Piles Capacity
Reference Manual

hetGE

Piles Capacity
Reference Manual

April 3, 2013

Version: PC-1.3.130403

Prologue

Piles Capacity is the "Estimator for Deep Foundation Designers", which is built to be employed by geo-professionals for investigating the undrained pile bearing capacity of cast-in-place bored piles (also referred as drilled shafts) constructed in various soil profiles consisting of Granular layers (sand, gravel), Cohesive layers (clay, silt) and IGM-Rock strata (intermediate geotechnical materials, weak rocks).

There are two versions of Piles Capacity for the most popular mobile and desktop platforms:

- **iOS version** running on iPhones, iPads, iPod Touches running system version 5.0 or higher,

- **XLS version** running on Windows-PC with Microsoft Excel 2003 or higher installed.

The user interfaces of these software are designed to be straightforward with no need for reading a user guide. In the iOS version, almost all labels visible on the screen can be tapped to carry out particular functions and modifications. Here are some examples:

- Tapping on the label with FoS on the main screen, toggles between different set of safety factors;

- To changes the soil type of a layer, just tap on its soil type label,

- To set the values of the soil parameters, just tap on them to bring up a numerical type pad,

- To change thickness of any layer, just drag the circular handle located at the bottom of the layer. Please note that layer thicknesses are rounded by 0.25 meters (SI units) or 1 feet (US units) by design of the touch driven interface.

Both versions of Piles Capacity share the same unique estimation engine which is:

- designed with speed and simplicity to overcome complexity of the problem at hand quickly,

- prepared by an extended research of latest literature on the topic,

- completely open with full references given in following pages.

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 document.

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

$$Q_u = Q_s + Q_b - W$$
$$Q_a = q_s \cdot A_s / FS_s + q_b \cdot A_b / FS_b - W$$

(1)

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 Soil Deposits

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

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

where,

p_a atmospheric pressure (101 kPa or 14.7 psi)

General notes for shaft friction in cohesive soil layers:

- Reference for Eq. 3—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 on 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:

$$N_c = \begin{cases} 9.0 & \text{for } h_{penet.} \geq 3B \\[2mm] 6 + \dfrac{h_{penet.}}{B} & \text{otherwise} \end{cases} \tag{6}$$

where,

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

General notes for tip resistance in cohesive soil layers:

- Reference for Eq. 5—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 Soil Deposits

For granular soil deposits, such as sands and gravels, the estimation of shaft friction and 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 shear resistance angle of soil layer

Coefficient of lateral earth pressure K is :

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

General notes for shaft friction in granular soil layers:

- Reference for Eq. 7—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:

$$q_b = N_q \cdot \sigma_v'$$ (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 factors for different shear resistance angles (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 SPT number of the bearing stratum at the pile toe. This value should be an average representing 3B thickness beneath the pile toe.

$$q_b = 57.5 \cdot N_{SPT} \quad (q_b \text{ in kPa})$$ (10)
$$q_b = 8.33 \cdot N_{SPT} \quad (q_b \text{ in psi})$$

General notes for tip resistance in granular soil layers:

- Reference for Eq. 9: Prakash and Sharmad (1990), pp. 221−222.

- Reference for Eq. 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 shaft friction and tip resistance are presented in the following sections.
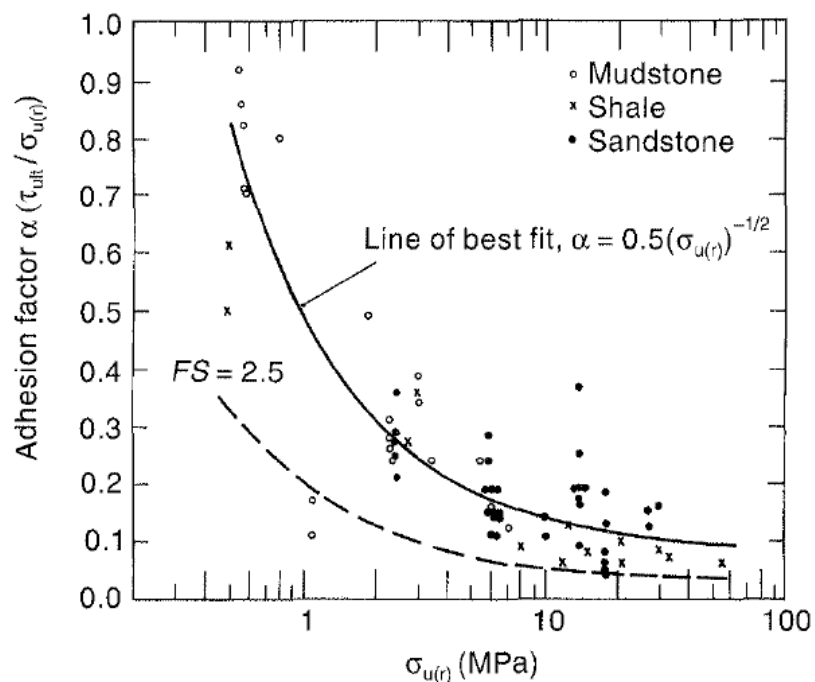
Shaft Friction in Weak Rocks and IGMs

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 using the empirical data from field tests (Figure 1)

Figure 1: Relationship between unconfined compressive strength of rock and factor of adhesion (Wyllie, 1999; after Williams and Pells, 1981, courtesy of Research Journals. National Research Council Canada). $\sigma_{u(r)}$: rock unconfined compressive strength; τ_{ult}: ultimate side-wall shear stress.

Thus, the shaft friction equation becomes:

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

General notes for shaft friction in weak rock:

- Reference for Eq. 11—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).

$$q_b = 4.83 \cdot \left(\sigma_c\right)^{0.51} \tag{13}$$
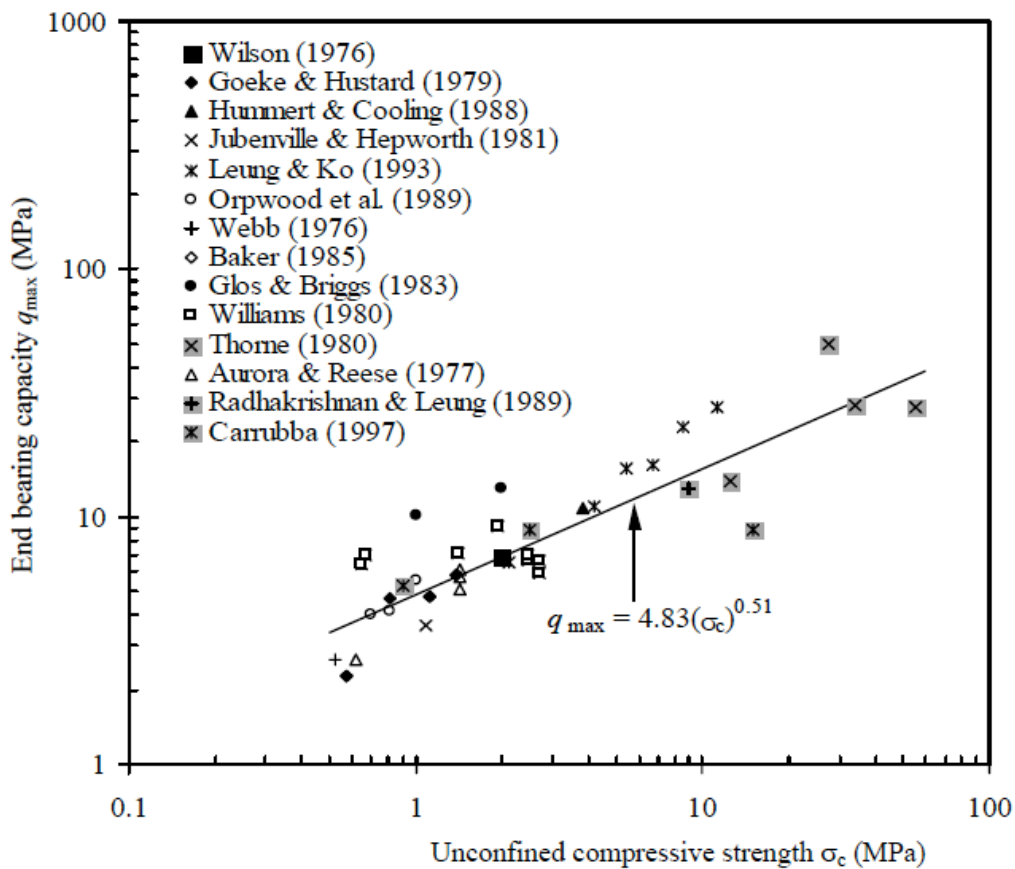
Figure 2: Relationship between compressive strength of weak rock and end bearing capacity (Zhang, 2004; after Zhang and Einstein, 1998)

General notes for tip resistance in weak rock:

- Reference for Eq. 13: Zhang (2004); after Zhang and Einstein (1998), pp. 211—219.

- Ultimate 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 generally the ultimate bearing capacity of rock sockets are actually limited by the compressive strength of reinforced-concrete 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 take into consideration 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 can be reduced at the pile tip. Because the temporary pile casing is generally terminated above the level of these stratum and only the drill lead (auger, bucket etc.) penetrates into these hard base materials (Figure 3).
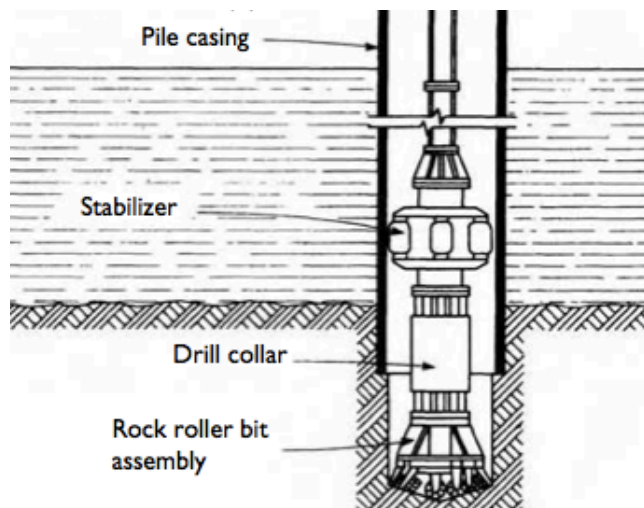

Figure 3: Typical pile tip drilling in rock (Tomlinson and Woodward, 2008)

To calculate the reduction in surfaces of pile shaft and pile 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.
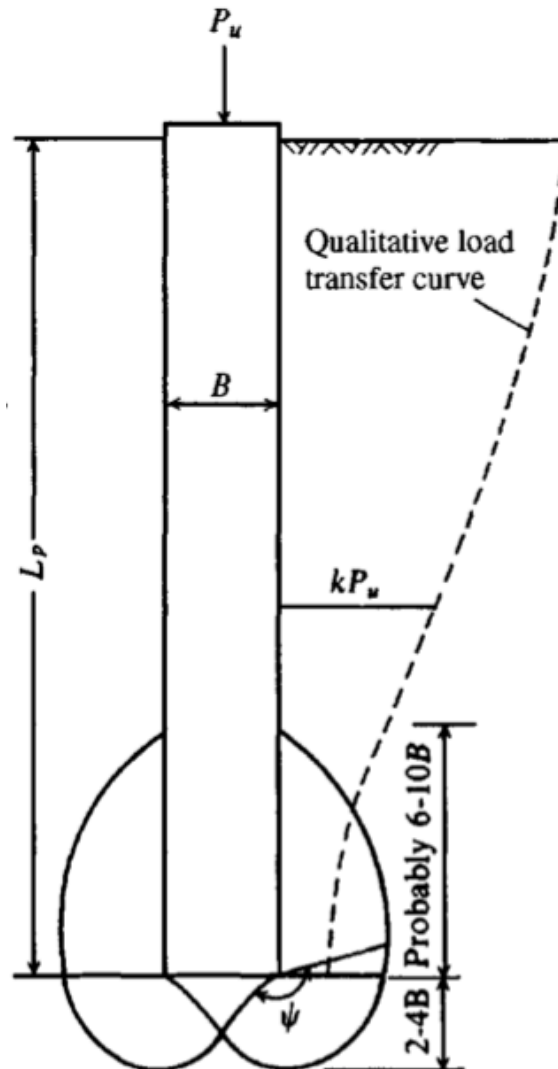
Tip Resistance Correction

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.
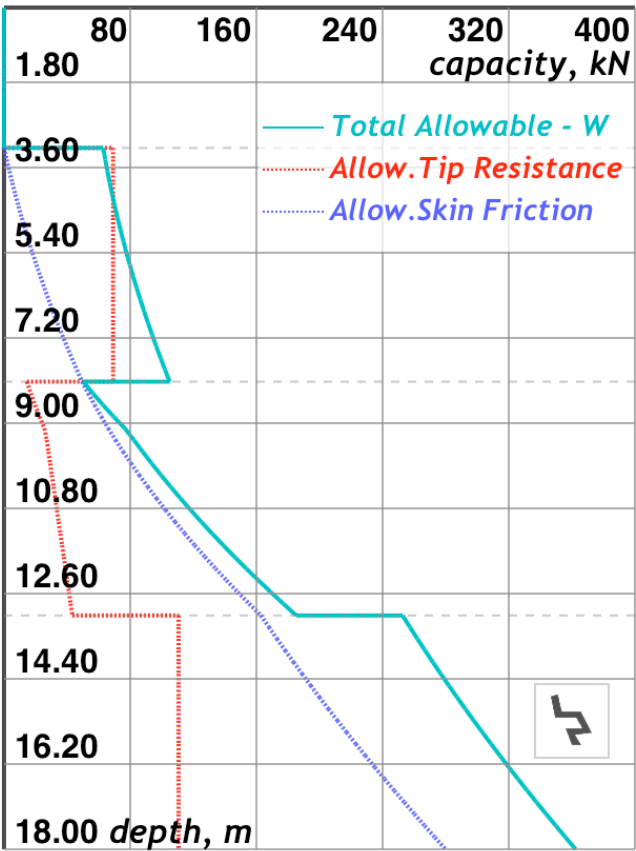
Figure 4: Depth vs. bearing capacity graph, produced with Piles Capacity ver. 1.2 with <u>Tip Resistance Correction turned off</u>.

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 5 on the next page.

Figure 5: 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 – by simply tapping the iconized button on the right bottom side of the graph –, 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 – above the boundary.

Here is how the same graph from Figure 4 looks, when the tip resistance correction is enabled. You can observe in Figure 6 that, the tip resistance values (shown with red lines) at the layer boundaries (shown with dashed horizontal gray lines) and at a distance of up to 3 times the pile diameter on the layer above the interface are unchanged after the correction. The tip resistance values residing in the range between these two locations are linearly interpolated, either decreasing or increasing the original end bearing values.
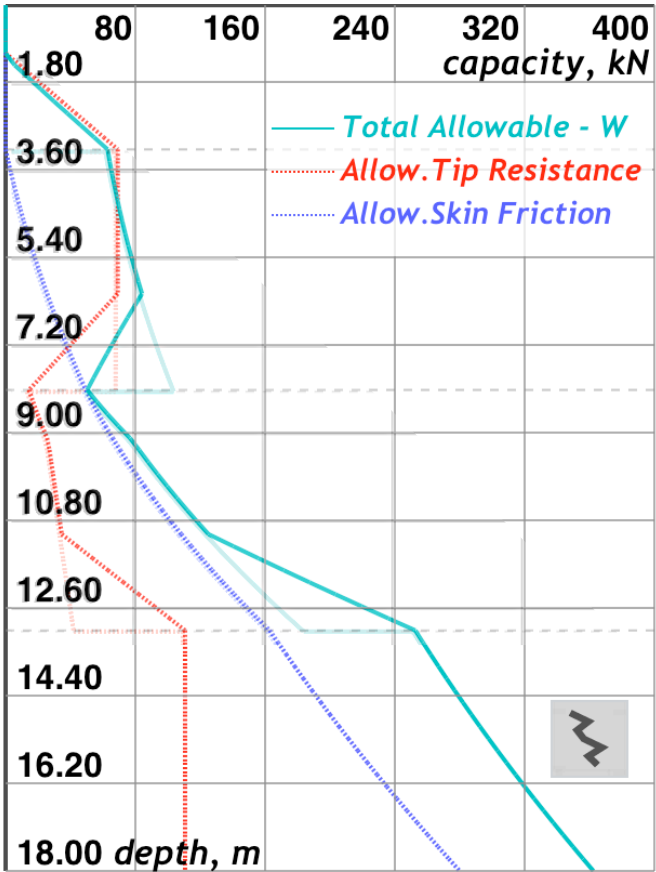
Figure 6: Depth vs. bearing capacity graph, produced with Piles Capacity ver. 1.2 with <u>Tip Resistance Correction turned on</u>. Old values are shown transparently.

Please note that this feature is currently only available in iOS version and that it is automatically disabled for cases when the current or the previous layer is Weak Rock or IGM.

Bibliography

Bowles, J.E. (1997) *Foundation Analysis and Design*, 5th ed. McGraw-Hill, New York.

Brown, D. A., Turner, J. P., Castelli, R. J. (2010) *Drilled Shafts: Construction Procedures and LRFD Design Methods*, FHWA-NHA-10-016.

Budhu, M. (2011) *Soil Mechanics and Foundations*, 3rd ed. John Wiley & Sons, New York.

Fleming, K., Weltman, A., Randolf, M. and Elson, K. (2009) *Piling Engineering*, 3rd ed. Taylor & Francis, New York.

Mullins, G. (2006) *Design of Drilled Shafts,* chapter in book edited by Gunaratne, M. (2006) *The Foundation Engineering Handbook,* CRC Press, Florida.

NAVFAC (Naval Facilities Engineering Command) (1986) Design Manual 7.02, Foundations & Earth Structures. U.S. Government Printing Office, Washington, D.C.

O'Neill, W. M. and Reese, C. L. (1999) *Drilled Shafts: Construction Procedures and Design Methods*, FHWA-IF-99-025.

Prakash, S. and Sharmad H. (1990) *Pile Foundations in Engineering Practice*, John Wiley & Sons, New York.

Tomlinson M. and Woodward, J. (2008) *Pile Design and Construction Practice*, 5th ed. Taylor & Francis, New York.

Wyllie, D.C. (1999) *Foundations on Rock*, E & FN Spon, London.

Zhang, L. (2004) *Drilled Shafts in Rock: Analysis and Design*, Taylor & Francis, London.

Epilogue

Results of different estimation methods show a quite good scatter for the axial bearing capacity of cast-in-place bored piles aka drilled shafts. Particular expertise for selecting the correct bearing capacity range is mostly based on presence of local practice.

In cases where no case history record is present for 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 XLS version named "Manual", where the user can directly enter the previously known tip resistance and skin friction values together with their increment with respect to depth. Using these data, actual bearing values can be analyzed easily 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 directly reach us from **hetGE.com/contact**.

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

Alternatively, here are the social networks which you can follow us from:

twitter.com/hetGE   **facebook.com/hetGE**   **linkedin.com/company/hetGE**