GEOTECHNICAL DESIGN CONSIDERATIONS FOR PRESTRESSED CONCRETE PILE FOUNDATIONS

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ABSTRACT:

Piles are structural members that are necessary when the upper soil layers are too weak to prevent excessive settlement of the structure, or when the structure is subject to large lateral loads. Consequently, the geotechnical design of pile foundations must consider combinations of axial and lateral loadings, and group effects.

Determination of the axial capacity of piles depends upon characterizing the skin friction and end bearing. Whereas, for lateral loaded piles, beam theory represents the pile, and an uncoupled non-linear load transfer function (p-y curve) represents the soil. When group action is considered, non-linear springs are used to accommodate the pile-soil interactions.

Currently, pile foundation design is conveniently handled via a myriad of computer software, i.e., SPT97, DRIVEN, SHAFTSPT, APILE+, UNIPILE, LPILE+, FB-Pier, GROUP(3D), etc. Table 1 summarizes the use, costs, and purchase location of these various programs.

The accuracy of design calculations depends upon the accuracy of characterizing the soil engineering properties. Insitu tests are preferred over laboratory tests to develop these properties. The more common insitu tests being: SPT, CPT, DMT, and PMT. The initial two are preferred for axial capacity and rely upon empirical correlations. The last two are used for lateral capacity and directly generate p-y curves.

Due to soil-pile interaction complexities, and limitations in describing engineering properties, pile load tests are often performed for verification.

Keywords: Pile Foundations, Insitu Tests, Standard Penetration Test, Load Tests, Pile Software

INTRODUCTION

Deep foundations are used, as illustrated in Figure 1, to: (a) transmit structural loads through weak upper layers to a deeper "bearing" stratum, (b) transmit loads through water (bridges, docks, wharves, offshore structures), (c) resist uplift, overturning, or lateral loads, (d) control settlement or heave under spread footings or mats, (e) support and isolate machines (presses, lathes, mills, turbines) and heavy loads (vaults), (f) allow for future excavation, potential scour under bridges, or liquefaction under structures, and (g) support retaining walls on soft ground. The disadvantages of deep foundations are: (a) they are more expensive than spread footings, (b) they require mobilization of special equipment (hammers, cranes, drill rigs, compressors, etc.), and (c) significant ground vibrations can occur during construction.

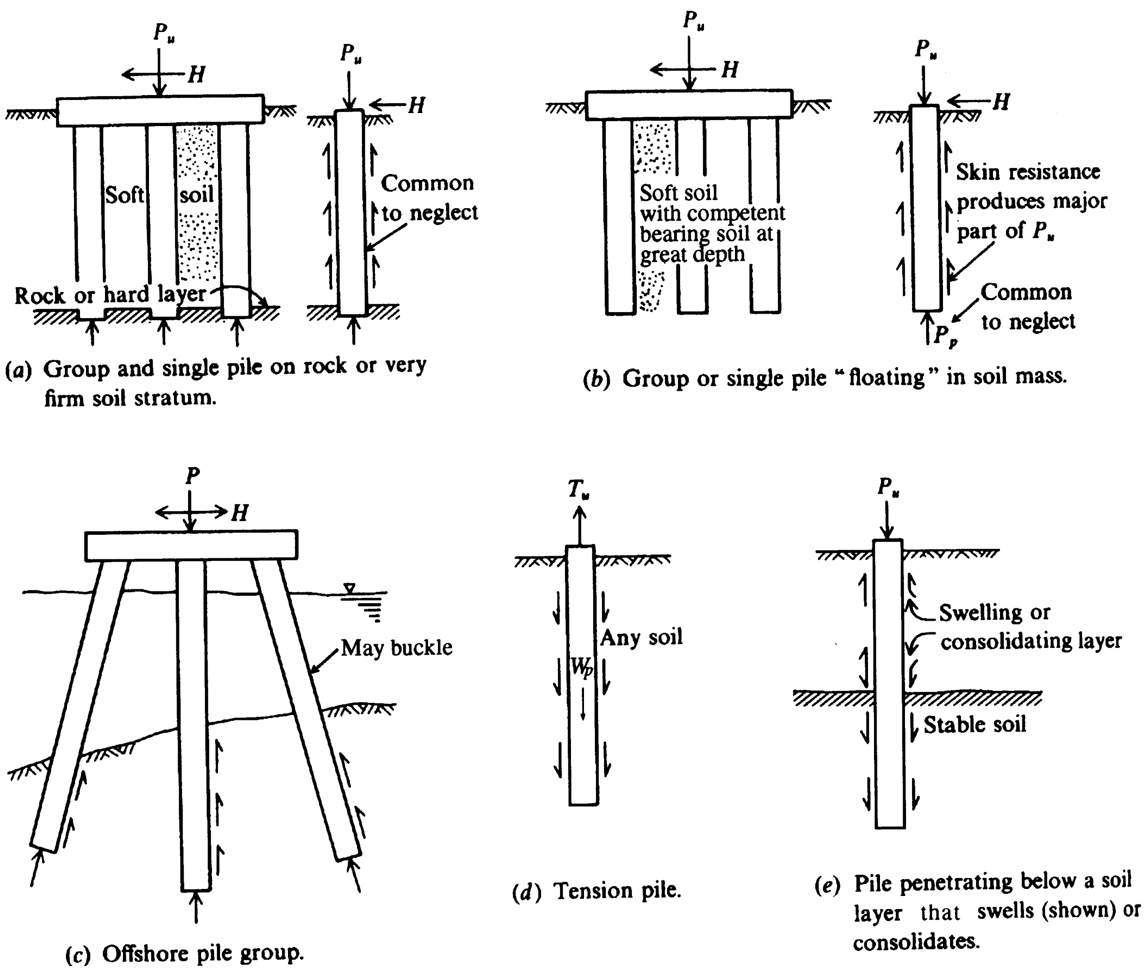


Figure 1 Illustration of Typical Pile Configurations (from Bowles, 1996)

DESIGN PHILOSOPHY

The geotechnical design of deep foundations considers the axial, lateral, and group effects imposed upon the pile members by the aforementioned loading considerations. The typical design philosophy used is illustrated in Figure 2.

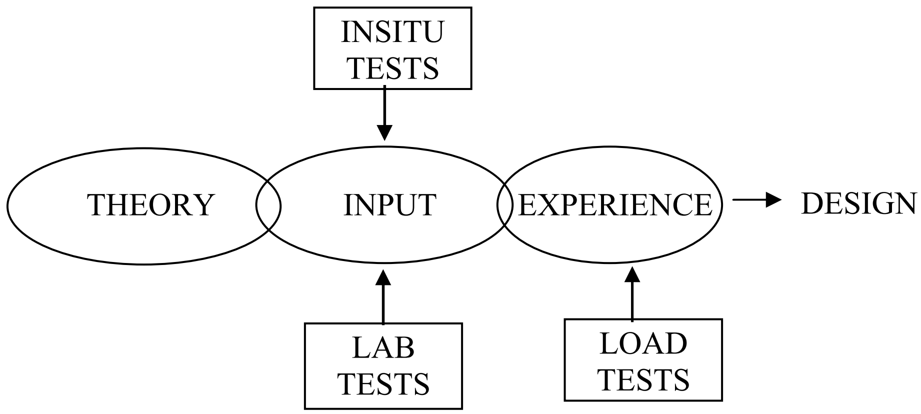


Figure 2 Geotechnical Engineering Design Paradigm

THEORY

The fundamental theory for estimating the axial capacity of piles depends upon characterizing the skin friction and end bearing as illustrated previously in Figures 1a & b. Vertical settlements are estimated using vertical t-z non-linear springs. Whereas, for lateral loaded piles, beam theory represents the pile as illustrated in Figure 3, while an uncoupled non-linear load transfer function (p-y curve) represents the soil (Figure 4).

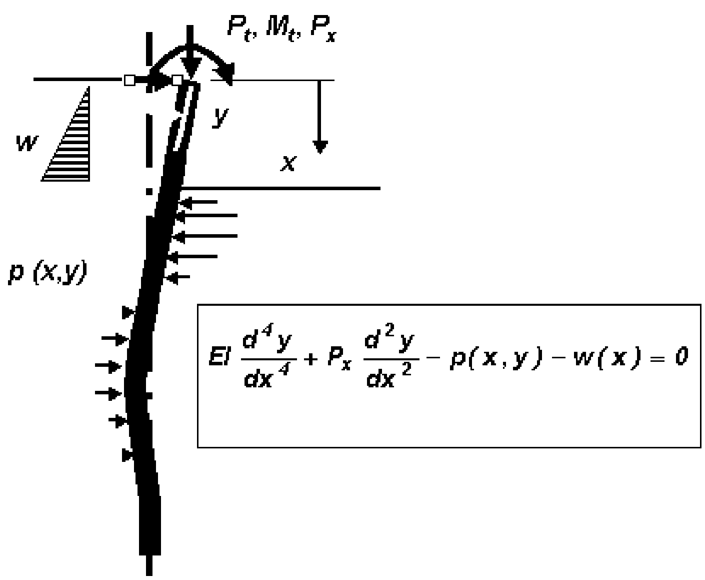


Figure 3 Beam Theory representation of Laterally Loaded Pile

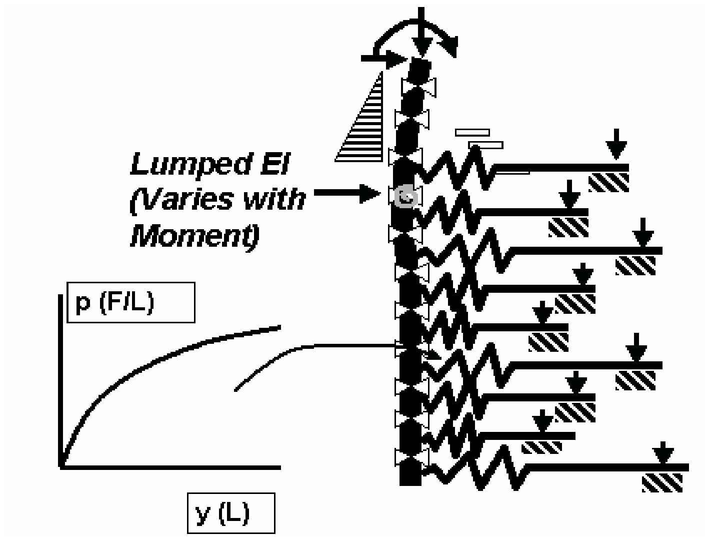


Figure 4 Representation of Soil Resistance by p-y Curve (Springs)

Torsional deformations are also estimated via non-linear springs. Figure 5 illustrates the combined axial, lateral, and torsional spring representation for estimating pile deformations under load.

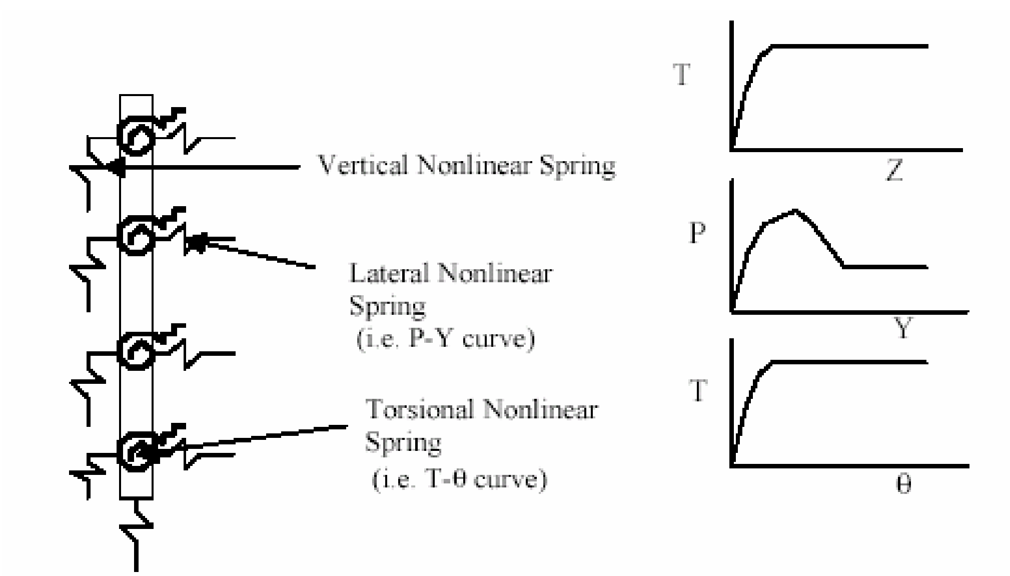


Figure 5 Near-Field Representation of Soil – Structure Interaction

When group action is considered, non-linear springs are used to accommodate the pile–soil interactions, and p-y multipliers are used to accommodate "shadowing effects" between the piles as illustrated in Figure 6. Figure 7 illustrates the group action effects for axial loaded pile groups; which has led designers to use a pile spacing of 3D.

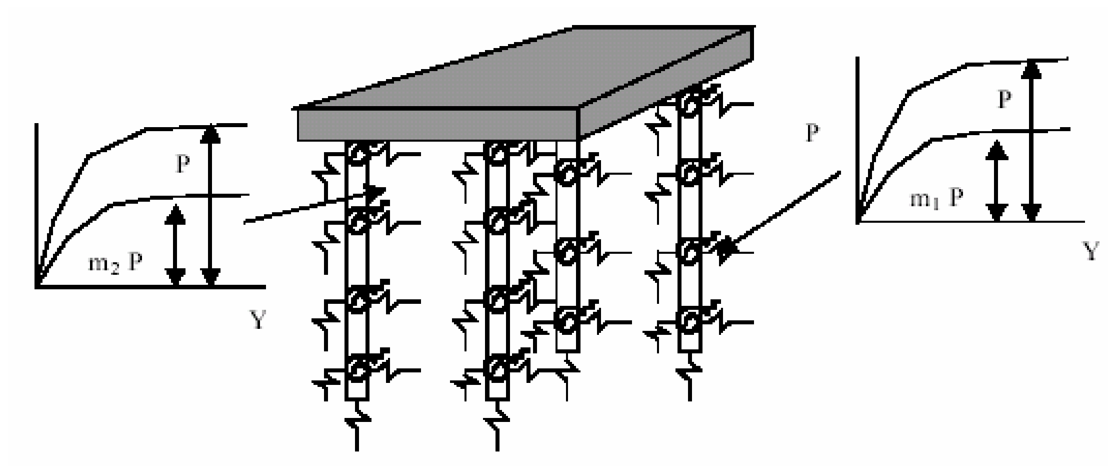


Figure 6 Illustration of p-y Multipliers for Lateral Loaded Group Effects

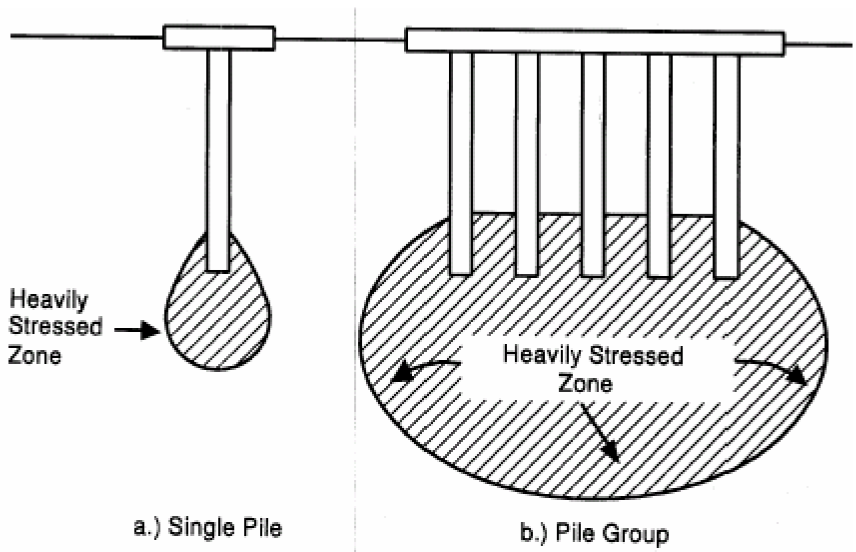


Figure 7 Stress Zones for Single and Pile Groups

Table 1 lists several computer programs commonly used to design the axial and/or lateral capacity of single piles or pile groups.

INPUT PARAMETERS

Obviously, sophisticated modeling is nothing more than an interesting exercise if the parameters used by these models are not well understood, or easily obtainable. Geotechnical parameters are obtained from either laboratory or insitu tests. However, because piles are long structural members often exceeding 70-ft., which would require many samples to be transported back to the laboratory, and sands below the water table make undisturbed sampling difficult, insitu testing is preferred for obtaining geotechnical engineering parameters.

Table 1 Common Computer Programs for Pile Design

Use	Program	Cost	Source
Axial Capacity	SPT97	Public	Contact FDOT Structure Design Office
	DRIVEN	Public	www.fhwa.dot.gov/bridge/geosoft.htm
	SHAFTSPT (FB-DEEP)	$400 Annual License	bsi.ce.ufl.edu
	UniPile	$620	www.unisoftltd.com
	APILE+	$690	www.ensoftinc.com
Lateral Deformation	LPILE 4+	$850	www.ensoftinc.com
Group Deformation	GROUP	$1450	www.ensoftinc.com
	FB-Pier	$1200 Annual License	bsi.ufl.edu

Insitu tests can be divided into 2 categories; (a) strength based, or (b) deformation based. The former is suited for capacity determinations, whereas, the latter is suited for settlement/ deformation determinations. The limitation of strength based insitu tests is that they rely upon empirical correlations to estimate engineering properties; i.e., SPT N-values correlated with friction angle, ϕ. Although deformation based tests likewise rely upon correlations, they are not as limited.

The common strength based insitu tests are; Standard Penetration (SPT) and Cone Penetration (CPT) Tests, while the deformation based tests are; Dilatometer (DMT) and Pressuremeter (PMT) Tests. Figure 8 illustrates these devices.

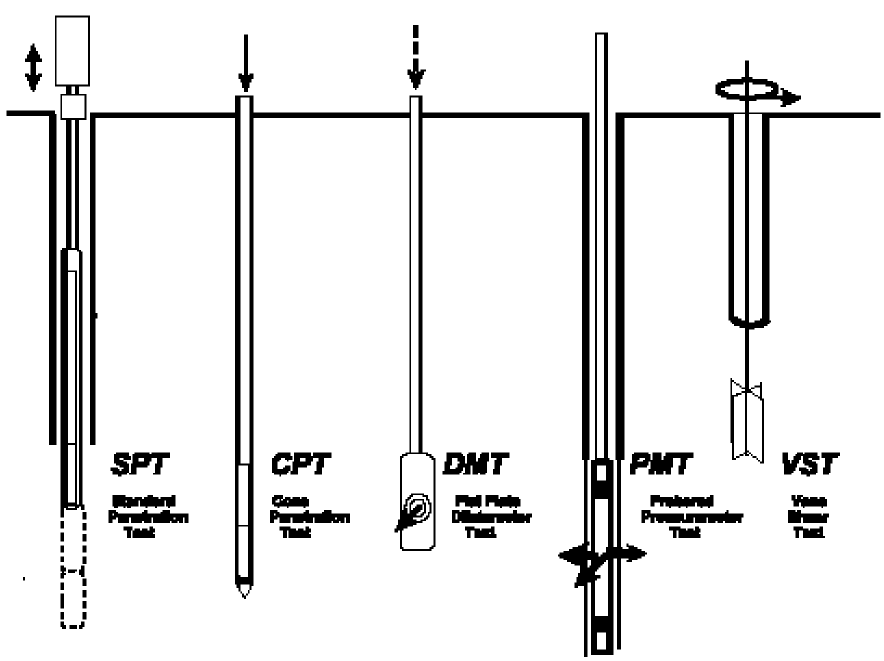


Figure 8 Schematic of Common Geotechnical Insitu Tests

Table 2 presents a summary of input parameters used by various computer programs for estimating pile capacity and deformations (vertical and lateral). As shown, soils are typically categorized as either "sands" (cohesionless) or "clays" (cohesive). The common engineering parameters are: friction angle (ϕ), unit weight (γ), and undrained shear strength (cohesion = c_u).

Table 2 Summary of Engineering Input Properties for Various Software Programs

Analysis	Program	Theory	Input Parameters
Axial Capacity	DRIVEN (FHWA)	Nordlund (1963)	Sands: ϕ,γ Empirical: K_δ,δ, C_F Clays: C_u, Empirical α
	SHAFTSPT (UF)	Meyerhof (1959)	4 Soil Types: Clay, Silty Sand, Sand, Limerock SPT – N correlations
	PL-AID	Nottingham & Schmertmann. (1975)	CPT only + Empirical C_f, K
Axial Settlement	APILE (Ensoft)	t-Z	Sand: ϕ,γ Empirical: K_o, N_q tip Clays: γ, $C_{u\ undisturbed}$, $C_{u\ disturbed}$ C/p
	FB-PIER (UF)	Meyerhof (1959), t-Z	Sands: ϕ, γ, G_i, μ, τ_f, Q_{Tip} Clays: C_u, γ,ε_{50}, ε_{100}, G_i, μ, τ_f, Q_{tip}
Lateral Capacity		Broms (1964 a&b)	Sand: ϕ, γ, Empirical: K_H, η Clay: C_u, Empirical: K_H, η
Lateral Deformation	LPILE+ (Ensoft)	Reese (2001), p-y	Sand: ϕ, γ Empirical: K_h Clays: C_u, ε_{50}
	FB-PIER (UF)	Reese (2001), p-y	Sand: ϕ, γ Empirical: K_h Clays: C_u, ε_{50}, ε_{100}

Several common empirical correlations relating insitu tests and engineering properties are presented below. The SPT and CPT tests cause failure to penetrate the soil, hence they are best suited for strength parameters. Conversely, the DMT and PMT tests are pressure tests and best suited for deformation parameters.

SPT CORRELATIONS

The equation used for overburden correction is:

$$C_N = 0.77 \log \frac{20}{\sigma_o'} , \ \sigma_o' \text{ tsf} \qquad (??)$$

For friction angle ϕ,

Kulhawy and Mayne (1990): $\phi = \tan^{-1}\left[\dfrac{N}{12.2 + 20.3 \log \sigma_o / P_a}\right]^{0.34}$ (??)

Peck et al. (1974) using uncorrected N-values as used in FB-PIER

$$\phi = 53.881 - 27.6034 * e^{-0.0147*N} \quad (??)$$

For undrained shear strength, C_u,

Sowers, (1979): $C_{tsf} = 0.04\,N$ (??)

Bowles, (1996): $C_{tsf} = 0.0625\,N$ (??)

For soil modulus values,

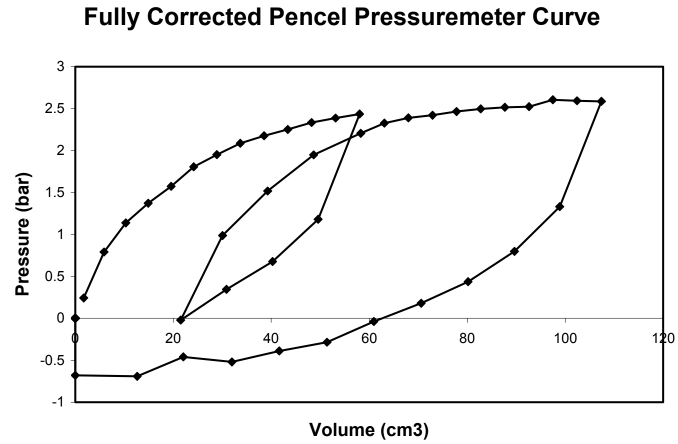
E (psf)	= 20,000 N_{60}	Sands
E (psf)	= 30,000 N_{60}	OC Sands
E (psf)	= 10,000 N_{60}	Sands with fines

The DMT does not directly measure E, but returns an estimate of the constrained modulus, M. Consequently, one must assume a value of Poisson's ratio (typically $\nu \approx 0.3$) to calculate E. $E = \dfrac{(1+\nu)(1-2\nu)}{(1-\nu)} M$, $\approx 0.8\ M_{DMT}$, if $\nu = 0.25 - 0.3$.

The PMT does not directly provide a modulus value, but is best suited for developing custom p-y curves for lateral loadings as illustrated in Figure 9.

EXPERIENCE (FACTORS OF SAFETY)

Inasmuch as pile driving is a brutal business requiring failure of the soil to insert the pile, considerable alteration (remolding) if the insitu soil occurs changing engineering properties. In addition, the pore water pressure (effective stress) regime is changed leading to pile set-up (pile freeze). These soil alterations coupled with construction uncertainties makes mathematical predictions of pile capacities/deformations difficult. Consequently, load testing to verify design assumptions is popular with the sophistication of load test leading to a hierarchy of safety factors shown in Table 3. Also presented in Table 3 are recommended LRFD ϕ factors. Currently a "disconnect" exists between traditional geotechnical and structural designers. The former tend to use Allowable Stress Design (ASD) factors, whereas the latter tend to use Load & Resistance Factor Design (LRFD) factors. Commingling of safety and ϕ factors can lead to miscommunication and overly conservative designs.



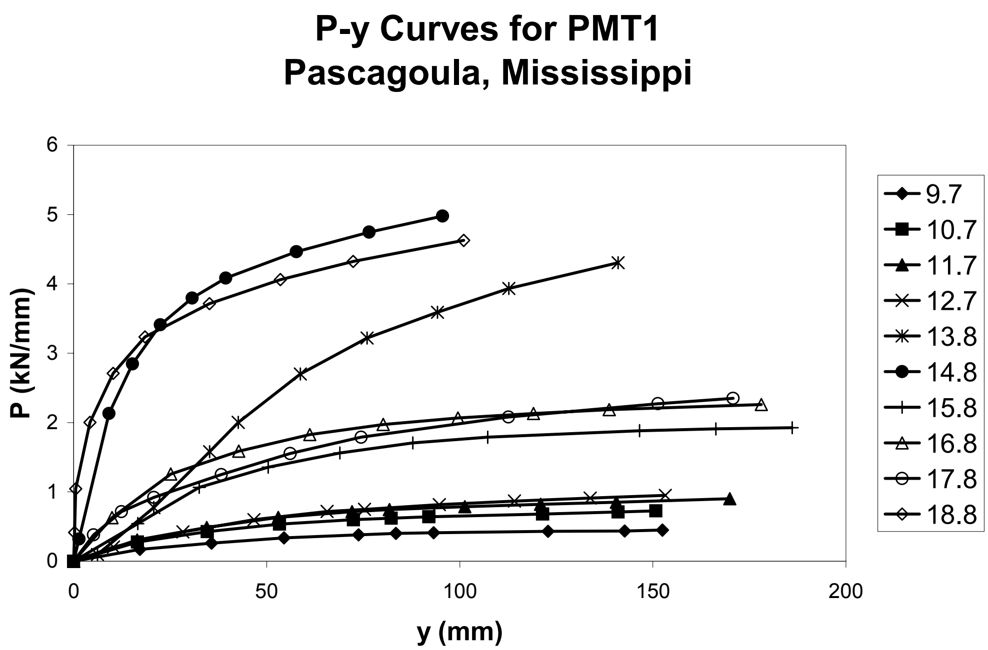


Figure 9 Illustration of Custom p-y Curves from PMT

The economics of load testing can be justified by considering that lower safety factors (higher ϕ) result in shorter pile lengths.

LOAD TESTING

The purpose of load testing is to; (a) prove that the foundation is capable of carrying the prescribed axial or lateral load, (b) confirm design assumptions, (c) verify construction performance, and (d) justify use of lower safety factors (higher resistance factors). The key components of a load test are; (a) some method of applying a load (jack, hammer, O-cell,

Table 3 FDOT Recommended Safety Factors and LRFD ϕ Factors

Construction Control Method ϕ Factor	Recommended Factor of Safety
Static Load Test ASTM 1143 0.80	2.00
WEAP/PDA (EOD) 0.65	2.50
Osterberg Cell 0.75	2.00
Statnamic Load Test 0.7	2.25

explosion), and (b) some way of measuring movement (gages, wireline, laser). The current methods available are listed in Table 3.

Static Load Test ASTM 1143

Figure 10 illustrates a static load test set-up. Typically a "quick" test is run using ~20 loads to 200% of the design capacity and holding each load for 5 minutes. Hydraulic jacks are used to apply the loads, which are measured using a load cell, while movement is measured with dial gages. The test requires the use of a load frame and corresponding reaction piles, which can be expensive and dangerous at high loads. Maximum load is approximately 1000 tons.

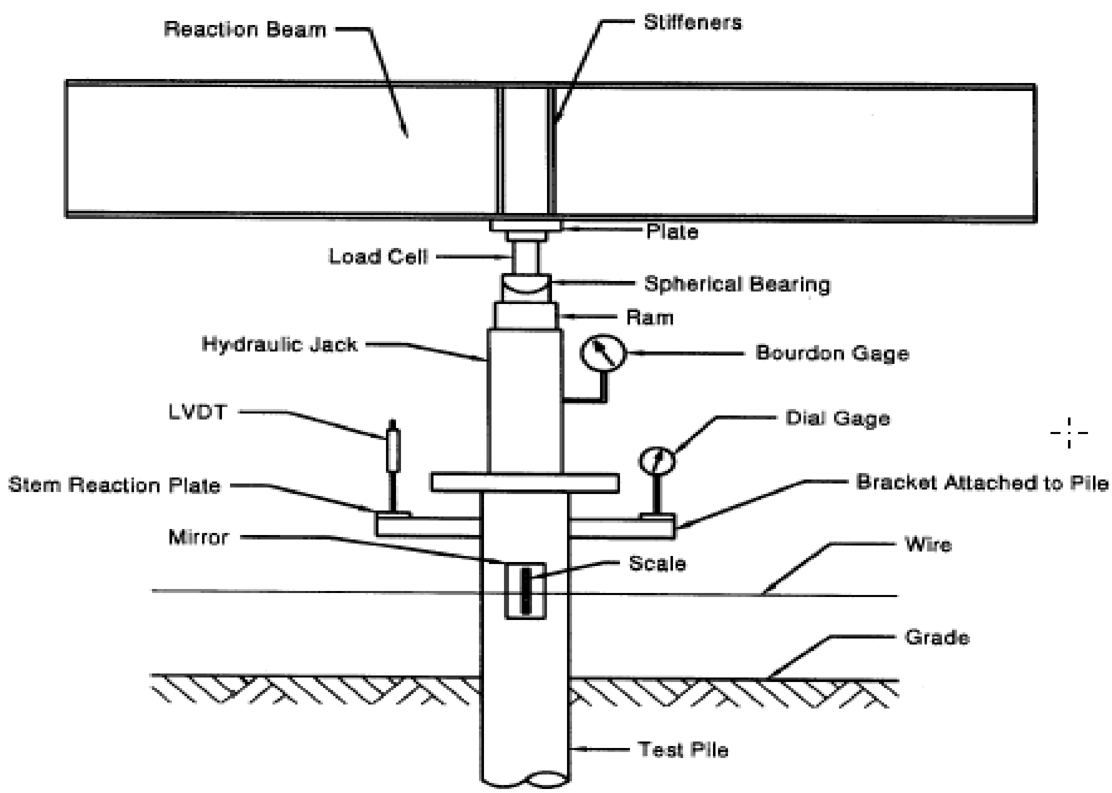


Figure 10 Illustration of Static Load Test

Osterberg Cell (O-Cell) Tests

Figure 11 illustrates the Osterberg cell test, which was developed by Prof. Osterberg. The concept is to eliminate the costly reaction piles and load frame of the conventional static load test by casting a non-recoverable single-use jack in the pile tip. Pressurizing the jack measures end bearing and side shear separately at the pile bottom essentially generating twice the load if the jack were place at the pile head. Failure is limited by the lesser of end bearing or side shear (one fails first and no more reaction is generated). By combining the bearing and shear load curves an equivalent top load deformation curve can be generated. Most tests are done by LoadTest Inc. (www.loadtest.com), with a maximum load of 15,000-ton (135 MN) equivalent top load test (end bearing + side shear).

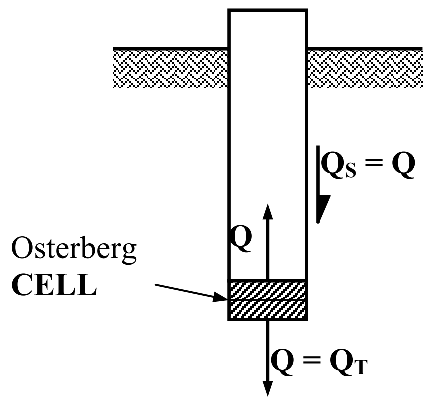


Figure 11 Illustration of O'Cell Load Test

STATNAMIC Load Test (www.berminghammer.com, www.testpile.com/)

Figure 12 illustrates the statnamic load test. As indicated by the name, the test is a hybrid static-dynamic test in which the load is applied by "launching" the reaction weights (~5% of the desired applied load) using an explosive propellant. In this fashion no reaction piles are needed. The moving mass of the pile is included in the calculations for the inertia forces, and a constant damping coefficient is used for the viscous forces to calculate an equivalent static load. Most US tests are done by Applied Foundation Testing in Green Cove Springs, FL. with a maximum load of ~30 MN (3300 tons).

CONCLUSIONS

1. The axial and lateral capacities of single piles are estimated based upon soil strength parameters, ϕ, C_u, and unit weight, γ. The strength can be estimated via SPT or CPT insitu test correlations.
2. The axial and lateral deformations of single piles and pile groups are estimated using non-linear springs expressed as axial τ - Z and lateral p-y curves. These relationships can be estimated from DMT or PMT insitu tests, while SPT and CPT correlations can also be used.

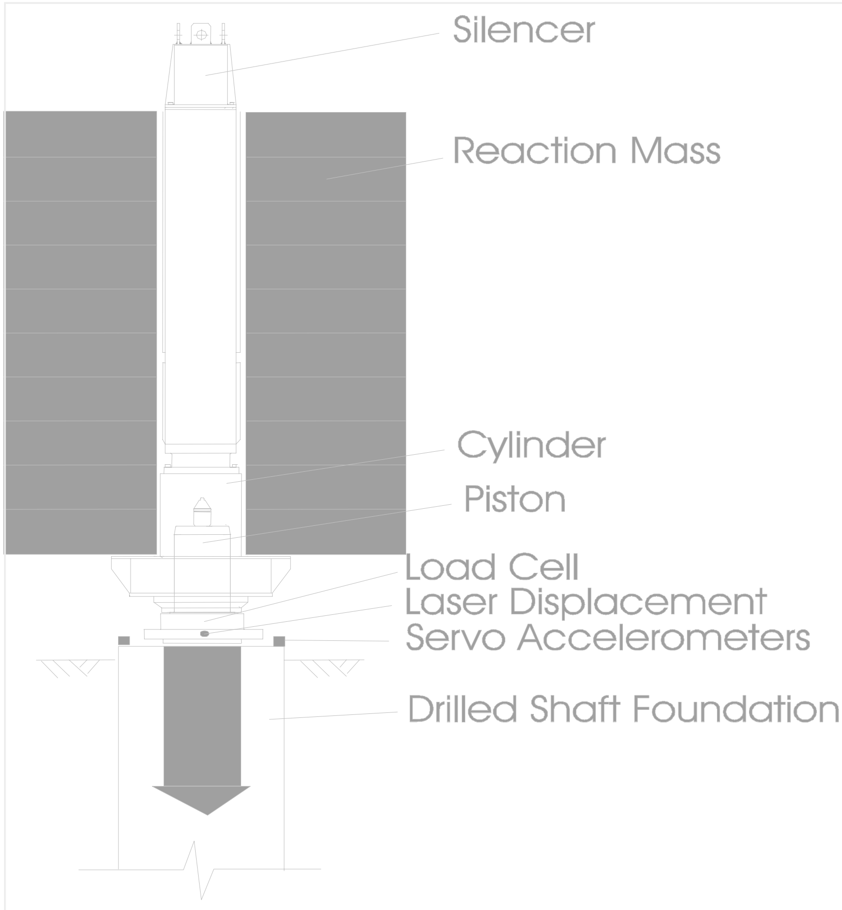


Figure 12 Schematic Drawing of the STATNAMIC Load Test.

3. Indiscriminant commingling of ASD safety factors with LRFD ϕ factors should be avoided.
4. Load testing can result in cost savings via the use of lower safety factors (higher ϕ factors).

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