2015 Purdue Road School Transportation and Conference and Expo

INDOT/Purdue Pile Driving Method for Estimation of Axial Capacity

Zaheer, Mir, INDOT
Salgado, Rodrigo, Purdue University
Prezzi, Monica, Purdue Unviersity
Han, Fei, Purdue University

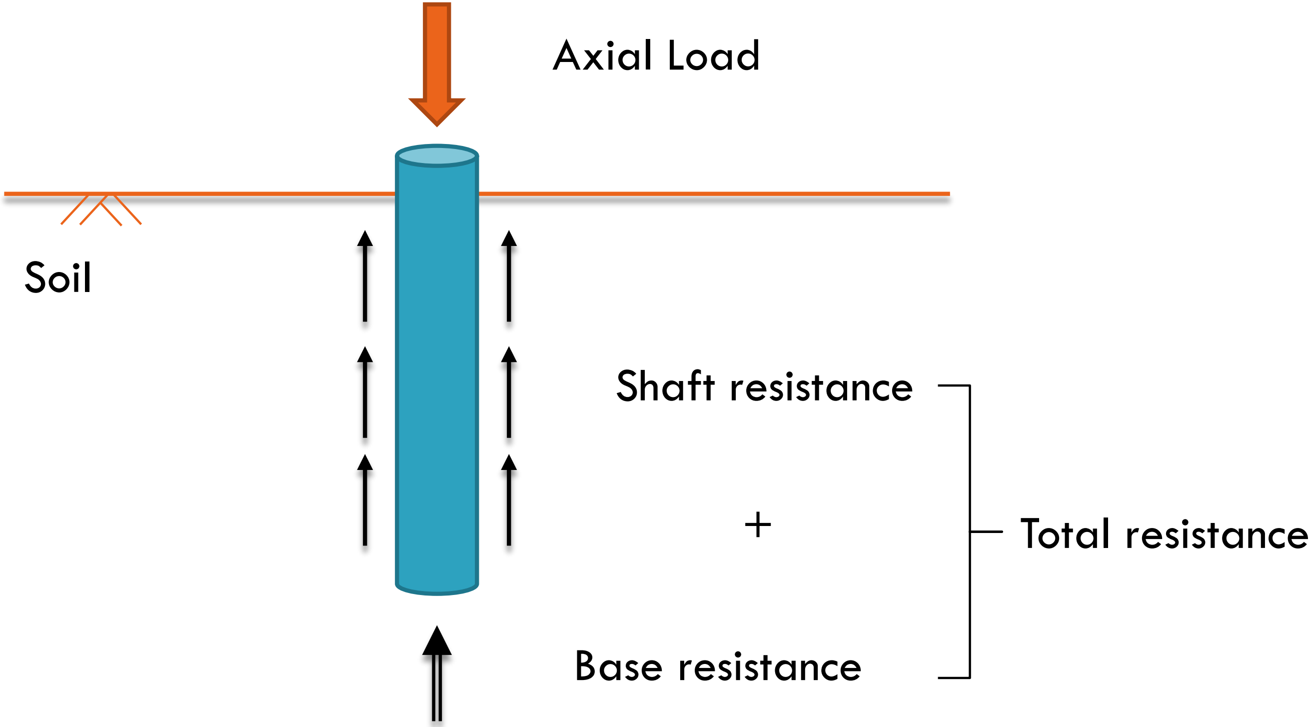
3/19/2015

Overview

- ❑ Purdue sand/ clay method
- ❑ Pile driving formula
- ❑ Case study

Purdue sand/clay method

Components of pile resistance



Axial Load

Soil

Shaft resistance

+

Base resistance

Total resistance

Purdue Sand Method[1]

- ❑ Unit base and shaft resistance for closed-ended pipe piles
  - o Unit base resistance ($q_{b,ult}$)

$$q_{b,ult} = Fq_{bL}$$

$$F = \min\left[1,\ 1.09 - 0.007D_R\right]$$

$$q_{bL} = 1.64\, p_A e^{0.1041\phi_c + (0.0264 - 0.0002\phi_c) D_R} \left(\frac{\sigma_h'}{p_A}\right)^{0.841 - 0.0047 D_R}$$

  - o Unit shaft resistance (q_{sL})

$$q_{sL} = (0.0574 D_R^{\ 0.013} - 0.051) \tan(0.9\phi_c) q_{bL}$$

CPT

$$D_R(\%) = \frac{\ln\left(\frac{q_c}{p_A}\right) - 0.4947 - 0.1041\phi_c - 0.841\ln\left(\frac{\sigma_h'}{p_A}\right)}{0.0264 - 0.0002\phi_c - 0.0047\ln\left(\frac{\sigma_h'}{p_A}\right)} \le 100\%$$

SPT

$$D_R(\%) = 100\sqrt{\frac{N_{60}}{A + BC\left(\frac{\sigma_v'}{p_A}\right)}}$$

A = 36.5, B = 27, C = 1 for NC soil

[1] Salgado, R., Woo, S. and Kim, D. (2011), "Development of load and resistance factor design for ultimate and serviceability limit states of transportation structure foundations", Publication FHWA/IN/JTRP-2011/03. *Joint Transportation Research Program*, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana.

Purdue Clay Method[1]

- Unit base and shaft resistance for closed-ended pipe piles
  - Unit base resistance ($q_{b,ult}$)

$$q_{bL} = 12.35 s_u + q_0$$

  - Unit shaft resistance (q_{sL})

$$q_{sL} = \alpha s_u$$

$$\alpha = 1.28 \left(\frac{s_u}{\sigma_v'} \right)^{-0.05} \left[A_1 + (1 - A_1) e^{-\left(\frac{\sigma_v'}{p_A} \right) (\phi_c - \phi_{r,\min})^{A_3}} \right]$$

$$A_3 = 0.64 + 0.4 \ln \left(\frac{s_u}{\sigma_v'} \right)$$

$A_1 = 0.43$ for $\phi_c - \phi_{r,\min} \geq 12°$, 0.75 for $\phi_c - \phi_{r,\min} \leq 5°$ and linearly interpolated value between them

CPT

$$s_u = \frac{q_c - \sigma_v}{12.35}$$

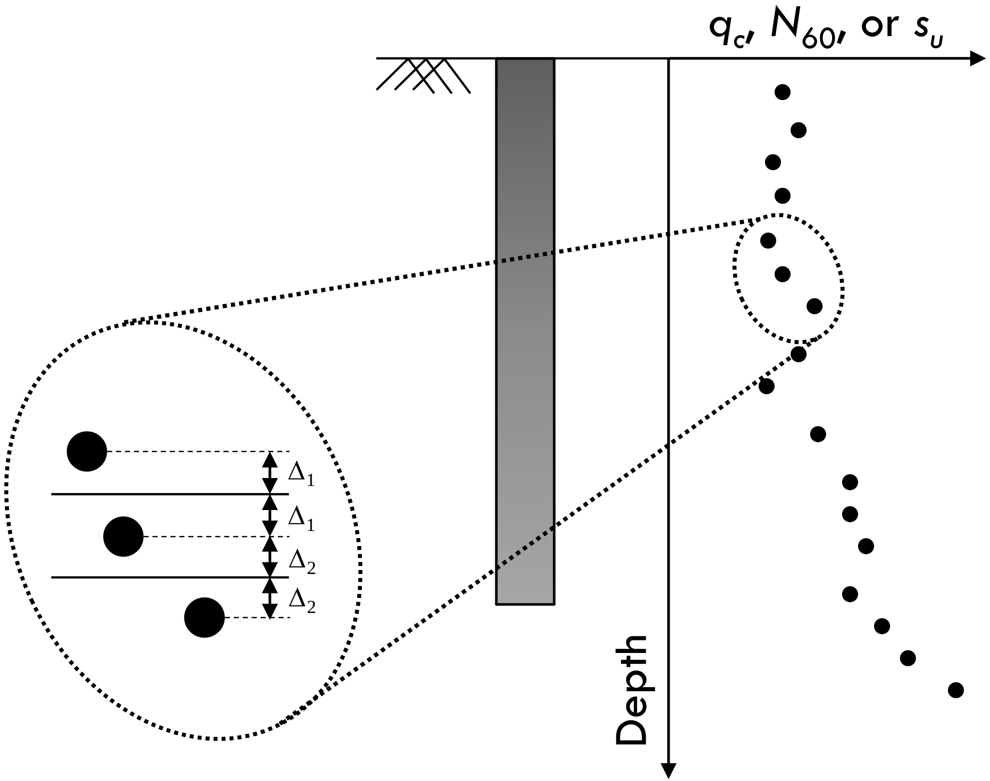
Unconfined Compression test

$$s_u = s_u$$

[1] Salgado, R., Woo, S. and Kim, D. (2011), "Development of load and resistance factor design for ultimate and serviceability limit states of transportation structure foundations", Publication FHWA/IN/JTRP-2011/03. *Joint Transportation Research Program*, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana.

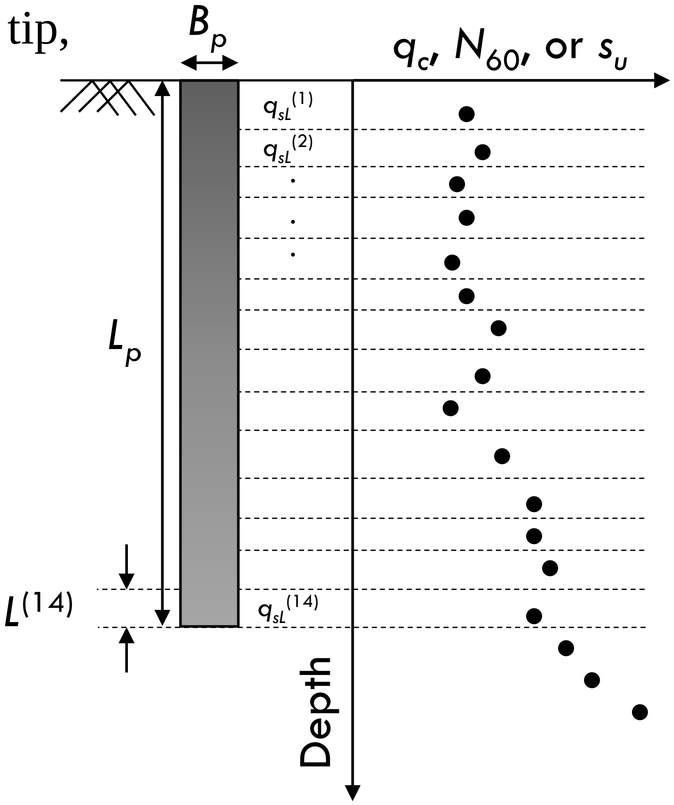
Calculation Process – shaft resistance

- Subdivide the soil layer according to field test (SPT, CPT) data points



Calculation Process – shaft resistance

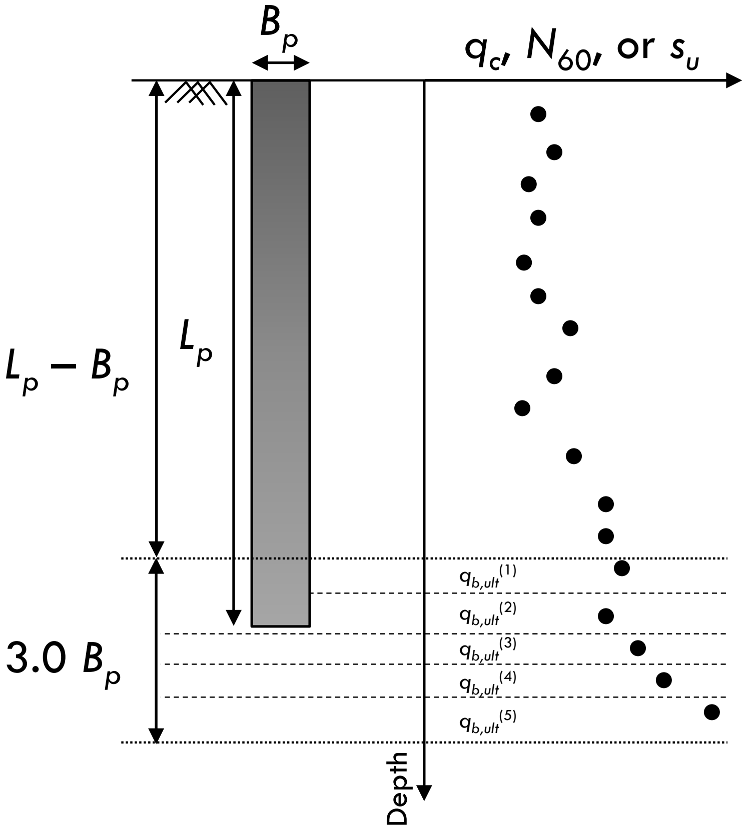
- For all sub-layers from the ground surface to the pile tip, calculate the unit shaft resistance $q_{sL}{}^{(i)}$ based on the test data and soil type
- Calculate shaft load capacity $Q_{sL}{}^{(i)}$ for ith sub-layer
  - $Q_{sL}{}^{(i)} = \pi B_p L^{(i)} q_{sL}{}^{(i)}$



Calculation Process – base resistance

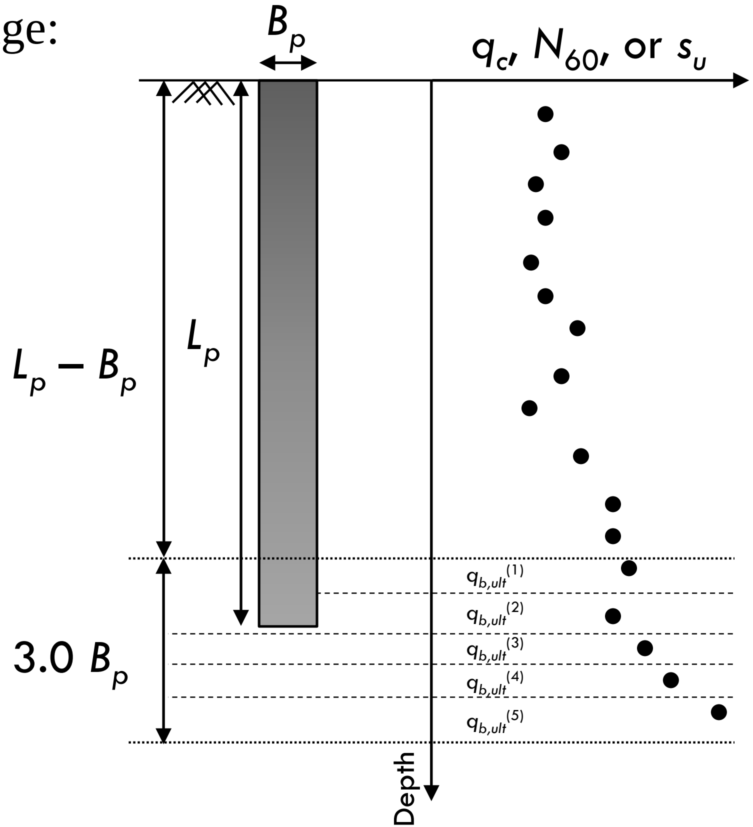
- Calculate unit base resistance $q_{b,ult}^{(i)}$

  for each sub-layer from depth $L_p - B_p$ to $L_p + 2B_p$



Calculation Process – base resistance

- Estimate $q_{b,ult}$ at $L_p + B_p / 2$ using weighted average:
  - $q_{b,ult} = [\Sigma\Delta^{(i)} q_{b,ult}^{(i)}] / [\Sigma\Delta^{(i)}]$
  - $\Delta^{(i)}$: distance from center of each sub-layer to $L_p + B_p / 2$
- Calculate total base load capacity $Q_{b,ult}$
  - $Q_{b,ult}$ = area × $q_{b,ult}$
- Calculate total ultimate load capacity:
  - $Q_{ult} = Q_{sL} + Q_{b,ult}$

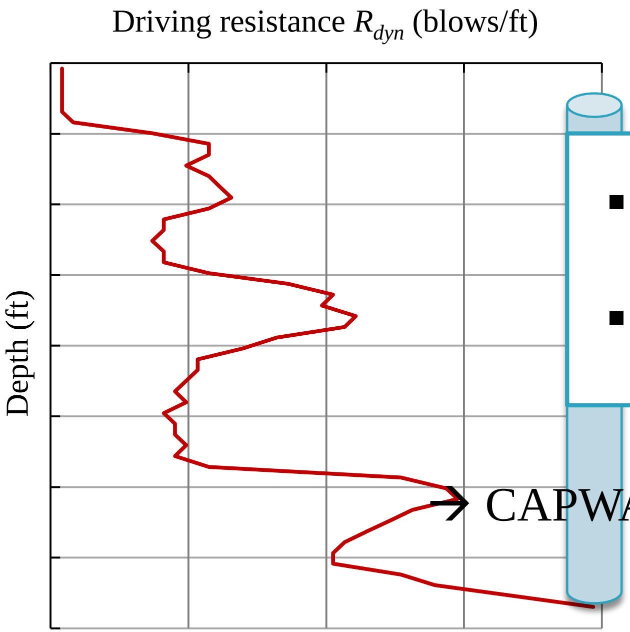


Demonstration of the web software

http://128.46.205.182:9898/

Pile driving formula

Pile driving formula



- Other variables ?
- $f(\ldots)$?

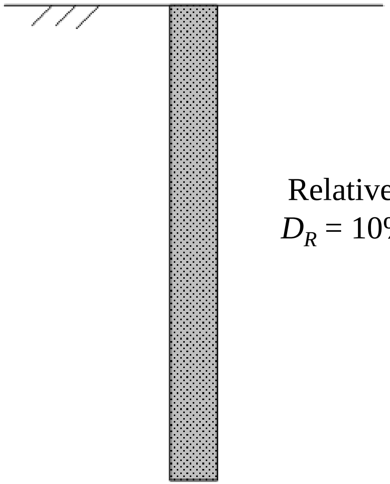
her variables …)

→ CAPWAP, Gates, Danish, **Purdue** …

Static load capacity Q_u

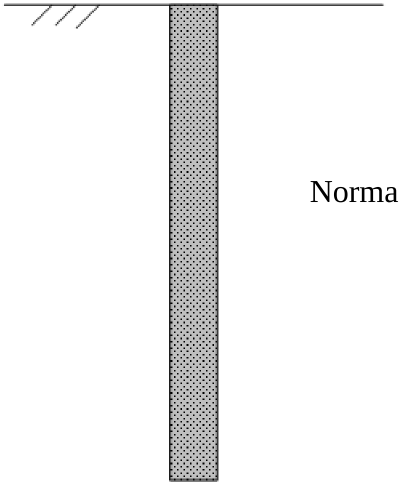
Typical Cases

Floating pile in
sand



Relative density
$D_R = 10\% \sim 90\%$

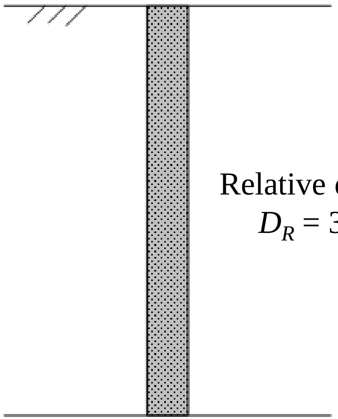
Floating pile in
clay



Normally consolidated clay
OCR = 1

Typical Cases

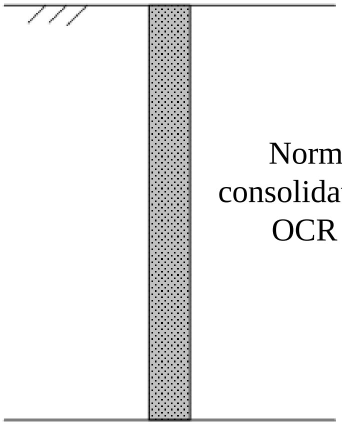
End-bearing
pile in sand



Relative density
$D_R = 30\%$

Relative density
$D_R = 30\% \sim 90\%$

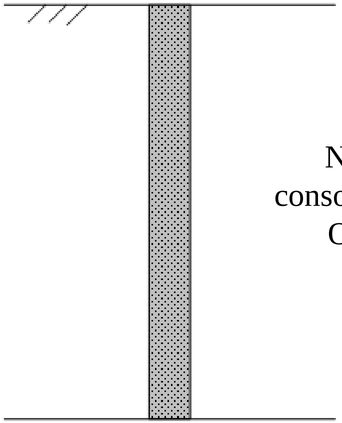
End-bearing
pile in clay



Normally
consolidated clay
OCR = 1

Overconsolidated Clay
OCR = 4, 10

End-bearing pile in
sand crossing clay



Normally
consolidated clay
OCR = 1

Relative density
$D_R = 40\% \sim 90\%$

Pile Driving Formulas

- For floating piles in sand, end-bearing piles in sand and piles crossing a clay layer and resting on sand:

$$\frac{Q_{b,10\%}}{p_a L_R^2} = \left(a\left(\frac{W_H}{W_R}\right)^b \left(\frac{e_{eff}E_h}{W_R L_R}\right)^c \exp\left(d\,\frac{D_R}{100\%}\right)\right)\left(\frac{s}{L_R}\right)^{e\frac{D_R}{100\%}+f}\left(\frac{W_H}{W_P}\right)^g$$

- For floating piles in clay and end-bearing piles in clay:

$$\frac{Q_{b,10\%}}{p_a L_R^2} = \left(a\left(\frac{W_H}{W_R}\right)^b \left(\frac{e_{eff}E_h}{W_R L_R}\right)^c\right)\left(\frac{s}{L_R}\right)^{e\frac{s_u}{\sigma'_v}+f}\left(\frac{W_H}{W_P}\right)^g$$

W_H = ram weight
e_{eff} = hammer efficiency
E_{h} = hammer energy
D_{R} = relative density
W_{P} = pile weight
s = observed pile set
W_R = 100 kN = 22.5 kips
L_R = 1 m = 3.28 ft =39.3”

Pile Driving Formulas

- ❑ Coefficients of pile driving formulas for **closed-ended steel pipe** piles

Variables Soil Profile	a	b	c	d	e	f	g	R^2
Floating piles in sand	23.03	1.04	0.22	1.37	0.07	-0.31	-1.04	0.988
End-bearing piles in sand	50.10	0.94	0.2	1.09	0.12	-0.17	-1.07	0.907
Floating piles in clay	3.94	0.73	0.45	*N/A*	-0.44	-0.36	-0.74	0.983
End-bearing piles in clay	12.49	0.95	0.31	*N/A*	-0.44	-0.22	-0.99	0.992
Piles cross clay resting on sand	22.61	0.98	0.24	-0.28	-0.14	-0.25	-1.03	0.959

Pile Driving Formulas

- Coefficients of pile driving formulas for **precast concrete** piles

Variables Soil Profile	a	b	c	d	e	f	g	R^2
Floating piles in sand	14.36	0.73	0.11	1.23	-0.02	-0.13	-0.69	0.982
End-bearing piles in sand	19.10	0.65	0.1	0.5	-0.09	-0.08	-0.61	0.934
Floating piles in clay	1.49	0.44	0.59	*N/A*	-0.29	-0.52	-0.26	0.919
End-bearing piles in clay	2.35	0.49	0.57	*N/A*	-0.30	-0.50	-0.31	0.951
Piles cross clay resting on sand	1.01	0.46	0.55	0.49	-0.01	-0.83	-0.29	0.990

Example calculation: US 31

- ❑ Pile information
  - Embedment depth: **50.6 ft**
  - Pile weight: 3.45 kips
- ❑ Hammer information (**APE D30-32**)
  - Maximum rated energy: 69.6 kip·ft
  - Ram weight: 6.61 kips
  - Stroke at rated energy: 10.53 ft
- ❑ Soil information
  - Averaged relative density along pile shaft: **75%**
- ❑ Driving record
  - The observed pile set at the end of pile driving: **0.25** inch

Example calculation: US 31

- Coefficients of pile driving formulas for **closed-ended steel pipe** piles

$$\frac{Q_{b,10\%}}{p_a L_R^2} = \left(a \left(\frac{W_H}{W_R} \right)^b \left(\frac{e_{eff} E_h}{W_R L_R} \right)^c \exp\left(d \, \frac{D_R}{100\%} \right) \right) \left(\frac{s}{L_R} \right)^{e \frac{D_R}{100\%} + f} \left(\frac{W_H}{W_P} \right)^g$$

Variables	a	b	c	d	e	f	g	R^2
Floating piles in sand	23.03	1.04	0.22	1.37	0.07	-0.31	-1.04	0.988

W_H = ram weight
e_{eff} = hammer efficiency
E_{h} = hammer energy
D_{R} = relative density
W_{P} = pile weight
s = observed pile set
W_R = 100 kN = 22.5 kips
L_R = 1 m = 3.28 ft =39.3”

Example calculation: US 31

- ❑ Pile capacity predicted by different pile driving formulas

Case	Static load test (kip)	**Purdue (kip)**	CAPWAP (kip)	Gates formula (kip)	Modified ENR (kip)	Danish formula (kip)
US 31	736	**719**	487	336	1864	399.2

Case Studies

Mir A. Zaheer, P.E.,

Geotechnical Design Engineer, INDOT

Case Study

- **SR 9 in Lagrange County (Pipe) -2000**
- **SR 49 in Jasper County (Pipe) - 2005**
- **SR 49 in Jasper County (H) - 2005**
- **SR 55 in Lake County (H) - 2014**
- **US 31 in Marshall County (Pipe) - 2014**

Different Codes or Standards

- Eurocode 7 - Geotechnical Design is based on Limit State Methods.
  - The pile load tests deliver values of nominal bearing resistance, recommended as the value at a settlement of 10% of the pile diameter out of which the value of the pile compressive resistance has to be selected.
- ASTM D1143 –Standard Test Method for Piles Under Static Axial Compressive Load
  - The term “failure” as used in this method indicates rapid progressive settlement of the pile or pile group under a constant load. Interpreted based on Davisson Offset limit method.

Widely Used Method in USA

- Davisson Offset Limit Method (1972).

In his paper, Davisson explains that the criterion was developed for point bearing driven piles but goes on to state that it can also be applied to friction piles.. In this method since the offset is defined by the pile diameter, the capacity is therefore dependent on pile diameter. In his words:

“*There are many ways of interpreting a load test; almost all of them are unsatisfactory for high capacity piles.”*

“It appears that engineering practice is based primarily on experience, precedent, ***and perhaps prayer,*** *even for low capacity piles*.”

Engineers need a scientific basis for making engineering decisions.

Case Study

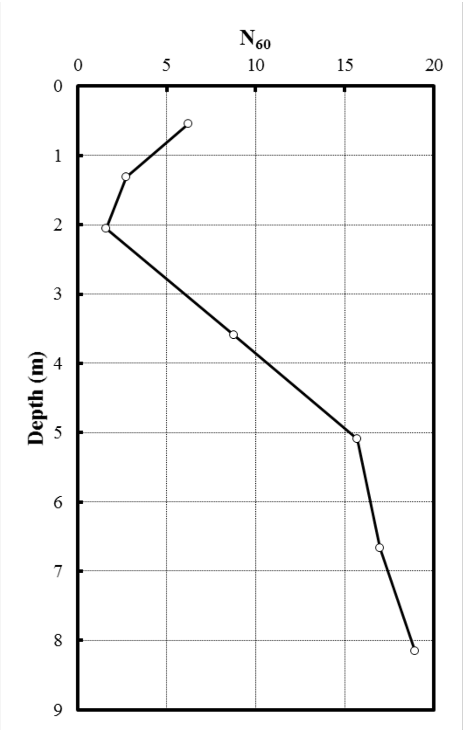
- **SR 9 in Lagrange County (Pipe) -2000**
- SR 49 in Jasper County (Pipe) - 2005
- SR 49 in Jasper County (H) - 2005
- SR 55 in Lake County (H) - 2014
- US 31 in Marshall County (Pipe) - 2014

Soil and Pile Information

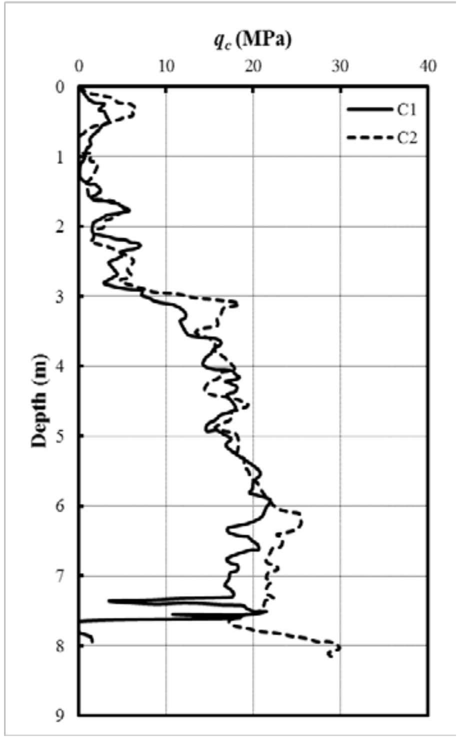
- Gravelly sand
- Unit weight: 104.27 lb/ft^3(at depth of 0 – 9.8 ft), 133.62 lb/ft^3 (at depth below 9.8 ft)
- Critical-state friction angle: 33.3^o
- K_0: 0.45 for loose sand (D_R < 35%), 0.4 for medium dense to dense sand ($D_R \geq$ 35%)
- Ground water table depth: 9.8 ft
- Closed-ended pipe pile 14 inch, 0.5 inch thick
- Pile length: 27.0 ft Embedment – 22.6 ft

Field Test Data

SPT



CPT



Comparison of Load Capacities

	Q_{sL} (kip)	Q_{bult}** (kip)	Q_{ult} (kip)
Measured*	142-146	195	**337**
Purdue method (SPT)	41	134	175
Purdue method (CPT)	112	206	**319**
DLT***	34	169	203
DRIVEN	44	59	103
SLT (Davisson)**	30	75	105

* Not accounting for residual loads

**Load at settlement of 10% of pile diameter

*** Davisson Method at 0.8 inches pile head movement

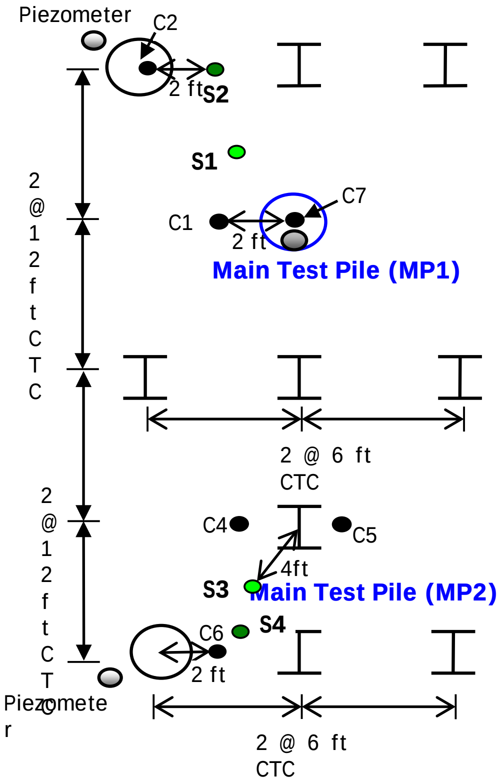
Case Study

- SR 9 in Lagrange County (Pipe) -2000
- **SR 49 in Jasper County (Pipe) - 2005**
- SR 49 in Jasper County (H) - 2005
- SR 55 in Lake County (H) - 2014
- US 31 in Marshall County (Pipe) - 2014

Schematics of Load Test Piles

- Pile Load Test Site
  - Closed-ended pipe pile
  - Pile base at 57 feet
  - Pile Diameter = 14 inches

- Site Investigation
  - 4 SPT borings with soil sampling
  - 6 CPT tests

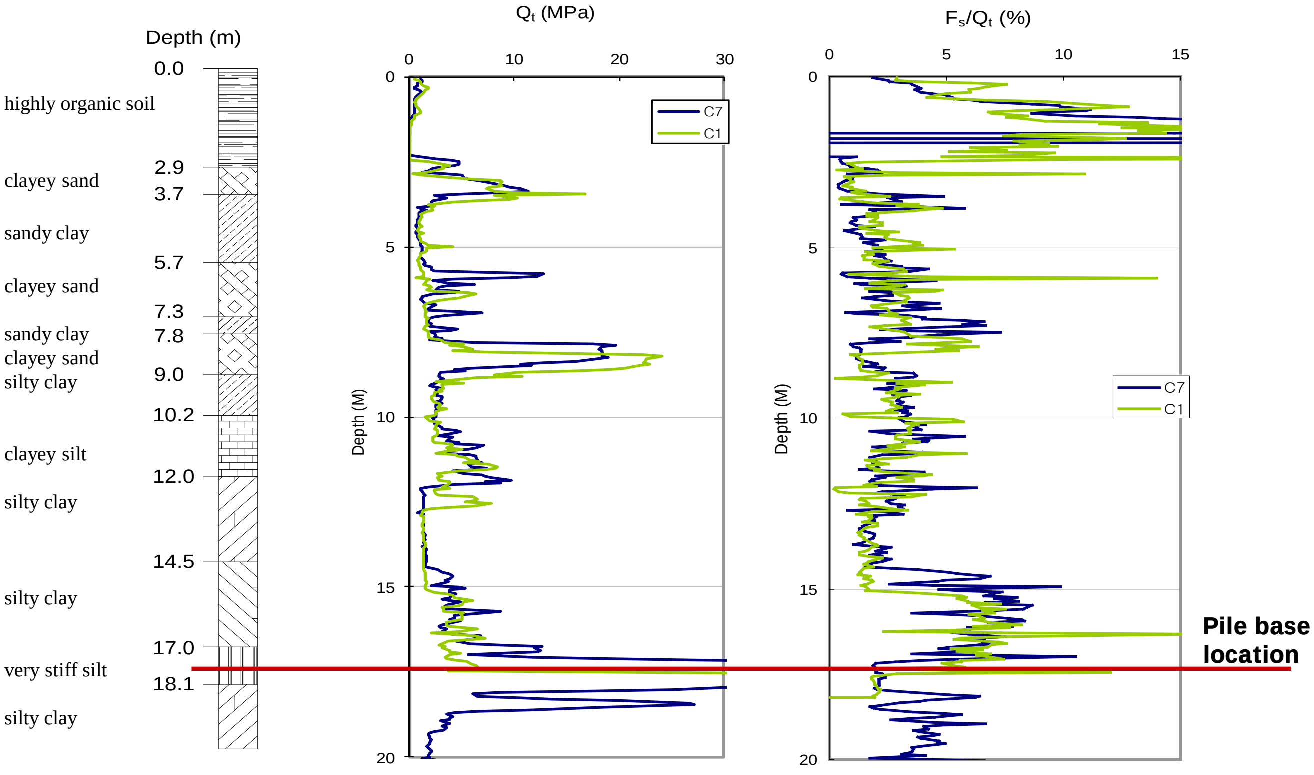


SR 49 Load Test

Soil and Pile Information

- K_0: 0.45 for loose sand ($D_R < 35\%$), 0.4 for medium dense to dense sand ($D_R \geq 35\%$)
- Ground water table depth: 3.3 ft
- Closed-ended pipe pile 14 inches, 0.5 inch thick
- Pile length: 65.3 ft
- Embedded depth: 57.1 ft

CPT Data

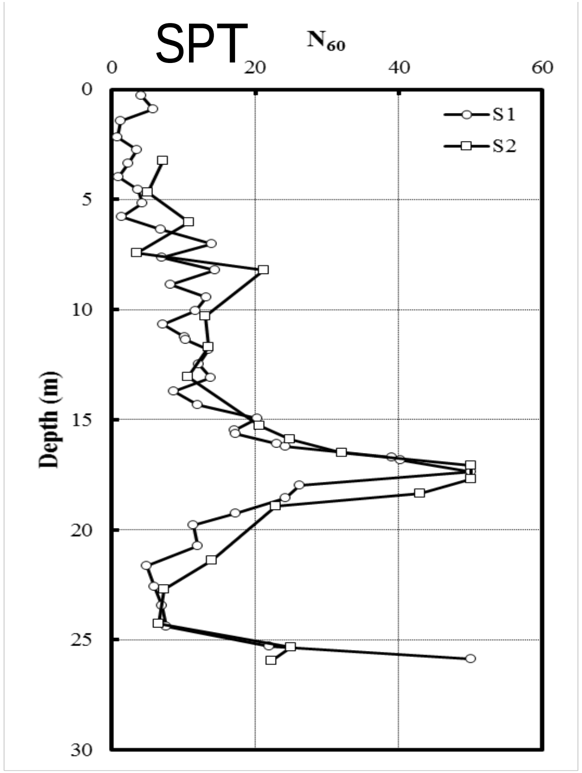


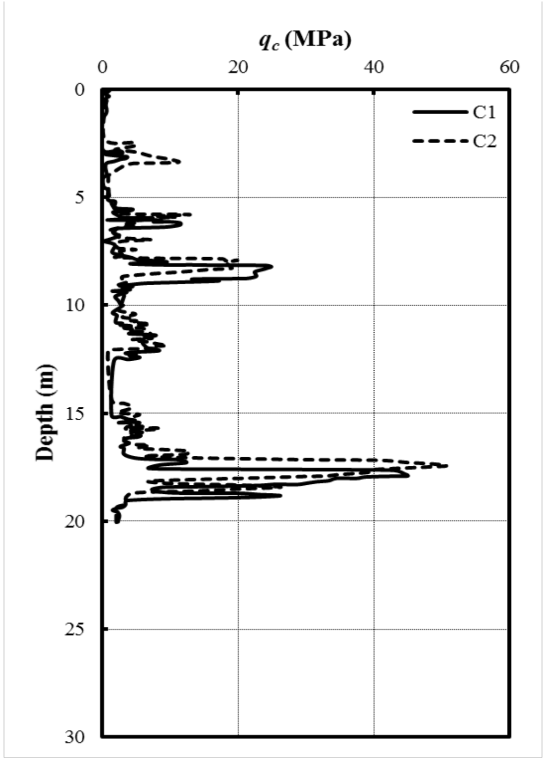
Pile base location

Field Test Data

CPT

SPT





Comparison of Load Capacities

	Q_{sL} (kip)	Q_{bult}^{*} (kip)	Q_{ult} (kip)
Measured/SLT	212	90	**302**
CAPWAP/DLT	331	178	**509**
Purdue method (SPT)	100	185	**285**
Purdue method (CPT)	112	204	**316**
DRIVEN	206	14	**220**

* Not accounting for residual loads

** Load at settlement of 10% of pile diameter

Case Study

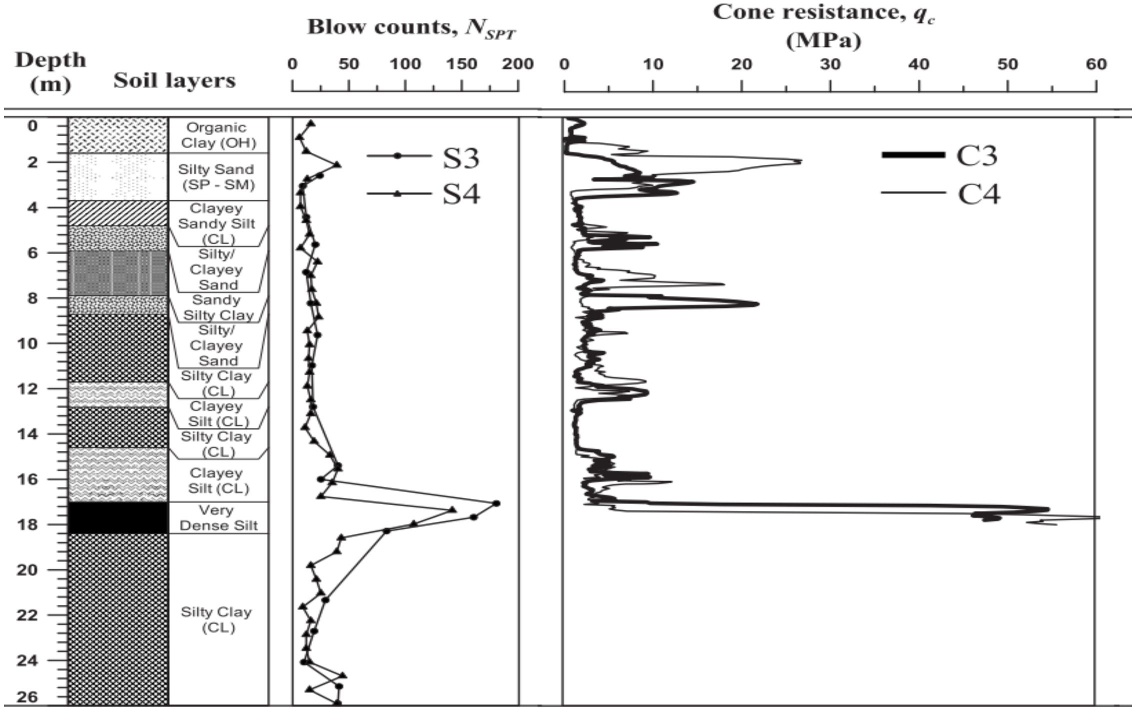
- SR 9 in Lagrange County (Pipe) -2000
- SR 49 in Jasper County (Pipe) - 2005
- **SR 49 in Jasper County (H) - 2005**
- SR 55 in Lake County (H) - 2014
- US 31 in Marshall County (Pipe) - 2014

Soil and Pile Information

- K_0: 0.45 for loose sand ($D_R < 35\%$), 0.4 for medium dense to dense sand ($D_R \geq 35\%$)
- Ground water table depth: 3.3 ft
- H pile: HP 310×110
- Embedded depth: 57.1 ft

Field Test Data

SPT



Comparison of Load Capacities

	Q_{sL} (kip)	Q_{bult}^{*} (kip)	Q_{ult} (kip)
Measured/SLT	237	204	**440**
CAPWAP/DLT	107	225	**332**
Purdue method (CPT)	279	182	**461**
DRIVEN	233	2	**235**

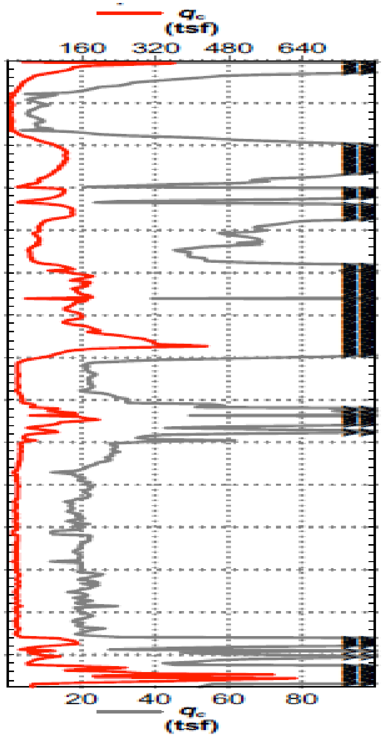
*Load at settlement of 10% of pile diameter

Case Study

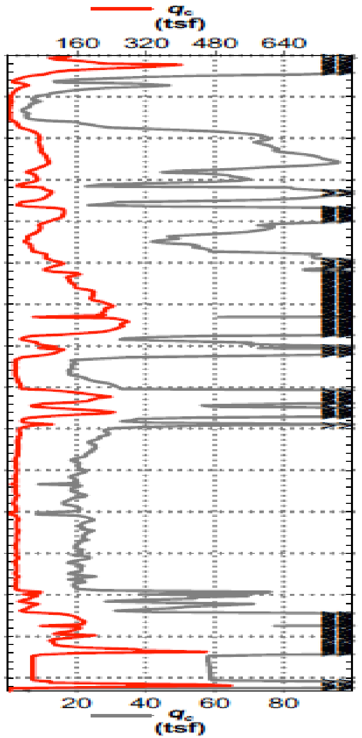
- SR 9 in Lagrange County (Pipe) -2000
- SR 49 in Jasper County (Pipe) - 2005
- SR 49 in Jasper County (H) - 2005
- **SR 55 in Lake County (H) - 2014**
- US 31 in Marshall County (Pipe) - 2014

Field Test Data

CPT-1



CPT-2



Soil and Pile Information

- Sand - 0 to 37 ft (N60 ~ 10-20)
- Silty Clay - 37 to 41 ft (N60 ~ 7-9)
- Sand - 41 to 45 ft (N60 ~ 20-30)
- Silty Clay - 45 to 66 ft (N60 ~ 8-9)
- Sand - 66 to 73 ft (N60 ~ 20-40)
- Silty Clay - 73 to 76 ft (N60 ~ 20)
- H-Pile 12x53
- Embedment Depth – 69.1 feet

Comparison of Load Capacities

Method	**Q_{SL} (kip)**	**Q_{bult} (kip)**	**Q_{ult} (kip)**
DLT/CAPWAP	219	138	357
Purdue (CPT)	334	67	401
DRIVEN	281	7	288

Case Study

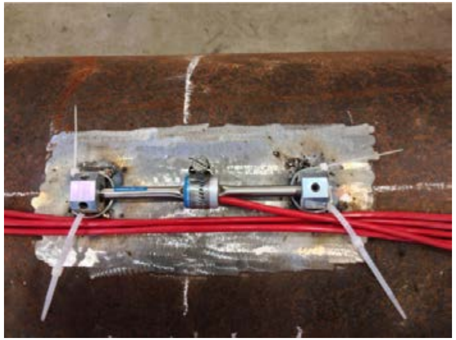
- SR 9 in Lagrange County (Pipe) - 2000
- SR 49 in Jasper County (Pipe) - 2005
- SR 49 in Jasper County (H) - 2005
- SR 55 in Lake County (H) - 2014
- **US 31 in Marshall County (Pipe) - 2014**

Soil and Pile Information

Layer number	Elevation (lft)	Soil	Total unit weight (lb/ft3)	Moisture content (%)
1	0-6.5	Brown, moist, stiff to very stiff loam	124.5	15.8
2	6.5-18	Brown, moist, medium dense sandy loam	133.0	11.7
3	18-23	Brown, moist, dense sandy loam	129.0	8.3
4	23-33	Gray, moist, very stiff loam	134.0	12.5
5	33-43	Gray, moist, medium dense to very dense sandy loam	133.1	11.8
6	43-81	Gray, moist, hard loam	130.5	9.6

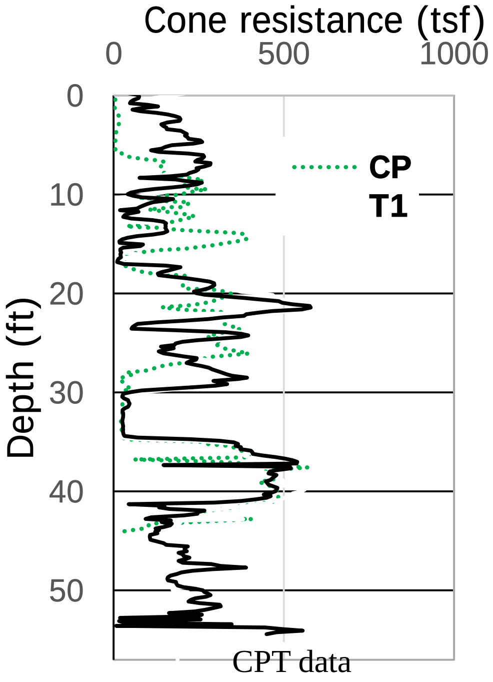
- Pipe Pile 14 inch, 0.375 inch thick
- Embedment Depth – 51.2 feet

Static Load Test (June 25th, 2014)

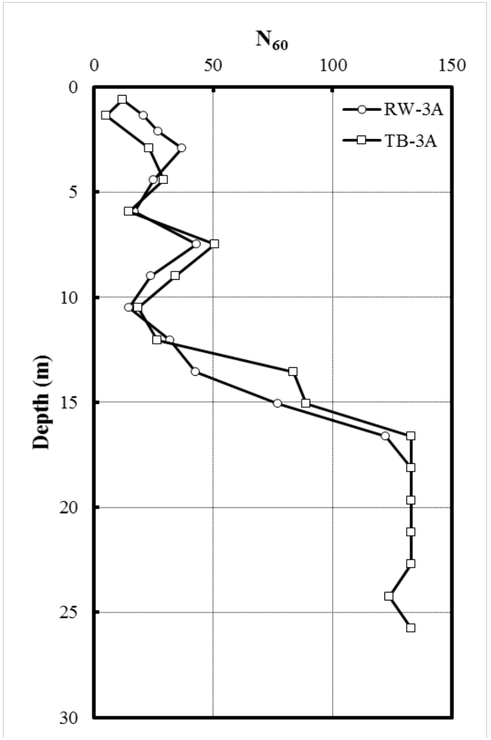


Field Test Data

CPT



SPT



Comparison of Load Capacities

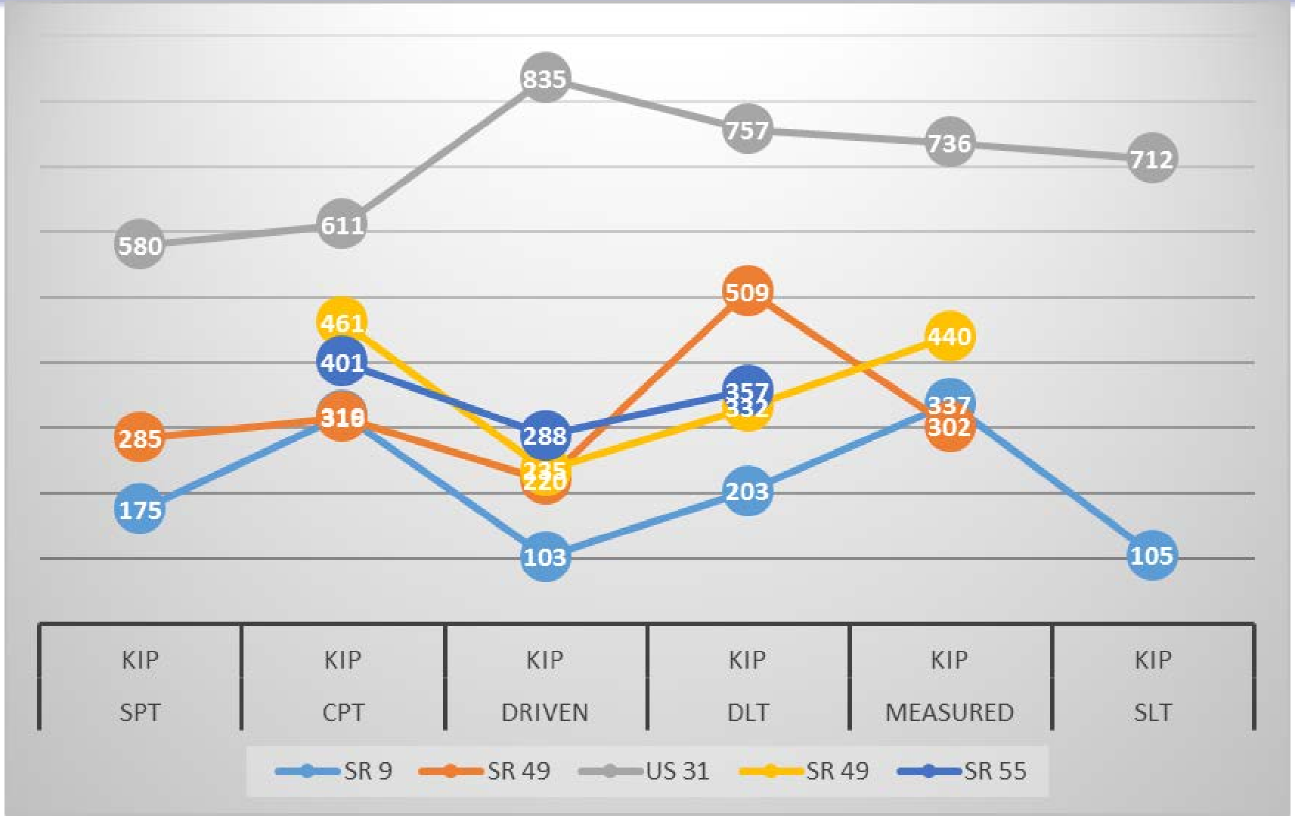
Method	Q_{sL} **(kip)**	Q_{bult}^{*} **(kip)**	Q_{ult} **(kip)**
Measured	527	209	736
Measured corrected by residual load	460	277	736
DLT/CAPWAP	382	375	757
Purdue (SPT with capping)	284	296	580
Purdue (SPT without capping)	338	352	691
Purdue method (CPT)	351	260	611
DRIVEN	297	538	835

* Load at settlement of 10% of pile diameter

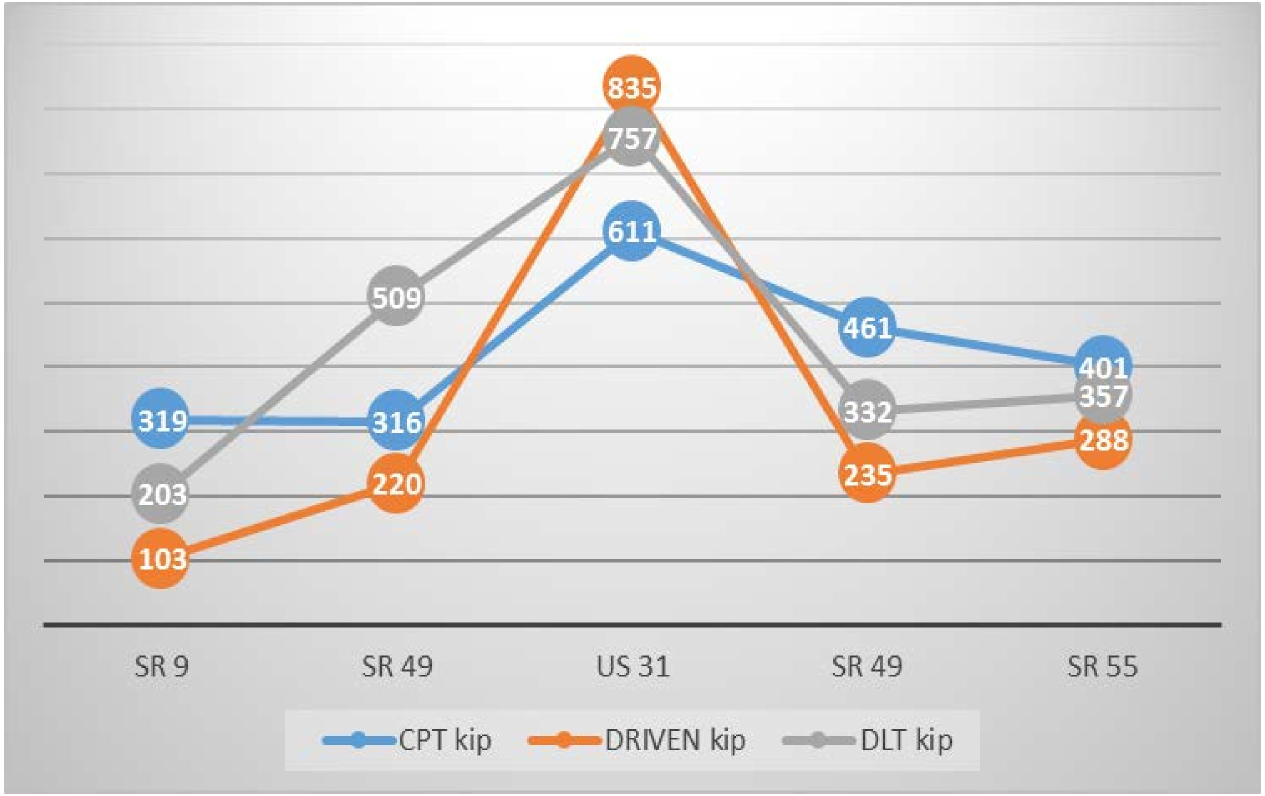
Reference Research Papers

- Paik, K., Salgado, R., Lee, J., and Kim, B. (2003). “Behavior of Open- and Closed-Ended Piles Driven into Sands.” *Journal of Geotechnical and Geoenvironmental Engineering*, 129(4), 296–306.
- “Assessment of Axially Loaded Pile Dynamic Design Methods and Review of INDOT Axially Loaded Pile Design Procedure ”, *JTRP Research – SPR-2856* – Report Number: *FHWA/IN/JTRP-2008/6*
- Kim, D., Bica, A. V., Salgado, R., Prezzi, M., & Lee, W. (2009). Load testing of a closed-ended pipe pile driven in multilayered soil. *Journal of Geotechnical and Geoenvironmental Engineering*, *135*(4), 463-473.
- Bica, Prezzi, Seo, Salgado and Kim (2012). “ Instrumentation and axial load testing of displacement piles” *Proceedings of the Institution of Civil Engineers*, Paper 1200080.
- “ Use of Pile Driving Analysis For Assessment of Axial Load Capacity of Piles ”, *JTRP Research - SPR-3378* - Report Number: *FHWA/IN/JTRP-2012/11*

Comparison of Data



Comparison of CPT, Driven & DLT



Conclusions:

- Since, designs are based on Limit states, design of piles should also be based on servicibility limit states, i.e. settlement.
- The most predominant and most reliable method of pile design shall be the CPT Design Method.
- More number of Static Load Tests needs to be performed.
- Measured capacities were based on Chin Method. However, in many cases failure could be extrapolated.

INDOT Pile Costs 2009 to 2014

Indiana Standard Spec. Method of Pile Driving	701.05 (a) (Gates)	701.05 (b) (DLT/ CAPWAP)	Totals
Plan Contract Length (lft)	246,052	995,100	1,241,152
Paid Pile Length (lft)	216,644	937,873	1,154,517
Pile Lengths underrun/overrun (lft)	(29,408)	(57,227)	(86,635)
Pile Lengths underrun/overrun %	(13.6%)	(6.1%)	(7.5%)
Cost Paid to Contractor	**$ 11,653,634**	**$ 46,178,800**	**$ 57,832,434**
Average Unit Cost (per lft)	**$ 53.79**	**$ 49.24**	**$ 50.09**

Conclusions

- **The use of pile dynamic formula (PDF) 701.05 (a) has economic drawbacks:**
    - Factored load carrying capacity of PDF pile is 21% less than a DLT pile.
    - For the same factored load pile lengths for PDF piles will be greater than DLT piles by 10 to 20%.
    - Pile support cost per kip of structure load is 39% higher than a DLT pile.
    - Based on past six years data, on an average per linear feet in ground cost of PDF piles is 9.2% more than the DLT piles.
    - On an average, DLT capacity is less than Davisson Offset limit Capacity.

Conclusions (Contd.)

- DLT does a better site coverage, hence minimizes variability and overruns and underruns.
- The use of DLT piles should be increased for:
  - All Piles designed for side friction
  - Piles driven in to soft shale's
- There is a lesser risk in DLT piles than with Static Load test pile.
- Based on past six years data, on an average per linear feet in ground cost of PDF piles is 9.2% more than the DLT piles.

Thank you !

Dynamic formula[1]

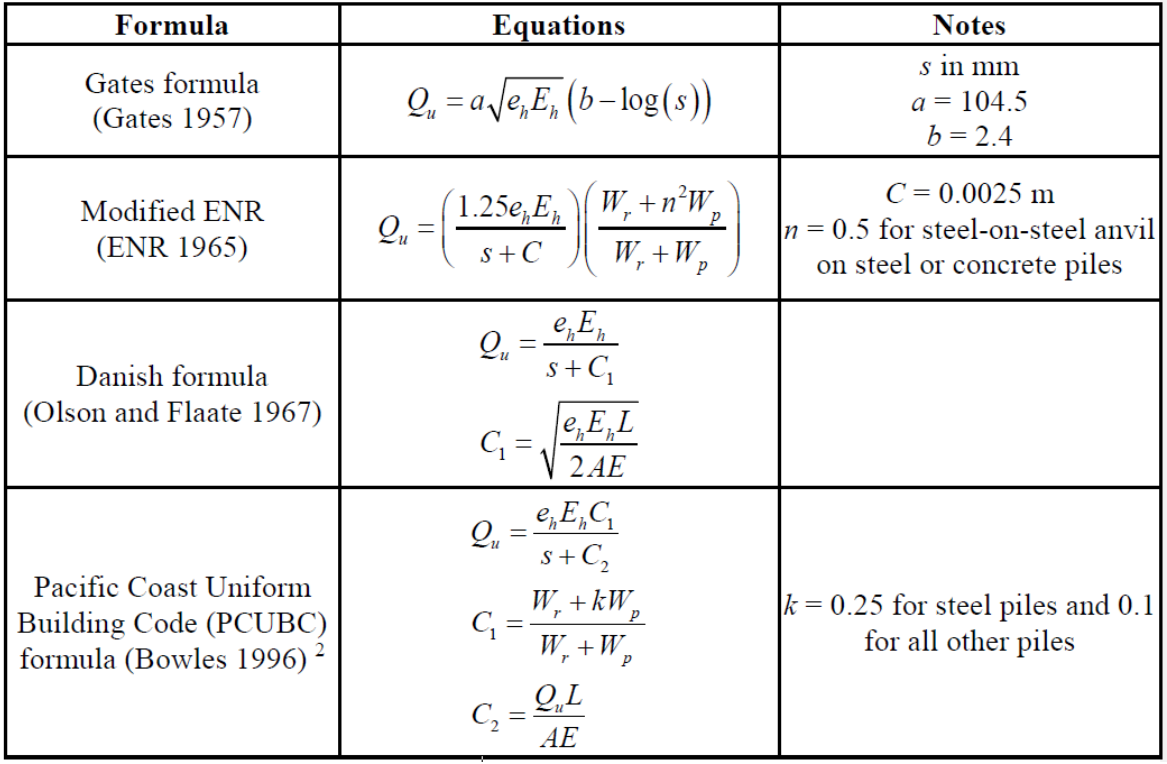
- ❑ Nominal driving resistance

$$R_{ndr} = 6.7\sqrt{E}\log(10N) - 445$$

  - R_{ndr} = nominal driving resistance (kN)
  - E = manufacturer’s rated energy (J) at the field observed ram stroke and not reduced for efficiency
  - Log(10N) = logarithm to the base 10 of the quantity 10 multiplied by N
  - N = number of hammer blows per 25mm at final penetration

[1] INDOT Standard Specifications 2012.

Traditional Pile Driving Formulas



Formula	Equations	Notes
Gates formula (Gates 1957)	$Q_u = a\sqrt{e_h E_h}\left(b - \log(s)\right)$	s in mm $a = 104.5$ $b = 2.4$
Modified ENR (ENR 1965)	$Q_u = \left(\frac{1.25 e_h E_h}{s + C}\right)\left(\frac{W_r + n^2 W_p}{W_r + W_p}\right)$	$C = 0.0025$ m $n = 0.5$ for steel-on-steel anvil on steel or concrete piles
Danish formula (Olson and Flaate 1967)	$Q_u = \frac{e_h E_h}{s + C_1}$ $C_1 = \sqrt{\frac{e_h E_h L}{2AE}}$	
Pacific Coast Uniform Building Code (PCUBC) formula (Bowles 1996) [2]	$Q_u = \frac{e_h E_h C_1}{s + C_2}$ $C_1 = \frac{W_r + kW_p}{W_r + W_p}$ $C_2 = \frac{Q_u L}{AE}$	$k = 0.25$ for steel piles and 0.1 for all other piles

ICP-05[1]

- Unit base resistance ($q_{b,ult}$) for closed-ended pipe piles
  - In sandy soils

$$q_{b,ult} = \left[1 - 0.5\log(B / B_{CPT})\right] q_c$$

B = pile diameter

B_{CPT} = 0.036 m

  - In clays

$q_{b,ult} = 0.8 q_{cb,avg}$ Undrained loading

$q_{b,ult} = 1.3 q_{cb,avg}$ Drained loading

$q_{cb,avg}$ = averaged q_c over a depth of 1.5B above and below the pile base level

[1] Richard Jardine, Fiona Chow, Robert Overy and Jamie Standing. (2005), "ICP Design Methods for Driven Piles in Sands and Clays", Published by Thomas Telford Publishing, Thomas Telford Ltd, 1 Heron Quay, London E14 4JD.

ICP-05[1]

- Unit shaft resistance (q_{sL}) for closed-ended pipe piles
  - In sandy soils

$$q_{sL} = (\sigma'_{rc} + \Delta\sigma'_{rd})\tan\delta_{cv}$$

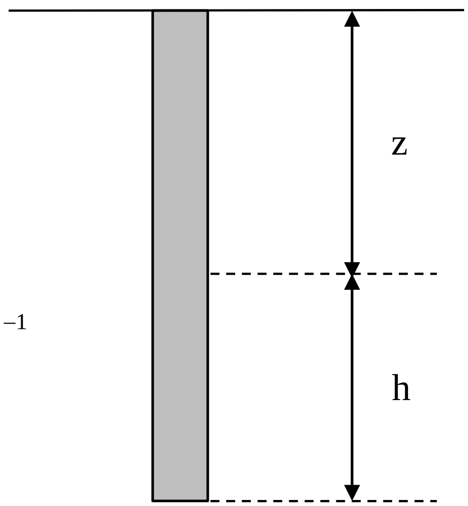
$$\sigma'_{rc} = 0.029 q_c \left(\frac{\sigma'_{v0}}{p_A}\right)^{0.13}\left(\max\left[\frac{h}{R},8\right]\right)^{-0.38}$$

$$\Delta\sigma'_{rd} = 2G\Delta r / R$$

$$G = q_c\left[0.0203 + 0.00125 q_c \left(p_A\sigma'_{v0}\right)^{-0.5} - 1.216\times10^{-6} q_c{}^{2}\left(p_A\sigma'_{v0}\right)^{-1}\right]^{-1}$$

R = pile radius
Δr = 0.02mm for lightly rusted steel piles
δ_{cv} = interface friction angle ($0.9\phi_c$)

Pile length = h + z



---

[1] Richard Jardine, Fiona Chow, Robert Overy and Jamie Standing. (2005), “ICP Design Methods for Driven Piles in Sands and Clays", Published by Thomas Telford Publishing, Thomas Telford Ltd, 1 Heron Quay, London E14 4JD.

ICP-05[1]

- Unit shaft resistance (q_{sL}) for closed-ended pipe piles
  - In clays

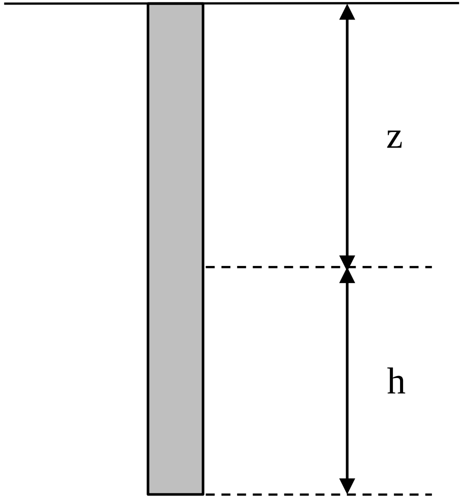
$$q_{sL} = 0.8 K_c \sigma'_{v0} \tan \delta_{cv}$$

$$K_c = \left[2.2 + 0.016 OCR - 0.870 \Delta I_{vy}\right] OCR^{0.42} \left(\max\left[\frac{h}{R}, 8\right]\right)^{-0.20}$$

$$\Delta I_{vy} = \log_{10} S_t$$

R = pile radius
S_t = Sensitivity of clay
δ_{cv} = interface friction angle ($0.9\phi_c$)

Pile length = h + z



[1] Richard Jardine, Fiona Chow, Robert Overy and Jamie Standing. (2005), “ICP Design Methods for Driven Piles in Sands and Clays", Published by Thomas Telford Publishing, Thomas Telford Ltd, 1 Heron Quay, London E14 4JD.

NGI-05[1]

- Unit base resistance ($q_{b,ult}$) for closed-ended pipe piles
  - In sandy soils

$$q_{b,ult} = \frac{0.8q_{cb,avg}}{1+\left\{0.4\ln\left[\frac{q_{cb,avg}}{22\left(\sigma'_{vb}p_A\right)^{0.5}}\right]\right\}^2}$$

$q_{cb,avg}$ = the representative cone resistance at the pile base level

[1] Clausen, C. J. F., P. M. Aas, and K. Karlsrud. (2005) "Bearing capacity of driven piles in sand, the NGI approach." Proceedings of Proceedings of International Symposium. on Frontiers in Offshore Geotechnics, Perth. 2005.

NGI-05[1]

- Unit shaft resistance (q_{sL}) for closed-ended pipe piles
  - In sandy soils

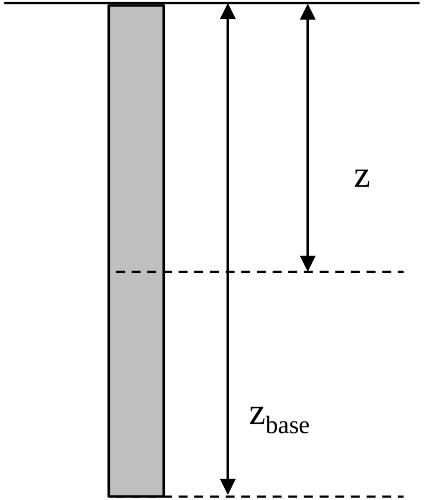
$$q_{sL} = \max\left[p_A \left(\frac{z}{z_{base}}\right)\left(\frac{\sigma'_v}{p_A}\right)^{0.25} F_{q_c} F_{tip} F_{load} F_{mat}, 0.1\sigma'_v \right]$$

$$F_{q_c} = 2.1\left[0.4\ln\left\{\frac{q_c}{22\left(\sigma'_{v0} p_A\right)^{0.5}}\right\} - 0.1\right]^{1.7}$$

$$F_{tip} = 1.6$$

$$F_{load} = 1.3$$

$$F_{mat} = 1.0$$



[1] Clausen, C. J. F., P. M. Aas, and K. Karlsrud. (2005) "Bearing capacity of driven piles in sand, the NGI approach." Proceedings of Proceedings of International Symposium. on Frontiers in Offshore Geotechnics, Perth. 2005.

NGI-05[1]

- ❑ Unit shaft resistance (q_{sL}) for closed-ended pipe piles
  - In clays

$q_{sL} = \alpha^{NC} s_u$ $\left(s_u / \sigma'_v\right) < 0.25$ NC clay

$\alpha^{NC} = 0.32(\mathrm{PI}-10)^{0.3}$ $0.20 \le \alpha^{NC} \le 1.0$

$q_{sL} = \alpha s_u F_{tip}$ $\left(s_u / \sigma'_v\right) > 1.0$ OC clay

$\alpha = 0.5(s_u / \sigma'_v)^{-0.3}$

$F_{tip} = 0.8 + 0.2(s_u / \sigma'_v)^{0.5}$ $1.0 \le F_{tip} \le 1.25$

$q_{sL} = \alpha s_u$ $0.25 < \left(s_u / \sigma'_v\right) < 1.0$

α is determined by a linear interpolation

---

[1] Karlsrud, K., Clausen, C.J.F. and Aas, P.M. (2005), "Bearing capacity of driven piles in clay, the NGI approach", Proc., 1st Int. Symposium on Frontiers in Offshore Geotechnics, Balkema, Perth, Ausralia, 677-681.

UWA-05[1]

- Unit base resistance ($q_{b,ult}$) for closed-ended pipe piles
  - In sandy soils

$$q_{b,ult} = 0.6q_{cb,avg}$$

$q_{cb,avg}$ = the representative cone resistance at the pile base level

[1] Lehane, B. M., Schneider, J. A., & Xu, X. (2005). The UWA-05 method for prediction of axial capacity of driven piles in sand. Frontiers in Offshore Geotechnics: ISFOG, 683-689.

UWA-05[1]

- Unit shaft resistance (q_{sL}) for closed-ended pipe piles
  - In sandy soils

$$q_{sL} = \frac{f}{f_c}\left(\sigma'_{rc} + \frac{4G\Delta r}{D}\right)\tan\delta_{cv}$$

$$\sigma'_{rc} = 0.03q_c\left[\max\left(\frac{h}{D},2\right)\right]^{-0.5}$$

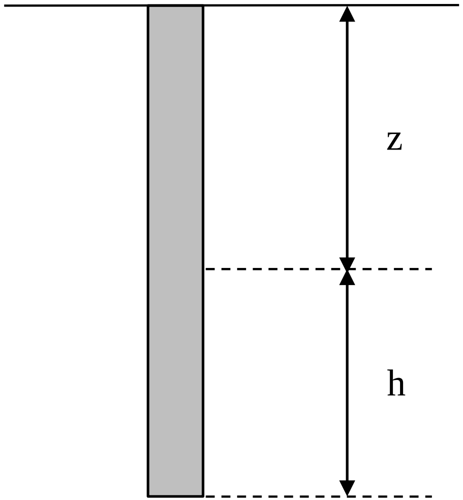
$$G/q_c = 185\left[\frac{q_c/p_A}{\left(\sigma_{v0}/p_A\right)^{0.5}}\right]^{-0.75}$$

$$\Delta r = 0.02mm$$

f/f_c = 1 for compression and 0.75 for tension

δ_{cv} = interface friction angle ($0.9\phi_c$)

Pile length = h + z



[1] Lehane, B. M., Schneider, J. A., & Xu, X. (2005). The UWA-05 method for prediction of axial capacity of driven piles in sand. Frontiers in Offshore Geotechnics: ISFOG, 683-689.