Amirkabir University of Technology
(Tehran Polytechnic)

50th Annual Conference on Deep Foundations

Conceptual Axial Stress-Strain Behavior of Drilled Displacement Piles Using Full-Scale Load Tests Database

(PID: DFI50-63)

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Outline

Scope

Stress-Strain Behavior of DD Piles

Objectives

Load-Displacement Significancy

Stress – Strain Framework

Data-Centric Approach

Energy-Based Evaluation

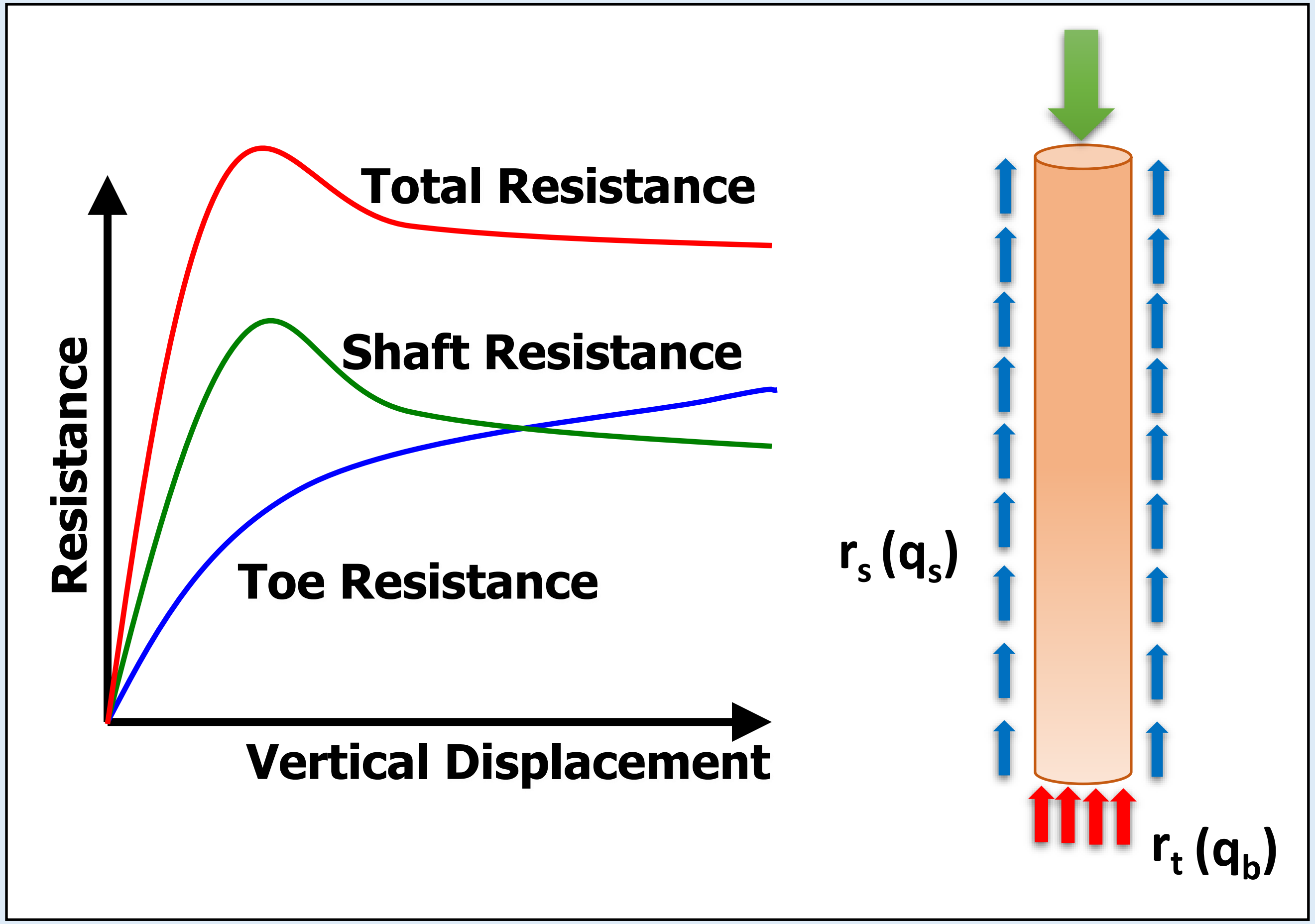
Foundation Alternatives

Aim

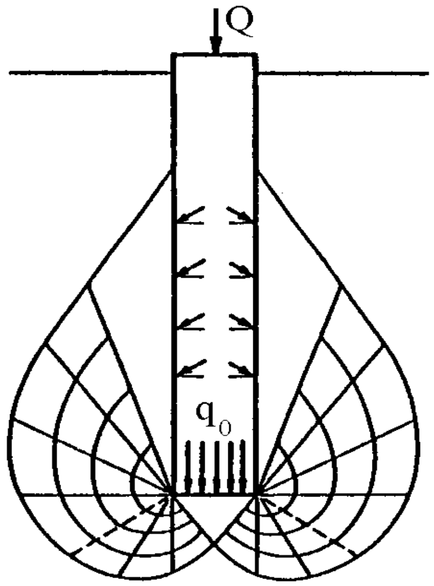
Resilient Foundations

Common Approaches for Bearing Capacity Appraisal

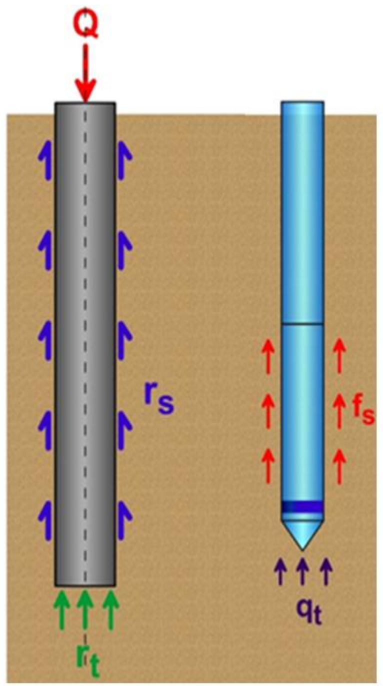
1. Static Analysis
2. In-Situ Tests Application
3. Static Load Test
4. Dynamic Analysis & Load Test
5. Numerical & Laboratory Modeling
6. Soft Computing: AI & ML



Common Approaches for Bearing Capacity Appraisal

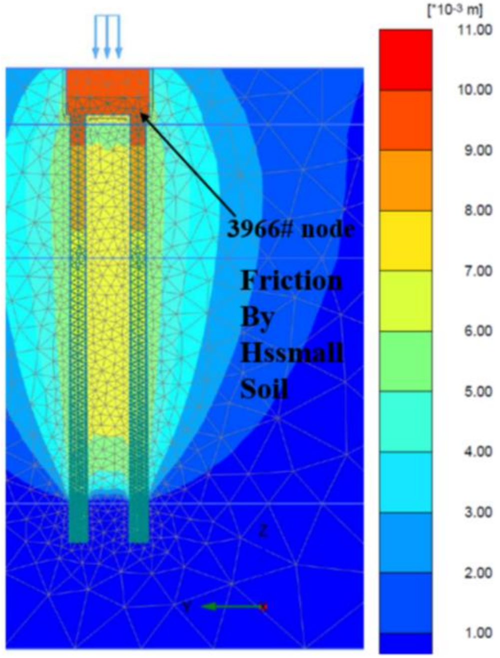


Pile failure zone
(Meyerhof, 1951)



CPT & pile resemblance
(Eslami et al., 2020)

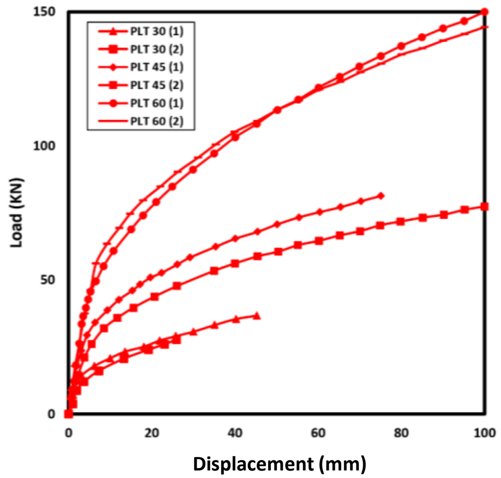
Field testing set-up
(Van Impe et al., 2013)



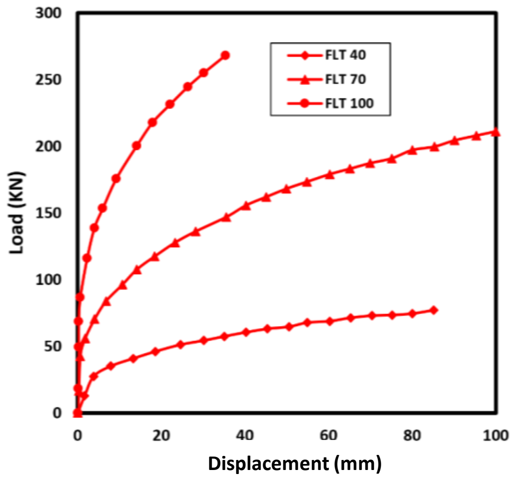
Numerical modeling of
piled raft (Xie, 2022)

Significancy of Load - Displacement

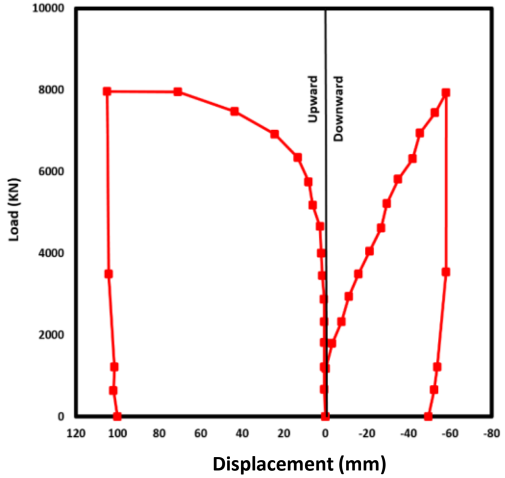
- ❖ Directly Reflects Critical Design Parameters
- ❖ Enables Accurate Bearing Capacity Determination
- ❖ Facilitates Settlement and Serviceability Checks
- ❖ Provides Essential Stiffness Parameters
- ❖ Proceeds Optimized Foundation Design



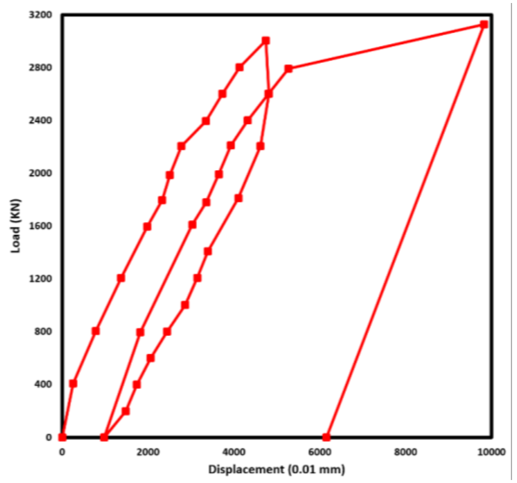
Circular PLTs
(Consoli et al., 1998)



Square Concrete Footings
(Consoli et al., 1998)



Bidirectional test on a bored pile
(Fellenius, 2023)



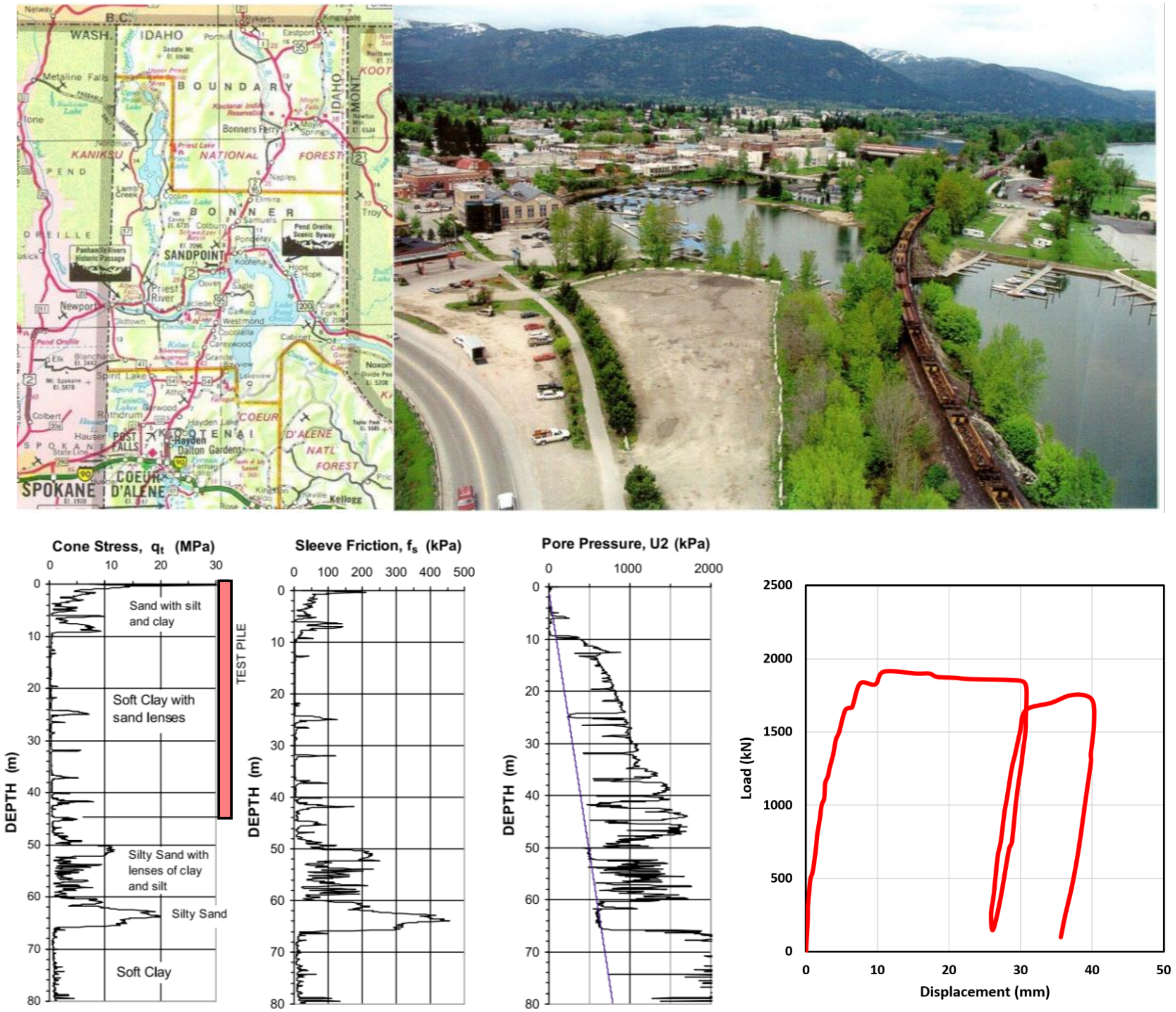
Driven pile, pull out test
(Eslami et al., 2011)

Load – Displacement; Dominant factors

❖ **Foundation**
- Geometry & Embedment
- Installation Effects
- Interface Properties
- Structural Material

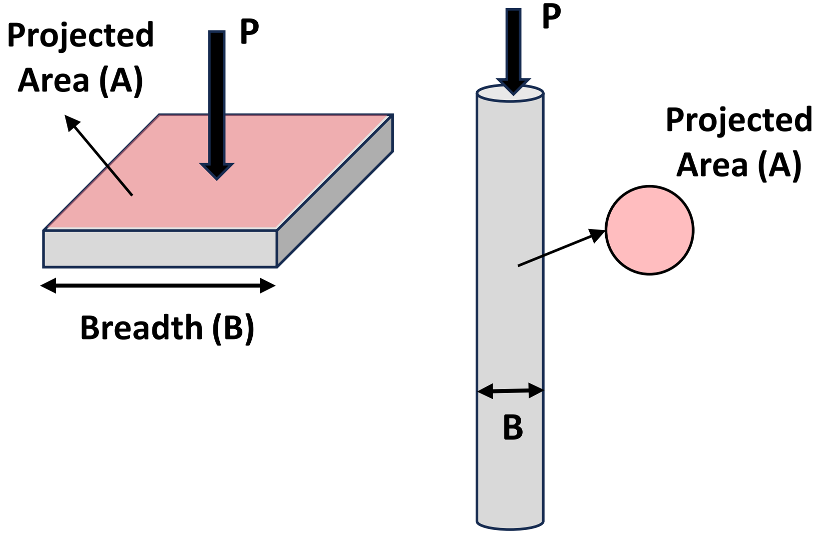
❖ **Geomaterial**
- Strength & Stiffness
- Drainage Condition
- Time History & Aging
- Sensitivity & Thixotropy

❖ **Loading**
- Pattern: Slow or Rapid
- Type: Compressive, Tensile, Cyclic



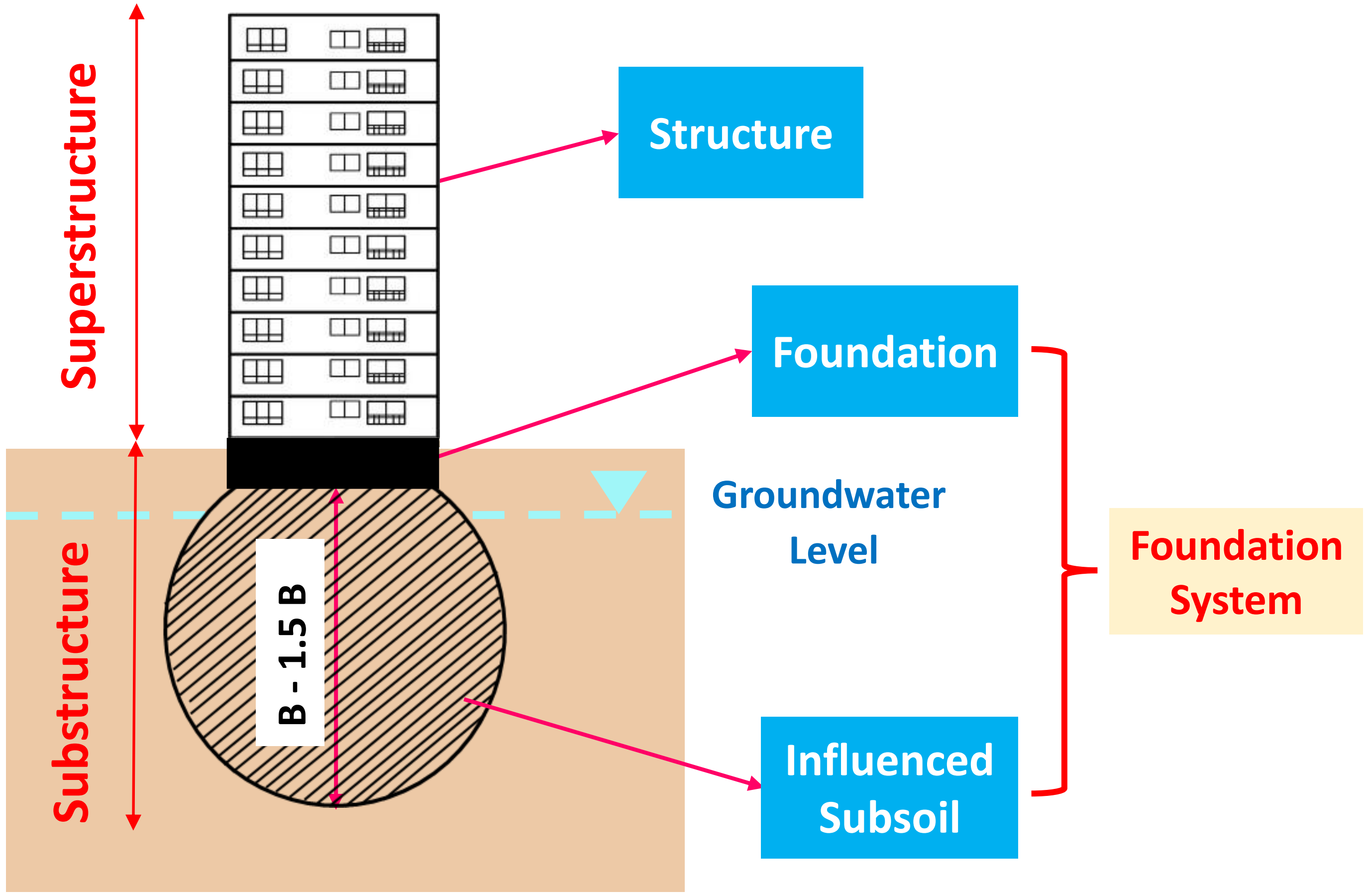
Static Loading Test on a 45 m Long Pipe Pile in Sandpoint, Idaho (Fellenius et al., 2004)

From Load-Displacement to Stress – Strain



$$\text{Stress } (\sigma) = \frac{\text{Axial Load (P)}}{\text{Projected Area (A)}}$$

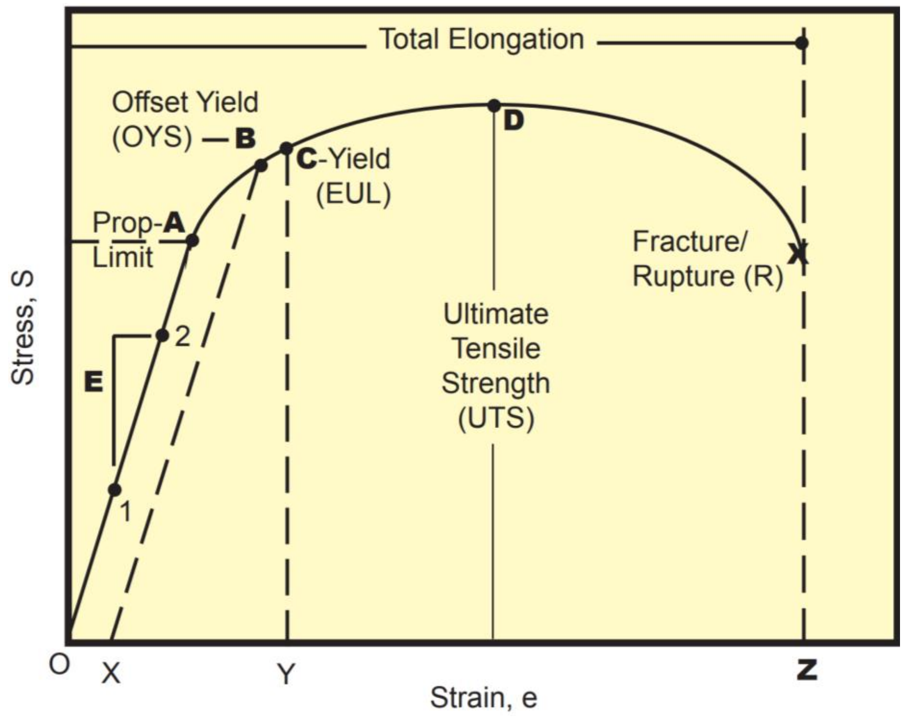
$$\text{Strain } (\varepsilon) = \frac{\text{Displacement}}{\text{Breadth (B)}}$$



Stress – Strain Behavior; Solid Mechanics

Engineering Parameters from Stress-Strain Curve

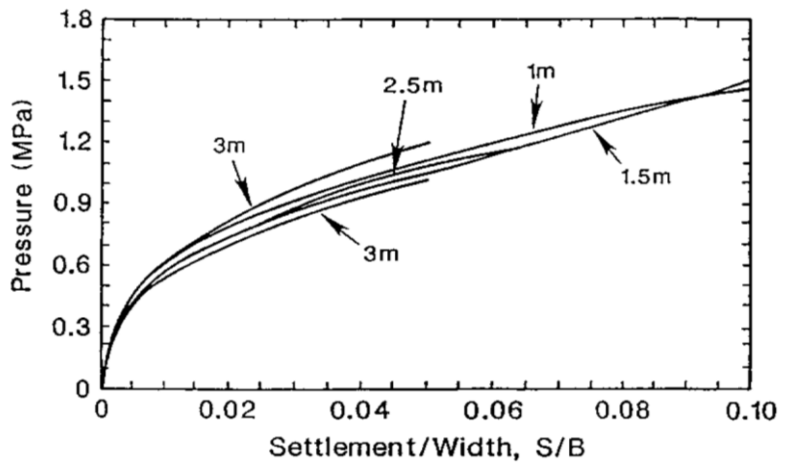
- Strength
- Toughness
- Elasticity
- Yield Point
- Strain Energy
- Resilience
- Elongation during Load



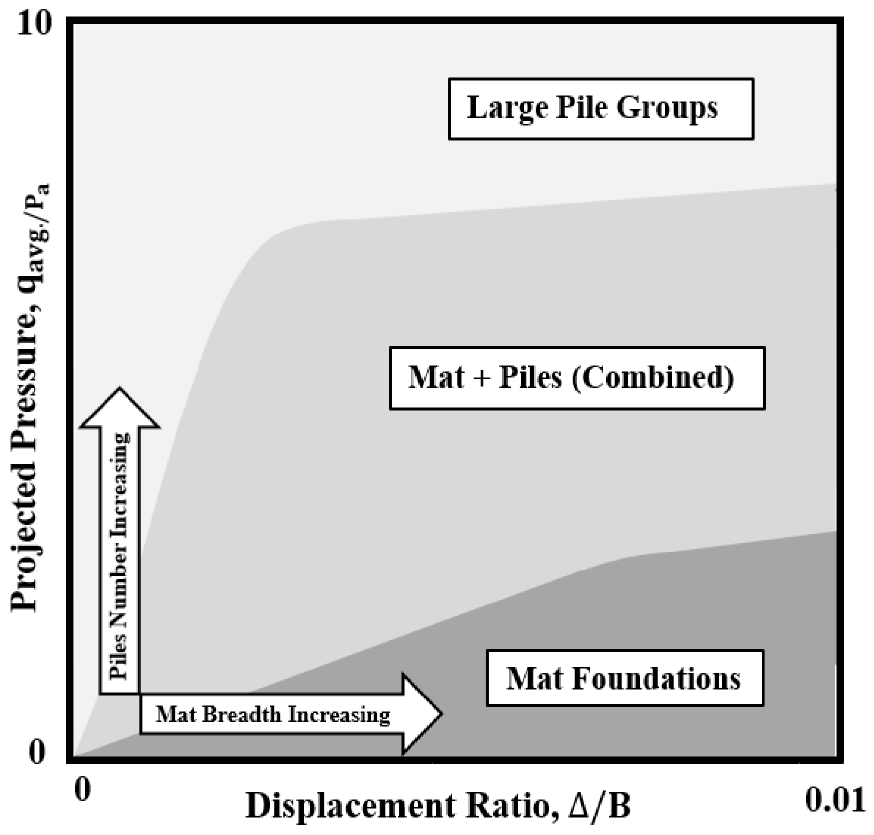
Typical stress-strain diagram (ADMET, 2013)

Stress – Strain in Foundation Engineering

- ❖ Providing a Unitless Framework
- ❖ Facilitating Broader Practical Application
- ❖ Enhancing Foundation Selection
- ❖ Aligning with Established Engineering Principles



Footings stress - strain (Briaud & Gibbens, 1999)



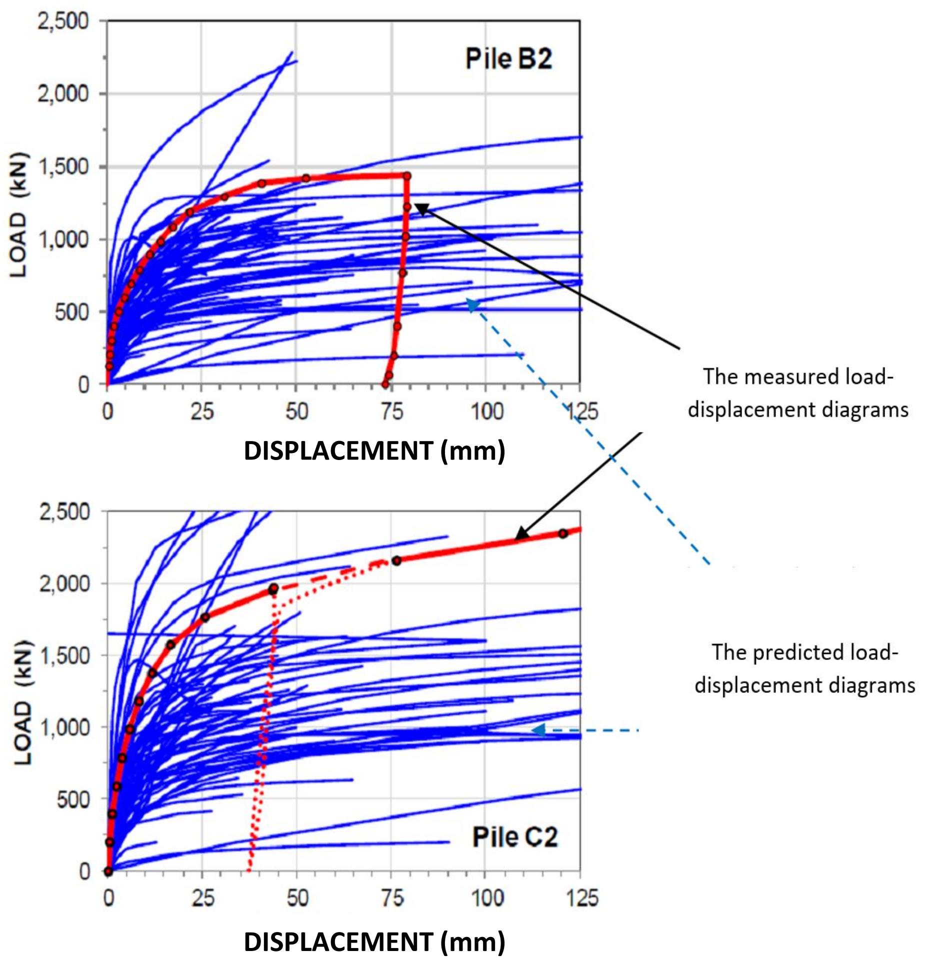
Conceptual stress – strain for large foundation (Eslami & Ebrahimipour, 2026)

Why Databases?

Databases: Collections of data, organized to facilitate access and retrieving data

❖ Some Topics of Databases in Geotechnics:

1. Geohazards
2. Earthquake Induced Liquefaction
3. Pile Loading Test
4. Geostructures Performance
5. In-situ Tests for Foundation Design



Predicted load-displacement diagrams vs. measured for Bolivian Contest (Fellenius et al., 2017)

Why Databases?

❖ Advantages and Applications:

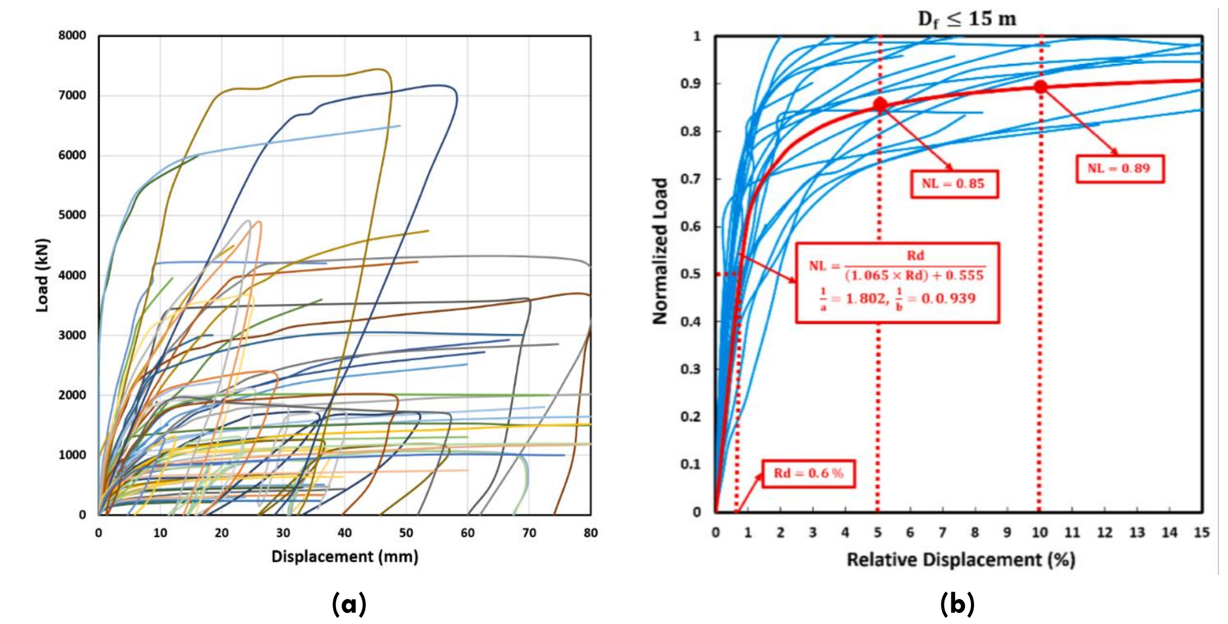
I. Cost saving and project execution time

II. Optimization of design methods

III. Evaluation of design methods

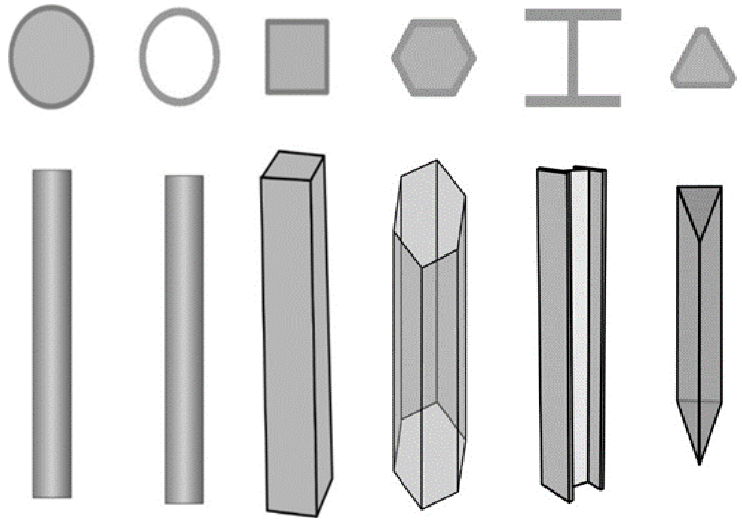
IV. Development of new methods

V. Improvement of geotechnical studies



Driven piles database: (a) Bunch of load-displacement records, (b) Analysis for normalized load vs. relative displacement (Eslami & Ebrahimipour, 2024)

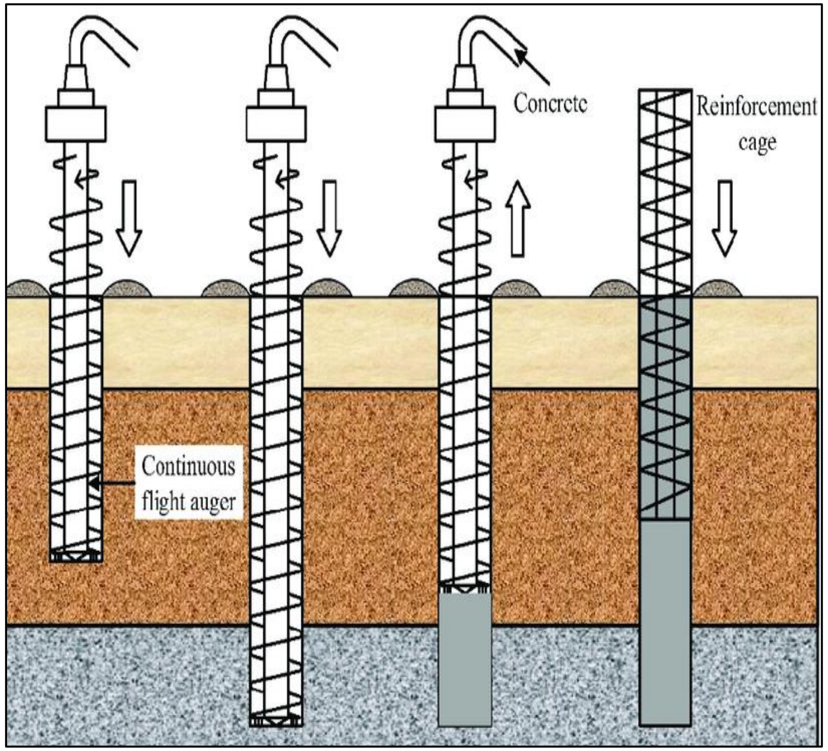
Types of Deep Foundations: Conventional Piles



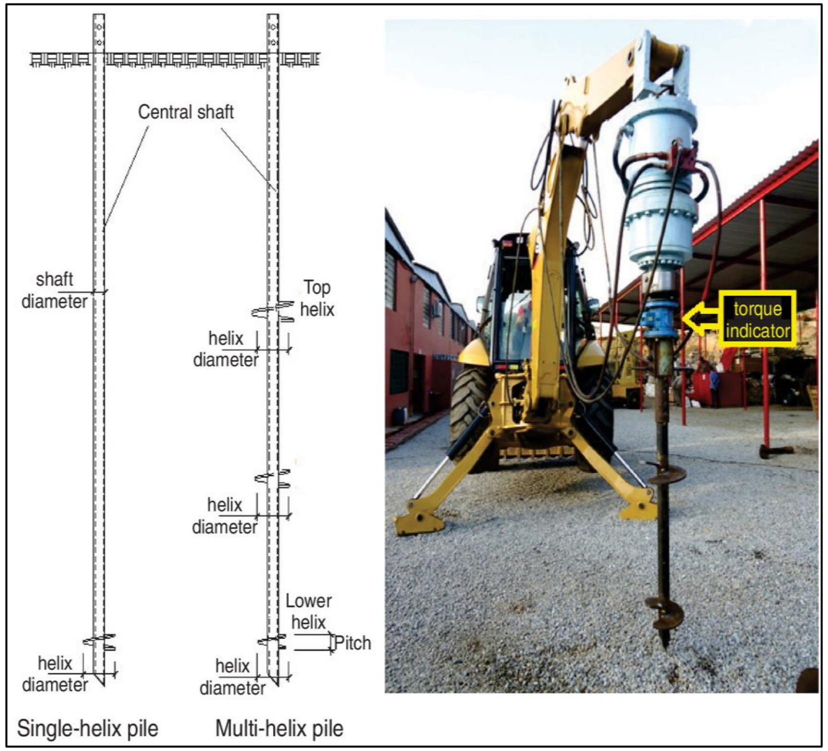
Driven piles variety

Drilled shafts implementation
(FHWA, 2018)

Types of Deep Foundations: Special Piles



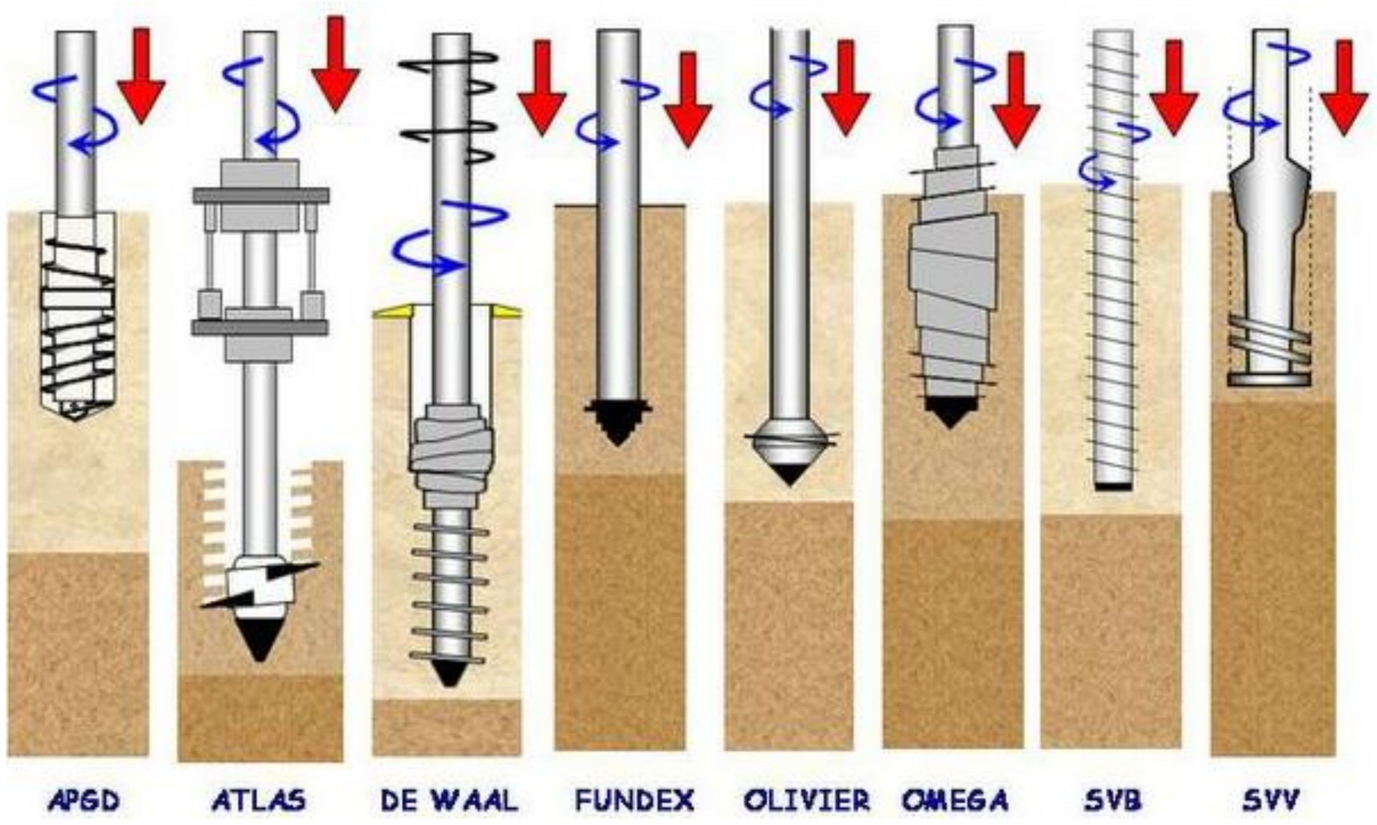
Schematic of CFA pile installation
(Josa et al., 2021)



Helical piles installation
(Mosquera et al., 2015)

DD Piles Advantages

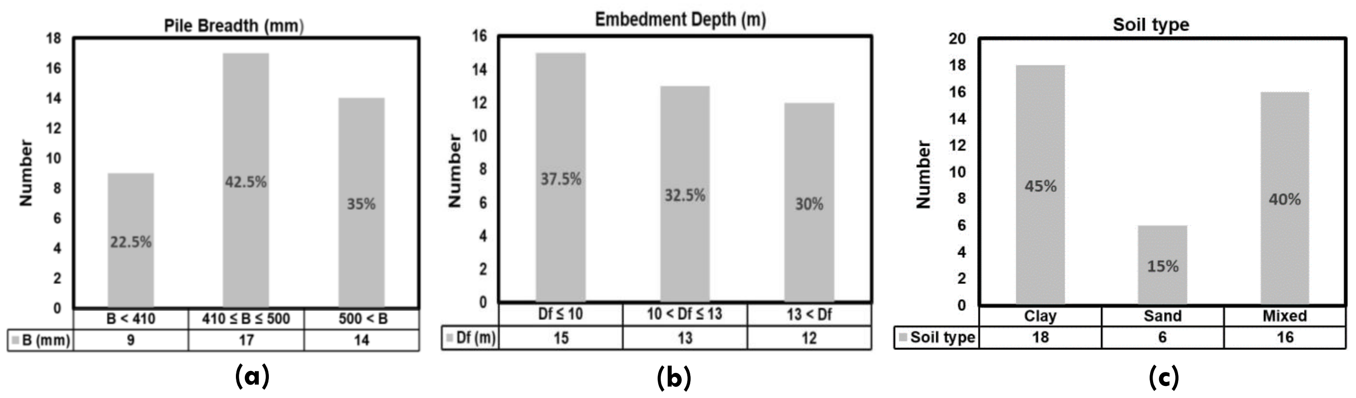
- ❖ Enhanced Soil Strength
- ❖ Minimal Boring Spoil Generation
- ❖ Reduced Environmental Impact
- ❖ Proven Reliability
- ❖ Economic and Feasibility Advantages



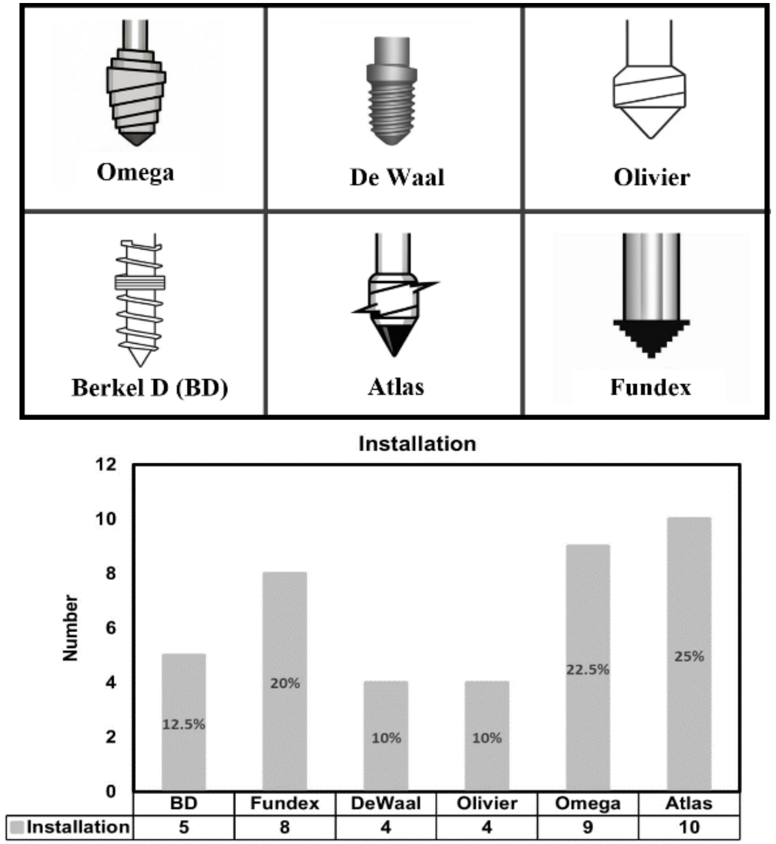
Installation procedure for common DD piles (Basu & Prezzi, 2005) ©Purdue University

Compiled Database Characteristics

- ❖ 40 full-scale static load tests from multiple countries
- ❖ Type: Fundex, Atlas, Omega, and Berkel D
- ❖ Diameter: from 356 mm to 650 mm
- ❖ Embedment Depth: from 7 m to 19.5 m
- ❖ Soil Conditions: Clay, sand, and mixed deposits



Graphical distribution of compiled records characteristics: a) breadth, b) embedment depth, c) surrounding soil type



Included DD piles configuration & number

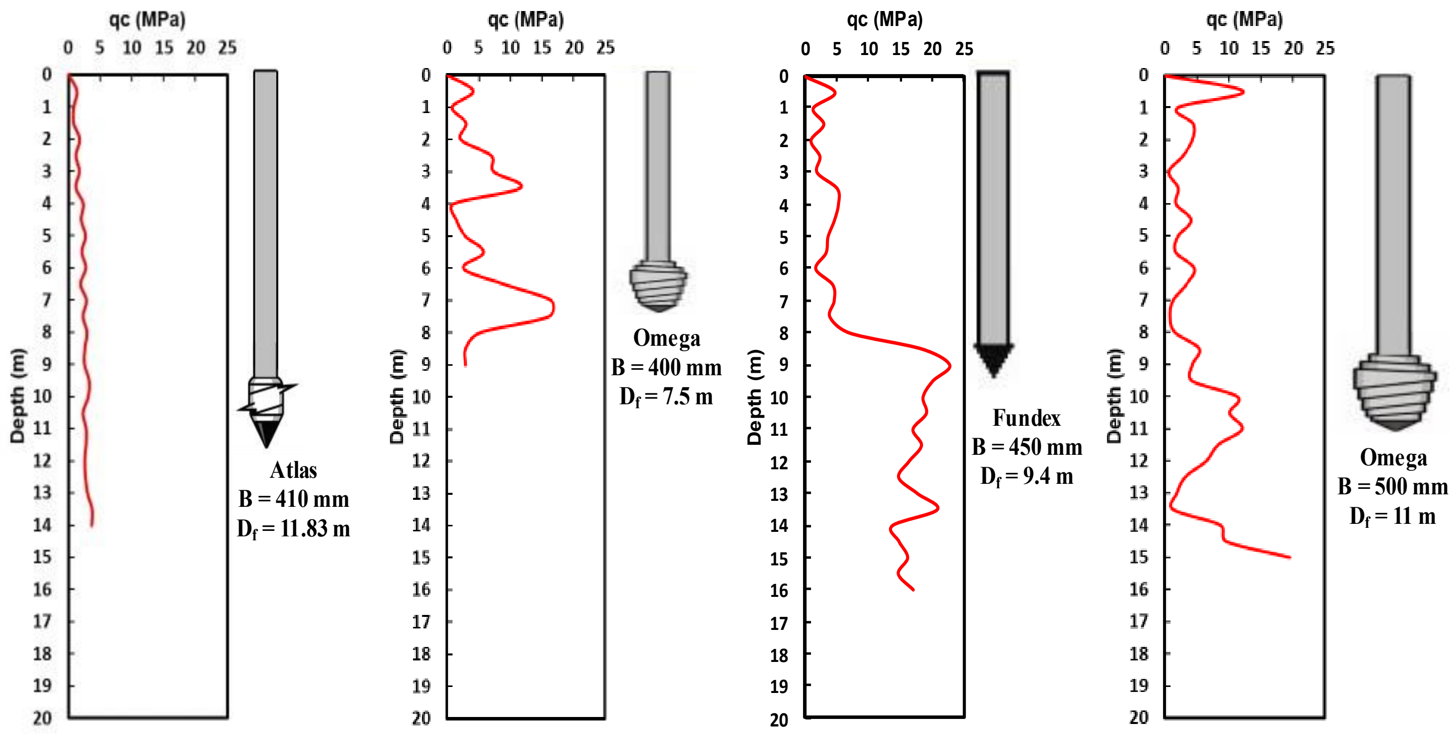
Table of Cases

Case No.	Reference	Location	Pile Data: Installation	D_{SN} (mm)	D_{BN} (mm)	D_f (m)	Deposit	Maximum Measurement: Load (kN)	Disp. (mm)
01	Holeyman et al. (2000a, b)	Belgium	Fundex	380	400	11.5	Clay	2000	15
02			De Waal	410	410	11.73	Clay	1800	18
03			Olivier	510	510	11.68	Clay	1900	20
04			Atlas	510	510	11.76	Clay	2100	22
05	De Cock (2001)	Belgium	Atlas	360	460	13.1	Clay	1765	35.5
06		Belgium	Atlas	360	460	13.1	Sand	2763	46.6
07		Belgium	Atlas	460	460	13.5	Sand	3000	66
08		Germany	Atlas	410	510	9.5	Mixed	2300	25.8
09		Germany	Atlas	410	510	7	Mixed	1710	29.8
10		Belgium	Atlas	360	500	13	Clay	1950	24.1
11		Belgium	Atlas	510	650	13.2	Clay	2487	64.9
12		Belgium	Atlas	360	500	13	Clay	2055	26
13		Netherlands	Fundex	450	560	11	Sand	3000	35.8
14		Germany	Fundex	420	560	14	Mixed	3000	31.4
15		Germany	Fundex	440	560	8.5	Sand	1752	28.2
16		Belgium	Fundex	380	450	13	Mixed	2400	45.6
17		Belgium	Fundex	380	450	13	Mixed	2063	42.1
18		Belgium	Omega	410	410	8.2	Sand	1900	55.9
19		Belgium	Omega	360	360	14.5	Clay	1200	46.2
20		Belgium	Omega	360	360	14.5	Clay	1350	46.6
21		Belgium	Omega	360	600	11	Clay	1500	42.9
22		Belgium	Omega	360	600	11	Clay	1800	42.5

Table of Cases; Continued

Case No.	Reference	Location	Pile Data				Deposit	Maximum Measurement	
			Installation	D_{SN} (mm)	D_{BN} (mm)	D_f (m)		Load (kN)	Disp. (mm)
23	Holeyman & Charue (2003)	Belgium	Fundex	390	450	9.5	Clay	3012	69
24			Olivier	550	550	9.2	Clay	3368	31.5
25			Omega	410	410	9.5	Clay	2826	54
26			DeWaal	410	410	9.5	Clay	2441	66
27			Olivier	550	550	9.1	Clay	2910	30
28			DeWaal	410	410	9.5	Clay	2267	86.5
29	NeSmith & NeSmith (2007)	USA	BD	406.4	406.4	18.3	Sand	3430	38.1
30	Park et al. (2012)	USA	BD	356	356	15.3	Mixed	3350	46
31			BD	356	356	19.5	Mixed	3000	30.5
32			BD	406	406	17.4	Mixed	3400	31
33			BD	356	356	15.2	Mixed	3200	32
34	Moshfeghi & Eslami (2018); Charue (2002)	Belgium	Atlas	510	510	9.6	Mixed	3603	65.5
35			DeWaal	410	410	9.5	Mixed	2653	63
36			Fundex	390	450	9.6	Mixed	3129	69.5
37			Omega	410	410	9.5	Mixed	3206	100
38			Olivier	550	550	9.5	Mixed	3062	31.5
39	Krasiński (2021)	Poland	Omega	400	400	12.6	Mixed	890	44.5
40	Krasiński (2023)	Poland	Omega	300	500	11	Mixed	993	40

Subsoil Condition; CPT Logs



Cone penetration test (CPT) q_c and schematic pile profile for selected cases

Case Study: Oil Tanks - Belgium (Van Impe et al., 2013 & 2015)

❖ **Tanks**

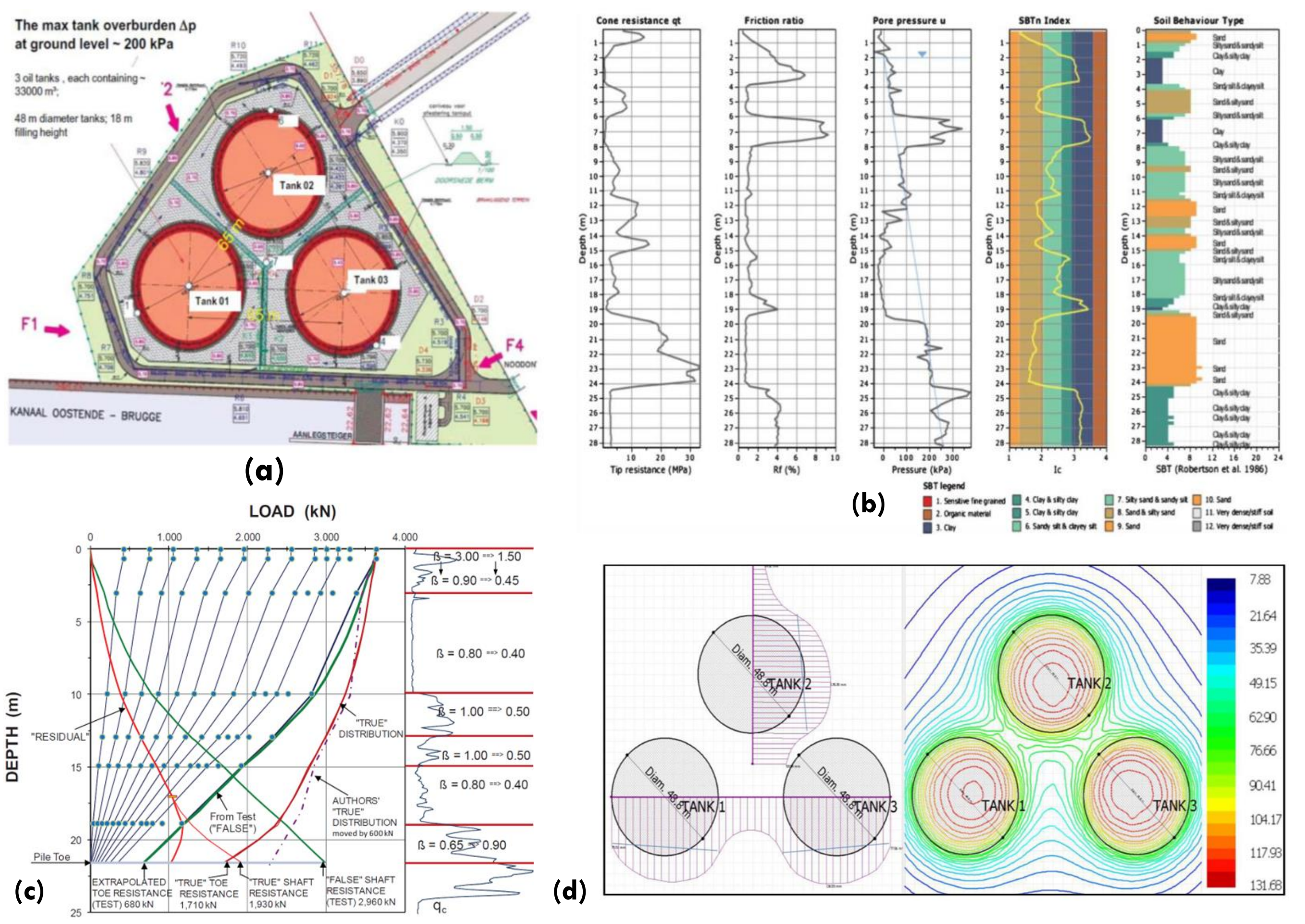
- 48 m diameter and 19 m height,
- Triangle configuration - 65 m center to center

❖ **Soil Profile**

- 0–12 to 15 m depth: Old fill (GWT at 2 m)
- 12-15 to 18 m depth: Sand
- 18 to 100-120 m depth: OC Clay

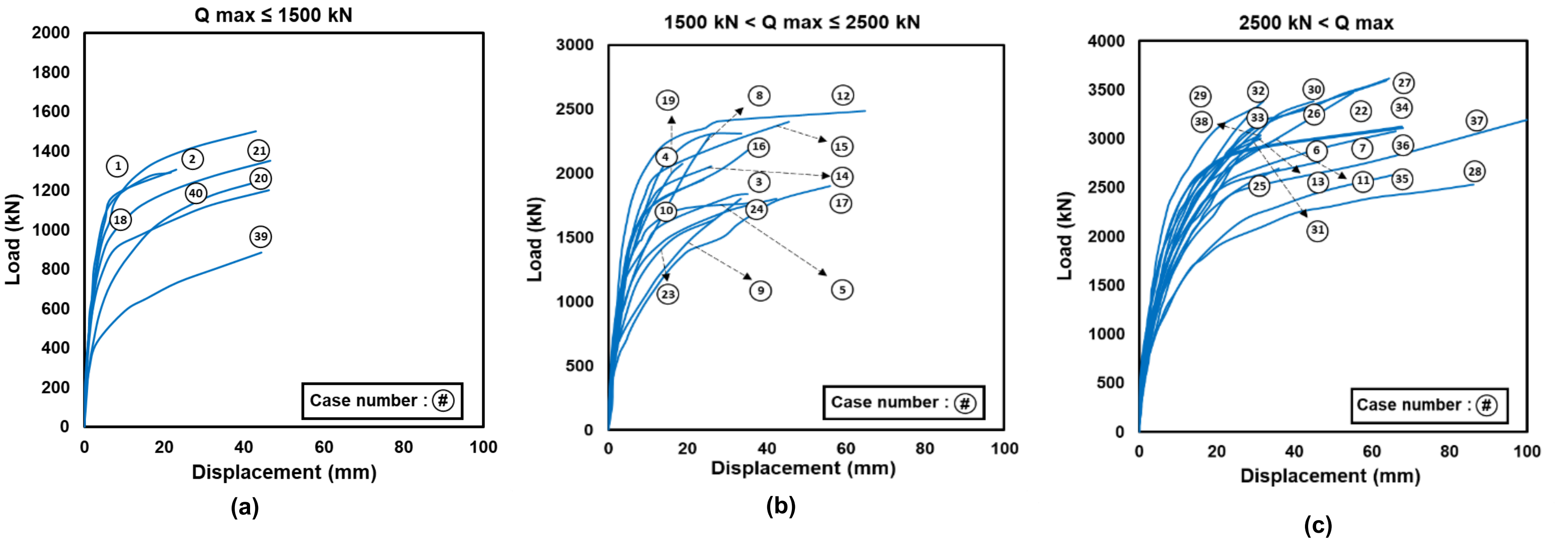
❖ **Foundation System**

- Pile Cap: 0.6 m thick and 49 m diameter
- 422 Omega Piles as pile group
- Piles: 460 mm in diameter and 22 m in depth



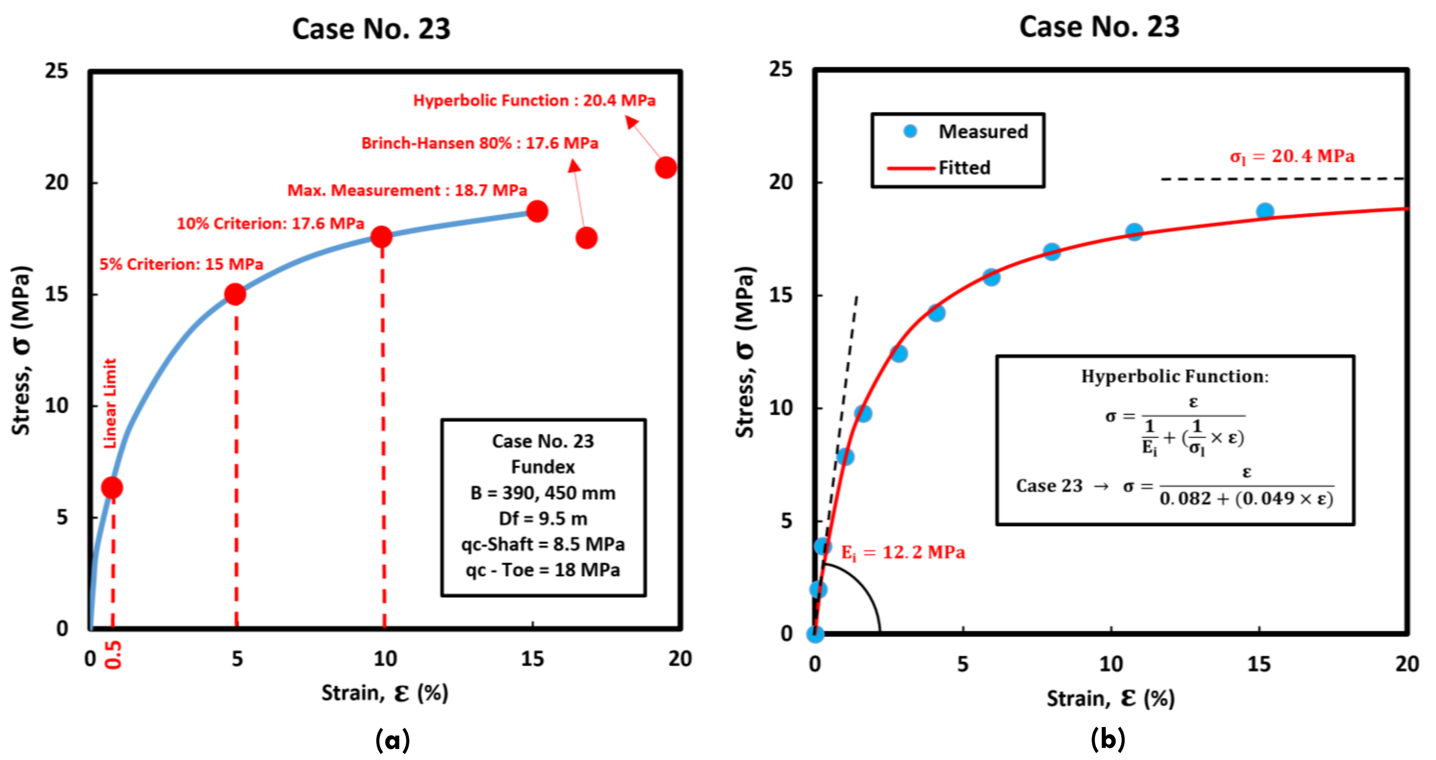
Three oil tanks case study: a) General view tanks, b) CPTu log (Van Impe et al., 2013), c) Load and resistance distribution (Fellenius, 2014), d) Settlement analysis under operational load (Van Impe et al., 2015)

Compiled Load-Displacement Records



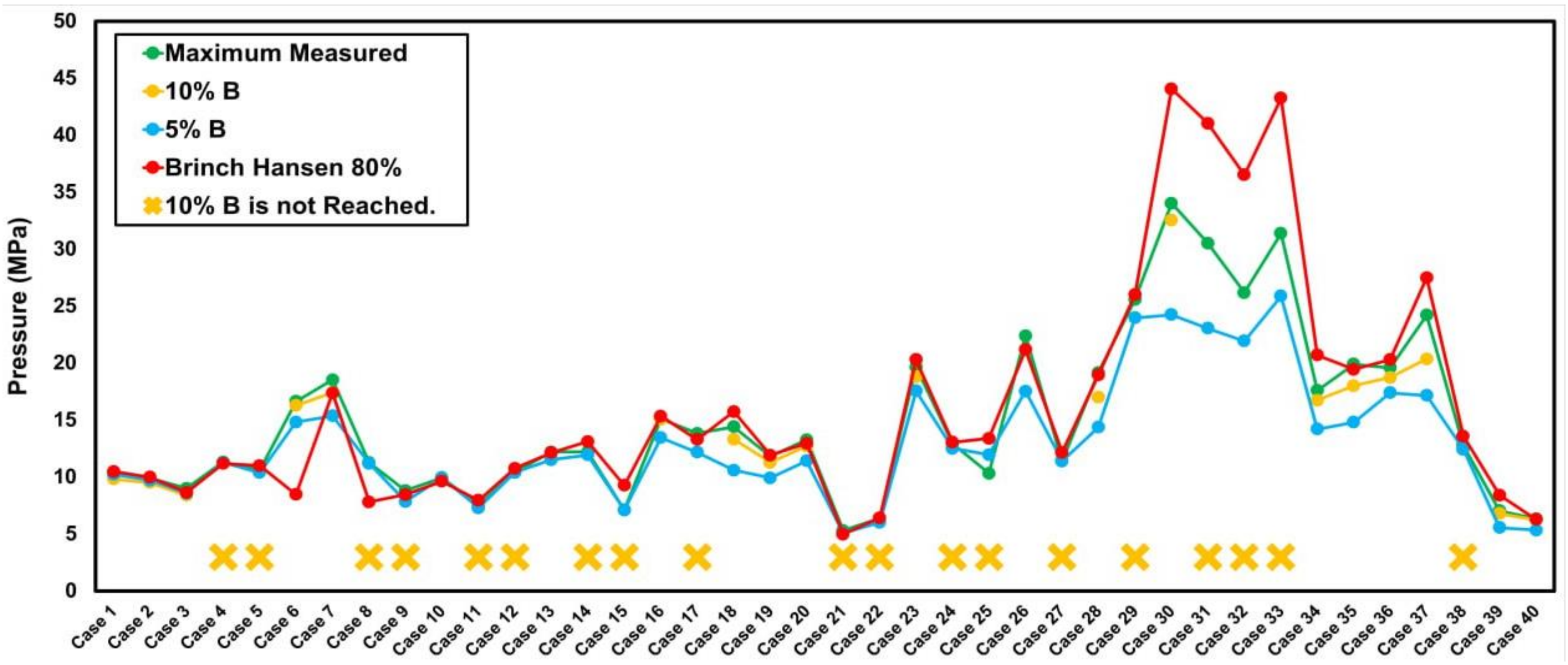
Load-displacement diagrams for all compiled cases: a) $Q_{max} \leq 1500$kN, b) 1500kN < $Q_{max} \leq 2500$kN, c) 2500kN < Q_{max}

Criteria Variety & Hyperbolic Fitting



Typical stress-strain and criteria for Case No. 23: a) Stress resultant from various criteria, b) Hyperbolic fitting and concepts

Ultimate Pressure Through Different Criteria

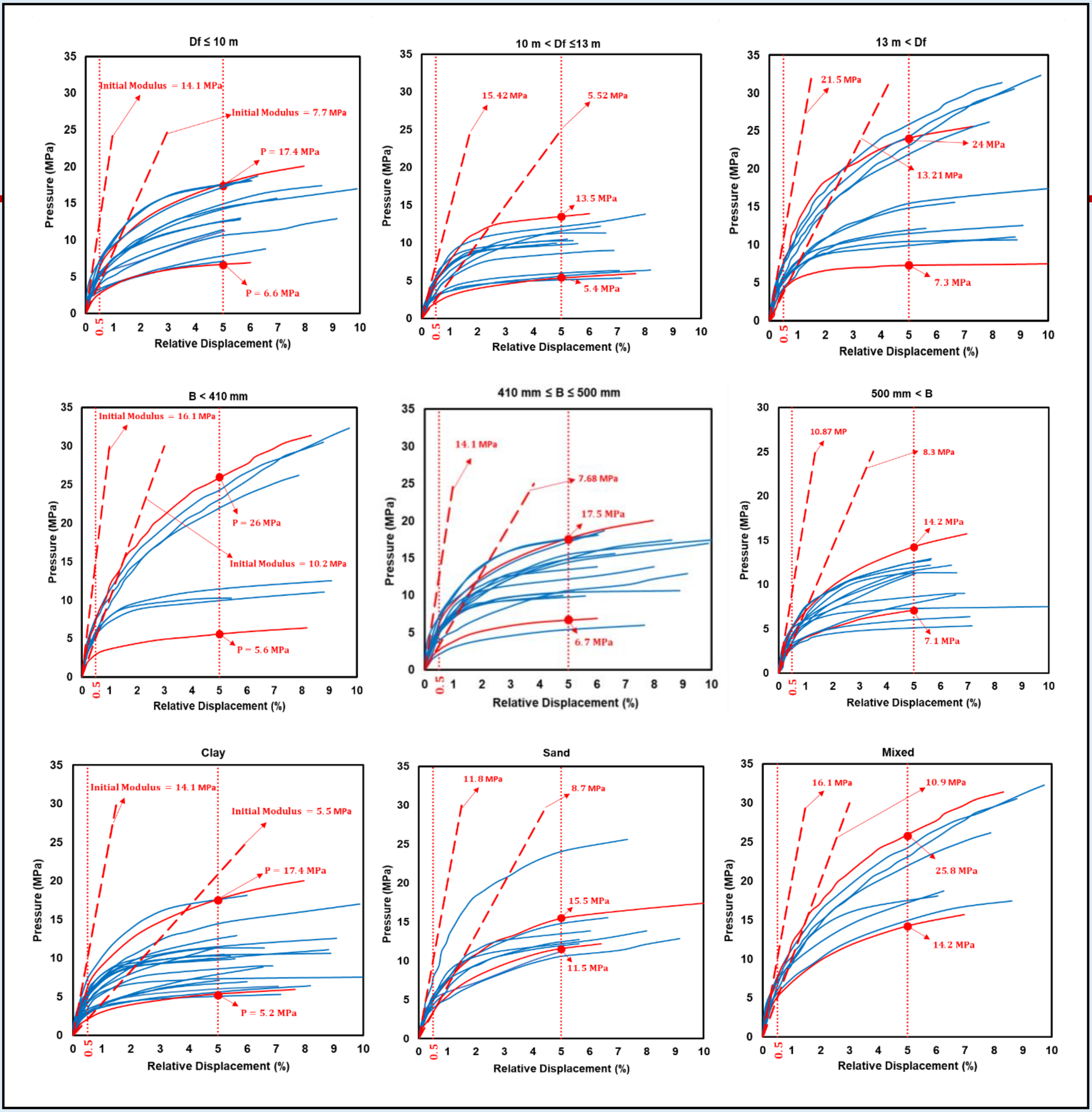


Comparison of records by analyzing ultimate pressure through different criteria

***5% B* and *Brinch-Hansen 80%* criteria opted for further analysis due to: *Simplicity, Efficiency* and *Adoptable* for All Cases**

Dominant Factors Assessment

- ❖ **Embedment Depth**
- ❖ **Pile Breadth**
- ❖ **Surrounding Deposit: (Shaft and Toe)**



Energy-Based Evaluation: Toughness and Resilience

$$\frac{Energy}{Volume} = \int_0^{\varepsilon} \sigma \, d\varepsilon$$

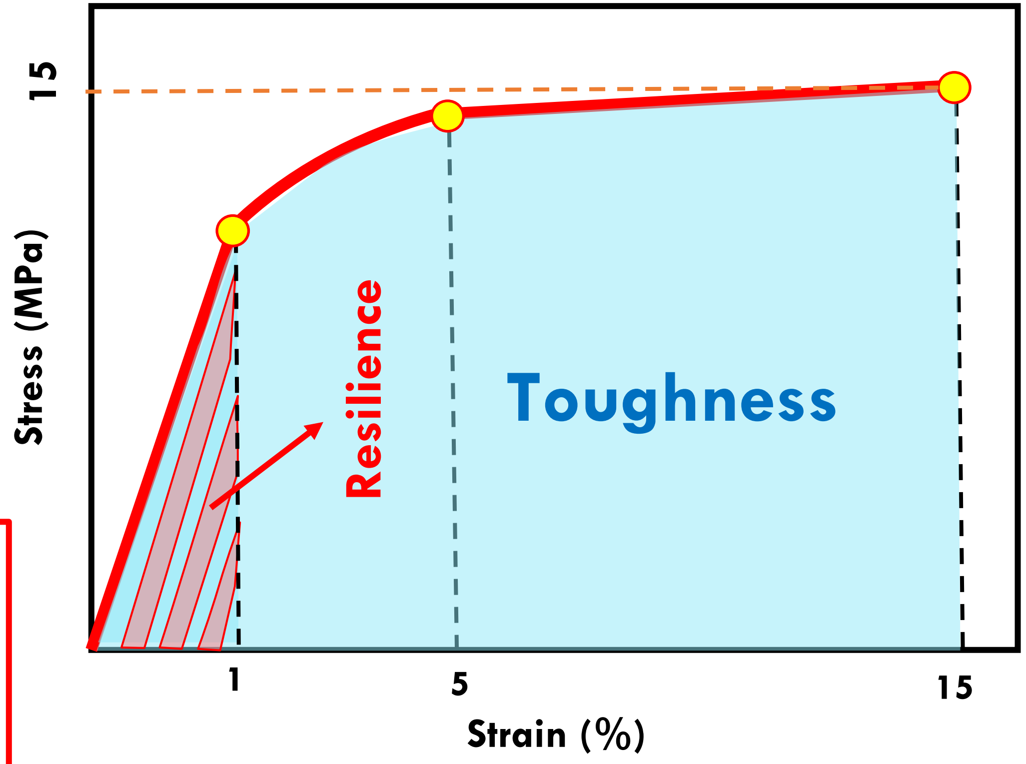
ε = Strain,

σ = Stress

Energy Absorption;

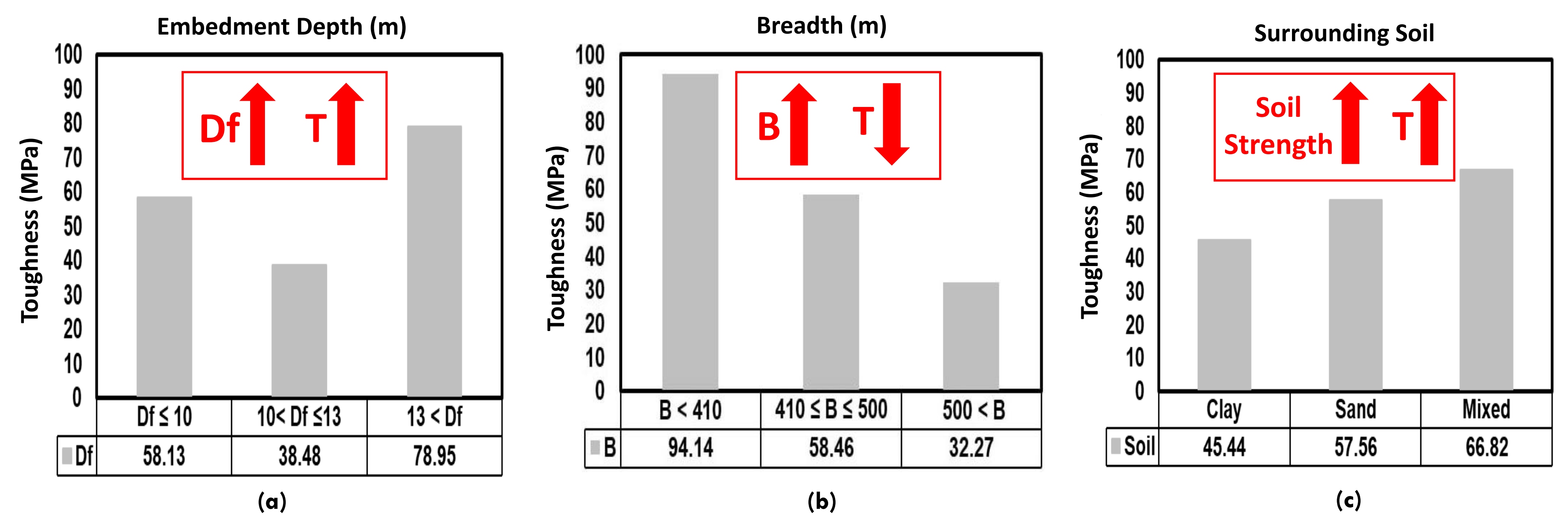
Resilience: Elastic Region

Toughness: Fracture Threshold



Resilience and toughness Concept

Dominant Factors on Toughness (T) Value



	Df ≤ 10	10< Df ≤13	13 < Df
Df	58.13	38.48	78.95

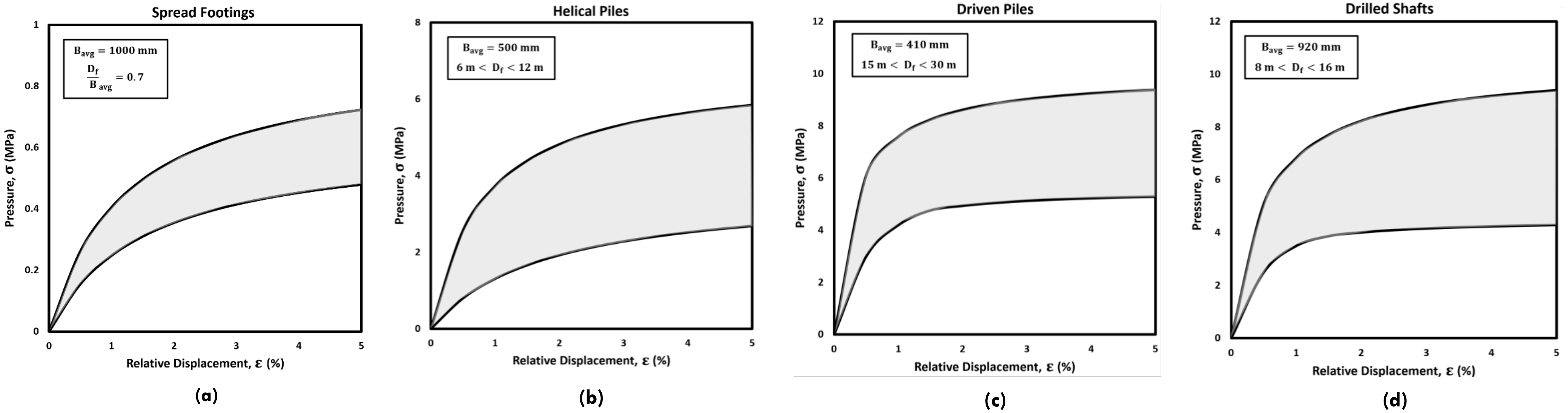
	B < 410	410 ≤ B ≤ 500	500 < B
B	94.14	58.46	32.27

	Clay	Sand	Mixed
Soil	45.44	57.56	66.82

Average toughness values up the displacement of 1 inch: a) Embedment depth, b) Breadth, c) Surrounding soil type

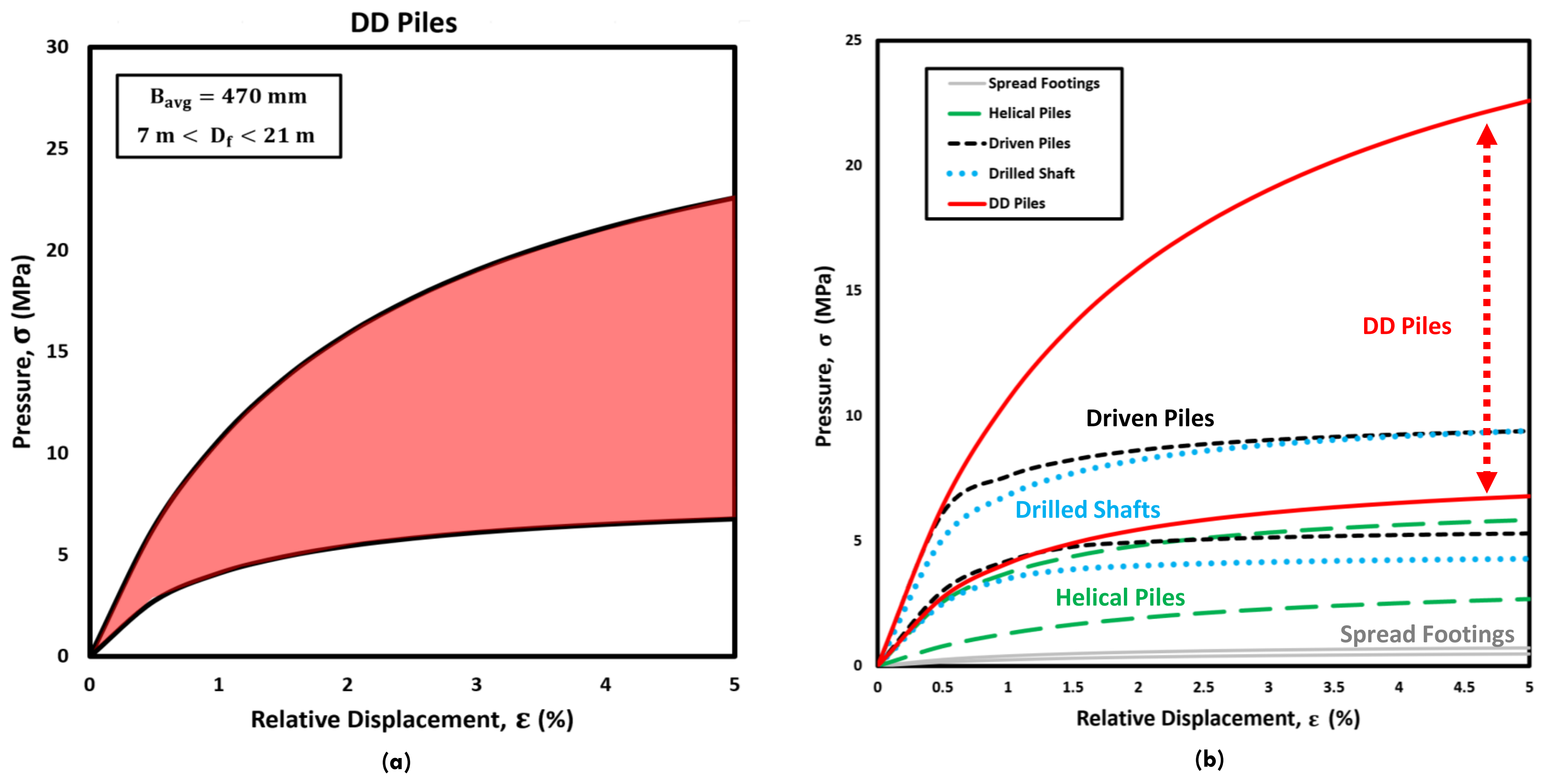
Longer, Narrower piles in Mixed soil condition lead to Higher toughness value

σ – ε Performance for Various Foundations



Pressure (Stress, σ) – relative displacement (Strain, ε) diagrams for various foundations: a) Spread Footings (Heidari et al., 2025), b) Helical Piles (Rahimi et al., 2024), c) Driven piles (Eslami & Ebrahimipour, 2024), d) Drilled shafts

$\sigma - \varepsilon$ Performance for Various Foundations



Pressure (Stress, σ) – relative displacement (Strain, ε) diagrams for: a) DD piles, b) All foundations

Remarks & Conclusions

Drilled Displacement (DD) Piles; Efficient and Sustainable Solution

Load-Displacement Records; Embracing Major Design Criteria

Stress-Strain Framework; Normalized Uniform Appraisal/Comparison

Data-Centric Approach; Tackling Uncertainty/Enhancing Prediction

Energy-Based Paradigm; Towards Resilient Foundations

Major References

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