GeoTerva

presentation · Piles

Pile bearing capacity in layered soil

Lecture: capacity of a pile passing through sand and clay layers. Which rule applies where, how effective stress accumulates through the layers; a worked example for each topic.

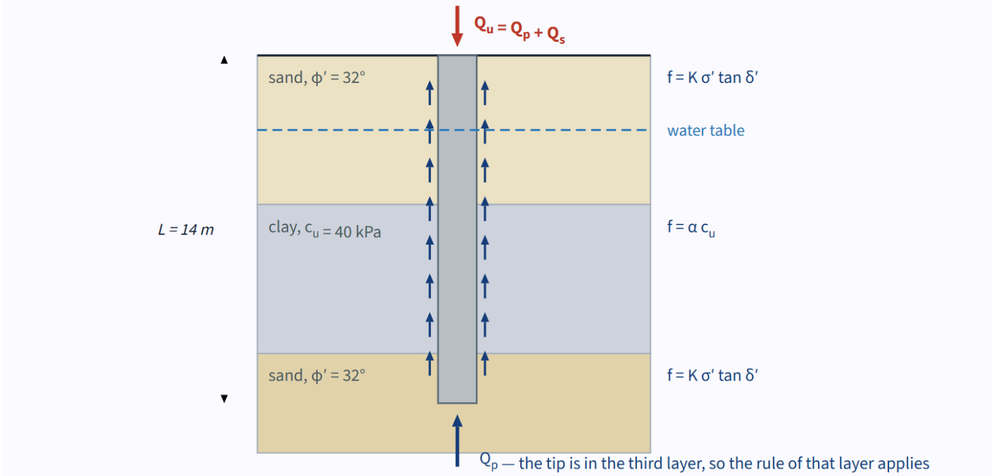
Layer-by-layer calculation

Tip: layer at the tip

Sand + clay rules

Bored pile

Worked examples



What will we learn in this lecture?

To **accumulate effective stress layer by layer**; to see how a clay layer, even though its own strength does not extend into the sand, affects the sand beneath it through its weight

To know that the **end resistance** depends only on the layer in which the tip is located and is calculated by the rule of that layer

Applying the K–δ rule **in the sand layer** (the critical depth $L' = 15D$ belongs to the entire pile) and the α, λ and β rules **in the clay layer**

How to **sum the shaft resistance across layers**; to interpret the jumps in friction at layer boundaries and the effect of pile length

To grasp that **in a bored pile** the α* window and c_{ub} may come from several layers

LECTURE FLOW

Each topic is covered in **three steps**:

1 · **Theory**: what is the rule, why is it so?

2 · **Problem statement**: given and required

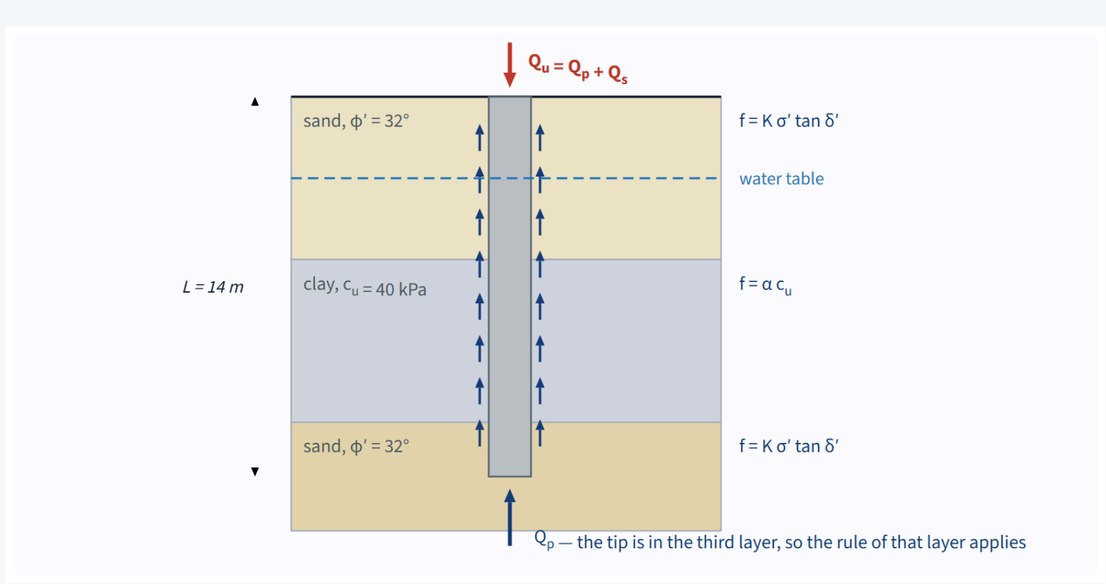
3 · **Solution**: step by step, with numbers

Most examples use the same pile: a 0.4 m diameter pile, 14 m long, passing through a sand–clay–sand profile.

This lecture builds on the **piles in sand** and **piles in clay** lectures: we learned the rules there; here we look at which applies where.

Each layer responds according to its own rule

THEORY



A pile rarely enters a single soil. The profile is **several layers**; each is defined as sand or clay and **the rule of its own material** is applied. The capacity again has two parts, but it is no longer read from a single formula; it is **built up piece by piece**:

$$Q_u = Q_p + Q_s \qquad Q_{all} = \frac{Q_u}{FS}$$

No new theory: sand rules belong to the sand module, clay rules to the clay module.

What is new is the **calculation scheme**: which rule applies in which part of the shaft and how effective stress accumulates from the layers above.

The end resistance comes from **a single layer**, the shaft resistance from **the sum of all layers**.

Stress continuous, friction stepped

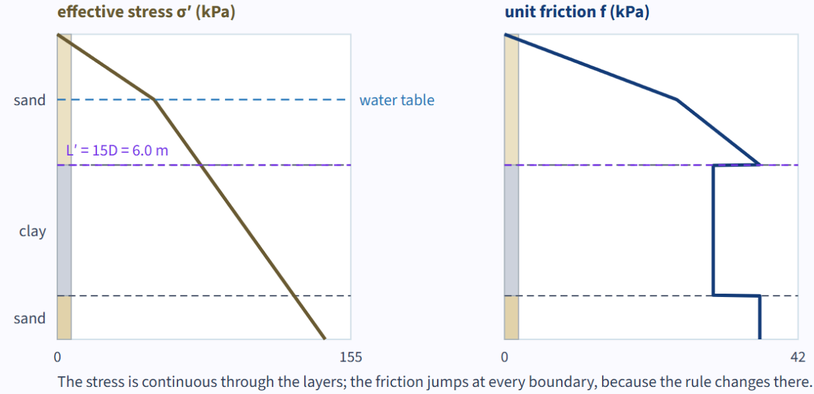
THEORY

Effective vertical stress is what links the layers together: **the weight of each layer above** accumulates; above the GWT the moist unit weight is used, below it the submerged unit weight.

$$\sigma'(z) = \sum \gamma_i h_i \qquad \text{(above GWT)}$$
$$+ \sum (\gamma_{sat,i} - \gamma_w) h_i \qquad \text{(below GWT)}$$

The clay layer does not contribute its own strength to the sand; but **through its weight** it alters the resistance offered by the sand beneath.

Friction, however, is not continuous: at the sand–clay boundary **the rule itself changes** and the unit friction may show a large jump. This jump is not an error of the calculation but the **signature** of the layered profile.



The stress is continuous through the layers; the friction jumps at every boundary, because the rule changes there.

Problem statement

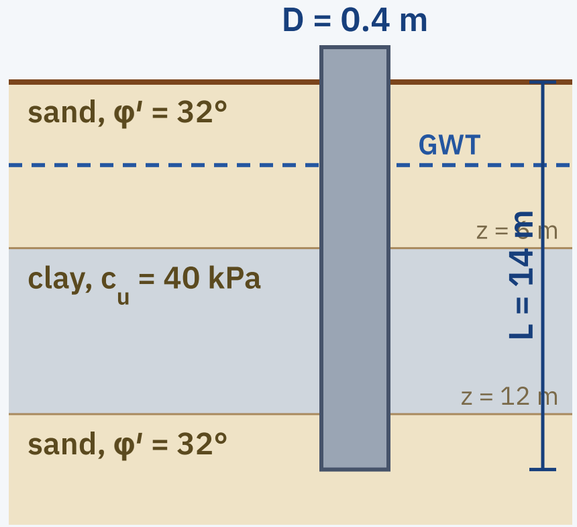
EXAMPLE

Given

Sand 1 (0–6 m)	$\varphi' = 32^\circ$
Clay (6–12 m)	$c_u = 40\ \mathrm{kPa}$
Sand 2 (12–16 m)	$\varphi' = 32^\circ$
Unit weight	$\gamma = 17,\ \gamma_{sat} = 18\ \mathrm{kN/m^3}$ **(three layers)**
Groundwater	**at 3.0 m depth**
Pile	**driven, D = 0.4 m, L = 14 m**
Unit weight of water	$\gamma_w = 9.81\ \mathrm{kN/m^3}$

REQUIRED

Find the effective vertical stress at depths of **3, 6, 12 and 14 m** (14 m = pile tip).



Solution (1/2)

SOLUTION

1 Down to the GWT (3 m): the entire layer is moist, γ = 17

$$\sigma'(3) = 17(3) = \mathbf{51.0}\ \text{kPa}$$

2 6 m (sand–clay boundary): below the GWT, $\gamma' = \gamma_{sat} - \gamma_w = 18 - 9.81$

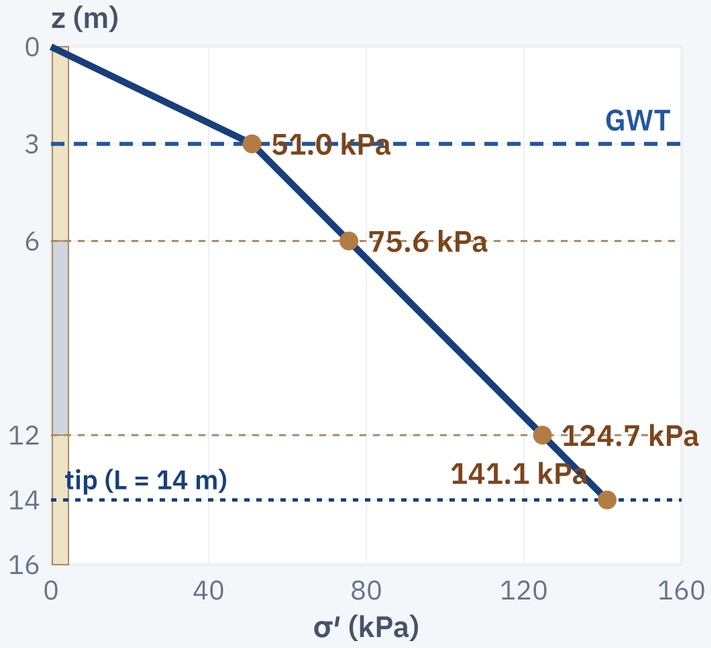
$$\sigma'(6) = 51.0 + (18 - 9.81)(3) = \mathbf{75.6}\ \text{kPa}$$

3 12 m (clay–sand boundary): the clay's γ_{sat} is also 18

$$\sigma'(12) = 75.6 + (18 - 9.81)(6) = \mathbf{124.7}\ \text{kPa}$$

4 14 m (pile tip)

$$\sigma'(14) = 124.7 + (18 - 9.81)(2) = \mathbf{141.1}\ \text{kPa}$$



Solution (2/2)

SOLUTION

5 In each segment the area of the σ′ diagram (trapezoid); these will give the average stress in the shaft calculation

$$A_{0-6} = \tfrac{1}{2}(0 + 51.0)(3) + \tfrac{1}{2}(51.0 + 75.6)(3) = 266.4$$
$$A_{6-12} = \tfrac{1}{2}(75.6 + 124.7)(6) = 600.8$$
$$A_{12-14} = \tfrac{1}{2}(124.7 + 141.1)(2) = 265.8$$

σ′ is **continuous across the layers**: there is no jump at the sand–clay boundary; the slope changes only at the GWT and where γ′ changes. These three areas will be used as the average σ̄′ in Examples 4 and 5.

Check the solution in GeoTerva ↗

The tip asks only its own layer

THEORY

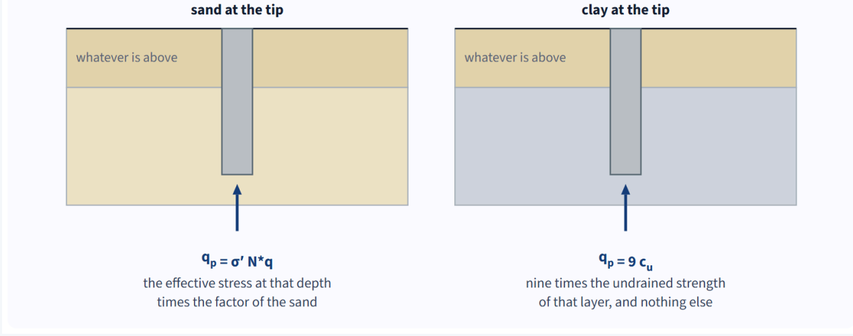
The end bearing belongs to **a single layer**: the layer in which the pile tip is located. It is calculated according to the material of that layer; the layers above act only through σ′ (**at a sand tip**) and **have no effect at a clay tip**.

$$\text{sand:}\quad Q_p = A_p\, q'\, N_q^* \le A_p\, q_l,\quad q_l = 0.5\, p_a N_q^* \tan\varphi'$$

$$\text{clay:}\quad Q_p = A_p\, c_u\, N_c^*,\quad N_c^* = 9\ \text{(Meyerhof)}$$

A pile whose tip coincides with **an exact boundary** is taken as resting on the layer **below** the boundary.

Coyle–Castello is a **sand** correlation; it has no meaning at a clay tip, and even if selected, the clay rule remains valid.



At the sand tip σ′ and N^*_q govern; at the clay tip only the c_u value of that layer.

Problem statement

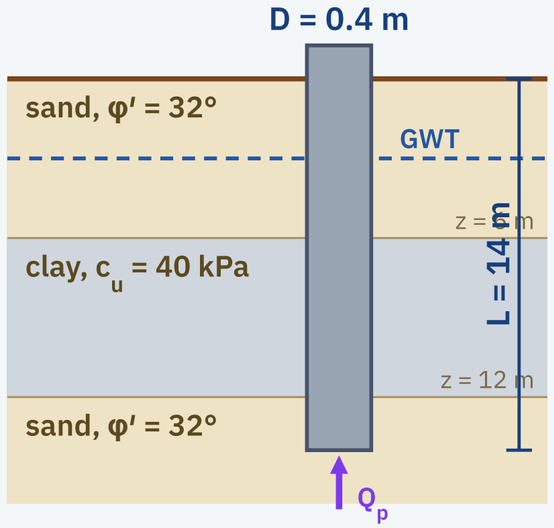
EXAMPLE

Given

Sand 1 (0–6 m)	$\varphi' = 32^\circ$
Clay (6–12 m)	$c_u = 40\ \mathrm{kPa}$
Sand 2 (12–16 m)	$\varphi' = 32^\circ$
Unit weight	$\gamma = 17,\ \gamma_{sat} = 18\ \mathrm{kN/m^3}$ **(three layers)**
Groundwater	**at 3.0 m depth**
Pile	**driven, circular section, D = 0.4 m, L = 14 m**
Tip method	**Meyerhof**
Atmospheric pressure	$p_a = 100\ \mathrm{kPa}$
Effective stress at the tip	$q' = \sigma'(14) = 141.1\ \mathrm{kPa}$ **(Example 1)**

REQUIRED

Determine the layer in which the tip lies and find the **tip resistance** Q_p.



Solution (1/2)

SOLUTION

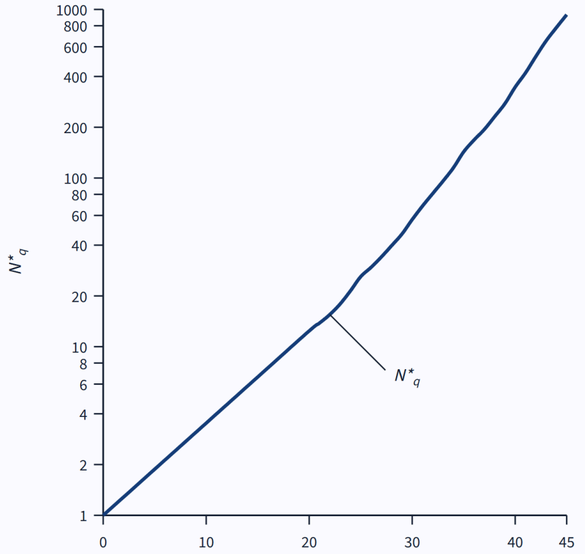
1 Layer of the tip: L = 14 m, within the sand between 12–16 m → sand rule (the clay above does not concern the tip)

$$\varphi' = 32^\circ \qquad q' = \sigma'(14) = 141.1\ \text{kPa}$$

2 N^*_q from the Meyerhof chart for φ′ = 32°; then the two values side by side

$$N_q^* = 81$$
$$q' N_q^* = 141.1(81) = 11{,}428\ \text{kPa}$$
$$q_l = 0.5(100)(81)\tan 32^\circ = 2{,}531\ \text{kPa}$$

The N^*_q value in the chart (at the side) is 81; $q'N^*_q$ = 11,428 kPa, far greater than the limit value q_l = 2,531 kPa: **the limit governs**.



Solution (2/2)

SOLUTION

3 Unit end bearing: the smaller of the two

$$q_p = \min(q' N_q^*;\ q_l) = \min(11{,}428;\ 2{,}531) = \mathbf{2{,}531}\ \text{kPa}$$

4 Area of the pile tip and end bearing

$$A_p = \frac{\pi (0.4)^2}{4} = 0.1257\ \text{m}^2 \qquad Q_p = A_p\, q_p = 0.1257(2{,}531) = \mathbf{318.0}\ \text{kN}$$

End bearing **318.0 kN**. Since the pile tip is in sand the sand rule applies; because the limit is engaged, the σ′ value does not change the result in this example.

Check the solution in GeoTerva ↗

Problem statement

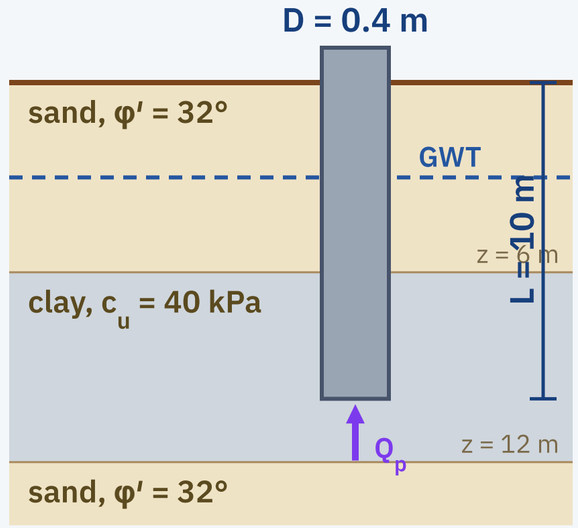
EXAMPLE

Given

Sand 1 (0–6 m)	$\varphi' = 32^\circ$
Clay (6–12 m)	$c_u = 40\ \mathrm{kPa}$
Sand 2 (12–16 m)	$\varphi' = 32^\circ$
Unit weight	$\gamma = 17,\ \gamma_{sat} = 18\ \mathrm{kN/m^3}$ **(three layers)**
Groundwater	**at 3.0 m depth**
Pile	**same pile, but L = 10 m**
Tip methods	**Meyerhof and Vesic**
Atmospheric pressure	$p_a = 100\ \mathrm{kPa}$

REQUIRED

If the pile is shortened to 10 m, determine the layer in which the tip remains and find the **tip resistance** by two methods.



Solution

SOLUTION

1 Layer at the end: L = 10 m, in the clay between 6–12 m → clay rule (sand and σ′ no longer enter the calculation)

$$c_u = 40\ \text{kPa} \qquad A_p = 0.1257\ \text{m}^2$$

2 Meyerhof: $N^*_c = 9$

$$q_p = 9\,c_u = 9(40) = 360\ \text{kPa} \qquad Q_p = 0.1257(360) = \mathbf{45.2}\ \text{kN}$$

3 Vesic: $I_{rr} = I_r = 347(c_u/p_a) - 33$

$$I_{rr} = 347(0.4) - 33 = 105.8$$

$$N_c^* = \tfrac{4}{3}(\ln 105.8 + 1) + \tfrac{\pi}{2} + 1 = 10.12$$

$$q_p = 40(10.12) = 405\ \text{kPa} \ \Rightarrow\ Q_p = 0.1257(405) = \mathbf{50.9}\ \text{kN}$$

For a pile with its tip in sand, Q_p = **318 kN**; in clay it is **45 – 51 kN**: about one-seventh. Extending the same pile by 2 m to reach sand sharply increases the tip resistance.

Check the solution in GeoTerva ↗

K–δ: the critical depth belongs to the whole pile

THEORY

In the sand layer, the shaft resists by friction against the horizontal effective stress. Each sand layer carries **its own** K and δ′ value:

$$f = K_i\,\sigma'\tan\delta_i' \quad (z \le L') \qquad f = f_{z=L'} \quad (z > L'), \quad L' = 15D$$

L′ belongs to **the entire pile**, not to a layer: below L′ the σ′ value is held at its value at L′.

A deep sand layer provides a **constant** unit friction along the layer, regardless of where its boundary lies.

Option: **Coyle–Castello**. The layer's own K (from the chart), δ′ = 0.8φ′ and the layer's average σ′ value; there is no critical depth, the average does the job.

COYLE–CASTELLO (PER LAYER)

$$f_i = K_i\,\bar{\sigma}_i'\tan(0.8\varphi_i')$$

$$Q_s = p\sum f_i\,\Delta L_i$$

In the K–δ method δ′ is often taken in the range 0.75φ′ – 0.8φ′; in this presentation **δ′ = 0.8φ′ = 25.6°** and **K = 1.0** will be used.

Problem statement

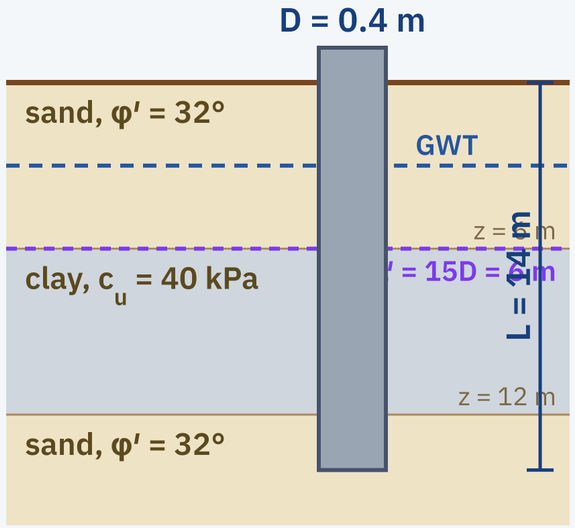
EXAMPLE

Given

Sand 1 (0–6 m)	$\varphi' = 32^\circ$
Clay (6–12 m)	$c_u = 40$ kPa
Sand 2 (12–16 m)	$\varphi' = 32^\circ$
Unit weight	$\gamma = 17,\ \gamma_{sat} = 18$ kN/m^3 **(three layers)**
Groundwater	**at 3.0 m depth**
Pile	**driven, D = 0.4 m, L = 14 m**
Perimeter	$p = \pi D = 1.257$ m
In sand layers	$K = 1.0,\ \delta' = 0.8\varphi' = 25.6^\circ$ **(enter these values in the module; the module opens with K = 0.66 and δ′ = 24°)**

REQUIRED

Find the shaft resistance of the **sand layers** (0–6 m and 12–14 m) by the K–δ method. Critical depth L′ = 15D.



Solution (1/2)

SOLUTION

1 Critical depth (single for the whole pile)

$$L' = \min(15D;\ L) = \min(15(0.4);\ 14) = \mathbf{6}\ \text{m} \qquad \sigma'(L') = 75.6\ \text{kPa (Example 1)}$$

2 Sand 1 (0–6 m): the layer lies entirely within L′; no cap; average σ′ = area / thickness

$$\bar{\sigma}'_1 = \frac{266.4}{6} = 44.4\ \text{kPa}$$

3 Unit friction and resistance

$$f_1 = K \tan\delta'\, \bar{\sigma}'_1 = 1.0(0.4791)(44.4) = 21.3\ \text{kPa}$$

$$Q_{s1} = p\, f_1 H = 1.2566(21.3)(6) = \mathbf{160.4}\ \text{kN}$$

Solution (2/2)

SOLUTION

4 Sand 2 (12–14 m): entirely below L′ → the σ′ value is held at its value at L′

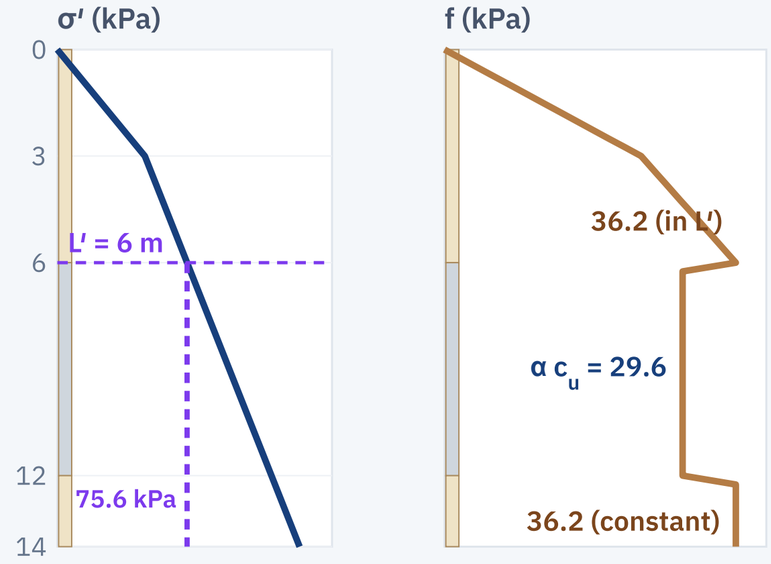
$$\sigma' = \sigma'(L') = 75.6\ \text{kPa}$$

$$f_3 = 1.0(0.4791)(75.6) = \mathbf{36.2}\ \text{kPa}$$

5 Resistance (thickness 14 − 12 = 2 m)

$$Q_{s3} = p\, f_3 H = 1.2566(36.2)(2) = \mathbf{91.0}\ \text{kN}$$

Without the critical depth, this segment would give σ′ = 132.9 kPa, f = 63.7 kPa and Q_{s3} = 160 kN. The **L′ cap** reduces the deep segment of the sand by **69 kN**.



Check the solution in GeoTerva ↗

In clay too, each layer selects its own method

THEORY

In the clay layer the shaft resists by **adhesion** or by **effective stress**; all three methods of the clay module can be used per layer:

$$\alpha: \ f = \alpha_i c_{u,i} \qquad \lambda: \ f_i = \lambda\,(\bar{\sigma}'_i + 2c_{u,i}),\ \lambda = \lambda(L)$$

$$\beta: \ \beta_i = (1 - \sin\varphi'_{R,i})\tan\varphi'_{R,i}\sqrt{OCR_i}, \quad f_i = \beta_i \bar{\sigma}'_i$$

α: **does not depend** on depth within the layer; friction is constant along the layer (uniform).

λ and β restore the effective stress; they produce a **step** depending on the overlying layers.

AN HONEST NOTE

Vijayvergiya and Focht wrote λ as **a single average over the entire embedded length**. Applying it separately to each clay layer in a layered profile (λ over length L, using that layer's average σ′ and c_u) is **an extension of the method specific to this program**; the module states this everywhere.

φ'_R and OCR are **entered**, not read from the soil by a correlation (opens with 30° and 1).

Problem statement

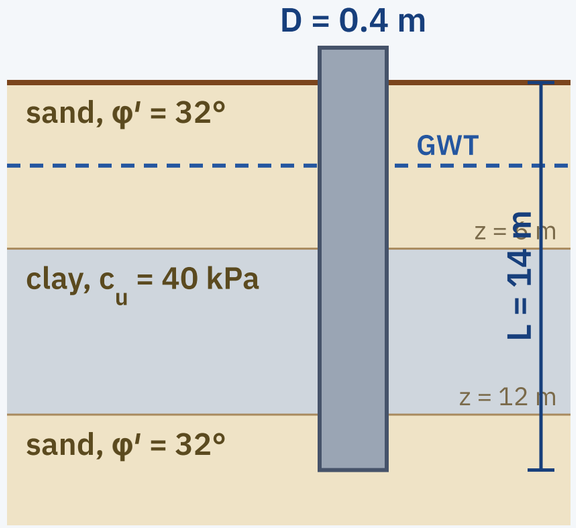
EXAMPLE

Given

Sand 1 (0–6 m)	$\varphi' = 32^\circ$
Clay (6–12 m)	$c_u = 40\ \mathrm{kPa}$
Sand 2 (12–16 m)	$\varphi' = 32^\circ$
Unit weight	$\gamma = 17,\ \gamma_{sat} = 18\ \mathrm{kN/m^3}$ **(three layers)**
Groundwater	**at 3.0 m depth**
Pile	**driven, D = 0.4 m, L = 14 m, p = 1.257 m**
Average σ′ of the clay	$\bar{\sigma}'_2 = A_{6-12}/6 = 100.1\ \mathrm{kPa}$ **(Example 1)**
for β	$\varphi'_R = 30^\circ,\ OCR = 1$
for α	$p_a = 100\ \mathrm{kPa}$**, α from table**

REQUIRED

Determine the shaft resistance of the clay layer (6–12 m) using the **α, λ and β** methods.



Solution (1/2)

SOLUTION

1 α method: from the table, α for $c_u/p_a = 0.4$

$$\alpha = 0.74 \quad f = \alpha c_u = 0.74(40) = 29.6\ \text{kPa} \quad Q_s = 1.2566(29.6)(6) = \mathbf{223.2}\ \text{kN}$$

2 λ method: λ from the table along the **pile length** (L = 14 m) ($\lambda_{10} = 0.245$; $\lambda_{15} = 0.200$)

$$\lambda = 0.209$$

$$f = \lambda(\bar{\sigma}_2' + 2c_u) = 0.209(100.1 + 2(40)) = 37.6\ \text{kPa}$$

$$Q_s = 1.2566(37.6)(6) = \mathbf{283.9}\ \text{kN}$$

Solution (2/2)

SOLUTION

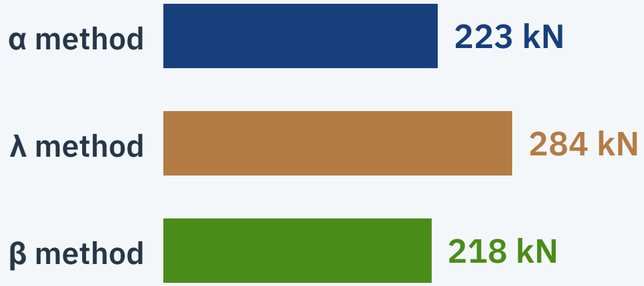
3 β method: $\varphi'_R = 30°$, OCR = 1

$$\beta = (1 - \sin 30^\circ)\tan 30^\circ = 0.289$$

$$f = \beta \bar{\sigma}'_2 = 0.289(100.1) = 28.9 \text{ kPa}$$

$$Q_s = 1.2566(28.9)(6) = \mathbf{218.0} \text{ kN}$$

The three methods give **223**, **284** and **218 kN** for the same clay layer: α and β are close to each other, while λ is about 27% higher. The difference stems from the assumptions underlying the methods; the use of λ per layer is moreover an extension.



Check the solution in GeoTerva ↗

A single integral: along the pile

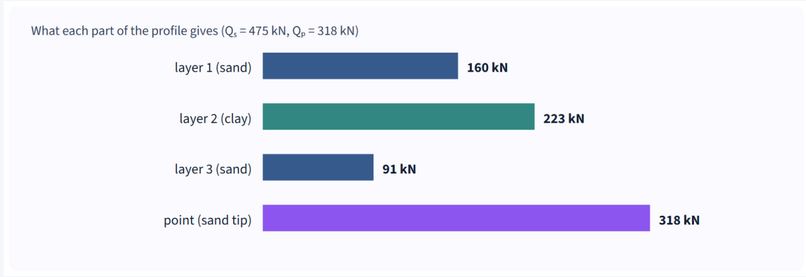
THEORY

The shaft resistance is the integral of the friction along the pile multiplied by the perimeter. The calculation is performed numerically; the boundary may be **anywhere**, and a pile ending in the middle of a layer does not require a special case:

$$Q_s = p \int_0^L f(z)\,dz \;\approx\; p \sum f_i\,\Delta z_i$$

Viewed this way, layering ceases to be a problem and becomes a **design question**: **which part** of the profile carries the pile?

How does the capacity change if the pile is extended beyond the next boundary or shortened?



Contribution of each section of the example pile (Q_s = 475 kN, Q_p = 318 kN).

Problem statement

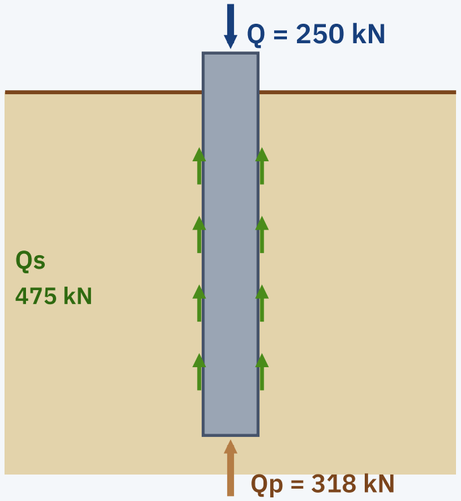
EXAMPLE

Given

Tip resistance	**Q_p = 318.0 kN (Example 2)**
Sand 1 (0–6 m)	**Q_{s1} = 160.4 kN (Example 4)**
Clay (6–12 m)	**Q_{s2} = 223.2 kN (α method, Example 5)**
Sand 2 (12–14 m)	**Q_{s3} = 91.0 kN (Example 4)**
Factor of safety	**FS = 3**
Working load on the pile	**Q = 250 kN**

REQUIRED

Find the **ultimate** and **allowable** bearing capacity of the pile; is the working load sufficient?



Solution

SOLUTION

1 Shaft resistance: sum of the segments

$$Q_s = 160.4 + 223.2 + 91.0 \approx \mathbf{474.5}\ \text{kN}$$

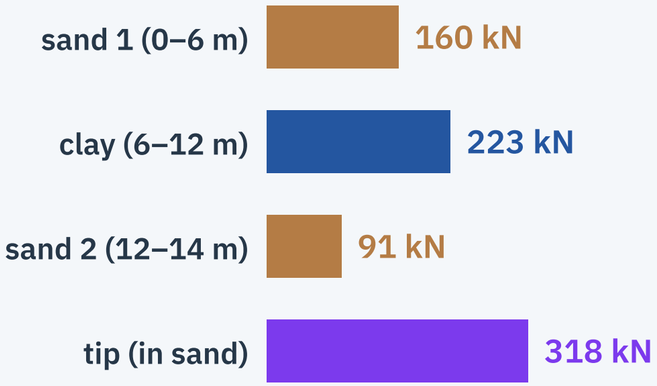
2 Ultimate bearing capacity

$$Q_u = Q_p + Q_s = 318.0 + 474.5 = \mathbf{792.6}\ \text{kN}$$

3 Allowable bearing capacity and check

$$Q_{all} = \frac{Q_u}{FS} = \frac{792.6}{3} = \mathbf{264.2}\ \text{kN}$$

$$Q = 250 \le 264.2 \ \Rightarrow\ \text{sufficient}$$



The utilization ratio is 0.95. The clay layer makes up only 43% of the shaft, but provides 47% of the capacity: beyond the critical depth the sand stops gaining σ′, while the clay gives the same α c_u value at every depth.

Check the solution in GeoTerva ↗

Problem statement

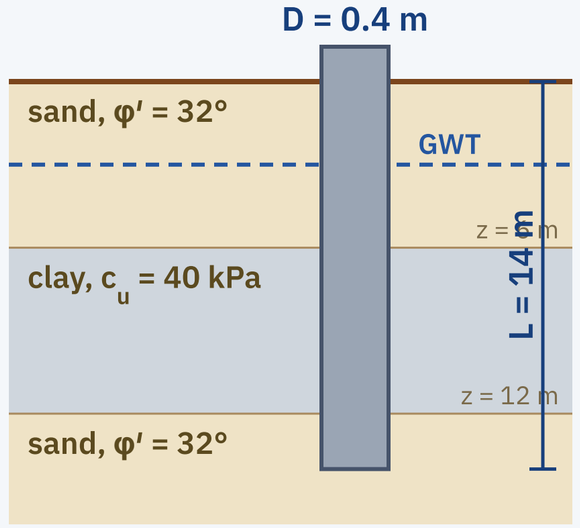
EXAMPLE

Given

Sand 1 (0–6 m)	$\varphi' = 32^\circ$
Clay (6–12 m)	$c_u = 40\ \mathrm{kPa}$
Sand 2 (12–16 m)	$\varphi' = 32^\circ$
Unit weight	$\gamma = 17,\ \gamma_{sat} = 18\ \mathrm{kN/m^3}$ **(three layers)**
Groundwater	**at 3.0 m depth**
Methods	**driven, D = 0.4 m; Meyerhof, α, K–δ**
Lengths	**L = 10, 12, 14 and 16 m**
Knowns	**Example 2–6 for L = 14 m**

REQUIRED

How does Q_u change if the pile length is **10, 12 and 16 m**? Explain the **reason** for the change.



Solution (1/2)

SOLUTION

1. L = 10 m: tip in clay (Example 3); clay section only 6–10 m

$$Q_p = 45.2\ ; \quad Q_s = 160.4 + 148.8 = 309.2\ ; \quad Q_u = \mathbf{354.4}\ \mathrm{kN}$$

2. L = 12 m: the tip is exactly at the boundary → **it bears on the sand below**; sand 2 does not yet enter the shaft

$$Q_p = 318.0\ ; \quad Q_s = 160.4 + 223.2 = 383.5\ ; \quad Q_u = \mathbf{701.6}\ \mathrm{kN}$$

3. L = 16 m: sand 2 is included in the shaft with a thickness of four meters (σ′ capped: f constant)

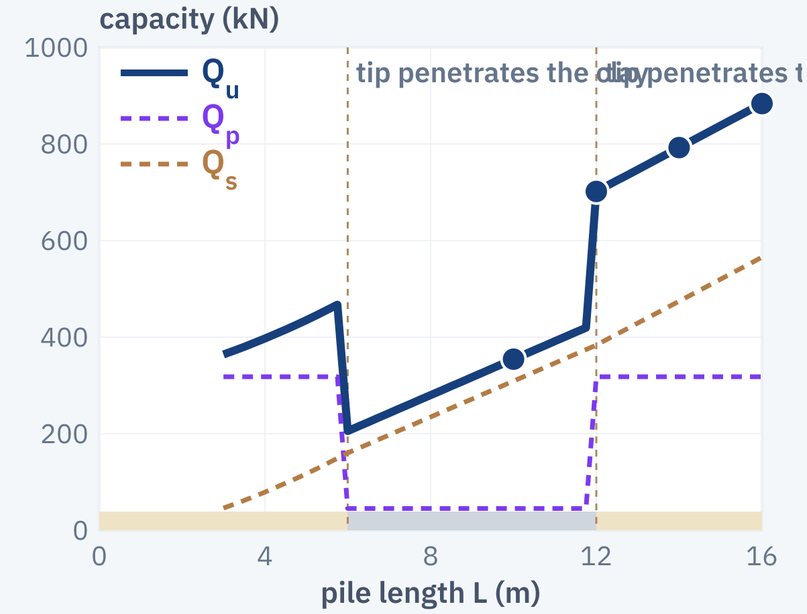
$$Q_p = 318.0\ ; \quad Q_s = 160.4 + 223.2 + 182.0 = 565.5\ ; \quad Q_u = \mathbf{883.6}\ \mathrm{kN}$$

Solution (2/2)

SOLUTION

L (m)	Tip layer	Q_p (kN)	Q_s (kN)	Q_u (kN)	Q_{all} (kN)
10	clay	45	309	**354**	118
12	sand	318	384	**702**	234
14	sand	318	475	**793**	264
16	sand	318	566	**884**	295

10 m → 12 m: capacity increases by **347 kN** (98%): 273 kN of this comes from **the tip penetrating into the sand**. Beyond 12 m, each metre adds only ≈ 45 kN. In a layered profile, what determines the pile length is **the layer in which the tip terminates**.



Check the solution in GeoTerva ↗

The rules of the bored pile also apply in a mixed profile

THEORY

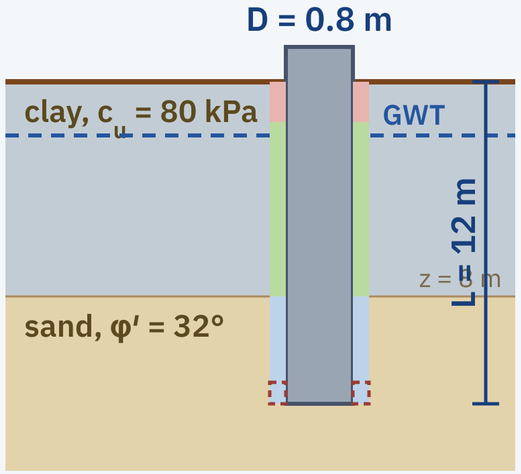
A hole is drilled, concrete is poured: the soil is not displaced, the clay softens on the borehole wall, cuttings may accumulate below the base. In a mixed profile, each half of the procedure is applied **where it belongs**:

Clay layers (α): α* = 0.55 ($c_u/p_a \le 1.5$); **top 1.5 m and bottom 1D**: α* = 0. The window belongs **only to α** and is not carried over to λ and β.

Sand layers retain their own K–δ or Coyle–Castello rule; K is around **$K_0 = 1 - \sin\varphi'$** since the soil is not displaced during driving.

If the **base** is in clay, Reese–O'Neill: $q_p = \min[6c_{ub}(1 + 0.2L/D_b), 9c_{ub}, 40p_a]$. c_{ub} is the average c_u over **$2D_b$** below the base; if the zone extends over more than one layer, it is weighted by thickness.

This zone must be **entirely clay**: if it extends into sand, the module stops and requires Meyerhof or Vesic to be selected.



Red: α* = 0 (top 1.5 m). Green: α* = 0.55. Blue: K–δ in sand. Dashed red: bottom 1D, no window in sand.

Problem statement

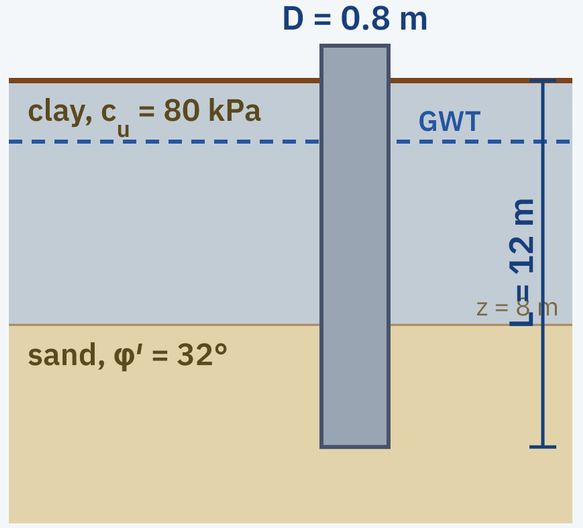
EXAMPLE

Given

Pile	**bored (drilled) pile, circular section, D = 0.8 m, L = 12 m**
Clay (0–8 m)	$c_u = 80\ \text{kPa},\ \gamma = \gamma_{sat} = 18\ \text{kN/m}^3$
Sand (8–20 m)	$\varphi' = 32^\circ,\ \gamma = 18,\ \gamma_{sat} = 19\ \text{kN/m}^3$
Groundwater	**at 2.0 m depth**
For sand	$K = K_0 = 0.47,\ \delta' = 0.75\varphi' = 24^\circ$
Tip	**Meyerhof; FS = 3**

REQUIRED

Determine the **end bearing**, **shaft resistance** and **allowable bearing capacity** of the bored pile.



Solution (1/3)

SOLUTION

1 Clay layer: α* and window (top 1.5 m and bottom 1D = 0.8 m discarded: 1.5 → 12 − 0.8 = 11.2 m)

$$\alpha^* = 0.55 \ (c_u/p_a = 0.8 \le 1.5) \qquad L_{eff} = 8 - 1.5 = \mathbf{6.5}\ \mathrm{m}$$

2 Unit friction and resistance

$$f = \alpha^* c_u = 0.55(80) = 44.0\ \mathrm{kPa} \qquad Q_{s1} = \pi(0.8)(44.0)(6.5) = \mathbf{718.8}\ \mathrm{kN}$$

Solution (2/3)

SOLUTION

3 Sand layer (8–12 m): its own K–δ rule; L′ = min(15D; L) = min(12; 12) = 12 m, i.e. no cap within the layer

$$\sigma'(8) = 85.1\ ;\ \sigma'(12) = 121.9\ \text{kPa} \qquad \bar{\sigma}' = \frac{414.1}{4} = 103.5\ \text{kPa}$$

4 Unit friction and resistance

$$f = K \tan\delta'\, \bar{\sigma}' = 0.47 \tan 24^\circ (103.5) = 21.7\ \text{kPa}$$

$$Q_{s2} = \pi(0.8)(21.7)(4) = \mathbf{217.8}\ \text{kN}$$

The **bottom 1D** portion of the α window (11.2 – 12 m) falls within the sand layer; since the window belongs to α, the sand maintains its friction over this 0.8 m as well.

Solution (3/3)

SOLUTION

5 Tip in sand → sand rule (Meyerhof); no additional reduction for drilling, the entered φ′ is used

$$q' = \sigma'(12) = 121.9\ \text{kPa} \qquad N_q^* = 81$$

$$q' N_q^* = 9{,}874 > q_l = 2{,}531\ \text{kPa} \ \Rightarrow\ q_p = 2{,}531\ \text{kPa}$$

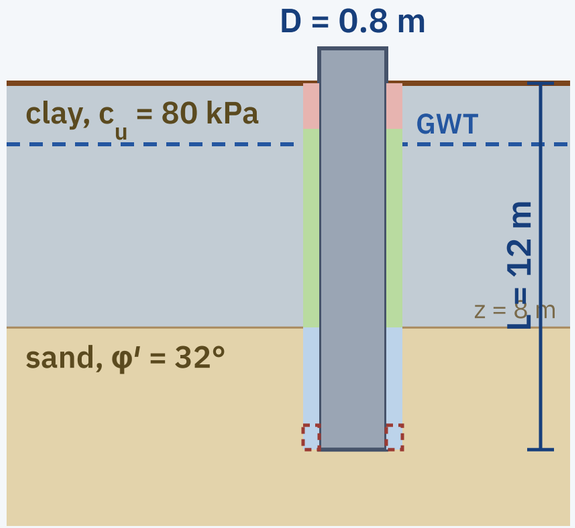
$$Q_p = A_p q_p = 0.5027(2{,}531) = \mathbf{1{,}272}\ \text{kN}$$

6 Total and allowable bearing capacity

$$Q_s = 718.8 + 217.8 = \mathbf{936.6}\ \text{kN}$$

$$Q_u = 1{,}272 + 937 = 2{,}209\ \text{kN}$$

$$Q_{all} = \frac{2{,}209}{3} = \mathbf{736}\ \text{kN}$$



Check the solution in GeoTerva ↗

Problem statement

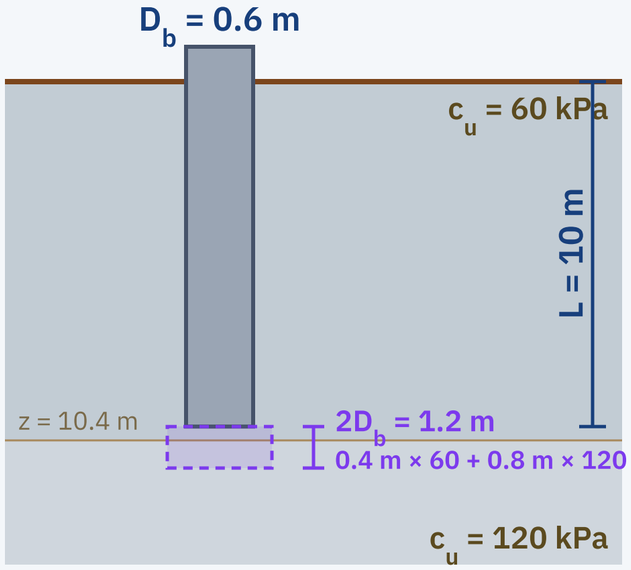
EXAMPLE

Given

Pile	**bored pile, $D_b = D = 0.6$ m, $L = 10$ m**
Clay 1 (0–10.4 m)	$c_u = 60$ kPa
Clay 2 (10.4–20 m)	$c_u = 120$ kPa
Base	**Reese–O'Neill; $p_a = 100$ kPa**

REQUIRED

Find c_{ub} in the $2D_b$ zone below the base, and the values of q_p and Q_p.



Solution

SOLUTION

1 Zone 10 → 10 + 2D$_b$ = 11.2 m; at the boundary 10.4 m: thickness-weighted average

$$c_{ub} = \frac{60(0.4) + 120(0.8)}{1.2} = \mathbf{100}\ \mathrm{kPa}$$

2 Smallest of the three values

$$6c_{ub}\left(1 + 0.2\frac{L}{D_b}\right) = 2{,}600\ ; \quad 9c_{ub} = 900\ ; \quad 40p_a = 4\,000 \ \Rightarrow \ q_p = \mathbf{900}\ \mathrm{kPa}$$

3 Base area and end resistance

$$A_b = \frac{\pi(0.6)^2}{4} = 0.2827\ \mathrm{m}^2 \qquad Q_p = 0.2827(900) = \mathbf{254.5}\ \mathrm{kN}$$

Had only the tip value c_u = 60 kPa been used, Q_p = 152.7 kN would result: the stiffer clay below gives **67%** more.

Check the solution in GeoTerva ↗

Single factor of safety, but the uncertainty is large

THEORY

The ultimate capacity is the sum of the two components; the allowable capacity is found by applying **a single factor of safety to the entire sum**:

$$Q_{all} = \frac{Q_p + Q_s}{FS}$$

For a single pile, usual **FS = 2.5 – 4**.

Upper end: where the profile is known from **few boreholes**. A layered profile is exactly this case: **the boundaries are most uncertain** between boreholes, and the example above showed how much a single metre of boundary shifts the capacity.

THE TWO ISSUES REQUIRE SEPARATE CALCULATIONS

In a layered profile, separately from the capacity calculation:

A soft layer settling and hanging on the pile as **negative skin friction**

Settlement governed by the compressible layer below the tip

Rules by layer and installation

THEORY

Layer	Shaft (Q_s)	Tip (Q_p): layer at the tip
Sand	K–δ (L′ = 15D, single value for the whole pile) or Coyle–Castello (K σ⃗ tan0.8φ′)	$q'N^*_q \le q_l$ (Meyerhof), Vesic, Coyle–Castello
Clay	α · λ (per layer: extension) · β	$9c_u$ (Meyerhof) · $N^*_c(I_{rr})$ (Vesic)
Fore, clay	α* = 0.55; top 1.5 m and bottom 1D = 0	Reese–O'Neill: average of $c_{ub} = 2D_b$
Fore, sand	$K \approx K_0 = 1 - \sin\varphi'$; the window is not applied	$q'N^*_q$ (entered φ′)

Each row is a separate selection for the relevant layer; **in the same pile** both the sand and clay rules are used.

Summary

Key points

Effective stress **accumulates across layers** and is continuous; unit friction, however, **jumps at boundaries**

The tip is calculated only using the rule for the layer in which the tip is located; a tip that coincides with a boundary is seated in the **underlying** layer

Sand: $f = K\sigma'\tan\delta'$ and **L′ = 15D applies to the whole pile** · **Clay**: α, λ (one extension per layer), β

The **shaft** is the sum of the layers: $Q_s = p\Sigma f_i \Delta z_i$; what determines the length is the layer in which the tip ends

Bored pile: the α* window is only for clay/α; if the base is in clay, c_{ub} over $2D_b$ (may be several layers)

$Q_{all} = (Q_p + Q_s)/FS$, FS = 2.5 – 4; for major works, a **load test**

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Das, B.M. (2016). Principles of Foundation Engineering, 8th ed. Cengage Learning, which brings these methods together in the form this page follows.

NOTE

The figures in this presentation are taken from the GeoTerva Theory page; all the numerical examples have been produced with the module's own calculation rules and library, and the module gives the same values.

GeoTerva

Online geotechnical analysis

From theory to practice

Calculate the example pile in this presentation step by step in GeoTerva: the numbers are the same.

Open the module →

Theory page →

Open on your phone
The example modules need no registration.

If you would like to use them in your lectures: info@geoterva.com