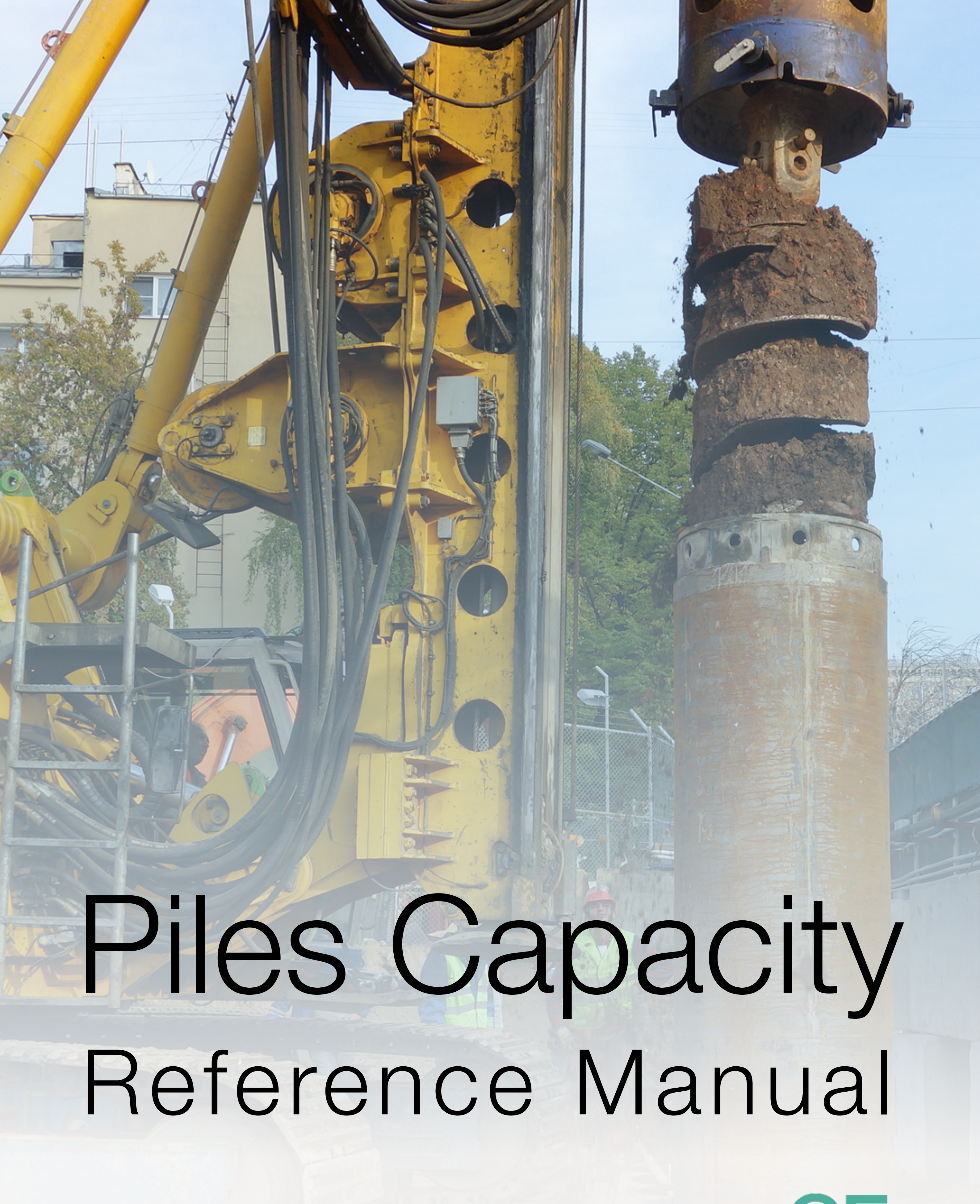


Piles Capacity

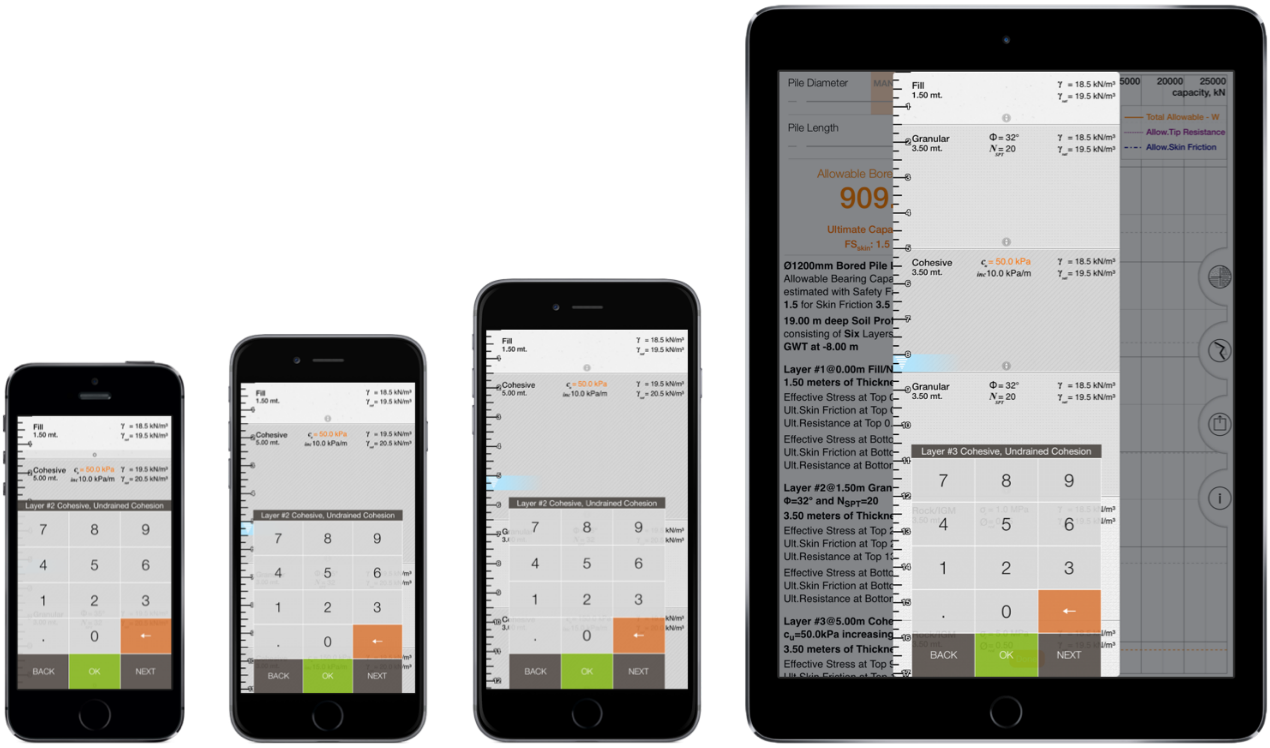
Reference Manual

hetGE
the new in geotechnics

Foreword

February 6, 2015

Piles Capacity is the mobile estimation tool for deep foundation designers dealing with pile bearing capacity of cast-in-place bored piles (also referred as drilled shafts) constructed in various soil profiles consisting of Granular layers (sand and gravel), Cohesive layers (clay and silt) and IGM-Rock strata (intermediate geotechnical materials and weak rocks).



Our touch-driven soil profile builder, the Touch Soil, is at the heart of Piles Capacity allowing you to see, touch, and manipulate the input with ease and convenience never before available in any other software. The rest of Piles Capacity has a modern design which priorities speed and simplicity to overcome complexity of the problem at hand.

For old school designers preferring keyboard and mouse, we have also developed a desktop version called **Piles Capacity XLS** for Windows-PCs with Microsoft Excel 2003 or higher installed.

Settings
Unit System: SI
☑ Optional Soil Parameters

General Properties
No. of layers: 10
z_w (m): 6.00
γ_w (kN/m³): 9.81

Pile Properties
D (mm): 1000
L (m): 9.00
γ_c (kN/m³): 25.00
W (kN): 153.60

Factor of Safety
F_s: 2.00

Calculation Results
Q_s (kN): 521.79
Q_b (kN): 235.62
Q_{ult} (kN): 603.81
Q_{all} (kN): 225.10
Q_{all} (tonne): 22.95

Layer Parameters

Layer #	1	2	3	4	5	6	7	8	9	10
Soil type:	Fill	Granular	Cohesive	Rock/IGM	Manual	Granular	Cohesive	Rock/IGM	Manual	Rock/IGM
H (m):	1.50	7.50	6.00	5.00	10.00	10.00	10.00	10.00	10.00	10.00
γ_t (kN/m³):	18.00	19.00	19.00	21.00	20.00	20.00	20.00	20.00	20.00	20.00
γ_{sat} (kN/m³):	19.00	19.00	19.00	22.00	21.00	21.00	21.00	21.00	21.00	21.00
c_u (kPa):	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
φ (°):	32.00	28.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00	32.00
σ_c (MPa):	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
q_s (kPa):	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
q_b (MPa):	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

Optional Parameters

	1	2	3	4	5	6	7	8	9	10
$c_{u,inc}$ (kPa/m):	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
N_{SPT}:	15	15	15	15	15	15	15	15	15	15
$Ø_{ucf}$:	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%
$q_{s,inc}$ (kPa/m):	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
$q_{b,inc}$ (kPa/m):	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Quick Reference

Editable regions are indicated by **yellow filled** cells. Data input mechanism is summarized below.

General Properties: Enter the number of layers, depth of GWT and the unit weight of water.

Pile Properties: Enter the diameter and the length of the cast-in-place bored pile and also the unit weight of concrete.

Factor of Safety: Enter the factor of safety to be used in the evaluation of allowable bearing capacity of the pile.

Layer Parameters: Enter the parameters of each layer of your soil profile. You may also input optional parameters if applicable.

Estimation Report

Detailed report of results and the graph of depth vs. bearing capacity are shown in: Estimation Report

User interfaces of these software are designed to be straightforward for seasoned pile designers; that means you don’t really need to read this or any other manual. This manual simply exists to clarify the estimation methods employed by our software.

In the pages of this manual, which is prepared by an extensive research of latest literature on the topic, you will find all references for our unique estimation engine utilised by both versions of Piles Capacity. There is also a detailed list of all references at the end of the manual.

Nomenclature

A_b	area of pile base
A_s	area of shaft surface
c_u	undrained cohesion at the pile toe
$c_{u,\mathrm{avg}}$	average undrained cohesion of soil layer
FS_b	factor of safety for tip resistance
FS_s	factor of safety for skin friction
$h_{penet.}$	depth of penetration into the layer
K	coefficient of lateral earth pressure
N_c	bearing capacity factor
N_q	bearing capacity factor (function of shear resistance angle, see Table 1)
N_{SPT}	standard penetration test blow count
p_a	atmospheric pressure (101 kPa or 14.7 psi)
Q_a	allowable bearing capacity
Q_b	ultimate tip resistance
q_b	ultimate unit tip resistance

Nomenclature (cont.)

Q_s	ultimate skin friction
q_s	ultimate unit skin friction
Q_u	ultimate bearing capacity
W	submerged pile weight
α	factor of adhesion (see Figure 1 for weak rock and IGMs)
ϕ'	effective angle of internal friction for the soil layer
ϕ_{red}	coefficient of diameter reduction for weak rock and IGMs
σ_c	unconfined compressive strength of the weak rock or IGM
σ'_v	vertical effective stress at the pile toe
$\sigma'_{v,\mathrm{avg}}$	average vertical effective stress along the layer

Table of Contents

General Approach

Let's start with simple clarifications for the sake of establishing a common understanding of the terms which are going to be used frequently throughout this manual.

Ultimate and allowable compressive load bearing capacities of bored piles (drilled shafts) with elements for skin friction and tip resistance, are defined below:

$$Q_u = Q_s + Q_b - W \tag{1}$$

$$Q_a = q_s \cdot A_s / FS_s + q_b \cdot A_b / FS_b - W \tag{2}$$

where

Q_u	ultimate bearing capacity
Q_a	allowable bearing capacity
W	submerged pile weight
FS_s, FS_b	factor of safety for skin friction and tip resistance, respectively
Q_s	ultimate skin friction
q_s	ultimate unit skin friction
A_s	area of shaft surface
Q_b	ultimate tip resistance
q_b	ultimate unit tip resistance
A_b	area of pile base

Please note that limiting values for ultimate skin friction and tip resistance, which will be given in the following chapters, are derived from Budhu (2011), pp. 544-545 except where noted.

Cohesive Soils

For cohesive soil deposits, such as clays and silts which are modestly characterised by the undrained shear strength parameter c_u, the evaluation of the shaft friction and the tip resistance is explained in the following sections.

Shaft Friction in Cohesive Material

The friction acting along the pile shaft in a cohesive layer can simply be estimated by:

$$q_s = \alpha \cdot c_{u,\,\mathrm{avg}} \tag{3}$$

where,

α factor of adhesion

$c_{u,\,\mathrm{avg}}$ average undrained cohesion of soil layer

Factor of adhesion α is equal to:

$$\alpha = \begin{cases} 0.55 & \text{for } c_u / p_a \le 1.5 \\ 0.55 - 0.1 \cdot \left(\dfrac{c_u}{p_a} - 1.5 \right) & \text{for } 1.5 < c_u / p_a \le 2.5 \end{cases} \tag{4}$$

where,

p_a atmospheric pressure (101 kPa or 14.7 psi)

General notes for shaft friction in cohesive soil layers:

- Reference for equations 3 and 4: O’Neill and Reese (1999), pp. B-27-28.
- Ultimate unit skin friction (q_s) has a limiting value of 380 kPa or 55 psi in cohesive soils.

Tip Resistance in Cohesive Material

The tip resistance of a pile resting in a cohesive layer is generally taken as:

$$q_b = N_c \cdot c_u \tag{5}$$

where,

N_c bearing capacity factor

c_u undrained cohesion at the pile toe

Bearing capacity factor N_c is equal to:

$$N_c = \begin{cases} 9.0 & \text{for } h_{penet.} \geq 3B \\ 6 + \dfrac{h_{penet.}}{B} & \text{otherwise} \end{cases} \tag{6}$$

where,

$h_{penet.}$ depth of penetration into the layer

General notes for tip resistance in cohesive soil layers:

- Reference for equations 5 and 6: Fleming et al. (2009), p. 108.
- Ultimate unit tip resistance (q_b) has a limiting value of 4000 kPa or 580 psi in cohesive soils.

Granular Soils

For granular soil deposits, such as sands and gravels, the estimation of the shaft friction and the tip resistance are presented in the following sections.

Shaft Friction in Granular Material

The friction acting along the pile shaft in a granular layer can be derived from:

$$q_s = K \cdot \sigma'_{v,\,\mathrm{avg}} \cdot \tan\phi' \tag{7}$$

where,

K	coefficient of lateral earth pressure
$\sigma'_{v,\,\mathrm{avg}}$	average vertical effective stress along the layer
ϕ'	effective angle of internal friction for the soil layer

Coefficient of lateral earth pressure K is defined as:

$$K = 0.85 \cdot (1 - \sin\phi') \tag{8}$$

General notes for shaft friction in granular soil layers:

- Reference for equations 7 and 8: Tomlinson and Woodward (2008), pp.165-171.
- Ultimate unit skin friction (q_s) has a limiting value of 200 kPa or 29 psi in granular soils.

Tip Resistance in Granular Material

The tip resistance of a pile resting on a granular layer is estimated by:

$$q_b = N_q \cdot \sigma'_v \tag{9}$$

where,

N_q bearing capacity factor (function of shear resistance angle, see Table 1)

σ'_v vertical effective stress at the pile toe

Table 1: Bearing capacity factor vs. angle of internal friction for granular soils, adapted from NAVFAC (1986), p.7.2-194.

ϕ	26	28	30	31	32	33	34	35	36	37	38	39	40
N_q	5	8	10	12	14	17	21	25	30	38	43	60	72

Ultimate unit tip resistance (q_b) can be also calculated using the standard penetration test (SPT) value of the bearing stratum at the pile toe. This value should be an average representing a thickness of 3 times the pile diameter (3B) beneath the pile toe. The SPT correlations are defined as:

$$\begin{aligned} q_b &= 57.5 \cdot N_{SPT} \quad (q_b \text{ in kPa}) \\ q_b &= 8.33 \cdot N_{SPT} \quad (q_b \text{ in psi}) \end{aligned} \tag{10}$$

General notes for tip resistance in granular soil layers:

- Reference for equation 9: Prakash and Sharmad (1990), pp. 221-222.
- Reference for equations 10: O’Neill and Reese (1999), p. B-22.
- Ultimate unit tip resistance (q_b) has a limiting value of 4312.5 kPa or 625 psi as advised by Mullins (2006), p. 307.

Weak Rocks and IGMs

For weak rock layers or IGMs (intermediate geomaterials), some simple methods for the estimation of the shaft friction and the tip resistance are presented in the following sections.

Shaft Friction in Weak Rocks and IGMs

The shaft friction along the part of the pile socketed in weak rock or IGMs can be approximated by:

$$q_s = \alpha \cdot \sigma_c \tag{11}$$

where,

σ_c	unconfined compressive strength of the weak rock or IGM
α	factor of adhesion obtained from the empirical data (Figure 1)

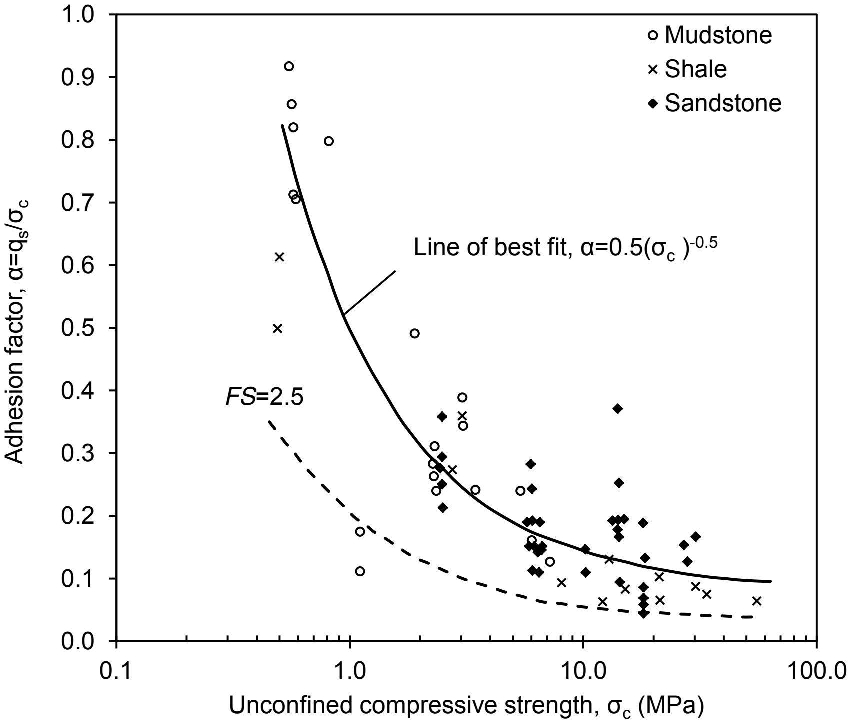


Figure 1: Relationship between the factor of adhesion and the unconfined compressive strength of rock (after Wyllie, 1999; after Williams and Pells, 1981).

Thus, the shaft friction equation becomes:

$$q_s = 0.5 \cdot (\sigma_c)^{0.5} \tag{12}$$

General notes for shaft friction in weak rock:

- Reference for equations 11 and 12, and Figure 1: Wyllie (1999), pp. 258-263.
- Ultimate unit skin friction (q_s) has a limiting value of around 10 MPa or 1450 psi since the adhesion factor converges to 0.10 for an extreme unconfined strength of 100 MPa as illustrated in Figure 1 for weak rocks and IGMs.

Tip Resistance in Weak Rocks and IGMs

The tip resistance of a pile socketed in weak rock or IGMs can be approximated with the following formula which uses a wide range of field test data (Figure 2).

$$q_b = 4.83 \cdot \left(\sigma_c\right)^{0.51} \tag{13}$$

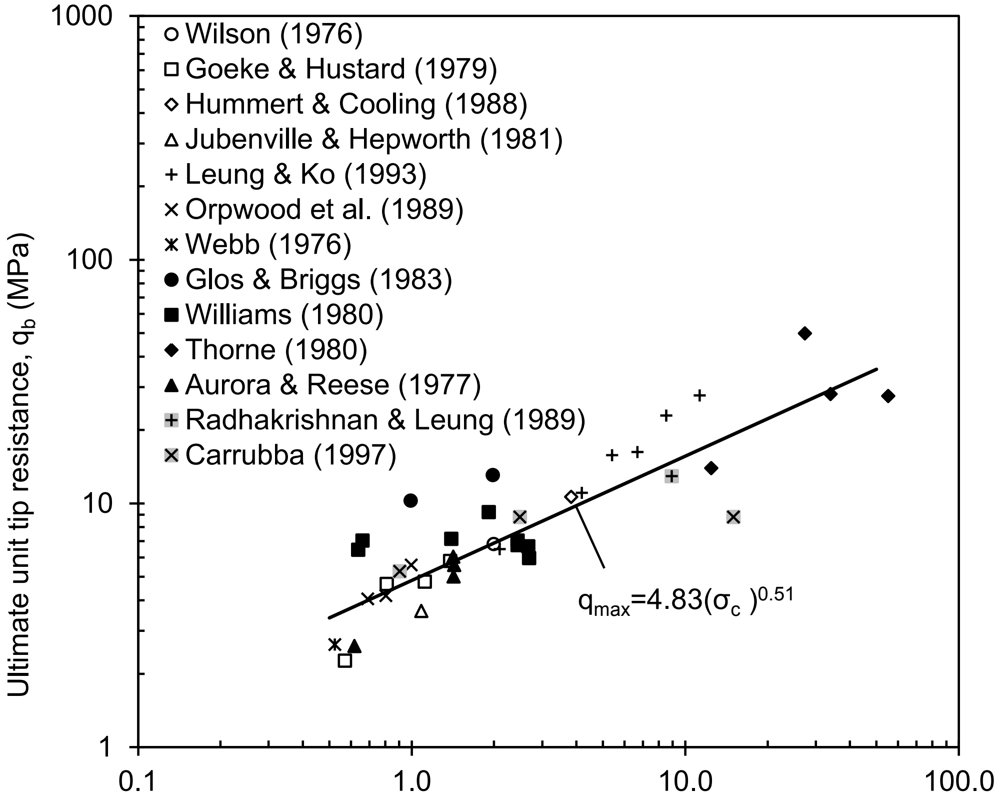


Figure 2: Relationship between the ultimate unit tip resistance and the compressive strength of weak rock (after Zhang, 2004)

General notes for tip resistance in weak rock:

- Reference for equation 13 and Figure 2: Zhang (2004), p. 219.
- Ultimate unit tip resistance (q_b) has a limiting value of 50 MPa or 7250 psi for weak rocks and IGMs as suggested by Figure 2. But the ultimate bearing capacity of rock sockets are generally limited by the compressive strength of the reinforced-concrete material inside the shaft.

We strongly recommend not to rely only on these simple approximations for pile bearing capacity in rocks, since there are many other methods which incorporate other crucial rock parameters such as the RQD, shaft roughness and the fracture structure at the rock socket, etc.

Diameter Reduction Coefficient in Weak Rocks and IGMs

For pile drilling in rocks or in stiff soil deposits like IGMs, the diameter of the pile body might be reduced due to the temporary pile casing being terminated above the level of these stratum leaving only the drill lead (auger, bucket etc.) penetrating into these hard base materials (Figure 3).

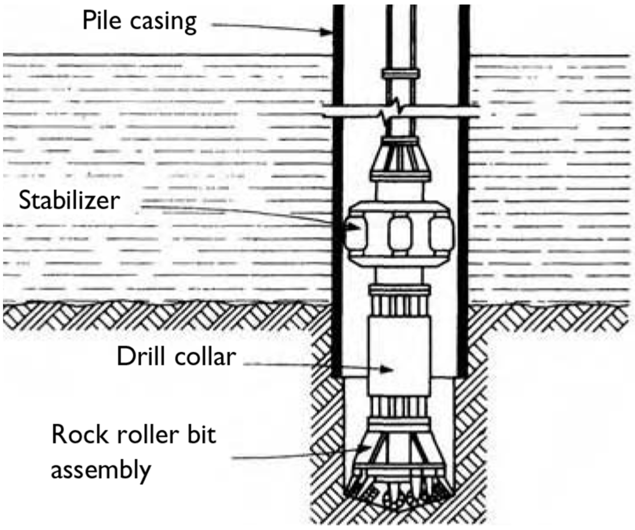


Figure 3: Typical pile tip drilling in rock (Tomlinson and Woodward, 2008)

To calculate the reduction in surface areas of the pile shaft and the tip, we have introduced a coefficient called Diameter Reduction (ϕ_{red}), which is the ratio of the pile diameter in rock or IGM layer (without casing), to the diameter in the rest of pile body (with casing). The maximum value for this parameter is 0.99≈1.

Tip Resistance Correction

Typical depth vs. bearing capacity graphs exhibit discrete change at layer boundaries, where the pile is just resting on (without any penetration into) a layer with different tip bearing characteristics.

Indeed this discrete change does not exist in reality due to the presence of the punching wedge at the pile tip, which is shown in Figure 4.

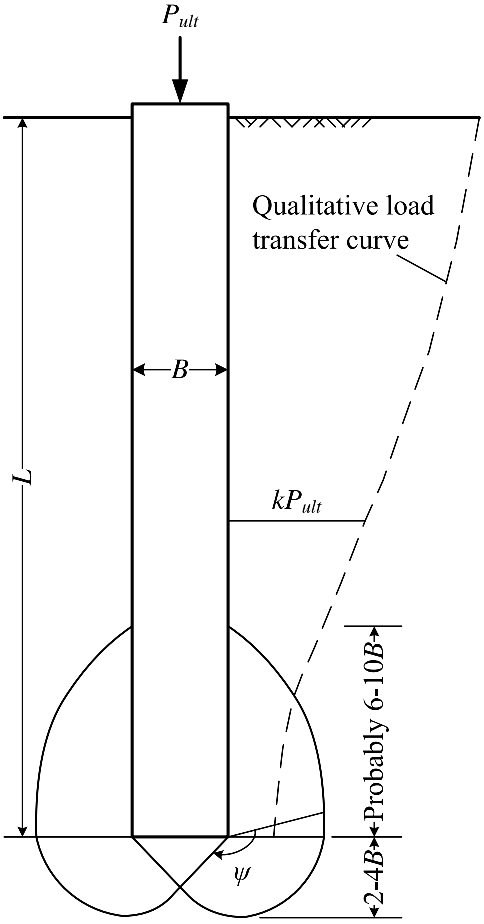


Figure 4: The soil wedge at the pile tip which goes as deep as 2 to 4 times the pile diameter. (Bowles, 1997)

Considering this fact, we have implemented the tip resistance correction feature which allows investigating the effect of underlying soil strata on the end bearing resistance of pile. When the tip resistance correction is enabled, the tip resistance graph is smoothed by linear interpolation between the tip resistance value of the pile resting on the underlying strata, and the tip resistance value at the level 3 times the diameter – median value for 2~4B from Figure 4 – above the boundary.

Figure 5 shows the depth vs. bearing capacity graphs for both cases where the tip resistance correction is disabled and enabled, respectively. In this figure, it can be observed that, the tip resistance values (shown with purple line) at layer interfaces (shown with dashed horizontal grey lines) and at a depth 3 times the pile diameter above those boundaries, remain unchanged, while the tip resistance values in between these two locations are linearly interpolated, either decreasing or increasing the original end bearing values.

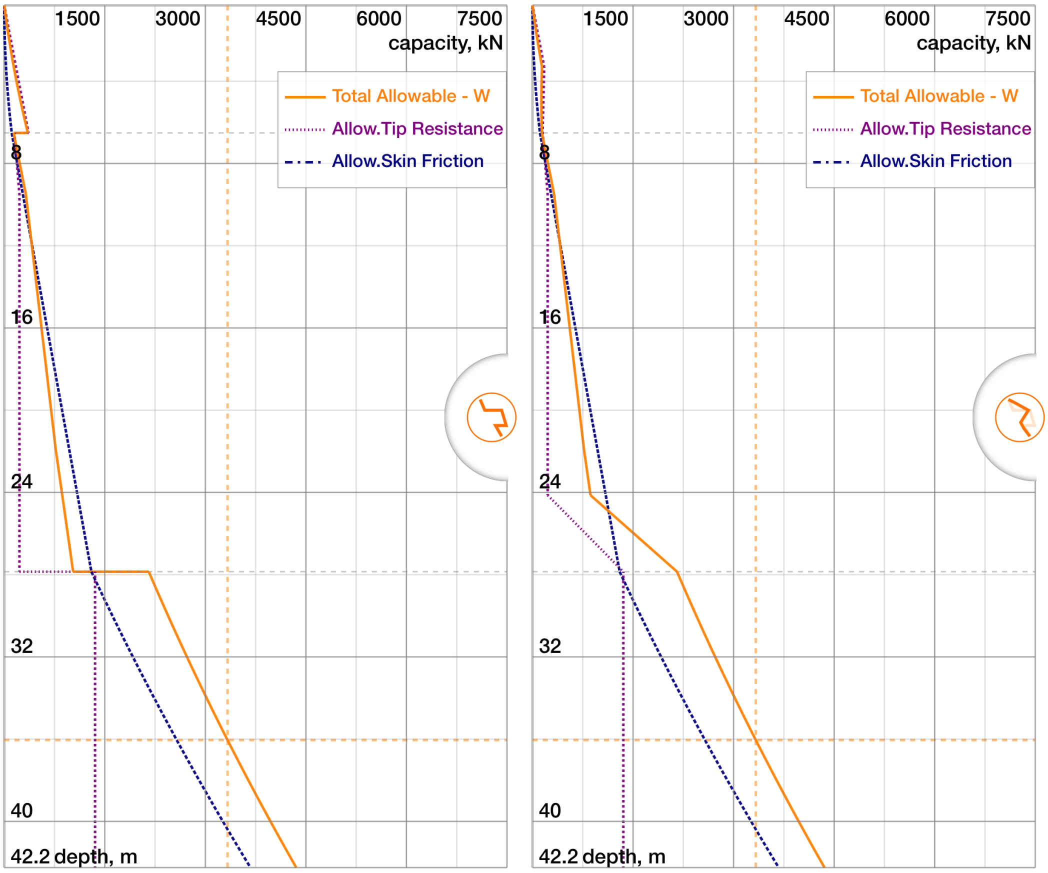


Figure 5: Depth vs. bearing capacity graph, produced with tip resistance correction is disabled (left) and enabled (right), respectively.

Please note that this feature is currently only available in **Piles Capacity for iOS**. It can be enabled by simply tapping the orange button on the right side of the graph, and it is automatically disabled for cases when the current or the previous layer is Weak Rock or IGM for which any punching wedge is unlikely to occur.

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Closing Remarks

We at hetGE, always believed that engineering software do not have to be over complicated, ugly and difficult to use. If you already have years of experience, education, training in piling, you shouldn't spend more time reading manuals (this manual you are reading simply exists for your reference and peace of mind), or playing guessing games with the software. This is why we started developing software in the first place.

Refined and globally accepted estimation methods wrapped into a clear and intuitive design, with **Piles Capacity** you can touch to build soil profiles, slide through different diameter and length combinations, and get reliable results faster than any other software in the industry.

But please do remember this; results of different estimation methods show a quite good scatter for the load bearing capacity of cast-in-place bored piles aka drilled shafts. Particular expertise for selecting the correct bearing capacity range is mostly based on the presence of local practice.

In cases where no case history record is present for estimating the pile bearing capacity, it is strongly advised to implement a full-scale load testing program and investigate typical tip resistance and skin friction values for underlying soil strata.

We have implemented a custom soil model in **Piles Capacity XLS** named "Manual", where the user can directly enter the previously known tip resistance and skin friction values along with their increment with respect to depth. Using these data, actual bearing values can be easily analysed by the software.

We would like to stress once again that our software is designed for geo-professionals with considerable experience. If you are not one, you should **consult an expert** whilst using our apps.

We are always looking for new user interface ideas and more contemporary estimation methods to improve Piles Capacity. For this reason or any other questions or comments, you can reach us at **hetGE.com/contact**.

There is also a newsletter which is published when we have important announcements to make. You can subscribe to it at **hetGE.com/newsletter**.

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