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THE LATERAL CAPACITY OF CONCRETE PILES IN STIFF CLAY TO DENSE SAND

Mina Mikaeel [1], Andrew G. Gouda[2]

[1] Principal Geotechnical Engineer, P.E., Kiro Engineering, LLC., Hamilton, NJ, USA mina@kiroengineering.com
[2] Assistant Lecturer , Construction & Building Eng. Dept., Arab Academy for Science & Technology and Maritime Transport AASTMT Portsaid, Egypt
andrew.gouda@aast.edu

Abstract

Pile foundations, either precast or cast-in-situ, are popular for usage worldwide in many important and costly projects, such as bridges, or jetties in harbor areas, etc. In addition, the stability and safety of such strategic structures count to a great extent on the serviceability of the carrying foundations system. Thus, the integrity of the soil-pile foundation systems governs sharply the service life of the supported structures.
Based on such complexity of modeling the problem, it may be beneficial to use field test results such as PDA tests and CAPWAP analysis to give a close estimate of the actual piles' lateral Capacity. Such results can act as proof testing, providing confirmation that the expected capacities assumed in design are in fact, available in the field.
Thus, based on accumulative results of PDA-CAPWAP tests in different types of soil for different types of piles and by modeling the soil pile system and asymptotically loading laterally till critical displacements are achieved, a stochastic equation is derived to correlate the piles' lateral capacities to available geotechnical information and PDA-CAPWAP tests. This is based on the assumption that the resistance to penetration can be divided into lateral and vertical components..

Keywords: soil-structure interaction, impact load, Structural Dynamics, Earthquake Engineering, Proceedings.

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1 INTRODUCTION

Design of foundations subjected to large lateral forces caused by wind, wave action, earthquake and lateral earth pressures is a challenging task especially if found in a soft soil which is usually prevalent in lowland regions of the earth pile Driving Analyzer (PDA) has to be mentioned as early as possible .In addition, structures such as transmission lines towers, bridges and hi-rise buildings, which are usually found on piles, must be designed to support both axial and lateral loads as well as moments. Therefore, the lateral resistance of piles is governed by several factors, the most important of which being the ratio of the structural stiffness of the pile to the soil stiffness. Moreover, the relative stiffness of the foundation element with respect to the soil controls the mode of failure and the manner in which the pile behaves under an applied lateral load. Thus, estimation of the lateral pile load capacity is a key design procedure for structures design, where lateral loads are predominant, such as in bridges, tall buildings, and transmission tower structures.

Furthermore, although the usual application of a pile foundation results primarily in axial loading, there exist numerous situations in which components of load at the pile head produce significant lateral displacements as well as bending moments and shear forces. Unlike axial loads, which only produce displacements parallel to the axis of the pile (a one-dimensional system), lateral loads may produce displacements in any direction. Unless the pile cross section is circular, the laterally loaded pile/soil system represents a three-dimensional problem. Most of the research on the behavior of laterally loaded piles has been performed on piles of circular cross section in order to reduce the three-dimensional problem to two dimensions. Little work has been done to investigate the behavior of noncircular cross-section piles under generalized loading. In many applications, battering of the piles in the foundation produces combined axial and lateral loads.

Piles during their lifetime may in practice be subjected to severe dynamic excitations as earthquakes. Damage resulting from such excessive lateral loading and its location are usually unexpected. This is the case together with knowing that economic and social effects of earthquake disasters can be efficiently reduced through a comprehensive assessment of seismic hazard and the associated risk [1]Thus, protection of piles against excessive loading hazards from earthquakes has become one of the essential goals for structural engineers.

However, the soil profile properties under any structure cannot be thus neglected in such an assessment. This is the case since the soil underneath structures is undoubtedly the medium that transfers the seismic excitation to the foundations of the structure. The process in which the soil response influences the motion of the structure and vice versa is termed as Soil Structure Interaction (SSI).) [2].

2 PROBLEM DEFINITION

Designers usually need to identify the lateral Capacity of piles to check for the stability of structures under lateral seismic loads. Pile foundations usually find resistance to lateral loads from (a) passive soil resistance on the face of the cap, (b) shear on the base of the cap, and (c) passive soil resistance against the pile shafts. The latter source is usually the only reliable one. Analysis of the problem yields deflections, rotations, moments, shears, and soil reactions as required for structural design. Beam-on-elastic-foundation theory is adequate for the analysis of the problem [3].

In addition, (PDA, CAPWAP) field tests are used to obtain the vertical Capacity of driven piles. In general, most piles are considered relatively flexible, but only short rigid piles are likely to require consideration of the lower boundary conditions in analysis. Non-dimensional solutions are available for both constant and linearly increasing modulus-depth relationships [3].

However, the majority of the research on lateral load behavior has been restricted to vertical piles subjected to loads that produce displacements perpendicular to the axis of the pile. In the discussions which follow, it is assumed that the pile has a straight centroid vertical axis. If the pile is non-prismatic and has a noncircular cross-section, it is assumed that the principal axes of all cross-sections along the pile fall in two mutually perpendicular planes and that the loads applied to the pile produce displacements in only one of the principal planes.

3 LITERATURE REVIEW

Laterally loaded piles may be classified as active piles or passive piles with regard to the loading transferring direction between the piles and the surrounding soils [4]. An active pile is principally loaded at its top, with the lateral load being transferred to the soil, such as piles acting as foundations for transmission towers, advertisement posts, and offshore structures. A passive pile usually sustains lateral thrusts along its shaft arising from horizontal movement of the surrounding soils, such as piles in a moving slope or landslides. A variety of design and analysis methods have been developed for both active and passive piles. These methods range from relatively simplistic approaches that calculate the ultimate lateral Capacity to relatively sophisticated methods involving advanced numerical analyses that estimate the pile deflections. By reviewing the approaches for analyzing piles, one can distinguish that these approaches are subdivided into five sections: (1) pile flexibility and critical length; (2) failure modes; (3) limiting force or ultimate soil resistance profiles; (4) ultimate lateral Capacity; and (5) load- deflection calculation of laterally loaded piles [5].

4 CASE STUDY

Evaluating the lateral load resistance of pile foundations is critically important in the design of structures which may be subjected to earthquakes, high winds, wave action, and ship impacts. However, this is hampered by the high cost and logistical difficulty of conducting lateral load tests on piles. Several case studies are conducted on 16 driven prestressed concrete piles within areas in Route 52 Causeway, New Jersey, United States of America (Fig. 1). As part of the site investigation, cone penetration tests are performed to characterize the subsurface conditions. The pile load testing program consisted of dynamic testing by means of the Pile Driving Analyzer (PDA), CAPWAP, and full-scale static load tests.

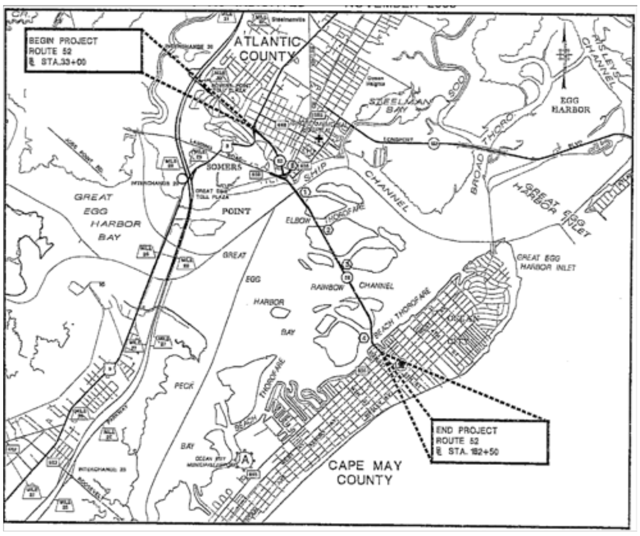


Figure 1. The region of the studied piles

The results of the cone penetration tests, dynamic and static load tests, and pile driving records were analyzed to form a database of high-quality, well-correlated data to inform the models. The results indicate that cone penetration tests can be used to accurately predict Capacity and required embedment lengths for the tapered piles. PDA and CAPWAP testing measures acceleration and strain imparted to a pile during driving. This data are then used in CAPWAP to calculate pile capacity. The CAPWAP program runs a numerical simulation of load testing the pile. The program compares the calculated Capacity to the acquired PDA data, iterating until it converges on the indicated pile capacity.

5 DATABASE

Data were collected from 16 PDA tests for the purposes of this study, where driven piles were installed for bridge foundations. Typical records of pile driving (pile penetration rate and hammer stroke) were accompanied with dynamic measurements using a Pile Driving Analyzer (PDA) for both ends of driving and the beginning of restrike conditions. All piles were square prestressed concrete piles driven with an impact hammer, and is presented in Table 1. For the case of the square piles, the equivalent diameter was calculated for simplicity. According to (AASHTO bridge design specifications) [6], the resistance factor for driven piles is 0.65.

6 SOIL STRATIFICATION

The subsurface profile was characterized using a variety of methods to provide basic geotechnical data for use in subsequent computer analyses of the test results, as shown in Fig. 2. Based on the results of the field and laboratory testing, and to simplify reading the soil properties of each layer, the soil profile shown in Table 2 was developed. The main studied soil profiles in this paper generally consider the general case of having two main layers. The first layer is stiff soil (e.g. clay), and the second layer is dense soil (e.g. sand).

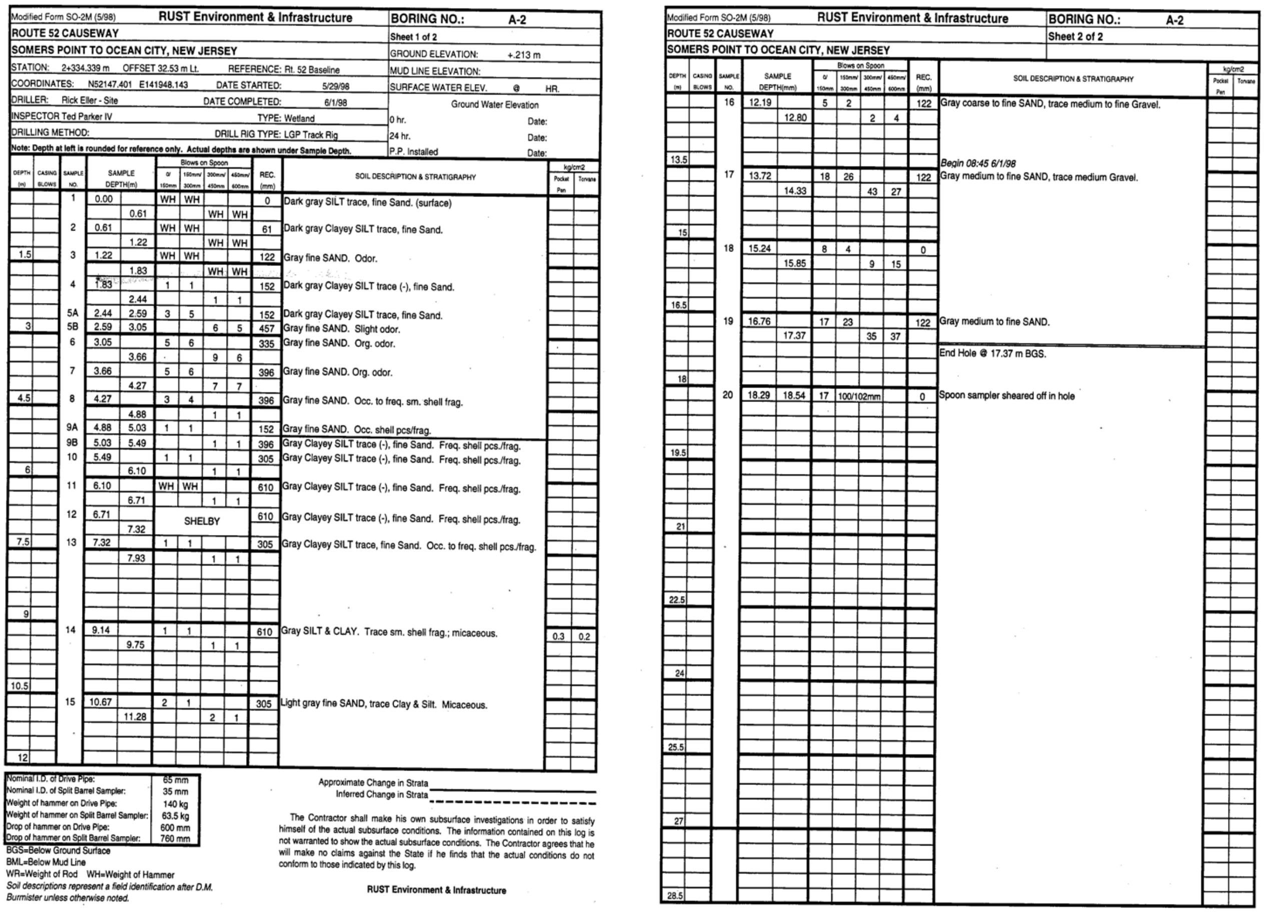
Table 1. Dimensions and allowable capacities of the studied piles

no.	Dimensions		Mobilized axial Capacity	allowable axial Capacity
	Side.	pile length		
	m	m	KN	KN
1	0.76	23.16	7302.03	4746.32
2	0.76	21.49	7671.35	4986.38
3	0.76	24.38	9744.93	6334.21
4	0.76	25.76	7475.57	4859.12
5	0.76	25.76	8232.02	5350.81
6	0.76	19.05	8543.50	5553.28
7	0.76	30.94	7706.95	5009.52
8	0.76	18.59	8721.49	5668.97
9	0.76	25.76	7653.55	4974.81
10	0.76	22.92	10367.90	6739.13
11	0.76	21.18	8948.43	5816.48
12	0.76	31.09	8410.01	5466.51
13	0.76	23.93	6603.42	4292.22
14	0.76	23.47	6941.60	4512.04
15	0.76	23.62	7965.04	5177.27
16	0.76	32.61	8677.00	5640.05

Table 2. The soil profile layers versus depth for one of the studied piles

Pile no.	clay			sand		
	Layer thickness	ɣ	c	Layer thickness	ɣ	ϕ
	m	kN/m3	kN/m2	m	kN/m3	
1	16.00	19.76	59.99	45.72	21.57	42
2	17.53	19.47	69.87	53.34	19.69	39

3	17.68	17.68	50.00	30.48	20.63	37
4	16.76	18.56	50.00	30.48	21.26	38
5	15.85	18.50	49.94	30.48	20.16	36
6	13.72	19.10	51.03	30.48	21.73	41
7	21.34	19.28	50.00	42.67	21.73	41
8	13.72	19.24	52.60	30.48	21.73	41
9	16.76	17.19	50.00	28.96	20.79	38
10	18.29	19.65	50.58	25.91	21.73	41
11	11.00	19.80	50.00	45.72	20.00	39.5
12	21.34	19.78	59.06	42.67	21.73	41
13	12.80	17.48	50.75	30.48	21.73	41
14	16.76	17.48	52.67	30.48	21.73	41
15	9.14	18.11	50.00	30.48	21.73	40
16	15.24	17.48	50.02	36.58	21.57	40



Modified Form SO-2M (5/98) — **RUST Environment & Infrastructure** — **BORING NO.: A-2** — Sheet 1 of 2

ROUTE 52 CAUSEWAY

SOMERS POINT TO OCEAN CITY, NEW JERSEY

STATION: 2+334.339 m OFFSET 32.53 m Lt. REFERENCE: Rt. 52 Baseline

COORDINATES: N52147.401 E141948.143 DATE STARTED: 5/29/98

DRILLER: Rick Eller - Site DATE COMPLETED: 6/1/98

INSPECTOR Ted Parker IV TYPE: Wetland

DRILLING METHOD: DRILL RIG TYPE: LGP Track Rig

GROUND ELEVATION: +.213 m

MUD LINE ELEVATION:

SURFACE WATER ELEV. @ HR.

Ground Water Elevation: 0 hr. Date: / 24 hr. Date: / P.P. Installed Date:

Note: Depth at left is rounded for reference only. Actual depths are shown under Sample Depth.

DEPTH (m)	CASING BLOWS	SAMPLE NO.	SAMPLE DEPTH(m)		Blows on Spoon 0/150mm	150mm/300mm	300mm/450mm	450mm/600mm	REC. (mm)	SOIL DESCRIPTION & STRATIGRAPHY	kg/cm2 Pocket Pen	Torvane
		1	0.00		WH	WH			0	Dark gray SILT trace, fine Sand. (surface)		
				0.61			WH	WH				
		2	0.61		WH	WH			61	Dark gray Clayey SILT trace, fine Sand.		
				1.22			WH	WH				
1.5		3	1.22		WH	WH			122	Gray fine SAND. Odor.		
				1.83			WH	WH				
		4	1.83		1	1			152	Dark gray Clayey SILT trace (-), fine Sand.		
				2.44			1	1				
		5A	2.44	2.59	3	5			152	Dark gray Clayey SILT trace, fine Sand.		
3		5B	2.59	3.05			6	5	457	Gray fine SAND. Slight odor.		
		6	3.05		5	6			335	Gray fine SAND. Org. odor.		
				3.66			9	6				
		7	3.66		5	6			396	Gray fine SAND. Org. odor.		
				4.27			7	7				
4.5		8	4.27		3	4			396	Gray fine SAND. Occ. to freq. sm. shell frag.		
				4.88			1	1				
		9A	4.88	5.03	1	1			152	Gray fine SAND. Occ. shell pcs/frag.		
		9B	5.03	5.49			1	1	396	Gray Clayey SILT trace (-), fine Sand. Freq. shell pcs./frag.		
		10	5.49		1	1			305	Gray Clayey SILT trace (-), fine Sand. Freq. shell pcs./frag.		
6				6.10			1	1				
		11	6.10		WH	WH			610	Gray Clayey SILT trace (-), fine Sand. Freq. shell pcs./frag.		
				6.71			1	1				
		12	6.71		SHELBY				610	Gray Clayey SILT trace (-), fine Sand. Freq. shell pcs./frag.		
				7.32								
7.5		13	7.32		1	1			305	Gray Clayey SILT trace, fine Sand. Occ. to freq. shell pcs./frag.		
				7.93			1	1				
9												
		14	9.14		1	1			610	Gray SILT & CLAY. Trace sm. shell frag.; micaceous.	0.3	0.2
				9.75			1	1				
10.5												
		15	10.67		2	1			305	Light gray fine SAND, trace Clay & Silt. Micaceous.		
				11.28			2	1				
12												

Nominal I.D. of Drive Pipe:	65 mm
Nominal I.D. of Split Barrel Sampler:	35 mm
Weight of hammer on Drive Pipe:	140 kg
Weight of hammer on Split Barrel Sampler:	63.5 kg
Drop of hammer on Drive Pipe:	600 mm
Drop of hammer on Split Barrel Sampler:	760 mm

BGS=Below Ground Surface
BML=Below Mud Line
WR=Weight of Rod WH=Weight of Hammer
Soil descriptions represent a field identification after D.M. Burmister unless otherwise noted.

Approximate Change in Strata
Inferred Change in Strata

The Contractor shall make his own subsurface investigations in order to satisfy himself of the actual subsurface conditions. The information contained on this log is not warranted to show the actual subsurface conditions. The Contractor agrees that he will make no claims against the State if he finds that the actual conditions do not conform to those indicated by this log.

RUST Environment & Infrastructure

Modified Form SO-2M (5/98) — **RUST Environment & Infrastructure** — **BORING NO.: A-2** — Sheet 2 of 2

ROUTE 52 CAUSEWAY

SOMERS POINT TO OCEAN CITY, NEW JERSEY

DEPTH (m)	CASING BLOWS	SAMPLE NO.	SAMPLE DEPTH(mm)		Blows on Spoon 0/150mm	150mm/300mm	300mm/450mm	450mm/600mm	REC. (mm)	SOIL DESCRIPTION & STRATIGRAPHY	kg/cm2 Pocket Pen	Torvane
		16	12.19		5	2			122	Gray coarse to fine SAND, trace medium to fine Gravel.		
				12.80			2	4				
13.5										*Begin 08:45 6/1/98*		
		17	13.72		18	26			122	Gray medium to fine SAND, trace medium Gravel.		
				14.33			43	27				
15												
		18	15.24		8	4			0			
				15.85			9	15				
16.5												
		19	16.76		17	23			122	Gray medium to fine SAND.		
				17.37			35	37				
										End Hole @ 17.37 m BGS.		
18												
		20	18.29	18.54	17	100/102mm			0	Spoon sampler sheared off in hole		
19.5												
21												
22.5												
24												
25.5												
27												
28.5												

Figure 2. Borehole sample for one of the studied piles

7 METHODOLOGY

The present study focuses on determining the pile-head deflections. Typically, these values may often govern the design of laterally loaded piles. Therefore, an estimate of these values is of primary importance. In the present study, the LPile program was utilized to determine the pile-head deflections corresponding to the applied lateral load of the pile head at the ground surface (i.e. lateral load applied at an eccentricity from the ground surface). The latter program has the capability to generate and take into account nonlinear values of flexural stiffness (EI). These values are generated internally by the program based on cracked/uncracked concrete behavior and user-specified pile dimensions, and material properties for reinforced concrete sections. The program includes a feature for analyzing prestressed concrete sections as well. LPile software can perform pushover analyses and analyze the pile behavior after a plastic hinge (yielding) develops. The soil-layers data structures can be entered conveniently with default values provided. Therefore, LPile may be advantageous over other applications for the subject handled in this research. However, future studies would use other techniques, such as finite element analysis for soil modeling in the studied problem for comparison.

The piles were assumed to be embedded in a uniform granular soil deposit. The LPile program was utilized to perform lateral load analyses for various pile types and pile sizes. The pile types included square concrete prestressed piles where the width ranges from 609.6 mm (24 in) to 762 mm (30 in).

By using (Poulos et al., 1980) [7] method, a linear elastic soil response due to lateral pile movements was assumed. A critical length, Lc, exists for a laterally-load pile, over which any increase in pile length has no influence on the ground line deflection δ. The critical pile length Lc is a function of the relative stiffness of the pile and soil nature [8]. Lc can be calculated from the following equations:

$$L_c = 4.44\sqrt[4]{\frac{E_p I_p}{E_s}}$$

Where: EpIp is the bending stiffness of the pile, and Es is Young's modulus of soil.

8 FAILURE CRITERIA

There are many methods of analyzing the response of a laterally loaded pile. These methods can be categorized into the subgrade reaction approach and elastic continuum approach. The subgrade reaction approach was initially proposed by Palmer and Thompson [9], and subsequently further developed by Reese and Matlock [9].Further advancements lead to the development of p-y curves which are commonly used to model the nonlinear pile and soil behavior. These have been described by McClelland [10], where nonlinearity often typifies the pile load-deflection behavior.

The p-y curve simply relates the unit soil resistance to pile deflection. Theoretically, it is normally assumed that the soil in the back and front of the pile will remain in contact with reference to the pile during lateral displacement. The slope of the p - y curve at any deflection represents the tangent soil stiffness at that deflection. The ratio p/y at any deflection represents the secant soil stiffness corresponding to that deflection [11].

Matlock and Hudson [12]developed the empirical expression to represent the p ‐ y curve defined by the power function of deflection normalized by pile deflection at 50% of the ultimate soil reaction. Integrated clay criteria [13] proposed three expressions to represent the different segments of the p ‐ y curve. The reference displacement (y_c) is taken as the displacement of a pile that will occur at 50% of the ultimate soil resistance. The ultimate soil resistance occurs at a displacement of y_u, and beyond, remains constant for ideally plastic clays [14] O'Neill and Gazioglu, Sal M. [13] proposed a p ‐ y curve development procedure that would be applicable to all clays in order to remove the subjective distinction associated with the characterization of cohesive soils as either soft clays or stiff clays. The integrated clay criteria is developed by making a number of reasonable assumptions regarding the influence of factors like pile diameter, pile length, and soil stiffness and by optimizing the several parameters to produce a procedure that provides the best agreement with the available field data. The following equation can be used to calculate the critical deflection

$$y_c = 0.8 * \varepsilon_{50} * d^{1/2} * (E_p I_p / E_s)^{1/8} \qquad (2)$$

Where:

- $E_p I_p$ = bending stiffness of pile
- E_s = Young's modulus of soil
- d= diameter of pile
- ε_{50}= strain at 50% of ultimate strength from a laboratory stress-strain curve from Table 3.

- Table 3. Values of undrained shear strength
-

Undrained Shear strength, c_u [kN/m^2]	**ε_{50}**
<12	0.02
12-24	0.02
24-48	0.01
48-96	0.006
96-192	0.005
>192	0.004

9 ANALYSIS OF CASE STUDY

Moreover, the soil is modeled as a linear hysteretic material of Young's modulus, E, Poisson's ratio, υ, material damping ratio, ζ, and shear velocity, vs, see Figure 3.. Meanwhile, to calculate the single pile stiffness in the strips embedded in the sandy soil or clay soil, the geotechnical engineering software LPile [15]is used. The software (LPile) directly uses COM624S calculation methods for lateral analysis. The COM624S program solves the nonlinear differential equations representing the behavior of the pile-soil system to lateral (shear and moment) loading conditions in a finite difference formulation using p-y method of analysis by Reese et [16]For each set of applied boundary loads the program performs an iterative solution which satisfies static equilibrium and achieves an acceptable compatibility between force and deflection (p and y) in every element. For details on COM624, please refer to the FHWA publications. In summary, COM624S uses the four nonlinear differential equations to perform the lateral analysis.

$$EI\frac{d^4Y}{dZ^4} + Q\frac{d^2}{dZ^2} - R - Pq = 0 \quad (3)$$

$$EI\frac{d^3Y}{dZ} + Q\frac{dY}{dZ} = P \quad (4)$$

$$\frac{dY}{dZ} = St \quad (5)$$

$$EI\frac{d^3Y}{dZ} = M \quad (6)$$

where Q is the axial compression load on the pile, y is the lateral deflection of pile at depth z, z is the depth from top of pile, R is the soil reaction per unit length, E is the modulus of elasticity of the pile, I is the moment of inertia of the pile, and Pq is the distributed load along the length of the pile, P is the shear in the pile, St is the slope of the elastic curve defined by the axis of pile, and M is the bending moment on the pile

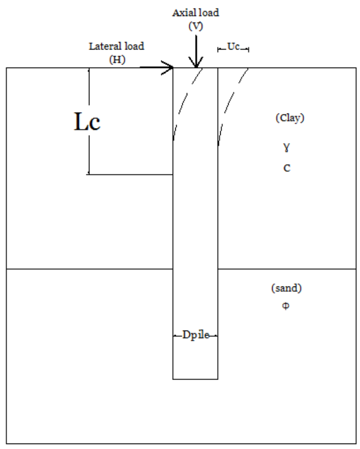


Figure 3. Pile-Soil system model

10 RESULTS AND DISCUSSION

For a given pile and a given set of soil conditions, pile-head load versus deflection curves were generated by increasing the lateral load as shown in Figure 4. For the range of pile sizes and soil parameters used in this study, it was determined that the minimum embedment depth beyond which the pile response remains unaffected after critical length. Most of the piles achieved complete bending with zero deflection at the pile tip.

Estimation of lateral load capacity of pile using LPile

LPile is capable to determine the flexural response of pile where the load is increased in a step by step manner. Passive resistance of soil is considered in the model and the program stops whenever the critical deformation is exceeded. This principle has been considered taking into the account the generated P-Y curves. In the present paper, the load acting at pile head and number of increments has been provided to reach the load. In LPile software, an automatic load increment feature is available which is used to estimate the lateral load capacity of pile as shown in Table 4. In the following Table 4, the lateral load capacity of piles have been estimated from the LPile software considering the permissible deflection at critical deflection capacity.

Table 4. The results of critical deflection and lateral Capacity for the studied piles

Pile no.	yc (critical def.)	(H) lateral Capac-ity
	cm	KN
1	0.478	353
2	0.464	380
3	0.498	307
4	0.498	317
5	0.498	314
6	0.496	318
7	0.498	317
8	0.492	321
9	0.498	314
10	0.497	310
11	0.498	314
12	0.480	345
13	0.496	322
14	0.492	326
15	0.498	314
16	0.503	303

ESTIMATION OF LATERAL LOAD CAPACITY OF PILE

From the above observation, the lateral load capacity of the pile has been estimated from the LPile software. The lateral load-carrying Capacity of a single pile depends not only on the horizontal subgrade modulus of the surrounding soil within the critical depth of the pile but also on the structural strength of the pile shaft against bending resulting from the application of the lateral load on the pile. While considering lateral loads on piles, the effect of other co-existent loads, including the axial load on the pile, should be taken into consideration for checking the pile's lateral Capacity.

Therefore, after the analysis of these results, it was tried to find a relation between the lateral load (H) versus the coefficient of cohesion (c), as well as the relation with the unit weight (ɣ) of the soil where the pile-soil system is assumed to deflect along the critical length. A nearly linear relations were found in both cases, as shown Figures 4, 5.

In addition, it was also observed that there isn't a clear relation between the lateral load capacity and axial load, therefore, it was tried to find a relation between the ratio (H/V) versus the axial vertical load (V). It is found that the relationship is nonlinear between H, and (H/V) as shown in Figure 6. Moreover, it is shown from Figure 6 that the lateral to vertical capacities ratio ranges from 5% to 7.5% of the axial Capacity.

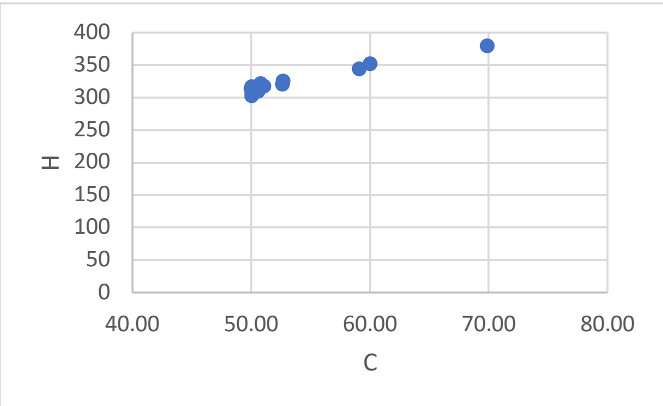


Figure 4. The relation between H in kN vs. the cohesion coefficient C in kN/m^2

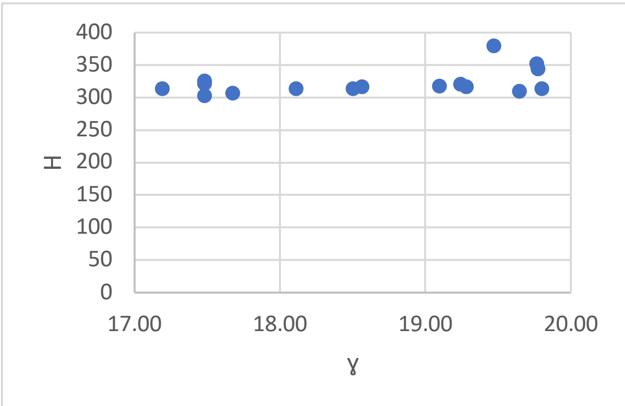


Figure 5. H in kN vs. the unit weight **ɣ in** kN/m^3

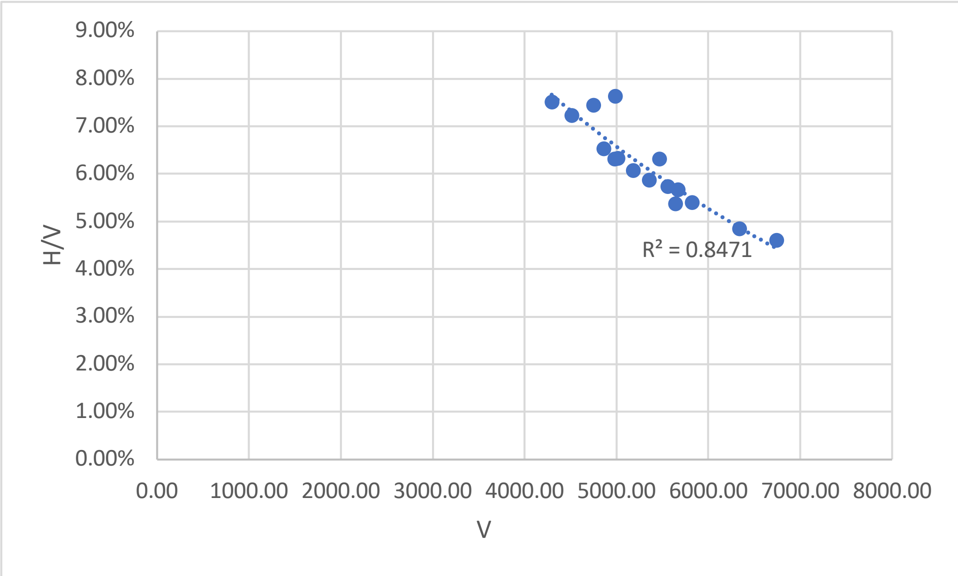


Figure 6. The relation between the ratio (*H/V*) vs. the axial load (*V*)

Based on the observed relations from Figures (4),(5),(6), one can distinguish that there are multiple parameters that affect the estimate of the lateral Capacity, such as the soil cohesion, c, the unit weight, ɣ, and the vertical Capacity, V. Moreover, studying the results as shown in Figure (6), one can realize that there is not one parameter that is solely sufficient to identify the lateral Capacity. Thus, a multiple nonlinear regression analysis using the SPSS program is applied to relate the correlated parameters to the lateral Capacity of piles. The latter analysis between the coefficient of cohesion (c), the soil unit weight (ɣ), and the axial load (V) is used to obtain a four-dimensional relationship between the above-mentioned parameters versus the lateral load capacity.

Moreover, from the defined nonlinear multi-parametric equation, by setting the unit weights to be in the range between 16 to 20 kN/m3, the space schematic shown in Figure (7) is obtained. The latter schematic incorporates the full results from the CAPWAP tests and the available soil profile properties for all piles to allow users to estimate a lateral capacity for any driven prestressed pile.

Furthermore, Figure (8) shows a three-dimensional surface that relates the soil properties and the CAPWAP results for the case of having a unit weight of 17 kN/m3 for the soil layers within the critical depth of the piles. Similarly, other three-dimensional surfaces can be obtained for other unit weights of the soil within the critical depth of the pile along which the pile deflects. The lateral Capacity for the driven piles can be obtained easily from such relations.

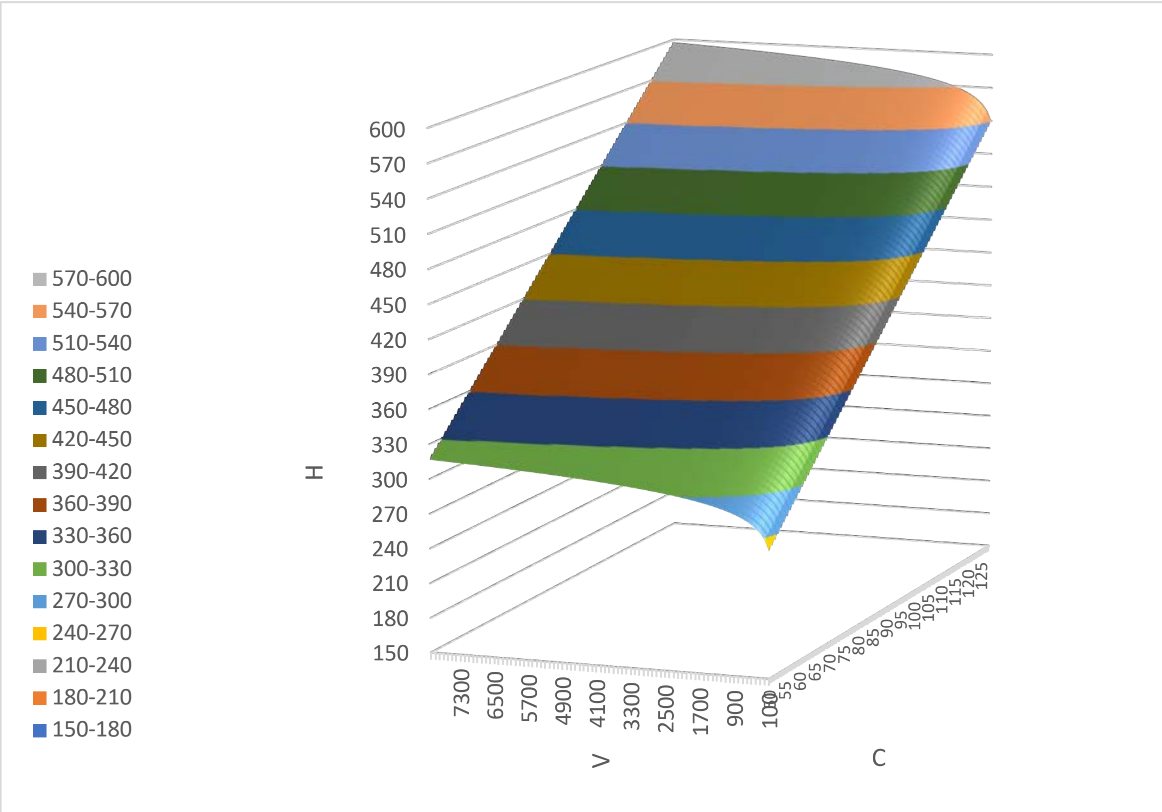


Figure (7) The relation between lateral Capacity (H), vertical Capacity (V) and cohesion coefficient (c) for a unit weight (ɣ) from 16-20(kN/m3)

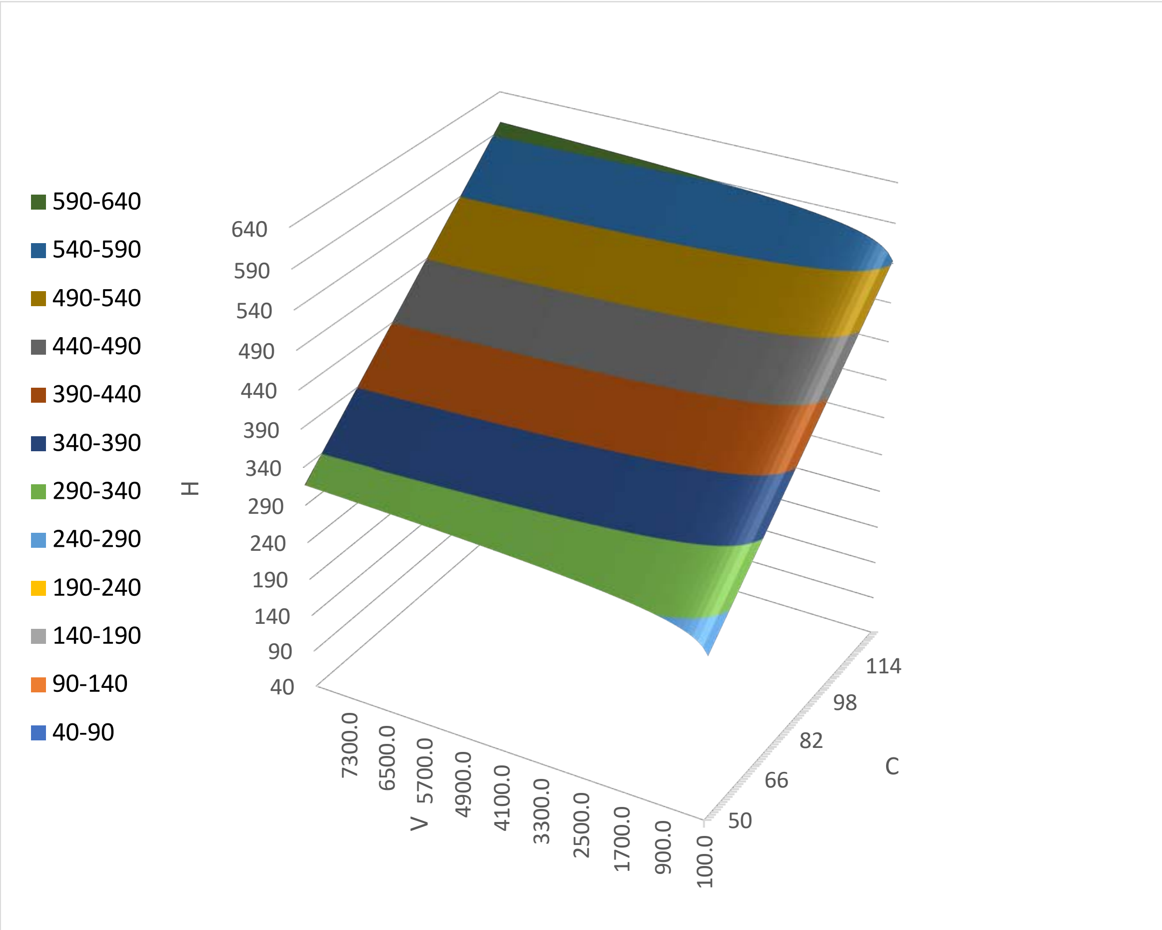


Figure (8) The relation between lateral load (H) & axial load (V) & coefficient of cohesion (c) at a unit weight (ɣ) =17(kN/m3

11 CONCLUSIONS

As Designers usually seek simpler methods for applications in their design and assessments, it would be beneficial to help designers to obtain estimates of the piles' lateral Capacity from available soil properties and axial load. This study focuses on piles behavior in soil profiles that are composed of soft stratum right below the surface, followed by a stiff stratum underneath. In this paper, the lateral Capacity of pile was found to depend mainly on three major parameters. These parameters include the coefficient of cohesion (c), and unit weight (ɣ) for the soil layers within the critical depth of the pile from the surface in which the pile is allowed to deflect, in addition to the vertical axial load capacity of piles (V).

Based on the present study and from the results of analysis, it is observed that the lateral load capacity of pile increases in nearly linear relation to the coefficient of cohesion (c), unit weight (ɣ), and a nonlinear logarithmic attitude is revealed on studying the relation between the vertical axial load capacity (V) and the ratio between the lateral and axial vertical capacities (H/V).

It was also found that the lateral capacity ratio mentioned above for prestressed driven piles ranges from 5% to 7.5% of the axial vertical Capacity. Finally, a multiple nonlinear regression was applied using SPSS software to identify the four-dimensional nonlinear relation between the lateral Capacity (H), the vertical Capacity (V), the soil cohesion (c), and the soil unit weight (ɣ). The resulting space schematic and three-dimensional surface relations can successfully be used to identify the lateral Capacity based on CAPWAP test results that identify the vertical Capacity and the soil properties within the critical depth of the studied piles.

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