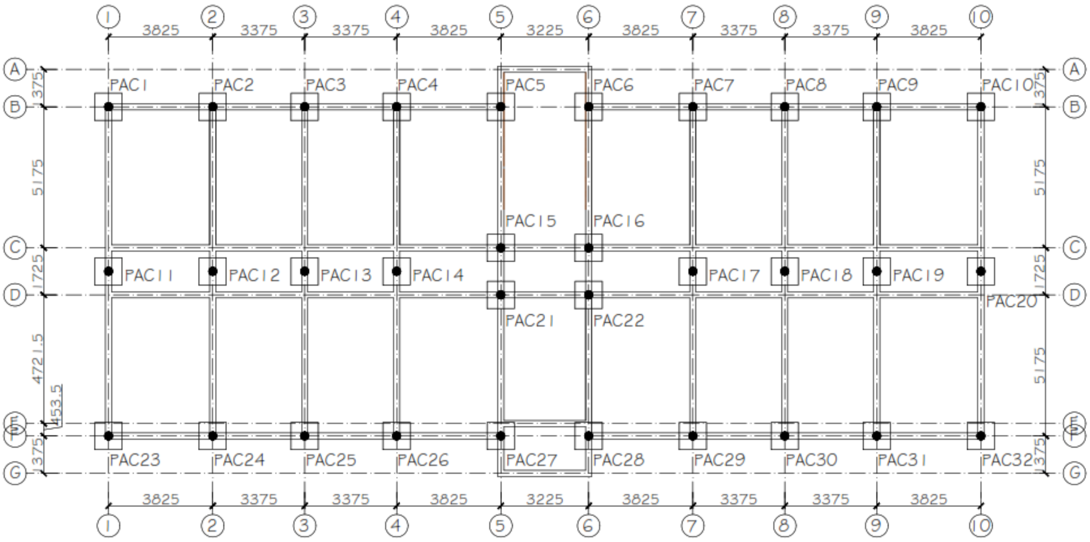

Fig. 1 Foundation Layout

The volumes of soil drilled and fresh concrete filled into the pile were determined. The weights of the reinforcement cage for each pile were also determined. The entire process was repeated for the remaining 31 piles, and the results were recorded accordingly.

Theoretically, the volume of soil drilled is equal to the volume of concrete poured. Equations (1) and (2) were used to determine the volumes and weights respectively:

$$V_{st} = V_{ct} = {}^{\pi D_p^2 L_p}/_{4} \quad (1)$$

$$W_{rt} = {}^{\pi D_{16}^2 \rho_s}/_{4} + {}^{\pi D_{10}^2 \rho_s}/_{4} \quad (2)$$

where V_{ct}, V_{st}, D_p, *and* W_{rt} are the theoretical volume of concrete, the theoretical volume of soil, the diameter of pipe, and the theoretical weight of the reinforcement cage. Similarly, D_{10}, D_{16}, ρ_s, *and* L_p are the diameter of 10 mm reinforcement, diameter of 16 mm reinforcement, density of steel, and length of pipe respectively. π is a constant (22/7), while the density of steel ρ_s is 7850 kg/m^3. Figs. 3 and 4 show the structural details of each pile. The cost of constructing each pile was determined by summing up the cost of each component of the construction of each pile.

III. Results and Discussions

Table I shows the actual cost for the pile operation for the 32 piles converted to U.S. Dollars at an exchange rate of N776.5 per US$ as of September 2023 (official rates). This includes the cost of reinforcement, concrete, PVC pipe, labor for installation, and every other associated cost during the operations. Table II shows the results of the actual volume of soil removed, the actual amount of concrete poured, and the actual weight of the reinforcement cage. Equation (3) is a multiple linear regression model as well as the objective function for the cost of the piling operations.

TABLE I
Actual Costs for Piling Operations

Pile Point	Actual cost, C (₦)	Actual cost, C ($)
P1	392,750.00	505.80
P2	560,000.00	721.18
P3	480,000.00	618.16
P4	495,000.00	637.48
P5	480,000.00	618.16
P6	565,000.00	727.62
P7	435,000.00	560.21
P8	500,000.00	643.92
P9	445,000.00	573.08
P10	515,000.00	663.23
P11	495,000.00	637.48
P12	450,000.00	579.52
P13	360,000.00	463.62
P14	480,000.00	618.16
P15	500,000.00	643.92
P16	460,000.00	592.40
P17	505,000.00	650.35
P18	420,000.00	540.89
P19	480,000.00	618.16
P20	400,000.00	515.13
P21	475,000.00	611.72
P22	480,000.00	618.16
P23	430,000.00	553.77
P24	330,000.00	424.98
P25	400,000.00	515.13
P26	490,000.00	631.04
P27	470,000.00	605.28
P28	385,000.00	495.81
P29	420,000.00	540.89
P30	495,000.00	637.48
P31	460,000.00	592.40
P32	505,000.00	650.35

$$C_p = J + KV_{sa} + LV_{ca} + YW_{ra} \quad (3)$$

where C_p is the predicted cost of construction of one pile, in

U.S$, while J, K, L, and Y are the model constants with units of U.S$, U.S$/m^3, U.S$/m^3, and U.S$/kg respectively. Also, V_{sa}, V_{ca}, and W_{ra} are the actual volume of soil, the actual volume of concrete, and the actual weight of reinforcement cage, in m^3, m^3, and kg respectively.

BOREHOLE LOG	
BOREHOLE NO.:	1
TOTAL DEPTH (m):	15
GROUND WATER LEVEL (m):	0.3
DATE:	29/8/2021

DEPTH (m)	DESCRITION	SOIL PROFILE	STANDARD PENETRATION TEST: SPT DEPTH (m)	BLOW COUNT: 0 - 150mm	150 - 300mm	300 - 450mm	SPT (N) 30
0.3	Black Silty Sand, top soil						
1	Loose dark greyish brown highly Silty fine Sand						
2	Loose dark greyish brown highly Silty fine Sand						
3	Loose dark greyish brown highly Silty fine Sand		-3	6	7	8	15
4	Loose to medium dense greyish m.caceous fine Sand						
5	Loose to medium dense greyish m.caceous fine Sand						
6	Loose to medium dense greyish m.caceous fine Sand		-6	8	14	10	24
7	Loose to medium dense greyish m.caceous fine Sand						
8	Loose to medium dense greyish m.caceous fine Sand						
9	Soft to stiff dark greyish peaty clay						
10	Soft to stiff dark greyish peaty clay						
11	Soft to stiff dark greyish peaty clay						
12	Soft to stiff dark greyish peaty clay		-12	15	22	30	52
13	Medium dense to dense light greyish fine sand with pockets of stiff peaty clay						
14	Medium dense to dense light greyish fine sand with pockets of stiff peaty clay		-14	15	25	31	56
15	Medium dense to dense light greyish fine sand with pockets of stiff peaty clay						

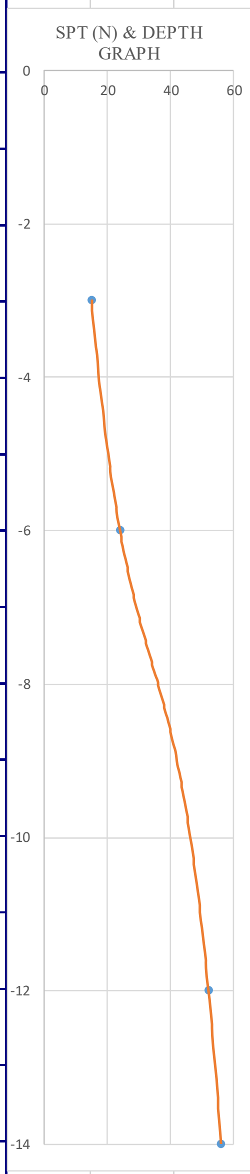

Fig. 2 Soil Profile

The actual volumes and weights were calculated by measuring the depths of voids and lengths of reinforcements submerged respectively. These were then substituted into (1) and (2) respectively. The analysis was done with SPSS.

The analysis resulted in the formulation of (4). It is called "the Oba's optimization equation for the cost of construction of a pile".

$$t_p = -5128.255 + 2873.323V_{sa} - 2098.34V_{ca} + 91.41W_{ra} \quad (4)$$

From Table III, the R^2 value of 0.833 indicates the model to be fit and of high capability to predict. Results from Table IV confirm the model to be adequate, while Table V shows the model coefficients with which the model was calibrated.

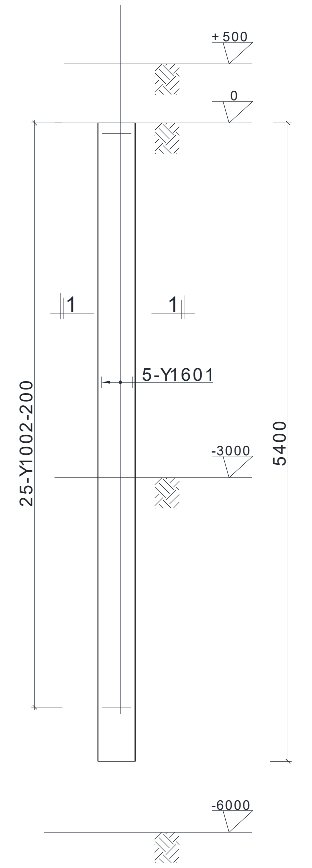

Fig. 3 Sectional Elevation of Pile

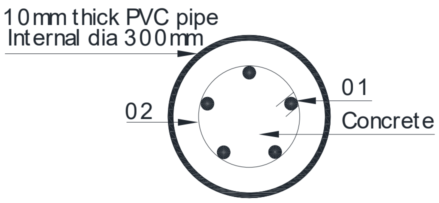

Fig. 4 Section 1-1

TABLE II
PILING DETAILS

Pile Point	Actual volume of soil removed, V_{sa} (m^3)	Actual volume of concrete poured, V_{ca} (m^3)	Actual weight of reinforcement cage, W_{ra} (kg)	Actual cost, C ($)
P1	0.399	0.35	58.35	505.80
P2	0.443	0.365	58	721.18
P3	0.410	0.377	58.2	618.16
P4	0.375	0.342	59.1	637.48
P5	0.389	0.38	59.34	618.16
P6	0.421	0.394	59.72	727.62
P7	0.380	0.378	58.91	560.21
P8	0.450	0.43	59.15	643.92
P9	0.386	0.385	59	573.08
P10	0.370	0.367	60.04	663.23
P11	0.395	0.389	59.55	637.48
P12	0.368	0.365	58.99	579.52
P13	0.381	0.388	57.94	463.62
P14	0.388	0.364	59.42	618.16
P15	0.399	0.4	59.68	643.92
P16	0.350	0.356	59.6	592.40
P17	0.400	0.398	59.79	650.35
P18	0.391	0.387	58.78	540.89
P19	0.386	0.382	59.44	618.16
P20	0.385	0.382	58.36	515.13
P21	0.383	0.383	59.57	611.72
P22	0.389	0.386	59.38	618.16
P23	0.374	0.399	59.54	553.77
P24	0.382	0.42	58.59	424.98
P25	0.392	0.4	59.22	515.13
P26	0.397	0.381	59.06	631.04
P27	0.415	0.395	58.55	605.28
P28	0.402	0.4	57.97	495.81
P29	0.394	0.4	58.86	540.89
P30	0.387	0.38	59.49	637.48
P31	0.390	0.391	59.35	592.40
P32	0.384	0.383	59.86	650.35

TABLE III
MODEL SUMMARY

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.913	.833	.815	29.38821	.833	46.646	3	28	.000

TABLE IV
ANALYSIS OF VARIANCE

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	120859.059	3	40286.353	446.646	.000
	Residual	24182.680	28	863.667		
	Total	145041.739	31			

IV. CONCLUSION

The volume of soil excavated, volume of concrete used, and weight of reinforcement cage were the most significant variables considered in this research. The actual quantities and cost of constructing each pile have been determined. The model was generated with the information obtained from the calculated quantities.

TABLE V
COEFFICIENTS

	Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-5128.255	601.438		-8.527	.000	-6360.245	-3896.265
	V_{sa}	2873.323	310.482	.829	9.254	.000	2237.329	3509.317
	V_{ca}	-2098.340	318.582	-.563	-6.587	.000	-2750.926	-1445.755
	W_{ra}	91.410	9.574	.783	9.548	.000	71.798	111.022

The derived model can be used to optimize the cost in order to tackle the problem of cost management and optimization in the construction of bored piles. This is a justification of the objectives and solution to the problem of the study. Secondly, the derived model, now called “the Oba’s optimization equation for the cost of construction of a pile” was found to be fit, adequate, and have high accuracy for prediction.

It is now recommended that the model should be used to monitor, control, and plan pile construction operations. The study was however limited to three variables. Further studies with other useful variables are also recommended for future pile construction-related research.

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