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Prediction of Bearing Capacity of Driven Piles Based on Dynamic Formulas

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Abstract:
The efficiency of six commonly used pile dynamic formulas in predicting capacity of pile foundations have been evaluated and compared in this paper. The methods considered for evaluation are Janbu, Modified ENR, Eytelwein, Gates, Danish, and Navy-McKay. Results of eleven pile driving records and pile load test performed in the Niger Delta region of Nigeria on 300mm diameter precast concrete pile were used in the study. Statistical approaches by way rating were employed to verify the accuracy of these methods. The evaluation revealed that the pile dynamic formulas are mostly underpredicting. Amongst the six methods, the Danish method gave the most realistic values of the pile capacity. As a result, it was ranked in the first order followed by the Navy-McKay method. The predictions using the Gates method were found to be overly lower than the measured values and was ranked least desirable amongst the methods.

Keywords: dynamic formula, precast concrete pile, pile driving records, pile load test

1.0 Introduction
Over the years, pile dynamic formulas have been widely used in the prediction of capacity of piles and as a construction control tool. The simplicity as well as low cost of implementation of the methods in projects has led to their significant use in geotechnical engineering practice (Salgado et al., 2017). Several methods are found in literature for the design of driven pile foundations (Rabe, 1946; Janbu, 1967; Modified ENR, 1965; Eytelwein, 1961; Hiley; Gates, 1957; Danish, 1967; ASSHTO, 1990). These methods are either based on Newton's impact theory or empiricism. Their major difference is in accounting for the energy losses involved in the driving process. These loses are due to elastic compression of the pile, helmet, packing, surrounding soils and due to the pile inertia (Tomlinson and Boorman, 2001). The derivations of these methods are discussed in details by Chellis (1961) and Likins et al. (2012).
Several research works have been conducted to compare the results of pile capacity based on dynamic formulas. Olson and Flaate (1967) considered the efficiency of pile dynamic formulas in predicting the capacity of piles and found that the Janbu's and Hiley's methods presented the least uncertainties. Vesic (1967) pointed out that the predictions from pile dynamic formula show great scatter; they largely over or under predict the observed values. Amongst all the formulas, the ENR's method has been documented as the most uncertain with the highest error and having the overall poor correlations with capacity determined from static load tests (Poulos and Davis, 1980). In a study of the relative performance of 10 pile driving formulas from 63 pile load test in the Western Washington and Northwest Oregon, it was revealed that the Gates formula provided the most consistent prediction of the pile capacity (Fragasny et al., 1988).
In this study, the efficiency of some commonly used pile dynamic formulas in predicting the capacity of driven concrete pile have been examined. The results from the dynamic formulas were compared to capacity from pile load test in order to ascertain the method that gives the most

realistic values. The bearing capacity of the piles from the pile load test was predicted based on Brinch Hanson method (1963).

2.0 Materials and Methods

The data used for the study were obtained from 3 sites situated in Niger Delta, southern Nigeria. The precast concrete piles are 300mm in diameter and were driven to depths between 15.75m and 19.75m using Delmag (D22) hammer type. Profile of the sites comprises of top sandy clay layer (6m to 15.0m thick) which overlies medium to dense sand deposits that extended to great depths. All piles were terminated within the sand layers. Static load tests were conducted on the piles to 150% to 200% of the design load based on ASTM D 1143-81. The different methods considered in the study are presented in Table 1.0 while the pile capacity obtained from their application are presented in Table 2.0. The interpretation of the pile capacity from the static pile load test based on Brinch Hason (1963) method is shown in Table 3.0.

Table 1.0: Dynamic formulas for Pile Capacity Prediction in the present study

Methods	Expression	Notations
Gates (1957) Method	$Q_u = a\sqrt{e_h E_h}(b - \log S)$	a, b = empirical constants e_h = Hammer efficiency E_h = Hammer energy rating S = pile set per blow
Eytelwein (1961) method	$Q_u = \dfrac{e_h E_h}{S + (W_P/W_r)}$	W_r = Weight of Ram W_P = Weight of pile
Modified ENR (1965) method	$Q_u = \dfrac{e_h E_h}{S + 2.54} \dfrac{W_r + n^2 W_P}{W_r + W_P}$	
Janbu (1967) method	$Q_u = \dfrac{e_h E_h}{K_u S}$ $K_u = C_d\left(1 + \dfrac{\lambda}{C_d}\right)$ $C_d = 0.75 + 0.15 \dfrac{W_P}{W_r}$ $\lambda = \dfrac{e_h E_h L}{AE S^2}$	L = Pile length A = Pile cross sectional area E = Modulus of elasticity
Danish (1967) method	$Q_u = \dfrac{e_h E_h}{C_1 S}$ $C_1 = \sqrt{\dfrac{e_h E_h L}{2AE}}$	C_1 = Constant
Navy-McKay method	$Q_u = \dfrac{e_h E_h}{S(1 + 0.3C_x)}$ $C_x = W_P/W_r$	

Table 2.0: Ultimate Capacity of Pile Foundation based on Dynamic Formulars

Site	Pile ref.	Gates	Modified ENR	Danish	Navy-Mckay	Eytelwein	Janbu
		Q_u (kN)	Q_u (kN)	Q_u (kN)	Q_u (kN)	Q_u (kN)	Q_u (kN)
1	PL1A	714	948	1223	1031	670	1051
	PL1B	624	723	996	767	509	938
	PL1C	775	1163	1408	1307	874	1134
	PL1D	669	820	1101	876	565	986
2	PL2A	878	1546	1690	1821	1174	1049
	PL2B	774	1130	1383	1256	804	1076
	PL2C	803	1250	1479	1417	926	1109
	PL2D	932	1816	1861	2226	1456	1002
3	PL3A	763	1089	1349	1202	765	1063
	PL3B	676	895	1156	981	707	1107
	PL3C	769	1109	1365	1227	781	1065

Table 3.0: Ultimate Pile Capacity from Pile Load Test

Site	**Pile ref.**	**Brinch Hansen (1963)**
		Q_u (kN)
1	PL1A	1042.6
	PL1B	1813.7
	PL1C	1863
	PL1D	2331
2	PL2A	3296.9
	PL2B	2008.1
	PL2C	1111.4
	PL2D	2564
3	PL3A	2112.9
	PL3B	1725
	PL3C	2094.3

3.0 Performance Evaluation of the Model

Statistical approach was adopted in the comparative study of the ultimate capacity obtained from the different methods. This approach has been extensively used by researchers to compare and ascertain the applicability of pile foundation predictive models for various locations outside the study area (Briaud and Tucker, 1988; Long and Shimel, 1989; Shariatmadari et al., 2008; Eslami et al., 2011; Eslami et al., 2014; Moshfeghi and Eslami, 2018; Awad-Allah, 2018). To evaluate the efficiency of the dynamic formulas, three different criteria were adopted. The comparison of the methods was achieved by way of ranking their individual performance for each of the criteria. The overall ranking is taken as the sum of the ranking values obtained from the criteria. The dynamic formula method with the lowest raking index is termed the better performed method. The four criteria used in the comparative study are described below.

1) Geometric Mean, Standard Deviation and Coefficient of Variation of (Q_p/Q_m) Criteria

The geometric mean, standard deviation and coefficient of variation of the (Q_p/Q_m) is obtained using equations:

$$\text{Geometric mean, } \mu = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{Q_p}{Q_m}\right) \quad 1$$

$$\text{Standard deviation, } STD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\left(\frac{Q_p}{Q_m}\right) - \mu)} \quad 2$$

$$\text{Coefficient of variation, } COV = \frac{STD}{\mu} \quad 3$$

With this criterion, the best performing method gives geometric mean value of unity and standard deviation and coefficient of variation of zero.

2) The Coefficient of Determination Criteria

The equation used to define the coefficient of determination is as follows:

$$COD = 1 - \frac{\sum_{i=1}^{n}(Q_{pi} - Q_{mi})^2}{\sum_{i=1}^{n}((Q_{mi} - \bar{Q}_m)^2} \quad 4$$

Where:
Q_{pi} = The predicted pile capacity
Q_{mi} = The measured pile capacity
$\bar{Q}_m$ = The mean of the measured pile capacity
In the case of this criterion, the method with the value of coefficient of determination close to 1 is taken as the best performed.

3) The Square Root of Sum Squares between the $(\frac{Q_p}{Q_m})$ Criteria

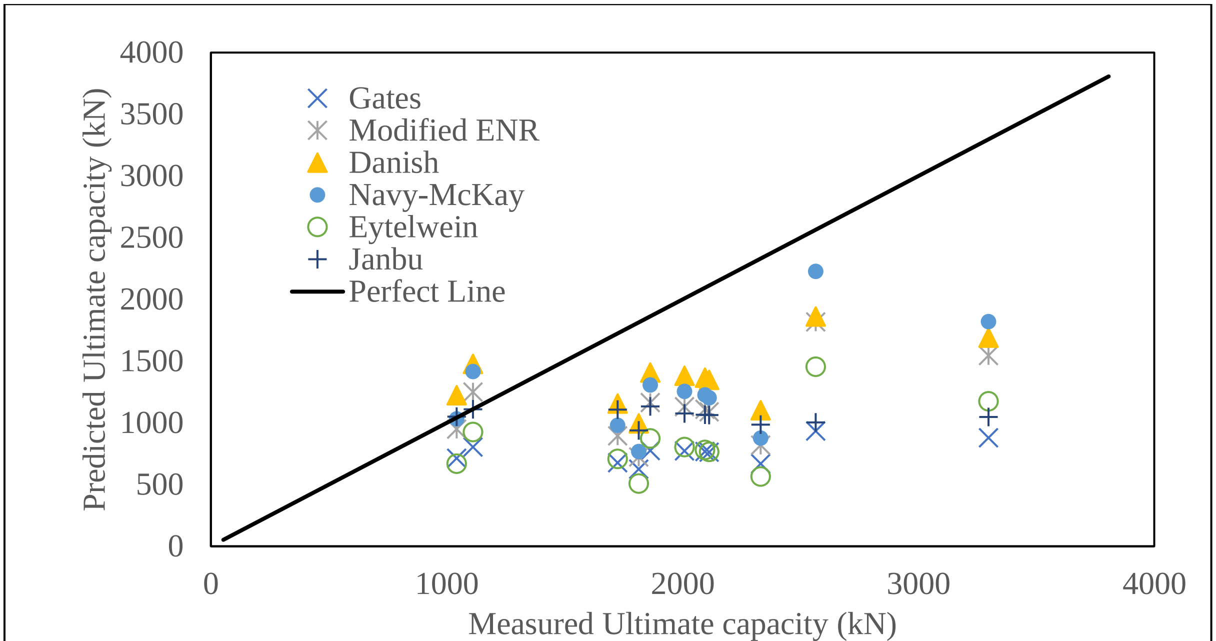
The square root of sum squares for measured and predicted capacities of the piles is determined by the expressions:

$$SRSS = \sqrt{\sum_{i=1}^{n}(}Q_{mi} - Q_{pi})^2 \quad 5$$

Based on this criterion, the method with the lowest square root is taken as the best performed approach.

4.0 Results and Discussion

The predicted capacity from the pile dynamic formulas were plotted against the values obtained from the Brinch Hanson and is presented in Figure 1.0. The plot showed that majority of the methods underpredicted the pile capacity. However, for pile PL2C, the Danish, Modified ENR and Navy-McKay was found to over predicted the pile capacity. The Danish method also overpredicted the capacity for PL1A.



The first criterion was the determination of the arithmetic mean, standard deviation and coefficient of variation of the ratios of the predicted capacities to the ultimate capacities. The results of the statistical analysis are presented in Tables 4.0. Although all the methods gave high values of COV (not asymptotic zero), the Danish method is considered more reliable than others. Its mean value is the most asymptotic or closer to 1 and as such has the lower prediction error. The Gates method performed poorly compared to others.

Table 4.0: Mean, standard deviation and coefficient of variation of dynamic formulas

Methods	Mean, μ	Standard deviation, s	Coefficient of variation, COV	Rating, R_1
Navy-McKay	0.685	0.264	0.385	2
Danish	0.742	0.269	0.362	1
Eytelwein	0.449	0.172	0.384	5
Janbu	0.587	0.225	0.384	4
Gates	0.417	0.148	0.356	6
Modified ENR	0.610	0.228	0.374	3

The second method considered the computation of the coefficient of determination, COD. Table 5.0 summaries the results of the computation alongside the ratings. In this case, the Danish method performed better than other dynamic formulas followed by the Navy-McKay method. The Gates method proved to be more less reliable than the others.

Table 5.0: Coefficient of determination of dynamic formulas

Methods	**Coefficient of determination, COD**	**Rating, R_2**
Navy-McKay	-1.17	2
Danish	-0.88	1
Eytelwein	-3.47	5
Janbu	-2.53	4
Gates	-4.1	6
Modified ENR	-1.8	3

The final criterion involves the use of the square roots of the sum squares (SRSS) method. Shown in Table 6.0 are the values of the square root of sum squares for each of the methods. Based on this criterion, the Danish method which recorded the least value of 2732 and as such has the better predictive ability. This is followed by the Navy Mackay method which has a $SRSS$ value of 2933. The method with the least accuracy is the Gates method with square roots of the sum squares (SRSS) value of 4503.

Table 6.0: Square root of square of sum values of dynamic formulas

Methods	**$SRSS$**	**Rating, R_3**
Navy-McKay	2933	2
Danish	2732	1
Eytelwein	4211	5
Janbu	3743	4
Gates	4503	6
Modified ENR	3330	3

The overall rating of these methods is evaluated based on the sum of the individual criterion that were considered above. The method with the least value is ranked first among others. As shown in Table 7.0 the Danish method ranked first with a ranking index of 3; followed by the Navy-Mckay method which had a ranking index of 6. The Gates method has a ranking index of 18 and was found to have performed poorly when compared to all the considered methods.

Table 7.0: Overall rankings for dynamic formulas

Methods	R_1	R_2	R_3	R_T	**Ranking**
Navy-McKay	2	2	2	6	2
Danish	1	1	1	3	1
Eytelwein	5	5	5	15	5
Janbu	4	4	4	12	4
Gates	6	6	6	18	6
Modified ENR	3	3	3	9	3

5.0 Conclusion

The efficiency of the pile dynamic formulas for the prediction of driven concrete pile capacity have been evaluated in the study. Dataset of static pile load test and pile driving records of 11 concrete piles obtained from the Niger Delta region of Nigeria was used in the study. The Brich Hanson method was employed in the determination of the measured pile capacity since the majority of test were not performed to failure. Predictions from the dynamic formula methods were compared with the measured capacity using a statistical ranking approach. The results of the study showed that the pile dynamic methods do not show consistency in the prediction of the pile capacity. Majority of the methods under-predicted the pile capacity. Based on the considered ranking criteria, the Danish method exhibited the highest level of accuracy, followed by the Navy-Mckay method. The method with the highest level of uncertainties is the Gates method.

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