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Uncertainty of Driven Pile Capacity using Dynamic Methods

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Abstract – Dynamic pile load testing (i.e., PDA and CAPWAP) was performed during the driving of six piles at two sites included large and low displacement H-piles, and actual pile capacity was determined during the end of drive. The load test provided an opportunity to compare pile design techniques to measured pile performance. The soils at one of presented sites prevent the pile driving process from being completed and the required pile length and capacity were not achieved due to early refusal. Therefore, the engineers redesigned the deep foundation system, whereby the large displacement prestressed concrete piles (PCP's) were replaced with low-displacement steel H-piles. In this paper, seven dynamic methods for predicting axial pile capacity of driven piles are investigated and summarized. The dynamic formulas included Eytelwein, Modified ENR, Janbu, Danish, Navy-Mckay, Gate, and PCUBC. The measured pile capacities were compared to the predictive capacities to evaluate which predictive method would be best suited for estimating the pile capacity at site where such difficult soils may encountered. The evaluation revealed that the pile dynamic formulas are mostly under-predicting pile capacity. Amongst the seven methods, the Danish method gave the most realistic values of the pile capacity. The predictions using the Gates and Modified ENR methods were found to be overly lower than the measured values and was ranked least desirable amongst the methods. The predictions at site where early refusal was encountered, found to be overly lower than the measured values. However, concrete piles were replaced by H-pile.

***Keywords*: Driven piles, dynamic formulas, PDA, blow counts

1. Background

The prediction of pile capacity is complicated by the large variety of soil types and installation procedures. In engineering practice, design and analysis of friction piles is carried out based on empirical formulas and depends to large extent on personal experience and judgment of the engineer. Because of many uncertainties associated with pile foundation analysis and design, full- scale pile load tests and dynamic load test are usually carried out at the site for important projects [1&2].

Driving a pile has different effects on the soil surrounding on the relative density of the soil, loose soils and sand soil is compacted. In dense soil, any further compaction is small, and the soil is displaced up ward causing soils surrounding pile tip to generate excess pore water pressures. In loose soils, pile driving is preferable to boring since compaction increases the end bearing capacity. In non-cohesive soils, skin friction is low because a low friction around the pile. The presence and movement of ground water the processes of construction and sometimes the durability of piles in service, the pile rebounds in these soils generally tends to increase as driving progresses due to increased pore water pressure. The incompressible water in the soil forces the pile rebound to increase. In some cases, rebound leads to pile damage, delaying of the construction project, and the requiring foundations redesign. This situation adversely affects pile drivability and complicates assessment of its load bearing capacity [3,4, 5].

Accurate prediction of pile capacity has always been a challenge of designer engineers. The dimensions of foundation and subsoil layers condition with different behaviors are the difficulties for evaluation of pile bearing capacity. Also, deep foundation as pile is usually applied in problematic soils and massive load. Therefore, it is a major concern in foundation design.

Contractors and engineers have experienced pile installation problems while driving high displacement piles with single-acting diesel hammers at Florida Department of Transportation (FDOT) construction sites located in the Central and of Florida [6]. Problems occur during pile driving, when a large initial penetration per hammer blow is followed by a large elastic rebound (termed High Pile Rebound or HPR) resulting in a small or negligible permanent-set per blow. Rebound in excess of 0.25 inches is considered to be high [7]. HPR may prevent the required driving resistance from being achieved and or stop the pile driving process, placing the foundation performance at risk or requiring redesign.

Dynamic methods are commonly utilized for determination of pile capacity. These methods are a convenient tool in the pile driving industry, and they are applied for any piles in various soils. Although dynamic methods have been used in practice for years, the actual accuracy of dynamic methods is vague because of the different natures of dynamic and static tests; these differences have not been completely studied [1, 8, 9, 10].

2. Objectives

The main objective of this research is to evaluate and compare prediction of axial pile capacity based on dynamic formula with data from actual dynamic load test.

3. Methodology

3.1.1. Site investigation program

A considerable quantity of well documented data was available from a number of FDOT construction projects presented by Cosentino et al. [6] and Jarushi et al. [3]. All of the PDA data was conducted by GRL, Inc. with a total number of 6 test piles included in this research. These sites are located at the central of Florida.

Split barrel and Shelby tube samples were used to visually classify soils and to establish the soil profile. The soil samples were classified in accordance with Unified Soil Classification System (USCS). Sand was the predominate soil at this site consistently representing over 50 percent of the soil. The soil strata were classified as one of the following groups: SC, SM-SC, SM, CL, SP-SM, and SP-SC. These soils displayed an olive green to light green color with visual descriptions ranging from clayey and silty fine sands, to highly plastic clays with low permeability

3.1.2. Pile Driving Operations, and PDA Output

During the initial installation, test piles at these sites were instrumented with PDA strain and displacement gauges to record hammer blows per foot, penetration depth per blow, hammer energy. Six piles included steel H-piles, square concrete prestressed piles, from two sites were selected for this study. PDA data was used to evaluate the pile movement per blow from the piles installation. Data obtained from different piles are presented in Table 1. The PDA software output included the following:

- The depth or elevation of the pile corresponding to hammer blows,
- The maximum displacement of the pile at the end of each record (i.e., DMX in the PDA output),
- The permanent-set of the pile
- The PDA time scale may be shorter or longer than the time that the piles actually move after each hammer blow.

Table 1. Piles and PDA Data

Site Name	Pile N0	Pile type	Pile size (mm)	Pile Length (m)	Hammer Type	Total CAPWAP Capacity (kN)	Stroke (m)	Ram weight (kN)	E of pile (kPa)
Anderson Street Overpass	Pier 3, Pile 28	Steel H-Pile	360x132	40.565	ICE I-30	1820	2,66	29	206 x 10^6
	Pier 4N, Pile 6	Steel H-Pile	360x132	39	ICE I-30	1720	2.2	29	206 x 10^6
	Pier 6, Pile 6	Concrete Square	610x610	32	Delmag D-62	3323	2.6	60	39 x 10^6
SR 435 (Kirkman Road)	End Bent 2S, Pile 14	Concrete Square	455x455	22	ICE 80S	1890	2.55	35,5	39 x 10^6

Over Florida Turnpike	End Bent 2S, Pile 23	Concrete Square	455x455	21	ICE 80S	2388	2.49	35,5	39×10^6
	End Bent 2N, Pile 12	Concrete Square	455x455	22	ICE 80S	1850	2.44	35,5	39×10^6

3.1.3. Pile Prediction Formulas

Dynamic formulas use empirical relationships between the energy imparted to a pile during driving and the resistance of the soil. These formulas typically calculate the pile capacity based on the hammer energy, pile penetration, and soil properties. Dynamic methods are commonly used for deep foundations, quicker and less expensive, as they can be performed during the pile-driving process without additional setups [1, 8,9,10].

Typically used for driven piles and often applied in field conditions where rapid estimates are needed. They are not as effective in soils with low resistance or cohesive soils like clay. The current methods considered in the study are presented in Table 2.

Table 2. Dynamic Methods for predicting pile bearing capacity used in this study

Methods	Expression	Remarks
Eytelwein [8]	$Qu = \frac{e_h \times E_h}{S + C(W_p / W_r)}$	C = 2.5mm
Modified ENR [8]	$Qu = \frac{e_h \times E_h}{S + 2.5} \times \frac{W_r + n^2 W_p}{W_r + W_p}$	
Janbu [8]	$Qu = \frac{e_h \times E_h}{K_u \times S}$	$K_u = C_d(1 + \frac{\lambda}{C_d})$ $C_d = 0.75 + 0.15\frac{W_p}{W_r}$ $\lambda = \frac{e_h \times E_h \times L}{AE \times S^2}$
Danish [8]	$Qu = \frac{e_h \times E_h}{C_1 + S}$ $C_1 = \sqrt{\frac{e_h E_h L}{2AE}}$	$C1 =$ Constant
Navy-McKay [8]	$Qu = \frac{e_h E_h}{S(1 + 0.3C_x)}$	Cx = Constant $C_x = W_p / W_r$
Gate [8]	$Qu = a\sqrt{e_h E_h (b - logs)}$	$a, b =$ empirical constants

Pacific coast uniform building code (PCUBC) method [12]	$Pu = \frac{e_h E_h C_1}{S + C_2}$ $C_1 = \frac{W_r + KW_p}{W_r + W_p}$	K= 0.25 for steel piles k= 0.25 for steel piles K= 0.10 for all other piles $C_2 = \frac{P_w L}{AE}$
eh = Hammer efficiency Eh = Hammer energy rating S = pile set per blow E = Modulus of elasticity	Wr = Weight of Ram WP = Weight of pile L = Pile length A = Pile cross sectional area	

4. Findings

4.1. Performance Evaluation of the Dynamic methods

The efficiency of seven commonly used pile dynamic formulas in predicting capacity of pile foundations have been evaluated and compared to the measured pile response during the dynamic load test at end of driving capacities. The calculated (estimated) and measured capacities are presented in Table 3 while the comparison between measured and estimated capacity is shown in Figure 2 and Figure 3. The ultimate resistance measured during the dynamic load testing when compared to the predictive methods varied significantly with the methods, depth and soil type. The Eytelwein [8], Modified ENR [8], Gate [8], PCUBC [12], Janbu [8], methods underestimated capacities within -15% and -40% of the capacities determined by the 1-day dynamic loading tests. In comparison, Danish [8] and Navy-Mckay [8] were in good agreement in estimating resistance with dynamic results at three piles out of six piles. The results indicated that these methods provide the greatest precision.

Table 3. Ultimate capacity of pile based on dynamic formulas and vs. measured Capacity from pile load test

Site Name	**Site 1 Anderson Street Overpass**			**Site 2 SR 435 (Kirkman Road) Over Florida Turnpike**		
Pile Number	**Pier 3, Pile 28**	**Pier 4 N, Pile 6**	**Pier 6, Pile 6**	**End Bent 2S, Pile 14**	**End Bent 2S, Pile 23**	**End Bent 2N, Pile 12**
Dynamic Methods	**Qu (kN)**	**Qu (kN)**	**Qu (kN)**	**Qu (kN)**	**Qu (kN)**	**Qu (kN)**
Eytelwein [8]	1513	1186	1982	1473	1817	1296
Modified ENR [8]	980	728	1267	913	1117	804
Janbu [8]	990	979	1662	1152	1274	1100
Danish [8]	2083	1675	2882	1866	2161	1742
Navy-Mckay [8]	1871	1321	2433	1946	2388	1713
Gates [8]	905	778	1006	770	843	722
PCUBC [12]	1716	1049	1326	1031	1238	923
CAPWAP Measured	1820	1720	3323	1890	2388	1850

As shown in Figure 2, the evaluation revealed that the pile dynamic formulas are mostly under-predicting pile capacity. It can be noticed that all of the methods under-predicted the pile capacity at Pier 6, the Anderson street overpass. This site exhibits HPR during driving of 610 mm concrete piles and therefore concrete piles were replaced by H-pile. Contractors and engineers have experienced pile installation problems while driving high displacement piles with single-acting diesel hammers, problem occur when a large initial penetration per hammer blow is followed by a large elastic rebound resulting in a small or negligible permanent-set per blow. Therefore, prevent the required driving resistance from being achieved and or stop the pile driving process, placing the foundation performance at risk or requiring redesign

Amongst the seven methods for site 2 SR435 as shown in Figure 3, the Danish [8] 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 [8] method. The predictions using the Gates [8], Modified ENR [8] methods were found to be overly lower than the measured values and was ranked least desirable amongst the methods.

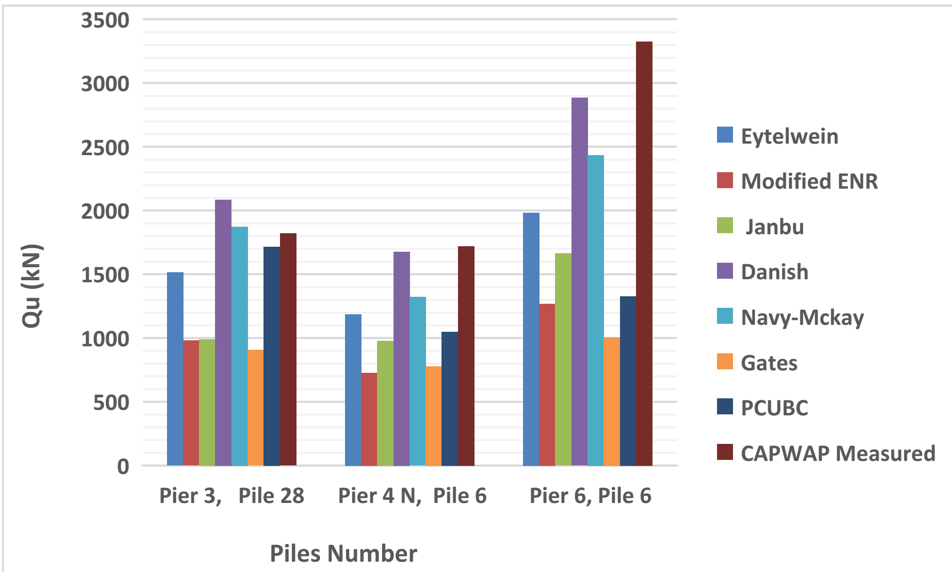

Fig.2: Dynamic Bearing Capacity of Used Piles versus Measured Capacity at Anderson Street Overpass

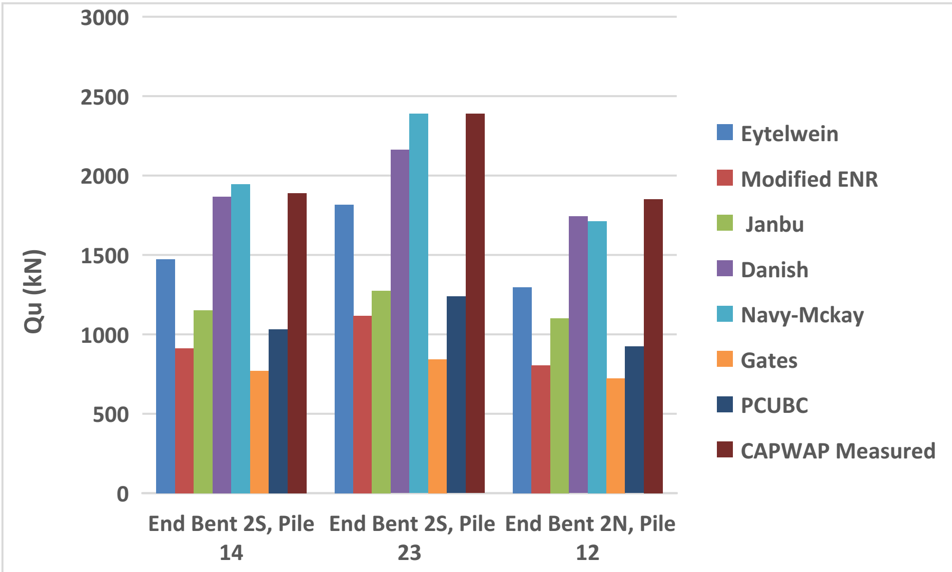

Fig.3: Dynamic Bearing Capacity of Used Piles versus Measured Capacity at SR 435 (Kirkman Road) Over Florida Turnpike

5. Conclusion

The efficiency of seven commonly used pile dynamic formulas in predicting capacity of pile foundations have been evaluated and compared in this work. Dynamic pile load testing (i.e., PDA and CAPWAP) was performed during the driving of piles at two sites included large and low displacement H-piles, and actual pile capacity was determined during the end of drive. At one of these sites, certain soils exhibit significant elastic behavior resulting in a small permanent set and consequently produce very high blow counts, does not provide a pile with adequate static capacity and prevent the pile driving process from being completed. Therefore, the engineers redesigned the deep foundation system, whereby the large displacement prestressed concrete piles (PCP's) were replaced with low-displacement steel H-piles.

The seven dynamic formulas included Eytelwein, Modified ENR, Janbu, Danish, Navy-Mckay, Gate, and PCUBC. The evaluation revealed that the pile dynamic formulas are mostly under-predicting pile capacities. Amongst the seven methods, the Danish [8] 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 [8] method. The predictions using the Gates [8], Modified ENR [8] methods were found to be overly lower than the measured values and was ranked least desirable amongst the methods.

All of the methods under-predicted the pile capacity at Pier 6, the Anderson street overpass site where HPR was encountered, however, concrete piles were replaced by H-pile at site. Based on the considered ranking criteria, the used dynamic methods with the highest level of uncertainties is the Gates method

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