Design of driven piles and drilled shaft foundations

NCHRP 368

Chapter 8

pages 57 to 64

The bearing resistance and settlement behavior of driven piles and drilled shafts can be calculated in two manners:

1. Indirect methods that use conventional soil mechanics methods.
    1. s_u, ϕ', E', E_u, and c_v determined from correlation with q_t, f_s, u_2, v_s and pore pressure dissipation tests.
    2. c_c and c_r determined from lab consolidation tests.
2. Direct methods that incorporate a combination of the measured cone tip resistance, sleeve resistance or pore pressure data in the formulae.

Direct methods for nominal axial resistance analysis of driven piles and drilled shafts

- LCPC method (1982) summarized in NCHRP 368, also in FHWA-SA-91-043, The Cone Penetrometer Test
- Norwegian Geotechnical Institute method (1996, 2001) in NCHRP 368
- Politecnico di Torino method (1995) in NCHRP 368
- Unicone method (1997, 2006) in NCHRP 368
- Takesue method (1998) in NCHRP 368

$$R_R = (\phi)\,(R_n) = (\phi_{stat})\,(R_{nstat}) = (\phi)\,(Q_n)$$

ϕ or $\phi_{stat} <= 0.7$ is recommended in Caltrans amendments to the LRFD BDS

The total axial compression resistance of a cylindrical drilled shaft

- $Q_{total} = Q_{nominal} = Q_s + Q_b$
- $Q_{nominal} = \Sigma\, f_p\, (A_p) + q_b\, (A_b)$
- $Q_n = \Sigma\, f_p\, (\pi)\, (d)\, (\Delta z) + q_b\, (\pi)\, (d/2)^2$
  - f_p is the unit side resistance of each soil layer (TSF or kPa)
  - d is the pile diameter
  - Δz is the vertical thickness of each soil layer
  - q_b is the unit end bearing (TSF or kPa)

LCPC method for the estimation of the nominal resistance of driven piles and drilled shafts in all soil types

For estimation of the side resistance:

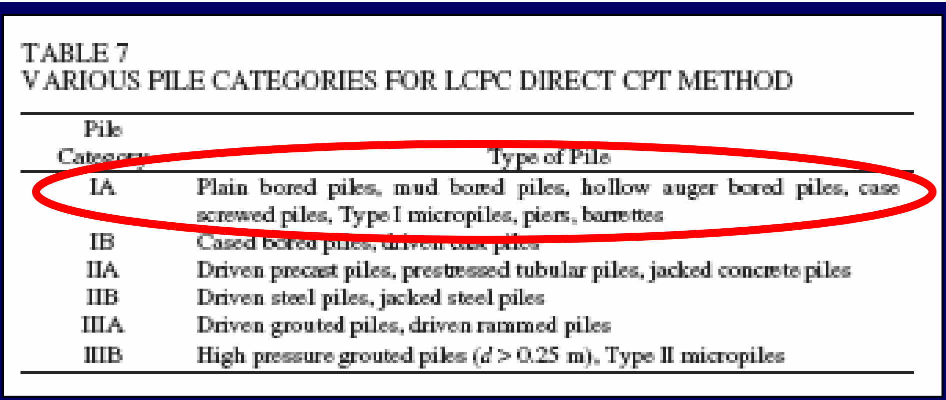
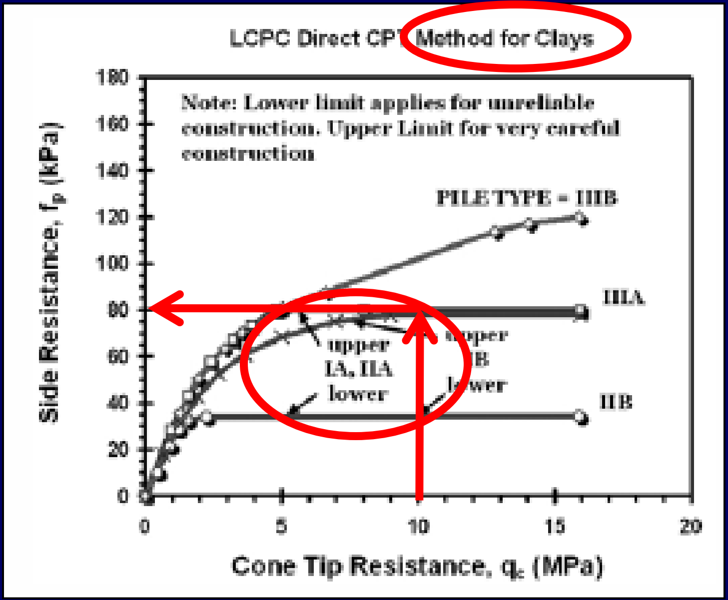


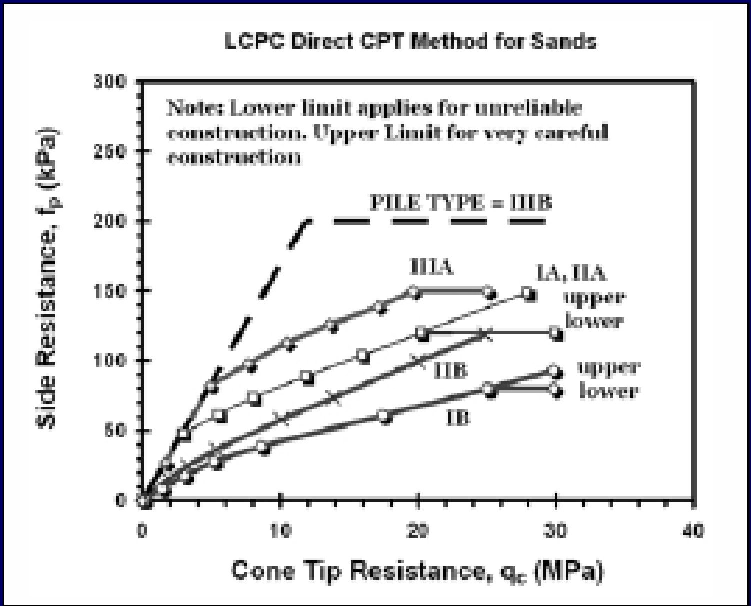
TABLE 7
VARIOUS PILE CATEGORIES FOR LCPC DIRECT CPT METHOD

Pile Category	Type of Pile
IA	Plain bored piles, mud bored piles, hollow auger bored piles, case screwed piles, Type I micropiles, piers, barrettes
IB	Cased bored piles, driven cast piles
IIA	Driven precast piles, prestressed tubular piles, jacked concrete piles
IIB	Driven steel piles, jacked steel piles
IIIA	Driven grouted piles, driven rammed piles
IIIB	High pressure grouted piles ($d > 0.25$ m), Type II micropiles



LCPC Direct CPT Method for Clays

Note: Lower limit applies for unreliable construction. Upper Limit for very careful construction



LCPC Direct CPT Method for Sands

Note: Lower limit applies for unreliable construction. Upper Limit for very careful construction

LCPC method for the nominal resistance of driven piles and drilled shafts in all soil types

For base resistance:

$$q_b = k_c (q_c)$$

k_c is determined from the pile soil type, as shown below

q_c is the arithmetic mean of all of the q_c data for a distance of 1.5 (B) above and below the pile tip:

$$q_{c\ (ave)} = ((q_{c1}) + (q_{c2}) + (q_{c3}) \ldots + (q_{cn})\ ) / n$$

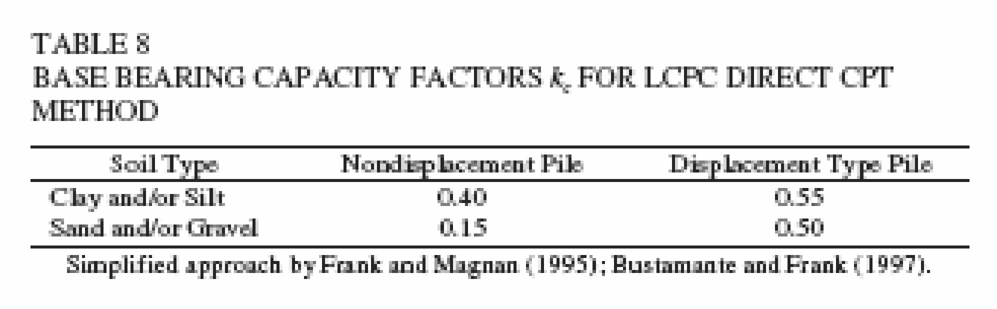


TABLE 8

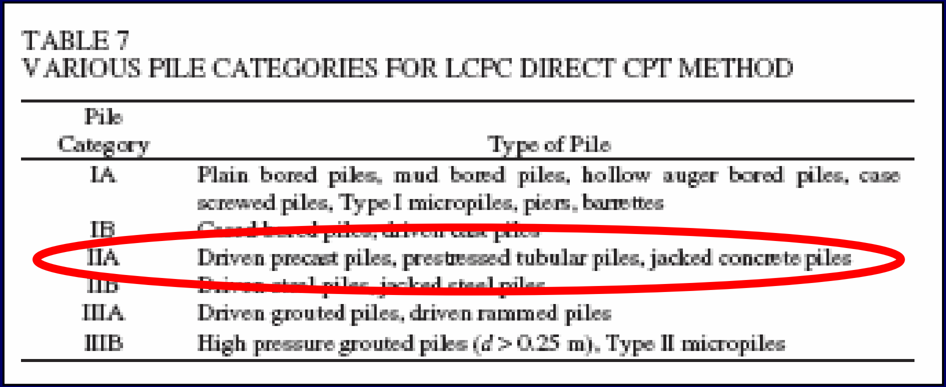
BASE BEARING CAPACITY FACTORS k_c FOR LCPC DIRECT CPT METHOD

Soil Type	Nondisplacement Pile	Displacement Type Pile
Clay and/or Silt	0.40	0.55
Sand and/or Gravel	0.15	0.50

Simplified approach by Frank and Magnan (1995); Bustamante and Frank (1997).

Example calculations for the LCPC method for the nominal resistance of a driven pile

- Foundation configuration
  - Driven square precast conc pile
  - d = 1.0 feet
  - L = Δz = 35 feet
- Soil conditions for side resistance:
  - soil type is intact clay
  - q_c = 10 TSF = 1 MPa
- Soil conditions for base resistance:
  - Soil type is sand
  - q_c = 200 TSF = 20 MPa



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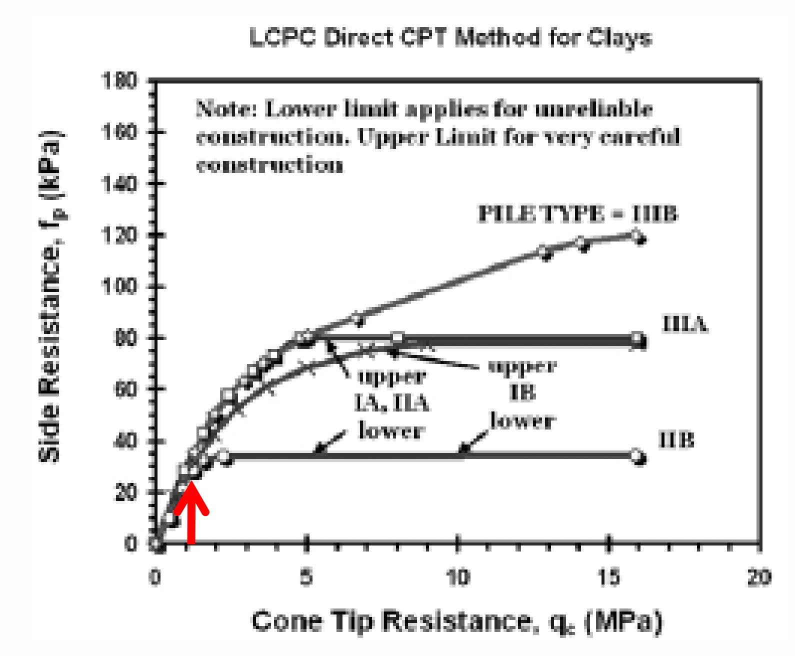
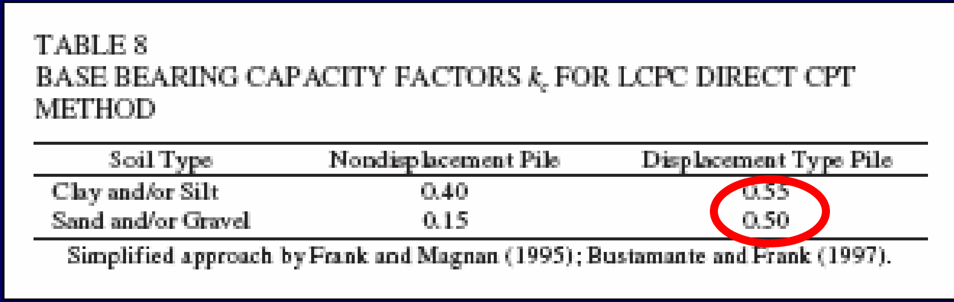


- Side resistance:
  - f_p = 24 kPa = 480 psf = 0.48 ksf

Example calculations using the LCPC method for the nominal resistance of a driven pile

- Foundation configuration
  - Driven square precast conc pile
  - $d = 1.0$ feet
  - $L = \Delta z = 35$ feet
- Soil conditions for side resistance:
  - soil type is intact clay
  - $q_c = 10$ TSF
- Soil conditions for base resistance:
  - Soil type is sand
  - $q_c = 200$ TSF



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Soil Type	Nondisplacement Pile	Displacement Type Pile
Clay and/or Silt	0.40	0.55
Sand and/or Gravel	0.15	0.50

Simplified approach by Frank and Magnan (1995); Bustamante and Frank (1997).

- Base resistance:
  - $q_b = k_c\,(q_c)$
  - $q_b = 0.50\ (400\text{ ksf}) = 200\text{ ksf}$

$$Q_{nominal} = \Sigma\, f_p\,(A_p) + q_b\,(A_b)$$

$$Q_{nominal} = 0.48\text{ ksf}\ (35)\ (4) + 200\ (1)$$

$$Q_{nominal} = 67 + 200 = 267\text{ kips}$$

Norwegian Geotechnical Institute method for the nominal resistance of driven piles in cohesive soil

For side resistance:

$$f_p = (q_t - \sigma_{v0}) / (10.5 + 13.3 (\log Q))$$

Q = normalized cone tip resistance

$$Q = (q_t - \sigma_{v0}) / \sigma_{v0}'$$

For base resistance:

$$q_b = (q_t - \sigma_{v0}) / k_2$$

$$k_2 = N_{kt} / 9$$

N_{kt} = 15 for soft to firm intact clays

All terms are assumed to be in units of MPa.

Example calculations for the NGI method for the nominal resistance of a driven pile in cohesive soil

- Foundation configuration
  - Driven square precast concrete pile
  - d = 1.0 feet
  - L = Δz = 35 feet
- Soil conditions for side and base resistance:
  - soil type is intact clay
  - q_t = 10 TSF = 1.0 Mpa

- Side resistance:
- $f_p = (q_t - \sigma_{v0}) / (10.5 + 13.3 (\log Q))$
- $Q = (q_t - \sigma_{v0}) / \sigma_{v0}'$
- $\sigma_{v0} = \sigma_{v0}' = (5 + 35/2) (0.110/2) = 1.24$ TSF = 0.124 MPa
- $Q = (1.0 - 0.124)/0.124 = 7.06$
- $f_p = (1.0 - 0.124) / (10.5 + 13.3 (\log 7.06))$
- $f_p = 0.876 / 21.79 = 0.0402$ Mpa = 40.2 kPa = 0.80 ksf

Example calculations using the NGI method for the nominal resistance of a driven pile in cohesive soil

- Foundation configuration
  - Driven square precast concrete pile
  - $d = 1.0$ feet
  - $L = \Delta z = 35$ feet
- Soil conditions for side and base resistance:
  - soil type is intact clay
  - $q_t = 10$ TSF $= 1.0$ MPa

- Base resistance:
- $q_b = (q_t - \sigma_{v0}) / k_2$
- $k_2 = N_{kt} / 9 = 15/9 = 1.67$
- $q_b = (1.0 - 0.124) / 1.67 = 0.524$ Mpa $= 5.24$ TSF $= 10.5$ ksf

$Q_{nominal} = \Sigma\ f_p\ (A_p) + q_b\ (A_b)$
$Q_{nominal} = 0.80$ ksf $(35)\ (4) + 10.5\ (1)$
$Q_{nominal} = 112.0 + 10.5 = 123$ kips

Politecnico di Torino method for the nominal resistance of drilled shafts in cohesionless soil

For side resistance:

$$f_p = (q_t / 274)^{0.75}$$

q_t and f_p are in units of Mpa (1 MPa = 10 TSF)

For base resistance:

$$q_b = q_t / (1.90 + (0.62/(s/d)))$$

s = pile base deflection

d = pile base diameter

(s/d) is often taken as 0.10 to limit the strain at the <u>defined</u> nominal resistance, which gives:

$$q_b = q_t / 8.10$$

Example calculations using the Politecnico di Torino method for the nominal resistance of a drilled shaft in cohesionless soil

- Foundation configuration
  - Drilled shaft without casing support
  - d = 2.0 feet = 0.61 meter
  - L = Δz = 35 feet = 10.67 meters
- Soil conditions for side and base resistance:
  - soil type: sand
  - q_t = 70 TSF = 7.0 MPa

- $f_p = (q_t / 274)^{0.75}$
- $f_p = (7.0 / 274)^{0.75}$ = 0.0639 MPa = 0.639 TSF = 1.3 ksf
- $q_b = q_t / 8.10$
- q_b = 7.0 / 8.10 = 0.864 MPa = 8.64 TSF = 17.3 ksf

$Q_{nominal} = \Sigma f_p (A_p) + q_b (A_b)$

$Q_{nominal}$ = 1.3 ksf (35) (π) (2.0) + 17.3 (π) $(1)^2$

$Q_{nominal}$ = 285.9 + 54.3 = 340 kips

Unicone method (Eslami and Fellenius) for the nominal resistance of driven piles or drilled shafts in all soil types

For side resistance:

$$f_p = C_{se}\,(q_E)$$

C_{se} is from Table 9 based on the soil classes from the Figure below

$$q_E = (q_t - u_2) \text{ in MPa}$$

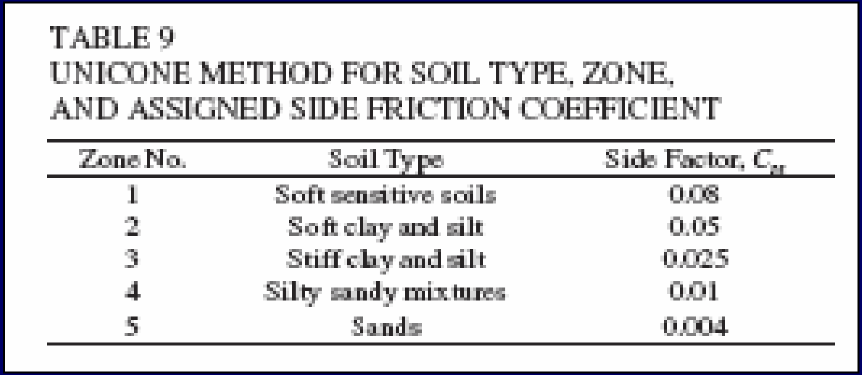
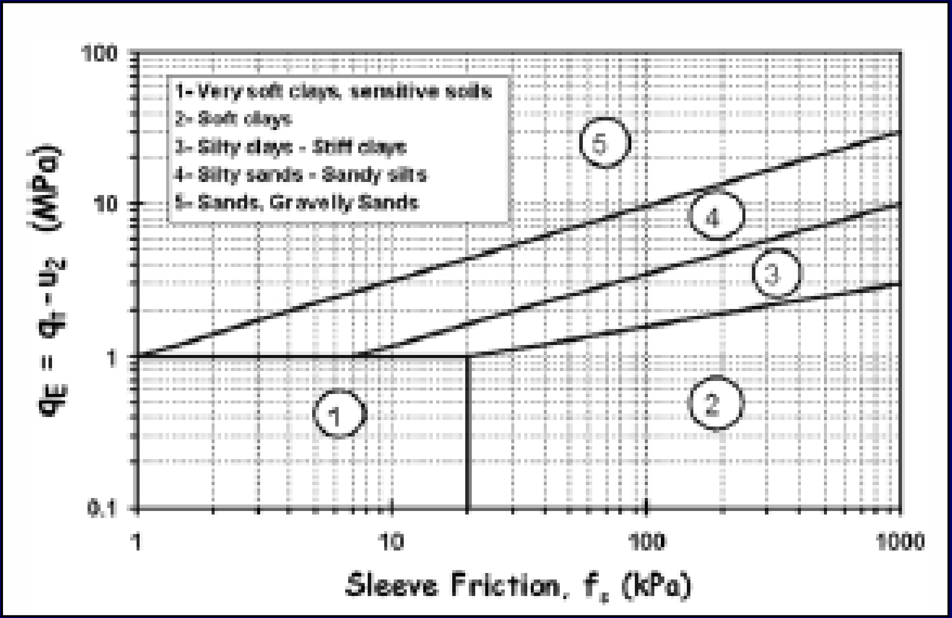


TABLE 9
UNICONE METHOD FOR SOIL TYPE, ZONE, AND ASSIGNED SIDE FRICTION COEFFICIENT

Zone No.	Soil Type	Side Factor, C_{se}
1	Soft sensitive soils	0.08
2	Soft clay and silt	0.05
3	Stiff clay and silt	0.025
4	Silty sandy mixtures	0.01
5	Sands	0.004



Unicone method (Eslami and Fellenius) for the nominal resistance of driven piles or drilled shafts in all soil types

For base resistance:

$q_b = C_{te} (q_E)$

C_{te} is generally taken as 1.0

$q_E = (q_t - u_2)$ in MPa

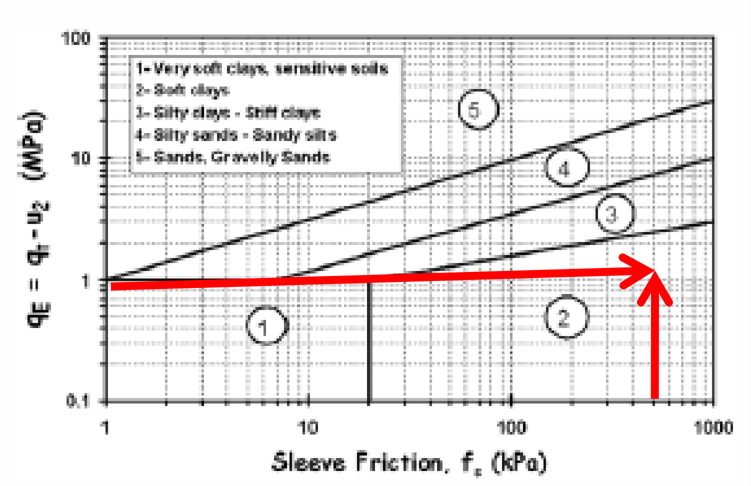
If the effective cone resistance profile (q_E) indicates significant variation, the authors recommend a geometric, not arithmetic mean be calculated:

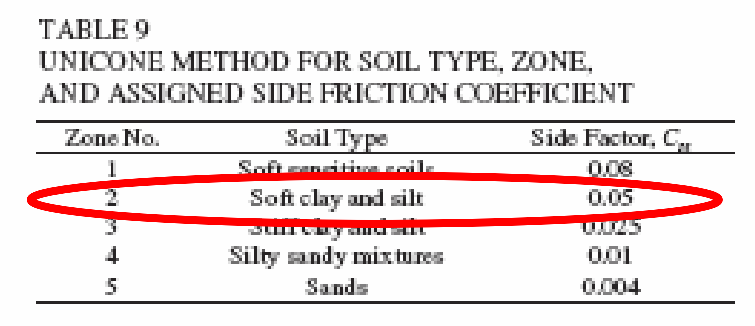
$q_E \text{ (ave)} = ((q_{E1}) (q_{E2}) (q_{E3}) \ldots (q_{En}))^{1/n}$

Example calculations using the Unicone method for the nominal resistance of a driven pile in cohesive soil

- Foundation configuration
  - Driven square precast concrete pile
  - d = 1.0 feet
  - L = Δz = 35 feet
- Soil conditions for side resistance:
  - soil type is intact clay
  - $q_t = 10$ TSF = 1.0 MPa
  - $u_2 = 20$ kPa = 0.02 MPa
  - $f_s = 500$ kPa

- Side resistance:
- $f_p = C_{se} (q_E)$
- $q_E = q_t - u_2 = 1.0 - 0.02 = 0.98$ MPa
- $f_p = 0.05 (0.98) = 0.049$ MPa = 49 kPa
- $f_p = 1.0$ ksf





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4	Silty sandy mixtures	0.01
5	Sands	0.004

Example calculations for the Unicone method for the nominal resistance of a driven pile in cohesive soil

- Foundation configuration
  - Driven square precast concrete pile
  - $d = 1.0$ feet
  - $L = \Delta z = 35$ feet
- Soil conditions for base resistance:
  - soil type is intact clay
  - $q_t = 10$ TSF $= 1.0$ MPa
  - $u_2 = 20$ kPa $= 0.02$ MPa

- Base resistance:
- $q_b = C_{te} (q_E)$
- $q_E = q_t - u_2 = 1.0 - 0.02 = 0.98$ MPa
- $q_b = 1.0 (0.98) = 0.98$ MPa
- $q_b = 9.8$ TSF $= 19.8$ ksf

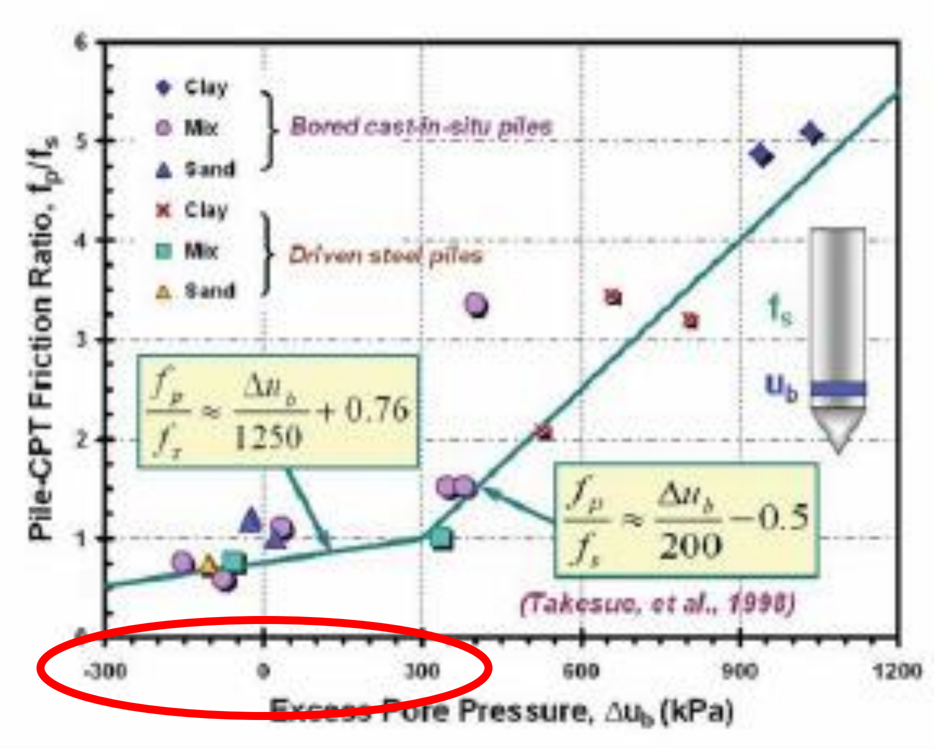
$Q_{nominal} = \Sigma f_p (A_p) + q_b (A_b)$

$Q_{nominal} = 1.0$ ksf $(35)(4) + 19.8 (1)$

$Q_{nominal} = 140 + 19.8 = 160$ kips

The Takesue method for the estimation of side resistance of driven piles or drilled shafts in all soil types

This method has the explicit capability of accommodating negative excess pore pressure, such as those that develop in silty sand and sandy silt.



I recommend that this method be used only for mixed soils and sands with Δu_2 values between -300 and 300 kPa:

$$f_p = (f_s)\,((\Delta u_t / 1250) + 0.76)$$

Example calculations using the Takesue method for the nominal resistance of a drilled shaft in cohesionless soil

- Foundation configuration
  - Drilled shaft without casing support
  - $d = 2.0$ feet $= 0.61$ meter
  - $L = \Delta z = 35$ feet $= 10.67$ meters
- Soil conditions for side and base resistance:
  - soil type: sand
  - $q_t = 70$ TSF $= 7.0$ MPa
  - $f_s = 100$ kPa
  - $\Delta u_t = 8$ kPa

- $f_p = (f_s)((\Delta u_t / 1250) + 0.76)$
- $f_p = (100)((8/1250) + 0.76) = 76.6$ kPa $= 1.5$ ksf
- $q_b = 7.0 / 8.10 = 0.864$ MPa $= 8.64$ TSF $= 17.3$ ksf from Politecnico method

$$Q_{nominal} = \Sigma f_p (A_p) + q_b (A_b)$$
$$Q_{nominal} = 1.5 \text{ ksf } (35)(\pi)(2.0) + 17.3 (\pi)(1)^2$$
$$Q_{nominal} = 329.9 + 54.3 = 384 \text{ kips}$$

Indirect methods for estimating the settlement of a single driven pile or drilled shaft

1. Approximate nonlinear methods for the immediate (drained) component of settlement for driven piles or drilled shafts embedded in cohesionless soils
2. Approximate nonlinear method for the immediate (undrained) component of settlement for driven piles or drilled shafts embedded in cohesive soils
3. Approximate nonlinear method for the recompression portion of consolidation (drained) for driven piles or drilled shafts embedded in cohesive soils
4. Conventional consolidation analysis for the virgin compression component of settlement. The pattern of stress distribution into the soil must be developed using a procedure such as the equivalent footing concept.

Approximate nonlinear method for the immediate settlement of one driven pile or one drilled shaft embedded in cohesionless soil

$$\boxed{w_t = ((Q_t)\ (I_\rho))\ /\ ((d)\ (E'))}$$

w_t = displacement at the top of the driven pile or drilled shaft
Q_t = Service Limit State Load on the pile
I_ρ = influence factor
d = pile diameter
E' = Young's modulus for drained conditions
$E' = E_0 (1 – (Q_t /Q_n)^{0.3})$ where E_0 is the drained small strain Young's modulus determined from v_s and ν'

$I_\rho = 1/(((1/(1 – (\nu')^2)) + (\pi/(1 + \nu'))\ ((L/d)\ /\ (\ln (5(L/d)\ (1 – \nu')))))$
ν' = poisson's ratio for drained conditions = 0.20

Approximate nonlinear method for the immediate settlement of one driven pile or one drilled shaft embedded in cohesive soil

$$w_t = ((Q_t)\ (I_\rho))\ /\ ((d)\ (E_u))$$

w_t = displacement at the top of the driven pile or drilled shaft
Q_t = Service Limit State Load
I_ρ = influence factor
d = pile diameter
E_u = Young’s modulus for undrained conditions
$E_u = E_0\ (1 – (Q_t\ /Q_n)^{0.3})$ where E_0 is the undrained small strain Young’s modulus determined from v_s and ν_u

$I_\rho = 1/(((1/(1 – (\nu_u)^2)) + (\pi/(1 + \nu_u))\ ((L/d)\ /\ (\ln\ (5(L/d)\ (1 – \nu_u)))))$
ν_u = poisson’s ratio for undrained conditions = 0.50

The calculation accounts for the portion of the applied pile load (Q) which results in a soil stress that is less than σ_p’.

Approximate nonlinear method for the recompression portion of consolidation for one driven pile or one drilled shaft embedded in cohesive soil

This calculation accounts for the portion of the applied pile load (Q) which results in a soil stress that exceeds σ_p'. This stress causes consolidation.

$$w_t = ((Q_t)\,(I_\rho))\;/\;((d)\,(E'))$$

w_t = displacement at the top of the driven pile or drilled shaft
Q_t = Service Limit State Load
I_ρ = influence factor
d = pile diameter
E' = Young's modulus for drained conditions
$E' = E_0\,(1 - (Q_t\,/Q_n)^{0.3})$ where E_0 is the drained small strain Young's modulus determined from v_s and ν'

In lieu of calculating I_ρ:

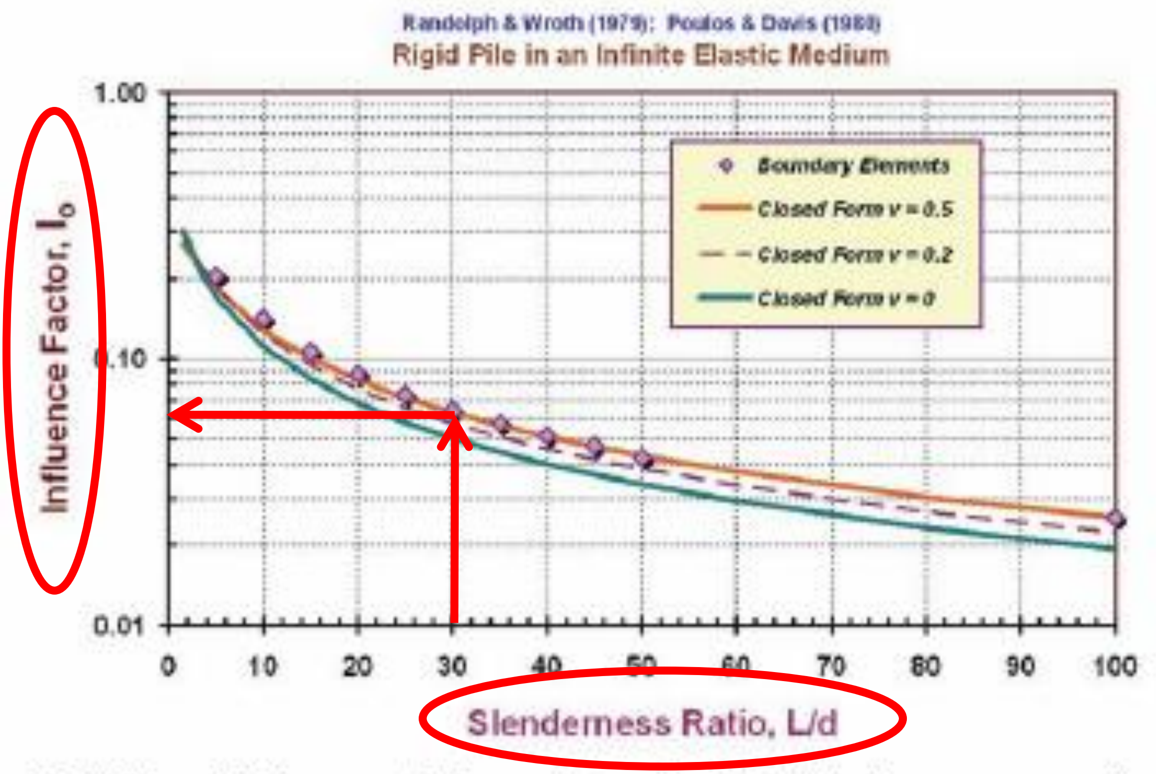


FIGURE 78 Displacement influence factors for rigid pile in homogeneous soil.

Summary and recommendations

- Nominal resistance of driven piles or drilled shafts:
  - Indirect methods using correlation derived conventional soil parameters for strength and unit weight
  - Direct methods using q_c, q_t, u_2, and f_s values

LCPC	driven and drilled	cohesionless and cohesive
NGI	driven piles	cohesive soil
Politecnico di Torino	drilled shafts	cohesionless soil
Unicone	driven and drilled	cohesionless and cohesive
Takesue	driven and drilled	cohesionless and mixed

Summary and recommendations

- Settlement calculations for deep foundations:
  - Indirect method based on approximate nonlinear theory using correlation derived E’ and E_0
  - Conventional consolidation analysis based on lab test results.
  - There are no direct methods available for settlement analysis.

Exercise 4
Determining the nominal bearing resistance of a driven pile